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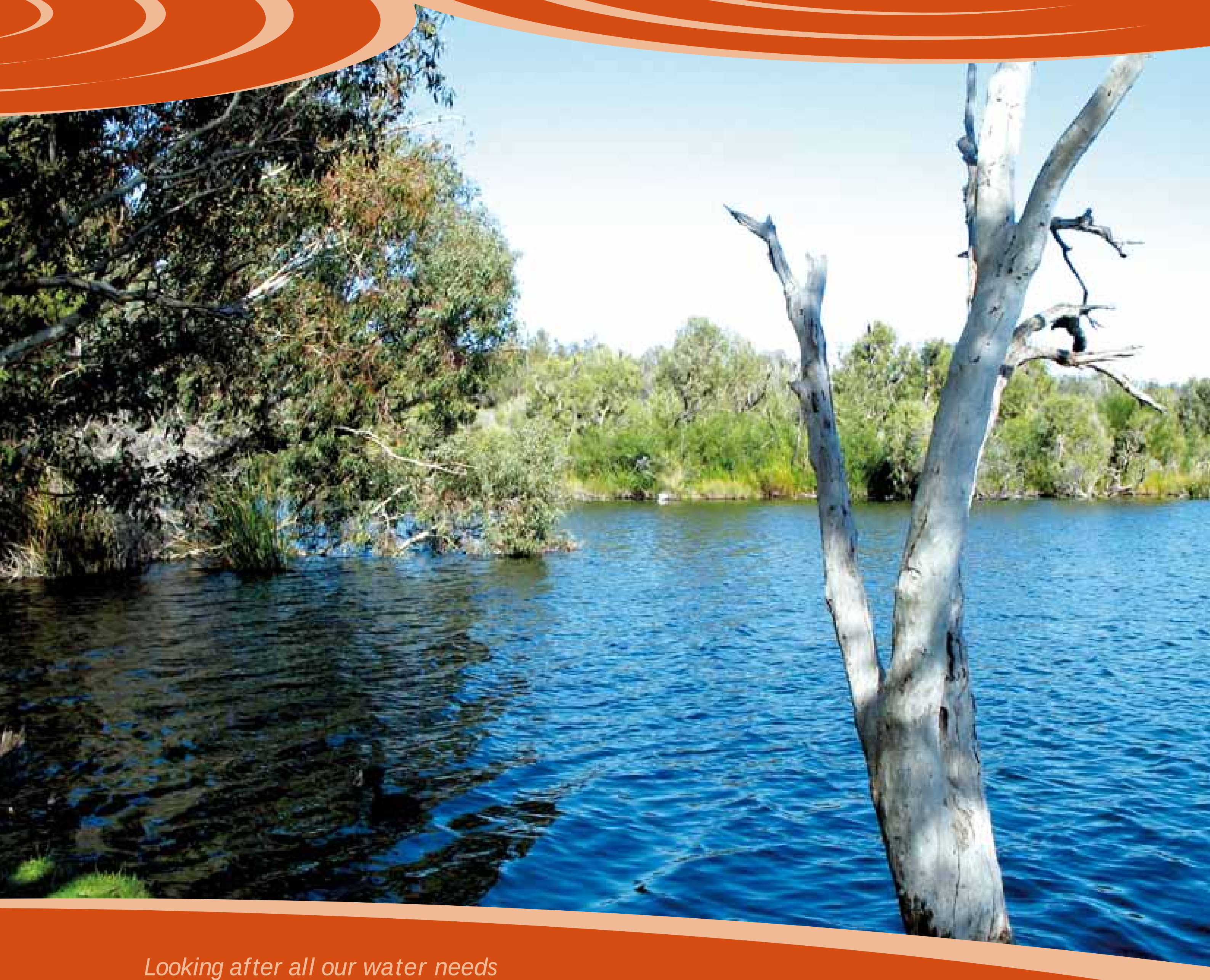

Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Loch McNess

Hydrogeological record series

Report no. HG43
March 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. Data interpretation for the report was carried out by Hydro Tasmania Consulting and Crisalis International Pty Ltd under commission to 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 Gnangara and Jandakot groundwater mounds, the most significant sources of groundwater for the Perth metropolitan area. The groundwater mounds also sustain numerous ecosystems that depend on shallow groundwater. Many of these ecosystems are currently stressed by land use changes, increased groundwater abstraction and a shift to a drier climate, resulting in a general deterioration in their social, cultural and environmental values.

The formulation of the investigation arose from the outcomes of a management area review conducted in 2006 (McHugh & Bourke 2007). This review summarised the current monitoring and management issues facing 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 30 wetlands on the Swan Coastal Plain, prioritised by a combination of ecological significance, management issues and geomorphic setting.

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

- redesign and upgrade the existing monitoring infrastructure and install new monitoring networks at ecologically important sites
- investigate the hydrogeology of selected lakes, wetlands and remnant wetlands to determine the interactions and connectivity of surface water bodies and groundwater
- investigate the palaeoclimate of 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

Loch McNess is one of the 28 sites in the Perth shallow groundwater system (SGS) investigation. This lake is entirely dependent on groundwater and is thus a groundwater-dependent ecosystem which is being affected by falling groundwater levels.

In 2008, the monitoring network at the site was upgraded by installing a cluster of groundwater monitoring bores along the western (down-gradient), eastern (up-gradient) and southern (shallow bore only) margins of the lake. A comprehensive 12 month sampling program of these and existing bores has improved understanding of how the lake functions hydrogeologically.

Previous investigations describe Loch McNess as a 'through-flow' lake with significant connection with groundwater flow of the Gnangara Mound and interaction with the superficial aquifer for most of the year.

The relationship between low rainfall in 2006 and the continuation of groundwater levels lower than in the lake on its down-gradient side, appears to indicate that a new hydrogeological regime has come into effect, whereby groundwater levels are maintained by leakage through lake sediments, not by direct discharge of lake water on the western edge of the lake. It is hypothesised that under this new hydraulic equilibrium the lake now recharges groundwater through a thin, unsaturated zone with a poor hydraulic connection between the lake and the groundwater in the Superficial aquifer. Essentially, the lake's hydrology has changed from a 'through-flow' regime to being 'partially perched on its western side'.

The changes in surface water–groundwater interaction at Loch McNess has affected the chemistry of both groundwater and lake water. Although water quality in Loch McNess is still considered good, deterioration has been recorded in some parameters, particularly in Loch McNess north. Electrical conductivity, turbidity, nutrient and chlorophyll-a levels have shown increases in recent years. These include sudden spikes as lake levels decrease and nutrient concentrations increase.

Although the lake is not yet showing signs of acidification that have been detected in other Gnangara Mound wetlands, acidification may still be taking place, with the effects masked by the buffering capacity of the lake's naturally high alkalinity. Continuing declines in water level will increase the risk of acidification. As the relative contribution of acidic groundwater inflow increases, the buffering capacity of the lake will be reduced. Although not a direct threat at this time, the effects of acidification are serious if pH values reach toxic levels.

There appears to be a relationship between anoxic conditions in groundwater and elevated concentrations of soluble iron and arsenic and possibly other metals. Elevated concentrations of metals in the groundwater, particularly arsenic, are a cause for concern and would require further investigation, although metal contamination is not currently affecting lake water quality.

The ecological consequences of falling water levels and associated water chemistry changes to date have been:

- degradation of water quality, particularly in Loch McNess north
- significant reductions in macroinvertebrate richness
- significant shifts in wetland vegetation range and community composition
- decline in vegetation health
- some terrestrialisation of wetland areas
- some encroaching of fringing vegetation into the lake basin
- reductions in habitat for aquatic macroinvertebrates, fish and waterbirds
- degraded, hydrologically linked, cave ecosystems.

Froend et al. (2004a) suggest a worst case scenario in which groundwater level declines decrease water levels in Loch McNess sufficiently to alter the hydrologic regime of the lake, changing it to a seasonally inundated sumpland or, at worst, a seasonally waterlogged dampland.

Downstream stressors (abstraction bores, land use, drainage) may be the cause of the increasing groundwater gradient downstream of the lake. This abstraction and its possible effect on the hydraulic gradient require further investigation. The cause of the lower inflow up-gradient is not clear. It may be pine plantation transpiration and/or onset of a drought dominated regime.

It is anticipated that if groundwater levels continue to fall, more significant shifts in the vegetation community will occur as groundwater levels approach the minimum requirements for species. As Loch McNess has shifted from a ‘flow-through’ lake to ‘a partially perched’ regime, the vegetation community has changed from one that is reliant on a saturated zone to being dependent on an unsaturated zone. This makes vegetation more sensitive to groundwater abstraction, which can further reduce groundwater availability and lead to a decline in vegetation health.

For water levels in the lake to recover, groundwater levels must be increased to pre-2006 levels to re-establish the historical through-flow hydrologic regime. Several years of good rainfall and low abstraction would be required for the lake to recover to Ministerial Criteria levels. If below average rainfall conditions and current abstractions persist, lake levels will not recover and irreversible ecological changes may result. It has been noted that the changes in the lake’s condition are proceeding at an increasing rate.

A minimum groundwater level of 5.27 m AHD at bore MCN-SWC would appear to be sufficient to maintain the connection between the vegetation and groundwater. Groundwater abstraction and land use in the Yanchep Groundwater Area should be managed with the aim of returning groundwater to this level.

If the maintenance of the historical hydrologic regime is desired, a minimum groundwater level of 7.0 m AHD at bore BD9 would appear to be sufficient to restore the connection between the lake and groundwater. Restoring this connection would assist in returning lake levels to above the Ministerial Criteria.

Recommendations

All recommendations are subject to Department priorities and the availability of resources.

Management Actions

- In order to meet the minimum groundwater requirements of all wetland vegetation on the southern vegetation transect, a groundwater level of 5.27 m AHD is required at bore MCN_SWC, and it is recommended that this is established as both a vegetation EWR and a Ministerial Criterion
    - *Implementation and responsibility: DoW to recognise in the next Gnangara water allocation plan due in 2012*

Future Monitoring

- Following on from the recommendation above, and as there is limited data associated with the SGS bores, monitoring of a number of the 'long term' bores should be maintained (i.e. YN3, YN5, BD7, BD9). This should include frequent (say, monthly) groundwater SWL monitoring including downstream of the lake along a given flow-path to the coast. The installation of continuous SWL recorders should be considered on bores BD7 and BD9
    - *Implementation and responsibility: DoW to review the monitoring program and document in a resource review report by 2015/2017.*

Future Investigation

- As the threatened plant *Baumea articulata* is still present at the northern vegetation transect site, but has not been recorded at the southern vegetation transect since 2005, a bore should be established associated with this transect
- To restore the connection between the lake and groundwater a minimum groundwater level of 7.0 m AHD at bore BD9 appears to be required. A separate study into options is recommended, such as an assessment of aquifer stressors particularly of down-gradient drawpoints, and the application of managed aquifer recharge (MAR) to recover the groundwater levels to the mound
- That the risk bands proposed herein are adopted as a management tool and trigger to assess the usefulness of any remedial measures.
    - *Implementation and responsibility: DoW to scope an investigative program.*

1 Context and objectives

Clifton and Evans (2001) described permanent wetlands of the Swan Coastal Plain as being entirely dependent on groundwater. Water levels in shallow groundwater systems (both lake and groundwater level) are declining across the Gnangara Mound, and have been linked to ecological deterioration, including loss of biodiversity (Clark & Horwitz 2005; Froend et al. 2004c). Water level declines in and around wetlands also substantially increase the risks associated with acid sulfate soils (ASS) (Appleyard 2005). The causes of this decline are a complex mix of natural and anthropogenic factors (Yesertener 2005). Regionally, the climate is becoming drier, reducing recharge and leading to lower groundwater levels. This trend is predicted to continue across the Swan Coastal Plain (Indian Ocean Climate Initiative 2002). Superimposed on this regional trend are the effects of localised land use, vegetation, urbanisation and abstraction changes.

Loch McNess is a conservation category wetland (Hill et al. 1996) located in Yanchep National Park and is listed in the *Directory of important wetlands in Australia*. It has high ecological and social values. Its vegetation is largely intact, it provides a range of habitat types, and it acts as a drought refuge (Froend et al. 2004c). It has an unusual hydrologic regime, normally displaying small annual depth fluctuations (~ 20 cm) (McHugh & Bourke 2007; Department of Water 2008). It is likely that Loch McNess is entirely groundwater dependent for biophysical processes, habitat and consumptive use. Formerly, long-term lake water levels were relatively stable, but there has been a decline in levels since 1995, although the wetland still contains permanent water. Under Ministerial Criteria, the summer absolute minimum EWR is set at 6.95 m AHD. This criterion has been breached each year in summer since 2003, and the spring maximum water levels in 2007 fell for the first time below this benchmark level, possibly indicating a threshold change.

The lake is classified as being at severe risk from possible drawdown (McHugh & Bourke, 2007). Bekesi (2007) considered that regional groundwater levels up-gradient of the wetland are likely to have dropped below the local groundwater mound supporting the lake, which has caused surface water levels to decline rapidly. This regional decline may also have impacts on the caves in the region and the groundwater-dependent cave ecosystems.

The *Management area review of shallow groundwater systems on the Gnangara and Jandakot mounds* (McHugh & Bourke 2007), considered that the situation at Loch McNess was severe enough to warrant a local area hydrogeological investigation because of the lake's high ecological value and the significant and abrupt decline in water levels within the lake since 2006.

The management area review and the most recent review of Ministerial Conditions on the Gnangara Mound (Department of Water 2008a) recommended that site specific data be collected and analysed to determine the current status of Loch McNess in terms of groundwater–surface water connectivity and groundwater quality and flow into and out of the wetland.

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2 Background

2.1 Location and climate

Loch McNess is located within the Yanchep National Park, 48 km north-west of Perth CBD, on the northern part of the Swan Coastal Plain and on the Gnangara Groundwater Mound (Figure 1).

It is situated in an interdunal depression within the Tamala Limestone. It apparently overflows to the south towards Lake Yonderup via Loch Overflow Cave (Rockwater 2003). The eastern side of the lake is characterised by fractured limestone with many small caves. There is no bathymetry available for the lake.

The lake has three well defined sections which differ in vegetation and hydrology and reflect different levels of disturbance from past developments. The northern end is undisturbed, while the southern end was dredged between 1936 and 1940 and again in 1968 around the periphery of the open water. A causeway has been constructed between the north and south parts of the lake. Much of the eastern perimeter of Loch McNess was cleared in the 1930s for an oval which was not developed and it has since overgrown with sedges, rushes and flooded gums.

The Swan Coastal Plain experiences a Mediterranean type climate with hot, dry summers and mild, wet winters. Rainfall occurs mainly between May and September. The annual rainfall recorded from the closest monitoring station to Loch McNess at Wanneroo, over a 100-year period (1907–2007) shows a declining trend (Figure 2).

It is of note that annual rainfall and peak lake water levels correlate poorly.

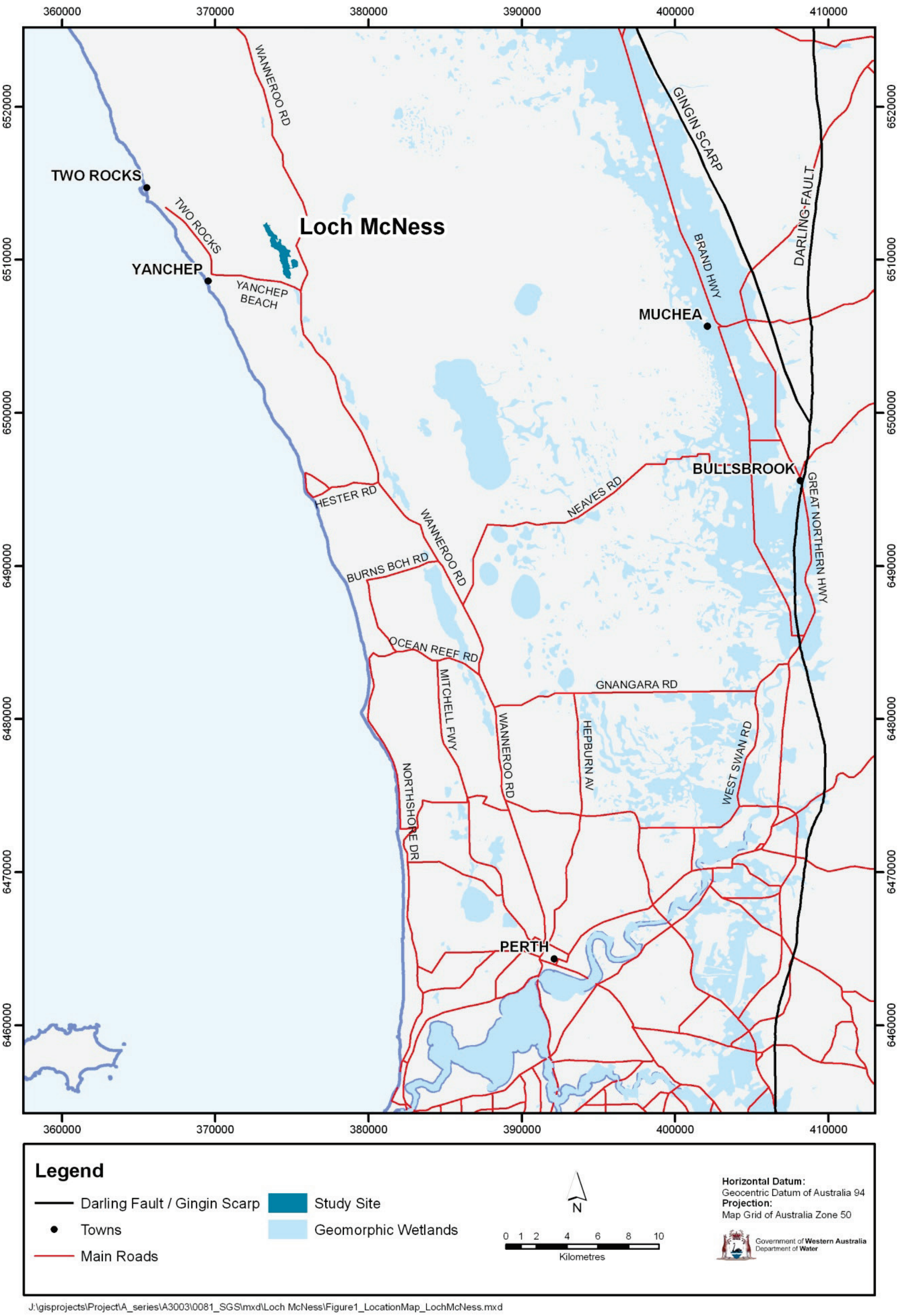

Figure 1 Location of Loch McNess

Table 1 Summary attributes of Loch McNess

Wetland or groundwater-dependent ecosystem	Loch McNess
AWRC No.	6162564
WIN site ID	14585
Location	E: 374395, N: 6509358
Wetland or groundwater-dependent ecosystem type and description	Permanently inundated
Ecological recognition	Conservation status: national importance
Aboriginal heritage	Two registered sites of significance (3186, 3742)
Wetland suite	Yanchep (S.1)
Physiographic wetlands Unit	Spearwood Dunes
Permanent lake area	210 to 290 ha
Management	Department of Environment and Conservation (DEC)

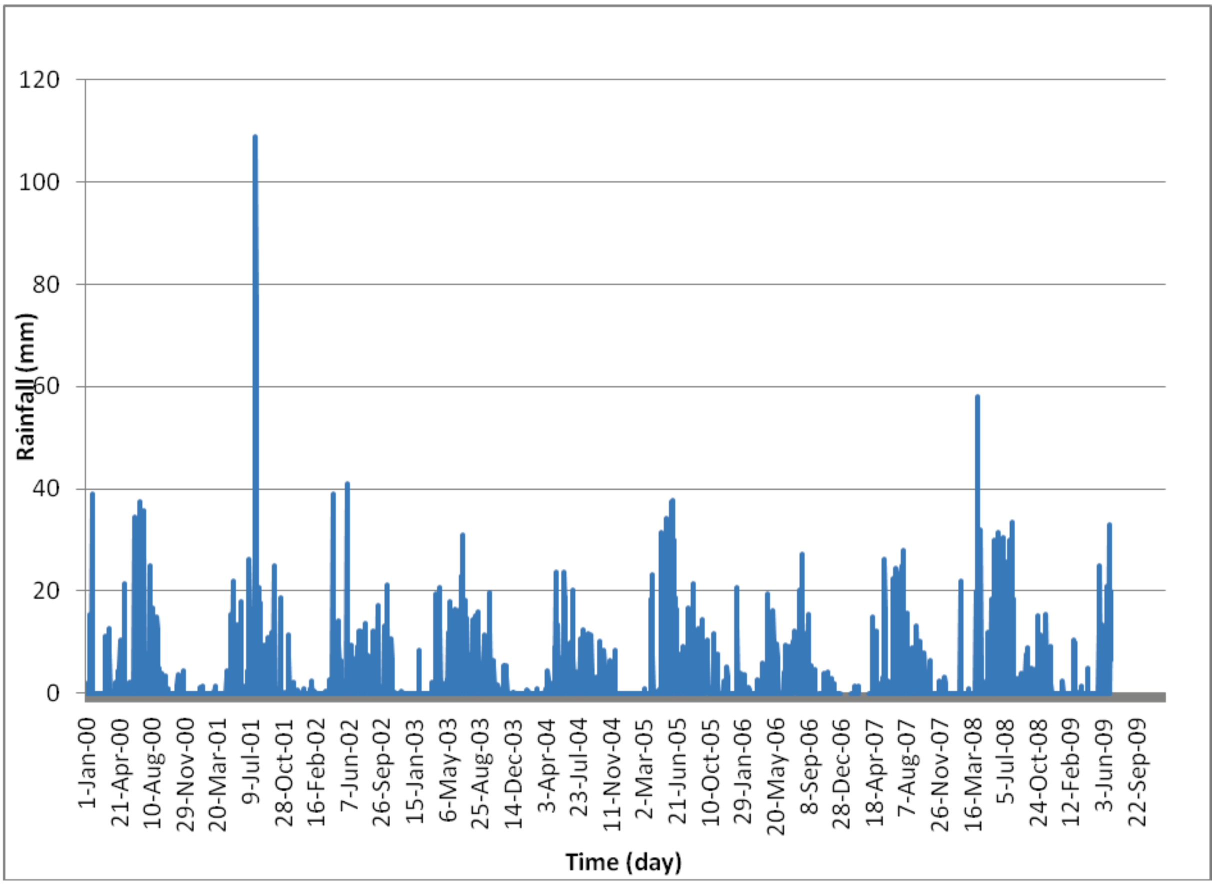

Figure 2 Monthly total rainfall for Wanneroo 2000 to 2009

The annual rainfall totals for each year from 2000 to 2009 are shown below. Of note is the low rainfall in 2006.

