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

Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Lake Nowergup

Hydrogeological record series

Report no. HG40
July 2011

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Preface

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

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

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

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

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

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

Summary

Lake Nowergup, situated on the Gnangara Mound, is one of the 28 sites in the Perth shallow groundwater system (SGS) investigation. The lake is a conservation category wetland and a Ministerial criteria site that the Department of Water manages to conserve its ecological values. Prior to this study, no detailed investigations on a local scale had been undertaken and the complex nature of this system was not fully understood.

A comprehensive 12-month sampling program of existing bores has improved understanding of how the lake functions hydrogeologically. A conceptual model of the relationship between wetland hydrogeology, chemistry and ecosystem function was developed. The conceptual model together with local area modelling was used to assess the adequacy of the current monitoring infrastructure, and the effectiveness of the artificial maintenance regime at the lake. The conceptual model and local area modelling were used to recommend improved management strategies.

To maintain lake levels against declining regional groundwater levels, Lake Nowergup has been supplemented with groundwater from the Leederville aquifer since 1989. As the regional watertable has not recovered since supplementation began, the department’s commitment to supplement lake levels has essentially became a long-term artificial maintenance regime.

Previous studies have described Lake Nowergup as a typical flow-through lake, but as a result of supplementation this flow regime has changed. Lake levels are now permanently maintained above groundwater levels amidst a regionally declining watertable. Our study and recent modelling shows that under artificial maintenance, the lake primarily functions as a recharge lake, with a minor component of flow through. Although water is currently pumped into the lake all year round, records show that when artificial maintenance stops, lake levels decline rapidly. This is due to the steep hydraulic gradients around the lake and the high hydraulic conductivity of the aquifer.

Regional groundwater decline and the changes in the interaction between surface water and groundwater at Lake Nowergup has affected the chemistry of both groundwater and lake water. Sediment analysis shows there are significant potential acid sulfate soils (PASS) within and around the lake, and groundwater chemistry suggests actual acid sulfate soils (AASS) could also be present. Shallow groundwater west of the lake is now acidic, with elevated concentrations of metals. At present, lake level maintenance is minimising the effects of acid sulfate soils (ASS), so the potential for increases in acidity should be taken into account when reductions to the maintenance regime are considered. Artificial maintenance has a threefold effect on preventing acidification in Lake Nowergup:

- Reducing oxidation of ASS by maintaining water levels
- Diluting any acidity which is produced

- Increasing buffering capacity by addition of higher alkalinity water than the surrounding shallow groundwater.

Artificial maintenance has also resulted in lower concentrations of several chemical components of the water. Comparisons of lake water chemical data from this investigation and the work of Turner and Townley (2006) show that major ion concentrations have decreased significantly since 1989. Despite the dilution effects of supplemented water, nutrient concentrations are high and the lake is at risk of eutrophication. Nutrient concentrations are likely to have resulted from the use of fertilisers on surrounding market gardens. If artificial maintenance were stopped, lake levels would fall rapidly. The lake would then function as a flow-through system again, with water quality in the lake more directly influenced by the shallow groundwater.

Artificial maintenance of lake levels has generally proved to be not successful in meeting Ministerial water level criteria and not successful in maintaining a number of the lake's ecological values, including its vegetation. Although there has been some decline in ecological condition, the current maintenance regime has slowed the decline in lake levels, and is protecting the lake from acidification and possibly from eutrophication.

Management options to protect the ecological values of Lake Nowergup should consider whether artificial maintenance is continued or gradually phased out and whether reducing abstraction would help protect the lake's ecological values.

This study suggests that artificial maintenance should be continued until it is re-assessed as part of the Gnangara groundwater allocation plan review. Continuing artificial maintenance will help maintain the lake's value as drought refuge for water birds and help maintain the lake's aquatic invertebrates, fish and turtles. Continuing artificial maintenance should also continue to protect the lake from acidification and possibly from eutrophication.

The Superficial aquifer and Leederville aquifer may be in connectivity at the location of the current supplementation bore, which could be decreasing the efficiency of the supplementation. The benefits of changing the location of the bore used to pump water into the lake to a location where there is no connectivity between the Superficial and the Leederville should be investigated.

Artificial maintenance is unlikely to maintain the lake's vegetation, particularly the high value woodland on the western shore. This is because artificial maintenance has resulted in seasonal declines of over 2 m in the groundwater that is used by the woodland vegetation. To maintain this vegetation these seasonal declines need to be prevented. This requires the recovery of regional groundwater levels. A recovery in regional groundwater levels would also mean that less supplemented water would be required to maintain lake levels.

Our results suggest it is unlikely that the current Ministerial criteria will be met by the continuation of artificial maintenance. Therefore, it is recommended that the current Ministerial water level criteria are no longer appropriate for the site. Based on modelling results of continuing maintenance and reducing abstraction, a spring peak criteria lake water level of 16.2 m AHD is recommended. It is recommended that the spring peak lake water level be gradually reduced (by 0.1 m per year) to this level from the 2009 peak of 16.5 m AHD.

Management actions should be undertaken to increase regional groundwater levels. These should include reducing abstraction in the Wanneroo groundwater area and the Nowergup groundwater subarea. The Forest Products Commission pine harvesting schedule should be continued to be endorsed but with the inclusion of water chemistry monitoring at the watertable. Water sensitive urban design in the Wanneroo groundwater area should also be supported.

Recommendations

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

Management actions

- The current artificial maintenance regime should be continued.
  - Implementation and responsibility: Department of Water to continue artificial maintenance and re-assess as part of the next Gnangara groundwater allocation plan.
- The Ministerial criteria for the lake should be revised. A lake water spring peak of 16.2 m AHD is recommended.
  - Implementation and responsibility: Department of Water to request revision of criteria level through the Section 46 process.
- Lake levels should be measured at the telemetry site (616139) (once surveyed) as levels less than 16 m AHD cannot be measured at the current staff gauges.
  - Implementation and responsibility: Department of Water to survey in telemetry site and begin measuring lake levels through the site.
- Groundwater levels should be measured at bore LN2-89 (61611247) when relating the watertable to the ecological condition of the vegetation transect.
  - Implementation and responsibility: Department of Water to provide groundwater level data from bore LN2-89 to vegetation monitoring contractor.
- Continue the recovery program of reducing licensed abstraction in the Wanneroo groundwater area and Nowergup groundwater subarea by 20% as per the *Gnangara Sustainability Strategy 2009*.
  - Implementation and responsibility: Department of Water to continue recovery program and to review allocation limits as part of the next Gnangara groundwater allocation plan.
- Investigate the use of solar panels to run the artificial maintenance pump.
  - Implementation and responsibility: Department of Water to undertake cost analysis.

Future monitoring

- A hydrochemical monitoring program should be initiated for this site and hydrochemical triggers and management actions could be developed for the Gnangara water management plan. The following hydrochemical sampling regime is recommended:
  - monthly sampling of pH, major ions and nutrients in Lake Nowergup

  - quarterly sampling of pH, major ions and nutrients in groundwater (bores LN8-89 and 40-89 (5 m))
  - quarterly sampling of heavy metal concentrations in lake water and groundwater
  - groundwater data should be collected on the same date as surface water data where possible.

- Data from the hydrochemical monitoring program should be reviewed every two years to assess whether the management objectives set are being met and whether trigger values need improvement.
  - Implementation and responsibility: Department of Water to design a suitable groundwater monitoring program that includes water chemistry sampling to inform the next Gnangara groundwater allocation plan.
- Additional modelling is required to investigate:

  i) the impact of further reducing private abstraction in the area on lake levels

  ii) the impact of pumping from an alternative bore located in an area where the confining layer between the Superficial and Leederville aquifers is more pronounced.

  - Implementation and responsibility: Department of Water to design and run modelling scenario by June 2012. Results to inform the next Gnangara groundwater allocation plan.

1 Context and objectives

Lake Nowergup is a conservation category wetland (Hill et al. 1996) and Ministerial criteria site (*Environmental Protection Act 1986*). As a permanent deep-water wetland the lake acts as a major drought refuge for waterbirds and supports aquatic invertebrates, fish and turtles. The lake also has large areas of sedges that minimise the effects of nutrient enrichment on aquatic fauna (WAWA 1995). The lake is a registered site of significance for Aboriginal heritage (McDonald et al. 2005).

In an attempt to maintain lake levels against a regionally declining watertable, the lake has been supplemented with groundwater from the Leederville aquifer since 1989. Although an increasing quantity of water has been pumped into the lake, artificial maintenance has mostly not been successful in meeting Ministerial water level criteria and in maintaining the lake's vegetation.

The management area review of shallow groundwater systems on the Gnangara and Jandakot mounds (McHugh & Bourke 2007) considered that it would be appropriate to undertake a hydrogeological investigation of Lake Nowergup. This was recommended as the hydrogeology of the lake was not well understood and because the lake was classified as being at severe risk due to groundwater drawdown (Froend et al. 2004a).

The management area review recommended that site-specific data be collected and analysed to determine the current groundwater–surface water connectivity, groundwater quality and flow into and out of the lake.

In line with these recommendations the objectives of this study were to:

- improve the department's understanding of how Lake Nowergup functions hydrogeologically
- determine the distribution of acid sulfate soils in and around the lake, and their impacts on water chemistry
- determine the effect of supplementation on the flow regime and water quality of Lake Nowergup
- develop a conceptual model of the relationships between wetland hydrogeology, chemistry and ecosystem function
- use the conceptual model, together with local area modelling, to assess the adequacy of the current monitoring infrastructure and the effectiveness of the artificial maintenance regime
- use the conceptual model and local area modelling to recommend improved management strategies
- determine an appropriate artificial maintenance management strategy to maintain the lake's ecological values
- highlight the water and land use issues to be addressed in the next water management plan for the Gnangara Mound.

2 Introduction

2.1 Location and climate

Lake Nowergup is located on the Gnangara Mound, approximately 37 km north of Perth CBD, and 15 km north-east of Wanneroo in Western Australia, in an area classified as the Swan Coastal Plain (Figure 1).

The Swan Coastal Plain experiences a Mediterranean type climate with hot dry summers and mild wet winters. Rainfall occurs predominantly between May and September each year. The annual rainfall recorded from the Wanneroo monitoring station over a 100-year period (1907 to 2007) shows a declining trend (Figure 2). The figure also shows average annual rainfall for 1907 to 2007 (819 mm), 1976 to 2007 (741 mm) and 1997 to 2007 (744 mm).

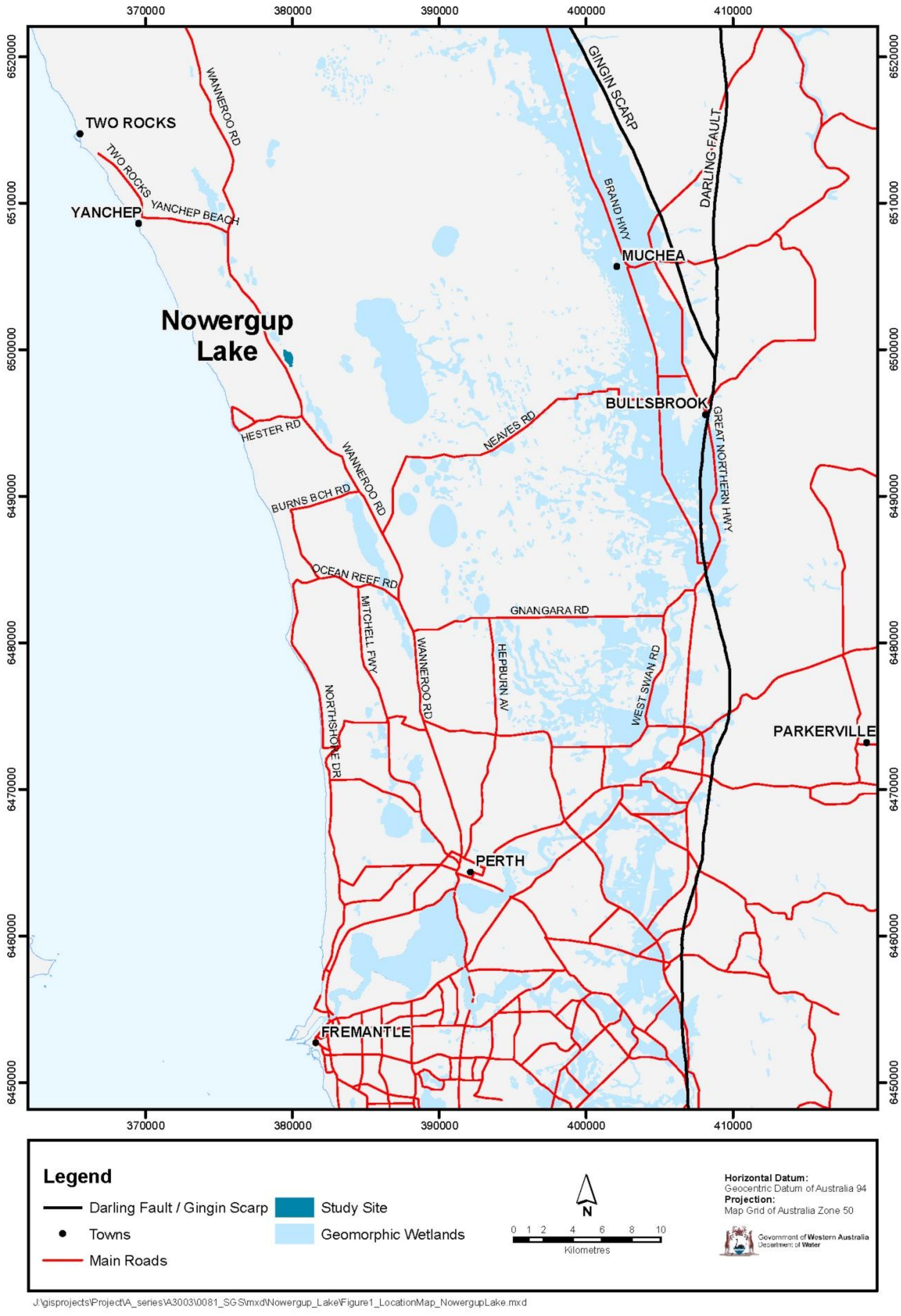


Figure 1   Regional location of Lake Nowergup

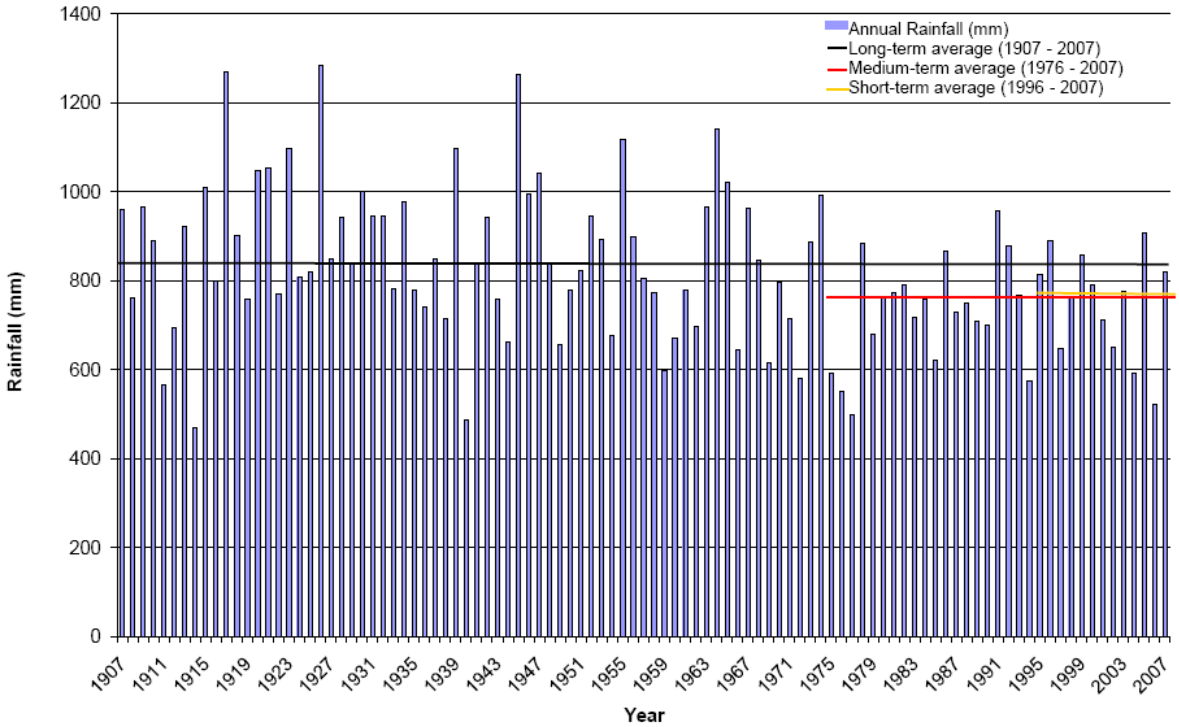


Figure 2 Annual rainfall for Wanneroo showing long-term, medium-term and short term averages

2.2 Cultural significance

Wetlands across the Swan Coastal Plain are spiritually significant to Indigenous groups, and were used extensively in traditional times (Wright 2007). Many lakes and swamps were used as hunting and gathering areas for flora and fauna (Estill 2005). Lake Nowergup is registered as a site of significance (DIA 17450) and reflects these Indigenous values.

In line with the *Aboriginal Heritage Act 1972* and the *Native Title Act 1993,* the department contracted an anthropologist to undertake an ethnographic survey of the Lake Nowergup region prior to the start of drilling works. The objectives of the survey were to determine the Indigenous heritage values of the wetland area and then to conduct archaeological and ethnographic surveys as required.

During the consultation process no adverse comments were raised in regard to the proposed groundwater monitoring program though it was stressed that the waterways of Western Australia were important as food sources and spiritual repositories, and that development should not be allowed in the vicinity of them.

As the proposed lake bed sampling will take place within the boundaries of registered site 17450 it was recommended that the department submit an application pursuant to Section 18 of the *Aboriginal Heritage Act 1972* before the start of works. An application was submitted to conduct works within the site and approval to proceed with the proposed works was granted under section 18(3) of the Act. Site works and disturbance were kept to a minimum by using smaller direct push drilling methods and infrastructure installed within existing disturbed areas.

2.3 Land and water management

The Department of Water has the statutory authority to manage Western Australia's water resources. The department develops water management plans for allocation which sets a balance between taking groundwater for short-term use, and retaining groundwater to maintain ecology, meet social and cultural needs and provide for future public and private use.

The *Gnangara groundwater areas allocation plan* (2009) sets out the approach to allocation and licensing for all water users on the Gnangara Mound. Through the plan the department aims to achieve a reduction in the total abstraction from the Superficial aquifer to address the trend of declining groundwater levels (DoW 2009). The department determines the spatial distribution of water abstracted from the Mound by assessing proximity to groundwater-dependent ecosystems, ecological condition and rate and magnitude of groundwater level change.

Lake Nowergup is located within the Wanneroo groundwater area and the Nowergup groundwater subarea (Figure 3). Yesertener (2008) found that private abstraction and climate were the primary cause of groundwater level decline in the Nowergup area. However, it is possible that the Pinjar bore field, located approximately 8 km east of Lake Nowergup, is also contributing to declines in the area.

In 2008–09, the groundwater allocation limit for the Wanneroo groundwater area of 27.45 GL was exceeded, with 31.58 GL actually abstracted (DoW 2010). The 2.00 GL allocation limit for the Nowergup subarea was also exceeded by 0.78 GL (DoW 2010). As both the Wanneroo groundwater area and Nowergup groundwater subarea are currently over-allocated, no further licences are being issued and the department is currently recouping unused entitlements.

Water use in the area is linked to the dominant land use (Figure 3). The eastern side of Lake Nowergup is used for irrigated horticulture and private small rural holdings. To the west is native woodland which is adjacent to Neerabup National Park. A small piggery which used to operate on the eastern side was thought to be a source of nutrients entering the lake (DoW 2006).

To better manage the resources of the Gnangara Mound a multi-agency team was established in 2007 to research and model possible land and water use scenarios for the region. The Gnangara Sustainability Strategy recommended that existing agricultural land at Nowergup be retained in the metropolitan region scheme for horticulture and other agricultural use for the long term. The strategy also recommended that 3000 ha of privately owned land in the vicinity of Carabooda and Nowergup be investigated for sustainable horticulture production.

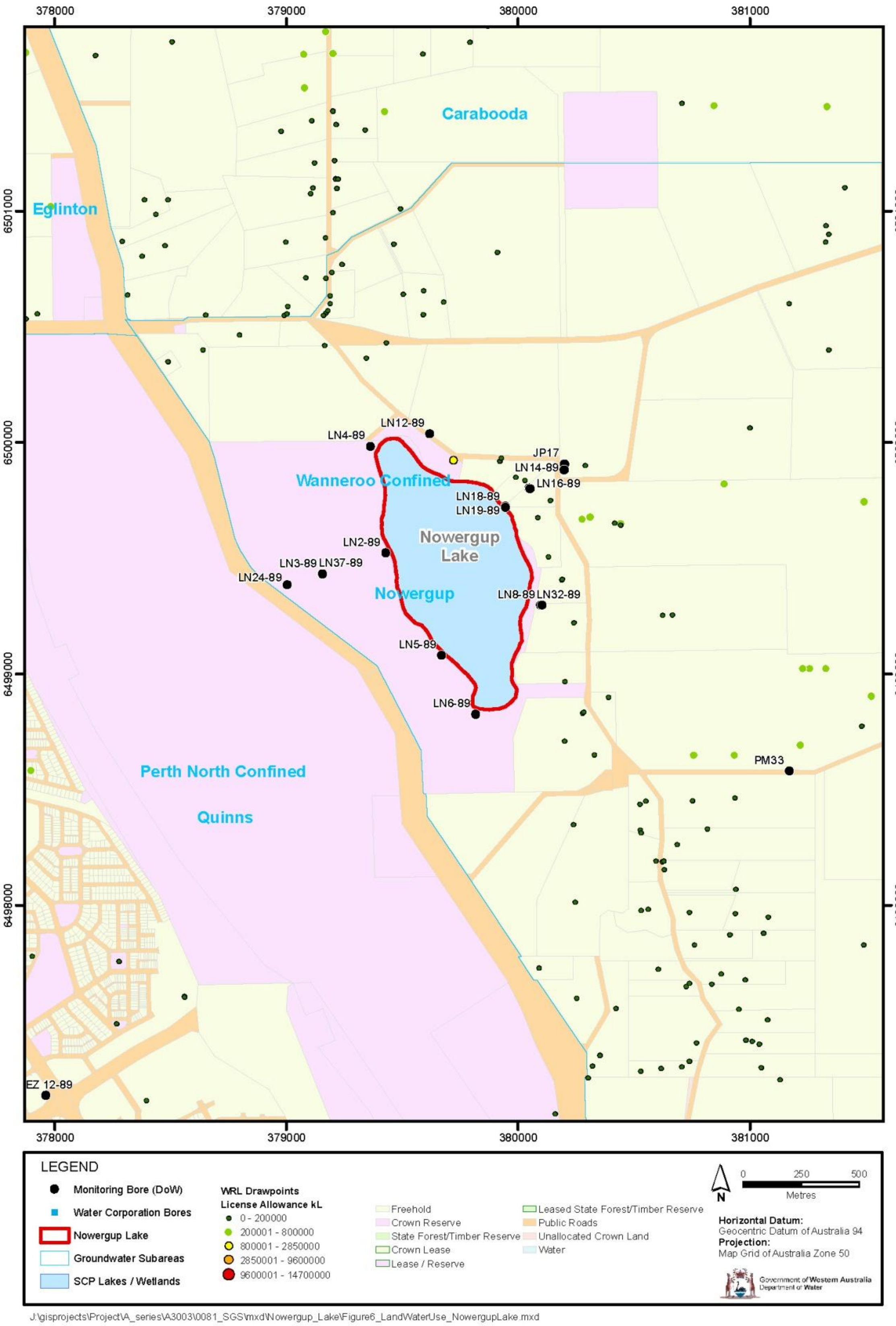


Figure 3 Land use and water licences in Lake Nowergup area

2.4 Management issues

2.4.1 Acid sulfate soils

Due to regional watertable decline, many of the wetlands on the Gnangara Mound, including Lake Nowergup, are progressively drying. The exposure of acid sulfate soils is a risk for environmental and groundwater degradation and requires careful management.

Acid sulfate soils are naturally occurring soils, sediments or organic substrates, formed under waterlogged conditions, that contain iron sulfide minerals (e.g. pyrite) or their oxidation products. When exposed to air due to the lowering of the watertable the sulfides in these soils oxidise releasing sulfuric acid and iron as well as other associated metals into the soil and groundwater according to the following chemical equation (Fältmarsch et al. 2008).

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

The resulting acidity then has the potential to mobilise other metals from the sediments into the groundwater flow system. The term acid sulfate soils includes both potential and actual acidity. Potential acid sulfate soils refers to the sediments which are still water logged or unoxidised. Actual acid sulfate soils refer to sediments which have been exposed to air and have produced acidity. Oxidation is commonly caused by lowering of the watertable (Ahern et al. 2004).

2.4.2 Ecological condition

Lake Nowergup is a conservation category wetland (Hill et al. 1996) and Ministerial criteria site (*Environmental Protection Act 1986*). The lake is valued as a permanent deep-water wetland that acts as a major drought refuge for waterbirds and supports aquatic invertebrates (one species of Cladocera, *Leydigia ciliatea* may be unique to the lake), fish (including the Swan River goby, *Pseudogobius olorum)* and turtles (Froend et al. 2004a). The lake has large areas of fringing sedges that minimise the effects of nutrient enrichment on aquatic fauna (WAWA 1995). The department is bound to the following ecological and water regime management objectives for the lake (WAWA 1995):

- to maintain the existing areas of fringing sedge vegetation
- to maintain deep, permanent water as a bird habitat and drought refuge and to protect aquatic invertebrates and fish dependent on permanent water
- to maintain the existing extent of *Baumea articulata* fringe between *Typha orientalis* stands and the fringing woodland
- to provide some area of wading bird habitat at the end of summer, although it is recognised that this is limited by the shape of the wetland
- to maintain the areas of fringing woodland on the western shore.

In 1988, Ministerial water level criteria were established at the lake. The criteria were modified in 1995 based on a greater knowledge of the ecological and social value of wetlands (WAWA 1995). Criteria levels are generally based on ecological water requirements (EWRs) which are the water regimes necessary to maintain a low level of risk to the ecological values (WRC 2000).The current Ministerial criteria for Lake Nowergup are designed to provide sufficient inundation to the sedge area to prevent encroachment into the basin and also to prevent a reduction in waterbird wading habitat (WAWA 1995). The criteria include:

- 16.8 m AHD absolute spring minimum peak
- 17.0 m AHD preferred spring minimum peak.

The Ministerial criteria for the lake also state that spring peak lake levels should not fall below the above levels more than twice in six years. The absolute and preferred spring minimum peak criteria are lake levels measured on staff gauge 6162567 (Figure 4). In six of the last ten years lake levels have failed to meet the absolute minimum spring peak criteria, and in the last six years lake levels have failed to meet the two-in-six-year spring peak criteria.

Water levels at Lake Nowergup have been declining since the 1970s as a result of successive years of low rainfall on the Gnangara Mound combined with groundwater abstraction for both public and private use and land use changes (Yesertener 2008; DoE 2004). As a result, the department is committed under conditions set by the Minister for the Environment to maintain the ecological values of the lake by artificially supplementing water levels. The commitment action, set in 1997 after a number of supplementation trials, states: ‘Should environmental water provisions (EWPs) in Lake Nowergup not be met by November 1, artificial supplementation will be used until the EWP is reached’ (Statement 438). Prior to the start of artificial supplementation in 1989, Lake Nowergup experienced declines in the condition and density of groundwater-dependent vegetation including *Melaleuca rhaphiophylla* and *Eucalyptus rudis*. There was also evidence of terrestrialisation, with encroachment of shrub and tree species and *T. orientalis* into the wetland basin and thinning of *B. articulata* bands.

While artificial maintenance appears to have reduced the degree of impact on fringing vegetation, there has been a severe decline in the condition of terrestrial vegetation upslope from the wetland. Sudden health declines and deaths of trees within the high value woodland on the western side of the lake were observed between February and May 2002. Terrestrialisation has continued since supplementation began, with shrub and tree species and *T. orientalis* encroaching into the basin. There has also been an ongoing decline in the health and width of *B. articulata* bands.

Though declining lake levels have played a role in declining macroinvertebrate family richness, artificial supplementation may be preventing more significant declines.

In 2004, the ecological values of Lake Nowergup were re-assessed and new EWRs were proposed (Froend et al. 2004a and b). Four new EWRs, as outlined below, were proposed for wetland vegetation, sediment processes, waterbirds and macroinvertebrates (Figure 5) (Froend et al. 2004b). These EWRs have not been adopted as Ministerial criteria, but are used by the department to assess the possible impact of current water levels on current ecological values.

- A groundwater end of autumn minimum of 15.22 m AHD is required to support groundwater dependent vegetation.
- To support sediment processes (to prevent oxidation of ASS) minimum surface water levels must not drop below 16.35 m AHD.
- Lake levels of 17.00 m AHD are required for two months of the year in at least four out of six years to support waterbirds.
- Lake levels of 16.85 m AHD are required for two months of the year in at least four out of six years to support macroinvertebrates.

Despite artificial supplementation, recent groundwater levels at Lake Nowergup have mostly failed to meet the EWRs recommended by Froend et al. (2004b) for vegetation, and the health of *E. rudis* and *M. rhaphiophylla* has declined significantly in recent years. *B. articulata* has thinned and *T. orientalis* and other exotics have encroached into the basin. Recent lake levels have mostly failed to meet EWRs recommended for sediment processes, waterbirds and macroinvertebrates.