Table 2 Annual rainfall at Wanneroo (2000 to 2009)

Year	Rainfall (mm)
2000	789
2001	718
2002	652
2003	775
2004	592
2005	908
2006	520
2007	619
2008	738

2.2 Geology and geomorphology

Regional geology and geomorphology

Loch McNess is located on Quaternary dune sands and coastal limestones of the superficial formation on the northern part of the Swan Coastal Plain in the Perth region. The dune sands between the Swan River and the Moore River to the north and the Darling and Gingin scarps to the east and the Indian Ocean to the west form a north-south trending dune system of crests and swales.

In the Perth region, the superficial formation has 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).

Younger sands and coastal limestones of the Spearwood Dune System (McArthur & Bettenay 1960) are found to the west of the Bassendean Sands and unconformably overly these sands. Wetlands, including Loch McNess, have formed where the shallow watertable in the unconfined Superficial aquifer intercepts the surface within dune swales. In addition, where the coastal limestone occurs within the zone of fluctuation of the watertable, this has resulted in formation of solution cavities and karst formation. Near Loch McNess, this has developed an extensive series of caves (Yanchep Caves) into which groundwater discharges.

The superficial formation in the region of Loch McNess is the Tamala Limestone (Figure 3) which is part of the Spearwood Dune System (McArthur & Bettenay 1960; Davidson 1995).

The Tamala Limestone is described by Davidson (1995) as leached yellow sand and aeolian calcarenite. The limestone (calcarenite) units contain numerous solution cavities, particularly in the region of watertable fluctuation. Sediments of the Quaternary Ascot Formation occur beneath the Tamala Limestone and are shown to occur by Davidson (1995) in areas to the west of the lake and possibly beneath the lake (see Section AA' from Davidson (1995) in Figure 4). The Ascot Formation is described as a calcarenite interbedded with sands, commonly containing glauconite and phosphatic nodules. If the Ascot Formation is present at Loch McNess, then it is likely to be relatively thin.

The Tamala Limestone in the region of Loch McNess is shown by Davidson (1995) to be underlain by relatively thin sediments of the Cretaceous Lancelin Formation which is described as a white to greenish brown glauconitic marl in the region around Guilderton, some distance to the north of the Yanchep area. Loch McNess is located close to the eastern edge of Cretaceous sediments where the Lancelin Formation pinches out, so it is possible that this formation is absent or very thinly developed beneath the lake. Davidson also reports Gingin Chalk below the Lancelin Formation to the west of the lake, although again this pinches out to the east and may not be present beneath the lake.

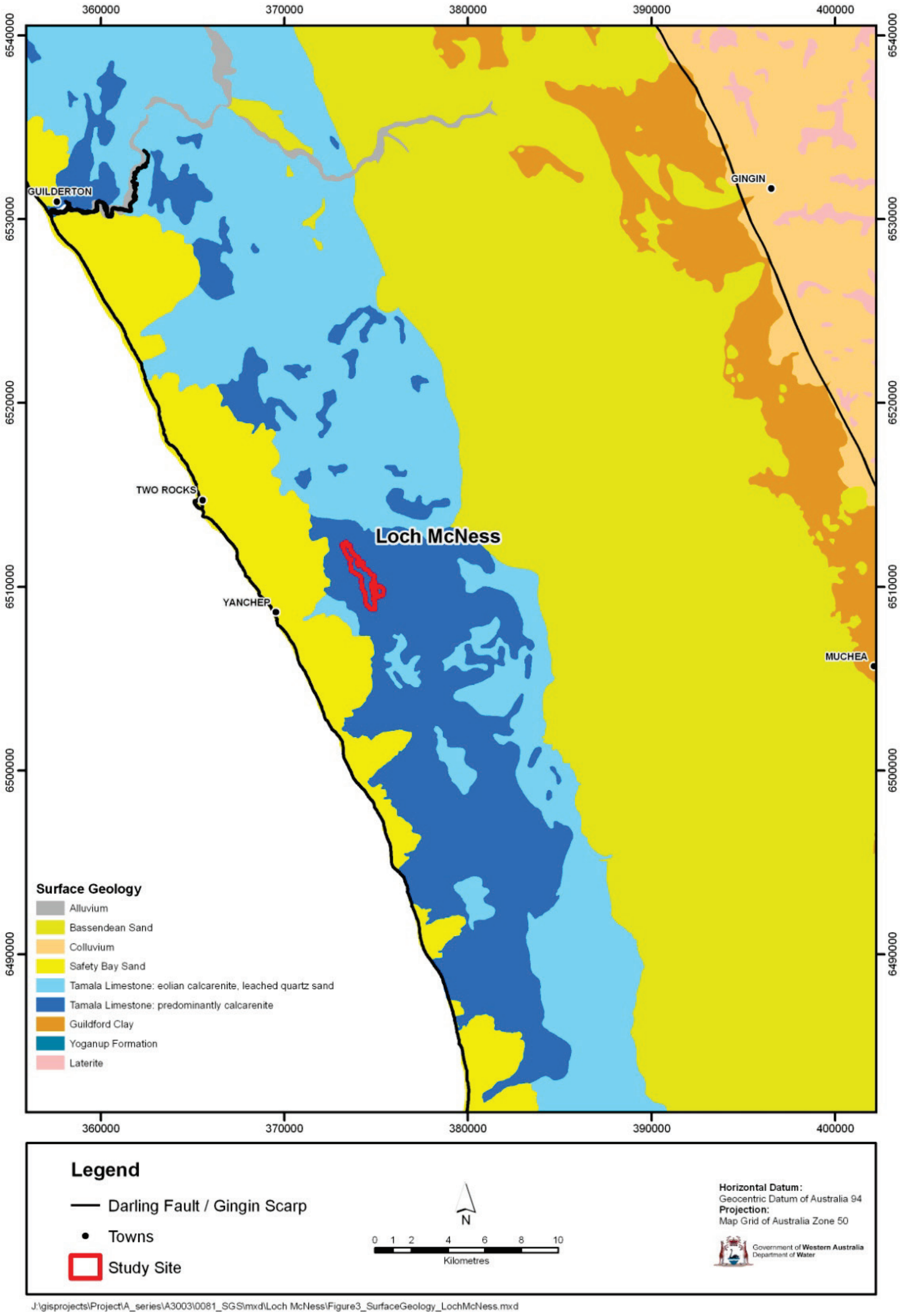

Figure 3 Generalised surface geology in the Loch McNess area

The Pinjar Member of the Leederville Formation unconformably underlies either superficial sediments (Tamala Limestone, possibly Ascot Formation) or thin beds of Cretaceous Lancelin Formation and Gingin Chalk. The Pinjar Member is about 50 m thick in the vicinity of the lake and consists of discontinuous interbedded sandstones, siltstones and shales. Sandstone units are reported to vary from 3 m to 6 m in thickness. The siltstones and shales are reported to be dark grey to black in colour.

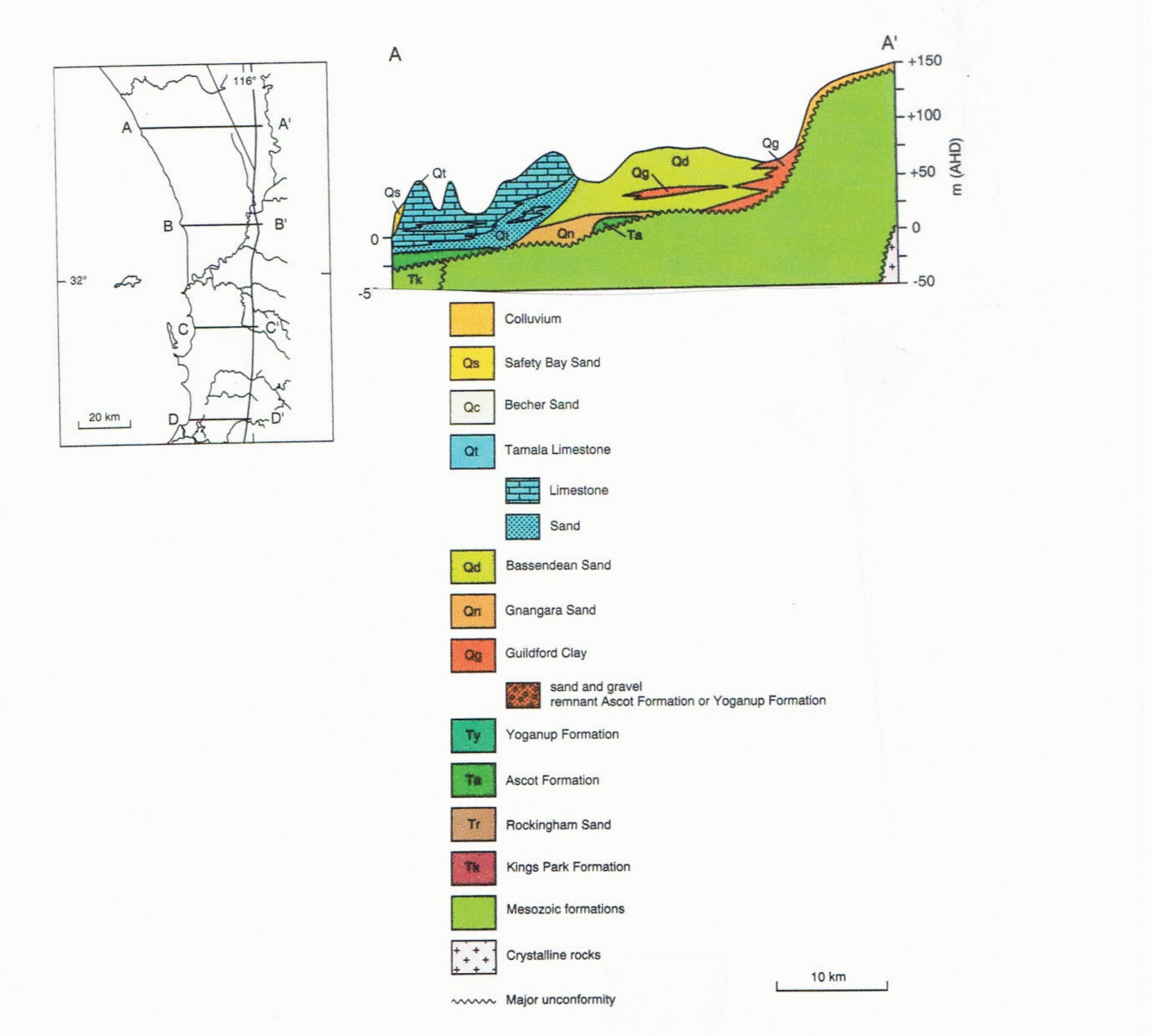

Figure 4 East-west geological cross-section through the superficial formation A-A' north of Loch McNess, from Davidson (1995)

Acid sulfate soils

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

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

The consequences that may result include:

- soil acidification
- changes in the quality of soil and water
- degradation in wetlands and water-dependant ecosystems resulting in loss of habitat and biodiversity
- reduction of soil stability and fertility
- creation of acid surface scalds in discharge areas
- risk of long-term infrastructure damage by acidic water corroding metallic and concrete structures
- blockage of reticulation systems and other small pipe systems by iron precipitates
- increased financial burden of treating and rehabilitating affected areas, and maintenance of infrastructure.

Loch McNess is at risk of acidification due to the exposure of acid sulfate soils and declining water levels in the area (McHugh and Bourke 2007; Froend et al. 2004c). However, because the lake is known to be well buffered, it appears that acidification is not yet apparent (Judd & Horwitz 2009).

2.3 Hydrogeology

Loch McNess lies on the western side of the Gnangara Groundwater Mound, situated between the Swan River to the south, the Moore River to the north, Ellen Brook and the Darling Scarp to the east and the Indian Ocean to the west (Figure 5). Groundwater broadly flows outwards from the crest of the mound, flowing westwards beneath Loch McNess towards the ocean.

Mesozoic semi-confined aquifers of the Leederville Formation occur beneath the Superficial aquifer. Davidson (1995) reports upward gradients from the Leederville Formation into the Superficial aquifer near Loch McNess.

Loch McNess lies on the western edge of a zone where the watertable has a steep hydraulic gradient (groundwater levels falling from 20 m to 5 m AHD along the coastal side of the Gnangara Mound). The change in gradient occurs where predominantly calcareous sediments of the Spearwood Dunes (and underlying sediments) abut and overlie the Bassendean Dunes. The change in gradient coincides with a zone of karstic development where caves and dolines are locally developed in the limestone and stream flow and local groundwater cascades occur in some caves (Rockwater 2003).

A number of wetlands on the Coastal Plain are considered to be ‘flow-through’ lakes, where groundwater discharges into the lake on the up-gradient (eastern) side and surface water in the lake discharges into the groundwater system on the down-gradient (western) side (e.g. see Townley et al. 1991 and Townley & Trefry 2000). Loch McNess is thought to be a flow-through system, although there have been no detailed field investigations to confirm this.

It is clear from previous investigations that groundwater levels on the Gnangara Mound have declined, largely because of reduced rainfall, groundwater abstraction for domestic and irrigation supplies and from water use by pine plantations (Rockwater 2003). In the Loch McNess area, the Yanchep Cave systems and their unique ecosystems have come under serious threat from lowered groundwater levels, with some caves such as Crystal Cave drying out, requiring artificial recharge to try and maintain the groundwater-dependent ecosystems (GDE) (e.g. see Barber & Felton 2005).

Water levels in Loch McNess have also declined, particularly since 2007 (Rockwater 2003; Bekesi 2007). This lake is entirely dependent on groundwater and is thus a groundwater-dependent ecosystem which is being affected by falling groundwater levels. As lake water levels recede, exposure of organic lake sediments to air can give rise to oxidation of sulfidic minerals within the sediments and production of acid conditions. This may then reduce lake water and groundwater quality (Appleyard & Cook 2009).

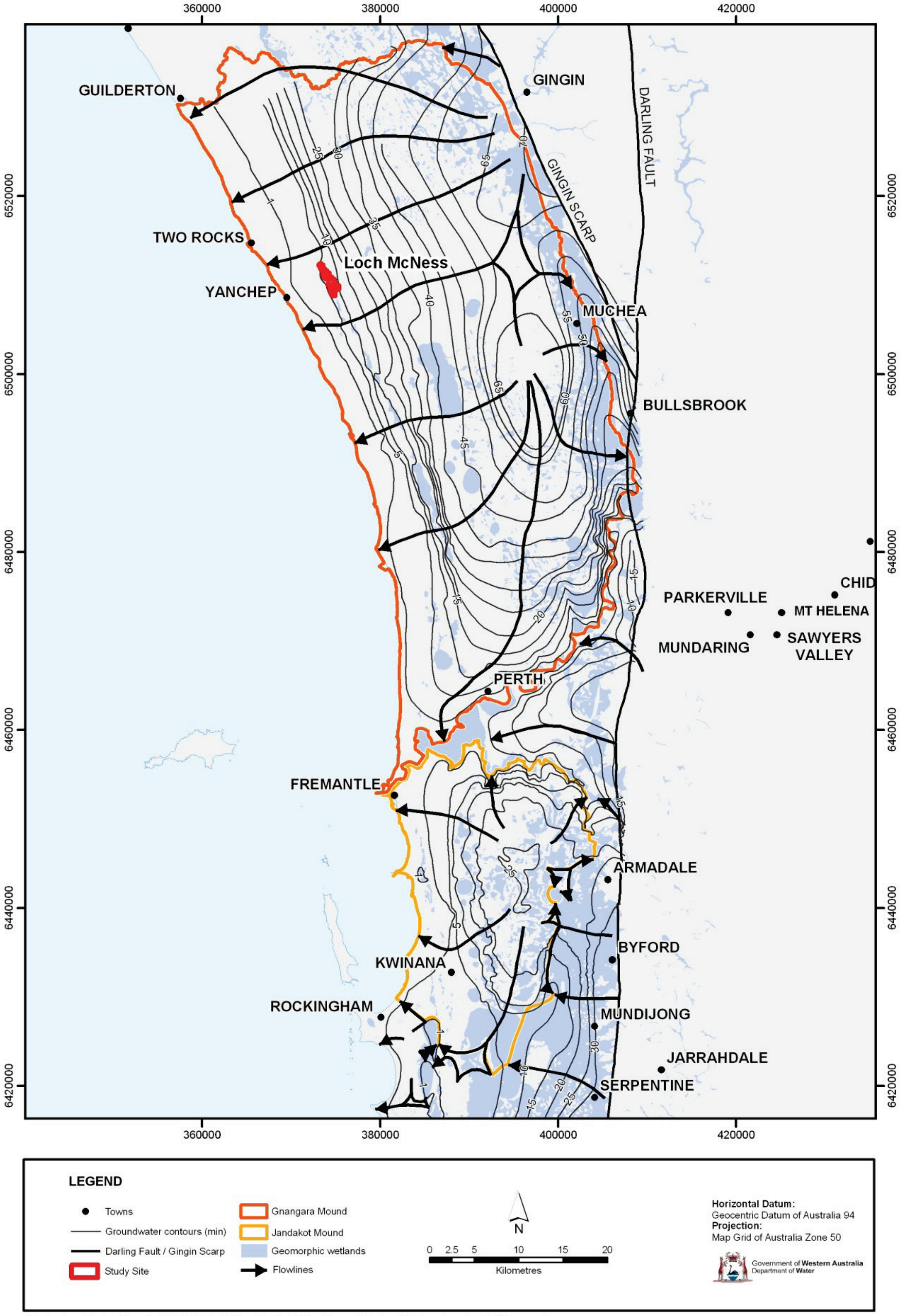

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Figure 5 Gnangara and Jandakot mounds showing flowlines

2.4 Previous studies

The sound management and sustainability of the Loch McNess wetland requires knowledge of the interaction of surface water and groundwater systems and the ability to model these interactions.

Krasnostein and Oldham (2004) developed a conceptual model to describe the interactions between Loch McNess itself, the surrounding catchment and local groundwater. A bucket model was used to simulate the different inputs and to determine lake water balance. Three different approaches and a variety of bucket configurations were used to investigate the possible hydrological processes contributing to the water balance. The model results showed that the 'interactive groundwater catchment–wetland system' was the most useful approach.

In an earlier study, Arnold (1990) suggested that channels link the southern end of Loch McNess to Lake Yonderup and several caves. However, later results from the interactive groundwater–wetland model mentioned above showed that outflows from the wetland were not via the channel (Krasnostein & Oldham 2004). A dye test conducted by Bridge (1969) showed:

- water infiltrates from the Loch McNess wetland into the Superficial Aquifer
- radial subsurface runoff from the wetland to the local groundwater system
- that the caves are linked to the local groundwater system.

In 2003, the then Department of Conservation and Land Management investigated ways of protecting cave fauna in the Yanchep National Park through localised artificial recharge of groundwater. The aim of this artificial recharge was to maintain groundwater levels within the most significant cave systems (AJ Peck & Associates 2003).

Monitoring of macroinvertebrates and water quality in some key Swan Coastal Plain wetlands has been undertaken since 1988 (WAWA 1995).

Monitoring of macroinvertebrates and water quality at Loch McNess (north and south) began in 1996 (Froend 2004c).

Annual reporting for the Wetland Macroinvertebrate Monitoring Program is carried out by the Centre for Ecosystem Management at Edith Cowan University, as part of the Gnangara Mound Environmental Monitoring Project. Results are reported chronologically as (survey and sampling) 'rounds' performed once in spring and once in summer or autumn. Clark and Horwitz (2005) reported rounds 18 and 19, McKay and Horwitz (2006) reported round 20 (in spring), Sommer and Horwitz (2007) reported rounds 22 and 23 and Judd and Horwitz (2009) reported rounds 26 and 27.

Water quality is monitored annually at the time of aquatic fauna monitoring for all wetlands in which water is present. Parameters monitored are total nitrogen, chlorophyll-a, pH, conductivity and temperature. These parameters are used to assess changes in water quality resulting from land-use development.

The Centre for Ecosystem Management also annually conducts wetland vegetation monitoring surveys of the Gnangara wetlands. In 2004, Bertuch et al. (2004) established two new vegetation health and composition transects on the western side of Loch McNess. One transect consisted of three plots at Loch McNess south and the other of four plots at Loch McNess north. Rogan et al. (2006) repeated these transects in September and October 2005. A fire during the summer of 2004–05 destroyed the monitoring transect at Loch McNess north. A newly realigned transect of four 10 x 10 m plots was established in 2005, once again running from the lake edge upslope towards a vehicle track. Pettit et al. (2007) summarised data collected in the 2006 survey. Boyd et al. (2008) reported the survey of August 2007. Generally, encroachment of vegetation, including weeds and over-storey species, into the wetland basin has been reported over the years.

For water allocation purposes, the Department of Water (2009) developed a water balance for each groundwater area and subarea using the Perth regional aquifer modelling system (PRAMS) model. The aquifer yield was calculated as a percentage of net rainfall recharge to the Superficial aquifer, based on the PRAMS water balance calculation (URS 2001). Cumulative deviation from mean rainfall (CDFM) was applied to examine the influence of different factors on groundwater levels for approximately 100 hydrographs across the Gnangara Mound (Yesertener 2008). Hydrograph trend analysis was used as a corrective tool for short-term to medium-term management toward achieving sustainability in the context of changing climate and declining groundwater levels (Bekesi 2007). The trend analysis was then used to determine a correction factor to the allocation limit based on the trends observed in hydrographs across the Gnangara system.

2.5 Ecological values and significance

Ecological values and management objectives

Wetland water levels are currently managed by adhering to environmental water provisions set as Ministerial Criteria. These were first set for wetlands and other groundwater-dependent ecosystems (GDEs) on the Gnangara Mound in 1986 (EPA Statement 438). For the Gnangara and Jandakot mounds, environmental water provisions (EWPs) have been set typically as minimum water levels at Ministerial Criteria sites which were chosen to represent the range of GDEs across the mounds. These water level criteria were established by determining ecological water requirements (EWRs). The persistent breaching of several water level and environmental criteria has prompted a review of environmental conditions through a Section 46 (Environmental Protection Act 1986) review which is currently in progress.

Loch McNess has been identified as a wetland of high ecological value within the Gnangara Mound groundwater wetland complex. Located within the Yanchep National Park, Loch McNess is listed in the *Directory of Important Wetlands in Australia* and the *Register of the National Estate* and is recognised as a regionally significant wetland (Department of Water 2008a; Froend et al. 2004a).

Loch McNess is considered to be a good example of a relatively undisturbed lake of the Swan Coastal Plain that is undergoing succession towards marsh and wooded swamp. It is also the only major wetland of the Swan Coastal Plain that is known to naturally exhibit a relatively small annual depth fluctuation (McHugh & Bourke 2007; Department of Water 2008). This wetland is relatively undisturbed with large areas of intact Herdsman Complex vegetation and relatively good water quality, providing habitat for water birds and other aquatic fauna (Froend et al. 2004c). Only one threatened species has been recorded from Loch McNess, the freckled duck (*Stictonetta naevosa*). In total, 70 wetland plants, 23 birds, 3 fish and 38 macroinvertebrate species have been recorded from the lake.

The lake may be divided into three components, north, east and south, based on their different hydrology and ecological values. Generally, Loch McNess has a constant water regime (Figure 6), with level varying < 20 cm per year on average. However, over the last three years, levels have fluctuated by up to 30 cm, with the lake level declining overall (such that it is below the Ministerial Criteria). Although Loch McNess always receives some surface water inflow and direct rainfall inflow, it is highly likely that the wetland is effectively dependent on groundwater for biophysical processes, habitat and consumptive use (Froend et al. 2004b; Krasnostein & Oldham 2004).

Due to its significant ecological values, Loch McNess was selected for management under the Gnangara Mound Water Resources Environmental Review and Management Program (WAWA 1986, referenced in WAWA 1995). This program identified the following ecological values for Loch McNess:

- undisturbed wetland
- unusual hydrologic regime
- rich aquatic fauna
- vegetation largely intact, providing a range of habitat types
- supports good populations of water birds and acts as a drought refuge
- excellent water quality.

A review of the ecological values by Froend et al. (2004a) updates these values to include:

- high environmental and human use attributes
- relatively good water quality
- habitat for water birds and aquatic fauna
- one of few Swan Coastal Plain wetlands containing nightfish (*Bostokia porosa*)
- rich in Odonata and Coleoptera macroinvertebrate species
- the surrounding Yanchep National Park which supports significant mammal and reptile species.

Management objectives were set in 1986 and later reviewed (WAWA 1995) to maintain the ecological values of the lake, as well as to protect social and economic uses of the site. The management objectives developed were:

- to maintain the environmental quality of Loch McNess
- to maintain the pristine state of Loch McNess north
- to continue to use Loch McNess south for low key recreation
- to maintain Loch McNess east in a natural state, so that where possible, natural water flow is restored.

A more recent review undertaken by Froend et al. (2004a) recommended reviewing the management objectives to recognise the cumulative impacts of abstraction history and long-term climatic and land-use change, and minimise the contribution of groundwater abstraction on the progressive decline of identified ecological values.

As part of the 1995 review (WAWA 1995) it was recognised that maintenance of the water regime in Loch McNess was vital given its high values, and that the EWP was equal to the EWR. A Ministerial Criterion for an ‘absolute minimum acceptable water level’ of 6.95 m AHD was set to ensure the future protection of Loch McNess (WAWA 1995). Under this criterion, no level below the absolute minimum level is considered acceptable. The Ministerial Criterion minimum water level was developed based on the known EWRs, or water regimes, considered necessary to maintain a low level of risk to the ecological values.

A more recent evaluation of EWRs (Froend et al. 2004b) still considers that the current requirement (i.e. maintaining water levels > 6.95 m AHD) for Loch McNess is appropriate to maintain vegetation, macroinvertebrate and vertebrate values and sediment processes.

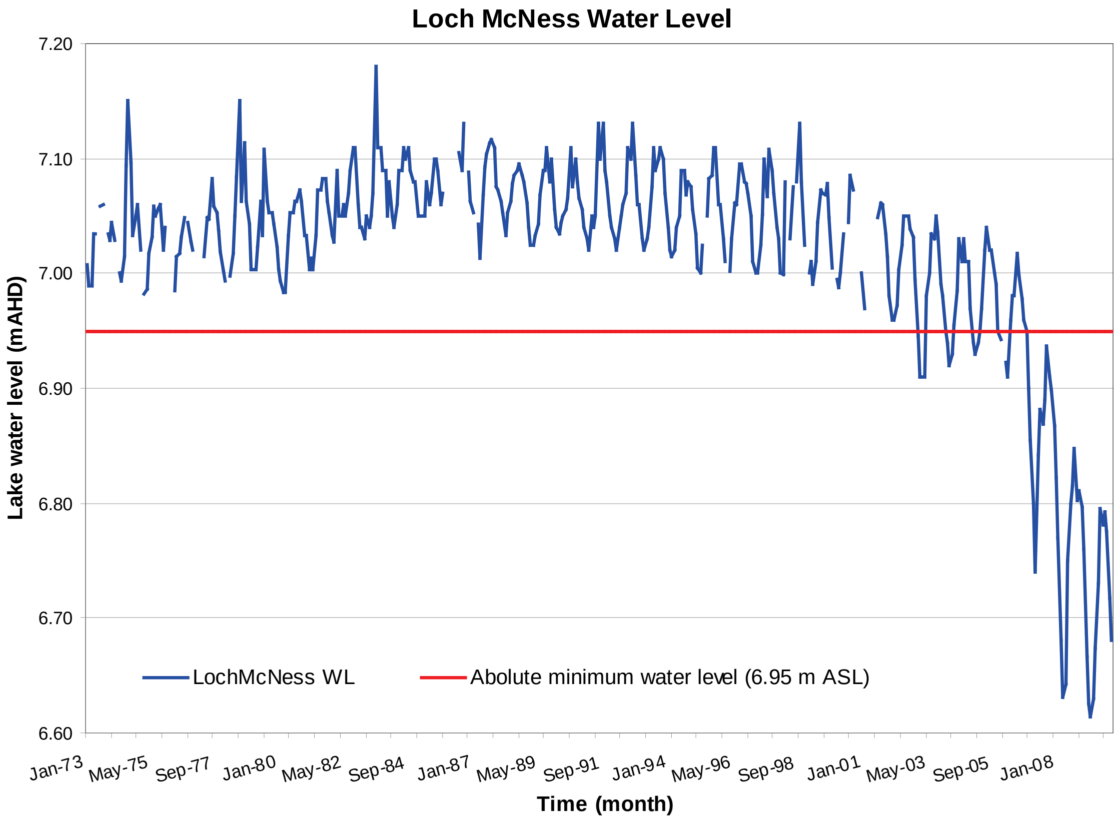


Figure 6 Water levels at Loch McNess

As can be seen from Figure 6, water Levels at Loch McNess have been declining over the last decade and have remained below the Ministerial Criteria absolute minimum level since November 2006 (followed by an unprecedented decline in water level (–0.28m) between October 2006 and March 2007). Since October 2006 A steep decline has also occurred in surface and groundwater levels for bore BH-LM2, Water Cave and to lesser extent Carpark Cave, and bore YN7 (Bekesi 2007).

Water levels recorded in 2008 were the lowest since recording began in the early 1970s, despite the higher than average rainfall experienced that year (Judd & Horwitz, 2009). In August 2008, peak winter and spring level was the lowest ever recorded (6.809 m AHD), and has since declined further. The peak water level for the two winters 2007 and 2008 failed to reach even the summer absolute minimum (6.95 m AHD). In March 2008 the wetland recorded its lowest ever level (6.631 m AHD) and in February 2009 water levels (6.650 m AHD) were already lower than those of February 2008 (6.680 m AHD). In the winter of 2008 there was less water in the lake than in any previous summer except the preceding one (Judd & Horwitz 2009).

Impacts of declining water levels on ecological values

This unprecedented rapid decline in water level suggests that regional groundwater levels up-gradient of Loch McNess have dropped below the levels required to recharge the lake (Department of Water 2008a).

In sampling round 27, one of the habitats normally sampled at this wetland was dry and did not appear to have been inundated at all in winter. Therefore, data for this wetland come from only one habitat sample. This has only happened once previously (round 17). Habitat depths in Loch McNess south are at their lowest levels (Judd & Horwitz 2009).

The decline in water levels has had a significant effect on the condition of Loch McNess and its ecological values over the last three years (Judd & Horwitz 2009, Cullinane, Wilson & Froend 2009), with the reduction in water level contributing to changes in water quality and availability in the lake and wetland which, in turn, affect the associated flora and fauna.

Although water quality in Loch McNess is still considered good (Department of Water 2008a), deterioration was been recorded in some parameters. The higher rainfall experienced in 2008 has, to some extent, reversed some of the water quality degradation recorded in 2006 and 2007, which were both unusually dry years (Judd & Horwitz 2009).

Of particular concern has been the water quality in Loch McNess north which is valued for its pristine state, where electrical conductivity, turbidity, nutrient and chlorophyll-a levels have shown increases in recent years, including some large spikes (Figures Figure 7 to 11). Algal levels in Loch McNess north have also increased significantly (Judd & Horwitz 2009). Conductivity, nutrient and chlorophyll-a levels have also shown increases in Loch McNess south in recent years (Figure 7 and Figures 9 to 11).

Although the lake is not yet showing the signs of acidification that have been detected in other Gnangara Mound wetlands, acidification may still be taking place, with the effects masked by the buffering capacity of the lake's naturally high alkalinity (Judd & Horwitz 2009).

The observed changes in water quality appear to be related to the concentration effects of lower lake levels in conjunction with the effects of surrounding land uses (pine forest and native vegetation).

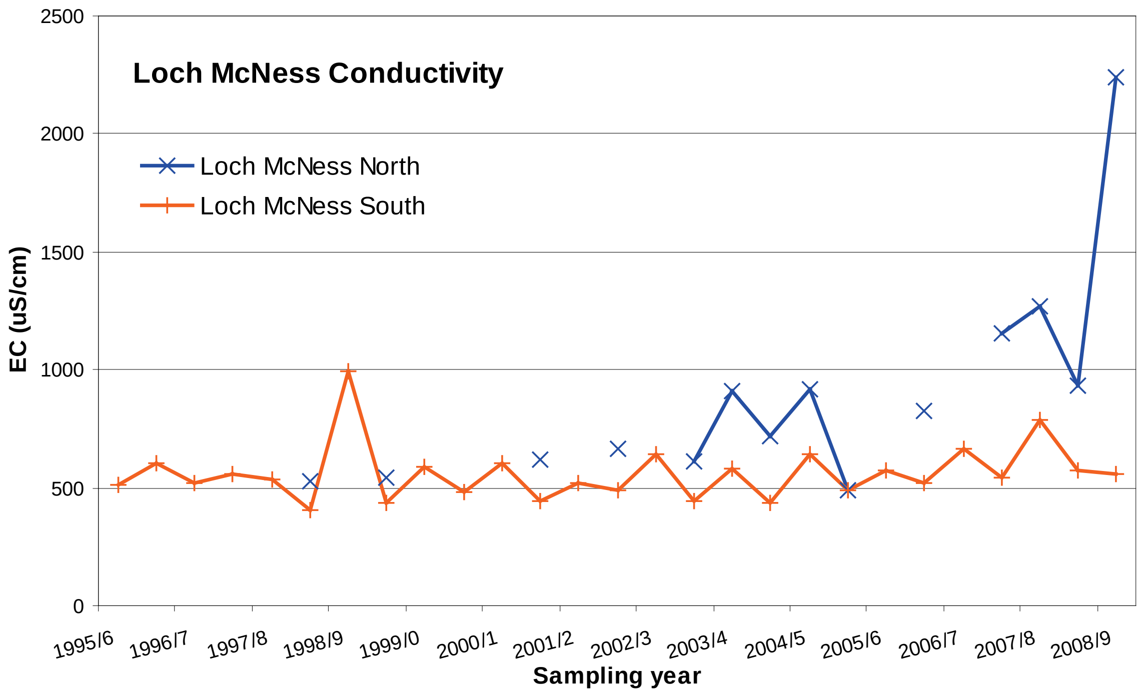


Figure 7 Electrical conductivity measurements in Loch McNess

Electrical conductivity measurements in Loch McNess show an increasing trend, with recent large spikes in Loch McNess north.

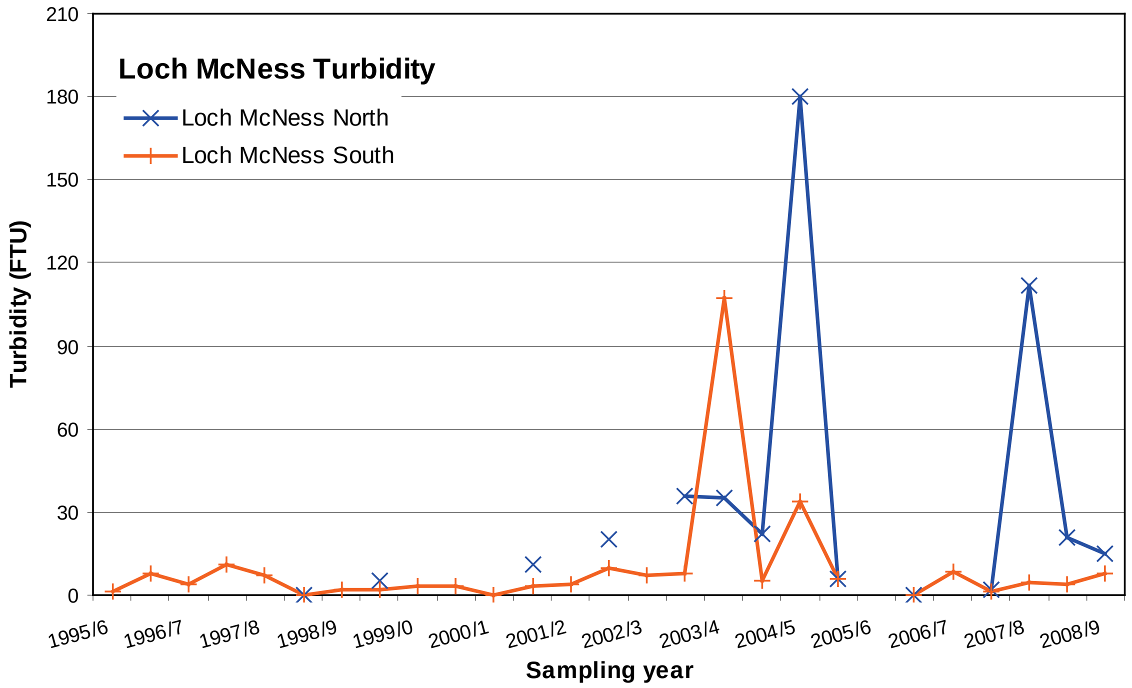


Figure 8 Turbidity levels in Loch McNess

Turbidity levels in Loch McNess are highly variable, but the frequency and magnitude of high turbidity spikes has increased as lake levels have fallen.