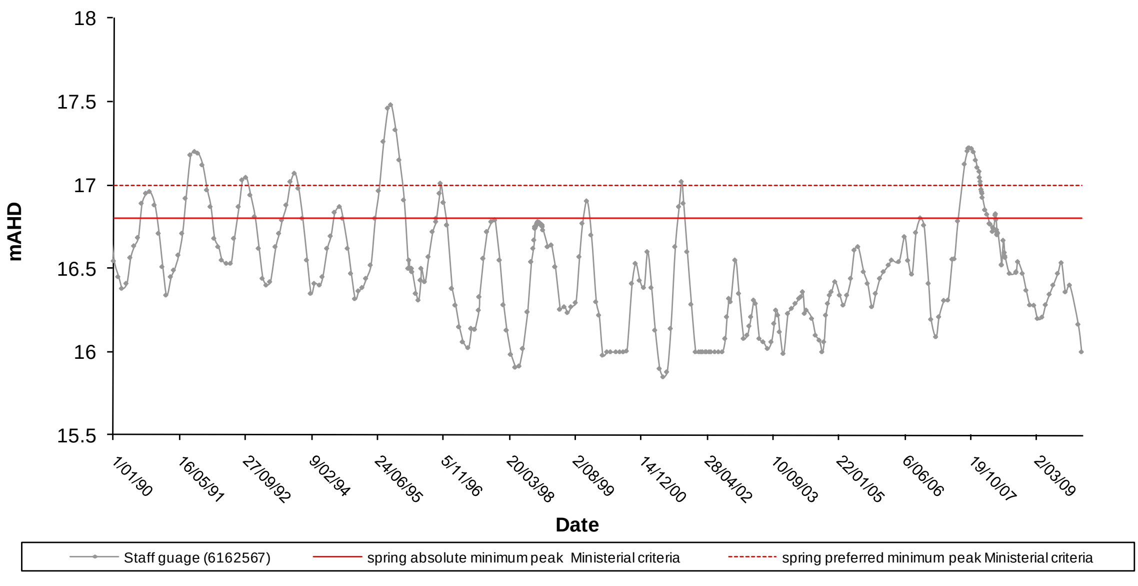


Figure 4 Hydrograph showing lake levels and Ministerial criteria

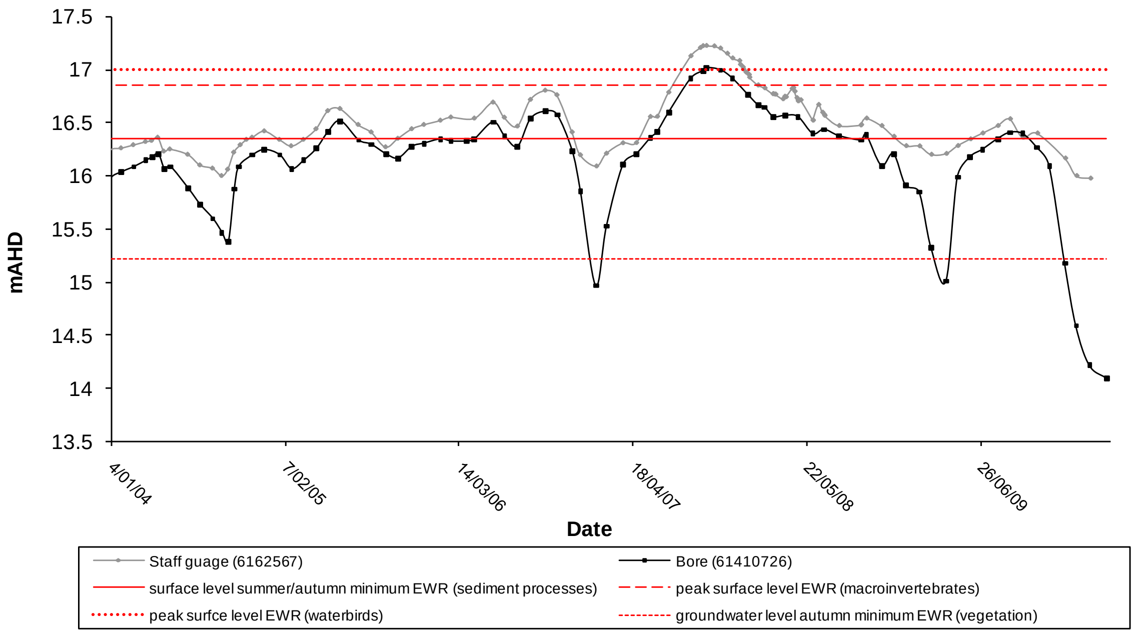


Figure 5 Hydrograph showing lake water and groundwater levels and current EWRs (Froend et al. 2004b)

2.4.3 Supplementation and long-term artificial maintenance

As the regional watertable has not recovered since supplementation of Lake Nowergup began, the department's commitment to supplement lake levels (when EWPs are not met by November 1 of each year) has essentially become a long-term artificial maintenance regime.

Long-term artificial maintenance is more complex than short-term supplementation. While short-term supplementation enables the short-term maintenance of environmental values within a relatively natural regime, the long-term artificial maintenance at Lake Nowergup has altered the natural flow regime in an attempt to replicate the historical regime.

Artificial maintenance requires:

- a management regime that considers not only static water levels, but also rates of water level rise, rates of fall, inter-annual variation or fluctuation and the quality of the water being used
- sufficient knowledge of the hydrogeological system to achieve appropriate water levels, rates of change and water quality requirements.

Artificial maintenance is practical only in a very limited number of situations as it requires a management regime that meets environmental objectives and that is feasible in terms of implementation and cost. As summarised in Figure 6, various regimes have been employed at Lake Nowergup since supplementation began. Previous regimes, that have attempted to meet the Ministerial criteria, have resulted in unnatural inter-seasonal changes in lake levels (with high levels over the summer) and have resulted in unnaturally large fluctuations in lake levels over the course of a year.

The current maintenance regime attempts to reflect historic rates of inter-seasonal change in lake levels by employing a rate of rise/fall strategy that manages fluctuations to prevent lake levels increasing or decreasing at rates much faster than what would have occurred under natural conditions. The rate of rise required is determined through the assessment of lake levels, winter rainfall and evaporation. The rate of fall is managed to gradually reduce levels from the spring peak to prevent dramatic declines in lake levels.

The management approach for the 2009/10 financial year (Figure *7*) involved:

- raising lake levels during winter in line with the natural winter filling of the Gnangara wetlands
- targeting a peak consistent with non-supplemented wetlands at the end of September or early October
- targeting a spring peak of approximately 16.5 m AHD
- gradually reducing lake levels following the spring peak to a summer minimum of approximately 15.9 m AHD.

The rate of rise/fall strategy was determined in an internal review of the management approach to artificial maintenance conducted in 2008. The review considered the levels sufficient to maintain fringing vegetation and a significant area of deep, permanent water as per the ecological and water regime management objectives for the lake. The review acknowledged that the targeted levels would not meet the Ministerial criteria or the Froend et al. (2004b) EWRs for sediment processes, waterbirds or macroinvertebrates. The volume of supplemented water required to meet these levels and the high cost of providing such a large quantity of water was deemed prohibitive.

The current licence volume for water pumped into Lake Nowergup is 1.2 GL. In 2009, artificial maintenance commenced mid-August for 98 hours each week (10 hours a day Monday to Friday, and 24 hours a day Saturday and Sunday, using off-peak electricity) resulting in 25 676 kL of water pumped into the lake each week, compared with 44 016 kL each week when water is pumped continuously.

Despite pumping at off-peak electricity times, artificial maintenance is very costly. Current annual electricity costs for off-peak pumping are approximately $28 000. With predicted increases in electricity rates[1], off-peak pumping may soon cost $2500–$3000 per month, as much as $36 000 per annum. Costs of annual testing of the pump are approximately $2000. Additional costs are associated if the testing finds that maintenance is required for the pump.

[1] The business use tariff for electricity increased 7.5% in April 2010 and is set to increase another 10% in July 2010 (www.synergy.net.au).

To date, the pumping regime has been successful in following the preferred inter-seasonal change in lake levels as per the rate of rise/fall strategy (Figure 7).

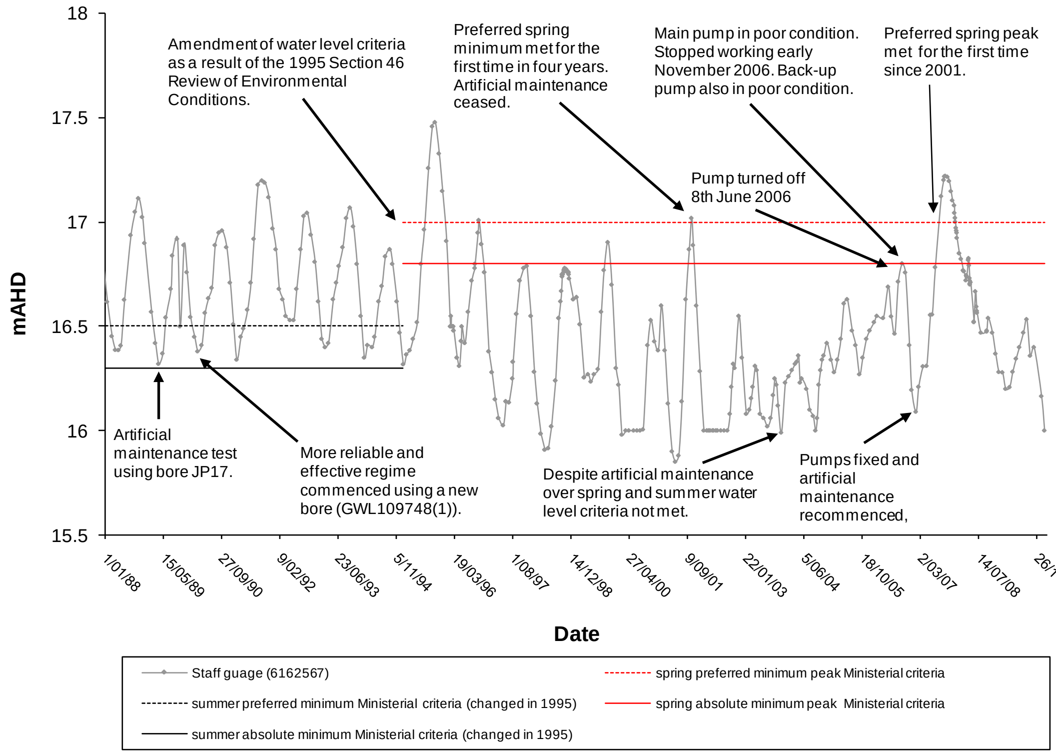


Figure 6 History of supplementation at Lake Nowergup

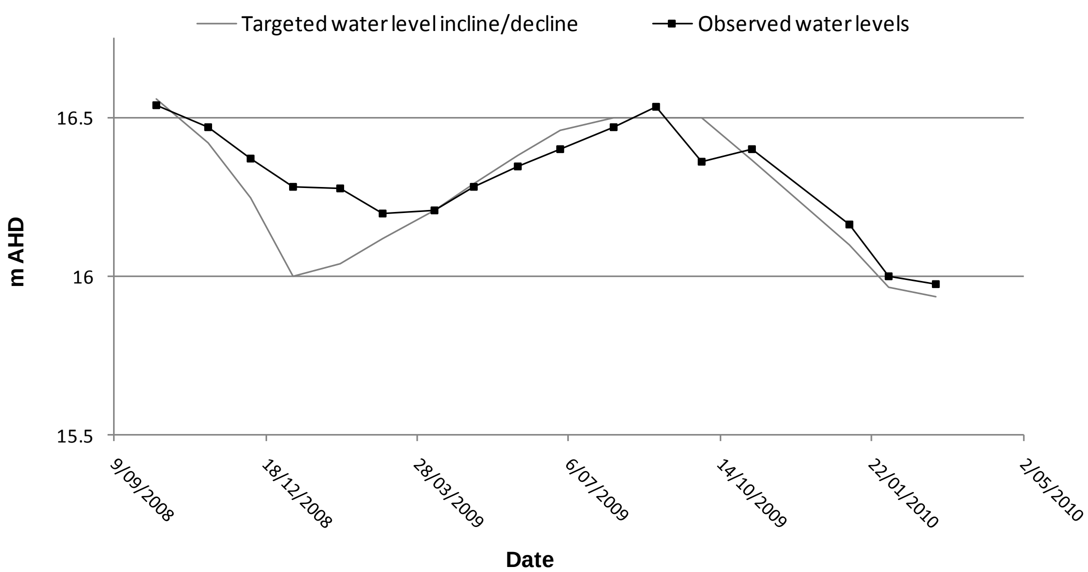


Figure 7 Current artificial maintenance regime at Lake Nowergup displaying targeted lake level rise and fall and observed lake levels

3 Investigation program

The management area review of shallow groundwater systems on the Gnangara and Jandakot mounds highlighted the need for site-specific information about wetland function to appropriately manage Lake Nowergup (McHugh & Bourke 2007). The review recommended water quality samples and water levels to be taken from pre-existing monitoring infrastructure at Lake Nowergup. An investigation into ASS was also recommended.

Figure 8 shows the sites of the bore clusters used for the water level monitoring and water quality sampling, as well as other bores in the area used for geological investigation. Figure 10 shows the location of sediment cores taken for ASS.

3.1 Water monitoring and sampling

Lake water and groundwater sampling and analysis was undertaken to determine the hydrochemical characteristics of each site, the distribution and availability of potential pollutants and the interaction between the wetland and the Superficial aquifer. The investigation also aimed to determine the effect of supplementation on the flow regime and water quality of Lake Nowergup.

The sampling regime comprised monthly sampling for both water quality and water levels for the period between September 2007 and September 2008. Table 1 lists the bores used in the investigation program and the monitoring details for each bore. A cluster of three bores on the eastern side of the lake was monitored for water quality and groundwater levels (Figure 8 and Figure 9). The bores are LN8-89 (shallow, screened at the watertable), LN32-89 (intermediate, screened approximately halfway through the Superficial aquifer) and LN33-89 (deep, screened at the base of the Superficial aquifer). On the western side water quality samples were taken from a multi-port bore (40-89) at a shallow and intermediate depth (5 m and 14 m). However, groundwater levels could not be taken from this bore due to the narrow diameter of the hole. The bore LN2-89 is located several metres away from bore 40-89, and was used to measure watertable depth.

Table 1 Details of bores used in the SGS investigation, Lake Nowergup

Bore name	AWRC reference	Screen interval	Location	Depth	Water levels	Water chemistry
LN8-89	61611228	6.4–8.4	East	Shallow	Yes	Yes
LN32-89	61611248	26.5–29.5	East	Deep	Yes	Yes
LN33-89	61611249	14.5–17.5	East	Intermediate	Yes	Yes
40-89 (5m)	61611256		West (NW)	Shallow	No	Yes
40-89 (14m)	61611257		West (NW)	Intermediate	No	Yes
LN2-89	61611247	5.2–7.2	West (NW)	Shallow	Yes	No

Figure 8 Location of bores used for sampling, monitoring and geological investigation

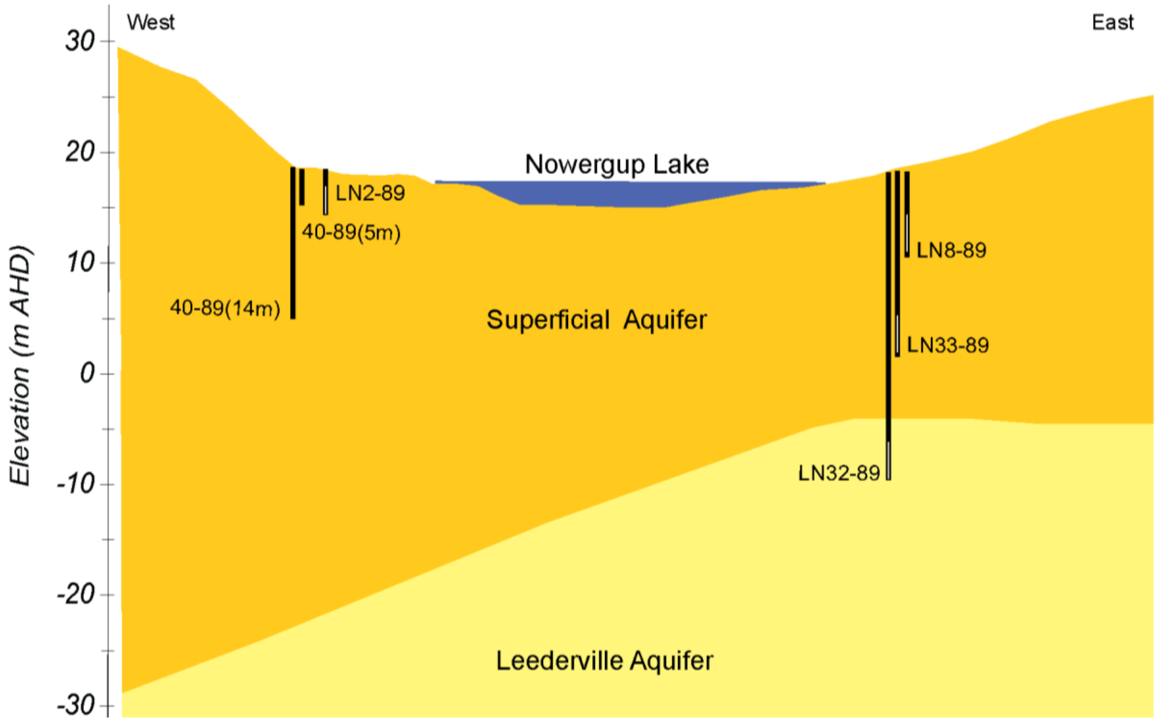


Figure 9 Water sampling bores

Samples were analysed for major ions, metals and nutrients as well as some herbicides and pesticides. Table 2 shows the analytes measured by the National Measurement Institute (NMI) for the SGS investigation program. Water level and chemical sampling methodology can be found in Appendix A. Field analysis was carried out for electrical conductivity (EC), pH, Eh, dissolved oxygen (DO) and temperature using a Quanta multi parameter probe. This probe adjusts Eh values to the standard H^+ half cell. Readings were taken when values for EC, pH and temperature stabilised. However, Eh and DO values remained variable.

Table 2 Water analysis conducted by the National Measurement Institute

Total metals	Hg, Al, As, Cd, Cr, Fe, Mn, Ni, Se, Zn
Dissolved metals	Ca, Mg, Na, K, B, Fe, Al
Nutrients	Ammonia (NH_3-N), total nitrogen (TN), total phosphorus (TP), oxides of nitrogen (NO_X), filtered reactive phosphorus (FRP)
Herbicides and pesticides	Chlordane {Tech; a+g}, DDD-p,p, DDE-p,p, DDT-p,p, Dieldrin, Endosulf sulfate, Endosulf-a, Endosulf-b , Endrin, HCH (BHC) a,b,d, HCH (BHC), Heptachlor, Heptachlor epoxide, Hexachlorobenzene, Methoxychlor, Ocs
Other	EC, total suspended solids (TSS), total dissolved solids (TDS), HCO_3, CO_3, Cl, F, SiO_2, SO_4, pH, acidity, alkalinity, disolved organic carbon DOC, dissolved organic nitrogen (DON)

A single sampling event took place in September 2010, on groundwater from the supplementation bore Lake Nowergup. A groundwater sample for metals was taken from the pump, however a build-up of iron oxide was observed and the remainder of the samples were collected from the outlet at the edge of the lake. The same series of analyses was carried out on these samples as for the rest of the program; except herbicides, pesticides and dissolved organic nitrogen were omitted.

3.2 Acid sulfate soils

Three sediment cores were hand augured or drilled to a maximum depth of 1.6 m on the south-eastern and northern margins of Lake Nowergup (Figure 10 and Table 3).

Table 3 Core details

Core ID	**Depth m**	**Easting**	**Northing**	**Coring method**
NGP_1a	1.35	380015	6499233	Hand augured
NGP_1b	1.3	380007	6499239	Hand augured
NGP_2a	1.6	379751	6499794	Direct push

Samples were collected approximately every 25 cm and analysed in the field for AASS and PASS according to the Department of Environment and Conservation's (DEC) *Investigation and identification of acid sulfate soils guide (2009),* summarised in Appendix B.

Laboratory analysis was conducted on 12 samples, including one duplicate, to provide an indication of the accuracy of the field results, as well as provide greater information on acid-base accounting. Three to four sediment samples per core were sent to the NMI. Approximately 200 g of sediment were placed into zip-lock plastic bags. All the air was expelled from the sample bag before being sealed and refrigerated. Samples were delivered to the NMI within 48 hours of sampling. The NMI used the chromium reducible sulfur suite (CRS) as well as the SPOCAS suite of analyses to conduct acid-base accounting (see Appendix C for laboratory methods).

Core samples were analysed for metals, metalloids and selenium concentrations using the analytical method NT2_49. In this method, samples are prepared and digested with HNO_3/HCl at 100^{o}C for two hours and diluted prior to analysis. The concentrations of acid extractable elements in sediments were determined by ICPMS (inductively coupled plasma mass spectrometer) and / or ICPAES (inductively coupled plasma atomic emission spectrometer) depending on the concentrations. All high concentrations which may have been due to matrix interferences were cross-checked once more using ICPMS. Metal concentrations were compared against sediment guidelines (DEC 2010).

Figure 10 Location of sediment cores used in ASS investigation

3.3 Local area modelling

As part of the Gnangara Sustainability Strategy, local-scale numerical modelling was undertaken in the Lake Nowergup area. Seven modelling scenarios (Table 4) were studied for the time period from January 2008 to December 2031, to investigate the effects of pine clearing, drying climate, reduction in private abstraction and changes to the artificial supplementation regime (SKM 2009). The results are shown in Section 5.6.

The base case scenario had:

- a climate regime based on that measured during 1997 to 2006
- public abstraction of 135 GL (as per the Water Corporation data base)
- private abstraction as 100% of current usage
- artificial lake supplementation equivalent to the current annual licence (1.2 GL)
- pine clearing as per the Forrest Product Commissions pine clearing schedule, with pines replaced by grassland.

To assess the relative effects of future land-use changes and water abstraction regimes, each of the other scenarios altered only one of these factors.

Table 4 Lake Nowergup model scenarios

Scenarios	**Parameters**				
	Climate	Public abstractions	Private abstractions	Lake artificial supplementation	Land-use change (pine harvest)
Base case	Median climate of 1997 to 2006	As per Water Corporation 135 GL dataset	100% of current usage	Equivalent to current annual licensed volume	Pines harvested as per LVL#, replaced with grass
1	11% drier				
2*			80% of current usage		
3					Immediate (2008) pine removal, replace with grass
4				No supplementation	
5				Continuous pumping	
6				Off-peak pumping	

Note: A blank cell indicates the parameter is not changed from the base case.

** In Scenario 2 the reduction in private abstractions does not apply to the lake supplementation bore. The lake supplementation bore remains at 100 % of current usage.*

#LVL – laminated veneer lumber agreement

For this investigation a new scenario was designed and run. Due to model calibration and seasonal variations, the original scenarios started the modelling period with water levels considerably higher than in recent years. The new scenario was run to assess the effects of starting the model run with lower initial water levels, close to current observed values. The scenario run for this investigation was the same as the original base case scenario, but with lower initial water levels.

3.4 Data precision and accuracy of water samples

Comparing the pH readings of water samples measured in the laboratory with those measured in the field immediately after sampling can indicate that a water sample has been altered. The water sample can be affected by the collection, transport or storage processes. There are numerous causes for a difference in field and laboratory pH reading, including reactions involving oxidation, precipitation and release of dissolved gases. These differences can highlight uncertainty in the reported chemical concentrations. The results showed that field pH values were generally lower than laboratory results. Samples which showed more than 1 pH unit difference were further investigated. None of these samples showed any other outlying characteristics in their chemistry. The correlation coefficient between field and laboratory pH values indicated that the laboratory results were reasonably reliable (r = 0.88). More than 75% of samples show less than 0.7 pH units difference between the two pH readings.

There is a degree of uncertainty with measured chemical parameters, and hence results from laboratory chemical analysis are not absolute. This uncertainty is caused by several contributing error sources, mainly precision errors and accuracy errors (Appelo & Postma 2005). Precision or statistical errors result from random fluctuations in the analytical procedure. Precision can be calculated by performing repeat analysis on the same sample. Eight laboratory duplicate samples, from four bores and the lake, were analysed as part of this investigation. Results from these indicate that laboratory precision is very good, with most duplicates being within 5% to 10% above or below the original sample.

Accuracy or systematic errors reflect faulty procedures or interference during analysis (Appelo & Postma 2005). An ‘electrical balance’ (or ion balance) is used to check the accuracy of analytical results. The sum of positive and negative charges in the water should be equal (Appelo & Postma 2007), and hence the sum of cations in solution should equal the sum of the anions.

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

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

Deviations of more than 5% indicate that sampling and analytical procedures should be examined (Appelo & Postma 2007). Samples taken for the SGS investigation which had an electrical balance greater than 6%, without satisfactory explanation, were left out of the analysis.

3.5 Data presentation and interpretation

The following methods were used to investigate the hydrogeological and hydrochemical characteristics of the Lake Nowergup area:

- re-interpretation of historical lithological logs
- construct geological cross-section
- analysis of hydrographs
- classification of redox processes
- groundwater contour mapping
- flow nets
- Piper diagrams for major ions

- time series plots for major ions, metals, nutrients, herbicides and pesticides and physical properties
  - creating and running a new scenario for the local area model.

4 Geology

4.1 Regional geology and geomorphology

Lake Nowergup is located on the superficial formations of the Swan Coastal Plain, within the Perth Basin. The Swan Coastal Plain is bound to the east by the Darling and Gingin Scarps, and the Indian Ocean to the west (Figure 11).

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

The Superficial formation is a collective term for the late Tertiary to Quaternary age sediments of the Swan Coastal Plain, which range in thickness from 20 to 100 m (Rockwater 2003). The formations include (in order of deposition) the Ascot Formation, Yoganup Formation, Guildford Clay, Gnangara Sand, Bassendean Sand, Tamala Limestone, Becher Sand and Safety Bay Sand (Davidson 1995). These formations consist of sand, silt, clay and limestone in varying proportions, and are the surficial material over most of the Swan Coastal Plain. Davidson (1995) and Moncrieff & Tuckson (1989) have described the lithology in detail. The porous sediments enable infiltration of rain to directly recharge the Superficial aquifer and facilitate groundwater flow. Geological location can influence the physical and chemical characteristics of the groundwater.

Lake Nowergup lies on the Tamala Limestone of the superficial formations, which are underlain by an erosional surface of older sediments (Davidson 1995).

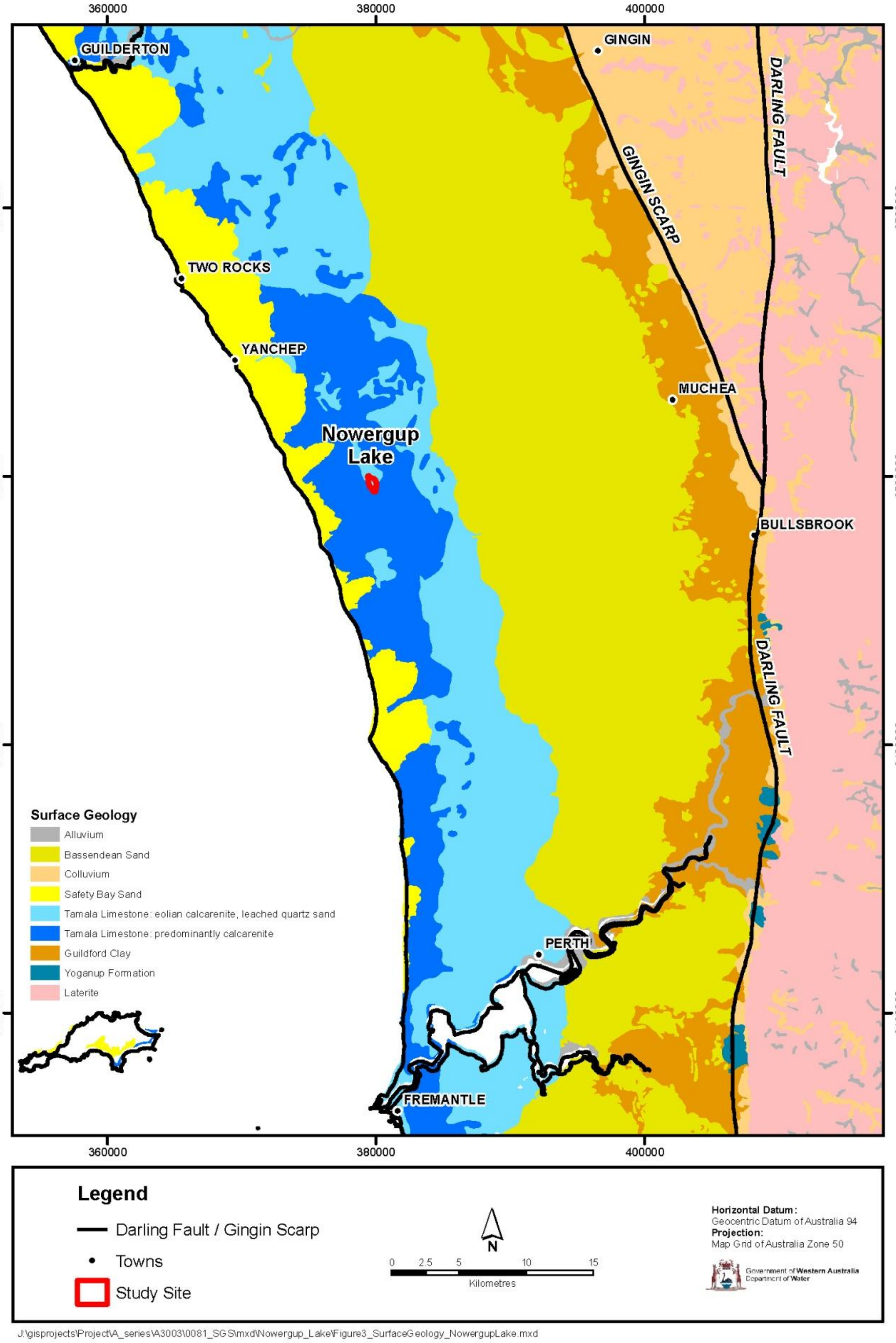


Figure 11 Generalised surface geology

4.2 Superficial and Mesozoic formations

No new drilling was conducted for the SGS investigation, but bore logs from drilling carried out in 1989 were interpreted with regard to regional formations. Lake Nowergup lies in a north to north-west trending depression within the Spearwood Dunes of the Tamala Limestone. Underlying this is the Ascot formation, which lies unconformably on the Pinjar Member of the Leederville formation. Table 5 summarises the lithology of the area while Figure 12 shows a geological cross-section along the line marked ‘geological transect’ in Figure 8.

Table 5 Generalised stratigraphy of the Lake Nowergup area

Age	**Unit**	**Thickness m**	**Lithology**
Quaternary	Tamala Limestone	49	Sand, limestone and clayey sand
Tertiary	Ascot Formation	30	Shelly sand with variable clay content and occasional limestone. Occasional to common phosphatic nodules.
Cretaceous	Leederville Formation (Pinjar Member)	Undetermined in this investigation	Black soft shale with variable lignite, as well as pyritic sandstone pieces.

Around Lake Nowergup, the Tamala Limestone generally consists of quartz sand and limestone nodules. Consolidated limestone is more common west of the lake, with nodules at depths of around 15 m. The lithology east of the lake is generally quartz sand and clayey sand to a depth of around 30 m. The Leederville aquifer is typically considered a major confined aquifer; however the lithological logs in the Lake Nowergup area suggest there is no extensive confining layer between the Superficial and Leederville aquifers in this area. Where shale is encountered, the unit is usually less than 1 m, and overlies sand, clayey sand and pyritic material.

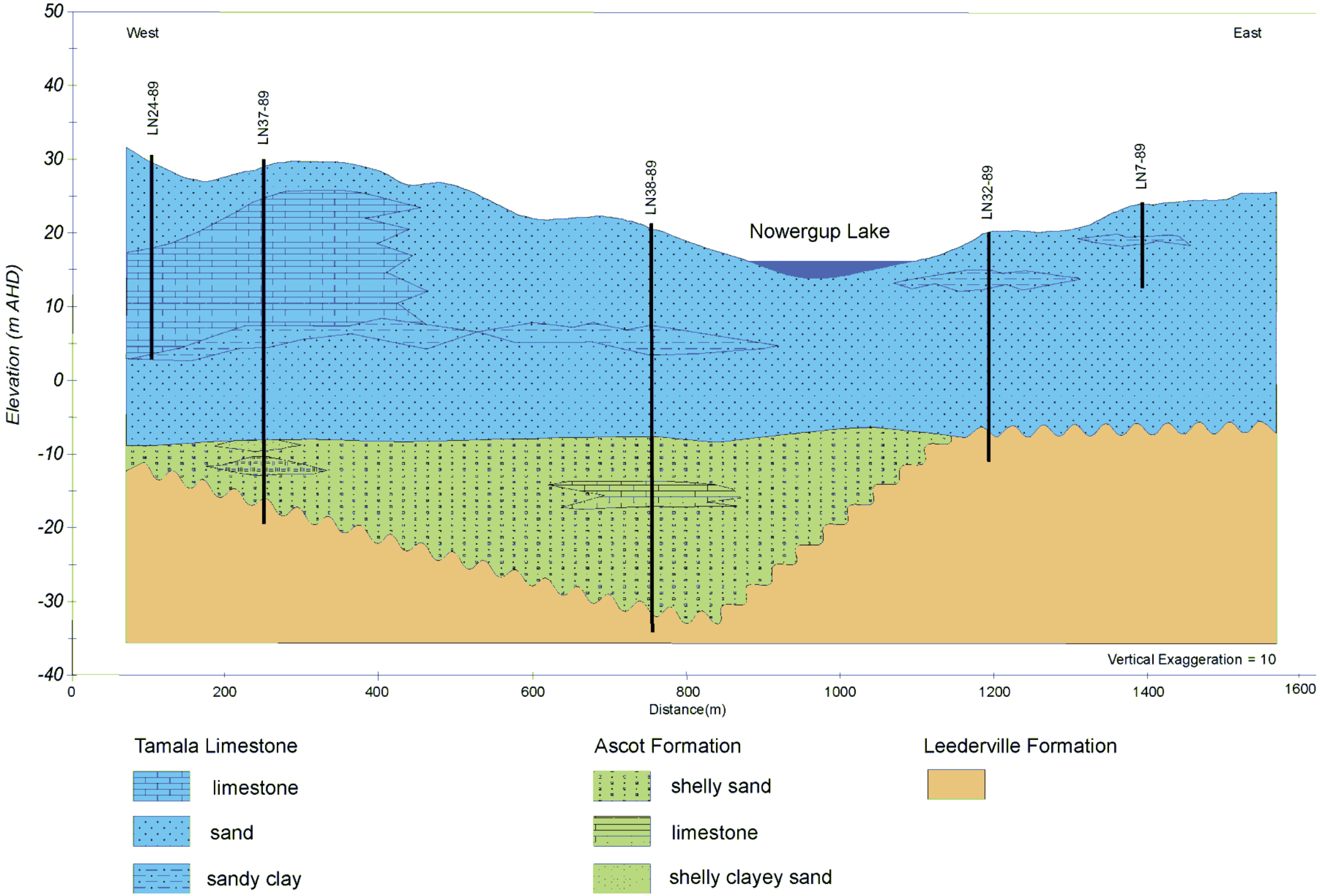


Figure 12 Geological cross-section of Nowergup Lake

4.3 Acid sulfate soils

Field tests for ASS were carried out on three sediment cores retrieved at Lake Nowergup. Laboratory analysis was conducted on 12 samples, including one duplicate, to provide an indication of the accuracy of the field results, as well as provide greater information on acid-base accounting.

Field results suggest that both AASS and PASS are present at Lake Nowergup. The presence of AASS is indicated at NGP_1a, as the pH_F was below 4.00. Sediment at depths of 0.4 m and 0.55 m had pH_F values of 2.74 and 2.59 respectively (Figure 13). The pH_{FOX} was less than 3.00 over the rest of the profile at NGP_1a, indicating PASS. At NGP_1b and NGP_2a, pH_{FOX} was < 3.00 and at corresponding depths pH_F was between 6.58 and 7.21, suggesting the presence of PASS (Figure 13 and Figure 14).

Laboratory results for pH_{KCl} and pH_{OX} are somewhat analogous to pH_F and pH_{FOX} as the natural and oxidised pH values. pH_{KCl} and pH_{OX} generally agree with field readings, suggesting the presence of PASS at the three sites and AASS at NGP_1a. Although NGP_1a and NGP_1b are very close to each other, NGP_1a is located further from the lake, where there is greater depth to the watertable and thus is exposed to air for longer than NGP_1b. The pH_{KCl} is generally less than pH_F, and pH_{OX} is greater than pH_{FOX}. This could be due to some level of oxidation and perhaps loss of volatiles prior to samples reaching the laboratory. Full laboratory results are reported in Appendix D.

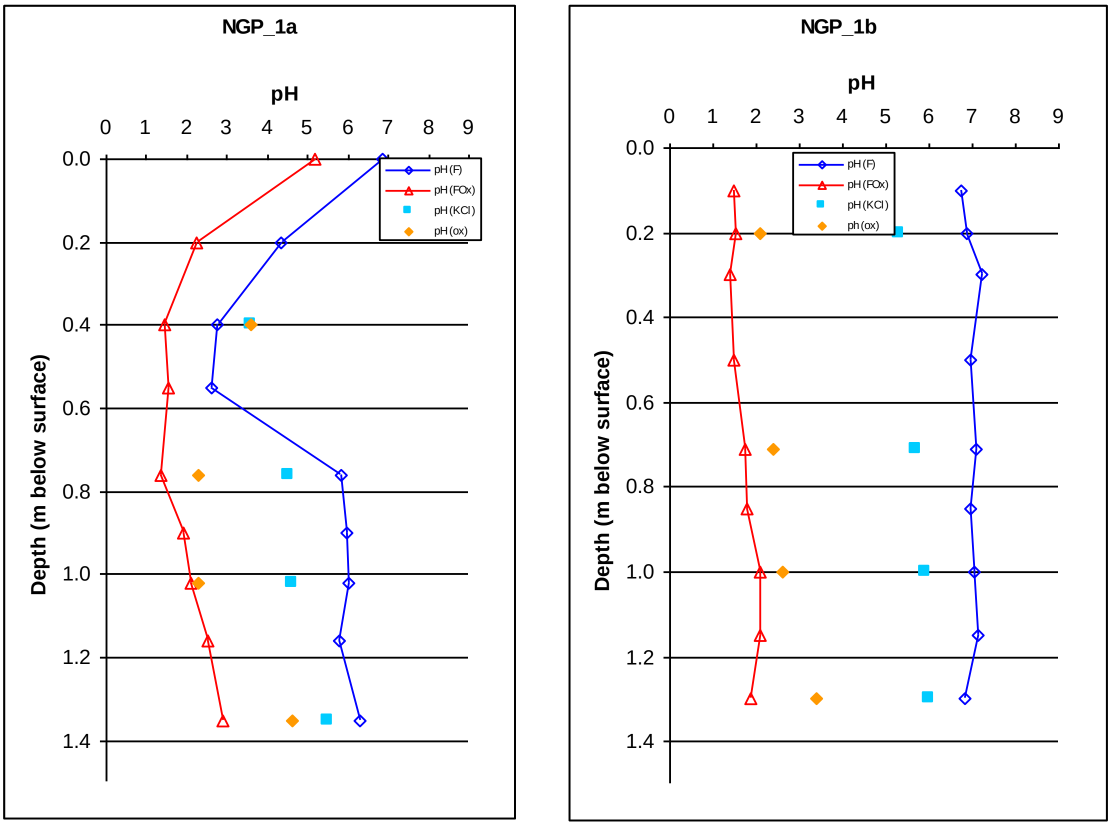


Figure 13 Field and laboratory reading of natural and oxidised pH at site NGP_1

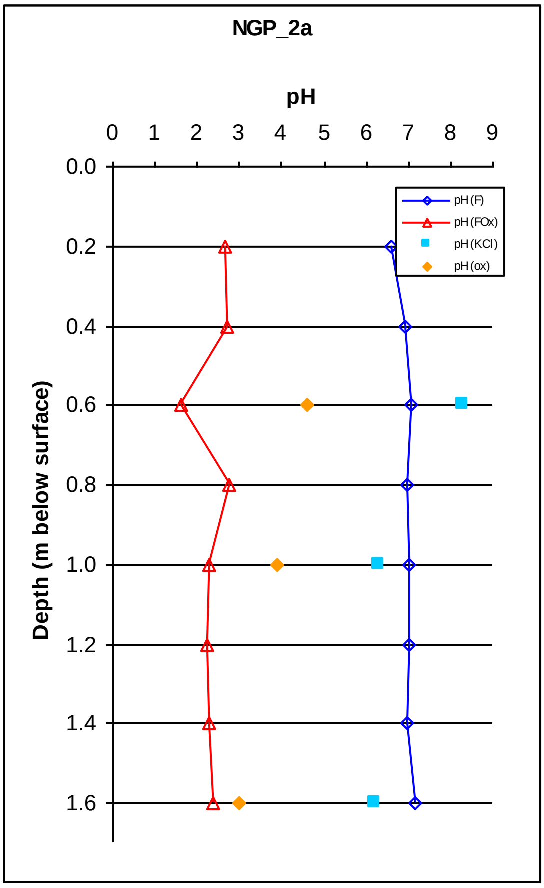


Figure 14 Field and laboratory readings of natural and oxidised pH at site NGP_2

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

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

Sediments with a net acidity of 18.7 mol H^+/t (0.03% sulfur) or greater are considered an acidification risk, and require careful management to prevent oxidation and/or ameliorate any current acidity (DEC 2009).

Ahern et al. (2004) described the terms used in the net acidity equation:

- *Actual acidity* (TAA) is the soluble and exchangeable acidity already present in the soil
- *Potential sulfidic acidity* is latent acidity that will be released if the sulfide minerals in acid sulfate soil are fully oxidised
- *Retained acidity* is the ‘less available’ fraction of the existing acidity which may be released slowly into the environment

- *Acid neutralising capacity* (ANC) is a measure of the soil's ability to buffer acidity and resist the lowering of soil pH
- *Fineness factor* is a factor applied to the acid neutralising capacity to allow for the poor reactivity of coarser carbonate or other acid neutralising material.

Results for sediment from Lake Nowergup showed no retained acidity and no ANC. Hence, the formula for ABA becomes:

Net acidity = potential sulfidic acidity + actual acidity (S_{Cr} or S_{POS}) + actual acidity (TAA)

Net acidity of samples from Lake Nowergup ranged from 2 to 1004 mol H^+/ t (Table 6). Both the SPOCAS and chromium methods reported that 11 of the 12 samples had net acidity above the action criteria set by the Department of Environment and Conservation (net acidity 18.7 mol H^+/ t). While the two methods of acid-base accounting are generally well correlated, it is common for the SPOCAS method to show a greater net acidity than the chromium method, as the SPOCAS method can inadvertently include sulfur from organic matter (Ahern et al. 2004). This general trend was true for most samples from Lake Nowergup, but there were three samples in which the SPOCAS method reported lower net acidities.

Soil samples were also analysed for a range of metals, metalloids and selenium concentrations (Table 7). Iron and aluminium concentrations were quite high in comparison to some of the other wetlands in the SGS investigation (e.g. Lake Mariginiup, Lake Bambun). Iron concentrations were between 620 and 16 700 mg/kg; aluminium concentrations ranged from 470 to 2830 mg/kg. Concentrations of arsenic ranged from below detection up to 110 mg/kg, and four samples breached the DEC sediment guideline of 20 mg/kg. Concentrations for chromium and nickel were between 2 and 14 mg/kg, manganese concentrations were up to 5 mg/kg and zinc concentrations ranged from below detection up to 2.2 mg/kg. Concentrations of selenium and cadmium were below detection limits for all samples.

High concentrations of sulfide (S_{CR} and S_{POS}) are correlated with high concentrations of iron and arsenic, which could suggest the presence of arsenopyrite (Figure 15 and Figure 16). The other metals however, do not appear to be associated with sulfide content.

Table 6 Summarised ABA for both the SPOCAS and chromium reducible sulfur suite of analyses

Site ID	Depth	pH_{KCl}	Potential acidity mol H+/ t		Actual acidity mol H+/ t		Net acidity mol H+/ t	
			S_{POS}	S_{Cr}	TAA SPOCAS	TAA S_{Cr}	Net acidity SPOCAS	Net acidity S_{Cr}
NGP_1a	0.30–0.40	3.6	0	0	19	19	19	19
	0.66–0.77	4.5	617	568	10	10	627	578
	0.90–1.02	4.6	193	162	7	7	200	169
	1.25–1.35	5.5	0	0	2	2	2	2
NGP_1b	0.20–0.30	5.3	998	686	6	6	1004	692
	0.20–0.30	5.4	811	811	5	5	816	816
	0.60–0.70	5.7	200	374	2	2	202	376
	0.90–1.00	5.9	168	112	1	1	169	113
	1.20–1.30	6.0	19	19	<1	0	19	19
NGP_2a	0.60–0.70	8.3	37	31	<1	0	37	31
	1.00–1.10	6.3	19	25	<1	0	19	25
	1.49–1.59	6.2	25	31	<1	0	25	31

Table 7 Metals, metalloids and selenium in sediment samples

Site ID	Depth	Fe mg/kg	Al mg/kg	As mg/kg	Cr mg/kg	Ni mg/kg	Mn mg/kg	Zn mg/kg	Se mg/kg	Cd mg/kg
NGP_1a	0.30–0.40	1 350	870	5.9	4.0	2.3	3.3	<0.5	<0.5	<0.5
	0.66–0.77	12 700	1 040	78.0	7.9	2.8	1.6	0.64	<0.5	<0.5
	0.90–1.02	4 710	1 290	31.0	10	11	2.0	2.0	<0.5	<0.5
	1.25–1.35	890	1 470	2.8	7.4	3.4	5.1	0.85	<0.5	<0.5
NGP_1b	0.20–0.30	16 700	2 080	110.0	14	5.7	4.3	0.63	<0.5	<0.5
	0.60–0.70	6 240	1 890	33.0	13	10	3.0	2.2	<0.5	<0.5
	0.90–1.00	2 960	1 680	10.0	9.6	5.4	2.8	2.2	<0.5	<0.5
	1.20–1.30	1 580	1 330	2.5	9.2	4.0	3.3	0.66	<0.5	<0.5
NGP_2a	0.60–0.70	3 100	2 830	1.7	11	2.9	3.9	0.53	<0.5	<0.5
	1.00–1.10	1 150	2 340	<0.5	8.5	2.5	3.1	0.69	<0.5	<0.5
	1.49–1.59	620	470	0.78	2.0	1.9	2.0	1.3	<0.5	<0.5

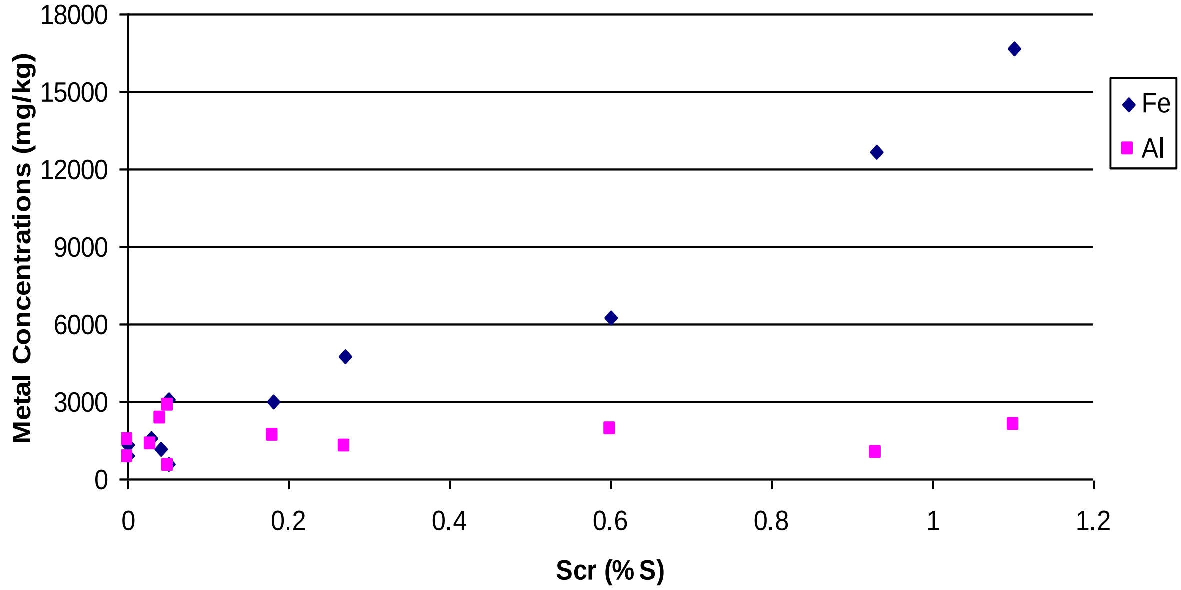


Figure 15 Relationship between iron, aluminium and sulfur in sediment

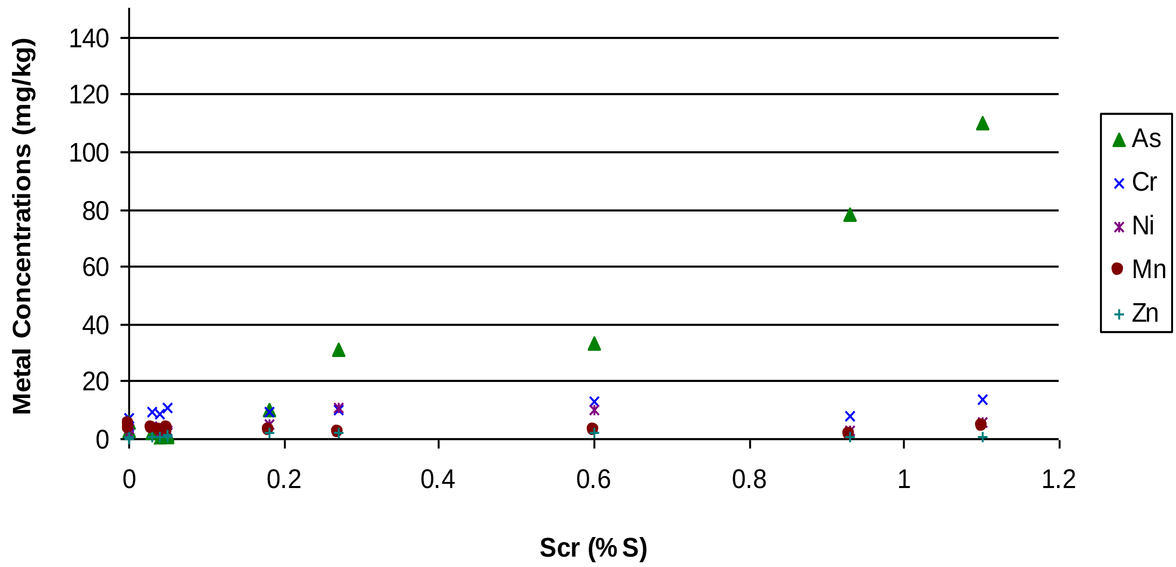


Figure 16 Relationship between various metals and sulfur in sediment

5 Hydrogeology

5.1 Regional hydrogeology

This study focuses on the Superficial aquifer, which is a regional unconfined aquifer made up of the sediments of the superficial formations of the Swan Coastal Plain. Table 8 outlines the historical physical and chemical properties of the Superficial aquifer. In the Lake Nowergup region, the Superficial aquifer overlies the formations of the Leederville aquifer (Davidson 1995).

The Superficial aquifer is mainly composed of porous, sands with high permeability (Section 2.2). Depending on geology, topography and discharge boundaries, hydraulic properties within the Superficial aquifer can vary significantly. Hydraulic conductivities range from 0.4 m/day in the clayey sediments of the Guildford clay to the east, an average of 15 m/day in the Bassendean and Safety Bay Sands, 8 m/day in the Ascot Formation. The hydraulic properties of the Tamala Limestone in which Lake Nowergup is located, vary widely due to solution channels and cavities. They can be as high as 100 to 1000 m/day, although the sandy beds such as those present at Lake Nowergup, are thought to have conductivities closer to 50 m/day (Davidson & Yu 2008).

Groundwater elevations caused by rainfall draining through these sands create two substantial groundwater mounds on the plain. To the north of Perth is the Gnangara Mound and to the south is the Jandakot Mound (Davidson 1995). Mounding of the watertable occurs in these locations as the vertical infiltration of rainfall exceeds the ability of the aquifer to transmit water away from the recharge zone. The Gnangara Mound and flow directions are illustrated in Figure 17. Where confining layers are absent, groundwater is connected between the Superficial aquifer and the underlying aquifers (Rockwater 2003).

A series of permanent and seasonal lakes and wetlands currently occur where these elevated groundwater mounds intercept the ground surface.

Table 8 Historical physical and chemical properties of the Superficial aquifer

Parameter	**Range**		**Reference**
	low	**high**	
Electrical conductivity	< 25 mS/m only near crest of mound	> 100 mS/m near the coast	PUWBS 1987
Total dissolved soils	140 mg/L (only near crest of the mounds)	550 mg/L near coast	PUWBS 1987
	130 mg/L	12 000 mg/L but rarely exceeds 1000 mg/L	Davidson 1995
pH	4.5–6.5 away from coast	6.5–7.5 in limestone	PUWBS 1987

Parameter	Range		Reference
	low	high	
	4	8	Davidson 1995
Hardness ($CaCO_3$ mg/L)	< 50 mg/L (Bassendean Sand)	500 mg/L (Tamala Limestone) >1000mg/L (Coast)	
Reduction potential (Eh)	No limit	> 0.3 V	PUWBS 1987
Nitrate	Mostly within drinking water limits	29 mg/L	PUWBS 1987
	0	> 60 mg/L	Davidson 1995
Phosphate	0	> 0.1 mg/L	PUWBS 1987
	0	0.1 mg/L occasionally 0.2 mg/L	Davidson 1995
Sulfate	0	200 mg/L	PUWBS 1987
		100 mg/L	Davidson 1995
Sulfate: chloride ratio		> 1	PUWBS 1987
	0.05	0.1	Davidson 1995
Iron (total dissolved)	Generally 1–5 mg/L	> 5 mg/L	PUWBS 1987
	< 1mg/L	> 50 mg/L	Davidson 1995
Total organic carbon	1 mg/L	> 50 mg/L	PUWBS 1987
Temperature	19 °C	23 °C	PUWBS 1987
Pesticides	All below potable limits		PUWBS 1987
Cadmium, chromium, copper, lead		Only localised elevated concentrations. No values.	PUWBS 1987

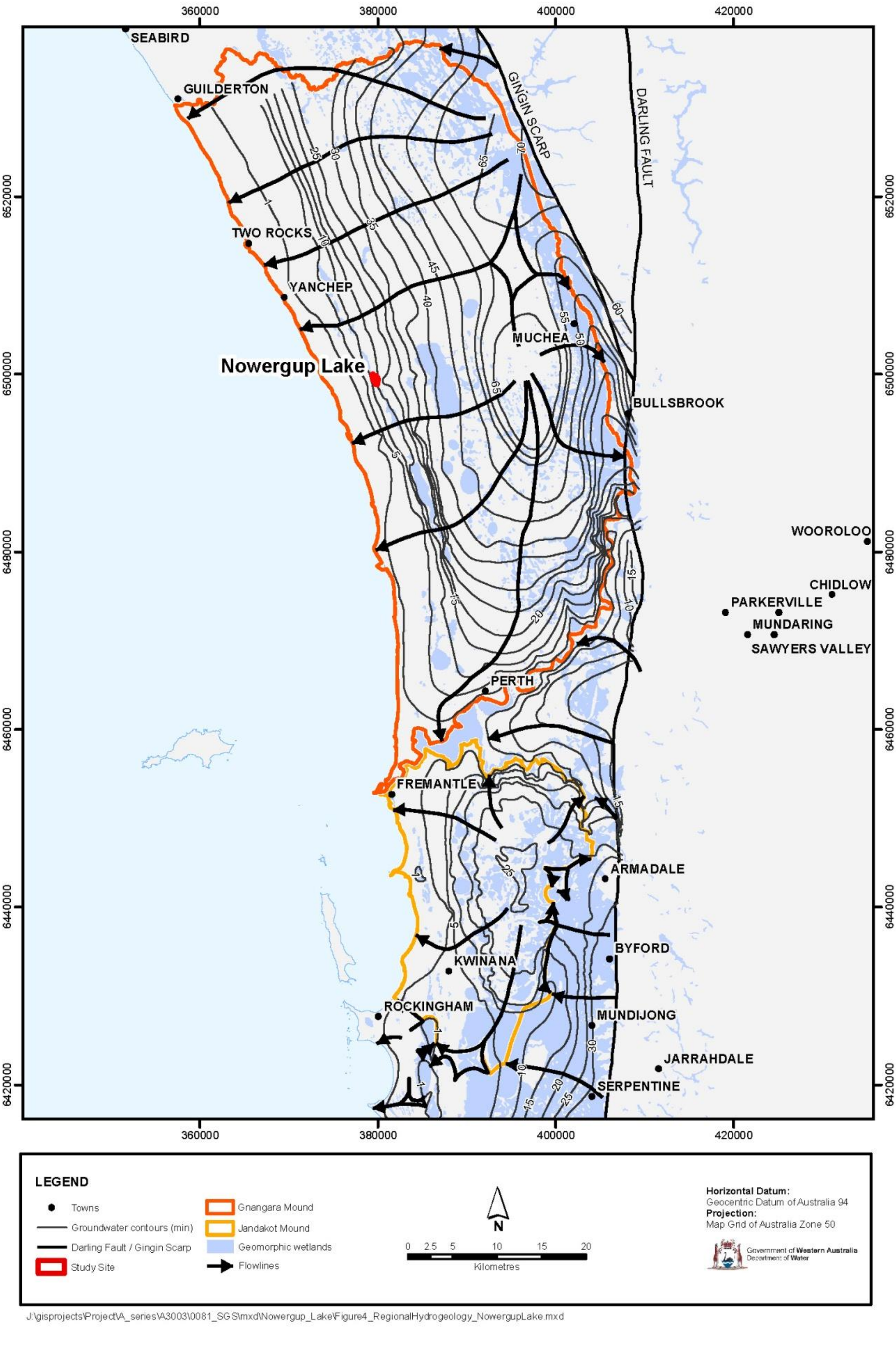


Figure 17 Gnangara and Jandakot mounds showing flow lines

5.2 Groundwater flow

The hydrogeology of Lake Nowergup is connected to the flow system of the Gnangara Mound (Figure 17). The many lakes and wetlands of the coastal plain are located where the watertable permanently or seasonally intersects the land surface. Surface water fluctuations are related to changes in groundwater levels. Townley et al. (1993) reported that most of the wetlands on the Swan Coastal Plain appear to act as flow-through lakes, which capture groundwater on the up-hydraulic gradient side and discharge lake water on the down-hydraulic gradient side. Rockwater (2003) found that wetlands on the Pinjarra Plain and Bassendean Dunes are usually flow-through lakes, while on the Spearwood Dunes cave systems can influence inflow and outflow.

Lake Nowergup is one of a chain of north to north-west trending linear lakes which occur in depressions of the Spearwood Dunes. It has previously been classified as a permanently inundated lake and is included in the Yanchep suite of wetlands (Hill et al. 1995). Townley et al. (1991) defines Lake Nowergup as a flow-through lake.

As Lake Nowergup has been supplemented by water from the Leederville aquifer for the past 20 years, and lake levels are now higher than the declining regional watertable, investigation into changes in the hydrological regime was required to better understand the system.

Groundwater flows from the Gnangara Mound east of Lake Nowergup, in a westerly direction towards the coast (as shown in Figure 18). The hydraulic gradient through the sand to the east of Lake Nowergup is low, while west of the lake there is a steep gradient (Figure 18 and Figure 19). The steep hydraulic gradient is likely to be a result of solution channels in the limestone, which is more common on the western side of the lake.

Regional decline in groundwater levels and artificial maintenance has changed the flow regime at Lake Nowergup. In recent times Lake Pinjar (4 km up-hydraulic gradient) has been dry, and there is now no overlap between the capture zone of Lake Nowergup and the release zone of Lake Pinjar. The ongoing pumping of water into the lake has prevented natural seasonal water level fluctuations, and resulted in localised mounding as shown in Figure 18 and Figure 19. Lake levels are now higher than the declining regional watertable, with water from Lake Nowergup recharging groundwater radially.

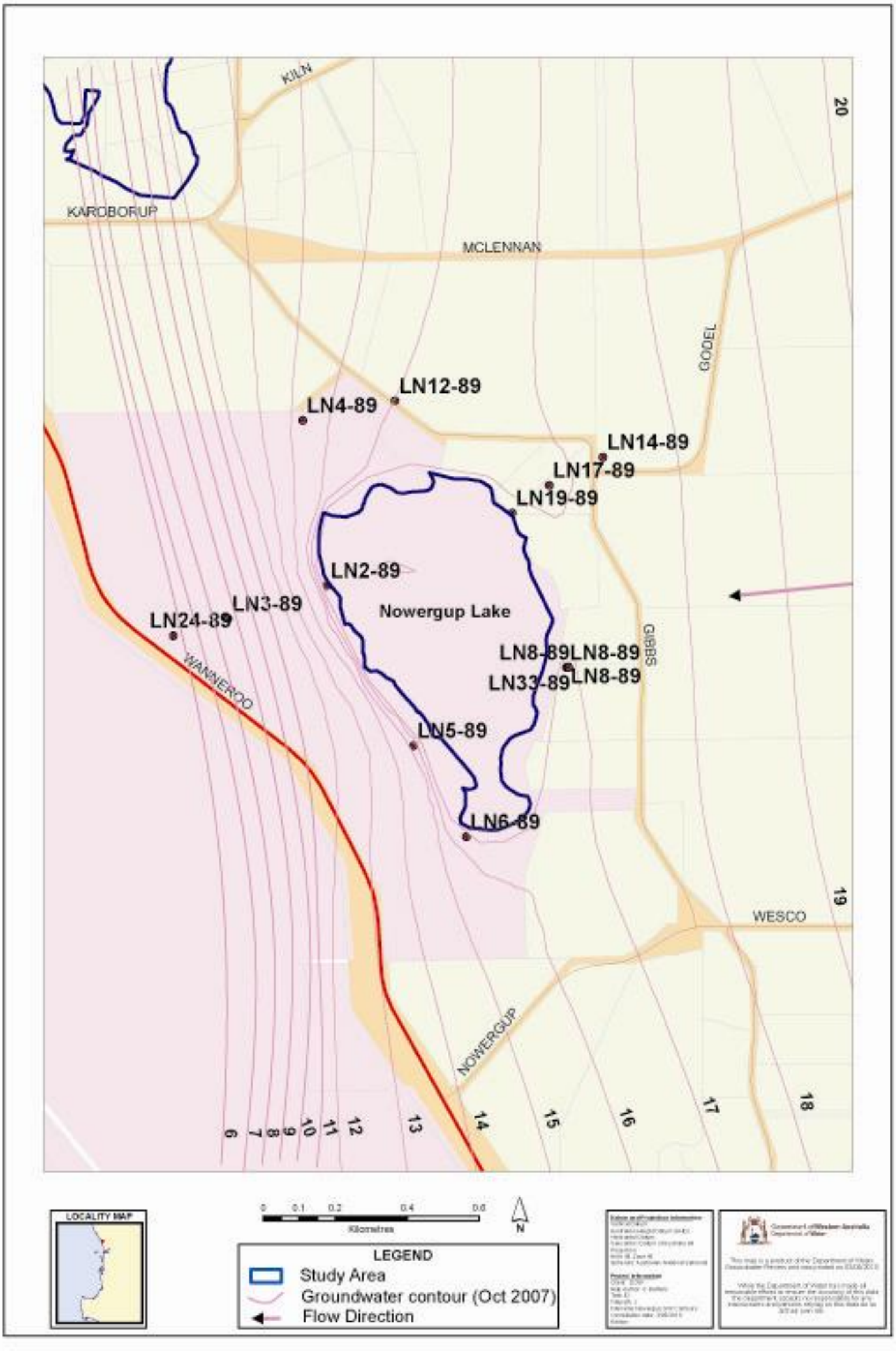


Figure 18 Local watertable contours around Lake Nowergup (Oct 2007).