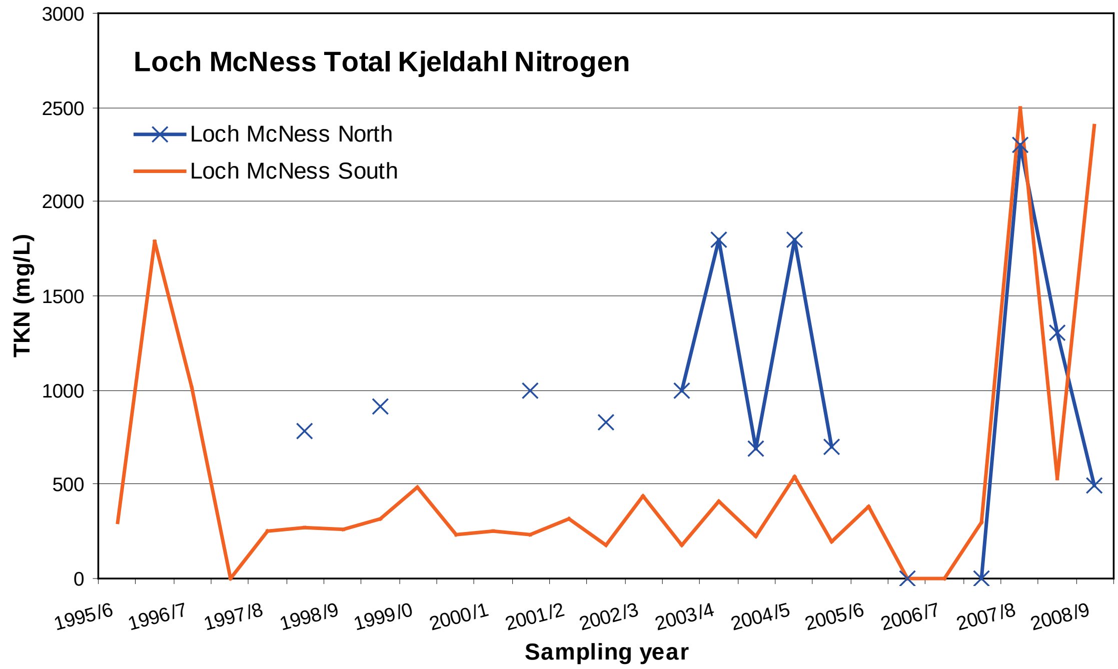


Figure 9 Total Kjeldahl nitrogen levels in Loch McNess

Total Kjeldahl Nitrogen levels in Loch McNess indicate rising nutrient concentrations at both Loch McNess north and south sites.

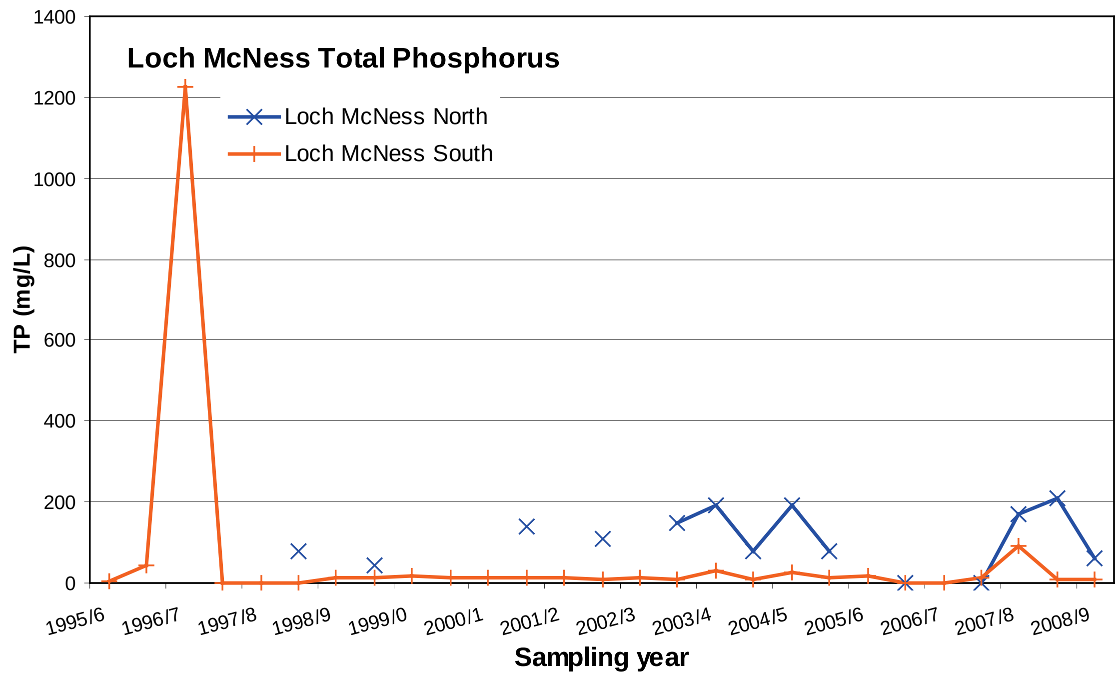


Figure 10 Total phosphorus levels in Loch McNess

Total phosphorus levels in Loch McNess are more stable than nitrogen levels however there is some evidence of an increasing trend in Loch McNess north.

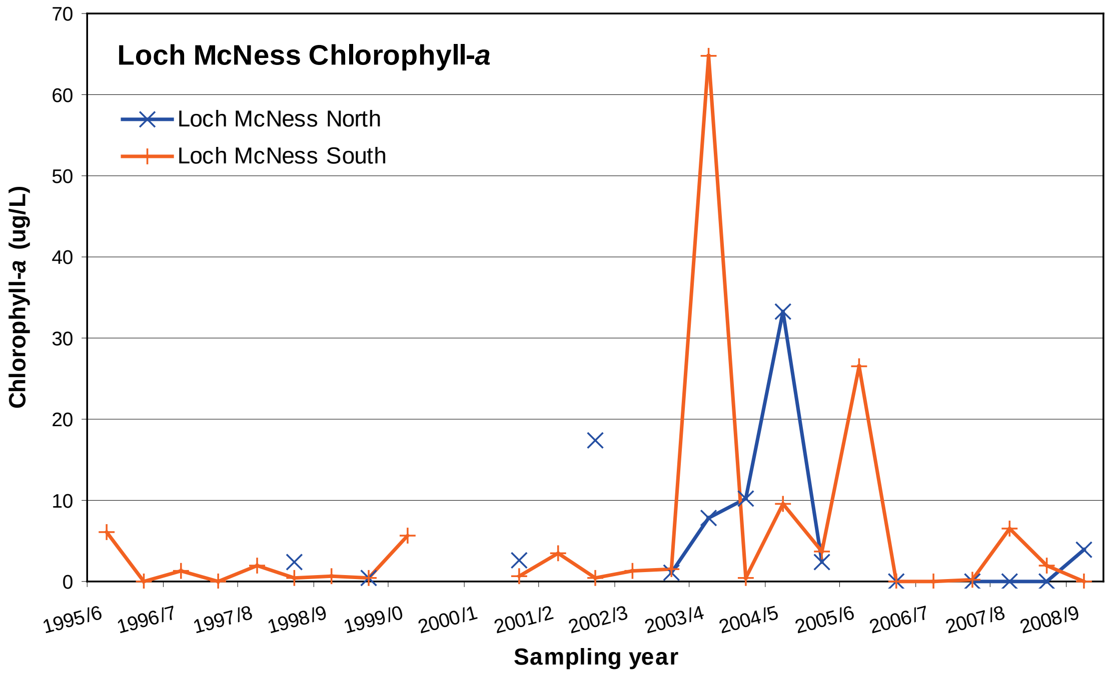


Figure 11 Chlorophyll-a concentrations for Loch McNess

Chlorophyll-a concentrations for Loch McNess have begun to show sudden spikes as lake levels decrease and nutrient concentrations increase.

Decreasing water levels have affected the macroinvertebrate community of Loch McNess which is valued for its high taxonomic richness (Department of Water 2008a). The availability of macroinvertebrate habitat has decreased, with habitats becoming shallower, with an increasing frequency and extent of drying in some areas. Overall, the taxonomic richness of macroinvertebrates is declining, with shifts in taxa assemblages occurring (Judd & Horwitz 2009).

Decreasing surface and groundwater levels have also reduced the distribution of wetland plant species, with a decrease in tree health and increase in exotic and weed species recorded from 2004 to 2006–07. Three wetland tree species (*Eucalyptus rudis, Melaleuca raphiophylla and Baumea articulata*) have shown significant shifts in their range in response to falling groundwater levels, but surveys in 2008 showed an improvement in tree health since the 2007 monitoring period. The abundance of weed species is increasing, with exotics out numbering native species at Loch McNess north (Cullinane, Wilson & Froend, 2009). There is also some evidence of terrestrialisation of wetland habitats, with woodland species replacing wetland species, along with some encroachment of infringing vegetation into the lake basin. The fire experienced in January 2005 may also have had some impact on vegetation communities (Department of Water 2008a).

Threats to ecological values

The changes described above have negatively affected the ecological values of Loch McNess. The rate of the decline in water levels since 2004 has exceeded the magnitude and rate of drawdown required to maintain a low risk of impact to the ecological values of Loch McNess (Department of Water 2008a). It is possible that, due to lag effects, the full effects of low water levels have not yet eventuated (Department of Water 2008a). Judd and Horwitz (2009) suggested that a possible threshold change in water level has already been reached in Loch McNess north, from which the system cannot recover. Further, the recent dramatic changes in groundwater level have had an effect on groundwater-dependent cave ecosystems (Department of Water 2008a).

Under the anticipated dryer climate scenario (CSIRO 2009), further declines in water level are likely. Froend et al. (2004a) anticipate further declines will result in:

- increased likelihood of poor water quality, including higher risks of eutrophication
- further reductions in habitats available for fish, macroinvertebrates and waterbirds
- drying of wetland habitats, leading to:
  - reduced plant vigour
  - shifts in plant distributions
  - changes in vegetation community composition, including increased terrestrialisation
  - increased opportunities for establishment of introduced species
  - increased susceptibility to fire
  - loss of habitat for vertebrate fauna.

They suggest a worst case scenario in which groundwater level declines affect water levels in Loch McNess sufficiently to alter the hydrologic regime of the lake, changing it to a seasonally inundated sumpland or, at worst, a seasonally waterlogged dampland. A change of this magnitude would represent the complete loss of the recognised ecological values of the lake (Froend et al. 2004a).

2.6 Cultural significance

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

Loch McNess is registered as a site of significance (DIA 3742) and reflects these Indigenous values. The level ground at the south-eastern corner of the lake was a traditional meeting, corroboree and ritual area. Central to this site was Wagardu Spring which supplied fresh water for the gatherings at Yanchep (McDonald et al. 2005).

The Nyungar people approach the issue of groundwater and surface water resources from a holistic perspective. For instance, they express the effects of water level change in spiritual terms. Just as the presence of the Waugal[1] created water related features, the declining water levels signal its disappearance. It is through the activities of this Waugal that the springs which feed the lake continue to flow (McDonald et al. 2005).

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

During the survey a stone cairn near Loch McNess was found but it was unclear as to whether it was of Aboriginal or European origin. No other archaeological sites or isolated artefacts were identified. The lack of artefacts was considered atypical. Archaeologists believe that it is likely that the site would have been used by Aboriginal people sometime in the past. Archaeologists concluded that over time soil movement, seasonal flooding, vegetation growth and ground disturbance has probably covered archaeological material. Therefore it is highly likely that ground disturbance will uncover archaeological sites and artefacts within these wetlands (Wright 2008).

2.7 Land and water management

The Gnangara Mound has been used for public and private groundwater abstraction for more than 35 years.

For the 2008–12 allocation plan, the Department of Water (*ibid.*) has used a revised variable groundwater abstraction rule to set the annual groundwater allocation for the Gnangara and Jandakot mounds. The department will review the allocation of groundwater for the integrated water supply system (IWSS) from 2012 following the commissioning of the Southern Seawater Desalination Plant. The review will be informed by the land-use and water-use recommendations of the *Gnangara sustainability strategy* (GSS), including the recommendation that the long-term total allocation should be reduced to 110 GL/year (down from 145 GL/yr for 2008–12). As such, the proposed 2012 statutory water management plan for Gnangara will review allocation limits for the Yanchep area.

In response to declining groundwater levels across the mound, the Department of Water (2009b) has developed an internal policy (Policy 4.1.1 reported in Department of Water 2009b) to limit or restrict the use of groundwater in environmentally sensitive areas. This policy informs assessments of water licence applications in areas where groundwater-dependent ecosystems are at high risk of impact from abstraction (including the Yanchep–Loch McNess area).

[1] A mythical water being.

WAWA (1995) stated that the environmental impacts of abstraction are considered to have been minor compared with those of urbanisation, agriculture and silviculture. However, since that time there has been a significant increase in abstraction. There are private licenses in the vicinity of Loch McNess, and a minor amount of abstraction for public use. Furthermore, regional groundwater levels, as well as local levels, are being affected by abstraction. Figure 13 illustrates drawpoints and allocations in the district.

The possible implications for Loch McNess of this increase in abstraction are discussed further in Section 7.

The *Gnangara groundwater areas allocation plan* (Department of Water 2009b) sets out the approach for the allocation and licensing of all water users on the Gnangara Mound. The Department of Water determines the volume and spatial distribution of water abstracted from the mound by assessing proximity to GDEs, ecological condition and rate and magnitude of groundwater level change. For allocation purposes the Gnangara Mound is divided into groundwater areas and subareas. Loch McNess is located in the proclaimed Yanchep Groundwater Area and subarea (Figure 13). Table 3 presents allocation data pertaining to the Superficial aquifer within the Yanchep Groundwater Area.

Table 3 Superficial aquifer allocation limits, licensed entitlements and water availability for new licences for the Yanchep Groundwater Area (adapted from Appendix H, Department of Water 2009)

Allocation limit	10.87 GL/a
Licensed Entitlements [1]	2.73 GL/a
Public water supply (reserved)	Yes (volume unspecified)
Water available [2,3]	Limited (unspecified)

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

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

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

Allocation limits for the Superficial aquifer are based on hydrogeological and ecological condition assessments (in addition to data on the current use and demand for the resource). Specifically, these are:

- hydrograph trend analysis
- PRAMS (water balance modelling)
- cumulative deviation from mean (CDFM) analysis
- information on groundwater-dependent ecosystems including the location and condition of environmental criteria sites.

Current and potential future land-use and water-use criteria for making allocation limit decisions are:

- reserving water for public water supply
- recognising existing water use
- allowing for water requirements to support land-use change and developments of significant public benefit
- the Department of Water's strategic direction in water management.

Land use surrounding Loch McNess is conservation including Banksia woodland. Yanchep National Park, one of Perth's most popular tourist attractions, provides important cultural, recreational and educational opportunities associated with the wetlands and cave systems. The south and west shores of Loch McNess are popular picnic areas. Significant Bush Forever sites are situated in the area. These provide ecological linkages to the Yanchep National Park (Department of Water 2009a).

Pine plantations are located across the East Yanchep subarea. During the 1990s, increasing density of pine plantations probably contributed to the decline in the watertable. WAWA (1995) reported that pine densities within the Yanchep plantation to the east of the Yanchep National Park 'are now well beyond that considered equal to native vegetation. Therefore, the pines are also now likely to be affecting groundwater levels to the east of the Park. Groundwater abstraction activities to the south of Yanchep National Park are not considered to affect water levels of Crystal Cave'.

Cognisant of pine plantation water usage, the GSS (Department of Water 2009a) recommends that a current state government approved program of pine thinning be accelerated, within the economics of existing commercial agreements. This should increase recharge to both the Superficial and Leederville aquifers and reduce the area that will experience lower groundwater levels in future. If the GSS recommendations are adopted, groundwater levels will increase after pine removal and will decline at lower rates under native vegetation if more frequent burning is feasible (*ibid.*).

3 Investigation program

3.1 Bore construction

The management area review recommended upgrading the groundwater monitoring network at Loch McNess so that hydrogeological, hydrochemical and geochemical investigations could be conducted. It was recommended that groundwater monitoring bores be installed in clusters of three, shallow (5 to 6 m of screen set at the watertable), intermediate (2 m of screen set approximately half-way through the Superficial aquifer) and deep (2 m screen set at the base of the Superficial aquifer). The clusters were positioned up-hydraulic gradient (east) and down-hydraulic gradient (west) of the lake so that both horizontal and vertical groundwater flow could be measured. The table below shows the naming system used.

Cluster	**Deep** **2 m screen set at the base of the Superficial Aquifer**	**Intermediate** **2 m of screen set approximately halfway through the Superficial Aquifer**	**Shallow** **5 to 6 m of screen set at the watertable**
Western MCN_West (down-gradient)	MCN_WA	MCN_WB	MCN_WC
Eastern MCN_East (up-gradient)	MCN_EA	MCN_EB	MCN_EC
Individual bore southern side of the lake			MCN_SWC

In addition to the eastern and western clusters, a shallow bore was placed on the southern side of the lake. Figure 12 shows the location of these bores. Figure 12 and Figure 13 show these bores and other monitoring boreholes drilled during previous investigations within the region of Loch McNess. Table 4 gives general details for the SGS project bores. These bores were installed in 2008 and the details of lithological and construction details are reported in Bourke (2008) and reproduced in Appendix C.

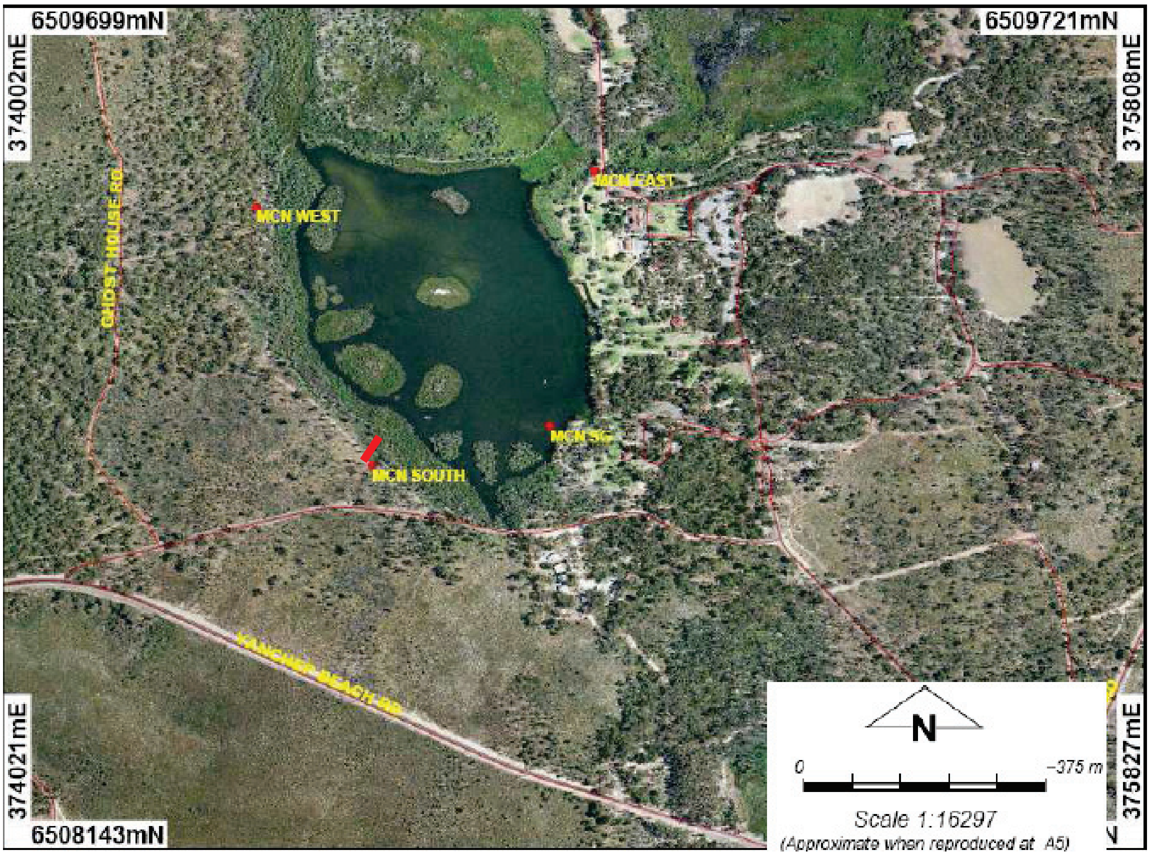


Figure 12 Location of bores used in the SGS Investigation at Loch McNess (red line shows vegetation transect)

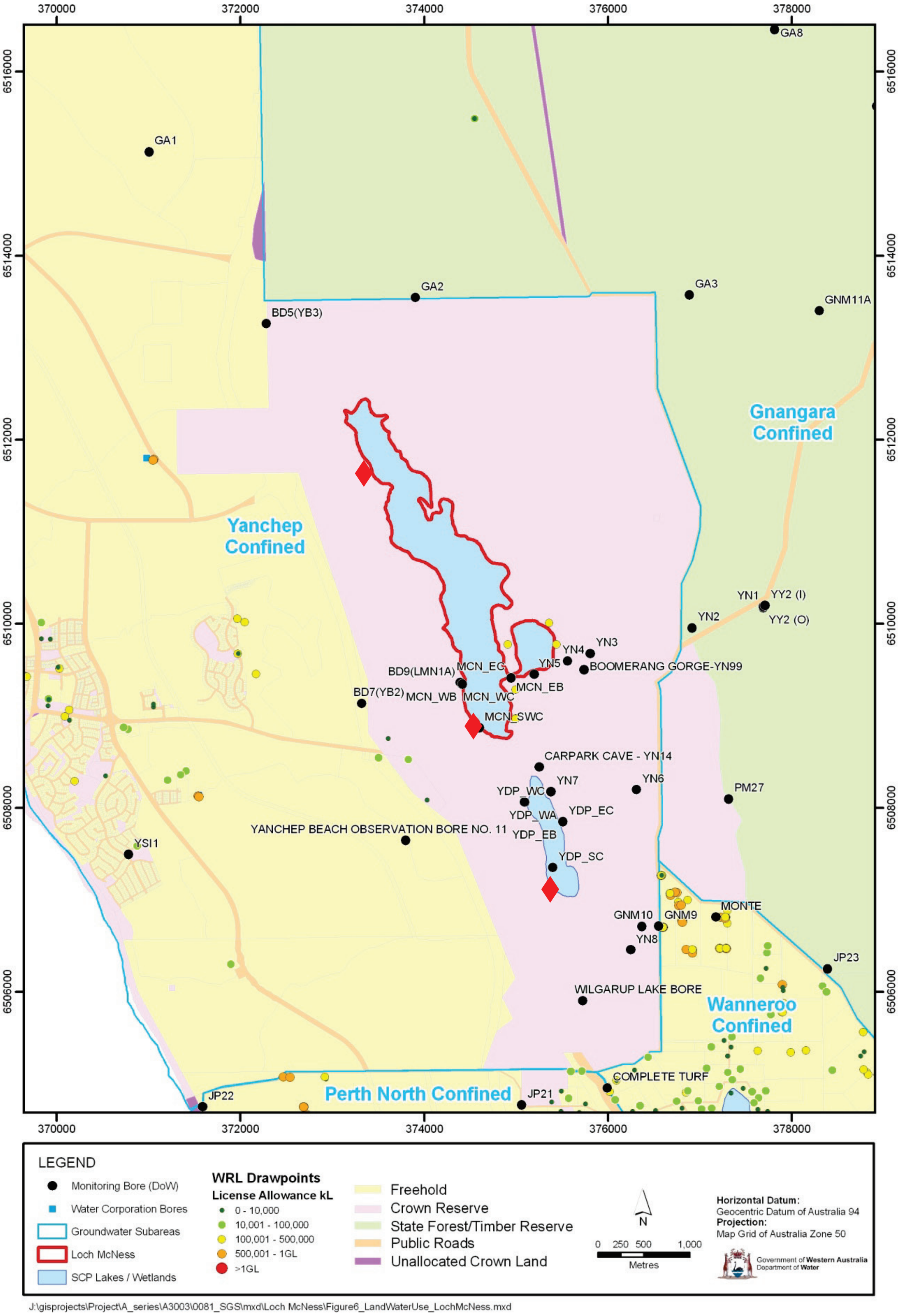


Figure 13 Bore locations in the region of Loch McNess (red diamonds indicate vegetation transects)

Shallow bores were installed using a Geoprobe 7720DT track mounted push core rig, which provided continuous core samples to depth. Intermediate and deep bores were installed using a GSD77 Aircore drill rig, with aggregate samples of drill cuttings collected every metre to depth. A Roto Sonic EP 26 rig was also used for some holes. This method provides a continuous uncontaminated sample and can drill to depths of around 40 m.

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

Table 4 Bores involved in the SGS investigation at Loch McNess

Bore cluster at the eastern site Loch Mc Ness (MCN_E)

Depth	AWRC name	AWRC number	Drilled depth mBNS	Screen interval mBNS
Deep	MCN_EA	61611845	39.0	34.2–36.2
Intermediate	MCN_EB	61611846	23.5	21.5–23.5
Shallow	MCN_EC	61611847	6.0	0.8–5.8

Bore cluster at the western site Loch Mc Ness MCN_W

Depth	AWRC name	AWRC number	Drilled depth mBNS	Screen interval mBNS
Deep	MCN_WA	61611841	49.0	39.6–41.6
Intermediate	MCN_WB	61611842	28.2	26.2–28.2
Shallow	MCN_WC	61611843	11.4	5.4 – 11.4

Bore at the southern site Loch Mc Ness MCN_SW

Depth	AWRC name	AWRC number	Drilled depth mBNS	Screen interval mBNS
Shallow	MCN_SWC	61611844	6.1	1.1–6.1

Other bores within the region

AWRC name	AWRC number	Drilled depth mBNS	Screen interval mBNS
YN3	61612102	32.9	27.1 – 33.1
YN5	61612104	8.8	2.9 – 8.9
BD7	61710025	N/A	N/A
BD9	61710028	N/A	N/A

3.2 Acid sulfate soils testing

To determine the distribution and characteristics of sulfidic sediments in Loch McNess and the potential of these to affect groundwater quality, a study was conducted as part of the SGS investigation. Samples were collected and analysed for potential and actual acid sulfate soils according to the Department of Environment's *Draft Investigation and Identification of acid sulfate soils guide* (2006) (see Appendix B for the full methods).

Field and laboratory tests were conducted on sediment recovered during drilling from SGS bores MCN_EC and MCN_WC during bore construction. No lake bed sediments were sampled.

Further laboratory testing was conducted for net acidity by the National Measurement Institute (NMI). Samples were stored in such a way as to limit air entering into the samples and were refrigerated until delivery at the laboratory. Samples were taken to the laboratory either the same day they were extracted from the ground, or the following day. The laboratory used the CRS (chromium reducible sulfur) suite as well as the SPOCAS suite of analyses to conduct acid–base accounting (see Appendix B for laboratory methods).

3.3 Water monitoring and sampling program

Lake water and groundwater samples were analysed determine the hydrochemical characteristics of each site, the distribution and availability of potential pollutants and the interaction between the wetland and the Superficial aquifer.

Water samples were collected using low flow pumping methods as explained in Appendix B. Analyses of water samples were conducted for major ions, metals, nutrients and a number of herbicides and pesticides. Figure 14 is a cross-section showing the location and depth of groundwater bore clusters used for monitoring the Loch McNess groundwater system.

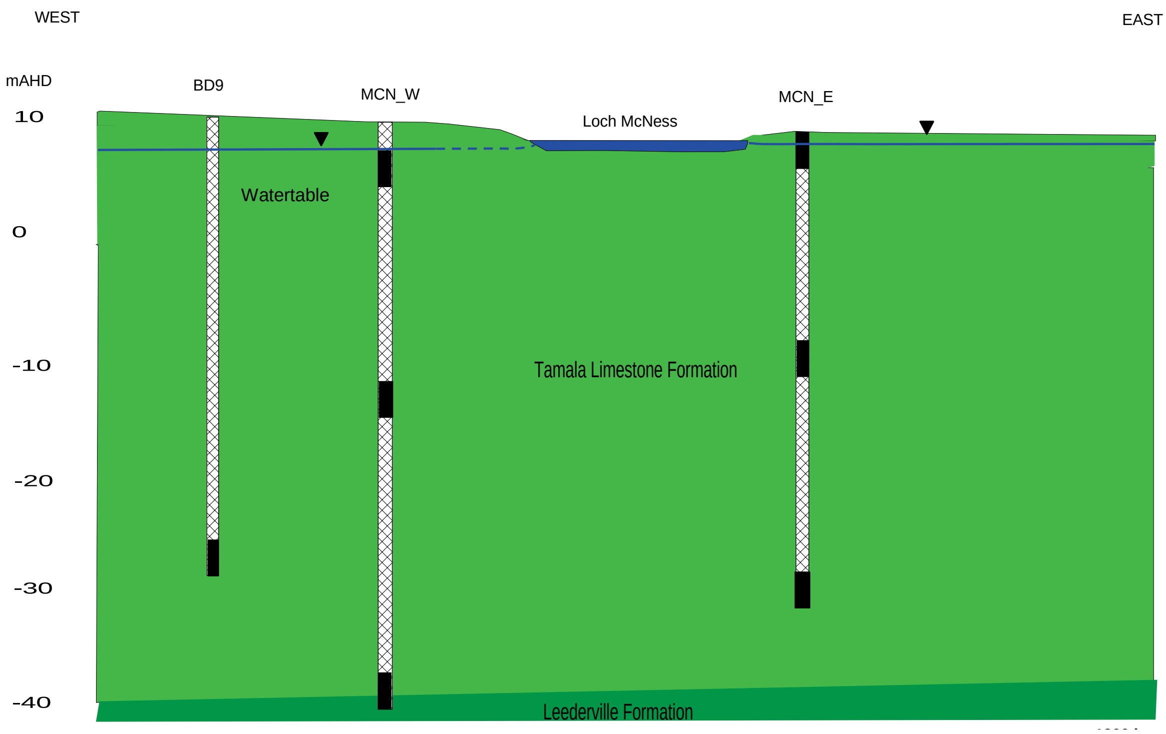


Figure 14 Location of bores used for sampling and monitoring

3.4 Data accuracy and precision

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

$$\text{Electrical balance (EB, \%)} = \frac{(\text{Sum cations} + \text{Sum anions})}{(\text{Sum cations - Sum anions})} \times 100$$

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

Deviations of more than 5% signal that sampling and analytical procedures should be examined (Appelo & Postma 2007). For the SGS Investigation, if the E.B was greater than 6%, without satisfactory explanation, then this sample was left out of the analysis.

Comparing the pH measured in the laboratory with that measured in the field immediately after sampling can indicate that a water sample has been altered by the collection, transport or storage processes. There are many possible reasons for a difference between field and laboratory pH reading (and for other 'unstable' determinants such as dissolved oxygen and reduction potential), including reactions involving oxidation, precipitation and release of dissolved gas. Only on-site analyses for pH, temperature, dissolved oxygen and reduction potential were used in the data analysis reported below to avoid introducing uncertainties, as recommended in state and national groundwater sampling procedures.

3.5 Data presentation and interpretation

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

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

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

4 Geology

4.1 Superficial and Mesozoic formations

Borehole logs for the deep bores, MCN_EA and MCN_WA (Table 5 and Figure 15) show that the depth to the superficial formation's sands and calcarenites is 37 m and 48 m respectively. The location of the bores is shown in Figure 12 and Figure 13.

The bore logs indicate that the Tamala Limestone consists of stratified silty sands, sands and lesser limestones in the region of Loch McNess. There is no obvious correlation of strata in either deep bores MCN_EA and MCN_WA located on the eastern and western sides of the lake respectively. Limestones are observed only at 34 to 36 m depth in MCN_EA, whilst the upper 7m in the down-gradient bore MCN_WA were recorded as limestones (see Figure 15).

Part of the lower 6 m of the superficial sediments, including sediments shown as limestones, were assigned to the Ascot Formation in bore MCN_EA, but mostly the superficial sediments were silty sands and sands of the Tamala Limestone.

Superficial sediments in bore MCN_EA were reported to be underlain by siltstones and mudstones of the Lancelin Formation, although Davidson (1995) shows Loch McNess to be close to the eastern edge of the area underlain by Lancelin Formation. It is possible that these are sediments of the Pinjar Member of the Leederville Formation, as the lithology more closely conforms to this Formation. In any case, if Lancelin Formation is present it is likely to be thin, and underlain by Pinjar Member mudstones or siltstones and sandstones.

In bore MCN_WA the Tamala Limestone was reported to be underlain by pyritic sandstone of the Leederville Formation (probably Pinjar Member). A bore drilled in 2004 near the CALM station on Yanchep Beach Road, approximately 1 km west of Loch McNess (Water Corporation 2004) found 22 m of sands and calcarenite underlain by black clay and sands or silts which was interpreted as Leederville Formation, conforming closely to the description of the Pinjar Member. As indicated above, the Pinjar Member is reported to be 50 m thick in the vicinity of Loch McNess (Davidson 1995).

Table 5 Borehole logs for deep MCN bores drilled as part of the SGS project

Bore ID	From	To	Formation	Code	Lithology
MCN_EA	0	2	Tamala Limestone	Qt	Sand
	2	3	Tamala Limestone	Qt	Silty sand
	3	9	Tamala Limestone	Qt	Silty sand
	9	17	Tamala Limestone	Qt	Silty sand
	17	33	Tamala Limestone	Qt	Silty sand
	33	36	Ascot Formation	Qt	Limestone
	36	37	Ascot Formation	Qt	Sandy silt
	37	39	Lancelin Formation	Kcl	Siltstone/mudstone
MCN_WA	0	1	Tamala Limestone	Qt	Topsoil, sand and limestone
	1	4	Tamala Limestone	Qt	Limestone
	4	5	Tamala Limestone	Qt	Soil and limestone
	5	6	Tamala Limestone	Qt	Soil and limestone
	6	7	Tamala Limestone	Qt	Limestone
	7	9	Tamala Limestone	Qt	Silty sand
	9	13	Tamala Limestone	Qt	Silty sand
	13	18	Tamala Limestone	Qt	Silty sand
	18	24	Tamala Limestone	Qt	Sand
	24	29	Tamala Limestone	Qt	Sand
	29	31	Tamala Limestone	Qt	Sand
	31	32	Tamala Limestone	Qt	Sand
	32	38	Tamala Limestone	Qt	Silty sand
	38	39	Tamala Limestone	Qt	Silt and silty sand
	39	48	Tamala Limestone	Qt	Sand
	48	49	Leederville Formation	Kwl	Pyritic sandstone

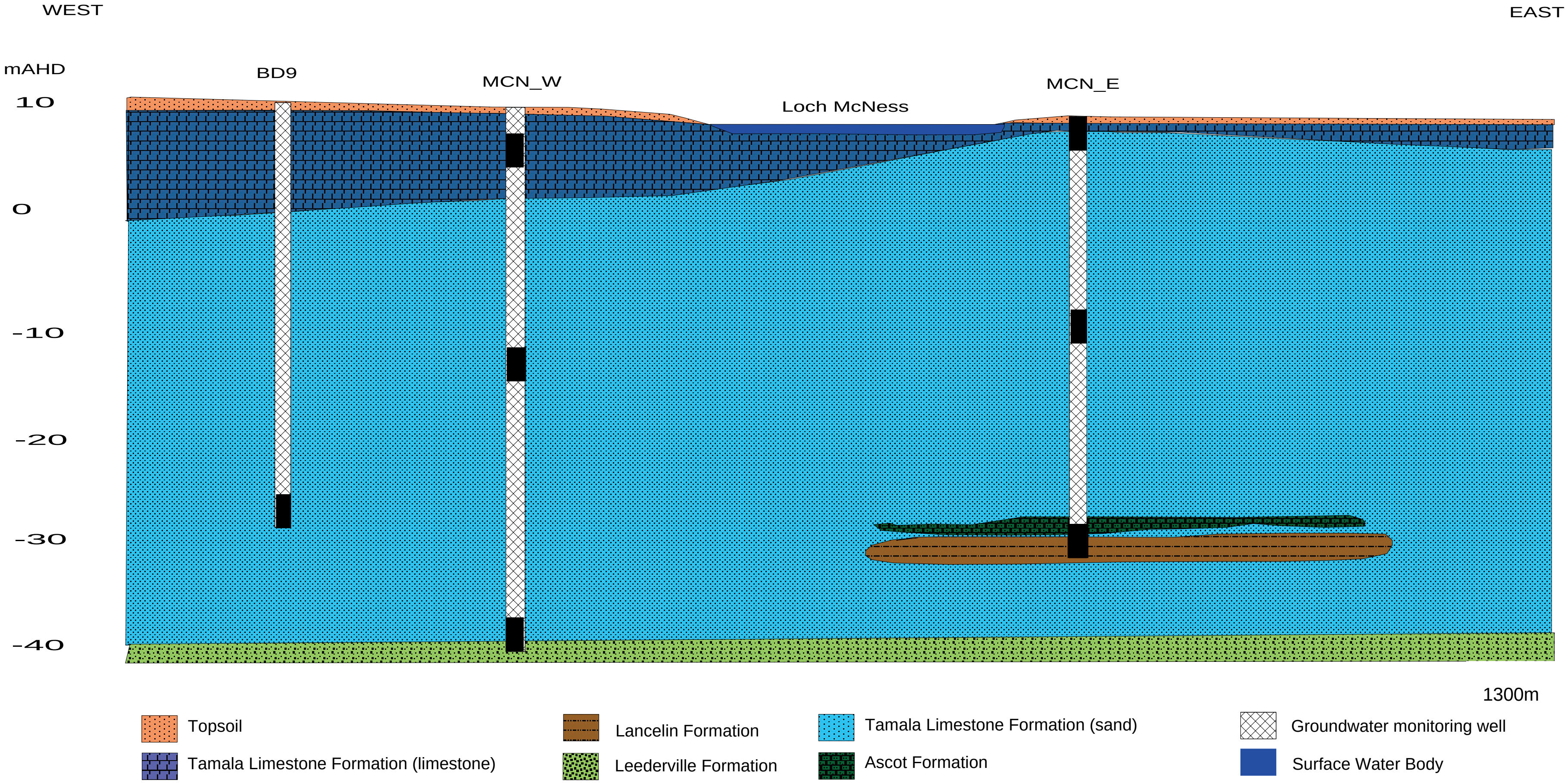


Figure 15 Geological cross-section at Loch McNess

4.2 Lake deposits

Loch McNess possibly infills a collapsed doline and has thick sediment on its floor that consists of chemogenic and biogenic lake deposits of sandy peat and diatomite. It is known to have been partly dredged in the mid 1980s (Rockwater 2003).

No further information appears to be available describing these deposits.

4.3 Acid sulfate soils

Lake perimeter

Field and laboratory testing was carried out on two sediment cores retrieved from Loch McNess. The cores were from bores MCN_EC and MCN_SWC. Laboratory analyses were conducted on 7 samples including one duplicate (MCN_EC (Duplicate)) to check the accuracy of the field results and provide better information for acid–base accounting. Full laboratory results are presented in Appendix D.

Samples analysed in the field exhibited pH_F and pH_{FOX} indicative of both actual and potential acid sulfate soils. Sediment at a depth of 1.9m from MCN_SWC had a pH_F of 2.89 indicating actual acid sulfate soils. The pH_F levels at MCN_EC were all above 7. The pH_{FOX} at MCN_SWC was below 3 at depths 1.9–2.6, 4.2–5.4 and 7.2–8.8 m indicating potential acid sulfate soils. pH_{FOX} was above 5 in sediments that were logged as containing quartz. The pH_{FOX} results from MCN_EC showed pH drops greater than two from pH_F indicating potential acid sulfate soils.

Three samples taken from MCN_SWC reported pH_{KCl} results at less than 6.5 (pH_{KCl} 3.1, 5.3 and 6.1). Of the three samples, two (reported at pH_{KCl} 3.1 and 6.1) exceed the net acidity action criteria of 18.7 $molH^+/t$ at 53 $molH^+/t$ and 101 $molH^+/t$, respectively (Table 6).