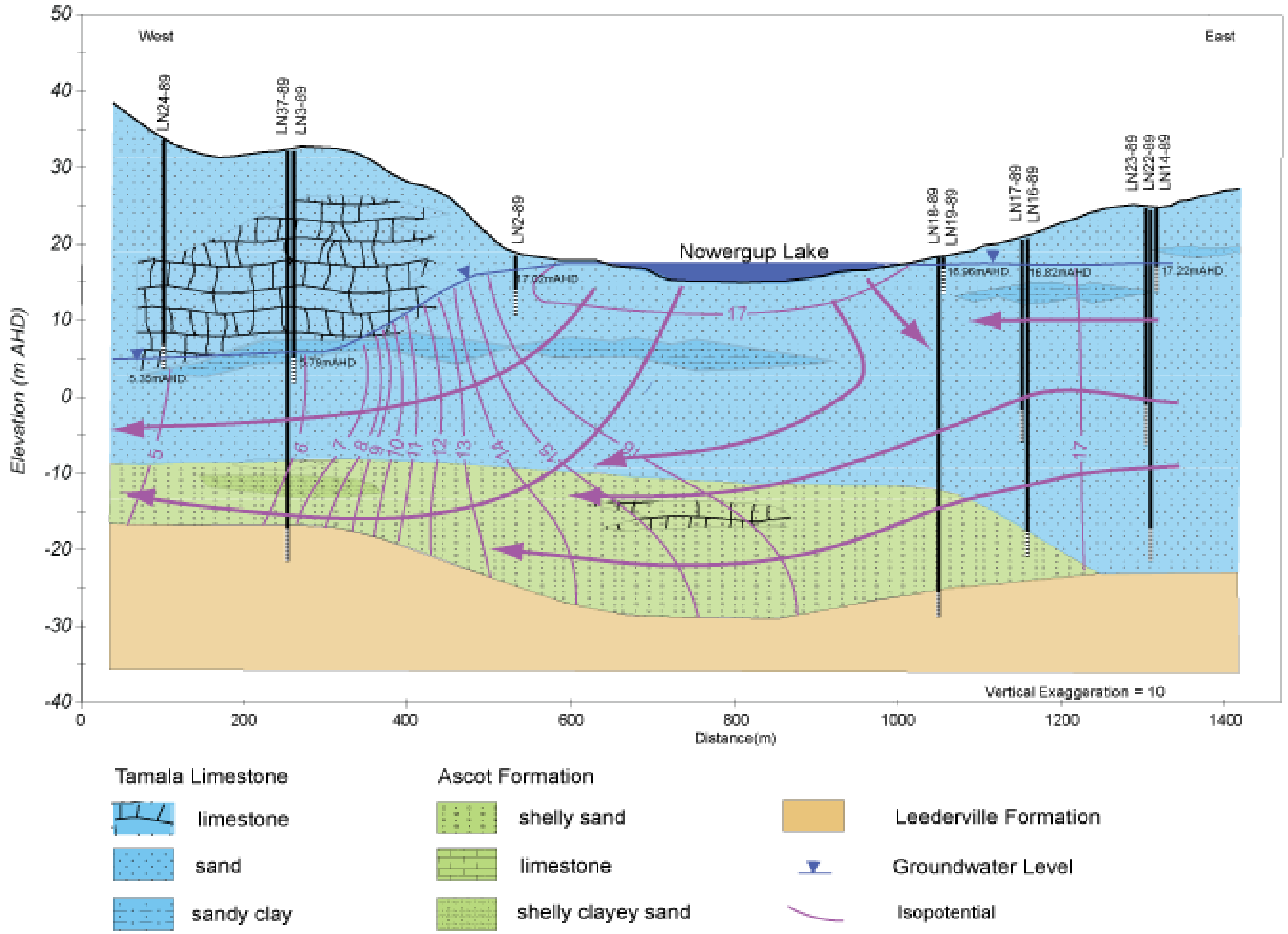


Figure 19 Nowergup Lake groundwater contours October 2007

Hydrograph analysis and the fact that there is no extensive confining layer suggest that the Superficial aquifer and Leederville aquifer are in hydraulic connectivity in the Lake Nowergup region. Figure 20 shows two nested sites, each with one bore screened in the Superficial aquifer and one in the Leederville. Bores LN18-89 and LN19-89 are located directly up-gradient from Lake Nowergup, and bores LN37-89 and LN3-89 are just down- gradient. The up-gradient bores show almost identical water levels, indicating strong hydraulic connection between the aquifers. If a significant confining layer is also lacking at the supplementation bore, which is only 300 m from these bores, the effectiveness of supplementation could be compromised.

The down-gradient bores show a separation of up to 3 m, although water level trends are similar, suggesting the presence of a locally confining unit. Figure 20 also shows the hydraulic separation has been decreasing which could indicate depressurisation of the Leederville aquifer, possibly due to abstraction for supplementation.

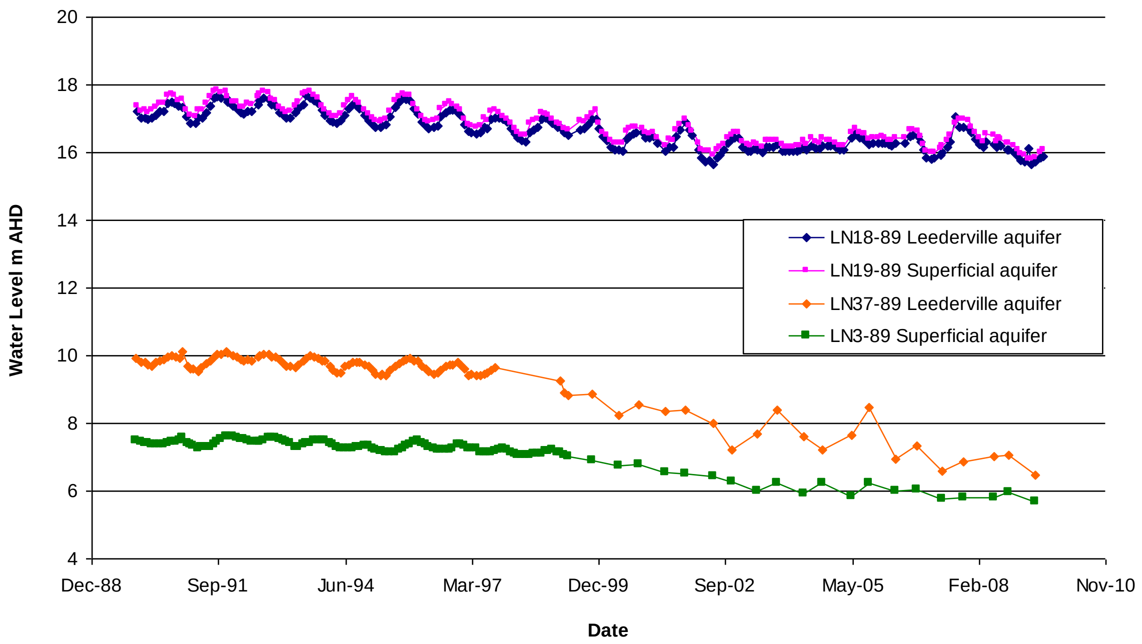


Figure 20 Aquifer comparisons at Lake Nowergup

5.3 Water levels

Analysis of hydrographs from Department of Water monitoring bores around Lake Nowergup show a decline in the groundwater levels of the Superficial aquifer (Figure 21). Lake levels have also been declining since the 1970s, despite supplementation from the Leederville aquifer. The increasing quantity of water needed to augment Lake Nowergup has failed to completely prevent the downward trend in lake levels. However, figure 22 shows that the rate of decline has slowed since supplementation began in 1989.

Historically, groundwater levels up-gradient and down-gradient of Lake Nowergup have been typical of flow-through lakes on the Swan Coastal Plain: higher on the eastern side of Lake Nowergup, and lower on the western side (Figure 21 and Figure 23). In 2002 this regime began to change, with lake levels periodically higher than groundwater levels east of the lake due to increased volumes of supplementation (Figure 23). Declines in groundwater levels in monitoring bores around Lake Nowergup slowed considerably in 2002, for the first time since supplementation began (Figure 23). By 2005, lake levels were permanently higher than the watertable as regional groundwater levels continue to decline. The lake is now a surface expression of an artificially created local groundwater mound. However, when pumping has been stopped, lake levels decline rapidly, presumably due to high hydraulic conductivity of the Tamala Limestone.

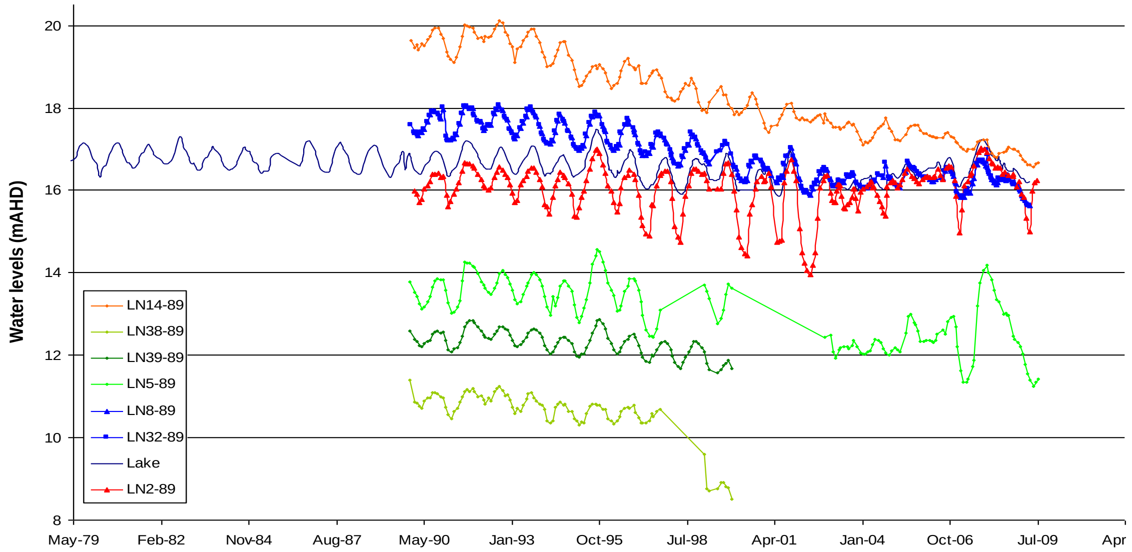


Figure 21 Hydrograph of bores in the Lake Nowergup area

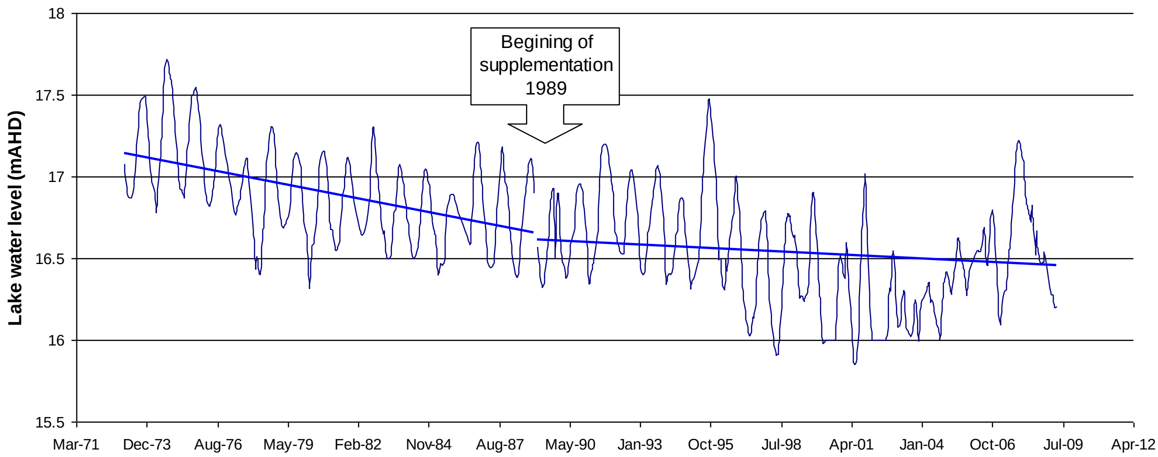


Figure 22 Lake Nowergup water levels

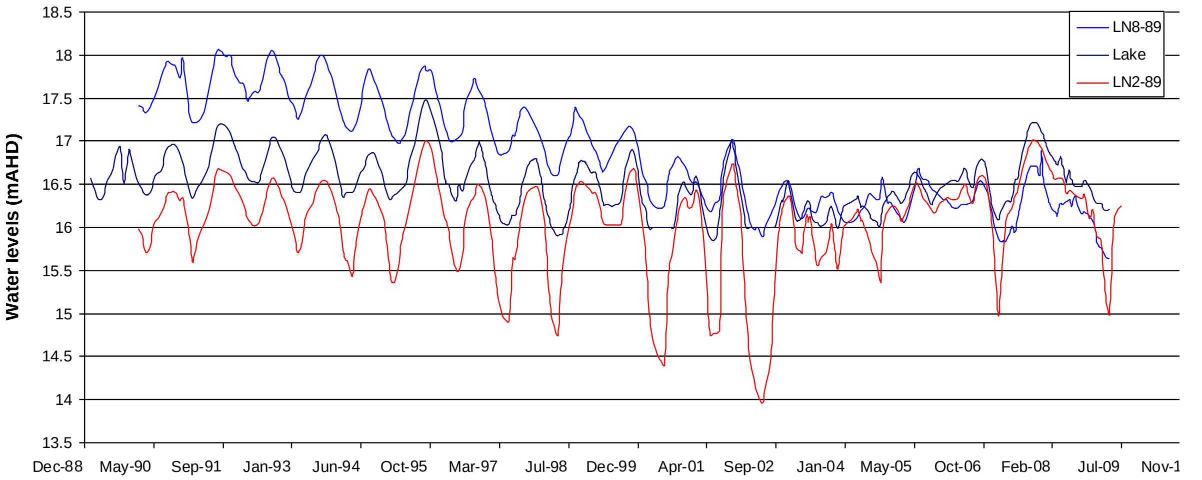


Figure 23 Watertable and lake levels at Lake Nowergup

Seasonal fluctuations in groundwater near Lake Nowergup and in lake levels have historically been in the order of 0.5 to 1.0 m. Lake levels, and groundwater on either side of the lake have varied in phase, indicating strong connectivity between the surface and groundwater. From around 2002 the fluctuations in water levels have become more erratic, and groundwater and lake levels are not as closely related.

The hydraulic gradient from the east to the west sides of the lake has decreased since the late 1980s, from around 1.5 m to less than 0.5 m (Figure 23).

Due to the consistency of the supplementation regime, there was no seasonal water level cycle during the SGS investigation monitoring program, and water levels declined throughout the investigation period (Figure 24).

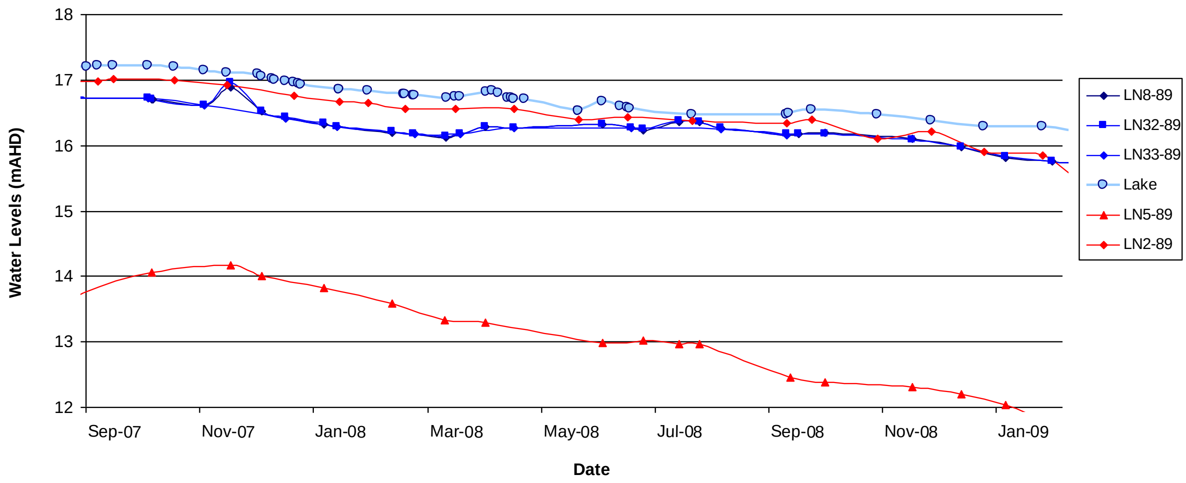


Figure 24 Water levels at Lake Nowergup over the SGS investigation period

5.4 Flow budget

The local-scale numerical modelling carried out by SKM (2009) allows an estimate of the water balance at Lake Nowergup. Figure 25 shows the average monthly water balance over the calibration period of the model (1991–2006). In the figure below, blue has been used to represent inputs to the lake, and red has been used to represent water leaving the lake.

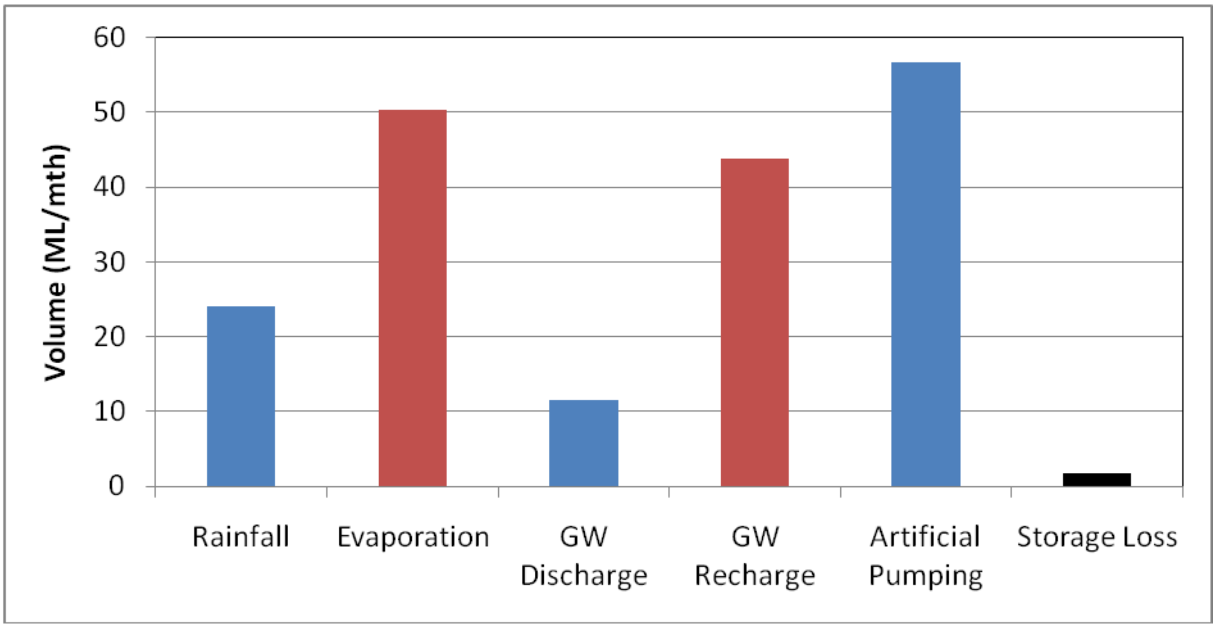


Figure 25 Average monthly water balance (From SKM 2009)

Although the artificial lake supplementation regime was not consistent throughout the calibration period, Figure 25 shows clearly that it is a major part of the water balance, accounting for around 62% of all inflow to the lake.

The time series plots (Figure 26) of the various components of the water balance allow greater understanding of changes to the system for the calibrated period. Throughout the 1990s groundwater discharge into the lake declined, and from around 2000 inflow to the lake from groundwater was negligible. This is a direct result of groundwater levels falling below the lake bed (SKM 2009). At this time rainfall was also lower. Conversely, groundwater recharge from the lake has been increasing, along with increased artificial maintenance.

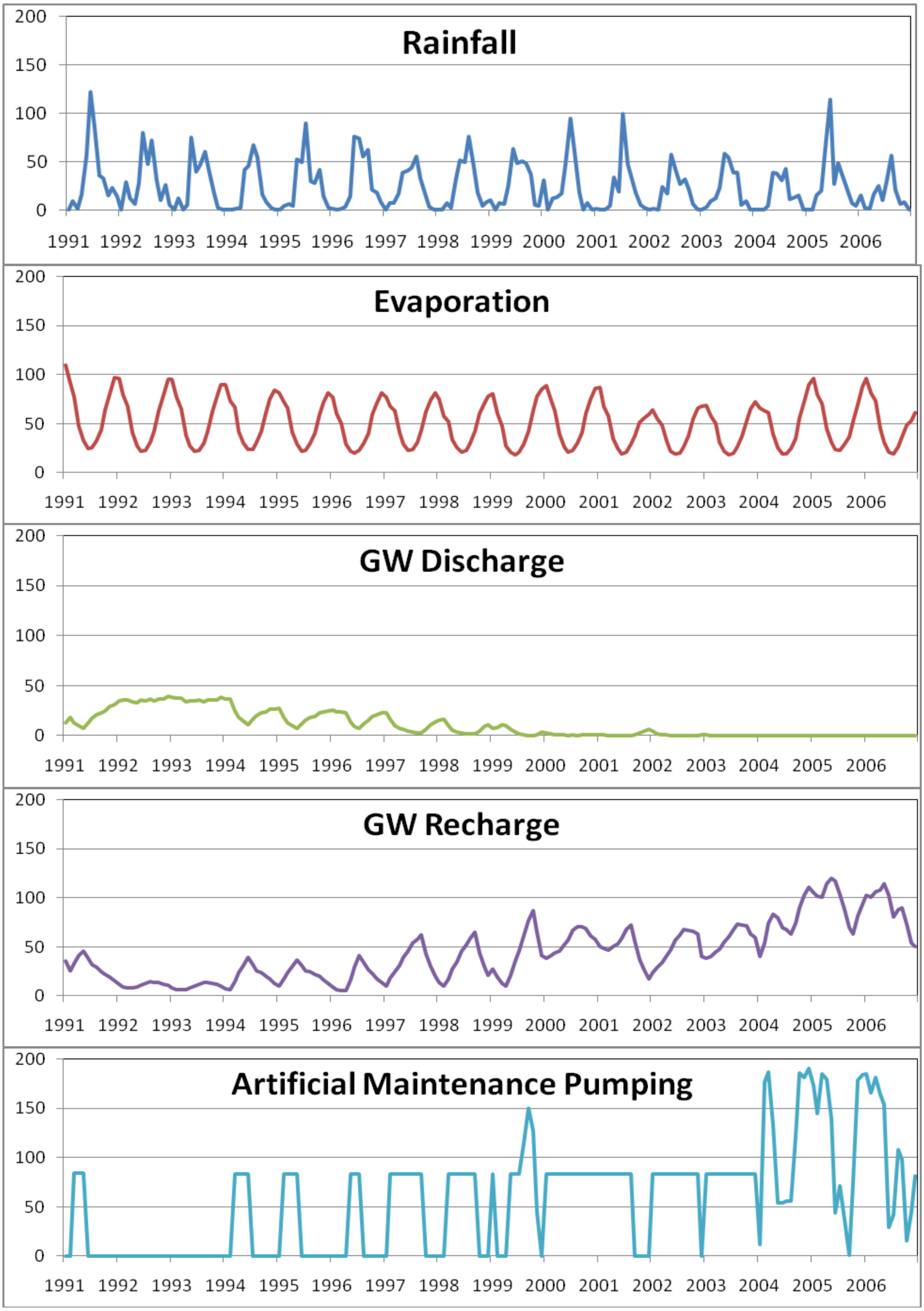


Figure 26 Inputs and outputs to Lake Nowergup (mL/month) (From SKM 2009)

5.5 Hydrogeochemistry

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

Chemical analysis was compared against the Department of Environment and Conservation's *Assessment levels for soil, sediment and water* (DEC 2010). These assessment levels have been taken from the *Australian and New Zealand guidelines for fresh and marine water quality* (ANZECC 2000) and the *Australian drinking water guidelines* (NHMRC & ARMCANZ 2004). As the main use for groundwater around Lake Nowergup is irrigation, groundwater quality has been assessed against the irrigation guidelines. Drinking water guidelines were also used to give a perspective on sample water quality and where no irrigation trigger level existed, used for reporting purposes (in accordance with the methods described in the Department of Environment and Conservation's 2010 guidelines).

The Department of Water considers that any untreated water taken from the environment is unsafe for human drinking.

Breaches of the irrigation water guidelines could affect agricultural productivity of market gardens and domestic users. The assessment levels for freshwater aquatic ecosystems in the same guidelines are also relevant for the lake and groundwater discharging to the lake as are the nutrient and physical property trigger values for wetlands and freshwater lakes in south west Australia (ANZECC 2000). Breaches of the freshwater (DEC), freshwater (ANZECC) or wetland (ANZECC) trigger values in samples from the lake or up-gradient of the lake could be detrimental to the vegetation, macroinvertebrates and fauna associated with the lake.

5.5.1 Physical and chemical properties

To characterise the water in the Superficial aquifer and lake water at Lake Nowergup, a number of ions and physical properties were measured. Concentrations of major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, and SO_4^{2-}) were used to create 'Piper diagrams'. Piper diagrams are a simple but useful method to help determine and present the geochemical nature of individual groundwater samples, and in turn help to compare and contrast samples with different chemical characteristics.

To provide an overview all the chemical composition data in this investigation, Piper diagrams, which display the main groundwater components at a glance and provide a basis for the descriptive classification of water type, have been used. The Piper diagram (Figure 27) displays the chemical composition by percentage for groundwater in the Superficial aquifer surrounding the lake and in Lake Nowergup. The water sample taken from the supplementation bore is also displayed on the diagram. Rainwater samples resemble highly diluted seawater, as ocean water and rainwater are positioned in same area at the right hand corner of the diamond diagram (Yesertener 2009). Groundwater within the sands and limestones of the

Tamala Limestone is $CaHCO_3$ type water. The groundwater in Bassendean Sand is of NaCl type, which is similar to rainwater (and sea water) especially within the groundwater recharge area, that is, the crest of the Gnangara Mound. Lake Nowergup and surrounding aquifer (LN2-89) have been found to be $CaHCO_3$ type water (Yesertener 2009). Yesertener's study concluded that lake water shows carbonate weathering and is saturated with respect to calcite, while shallow groundwater at the western site of the lake shows silica weathering, ferromagnesium minerals and gypsum dissolution as hydrochemical processes. Yesertener concluded that Lake Nowergup is very well connected with the groundwater system.

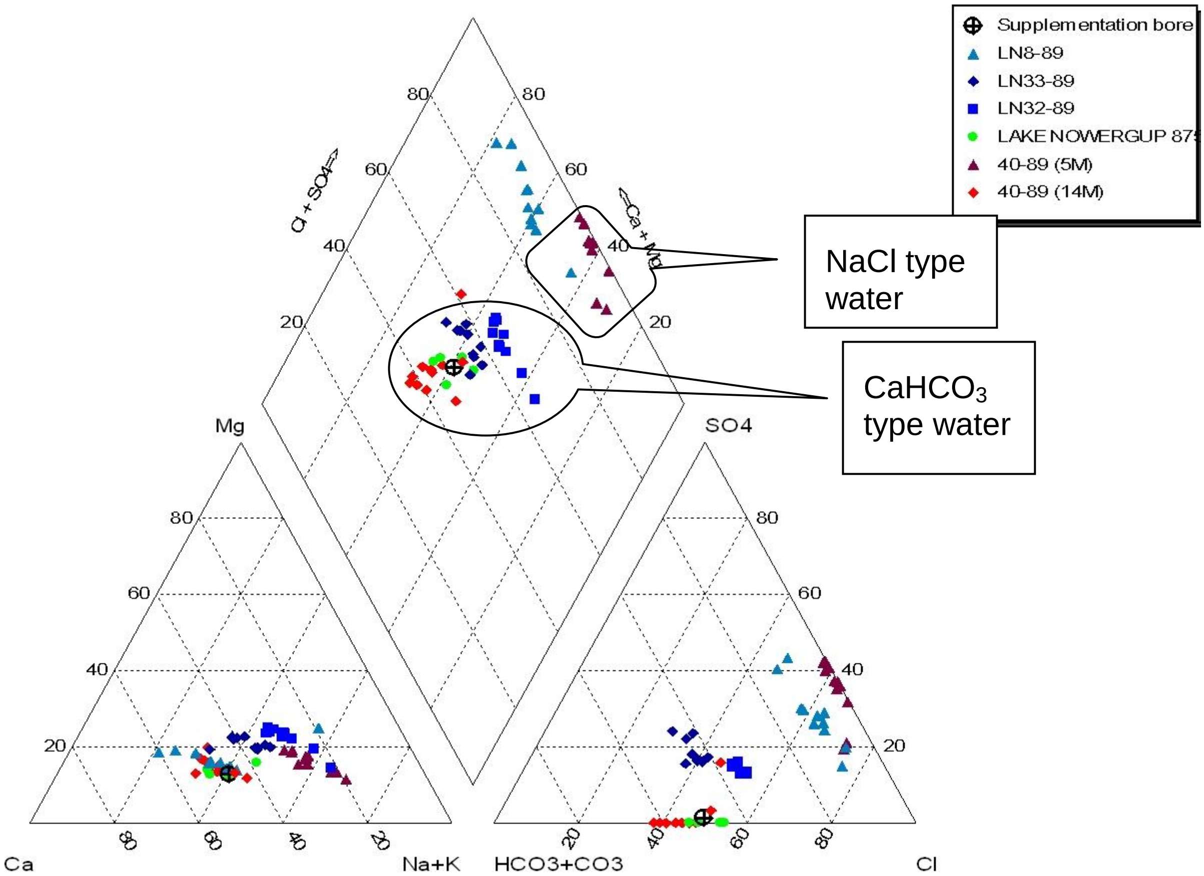


Figure 27 Piper diagram of lake and groundwater at Lake Nowergup

A piper diagram plotting all water samples for this investigation is presented above (Figure 27). Several samples from each of the bores and the lake did not have a satisfactory ionic balance, and so were left out of the diagram. Our data provides greater understanding of local-scale processes occurring at Lake Nowergup.

Samples from the lake, both intermediate bores, the eastern deep bore as well as the supplementation bore plot in a consistent position close to the middle of the graph, indicating $CaHCO_3$ type water. The shallow bores, however, do not show $CaHCO_3$ type water characteristics. Groundwater at the shallow western bore is mostly NaCl type water, which could indicate a lack of connection with the surrounding groundwater and lake flow. Groundwater in both east and west shallow bores is strongly influenced by sulfate and chloride. The shallow eastern bore is also high in calcium compared to the other bores and the lake water. The characteristics of this bore could result from ion exchange or as with the shallow western bore, could indicate lack of connection with the surrounding flow system. The chemical characteristics at the watertable could be due to evaporative concentration (Cl^-), ASS oxidation (SO_4^{2-}), and or gypsum dissolution (Ca and SO_4^{2-}).

The similar hydrochemical characteristics of the lake water and groundwater in intermediate bores suggest that water flows downwards from the lake, below the level of the shallow bores. Building on the work of Yesertener (2009), results of this study suggest the shallow zone of the aquifer is somewhat disconnected from the surrounding groundwater and lake.

Comparisons of our lake water chemical data and the work of Turner & Townley (2006) (Table 9) show that major ion concentrations and TDS have decreased significantly since 1989. Low ionic concentrations in lake water have also been recorded from recent wetland monitoring (Judd & Horwitz 2010) and are generally the lowest for flow-through wetlands on Tamala Limestone (Table 10). The increasing volume of low ionic concentration supplementation water into Lake Nowergup is the likely cause of these hydrochemical changes.

Table 9 Change in lake water major ion concentrations in Lake Nowergup

Major ion	**Concentrations mg/L**				
	1989 (Turner & Townley 2006)		**2007 (This study)**		
	Minimum	**Maximum**	**Supplementation bore (2010)**	**Minimum**	**Maximum**
Na	180	366	40	30	41
K	16.3	30.6	4	3	5
Ca	50.9	120.9	42	36	42
Mg	20.3	47.4	7	6	9
Cl	366	600	70	60	80
SO_4	59.1	207.9	< 5	< 5	< 5
TDS	806	1619	240	200	250

Table 10   Chemical analysis of flow-through wetlands on Tamala Limestone (from Judd & Horwitz 2010)

Wetland	**SO_4 mg/L**		**Cl mg/L**		**Ca mg/L**		**K mg/L**		**Mg mg/L**		**Na mg/L**	
	Spring	**End of summer**	**Spring**	**End of summer**	**Spring**	**End of summer**	**Spring**	**End of summer**	**Spring**	**End of summer**	**Spring**	**End of summer**
Goollelal	108	121	162	162	61.9	70.5	11.3	12.9	24.8	30.1	96.4	116
Joondalup North	96.1	108	299	325	37.2	45.1	10.1	12.5	30.2	34.9	183	184
Joondalup South	40.3	64.4	131	121	50.2	59.5	5.7	9.2	13.4	25.9	72	134
McNess North	30.9	277	173	273	83.5	178	3.8	7.9	10.5	24.9	84.1	152
Nowergup	1.9	1.8	71	72	44.7	33.2	4.8	4.2	7.1	7.4	41.7	41.8
Yonderup	70.4	82	125	96	51.1	53.8	2.5	2.6	8.8	9.4	60.3	64.8
Average	57.9	109.0	160.2	174.8	54.8	73.4	6.4	8.2	15.8	22.1	89.6	115.4

Chloride (Cl^-)

Chloride concentrations measured in 1989 on the east side of Lake Nowergup (Turner & Townley 2006) ranged from 54 to 217 mg/L and from 167 to 577 mg/L on the down-hydraulic gradient side (west), and from 370 to 600 mg/L in the lake water. Our investigation shows chloride concentrations are now much lower in and around Lake Nowergup. Chloride concentrations in all aquifer zones and the lake now range from 50 to 300 mg/L, with an average value of 109 mg/L. Chloride is generally highest in the shallow bores. Chloride concentrations only exceeded the drinking water assessment level of 250 mg/L in two samples. Both samples were taken from the shallow eastern bore LN8-89, with concentrations being less than 300 mg/L.

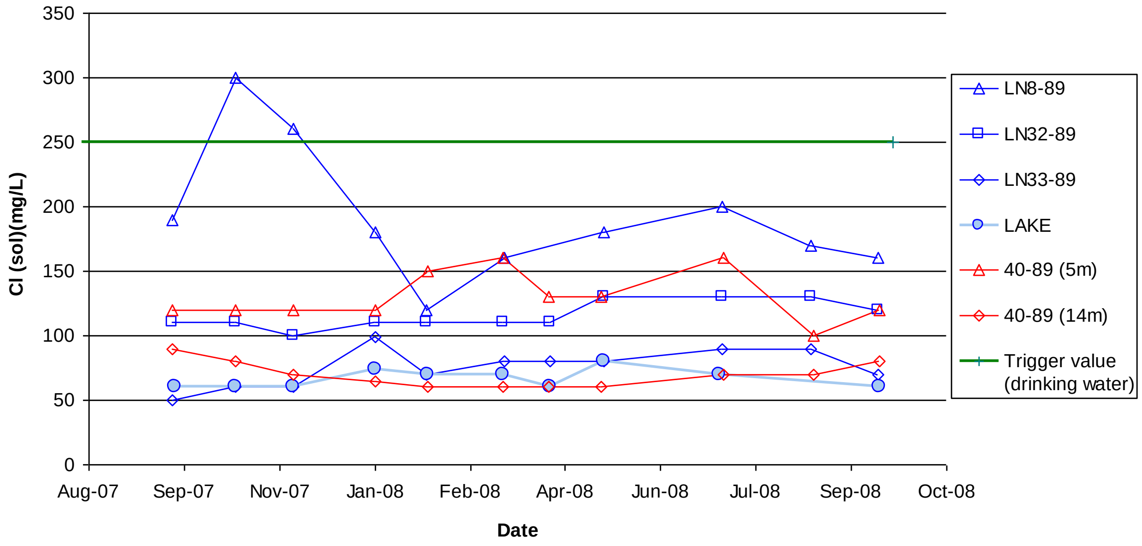


Figure 28 Chloride concentrations in lake and groundwater

Sodium (Na^+)

Sodium concentrations are generally between 30 and 90 mg/L, with the western intermediate bore (40-89 (14 m)) and lake water displaying very similar values. Sodium concentrations in the lake have decreased by almost an order of magnitude from1989 (Tuner & Townley 2006) to 2007–08.

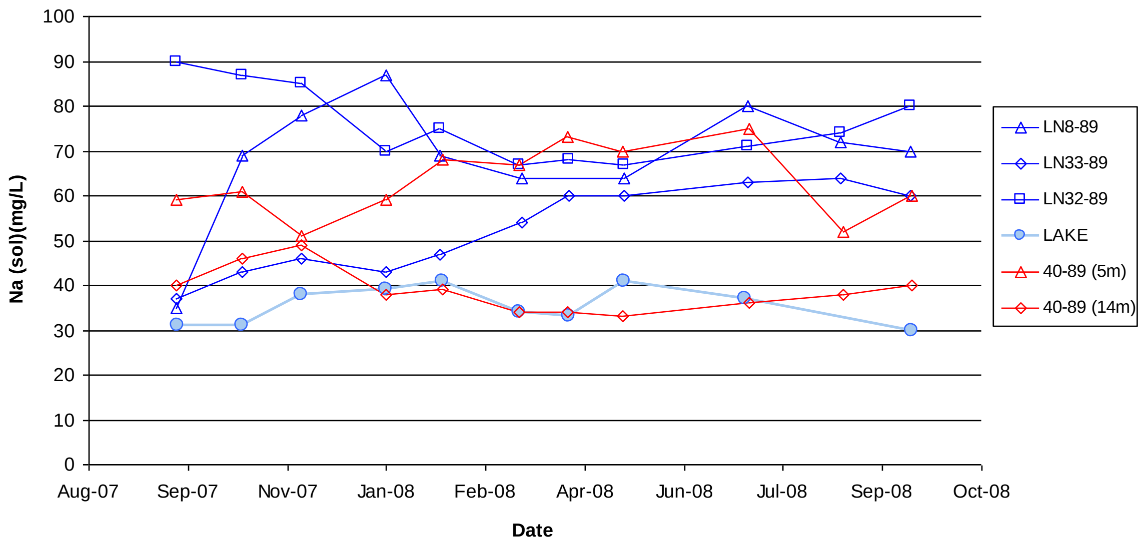


Figure 29 Sodium concentrations in lake and groundwater

Calcium (Ca^{2+})

The greatest concentrations of calcium are in the shallow zone of the aquifer, east of the lake. The eastern shallow bore (LN8-89) has calcium concentrations ranging from 68 to 140 mg/L, with an average of 90.18 mg/L. All other bores and lake water have significantly lower concentrations (between 14 and 62 mg/L, with an average of 39.8 mg/L). The shallow bore on the western side (40-89 (5 m)) has the lowest calcium concentrations.

Concentration of calcium in Lake Nowergup have decreased from a range of 50.9 to 120.9 mg/L in 1989 (Turner & Townley 2006) to 32 to 42 mg/L in 2007–08.

Magnesium (Mg^{2+})

Concentrations of magnesium are higher on the western side of Lake Nowergup than on the east. Lake water has the lowest magnesium concentrations, with a small range of 6 to 8 mg/L. Magnesium concentrations for all samples are below 30 mg/L. As there is limestone to the west and sand to the east, the higher magnesium concentrations probably result from rock–water interaction with the limestone.

Concentrations of magnesium in Lake Nowergup have decreased from a range of 27.6 to 47.4 mg/L in 1989 (Turner & Townley 2006) to 6 to 8 mg/L in 2007–08.

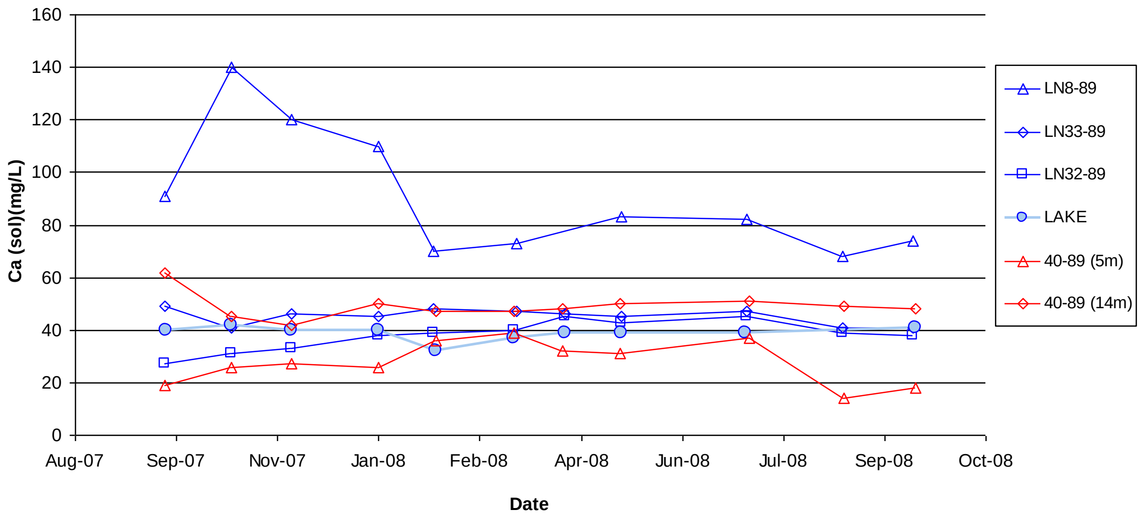


Figure 30 Calcium concentrations in lake and groundwater

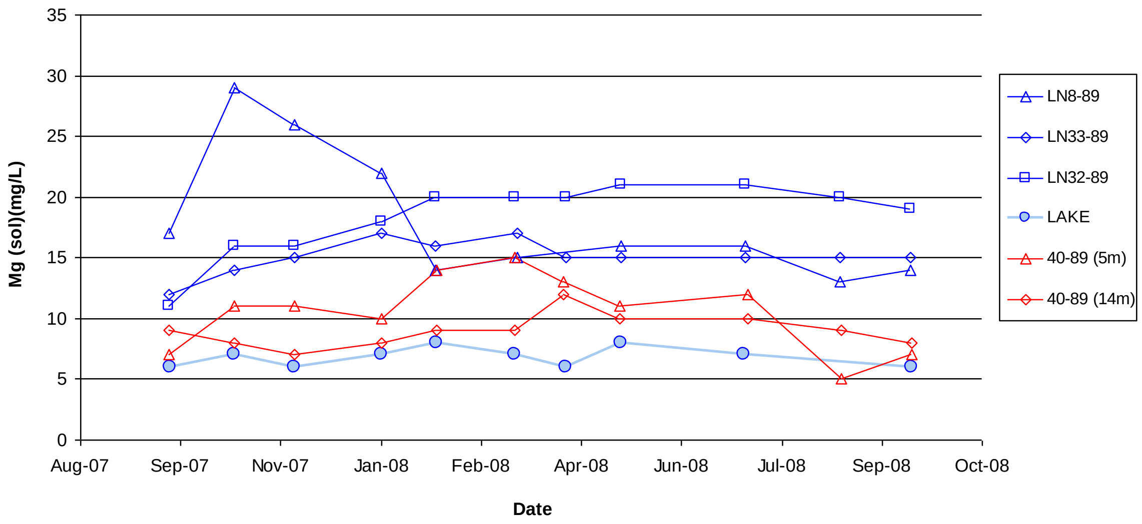


Figure 31 Magnesium concentrations in lake and groundwater

Sulfate (SO_4^{2-})

The shallow bores on either side of Lake Nowergup (40-89 (5 m) and LN8-89) have the highest concentrations of sulfate, ranging from 43 to 220 mg/L. The deep and intermediate bores on the eastern side (LN32-89 and LN 33-89) have relatively stable sulfate concentrations, ranging from 39 to 54 mg/L. Lake water and samples from the intermediate western bore (40-89 (14 m)) are mostly below the limits of detection.

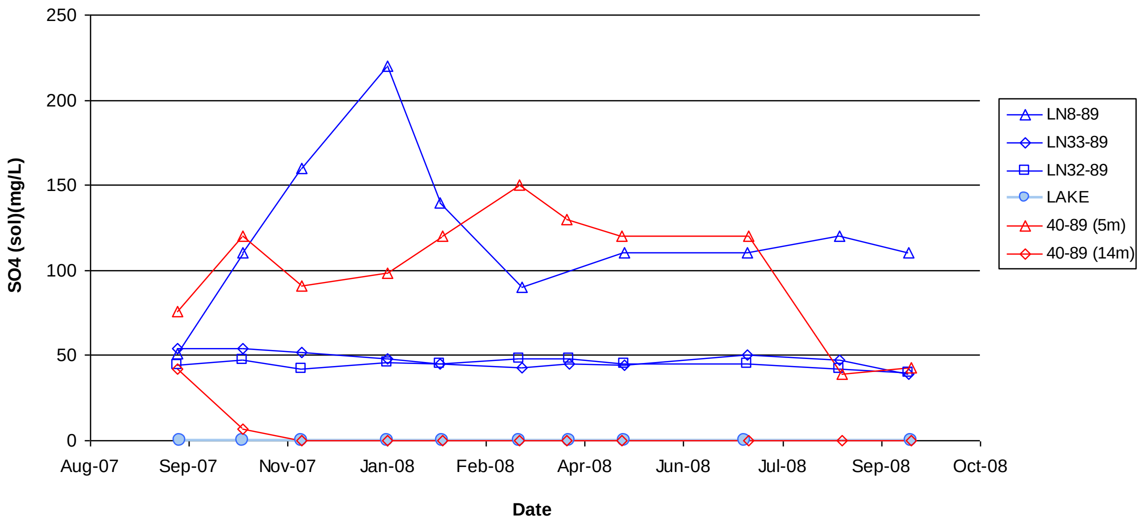


Figure 32 Sulfate concentrations in lake and groundwater

pH and alkalinity

Field pH readings are used in this section in preference to the laboratory measurements. During our investigation, most samples showed pH values within the healthy range given by ANZECC and DEC for fresh water (6.5 to 8.5), while the shallow western bore (40-89 (5 m)) was shown to be acidic. The pH values in and around Lake Nowergup are slightly lower than historical values. Davidson (1995) reports pH values of water within the Tamala Limestone to generally be between 7 and 8. Results from the SGS investigation show the average pH of lake water is 7.40 and the average pH for groundwater samples (except the shallow western bore) is 6.98.

Most bores and the lake water show a peak in pH levels in March 2008 (Figure 33). Since the laboratory results do not show a corresponding spike in pH, these are considered to be either instrument or human errors in the field readings.

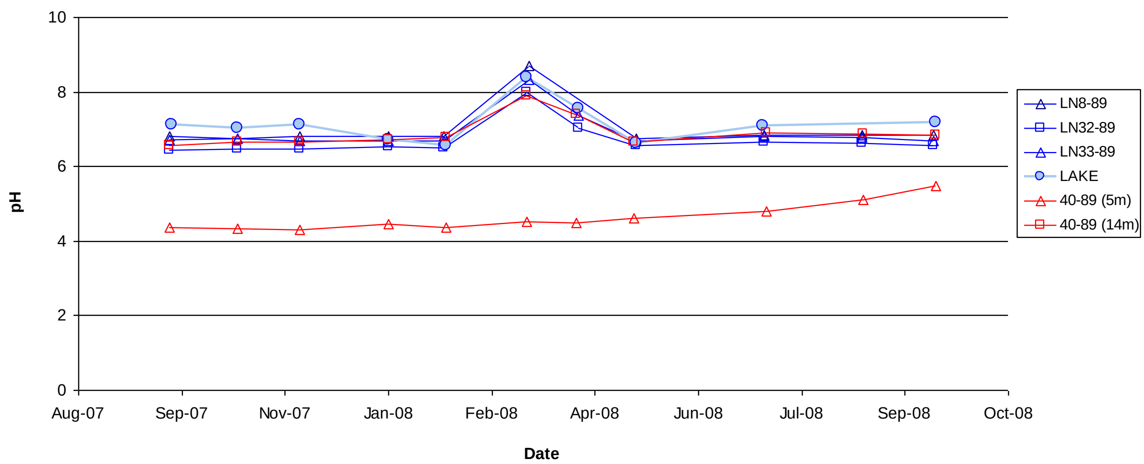


Figure 33 pH values in lake and groundwater

Apart from the shallow eastern bore, alkalinity and pH generally correspond. Both parameters are high for lake water and the intermediate and deep bores, while the shallow western bore has very low alkalinity (< 1 to 21 mg/L $HCO_3 – CaCO_3$) (Figure 34) and also has low pH values (4.38 to 5.49) (Figure 33). Water from the supplementation bore had alkalinity of 120 mg/L. This value is much higher than water from the shallow bores, but generally lower than samples from the other bores, which are screened in the Tamala Limestone.

Figure 35 shows the maximum and minimum recorded pH values in the lake over the past 14 years. pH values exceeding the upper limit set by DEC for fresh water are common.

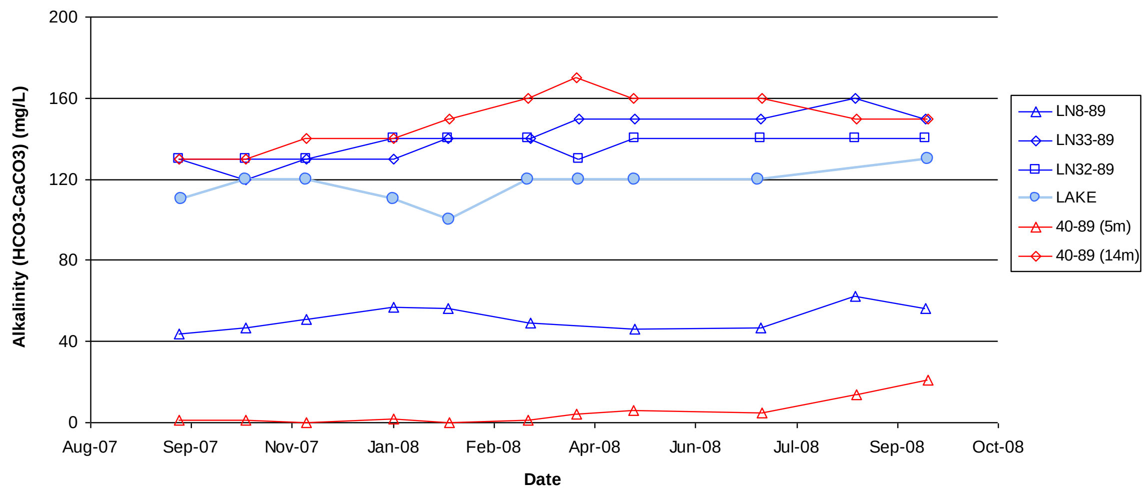


Figure 34 Alkalinity concentrations in lake and groundwater

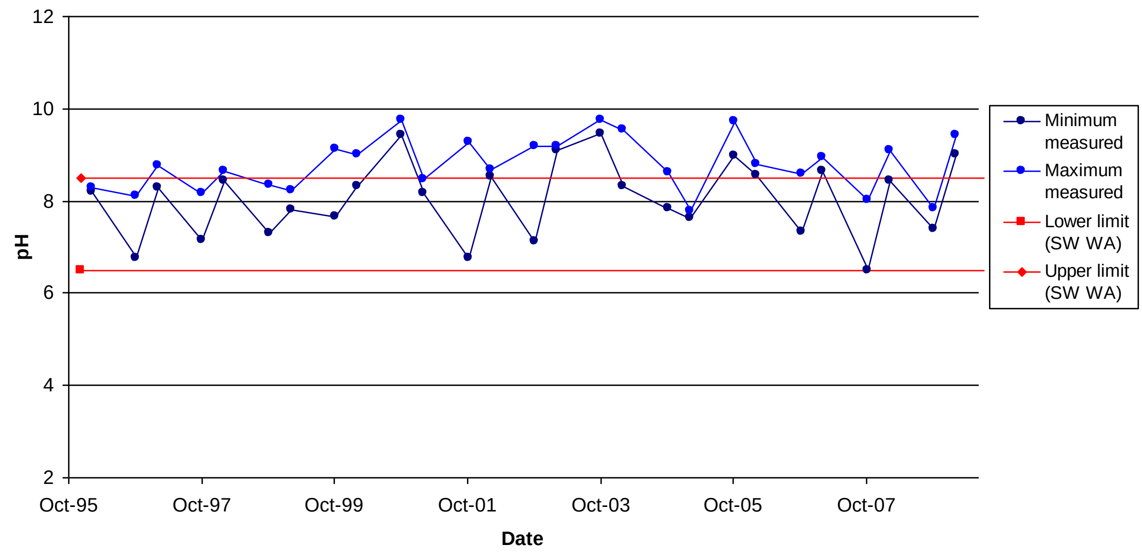


Figure 35 Long-term pH measurements in Lake Nowergup

Salinity as total dissolved solids

Historical values of total dissolved solids range from 130 to 12 000 mg/L in the Superficial aquifer; but generally do not go above 1000 mg/L (Davidson 1995). Results from the SGS study at Lake Nowergup fall within this range, with most samples having concentrations between 300 and 600 mg/L. The two shallow bores have the highest TDS, with the eastern one reaching 900 mg/L, while the lowest TDS comes from the lake water and the intermediate western bore (40-89 (14 m)) (Figure 36). Water from the supplementation bore also has low TDS (240 mg/L).

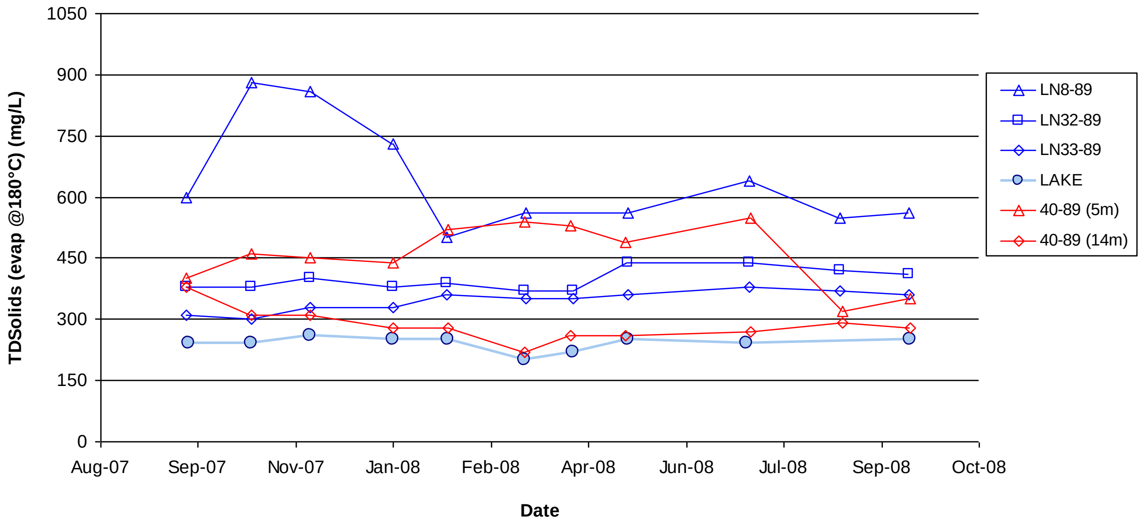


Figure 36 Total dissolved solids concentrations in lake and groundwater

Dissolved oxygen

Dissolved oxygen saturation in lake and groundwater can indicate whether an environment is generally oxic or anoxic. However, during this study field measurements were recorded before DO stabilised, and so they can only be considered as broadly indicative. DO in Lake Nowergup is inadequate when measured against the Department of Environment and Conservation guidelines for wetlands or freshwater lakes. The guidelines state that the lower limit for DO should be 90% saturation. Water from Lake Nowergup has an average DO of 58%, and ranges from 32.8 to 79.3%. All groundwater samples have DO less than 70%, and most were below 20%.

Figure 37 shows that dissolved oxygen concentrations for Lake Nowergup over the past 14 years are highly variable. Over time, a slight trend of increasing maximum concentrations of DO can be observed.

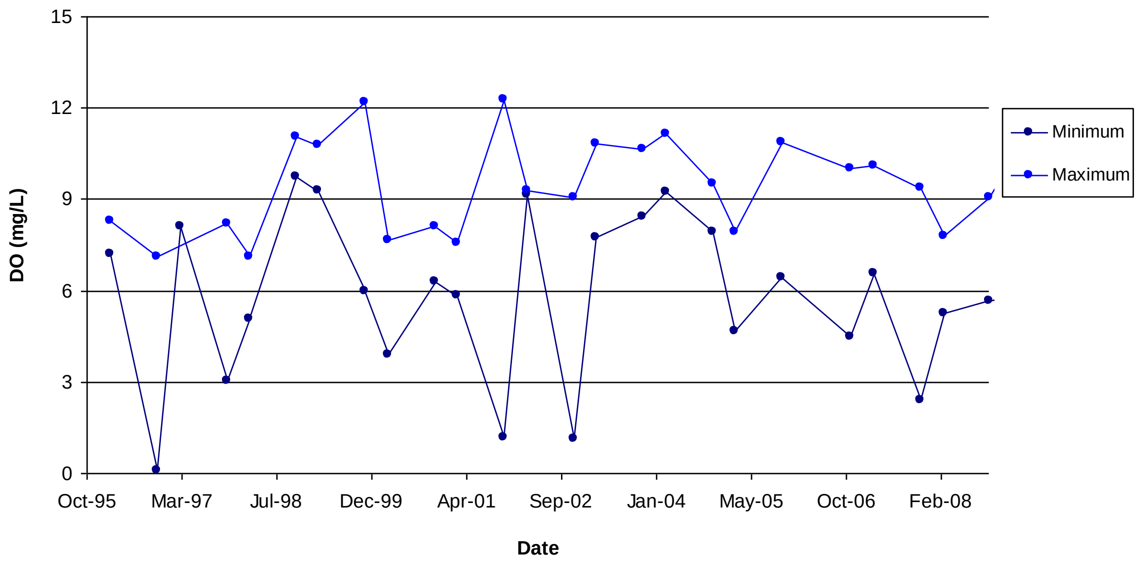


Figure 37 Long-term dissolved oxygen measurements in Lake Nowergup

Redox conditions

Eh readings are a measure of the electron activity of aqueous solutions. Eh, measured in millivolts (mV), is useful to give a qualitative indication of redox condition (Yesertener 2009). Only samples from the lake and shallow western bore showed positive Eh values, indicating that the Superficial aquifer around Lake Nowergup is mostly a reducing environment.

Using the framework devised by Jurgens et al. (2009), dissolved oxygen, nitrate, manganese, iron, sulfate and sulfide concentrations were used to classify the redox state of groundwater, and to identify the dominant oxidation or reduction processes. Using only water samples which had at least five parameters, the following redox categories and processes were identified:

- Anoxic conditions were dominated by iron (III) and, (or) sulfate reduction. The shallow and intermediate bores on both sides experienced this redox condition.
- Mixed (oxic–anoxic) conditions were dominated by oxygen reduction, as well as iron (III) or sulfate reduction. This took place in the shallow eastern bore (LN8-89), intermediate western bore (40-89 (14 m)) and the lake.
- Oxic conditions were dominated by oxygen reduction, and occurred in samples from the deep eastern bore and the lake.
- The term ‘mixed’ indicates that two processes are dominant. That is, either both anoxic (mixed (anoxic)), or one oxic and the other anoxic (mixed (oxic-anoxic)).
- Many samples did not have all the redox variables and therefore the whole annual cycle was not represented. Hence, correlating these processes with seasonal events was not possible.

5.5.2 Water quality

Nitrogen compounds

All of the samples taken at Lake Nowergup for the SGS investigation have total nitrogen (TN) concentrations less than the trigger value for wetlands in south-west Australia (15 mg/L), and some exceed the trigger values for freshwater lakes (0.35 mg/L). TN concentrations were higher in groundwater samples from the west of the lake than samples from the east. To the west, the shallow bore had greater TN than the intermediate. To the east, the deep bore had more TN than the intermediate or shallow bores. The western bores, as well as some of the samples from the lake and deep eastern bore exceed the freshwater trigger value.

Concentrations of ammonia and ammonium (NH_3-N/NH_4-N) from all samples taken from all five bores exceeded both the wetland and freshwater trigger. As with TN, concentrations of NH_3-N/NH_4-N were greater in groundwater west of the lake. The shallow western bore had the greatest concentration out of the groundwater samples, while the intermediate and shallow eastern bores had the lowest. Lake water samples were all below the wetland trigger value, but twice exceeded the freshwater trigger value.

Concentrations of NO_x (oxides of nitrogen) were minimal, with only two samples above detection limits. One sample, from the eastern shallow bore, exceeded the freshwater lakes trigger value of 10 µg/L with a concentration of 17 µg/L. Although conversion of NO_x to nitrate was not possible since most values were below detection limits, Yesertener (2009) reported high nitrate concentrations in groundwater at Lake Nowergup (up to 53.15 mg/L NO_3 from bore LN 7-89).