At MCN_EC, laboratory pH_{OX} results (Table 6) reported pH range from 8.1 to 8.6, whereas the field pH_{FOX} results (Figure 18) indicated that the pH of the soils were between 4.77 and 6.23. Results for MCN_SWC recorded pH_{FOX} ranging from 2.05 to 6.35 (Figure 17), and the pH_{OX} ranging from 2.5 to 3.6 (Table 6). It is possible that samples undergoing oxidisation prior to the laboratory analyses may have contributed to the variations between the field and laboratory pH results.

Note that the laboratory pH_{OX} results do not have reported depths and therefore, were not plotted in Figures 17 and 18.

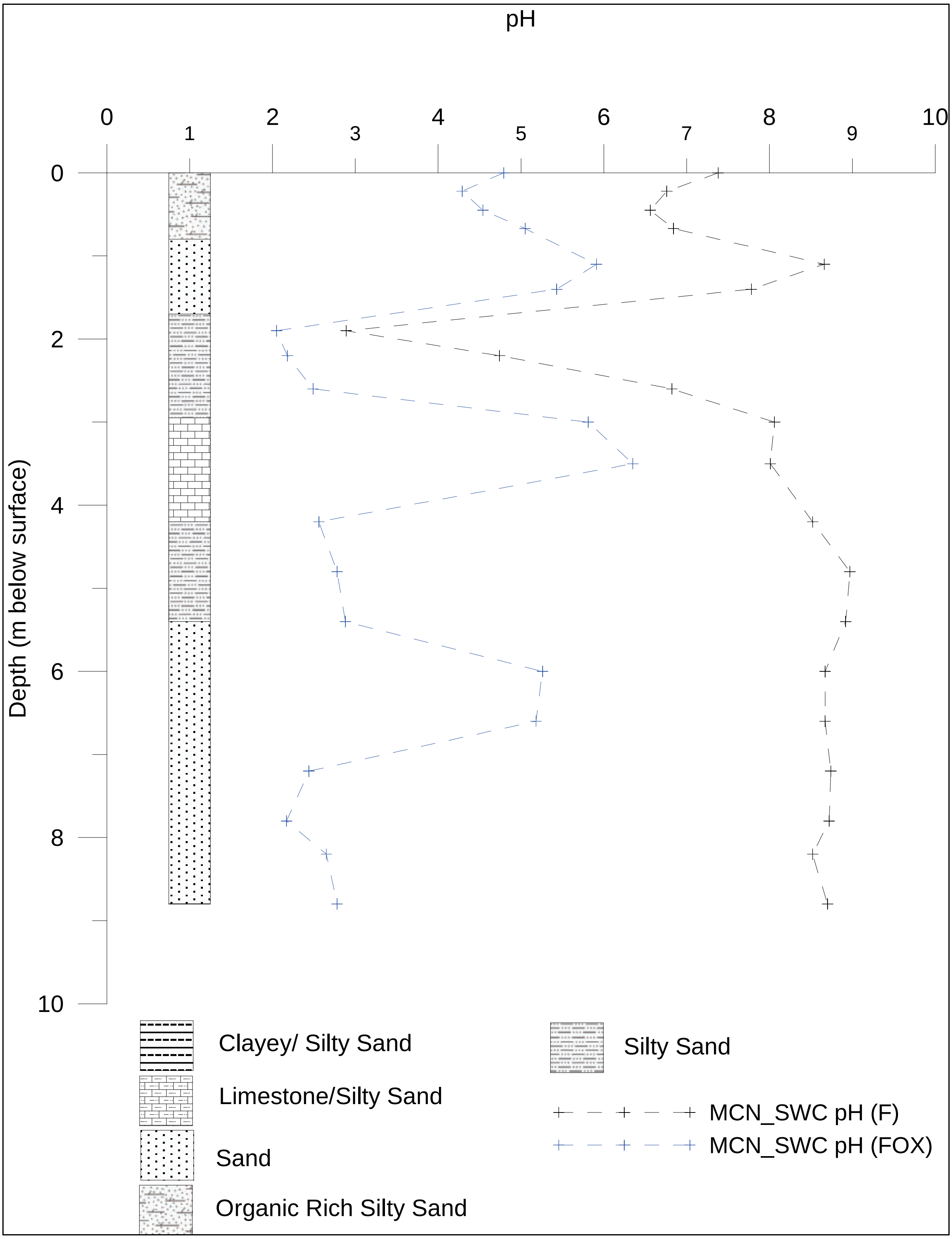


Figure 16 Natural and oxidised field pH measurements correlated with lithological units for MCN_SWC

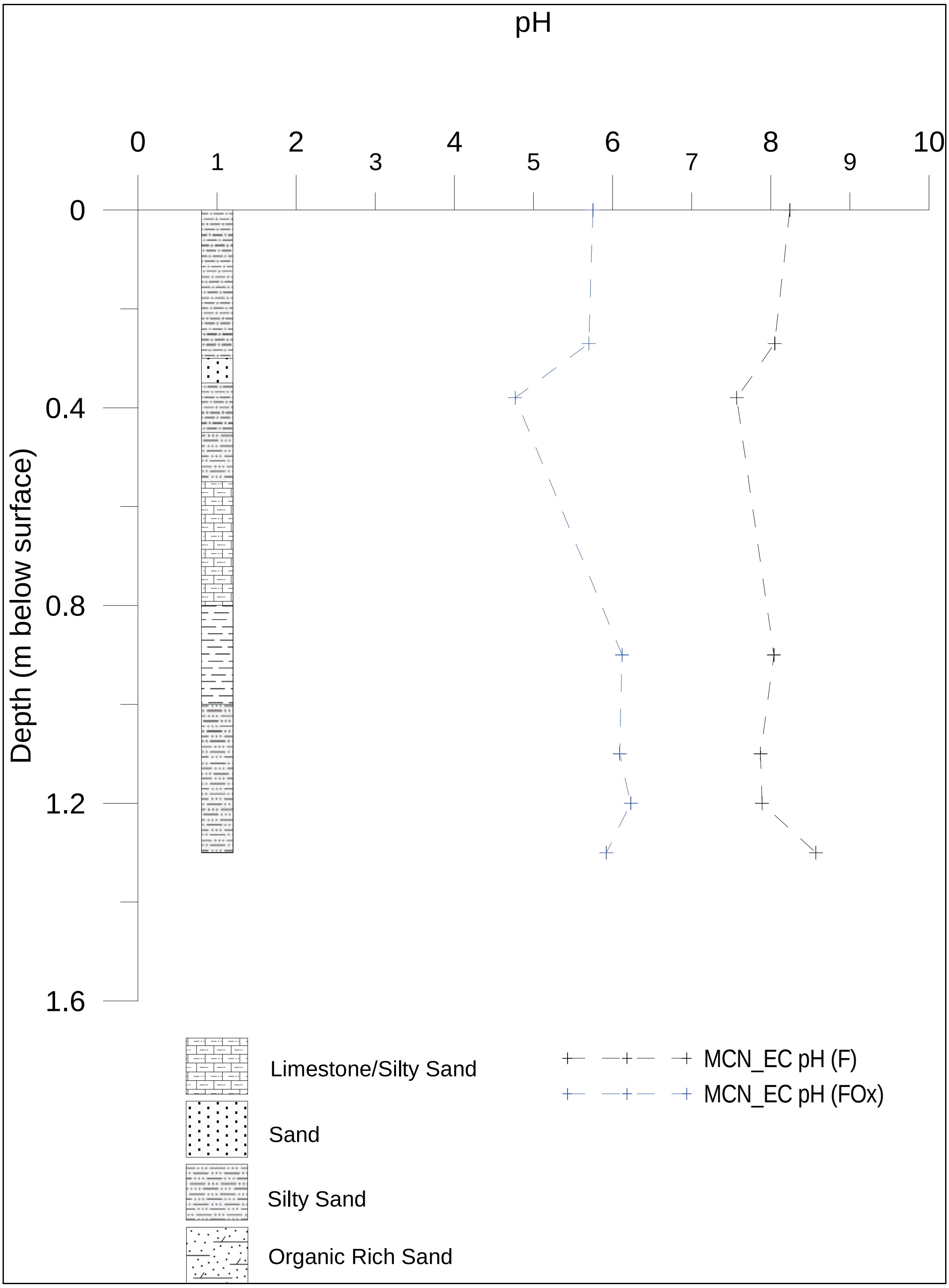


Figure 17 Natural and oxidised field pH measurements correlated with lithological units for MCN_EC

The laboratory analyses 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:

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

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

- actual acidity is the soluble and exchangeable acidity already present in the soil
- potential sulfidic acidity is latent acidity that will be released if the sulfide minerals in acid sulfate soils are fully oxidised
- retained acidity is the 'less available' fraction of the existing acidity which may be released slowly into the environment
- acid neutralising capacity (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.

Laboratory results for the superficial sediments at the MCN_SWC site showed no retained acidity or acid neutralising capacity (Table 6). In this case, the formula for ABA for these samples becomes:

$$\text{Net acidity} = \text{potential sulfidic acidity (Scr or Spos)} + \text{actual acidity (TAA)}$$

Sediments with a net acidity of 18.7 mol H+/t (0.03% sulfur) or greater for either chromium and SPOCAS ABA methods are considered an acidification risk and require careful management to prevent oxidation and/or ameliorate any current acidity (Department of Environment 2006).

Net acidity at MCN_SWC ranged from 1.0 to 101 molH^+/t (Table 6). The SPOCAS method reported net acidity for one of 7 samples being above the action criteria set by the Department of Environment (18.7 molH^+/t), whereas the chromium ABA method showed two samples to exceed the action criteria. No samples from MCN_EC exceeded 18.7 molH^+/t. Due to the discrepancy between the two ABA methods, Ahern et. al. (2004) suggests that the chromium ABA results take precedence over the SPOCAS ABA results in this investigation as the chromium method is not subject to any interferences from sulfur in organic matter or other sulfate minerals present (Department of Environment 2006).

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

Site ID	pH_{KCl}	pH_{OX}	Acid neutralising capacity $\%CaCO_3$		Potential acidity% S[1]		Actual acidity molH+/t)		Net acidity molH+/t)	
			Spos	Scr	Spos	Scr	SPOCAS	Scr	SPOCAS	Scr
MCN_EC	9.2	8.1	NA	2.4	NA	<0.01	<1	<1	-102	0.00
MCN_EC	9.3	8.6	NA	13.00	NA	<0.01	<1	<1	-555	0.00
MCN_EC (Duplicate)	9.4	8.5	NA	13.00	NA	<0.01	<1	<1	-555	0.00
MCN_SWC	3.1	2.9	NA	NA	<0.01	<0.01	53	53	53	53.00
MCN_SWC	5.3	2.7	NA	NA	NA	0.01	3	3	3	9.00
MCN_SWC	6.1	2.5	NA	NA	NA	0.16	1	1	1	101.00
MCN_SWC	8.2	3.6	NA	NA	NA	0.02	<1	<1	5	12.00

Note: Laboratory results did not have reported depths so they were not included.

NA: Not analysed.

[1] Laboratory results for potential acidity were reported in %S only, not $molH^+/t$.

Acid neutralising capacity values were recorded in all samples at MCN_EC indicating that the sediments have an inherent buffering capacity. Buffering is likely to be provided by carbonate minerals, given the presence of limestone in the region of the lake.

Because bore MCN_SWC reported pH_{KCl} results lower than 6.5, the ANC was not measured (Ahern et. al., 2004). Hence it is not possible to compare its acid neutralising capacity with that of bore MCN_EC.

Given the low net acidity values and buffering capacity of the sediments recorded from MCN_EC, which was located up-gradient of the lake, it is likely that groundwater discharge would have a negligible impact on the pH of the lake. Although one sample from MCN_SWC exceeded the action criteria (Department of Environment 2006) for both chromium and SPOCAS ABA methods, groundwater in this locality is unlikely to discharge into the lake and hence would have no impact on lake pH.

The ABA analyses indicate that the superficial sediments towards the east of the lake are sufficiently buffered, presumably by carbonate minerals given the presence of limestone in the region of the lake.

Acid sulfate soil testing was not carried out on lake sediments which could have potential acid sulfate soil characteristics, although the sediments may also have significant acid neutralising capacity which would ameliorate any impacts of sulfide mineral oxidation as the lake sediments become exposed to oxygen as lake levels drop. In order to assess possible sulfide oxidation within the lake sediments, $Cl^-:SO_4^{2-}$ ratios in up-gradient (east) and down-gradient (west) groundwater and lake water have been plotted in Figure 18 and Figure 19. These have been compared with the average $Cl^-:SO_4^{2-}$- ratio of seawater (which is 7.2) which would be expected to be typical for groundwater recharge unaffected by chemical reaction within the Superficial Aquifer.

Figure 18 shows that the shallow sediments towards the south-west and east have excess sulfur present as indicated by the $Cl^-:SO_4^{-2}$ falling below the seawater line of 7.2. They are generally less than 4.0 indicating that oxidation is occurring at the site. Figure 19 shows that MCN_WA and MCN_WB have $Cl^-:SO_4^{-2}$ ratios which vary seasonally. They are less than 4 during June 2008, which may be due to the fluctuations in the watertable[2].

[2] $Cl^-:SO_4^{-2}$ ratio was used instead of $SO_4^{-2}:Cl^-$ according to assessment guidelines by Ahern et.al. (2004) for excess sulfur content in groundwater to be compared to that of seawater, in order verify whether sulfides in the area have undergone oxidation at some point.

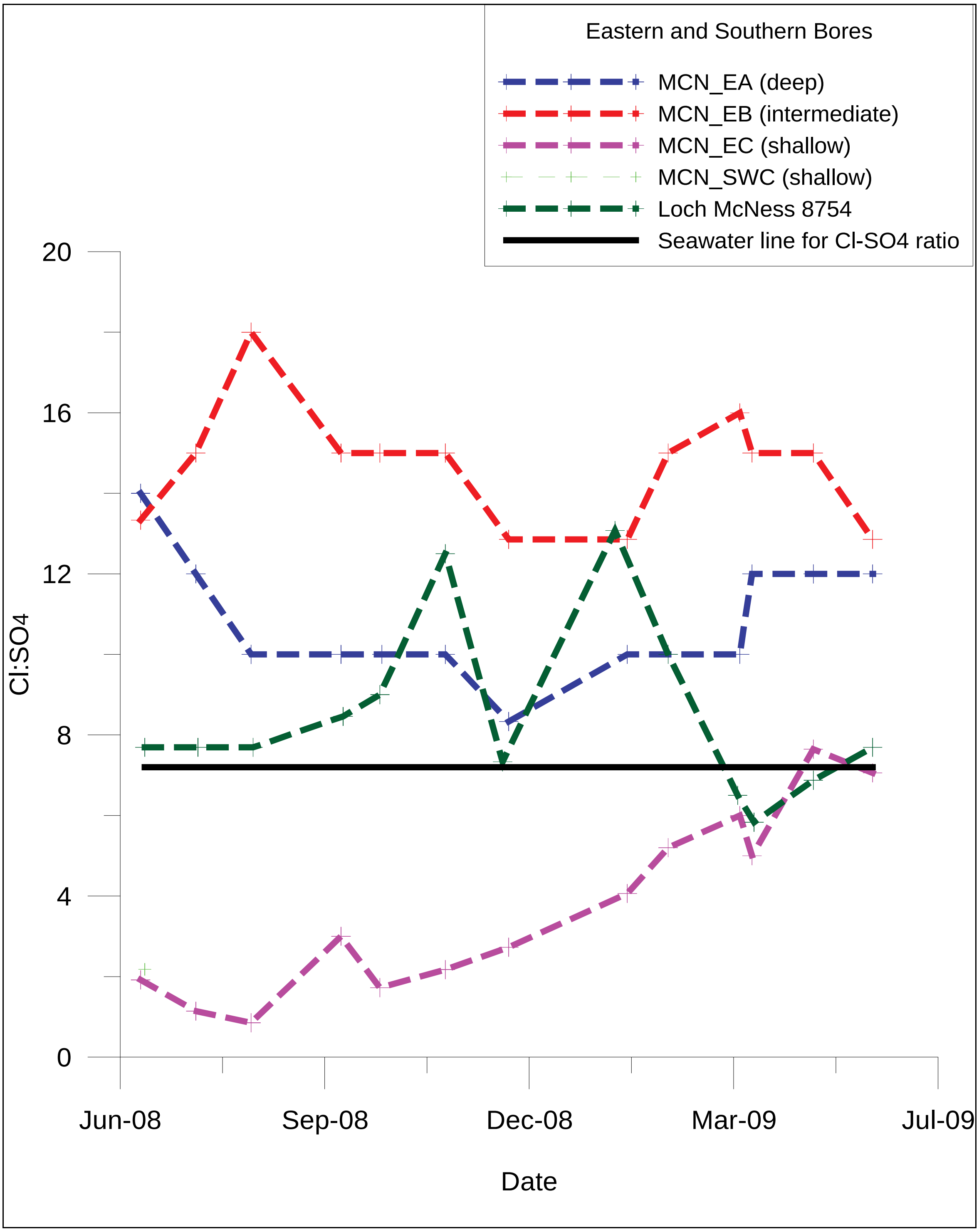


Figure 18 $Cl^{-}:SO_4^{-2}$ ratio plot for the eastern and southern bores at Loch McNess

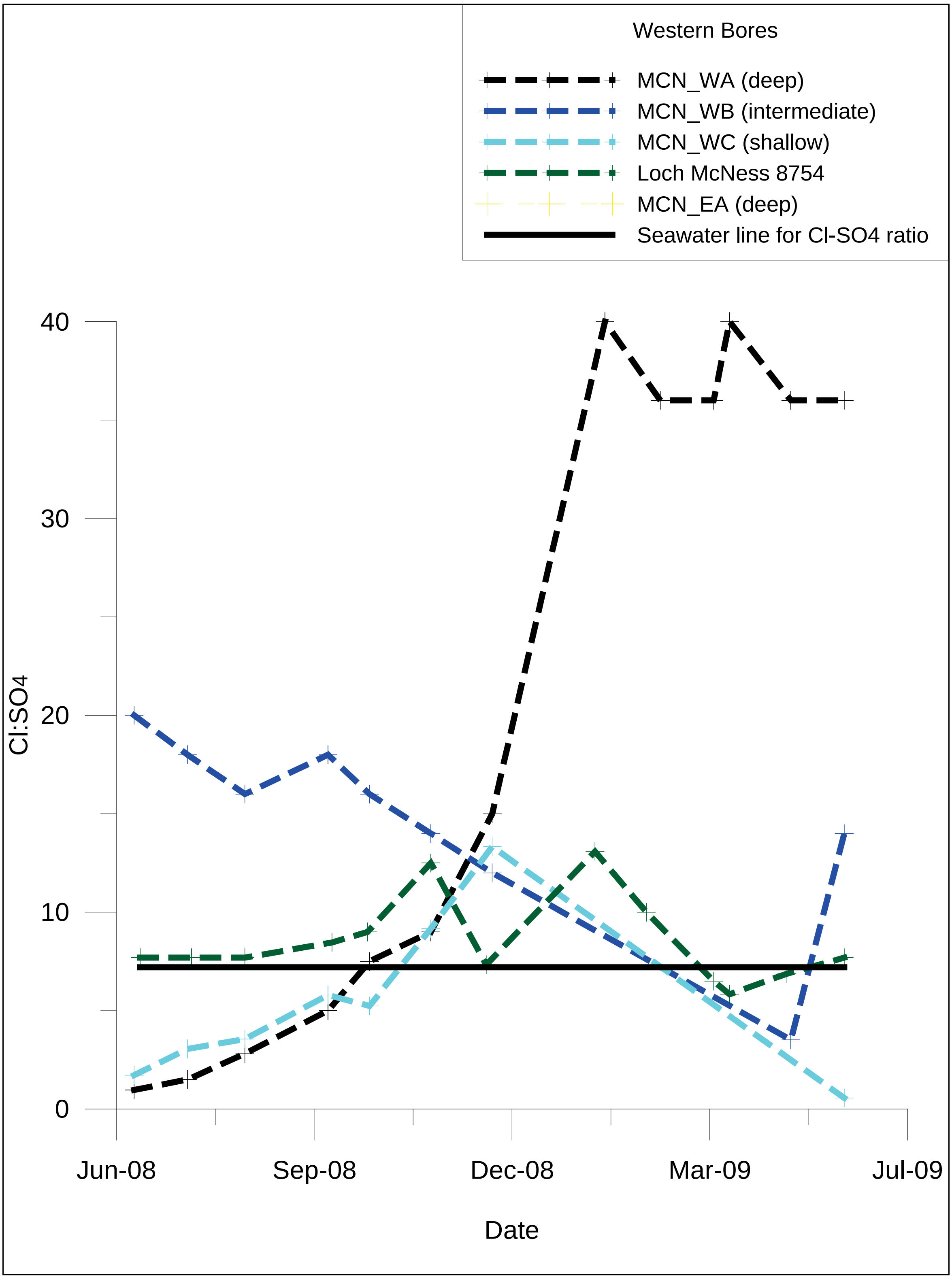


Figure 19 *Cl^-:SO_4^{-2} ratio plot for the western bores at Loch McNess*

Core samples from the Superficial aquifer were analysed for metals, metalloids and selenium concentrations (Table 7) using the analytical method NT2_49.

Samples analysed for metals were correlated with ‘ecological investigation levels’ (Department of Environment 2006) to determine whether they pose a risk to groundwater and the environment at Loch McNess.

The laboratory results showed that metal concentrations in all sediment samples were below the ecological investigation levels (Table 7). Cadmium and selenium concentrations were below the detection limits in all samples, though one of the MCN_SWC samples had chromium concentration levels only slightly below the guidelines.

Table 7 Heavy metal concentrations in MCN_EC and MCN_SWC compared with ecological investigation levels

Site ref no.	**Al mg/kg**	**As mg/kg**	**Cd mg/kg**	**Cr mg/kg**	**Fe mg/kg**	**Mn mg/kg**	**Ni mg/kg**	**Se mg/kg**	**Zn mg/kg**	**Total solids %**
MCN_EC	3200	3.1	<0.5	17	3000	10.0	1.3	<0.05	2.4	93.9
MCN_EC	2000	5.5	<0.5	12	2600	14.0	1.0	<0.05	0.5	80.3
MCN_SWC	2800	3	<0.5	22	2400	3.0	0.86	<0.5	0.68	92.1
MCN_SWC	3600	2.4	<0.5	31	2700	3.8	2.0	<0.5	0.95	88.4
MCN_SWC	2400	4.6	<0.5	41	3900	2.5	1.0	<0.5	1.0	90.7
MCN_SWC	1300	<0.5	<0.5	14	8700	1.0	<0.5	<0.5	<0.5	87.5
Ecological investigation level	NA	20	3	50	NA	500	60	NA	200	NA

Note: Laboratory results did not have reported depths so they were not included.

NA: Not analysed.

High concentrations of sulfur (S_{cr} and S_{pos}) do not appear to correlate with high concentrations of aluminium and iron (Figure 20 and Figure 21). The other metals do not appear to be associated with sulfur content either.

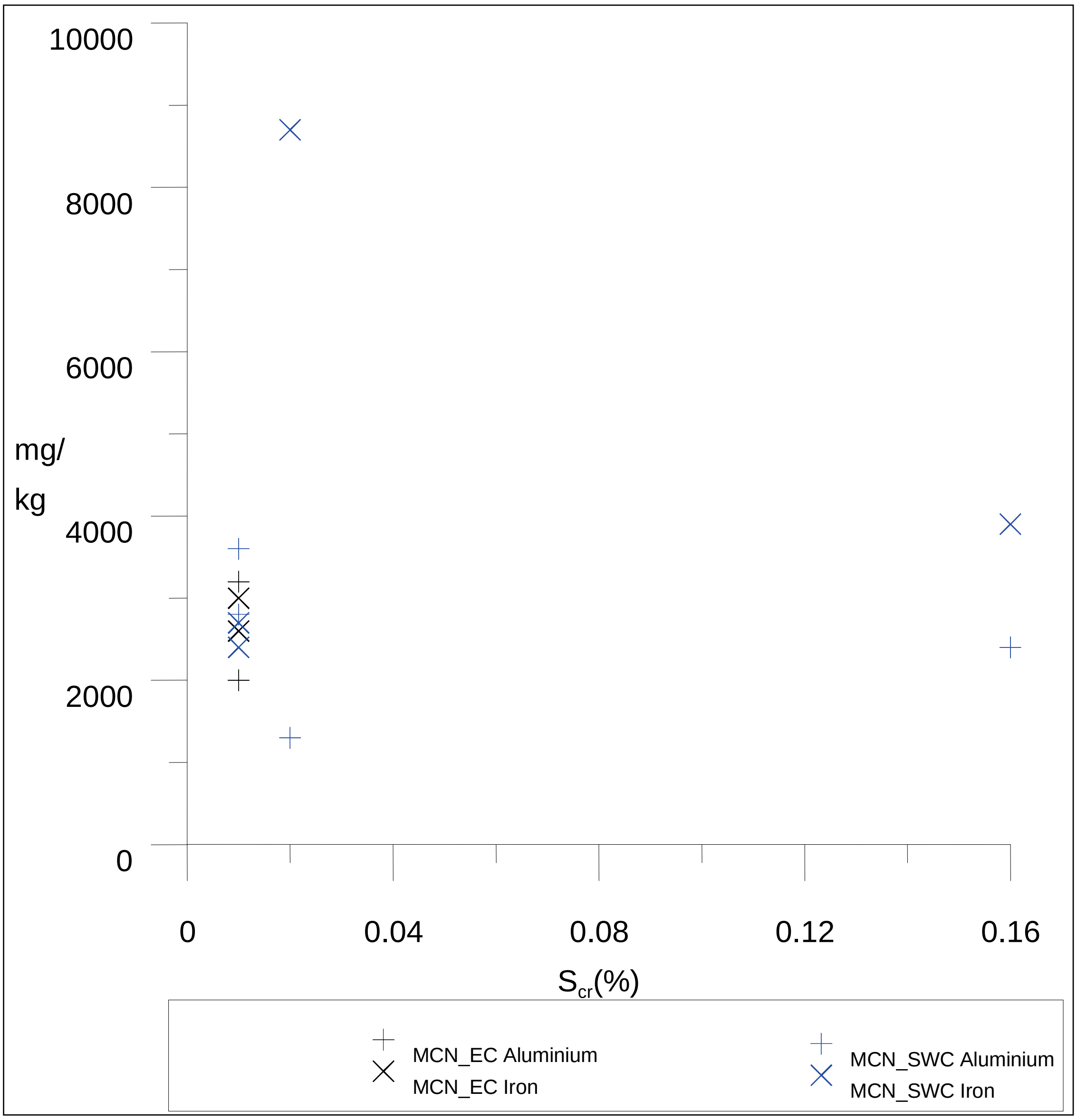


Figure 20 Plot showing the relationship between aluminium, iron and sulfur in sediments at Loch McNess

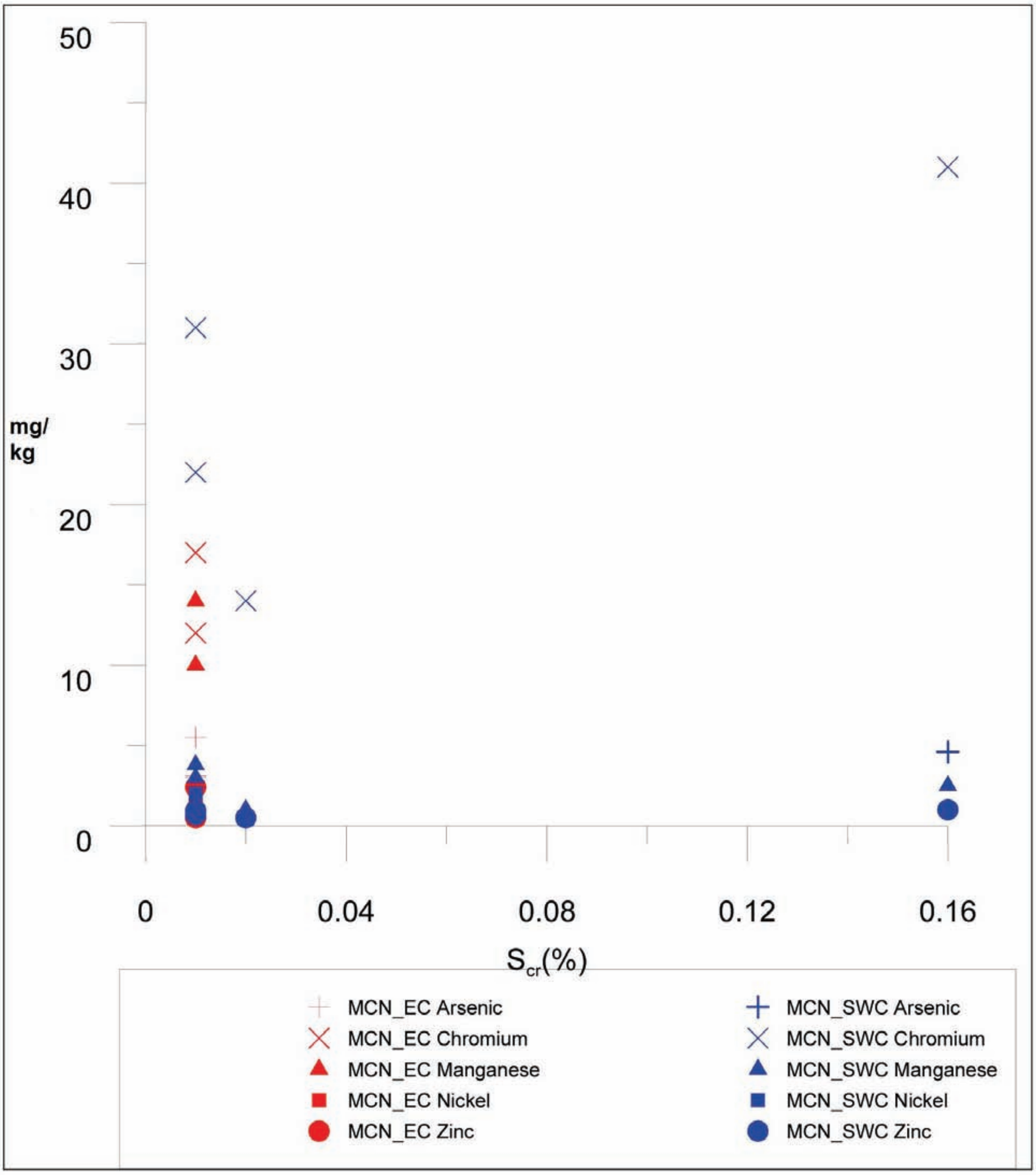


Figure 21 Plot showing the relationship between various metals and sulfur in sediments at Loch McNess

5 Hydrogeology

5.1 Water levels

The network of cluster bores established by Department of Water in 2008 for the SGS project and some non-SGS bores were used to analyse lake and groundwater levels. These bores provide 18 years of twice-yearly data. The analysis of hydrographs and watertable contours of the region provide important clues regarding the general hydrology of the Superficial aquifer around Loch McNess.

Figure 22 indicates that groundwater levels (YN3 and YN5 up-gradient, and BD7 down-gradient) near Loch McNess have been decreasing since about 1992 (marked by the dotted line in Figure 22), following a general trend of decreasing annual rainfall. However, groundwater levels immediately adjacent to Loch McNess (BD9) were relatively stable until 2006 (marked by dotted line in Figure 22) when there was a significant decline. This decline was reflected by a lagged drop in lake level, suggesting that lake levels were able to buffer changes in groundwater level between 1992 and 2006, despite the low rainfall.

The significant decline in lake level from 2006 to below the Ministerial Criterion minimum water level suggests that the lake was no longer able to buffer the changes in groundwater levels. This change indicates that Loch McNess has crossed a hydrologic threshold (Horwitz et al. 2009), changing from a flow-though regime to a partial flow-through regime with losses to groundwater by leakage through lake sediments. This change will have prolonged effects on water levels in Loch McNess. As long as groundwater levels down-gradient remain below lake levels, water will be lost from the lake to groundwater and lake levels will remain low.

For water levels in the lake to recover, groundwater levels must be increased sufficiently to re-establish the historic flow-through hydrologic regime. Several years of good rainfall and low abstraction would be required to allow for lake level to recover to Ministerial Criterion water levels. If below average rainfall conditions and current abstractions persist, lake levels will not recover and a permanent change in the character of the lake is expected.

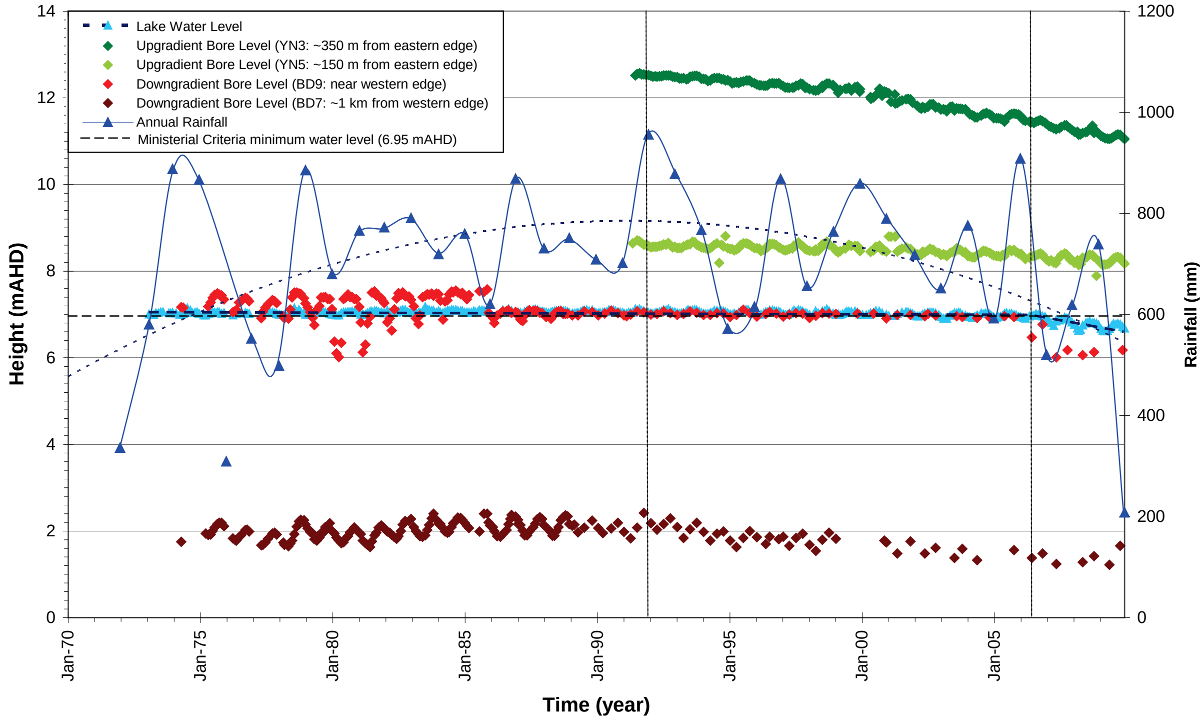


Figure 22 Annual rainfall, lake level and groundwater level (western side, down-gradient) for Loch McNess from 1971 to 2009 (dashed line = rainfall trend line)

The eastern bores (MCN_EA, MCN_EB and MCN_EC) displayed seasonal fluctuations over the SGS study period (June 2008 to June 2009, as shown in Figure 23). Groundwater levels for these up-gradient bores are always higher than the water level for Loch McNess (location 8754 on the southern tip of Loch McNess). Similarly, groundwater levels for boreholes MCN_WA, MCN_WB and MCN_WC) located on the western side of the lake are always lower than the lake water level (Figure 23). Bore MCN_SWC located on the south side of the lake shows similar water levels to MCN_WC.

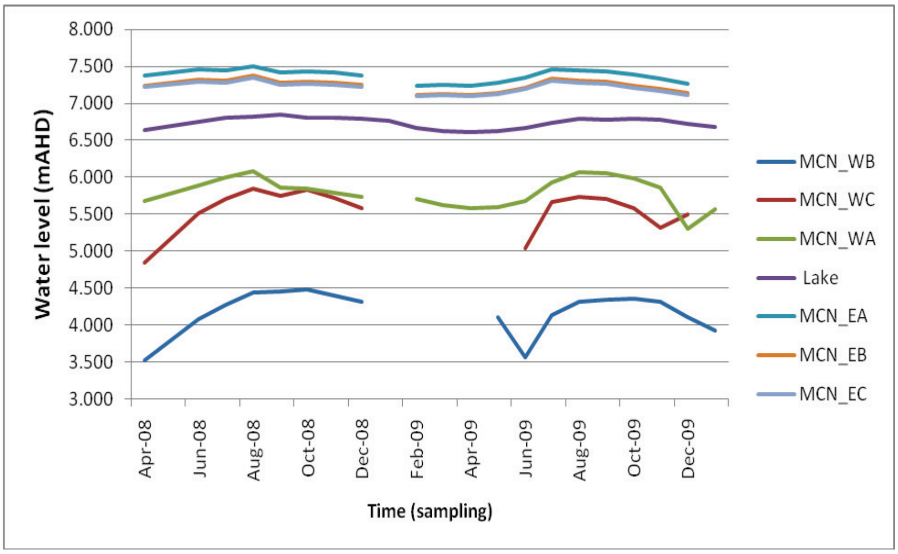


Figure 23 Bore hydrographs for up-gradient bores and down-gradient bores compared with water levels in Loch McNess (location 8754)

The lake levels and local watertables were found to vary in phase, although it was observed that heavy rainfall events affect the lake more rapidly than they affect the groundwater. Summer minimum levels (Figure 23) occur in March and April. Winter maximum levels were recorded in August and September.

The large fluctuation in hydraulic head in the shallow down-gradient bore MCN_WC is matched by similar variation in the intermediate and deep down-gradient bores. Variability in heads down-gradient contrast with the much more subdued variability in up-gradient bores MCN_EA to MCN_EC and in the lake (Figure 23).

The relationship between monthly water levels in the lake is spatially consistent for all other non-SGS bores (YN3 and YN5 on the up-gradient and BD7 and BD9 which are on the down-gradient side of the lake (see Figure 24 and Figure 25)). BD9, which is located on the fringe of the lake on the western side, shows similar water level fluctuations to those for the lake. However, in 2006, the water level in BD9 dropped lower than the lake level and consistently remained lower than the lake level after this (Figure 25). YN3 on the up-gradient side of the lake showed a steady decline in groundwater level (12.5 m AHD in 1991 to 11.00 m AHD in 2009), probably due to a decline in the annual rainfall (see Figure 2 in Section 2.1). However, YN5 shows a small steady decline (8.6 m AHD in 1991 to 8.3 m AHD in 2009) (Figure 24).

The water level for Loch McNess (as shown in Figure 6) is shown in Figure 25 compared with bore hydrographs for down-gradient bores BD9 and BD7. Figure 26 shows this in more detail. The lake level has declined from 7.05 m AHD to 6.70 m AHD in the last 36 years. The hydrograph shows that Loch McNess had a remarkably stable water level and small annual water level range until late 2006 (Figure 27) declining very gradually since 1973, with an increase in the declining trend evident after 1998. The water levels vary seasonally by about 0.1 m. Since 2006, the water level in the lake declined to 6.70 m AHD although it is not clear whether the decline has ceased or whether further declines can be expected.