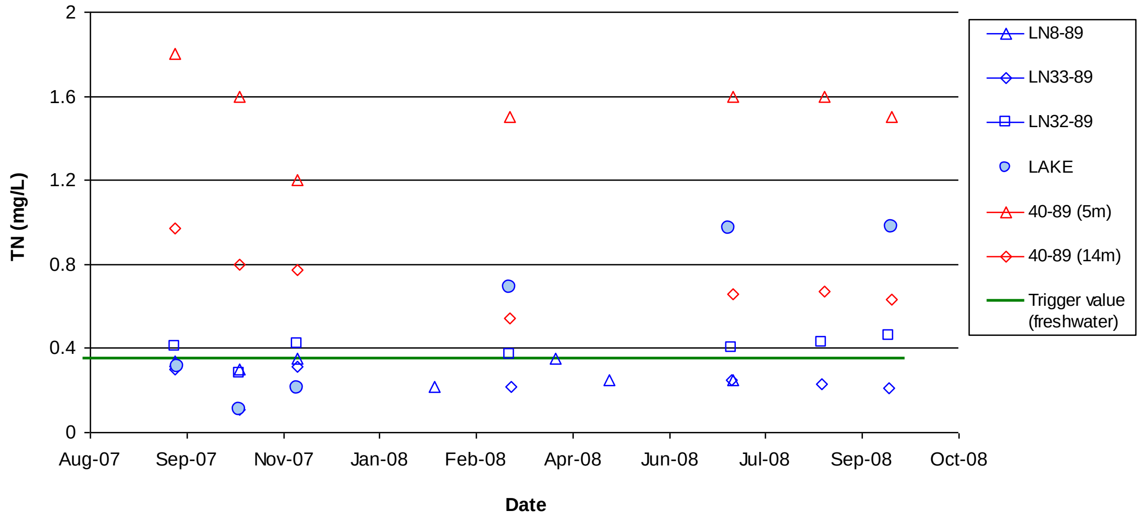


Figure 38 *Total nitrogen concentrations in lake and groundwater*

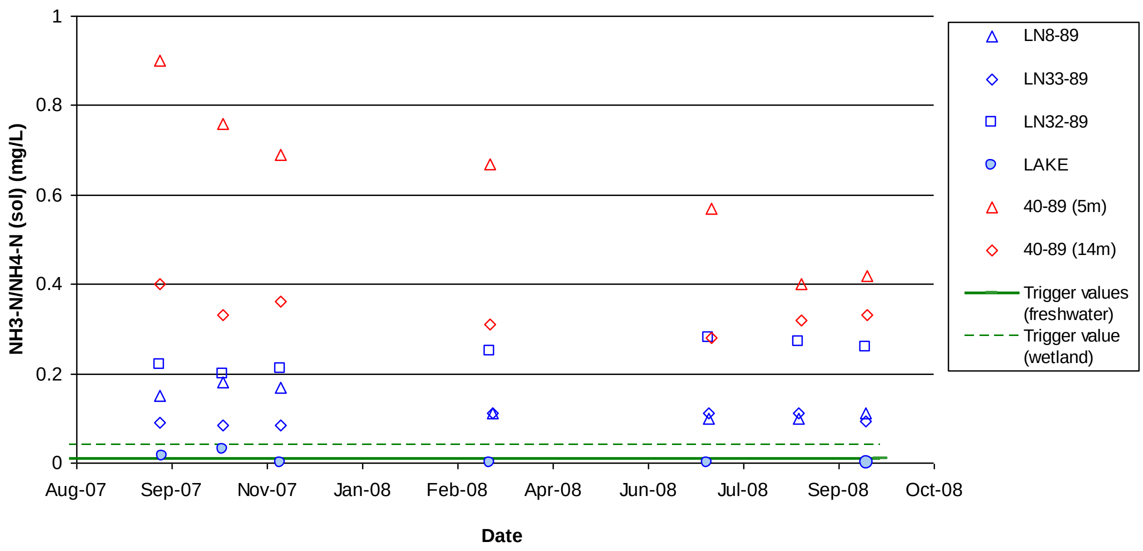


Figure 39 Ammonia / ammonium concentrations in lake and groundwater

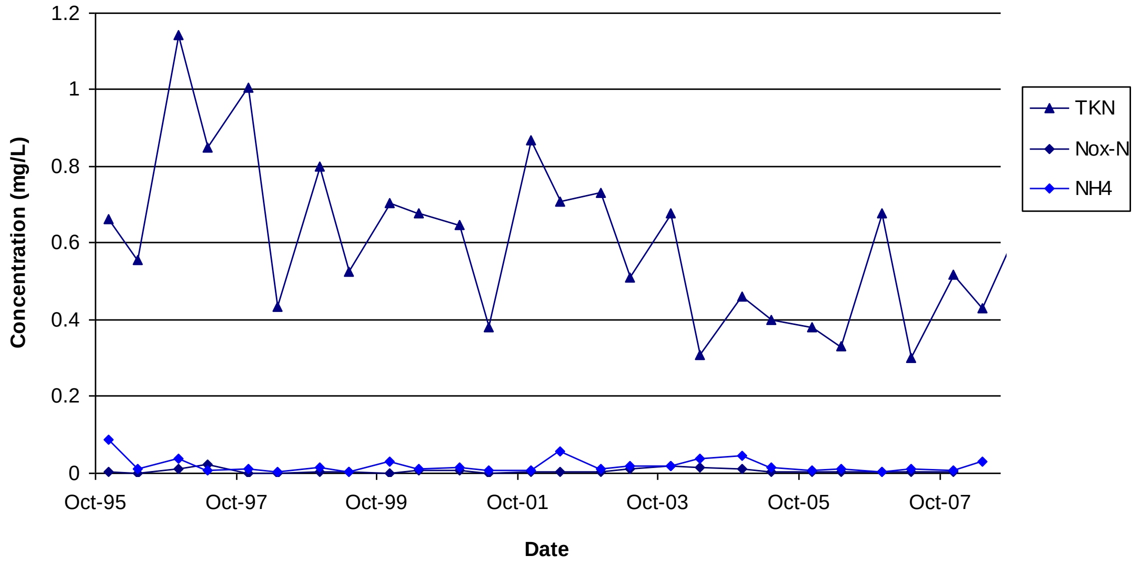


Figure 40 Long-term nitrogen concentrations in Lake Nowergup

Long-term monitoring of the lake water carried out for the Department of Water (Judd & Horwitz 2010) showed concentrations of ammonium (NH_4) and total Kjeldahl nitrogen (TKN) were decreasing over the last 14 years. These declines can be attributed to continued dilution with fresh water from the supplementation bore. The sample from the supplementation bore reported the lowest concentrations of TN, TKN and NH_4 in the SGS investigation. Measures of nitrate and nitrite (NO_x-N) have remained fairly constant during the long-term monitoring.

Phosphorus

Most groundwater samples have total phosphorus (TP) concentrations which exceed the trigger value for freshwater (0.01 mg/L), but are below the trigger value for wetlands in south-west Australia (0.06 mg/L). The shallow bores have the lowest TP concentrations, while lake water has the highest, exceeding both trigger values. During the SGS investigation Lake Nowergup displayed a concentration range of 0.061 to 0.17 mg/L TP. Data collected for long-term wetland monitoring showed a decline in TP concentrations from 1995 to the present. However the range of concentrations (< 0.01 to 0.078 mg/L TP) is much lower than the SGS investigation results. The long-term wetland monitoring (Judd & Horwitz 2010) takes samples from five sites around the lake, then mixes them equally to analyse a composite sample, whereas the procedure for this investigation was to take one sample, from the northern part of the lake near the staff gauge. This difference in concentration indicates that there is a source of phosphorus close to the SGS sampling site, and that this is diluted in the composite sample.

Concentrations of soluble reactive phosphorus (SRP) vary between less than the freshwater lakes trigger value (5 µg/L) and above the wetland trigger value (60 µg/L). The shallow bores (40-89 (5 m) and LN8-89) have the lowest concentrations while the lake, deep eastern bore (LN32-89) and intermediate western bore (40-89 (14 m)) have the highest concentrations of phosphate. SRP/FRP has remained stable in Lake Nowergup over the past 14 years. As with TP concentration, the SGS investigation results for lake water greatly exceed the PO_4-P concentrations from the composite samples.

The sample from the supplementation bore had high concentrations of TP and SRP (0.11 mg/L and 0.042 mg/L respectively).

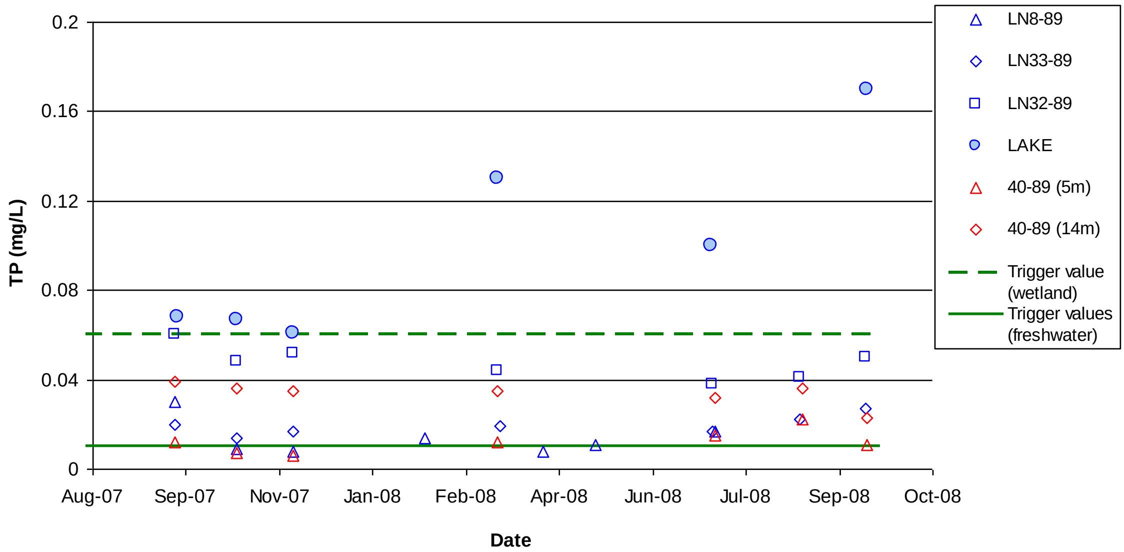


Figure 41 Total phosphorus concentrations in lake and groundwater

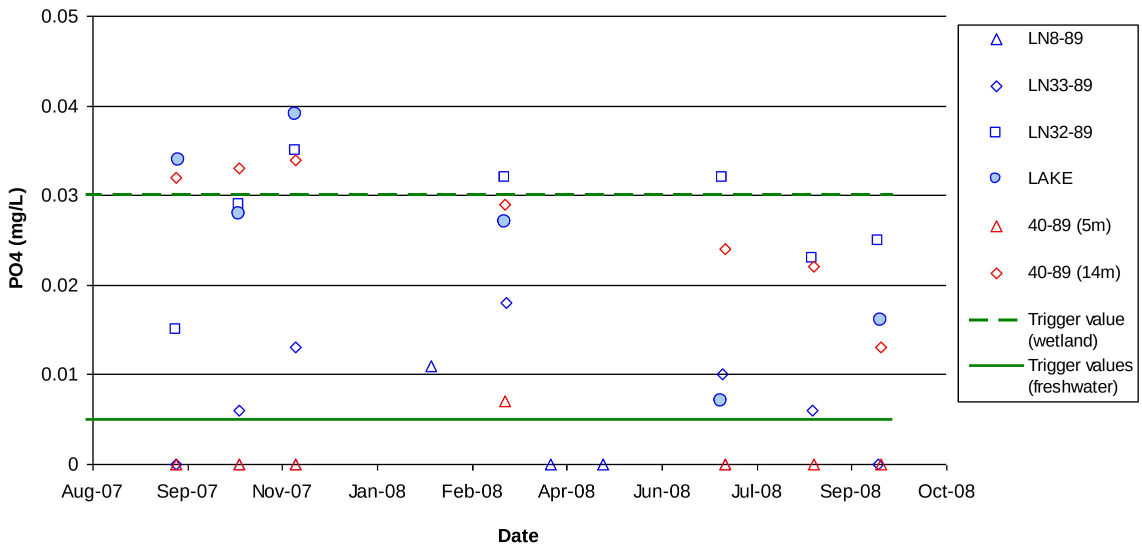


Figure 42 Soluble reactive phosphorus concentrations in lake and groundwater

Herbicides and pesticides

All lake and groundwater samples had herbicide and pesticide concentrations below detection limits. However, some of the assessment levels for these substances are actually below the laboratory limits of detection, so it is not possible to know in these cases if the levels exceed assessment levels.

Aluminium

Soluble aluminium concentrations in the shallow western bore (40-89 (5 m)) exceed the trigger values for fresh water (0.055 mg/L) and for drinking water (0.2 mg/L), but are below the irrigation trigger value (5 mg/L). Groundwater from this bore ranges from 0.37 to 1.1 mg/L, with the highest concentrations measured during summer. All other samples have concentrations less than 0.05 mg/L.

Arsenic

The guidelines use the dissolved concentration as a trigger value, whereas the SGS investigation reports the total concentration. Although these are not identical, comparison to the guidelines was still carried out to provide a reference. Concentrations of total arsenic are below detection limits in the lake water as well as in the intermediate and deep eastern bores (LN32-89, LN33-89). One sample from the shallow eastern bore (LN8-89) exceeded trigger values for drinking water (0.007 mg/L) and fresh water (0.024 mg/L) but not irrigation water (0.1 mg/L). All other samples had concentrations lower than all assessment levels.

Boron

Concentrations of soluble boron were below all trigger values, for all samples. Boron concentrations ranged from below detection to 0.15 mg/L.

Cadmium

As with arsenic, the guidelines use the dissolved concentration of cadmium, whereas the SGS investigation reports the total concentration. Comparison to the guidelines was carried out to provide a reference point only. Total cadmium concentrations exceeded the freshwater trigger value (0.0002 mg/L) in all three eastern bores for four months (October 2007 to January 2008), and then again in the deep bore during May 2008. Samples from the lake and the western bores were below detection limits.

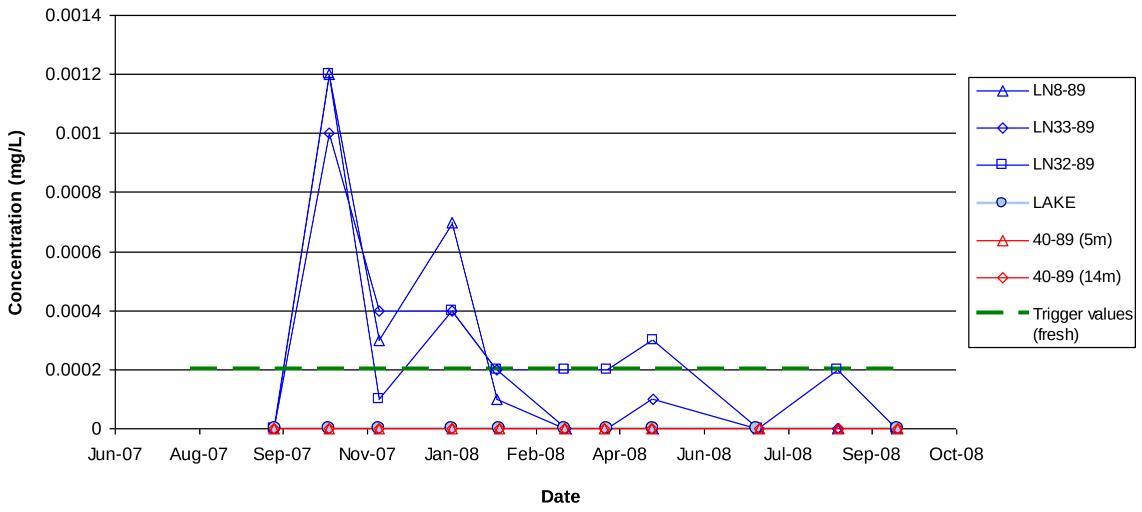


Figure 43 Total cadmium concentrations in lake and groundwater

Chromium

Lake water and the intermediate western bore (40-89 (14 m)) have total chromium concentrations below detection limits. The three eastern bores have concentrations below trigger values, while the shallow western bore (40-89 (5 m)) exceeds freshwater guidelines (0.01 mg/L), but not irrigation limits (0.1 mg/L).

Iron

The intermediate and deep eastern bores (LN33-89, LN32-89) have soluble iron concentrations below all assessment levels. Lake water samples exceed both drinking and irrigation trigger values during summer (0.3 mg/L and 0.2 mg/L respectively). The average concentration from the shallow eastern bore (LN8-89) and intermediate western bore (40-89 (14 m)) exceed irrigation water guidelines by a factor of 10 and 16 respectively. Iron concentrations in the shallow western bore are even higher, with an average value almost 90 times the trigger value.

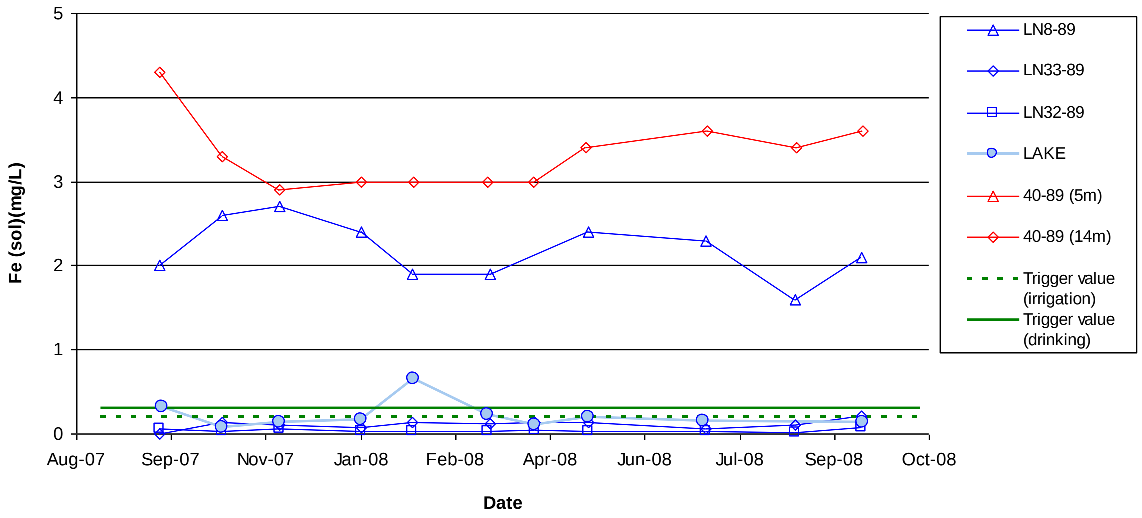


Figure 44 Soluble iron concentrations in lake and groundwater

5.5.3 Summary of assessment and trigger level breaches

As outlined at the beginning of Section 5.5, trigger values for fresh water, irrigation water (and drinking water for comparison) were taken from and applied in accordance with the Department of Environment and Conservation's 2010 *Assessment levels for soil, sediment and water*, and the trigger values which are specific to south-west Australia (wetlands and freshwater) were taken from the ANZECC (2000) guidelines. Table 11 summarises those parameters which were found to be in breach of the various trigger values. Significant breaches of assessment and trigger levels based on beneficial end use of water are outlined below.

Freshwater and wetlands

Samples of lake water, groundwater up-hydraulic gradient of the lake, and the shallow western bore were compared against the freshwater and wetland guidelines.

- All lake samples exceeded trigger values for TP, and some lake samples exceeded trigger values for NH_3-N/NH_4-N, TN and SRP.
- Samples from the shallow western bore always breached the pH, Al (sol), and TN trigger values.
- Water samples from the shallow eastern bore commonly exceeded assessment levels for Zn (tot), and rarely for Cr (sol) and As (tot).
- All eastern bores occasionally breached the Cd (tot) trigger value.
- All bore samples exceeded trigger values for NH_3-N/NH_4-N.
- Occasionally deeper bores exceeded the trigger values for SRP.

Irrigation water

All groundwater samples were compared against the irrigation guidelines, as irrigated horticulture is a major use for water in the area.

- The irrigation water assessment level for As (tot) was breached by groundwater samples in two bores.
- Fe (sol) concentrations in the shallow eastern bore and western intermediate bore breached the guidelines throughout the sampling period.

Drinking water

There is no abstraction for public water supply in the Nowergup groundwater subarea. The Department of Water considers that untreated water taken from the environment is unsafe for human drinking (Water quality protection note 41, *Private drinking water supplies* 2006). Data from this study supports this view.

- All samples from the shallow western bore breached the guidelines for pH and Al (sol).
- Some samples breached the trigger values for Fe (sol) and As (tot).

Table 11 Summary of water quality breaches from DEC (2010) guidelines

Parameter	**Australia wide trigger values**		
	Fresh waters	**Irrigation water**	**Drinking water**
pH	All samples from the shallow western bore (40-89 (5 m)) are more acidic than the limit, while most samples from the deep eastern bore (LN32-89) are at the limit.	Not listed	As for Australian freshwater.
Al	All samples from the shallow western bore (40-89 (5 m)) exceed the trigger value.	No samples exceed.	All samples from the shallow western bore (40-89 (5 m)) exceed the trigger value.
Fe	Not listed	As for drinking water, plus one sample from the intermediate eastern bore.	Some samples from the lake and all samples from the shallow eastern bore (LN8-89) and intermediate western bore (40-89 (14 m) exceed the trigger value.
Cd (trigger value is dissolved concentration while investigation results are total concentration)	Commonly samples from the deep eastern bore (LN32-89), occasionally samples from the intermediate and shallow bores (LN_33-89 and LN8-89) exceed the trigger value.	No samples exceed.	No samples exceed.
Zn	Samples from the shallow eastern bore commonly exceed the trigger value.	No samples exceed.	No samples exceed.
Cr	Two samples from the eastern shallow bore exceed the trigger value.	No samples exceed.	Not listed
As (trigger value is dissolved concentration while investigation results are total concentration)	One sample from the shallow eastern bore (LN8-89) exceeds the trigger value.	No samples exceed.	One sample from the shallow eastern bore exceeds the trigger value, and two samples from the intermediate western bore (40-89 (14 m)) are at the trigger value.

Table 12 Summary of water quality breaches from ANZECC (2000) guidelines

	Specific trigger values for south-west Australia	
	Wetlands	**Fresh water**
pH	40-89 (5 m) is always below minimum limit, all other bores below except March and April. Lake only below a couple of times. LN8-89 exceeds once.	All samples are generally within limits, 3 eastern bores exceed in march.
TN	Only 40-89 (5 m) exceeds	Mostly at or above except LN33-89 and LN8-89. Lake sometimes over
Nox	No samples exceed.	One sample breaches (from LN8-89) and one sample is at the trigger value (from 40-89 (5 m)).
NH_3-N/NH_4-N	All bore samples exceed.	All bore samples exceed, lake water rarely exceeds
TP	All lake values at or above.	All samples at or above trigger values except occasionally from the shallow bores. Lake greatly exceeds.
SRP	Some samples from the lake and deep bores exceed.	Only samples from the shallow bores are below trigger values.

5.5.4 Interactions between surface water, groundwater and aquifers

Analysis of the local hydrogeology at Lake Nowergup and the detailed groundwater and lake chemical analysis (Section 5.5) allow an interpretation of interactions between surface water and groundwater at the lake to be made.

Turner & Townley (2006) used isotope and chloride measurements taken in 1989 to demonstrate that Lake Nowergup was a typical flow-through lake. However, these data are no longer representative of the current flow regime. The information collected for this investigation indicates that supplementation has altered this system by diluting several water quality parameters, and changing the dominant flow pattern from flow-through to recharge. Analysis of water levels and the hydrochemistry of the lake and groundwater have shown that Lake Nowergup now primarily acts as a recharge lake.

The progressive increase in supplementation volumes has caused lake levels to become higher than surrounding groundwater. Lake Nowergup is now a surface expression of an artificially created local groundwater mound, with lake water recharging the regionally declining groundwater. The regional east-west groundwater flow still contributes to the lake, but has a reduced influence on the system. Supplementation has slowed but not prevented the decline of lake levels. Monitoring data show that when artificial maintenance stops, the lake level declines rapidly, due to the steep gradients around the lake and the high hydraulic conductivity of the aquifer. If artificial maintenance stopped and lake levels fell, the lake would function more as a natural flow-through system with water quality in the lake more directly influenced by the shallow groundwater.

The area around Lake Nowergup lacks a significant confining layer between the Superficial and Leederville aquifers. Because of this, obtaining the supplementation water from the Leederville aquifer in this area may not be an efficient option for maintaining water levels. The potential for better lake level management by supplementing the lake from a bore in a more thoroughly confined aquifer should be investigated.

Evaporative concentration of chloride and TDS in the lake and groundwater on the outflow (western) side is typical in flow-through lakes but is not evident at Lake Nowergup. This supports the interpretation that the system has a reduced flow-through component. These results also suggest that supplementation water is counteracting evaporative processes, maintaining fresh lake water. Enrichment of TDS and chloride in the shallow bores suggests evaporation and evapotranspiration through the soil.

A number of analytes show similarities in concentration and trends between the lake and middle zone of the aquifer, especially on the western side (Na, TDS, Cr, SO_4 and SO_4/Cl). The similarity in hydrochemical composition suggests that water flows out from the lake with a downward flow component, into the middle part of the aquifer, below the shallow / watertable zone.

Comparison of SGS data with historical data suggests supplementation has not only changed the flow regime, it has altered the hydrochemistry. Concentrations of several water quality parameters in the lake and groundwater (Cl^-, Na^+, Ca^{2+}, Mg^{2+} TP, TKN, $NH_3/_4$) are significantly lower in this investigation than data collected in the 1980s (Turner & Townley 2006). This is likely to result from dilution effects of supplementation, which has reduced the effect of evaporative concentration. Despite this, a number of metals and nutrients still exceed trigger values (TP, TN, NH_3-N/NH_4-N, SRP, Al, Fe, Cd, Zn).

The results from this investigation suggest that oxidation of acid sulfate soils is a likely cause of elevated metal concentrations. Analysis of sediment samples has confirmed the presence of ASS at Lake Nowergup (see Section 4.3). Most sediment samples were found to be potential acid sulfate soils, with one sample indicating actual acid sulfate soils. Analysis of the groundwater chemistry supports the presence of ASS. However, it suggests that oxidation could be more widespread than the sediment findings indicate. Several factors can help determine whether oxidation of ASS is affecting the lake and groundwater. These factors include:

- sulfate to chloride ratios (SO_4:Cl)
- calcium to calcium plus sulfate ratios (Ca:(Ca + SO_4))
- low pH, high sulfate, and high iron.

Ratios of SO_4:Cl higher than 0.5 represent sulfide oxidation, and values greater than 0.9 can indicate significant sulfide oxidation (Vogwill et al. 2005). High SO_4:Cl ratios can also occur when groundwater has been affected by fertiliser use (Hirschberg & Appleyard 1996). Samples from both shallow bores (40-89 (5 m) and LN8-89) and the intermediate eastern bore (LN33-89) have SO_4:Cl ratios which commonly exceed 0.5, and occasionally exceed 0.9. This suggests that oxidation of ASS has affected groundwater quality at the watertable on both sides of the lake, and also deeper into the aquifer east of the lake.

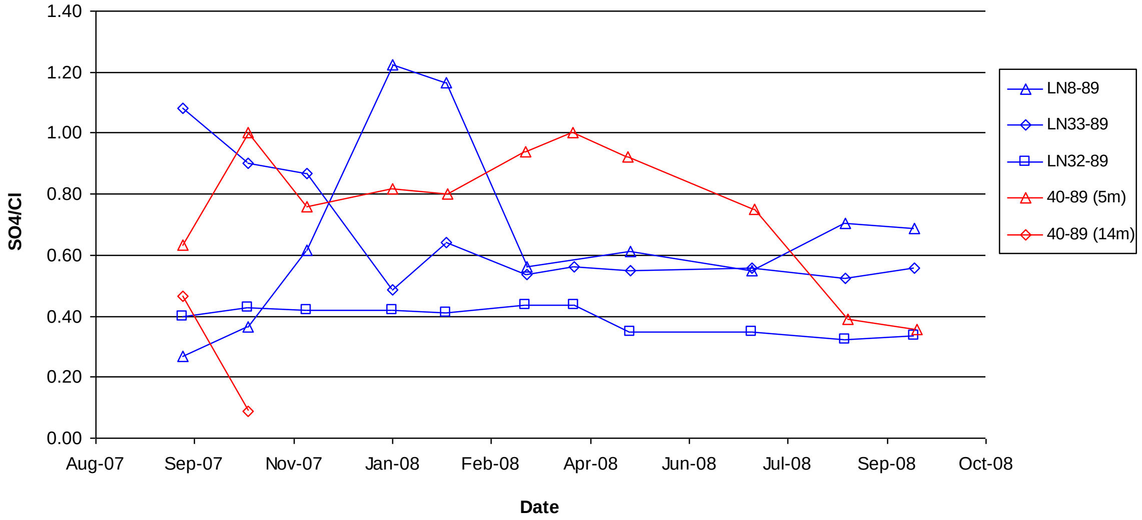


Figure 45 Sulfate:chloride ratios in lake and groundwater at Lake Nowergup

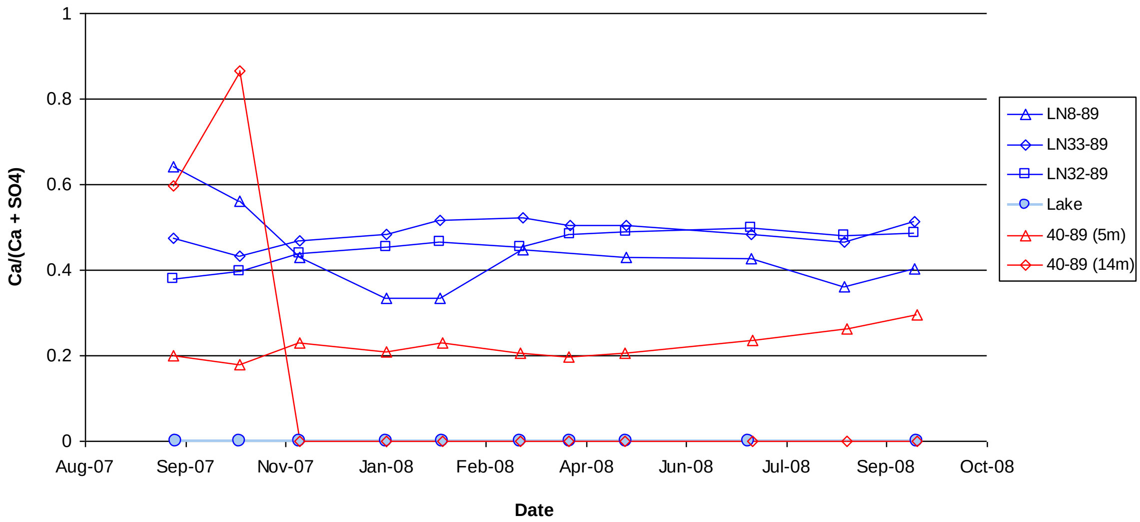


Figure 46 Calcium:calcium plus sulfate ratios in lake and groundwater

Pyrite oxidation is indicated by Ca:(Ca + SO_4) ratios which are less than 0.5, and have a pH value below 5.5 (Yesertener 2009). Water samples from all bores have Ca:(Ca + SO_4) ratios close to or less than 0.5, but only the western watertable bore (40-89 (5 m)) has pH values below 5.5, demonstrating that the watertable zone west of the lake has been affected by oxidation of ASS. High concentrations of calcium and to a lesser extent magnesium, in the shallow eastern bore (LN8-89) relative to the other bores or lake water, could indicate ongoing buffering of acidity, and explain why SO_4:Cl ratios suggest oxidation of ASS while the pH does not.

At Lake Nowergup, two processes could be contributing to the oxidation of ASS (Figure 47). These are infiltration of atmospheric oxygen triggered by declining water levels, according to the equation:

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

and leaching of nitrate from agricultural areas according to the equation:

$$FeS_2 + 3NO_3^- + 2H_2O \rightarrow Fe(OH)_3 + 1.5N_2 + 2SO_4^{2-} + H^+$$

Oxidation of ASS has released iron and sulfuric acid into the groundwater. Nitrification resulting from excess ammonia from fertiliser use in the market gardens up-hydraulic gradient from Lake Nowergup, could also be contributing to acidification according to the equation:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

Figure 47 shows how the nitrogen and sulfur cycles interact.

The increased acidity is likely to have mobilised aluminium, and possibly other metals, from the soil matrix into the lake and groundwater. The shallow western bore (40-89 (5 m)) was the only bore found to be acidic, and correspondingly reported the highest concentrations of iron, aluminium and chromium.

Although, the shallow bore on the western side of the lake (40-89 (5 m)) is acidic (pH 4.38 to 5.49), the pH increased in this zone of the aquifer throughout the one-year sampling period of the SGS investigation, from 4.4 to 5.5. Data from the long-term wetland monitoring (Judd & Horwitz 2010) indicated that the pH of Lake Nowergup has increased since 1995. Artificial maintenance could be the cause of the pH increase directly and indirectly; firstly by maintaining water levels and thus reducing oxidation of ASS, and secondly by diluting any acidity currently being generated.

Lake Nowergup sits on the Tamala Limestone, and Yesertener (2009) found the lake and surrounding aquifer to be $CaHCO_3$ type water. However, this study has provided a greater understanding of the system, showing that the top portion of the superficial formations is mostly quartz sand, and the aquifer at the watertable is NaCl type water with low alkalinity.

Analysis of alkalinity has highlighted a risk of acidification for groundwater in the shallow zone of the aquifer on the eastern side of the lake. Although the samples from the bore in this zone (LN8_89) have near neutral pH values, they also display a relatively low alkalinity (44 – 62 mg/L HCO_3-$CaCO_3$). Acid neutralising capacity of the sediment was also reported to be negligible. This suggests that although this zone of the aquifer is not yet acidic, should oxidation of ASS continue, the shallow groundwater has only a limited capacity to buffer acidity.

If artificial maintenance were to cease, the lake level would drop rapidly and it is likely Lake Nowergup would return to a more natural flow-through regime. As seen in other flow-through lakes on the Swan Coastal Plain, when lake levels become low, only the shallow part of the aquifer contributes water to the lake (Searle et al. 2010). The supplementation water (relatively high HCO_3 concentration), is presently providing Lake Nowergup with good buffering capacity. When the flow-through regime re-commences, only the shallow groundwater, which is NaCl type water with low alkalinity, will be discharging into the lake, leaving Lake Nowergup more vulnerable to acidification.

At present the supplementation is minimising the effects of ASS, and so the potential for increases in acidity should be taken into account when reductions to the supplementation regime are considered. Artificial maintenance has a threefold effect on preventing acidification in Lake Nowergup:

- reducing oxidation of ASS by maintaining water levels
- diluting any acidity which is produced
- providing greater buffering capacity in the lake water.

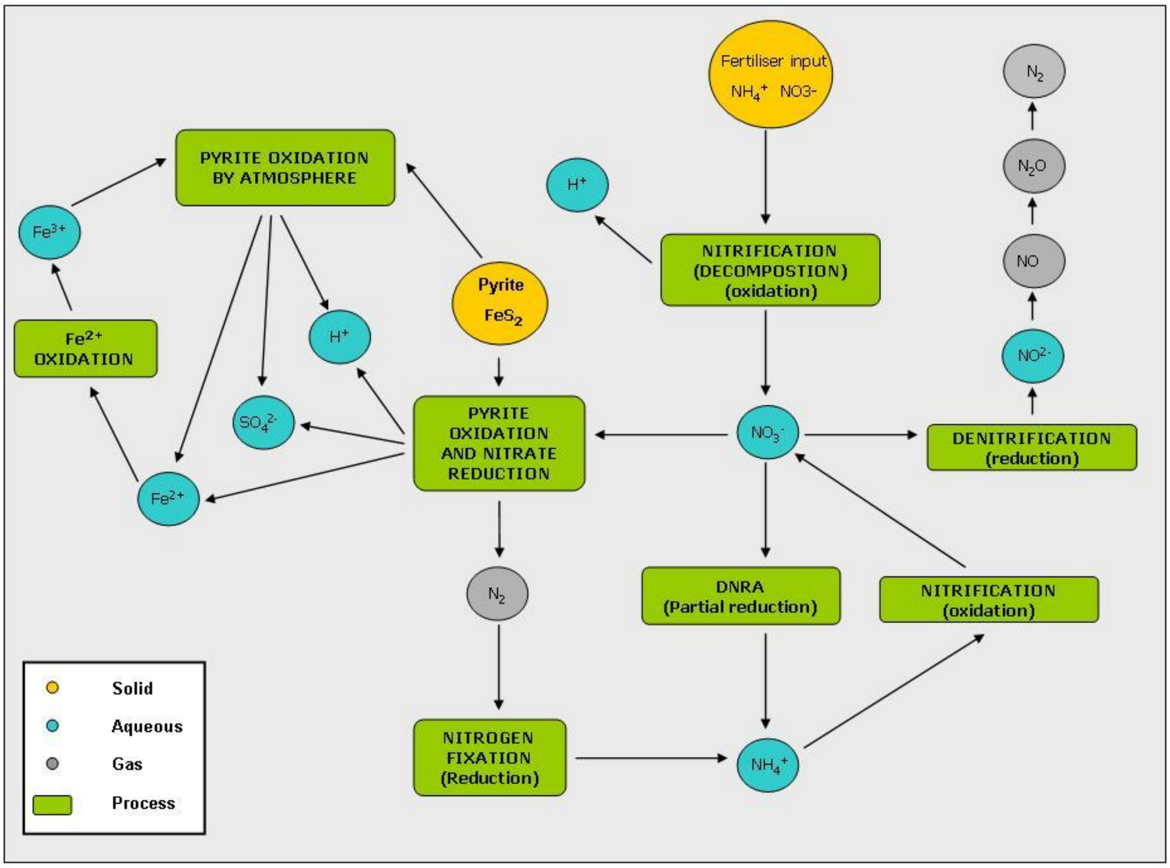


Figure 47 Interaction of the nitrogen and sulfur cycles

Water level decline can lead to the progressive oxidation of organic rich sediments near wetlands, which can release both nitrogen and phosphorus into the groundwater (internal eutrophication) (Smolders et al. 2006). The lack of natural water level fluctuation (temporary desiccation in summer) may also exacerbate internal eutrophication (Smolders et al. 2006). This process, along with fertiliser use up-hydraulic gradient, is thought to be responsible for the enrichment in total nitrogen, ammonia/um and soluble reactive phosphorus. Internal eutrophication can also explain why total nitrogen and ammonia/um concentrations are highest down-hydraulic gradient of the lake.

Although several nutrient parameters have been declining in the lake water since monitoring began in1995 (TP, TKN, NH_3-N/NH_4-N), concentrations of nitrate and phosphate (NO_x and SRP) have not. This could be related to the increase in dissolved oxygen in the lake water over this time period. The increase in DO is likely to result from aeration during pumping for artificial maintenance.

Concentrations of nutrients did not relate to the recorded redox conditions (Eh or DO) for samples from the SGS investigation. However, as mentioned in Section 3.1, Eh and DO did not stabilise before the field readings were taken, and so are only broadly indicative of the real redox conditions.

The analysis of local hydrogeology and aquatic chemistry at Lake Nowergup has shown that the flow regime is now that of a recharge lake. Water quality is suffering eutrophic pressures and the threat of acidification and associated metal toxicity. These water quality problems are all mediated to some degree by the supplementation regime at Lake Nowergup. Land use is also likely to be affecting the water quality in the lake and groundwater.

5.6 Local area modelling

Local area modelling is useful for predicting long-term water level trends (10 to 30 years) rather than short-term trends. The results of the local area modelling conducted as part of the Gnangara Sustainability Strategy found that under all scenarios, lake levels increased, reaching a stable level by around 2025 (Figure 48). Although the modelling predicted water level rise in Lake Nowergup, a rerun of the model conducted as part of this investigation suggests the rise is an artefact of the low initial water levels used in the original modelling.

The original model scenarios used 15.7 m AHD as the initial lake level, whereas the rerun conducted as part of this investigation used 16.1 m AHD, which was closer to the measured initial conditions. Figure 49 compares the rerun of the base case scenario with higher initial conditions to the original base case scenario. By 2020 the predicted water levels in the rerun were very similar to the initial modelling run. Both modelling runs indicate that lake levels will not meet the Ministerial water level criteria of 16.8 m AHD under any scenario.

The modelling also suggests that the EWRs for sediment processes, waterbirds and macroinvertebrates will not be met under any scenario, even the continuous pumping ongoing supplementation scenario (Figure 48).

A number of scenarios, including continuous supplementation and a 20% reduction in abstraction predict increased lake levels when compared to the base case. An increase in levels would help maintain the lake as a bird drought refuge and is also likely to help maintain the lake’s aquatic invertebrates, fish and turtles. The continuous ongoing supplementation is deemed prohibitive because the volume of water pumped would exceed the department’s licensed allocation of 1.2 GL. Therefore, the modelling suggests the most appropriate management strategy to increase lake levels is reducing surrounding abstraction.

The modelling suggests that if supplementation ceased immediately, lake levels would eventually stabilise between 14.5 and 15.5 m AHD. This would maintain permanent water at the lake but would significantly reduce surface water area and lead to the oxidation of PASS and acidification.

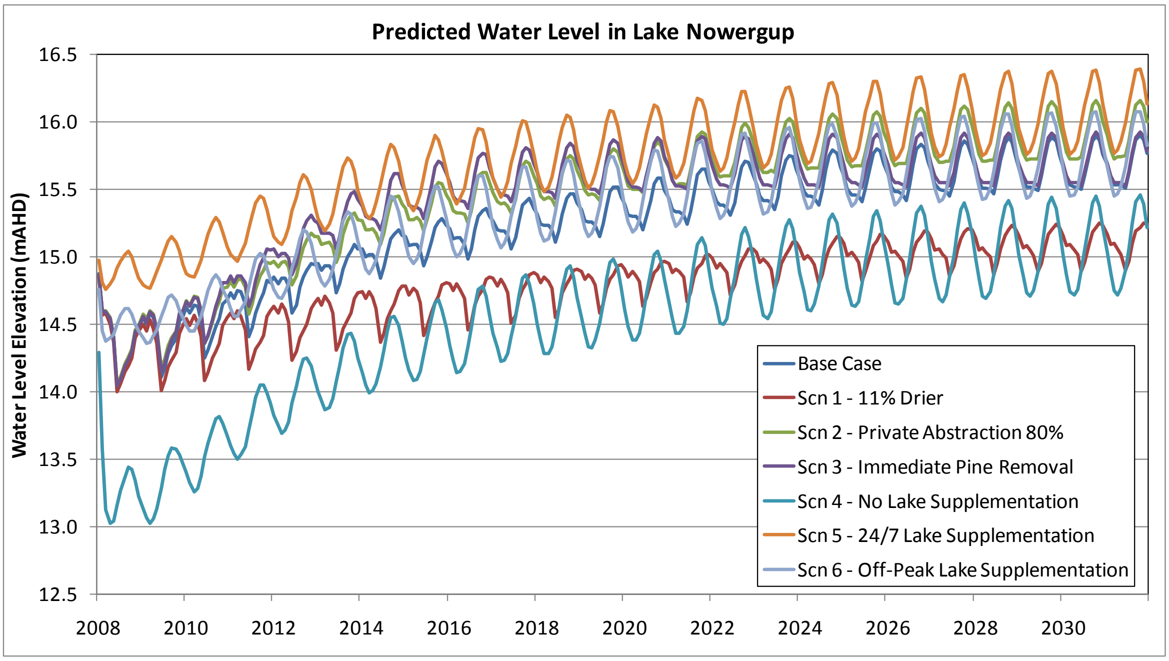


Figure 48 Predicted lake levels at Lake Nowerup under various land and water use scenarios

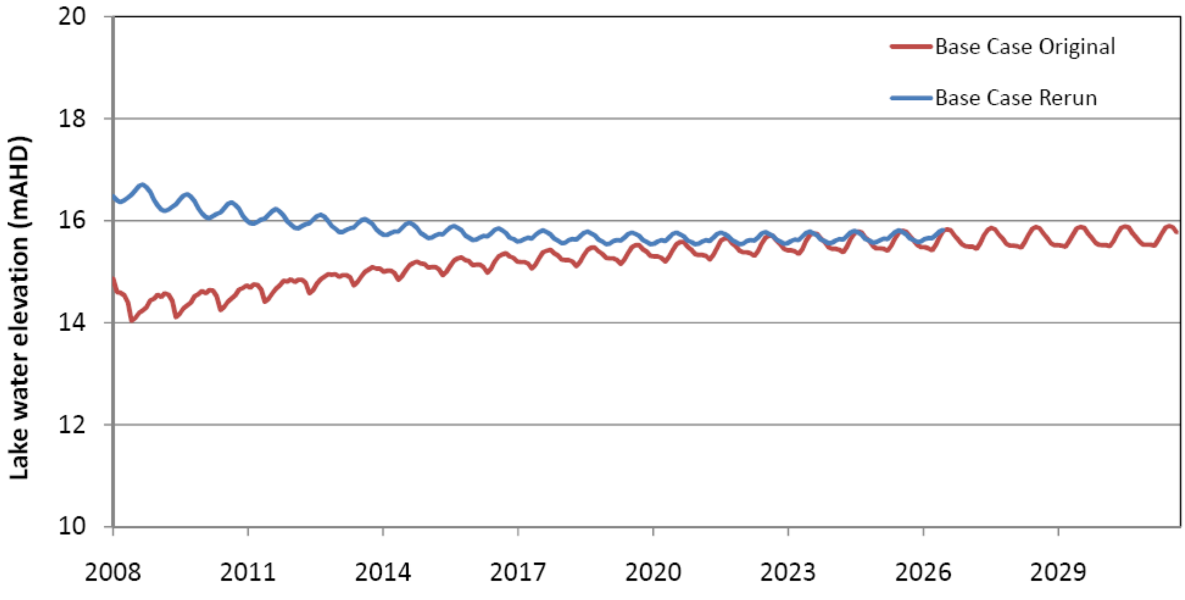


Figure 49 Predicted lake levels in Lake Nowergup from the model rerun with a higher initial lake level (base case scenario)

6 Implications for ecological values and management recommendations

The results of the SGS investigation have provided an improved understanding of the local geology (Section 4), hydrogeology and chemistry (Section 5) at Lake Nowergup. This understanding has been linked with ecological condition at the lake (Section 2.4) to provide a basis for improved management strategies. Note: in the following section, additional recent water levels, outside the investigation period, are discussed in terms of ecological implications and management recommendations. These are used to give the most up-to-date understanding of the system at Lake Nowergup.

6.1 Monitoring infrastructure

An assessment of the suitability of the monitoring infrastructure at the lake was conducted as part of the investigation. The assessment found that the staff gauges located at the northern end of the lake were unsuitable for measuring the Ministerial water level criteria, as they were periodically stranded due to declining lake levels. A recently installed telemetry site (616139) is more appropriate for measuring lake levels, especially when levels fall below 16 m AHD. The telemetry site, which consists of a hydrostatic probe that continually feeds monitoring data to a logger, began monitoring lake levels in November 2009. The telemetry site requires surveying before it can be used to measure water level criteria.

This investigation also found that difference between lake levels and groundwater levels at bore LN2-89 (61611247), used to measure the vegetation EWR, vary considerably throughout the year. Lake levels and bore levels are similar throughout spring and winter (0.1 to 0.3 m difference) while lake levels are high, during which time bore levels are affected by discharge from the lake flowing through the area where the bore is located (Figure 51, Table 13). However, when the lake level is low, its influence on groundwater levels at the bore decreases as water discharges more vertically from the lake bed. This creates a difference of up to 2 m between lake and bore levels during summer and autumn (Figure 51, Table 13). The approximate lake level at which the bore ceases to be influenced by water flowing out of the lake is 16.3 m AHD (Figure 51). This finding is significant in that it shows that maintenance of lake levels can not be used to manage groundwater levels near the vegetation transect when lake levels fall below 16.3 m AHD.

Due to the variation between lake and groundwater levels, bore LN2-89 should be used when assessing the health of vegetation at the Lake Nowergup.

Table 13 Differences between lake levels and groundwater levels at bore LN2-89

Date	Lake levels m AHD	Bore LN2-89 levels m AHD	Difference m
8/4/2009	16.21	15.01	1.20
4/05/2009	16.28	15.99	0.30
2/06/2009	16.35	16.18	0.17
30/06/2009	16.40	16.25	0.15
4/08/2009	16.47	16.35	0.12
1/09/2009	16.53	16.41	0.13
3/11/2009	16.40	16.27	0.13
6/01/2010	16.17	15.18	0.99
1/02/2010	16.00	14.59	1.41
5/03/2010	15.98	14.22	1.76

6.2 Ecological implications

Despite artificial maintenance, recent water levels at Lake Nowergup have mostly failed to meet the EWRs recommended by Froend et al. (2004b) for vegetation, sediment processes, waterbirds and macroinvertebrates (Figure 50 and Figure 51).

Groundwater levels measured at shallow monitoring bore (LN2-89) near the vegetation transect have fallen below the EWR for wetland vegetation (15.22 m AHD) in three of the last four years (Figure 51). No severe declines in vegetation were observed when groundwater levels fell below the vegetation EWR for one month in both 2007 and 2009. However, at the time of writing (April 2010), groundwater levels at bore LN2-89 had been measured below the vegetation EWR for four consecutive months. Groundwater levels at the bore declined rapidly from September 2009 to April 2010, from 16.41 to 14.10 m AHD, a fall of approximately 2.3 m (Figure 51). Groundwater levels fell despite the successful maintenance of lake levels through continued off peak pumping. As discussed previously, this is due to lake levels ceasing to influence groundwater levels to the west of the lake when lake falls below 16.3 m AHD, as lake water discharges more vertically from the lake bed (Figure 51).

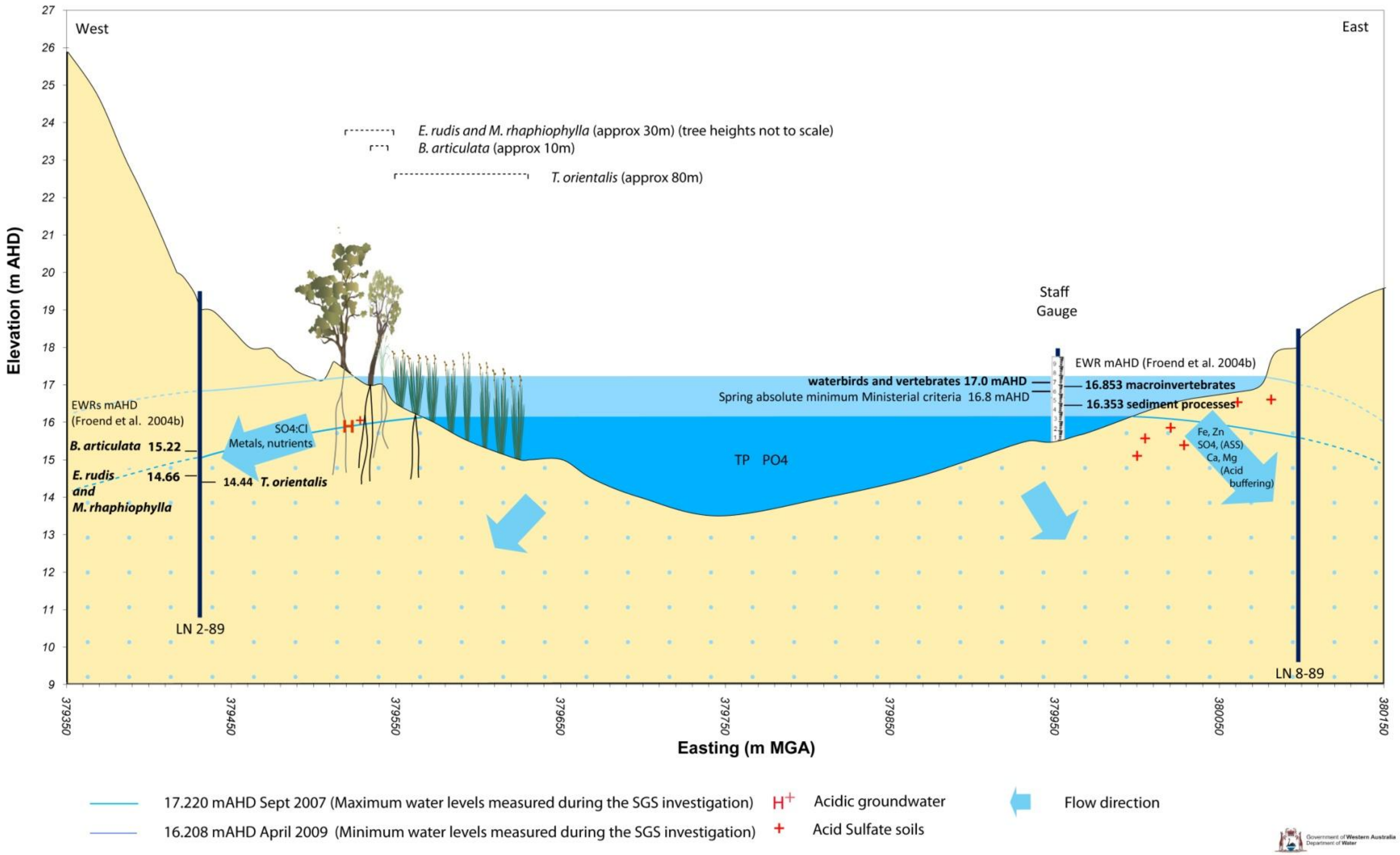


Figure 50 EWRs for groundwater-dependent ecosystems at Lake Nowergup

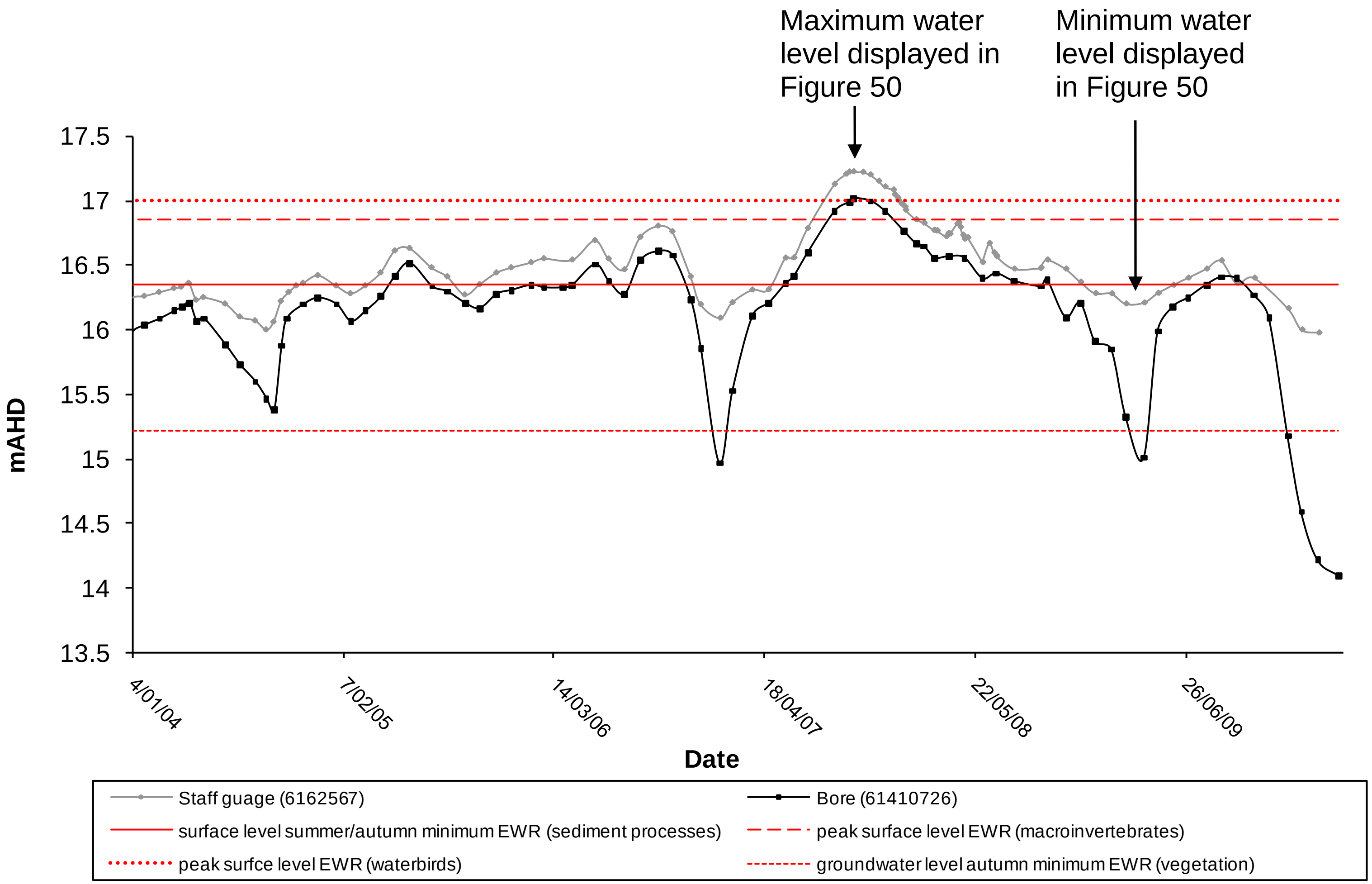


Figure 51 Hydrograph showing surface water and groundwater levels and current EWRs (Froend et al. 2004b)

The rapid decline in groundwater levels near the vegetation transect discussed above is of considerable concern given the sudden health declines and deaths of fringing wetland trees (*M. rhaphiophylla and E. rudis*) on the western side of the lake that were similar to the declines that occurred under similar conditions in 2002. This period of historically low groundwater levels is expected to result in siginificant declines in the health of wetland vegetation at the lake.

Declines in water quality pose a serious threat to the ecological values of Lake Nowergup. Artificial maintenance is currently diluting concentrations of several water quality parameters. Maintenance water is obtained from the Leederville aquifer and the altered water chemistry of the wetland has in part been affected by the water chemistry of the supplementation source.

For the most part, recent lake levels have failed to meet the EWR for sediment processes recommended to prevent the oxidation of ASS (Figure 51). However, the current artificial maintence regime is limiting the extent of oxidation of ASS at the lake. As mentioned earlier, artificial maintenance has a threefold effect on preventing acidification in Lake Nowergup:

- reducing oxidation of ASS by maintaining water levels
- diluting any acidity which is produced
- increasing buffering capacity by addition of higher alkalinity water than the surrounding shallow groundwater.

This investigation has confirmed that Lake Nowergup as being at high risk of acidification. Shallow groundwater to the west of Lake Nowergup is already acidic, and the relatively low alkalinity found on the eastern side of the lake suggests that if an acidifying event such as oxidation of ASS occurs, the groundwater has only a limited buffering capacity to prevent acidification. An increase in the acidity at Lake Nowergup would stress its aquatic ecosystem and could be directly toxic to the lake's aquatic organisms (ANZECC 2000).

The increased acidity a Lake Nowergup has mobilised aluminium, and possibly other metals, such as zinc, chromium and cadmium (Figure 51). At present, metal enrichment is restricted to the groundwater. However changes to the supplementation regime could increase flow from the groundwater into the lake, bringing metals with it. The mobilisation of aluminium into the groundwater may have put the lake's vegetation at risk of 'acid toxicity'. Acid toxicity occurs when the mobilisation of aluminium induces a reduction of the molar calcium:aluminium and magnesium:aluminium ratios in the groundwater which reduces root growth, inhibits the uptake of calcium and magnesium by fine roots, and reduces the water conductivity of the roots (Caspary 1991). This is compounded by further depeletion of calcium and magnesium from sediment by acidic groundwater. Acid toxicity can be responsible for declines in health of riparian vegetation. The low pH and high aluminium recorded in this investigation near bore LN2-89, adjacent to the vegetation transect, is of particular concern and may be affecting the health of vegetation at the transect. This highlights the fact that water quality, in addition to assessing compliance with criteria levels and EWRs, should be assessed when assigning causes for change in ecological condition.

Dissolved oxygen in Lake Nowergup is inadequate when measured against the DEC guidelines for wetlands or freshwater lakes. Low DO can result from high levels of nutrients and the oxidation of ASS. The majority of total nitrogen, total phosphorous and soluble reactive phosphorus concentrations measured during this investigation exceeded trigger levels for freshwater ecosystems and wetlands in south-west Australia. The high nutient levels recorded at the bore adjacent to the vegetation transect may be affecting the health of vegetation along the transect.

Despite the dilution effects of supplementation, nutrient concentrations are high in the lake and it is at risk of eutrophication. Nutrients are likely to result from fertilisers from surrounding market gardens. The high concentration of nutrients in the lake may be stimulating plant and algal growth and leading to a build-up of organic matter in the sediments. The decomposition of organic matter could be causing the depletion of DO. Dissolved oxygen is an important indicator of a healthy aquatic ecosystem as oxygen is essential for aquatic organisms. Aquatic organisms, including fish, require oxygen in specified concentration ranges for respiration and efficient metabolism (ANZECC 2000). The low DO concentrations measured in this investigation may be elevating the susceptibility of the lake’s fish species to disease as the exposure of fish to low oxygen concentrations can reduce their immunity (Mellergaard & Nielson 1987). The low DO may also be changing the structure and diversity of the lake’s aquatic communities by causing the death of immobile organisms and avoidance of low-oxygen conditions by mobile organisms (Connell & Miller 1984).

All groundwater and a number of lake water samples measured during this investigation had ammonia and ammonium concentrations which exceeded freshwater and wetland trigger levels. The high levels of ammonia and ammonium at Lake Nowergup may be toxic to the its aquatic organisms, particularly the fish that inhabit the lake (Connell & Miller 1984).

Changes to groundwater chemistry at depth may not directly affect ecosystems, but can have social implications. A number of lake water and bore samples at Lake Nowergup exceeded irrigation water guidelines for iron. Iron concentrations in the shallow western bore were almost 90 times the trigger value. The iron concentrations in the lake are a concern for horticulturalists using groundwater around the lake. If used untreated, groundwater in this area could pose a health risk as it has been shown to breach the drinking water guidelines for arsenic and chloride as well as soluble aluminium and iron.

6.3 Artificial maintenance options

A significant finding of this investigation is that as a result of artificial maintenance, lake levels at Lake Nowergup are now permanently higher than the watertable. Subsequently, the maintenance of many of the ecological values at Lake Nowergup is dependent on the management of the artificial maintenance regime at the lake.

Artificial maintenance of water levels at Lake Nowergup has proved to be not successful in meeting the Ministerial water level criteria and to be not successful in maintaining a number of the lake's ecological values, including its vegetation. Though some decline in ecological condition has been observed at Lake Nowergup while it has been artificially maintained, the current maintenance regime is protecting the lake from acidification and possibly from eutrophication.

A study conducted by Loomes et al. (2003) suggested that continuing artificial maintenance indefinitely may be more detrimental to the lake's vegetation than if artificial maintenance was slowly phased out. The study suggested the physiological stress caused by repeated and severe declines in groundwater (that have occurred in recent summers and autumns) can be very damaging to wetland vegetation. The study suggested that the most ecologically acceptable management option for artificial maintenance at the lake would be to allow a gradual decline in spring peak water levels, managing the rates of rise or fall to prevent lake levels increasing or decreasing at rates much faster than what would have occurred under natural conditions. The study identified that, in general, long-term water level decline in wetlands will result in the gradual redistribution of plant species and compositional changes, reflecting the dynamic and resilient nature of littoral communities (Loomes et al. 2003). The study also suggested that if the annual rate of change of water levels did not exceed 0.1 m/yr, wetland vegetation could be maintained with a low level of risk (Loomes et al. 2003).

Managing the maintenance regime to allow a gradual decline in lake levels is likely to lead to encroachment of *T. orientalis* into the wetland. However, due to the geomorphology of the lake, permanent water should persist in the basin. The persistence of permanent water would provide at least some area of open water for waterbirds and thus retain some of the lake's value as a waterbird drought refuge. In addition, an enlarged area of *T. orientalis* may provide further habitat for other species of waterbirds and other fauna (Bamford 2003). The permanent water maintained would also continue to provide an interannual and seasonal refuge for macroinvertebrates (Froend et al. 2003b). If the maintenance regime was managed to allow a gradual decline in lake levels Loomes et al. (2003) suggest mature *M. rhaphiophylla and E. rudis* on the western side of the wetland should be able to adapt to drying conditions and that younger individuals may be able to respond by altering root morphology. Loomes et al. (2003) also suggest that recruitment of vegetation is likely to occur as seed banks in sediments are gradually exposed and that successful recruitment may allow the migration of vegetation down slope towards the wetland basin. The study also identified that recruitment of native vegetation could be limited by weed invasion.

Findings from this investigation show that a major ecological risk in allowing a gradual decline in lake levels is the oxidation of PASS found within and around the lake, which would increase the acidity of the lake and shallow groundwater. This would lead to the accelerated leaching of aluminium and associated metals. Allowing a gradual decline in lake levels through a reduction in the volume of supplemented water would increase acidity and affect the lake’s ecology in three ways. Firstly by exposing more PASS to oxidation, secondly by reducing the dilution of any acidity produced, and thirdly by decreasing the buffering capacity, since the supplementation water has higher alkalinity than the shallow groundwater. Increased acidity and metal concentrations (from allowing a gradual decline in lake levels through a reduction in the volume of supplemented water pumped) are likely to cause further declines to the lake’s ecology through acid toxicity and calcium limitation.

Allowing a decline in lake levels may also exacerbate nutrient enrichment by reducing the dilution effect of supplementation, and cause further eutrophication from the drying of organic sediments. However, studies have shown that natural seasonal water level fluctuation (temporary desiccation in summer) may prevent internal eutrophication (Smolders et al. 2006). Depending on the source of nutrients in the Lake Nowergup area, returning Lake Nowergup to a more natural regime could relieve the eutrophic pressures.

6.4 Management recommendations

The results of this investigation suggest it is unlikely that the current Ministerial criteria, or most of the Froend et al. (2003) EWRs will be met through the continuation of artificial maintenance. However, continuing artificial maintenance will help maintain the lake’s values as drought refuge for water birds and help maintain the lake’s aquatic invertebrates, fish and turtles. Continuing artificial maintenance will also continue to protect the lake from acidification and possibly from eutrophication.

We recommend that artificial maintenance should be continued until it is re-assessed as part of future groundwater allocation plan. As the current Ministerial water level criteria is no longer appropriate, we recommend a new lake water level criteria of 16.2 m AHD.

The scheduled Gnangara areas groundwater allocation plan should consider whether maintenance ought to be continued, including the increasing costs associated with pumping supplemented water in this consideration.

As previously discussed, reducing lake levels by phasing out abstraction is likely to increase oxidation of PASS, increasing acidity and metal concentrations, and possibly causing the lake to become eutrophic. These consequences must be taken into consideration in determining whether artificial maintenance should be continued or gradually phased out.

Regardless of management approach taken for artificial maintenance in future plans, management action should be undertaken to increase groundwater levels in the area, including reducing abstraction in the Wanneroo groundwater area and the Nowergup subarea. The Forest Products Commission pine harvesting schedule should be continued to be endorsed and water sensitive urban design in the Wanneroo groundwater area should also be supported.

These recommendations are subject to departmental priorities and the availability of resources.

Management actions

- The current artificial maintenance regime should be continued.
  - Implementation and responsibility: Department of Water to continue artificial maintenance and re-assess as part of the next Gnangara groundwater allocation plan.
- The Ministerial criteria for the lake should be revised. A lake water spring peak of 16.2 m AHD is recommended.
  - Implementation and responsibility: Department of Water to request revision of criteria level through the Section 46 process.
- Lake levels should be measured at the telemetry site (616139) (once surveyed) as levels less than 16 m AHD cannot be measured at the current staff gauges.
  - Implementation and responsibility: Department of Water to survey in telemetry site and begin measuring lake levels through the site.
- Groundwater levels should be measured at bore LN2-89 (61611247) when relating the watertable to the ecological condition of the vegetation transect.
  - Implementation and responsibility: Department of Water to provide groundwater level data from bore LN2-89 to vegetation monitoring contractor.
- Continue the recovery program of reducing licensed abstraction in the Wanneroo groundwater area and Nowergup groundwater subarea by 20% as per the *Gnangara Sustainability Strategy 2009*.
  - Implementation and responsibility: Department of Water to continue recovery program and to review allocation limits as part of the next Gnangara groundwater allocation plan.
- Investigate the use of solar panels to run the artificial maintenance pump.
  - Implementation and responsibility: Department of Water to undertake cost analysis.

Future monitoring

- A hydrochemical monitoring program should be initiated for this site and hydrochemical triggers and management actions could be developed for the Gnangara water management plan. The following hydrochemical sampling regime is recommended:
  - monthly sampling of pH, major ions and nutrients in Lake Nowergup
  - quarterly sampling of pH, major ions and nutrients in groundwater (bores LN8-89 and 40-89 (5 m))
  - quarterly sampling of heavy metal concentrations in lake water and groundwater

  - groundwater data should be collected on the same date as surface water data where possible.

- Data from the hydrochemical monitoring program should be reviewed every two years to assess whether the management objectives set are being met and whether trigger values need improvement.

  - Implementation and responsibility: Department of Water to design a suitable groundwater monitoring program that includes water chemistry sampling to inform the next Gnangara groundwater allocation plan.

- Additional modelling is required to investigate:

  iii) the impact of further reducing private abstraction in the area on lake levels

  iv) the impact of pumping from an alternative bore located in an area where the confining layer between the Superficial and Leederville aquifers is more pronounced.

  - Implementation and responsibility: Department of Water to design and run modelling scenario by June 2012. Results to inform the next Gnangara groundwater allocation plan.

Appendices

Appendix A —Groundwater sampling methodology

Water samples were collected using low-flow pumping methods. The low-flow sampling technique provides a low-stress, low-impact, minimal draw down purging method of groundwater sampling. The pump is lowered to the screened interval of the bore and purged until the water quality parameters of pH, EC and temperature have stabilised. Once stabilised in situ readings can be recorded and samples collected for further laboratory analysis. The method requires smaller volumes of water to be withdrawn than conventional techniques and 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.

Low flow bladder pump and water quality procedures

- Ensure all equipment is washed and decontaminated
- All instrumentation and equipment (e.g. pumping equipment, hoses, and standing water level recorders) is to be decontaminated prior to and after sampling at each site location. Decontamination is conducted by firstly rinsing with a mixture of Decon-910® and scheme water. A second thorough rinse is performed using just scheme water, and then a final very thorough rinse is conducted using the standard laboratory purchased deionised water
- Use new (disposable) air and water tubing for each sampling event
- Ensure water quality meters are functional and calibrated
- Dip bore for groundwater level and record
- Identify screen depth from records and lower low flow bladder pump to midway between screened interval. If sampling a shallow bore (full length screen) lower pump to 0.5m 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
- Other field observations such as interesting sample colour, presence of large quantities of particulate matter, and smell should be noted
- Groundwater quality should be measured for the in situ field parameters: pH, conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell. Record readings every 5 minutes until the parameters stabilise then a final reading recorded.

- Record results on a field observation form for submission to the Department of Water database.

Once physical in situ field parameters have stabilised and been recorded, samples are taken for laboratory analysis. All sample bottles should be filled to the shoulder of the bottle leaving a small airspace at the top of the bottle.

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

Appendix B — ASS methods (field)

These were modified from those of Ahern et al*.,* (1998), and described in *Identification and investigation of acid sulfate soils and acidic landscapes*, Department of Environment and Conservation 2009.

Field pH testing

Before sampling:

1. Set up clean, dry beakers in rack designed to measure pH_F on the right and pH_{FOX} on the left.
2. Calibrate pH measuring equipment using appropriate solutions.
3. Adjust the pH of around 1L of 30% hydrogen peroxide (suitable for a day's worth of measurements) to between pH 4.5 and 5.5 using drop-wise addition of 1M NaOH.
4. Collect sediment cores and return to 'field laboratory' setup to perform field tests before oxidation of sediments is able to occur.

Field pH_F and pH_{FOX} testing

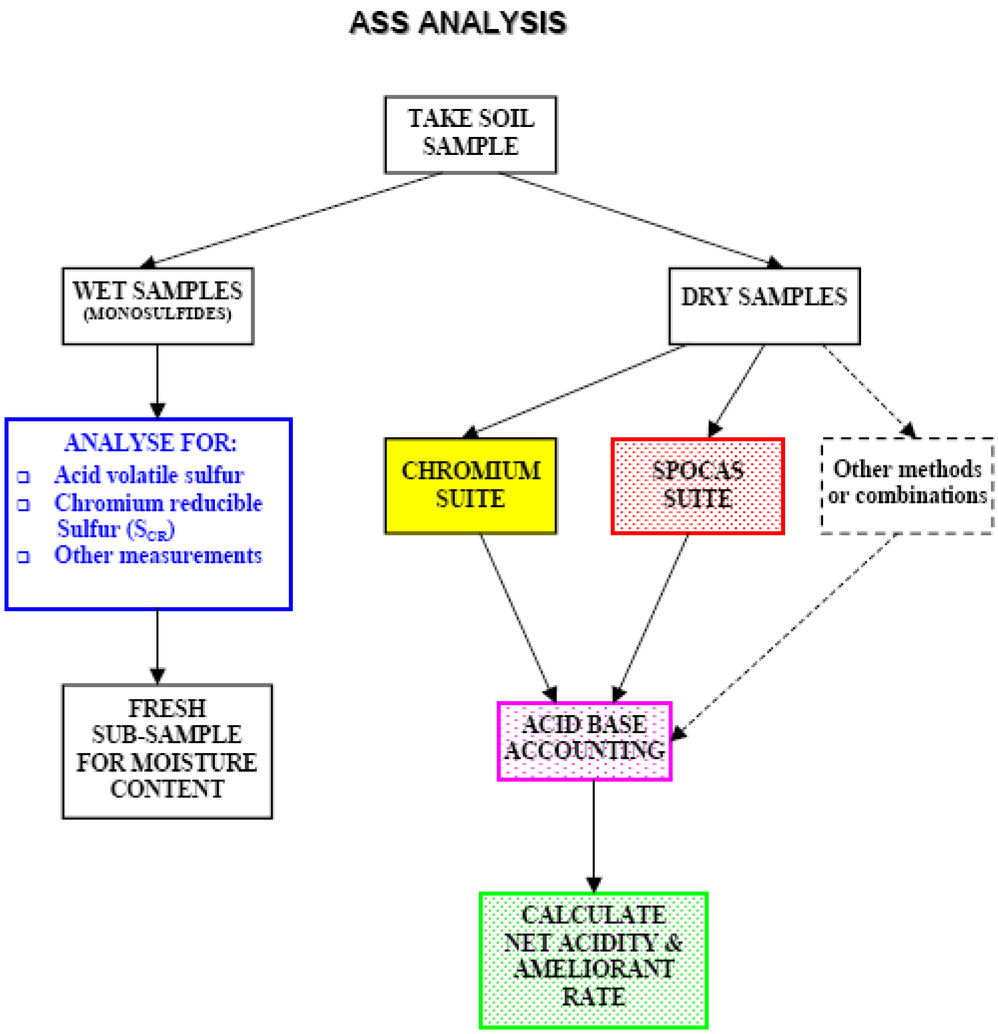
1. Take ½ teaspoon sized sample of sediment approximately every 25 cm or when a lithology change is noted (whichever is lesser), noting the depth of the sample
2. Place into beaker used for pH_F tests and add 12 ml of water from a clean syringe (marked pH_F) to make a 1:5 soil:water solution and shake well
3. Take another ½ teaspoon sized sample of sediment from the same place as the previous sample used for the pH_F measurement, and place into a beaker used for measuring pH_{FOX}
4. Add 12 ml of pH adjusted 30% hydrogen peroxide using a second syringe (marked pH_{FOX}) to make a 1:5 soil:peroxide solution, and shake well
5. Repeat above steps until entire core has been sampled
6. Shake all beakers well and leave for approximately 1 hour (during which time logging of cores can be done)
7. Regularly shake (i.e. every 5 to 10 minutes) all beakers to ensure maximum amount of sediment goes into solution
8. After 1 hour record pH_F and pH_{FOX} readings, taking all pH_F measurements first (to ensure no contamination with peroxide and also to allow maximum time for peroxide to react with the sediments). Clean pH probe with distilled water between each reading
9. Dispose of solutions into an appropriate container (although hydrogen peroxide rapidly decomposes to water and oxygen so is not harmful to the environment) and thoroughly clean all beakers, syringes and other equipment using Decon (detergent) and water.

Appendix C — ASS methods (laboratory)

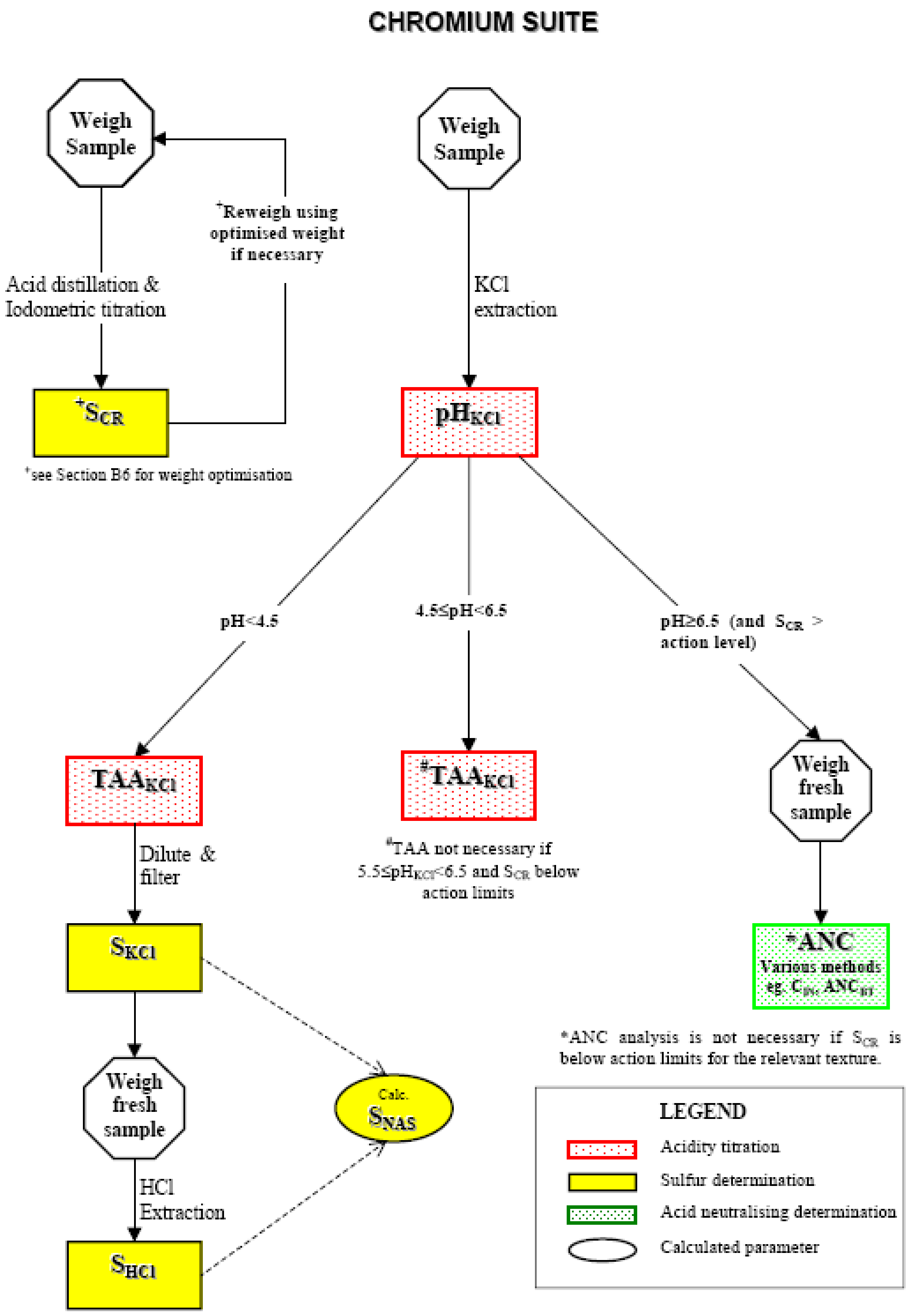
Laboratory methods

(After Ahern et al., 2004)

Flow diagram representation of methods followed when analysing acid sulfate soils. For full method description, refer to Ahern et al. (2004).

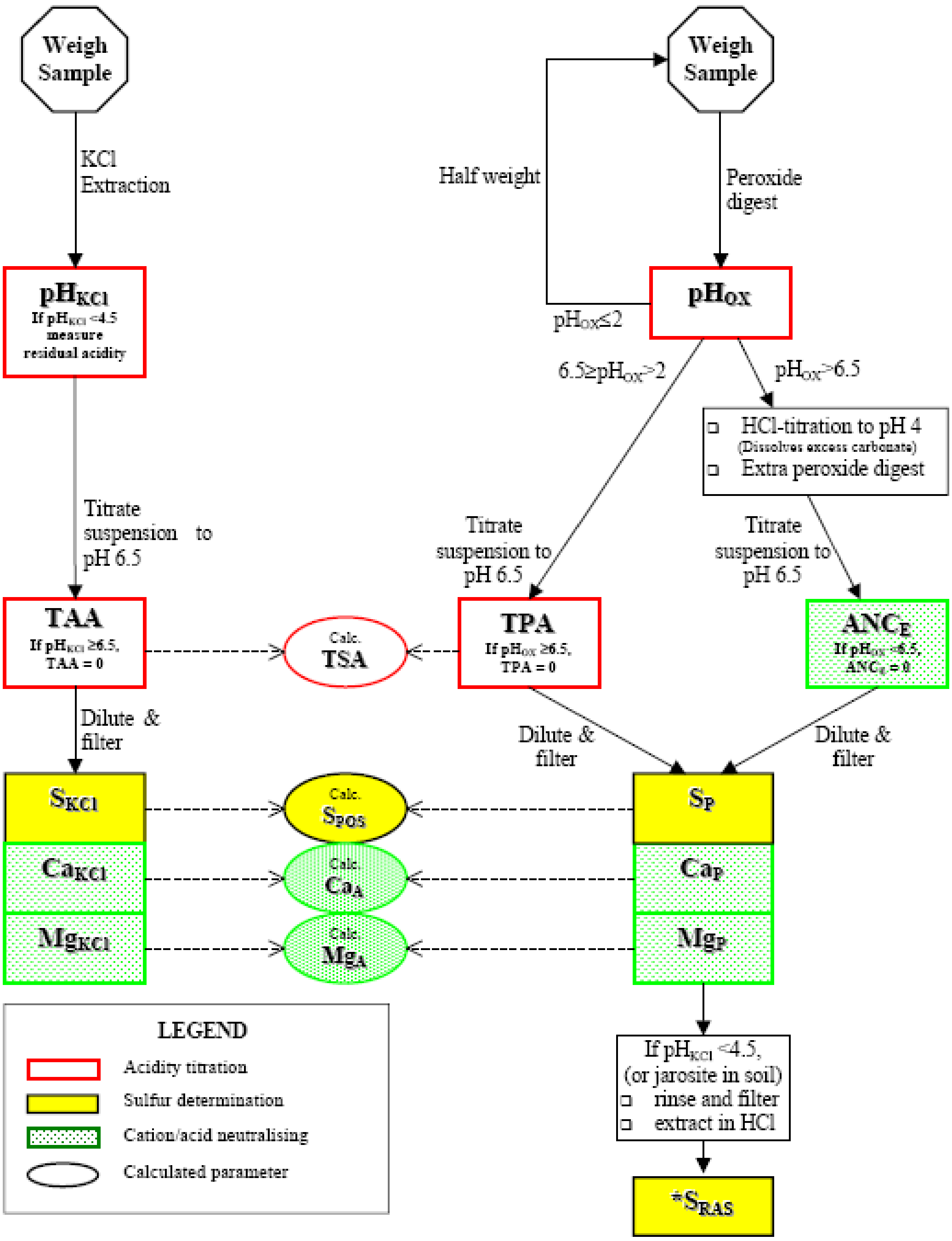


Flow diagram for overall methods used in the quantitative analyses of ASS (from Ahern et al. 1998)



Flow diagram of steps involved using the chromium suite (from Ahern et al. 1998)

SPOCAS: FLOW DIAGRAM



Flow diagram of steps involved in analysis using the SPOCAS suite (from Ahern et al. 1998)

Appendix D — ASS results (laboratory)

Acid-base accounting for SPOCAS suite

NMI lab number	Client sample number	ANC_E Excess acid neutral ising capacity	pH_{KCl} pH of KCl extract	TAA Titratable actual acidity	TPA Titratable peroxide acidity	TSA (Calc) Titratable sulfidic acidity	Ca_A (Calc) Reacted Ca	Mg_A (Calc) Reacted Mg	S_{NaS} (Calc) Retained acidity	S_{POS} (Calc) Potential sulfidic acidity	Net acidity	Alternative calculation Net acidity	Net acidity	Alternative calculation Net acidity
Units		% $CaCO_3$		mol H^+/ t	mol H^+/ t	mol H^+/ t	% Ca	% Mg	% S	% S	as % S	as % S	as mol H^+/ t	as mol H^+/ t
Limit of reporting		<0.05		<1	<1	<1	<0.1	<0.1	<0.01	<0.01				
W09/006076	200720901		3.6	19	7	<1	<0.1	<0.1	<0.01	<0.01	0.03	N/A	19	N/A
W09/006077	200720902		4.5	10	380	370	<0.1	<0.1		0.99	1.01	N/A	627	N/A
W09/006078	200720903		4.6	7	150	140	<0.1	<0.1		0.31	0.32	N/A	200	N/A
W09/006079	200720904		5.5	2	1	<1	<0.1	<0.1		<0.01	0.00	N/A	2	N/A
W09/006080	200720905		5.3	6	540	530	<0.1	<0.1		1.6	1.61	N/A	1004	N/A
W09/006080-D	200720905		5.4	5	500	490	<0.1	<0.1		1.3	1.31	N/A	816	N/A
W09/006081	200720906		5.7	2	140	140	<0.1	<0.1		0.32	0.32	N/A	202	N/A
W09/006082	200720907		5.9	1	99	98	<0.1	<0.1		0.27	0.27	N/A	169	N/A
W09/006083	200720908		6.0	<1	12	12	<0.1	<0.1		0.03	0.03	N/A	19	N/A
W09/006084	200720909		8.3	<1	<1	<1	<0.1	<0.1		0.06	0.02	0.06	12	37
W09/006085	200720910		6.3	<1	4	4	<0.1	<0.1		0.03	0.03	N/A	19	N/A
W09/006086	200720911		6.2	<1	16	16	<0.1	<0.1		0.04	0.04	N/A	25	N/A

Acid-base accounting for SPOCAS suite (cont'd)

NMI lab number	Client sample number	Fineness factor	Safety factor	Soil bulk density	Liming rate for ag lime	Alternative calculation Liming rate for ag lime
Units				t/ m^3	kg $CaCO_3$/ t	kg $CaCO_3$/ t
Limit of reporting						
W09/006076	200720901	1.5	1.5	1.0	1.5	N/A
W09/006077	200720902	1.5	1.5	1.0	49.1	N/A
W09/006078	200720903	1.5	1.5	1.0	15.7	N/A
W09/006079	200720904	1.5	1.5	1.0	0.2	N/A
W09/006080	200720905	1.5	1.5	1.0	78.5	N/A
W09/006080-D	200720905	1.5	1.5	1.0	63.8	N/A
W09/006081	200720906	1.5	1.5	1.0	15.8	N/A
W09/006082	200720907	1.5	1.5	1.0	13.2	N/A
W09/006083	200720908	1.5	1.5	1.0	1.5	N/A
W09/006084	200720909	1.5	1.5	1.0	1.0	2.9
W09/006085	200720910	1.5	1.5	1.0	1.5	N/A
W09/006086	200720911	1.5	1.5	1.0	2.0	N/A

Acid-base accounting for chromium suite analyses

NMI lab number	Client sample number	ANC $_{bt}$ Acid neutralising capacity back titration	Scr Potential sulfidic acidity	TAA Actual acidity	S_{NaS} (Calc) Retained acidity	Net acidity	Net acidity	Fineness factor	Safety factor	Soil Bulk density	Soil Liming rate for ag lime
Units		% $CaCO_3$	% S	mol H^+/ t	% S	as % S	as mol H^+/ t			t/m^3	kg $CaCO_3$/ t
Limit of Reporting		<0.05	<0.01	<1	<0.01						
W09/006076	200720901		<0.01	19	<0.01	0.03	19	1.5	1.5	1.0	1.5
W09/006077	200720902		0.91	10		0.93	578	1.5	1.5	1.0	45.2
W09/006078	200720903		0.26	7		0.27	169	1.5	1.5	1.0	13.2
W09/006079	200720904		<0.01	2		0.00	2	1.5	1.5	1.0	0.2
W09/006080	200720905		1.1	6		1.11	692	1.5	1.5	1.0	54.1
W09/006080-D	200720905		1.3	5		1.31	816	1.5	1.5	1.0	63.8
W09/006081	200720906		0.60	2		0.60	376	1.5	1.5	1.0	29.4
W09/006082	200720907		0.18	1		0.18	113	1.5	1.5	1.0	8.9
W09/006083	200720908		0.03	<1		0.03	19	1.5	1.5	1.0	1.5
W09/006084	200720909	<0.05	0.05	<1		0.05	31	1.5	1.5	1.0	2.4
W09/006085	200720910		0.04	<1		0.04	25	1.5	1.5	1.0	2.0

NMI lab number	Client sample number	ANC $_{bt}$ Acid neutralising capacity back titration	Scr Potential sulfidic acidity	TAA Actual acidity	S_{NaS} (Calc) Retained acidity	Net acidity	Net acidity	Fineness factor	Safety factor	Soil Bulk density	Soil Liming rate for ag lime
Units		% $CaCO_3$	% S	mol H^+/ t	% S	as % S	as mol H^+/ t			t/m^3	kg $CaCO_3$/ t
W09/006086	200720911		0.05	<1		0.05	31	1.5	1.5	1.0	2.4

Shortened forms

AASS	Actual acid sulfate soils
ABA	Acid-base accounting
AHD	Australian height datum
ANC	Acid neutralising capacity
ARMCANZ	Agriculture and Resource Management council of Australia and New Zealand
ASS	Acid sulfate soils
ANZECC	Australia and New Zealand Environment and Conservation Council
CRS	Chromium reducible sulfur suite of analyses
DEC	Department of Environment and Conservation
DO	Dissolved oxygen
DOE	Department of Environment
DOW	Department of Water
EC	Electrical conductivity
EWP	Environmental water provision
EWR	Ecological water requirement
FRP	Filterable reactive phosphorus
ICPAES	Inductively coupled plasma atomic emission spectrometer
ICPMS	Inductively coupled plasma mass spectrometer
NHMRC	National Health and Medical Research Council
NMI	National Measurement Institute
PASS	Potential acid sulfate soils
SGS	Shallow groundwater systems
SKM	Sinclair Knight Merz
SPOCAS	Suspension peroxide oxidation combined acidity and sulfur suite of analyses
SRP	Soluble reactive phosphorus

TAA	Titratable actual acidity
TDS	Total dissolved salts
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TSA	Titratable sulfidic acidity
TSS	Total suspended solids
WRC	Water and Rivers Commission
WAWA	West Australian Water Authority

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 buffering capacity — A measure of the resistance to changes in pH following the addition of an acid.

Acid neutralising capacity — A measure of the soil's ability to buffer acidity and resist the lowering of soil pH.

Acidification — The process by which soil, or water becomes more acidic (decreasing pH).

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.

Actual acidity — The soluble and exchangeable acidity already present in the soil.

AHD — Australian Height Datum.

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.

Algal blooms — The rapid excessive growth of algae, generally caused by high nutrient levels and favourable conditions. Can result in water-column deoxygenation when the algae die.

Alkalinity — A measure of a solutions 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.

Aquifer	A geological formation or group of formations able to receive, store and/or transmit large amounts of water.
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.
Conformably	Sediments deposited in a continuous sequence without a break.
Contaminants	A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful effects to humans or the environment.
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).

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 or engineering works.
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	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.
Environmental water requirements	The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.
Equilibrium	The condition of a system or reaction in which competing influences are balanced.

Eutrophic	An excess of nutrients (nitrogen and phosphorus) in an ecosystem, often resulting in excessive primary production.
Evapotranspiration	The combined loss of water by evaporation and transpiration. Includes water evaporated from the soil surface and water transpired by plants.
Fineness factor	A factor applied to the acid neutralising capacity to allow for the poor reactivity of coarser carbonate or other acid neutralising material.
Formation	A group of rocks or sediments that have certain characteristics in common, were deposited about the same geological period, and that constitute a were deposited about the same geological period, and that constitute a convenient unit for description.
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-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-shape formation of the water table resulting from rainwater trickling down into the open space between particles in an elevated area of deep sand or other porous material. Groundwater will move slowly away from the central area to discharge into wetlands, rivers and oceans.
Groundwater recharge	The rate at which infiltration water reaches the water table.
Hydraulic gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction.
Ion	An atom which has lost or gained electrons and therefore carries an electrical charge.

Leach	Remove soluble matter by percolation of water.
Mesozoic	An Era of geological time; 250–65 million years ago. It included the Triassic, Jurassic and Cretaceous periods.
Neutralisation	The chemical reaction in which an acid and a base react to produce salt and water (H2O).
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.
pH	The negative logarithm of the concentration of hydrogen ions.
pH_F	Field pH. Field determination of pH in a soil:water mixture
pH_{FOX}	Field peroxide pH. Field determination of pH in a soil:water mixture after reaction with hydrogen peroxide.
pH_{KCl}	Potassium chloride pH. pH measured in the laboratory in a 1:40 (W/V) suspension of sediment in a solution of 1 M potassium chloride measured prior to TAA titration.
pH_{OX}	Peroxide oxidised pH. pH measured in the laboratory
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 = 1mV). 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.0–500 mg/L; fresh500–1500 mg/L; fresh to marginal1500–3000 mg/L; brackish>3000 mg/L; saline.
Sulfate reduction	In the aquatic environment, the microbially catalysed process which converts sulfate to sulfide.
Surficial	Pertaining to the surface.
Terrestrial	Refers to an organism (or ecosystem) being of land origin.
Tertiary	The first period of the Cainozoic era; 2–65 million years ago.
Toxicity	The degree to which a substance is able to damage an exposed organism.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Transpiration	The loss of water vapour from a plant, mainly through the leaves.
Unconfined aquifer	A permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure.
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

Well	An opening in the ground made or used to obtain access to underground water. This includes soaks, wells, bores and excavations.

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