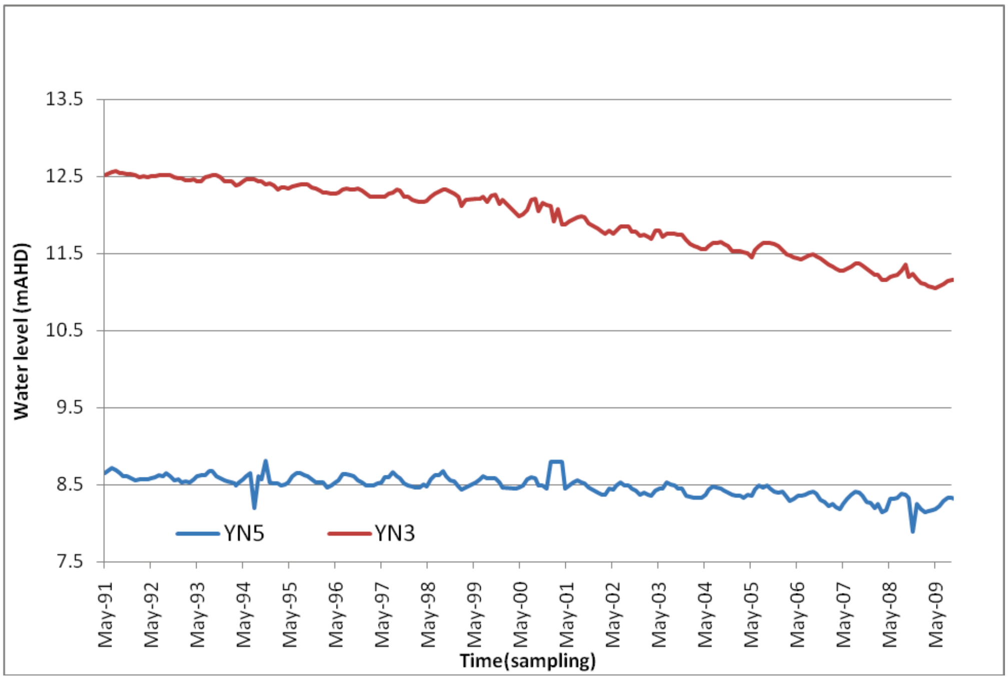


Figure 24 Hydrographs of non-SGS bores up-gradient of Loch McNess

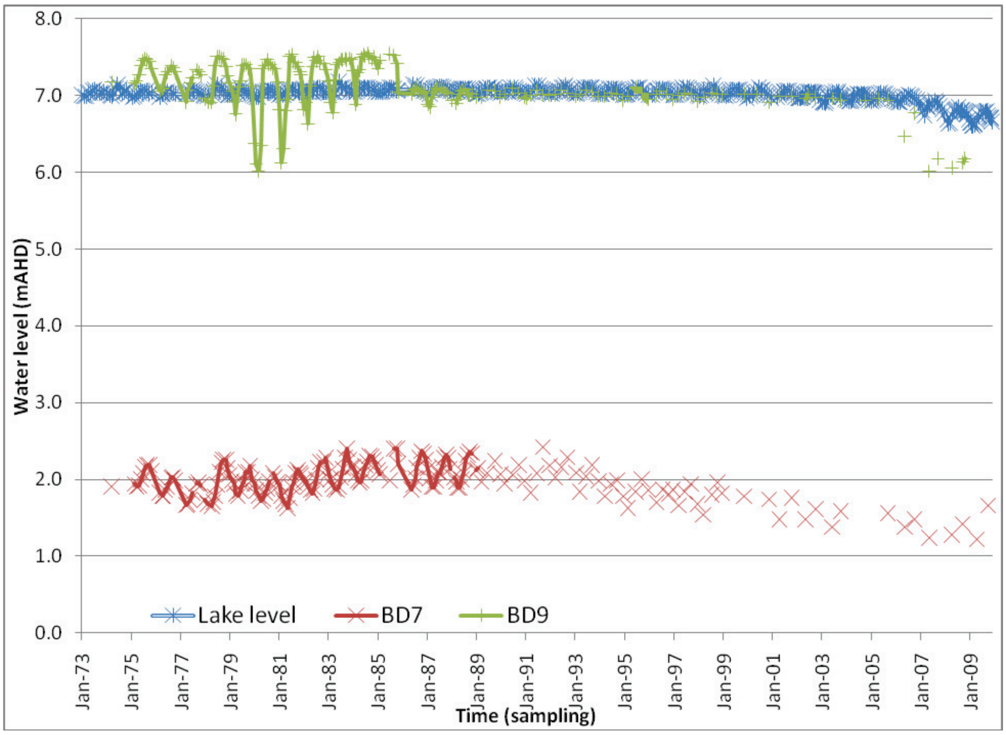


Figure 25 Hydrographs of non-SGS bores down-gradient of Loch McNess compared with lake water level

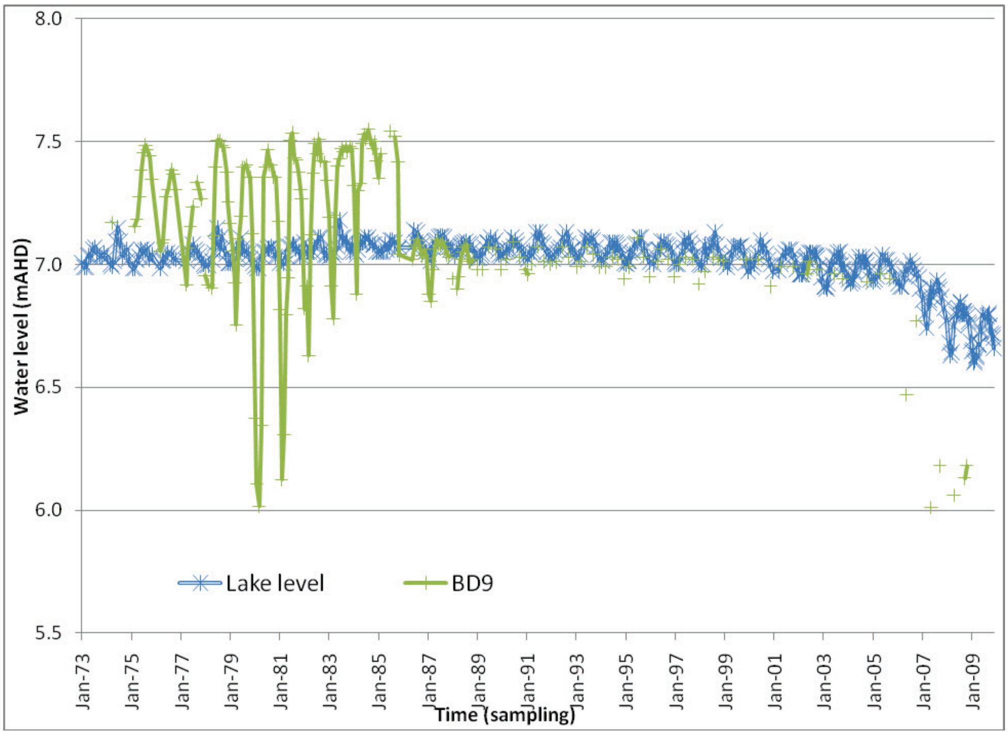


Figure 26 Hydrographs of non-SGS bores down-gradient of Loch McNess compared with lake water level (BD9 and lake only)

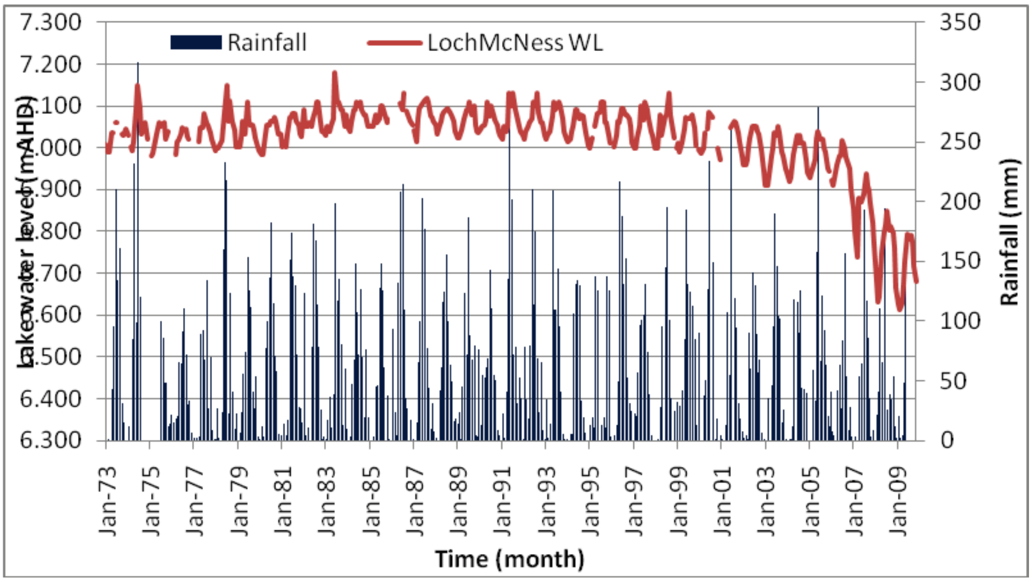


Figure 27 Loch McNess hydrograph for location 8754 compared with monthly rainfall 1973 to 2009[3]

The longer term relationship between groundwater levels on the down-gradient side of the lake and within the lake needs further consideration, as this is fundamental to lake–groundwater behaviour. Groundwater levels in bore BD7 approximately 1 km down-gradient of the lake are much lower than the lake and show a seasonal variability and a slow decline in level. Bore BD9, which is located close to the lake shore, shows strong seasonal variability synchronised with levels in the lake between 1980 and 1987, with average groundwater levels being similar to those in the lake, but bore hydrograph peaks are higher than lake levels and bore hydrograph troughs are significantly lower than those in the lake (Figure 26). The bore hydrographs after 1987 become less variable seasonally, although the frequency of measurement is much less (only two per year) and, although the seasonality of lake levels is still observed, groundwater levels in bore BD9 remain very similar to those in the lake until 2006.

In 2006–07, groundwater levels in bore BD9 declined rapidly to approximately 1 m below 2006 levels by the end of 2007. Thereafter they remained reasonably constant. In contrast, lake levels started to decline by about 0.3 m in late 2006 to early 2007 (Figure 26 and Figure 27). There is an indication of a flattening out of lake levels in early 2009 (Figure 27).

The bore hydrographs for BD9 and lake water levels indicate that at times of summer troughs in bore hydrographs, lake water levels ‘detach’ from lake levels and the flow-through lake character no longer applies. For example, during the pre-1987 period and post-2006 period. In the earlier period, groundwater levels strongly rebound and show higher levels than in the lake, but this is not evident after 2006. The recent strong decline in groundwater levels immediately down-gradient of the lake and the

[3] Note: small decline in lake water level 2001 to 2006 when rainfall was generally lower, and rapid decline post 2006 due to dry years 2006–07.

smaller and slightly lagged decrease in lake water levels must be related to the very low rainfall in 2006 (520 mm, see Table 2), in the absence of other obvious changes in the area.

The latter relationship between low rainfall in 2006 and continuation of groundwater levels lower than in the lake on its down-gradient side, suggests a detachment of lake levels from groundwater on the western side of the lake. This would seem to have given rise to a new hydrogeological equilibrium down-gradient of the lake. Thus groundwater levels are maintained at a new equilibrium level by leakage through lake sediments, not by direct discharge of lake water on the western edge of the lake. It remains to be seen whether the lake water levels remain at this level or whether further declines might be expected, particularly if rainfall patterns of 2006 are repeated.

5.2 Groundwater flow

The saturated thickness of the Superficial aquifer is some 30+ m at Loch McNess. As the Superficial aquifer behaves as a phreatic aquifer then any reduction in saturated thickness will reduce the transmissivity and storage of the aquifer.

The groundwater hydraulic heads follow the topography (Figure 5), exhibiting the highest values in the eastern (elevation of the Gnangara Mound) and lowest in the coastal plain. Flow is indicated as being predominantly east to west. Loch McNess is in hydraulic connection with the regional groundwater flow system and is in a dynamic balance between topography, geology and climatic factors. The lake generally is a minor component of the overall flow system acting as a partial flow-through lake with the local groundwater flow determined by the relative hydraulic head difference between the lake and the surrounding groundwater, tending toward a natural equilibrium of continuity of groundwater and lake water levels.

The groundwater contours derived from the SGS monitoring program and nearby monitoring bores show groundwater flowing from the east to the west (Figure 28 and Figure 29). The groundwater gradient is relatively gentle on the east side of the lake and very flat near the ocean. Rockwater (2003) report there is some flow normal to the E_W cross-section towards caves south of Loch McNess, similar to flowfields for generalised wetlands shown by Townley et al. (1991), and Townley and Trefry (2000) (not shown at Figure 29).

Figure 28 shows the watertable contours and groundwater flow paths for May 2008, when water levels are lowest at the end of summer. Figure 29 shows that at the end of winter, watertable contours are similar, but there is about a 0.2 m increase on either side of the lake, when compared with minimum levels.

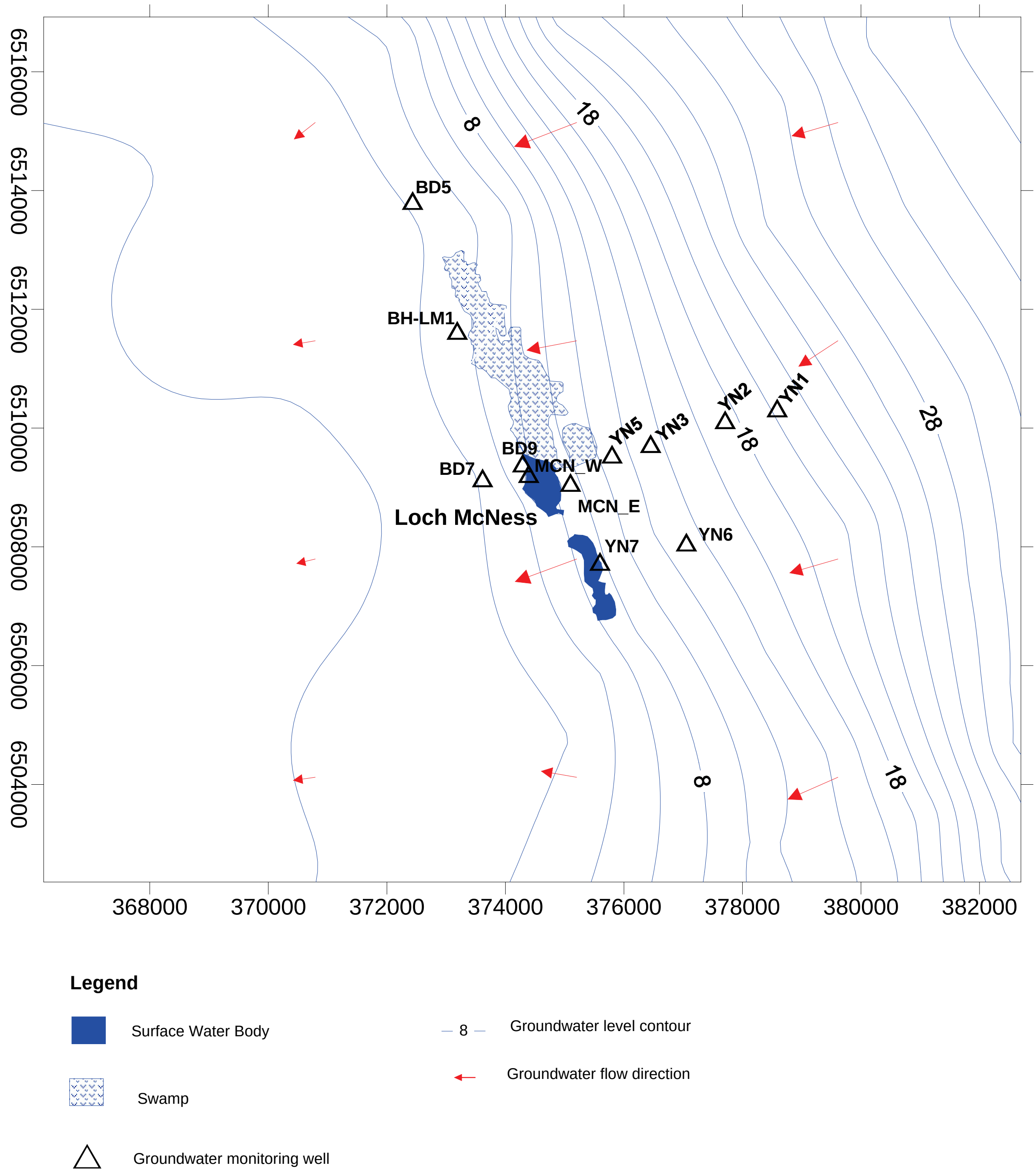


Figure 28 Watertable contours and groundwater flow paths for May 2008

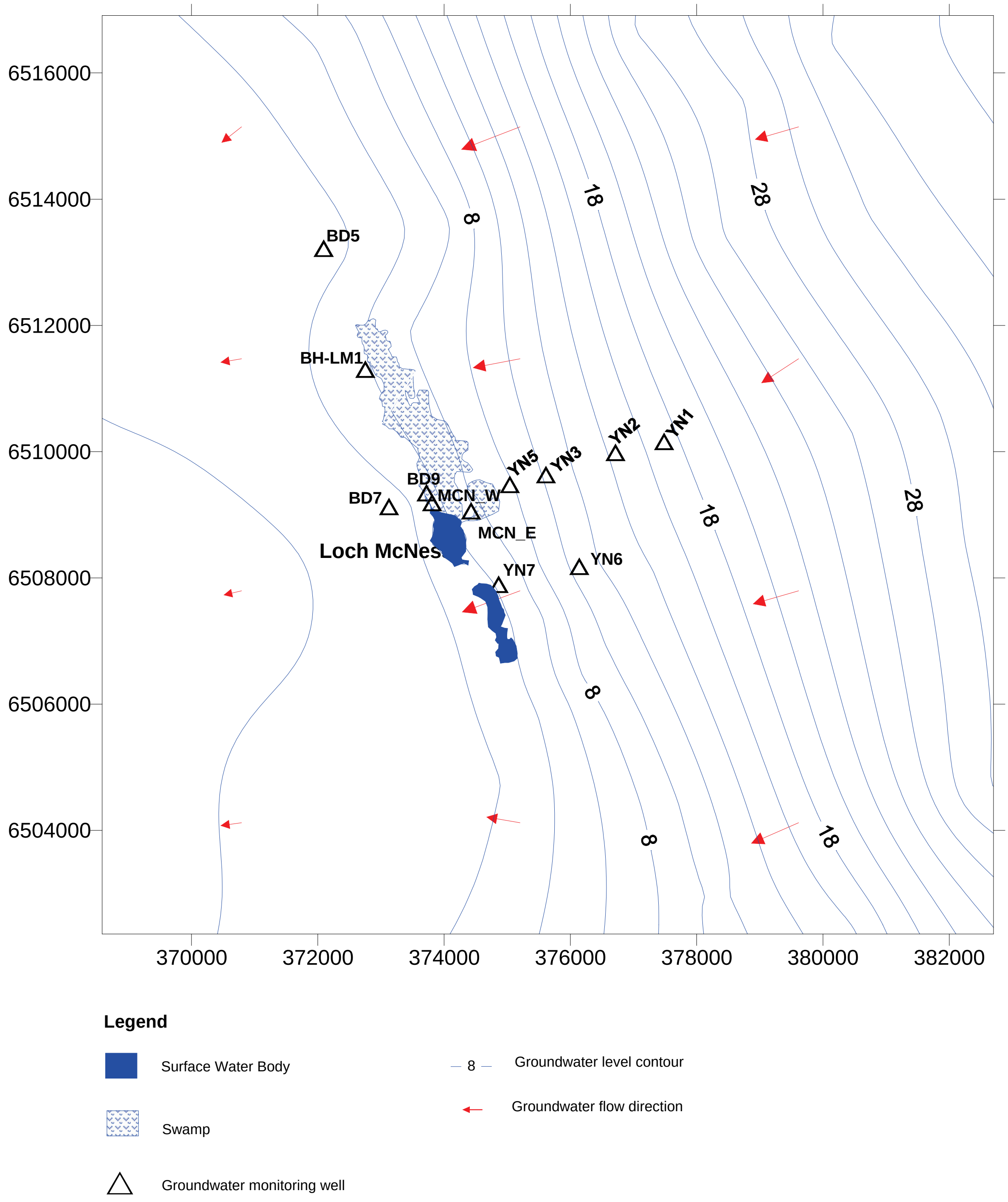
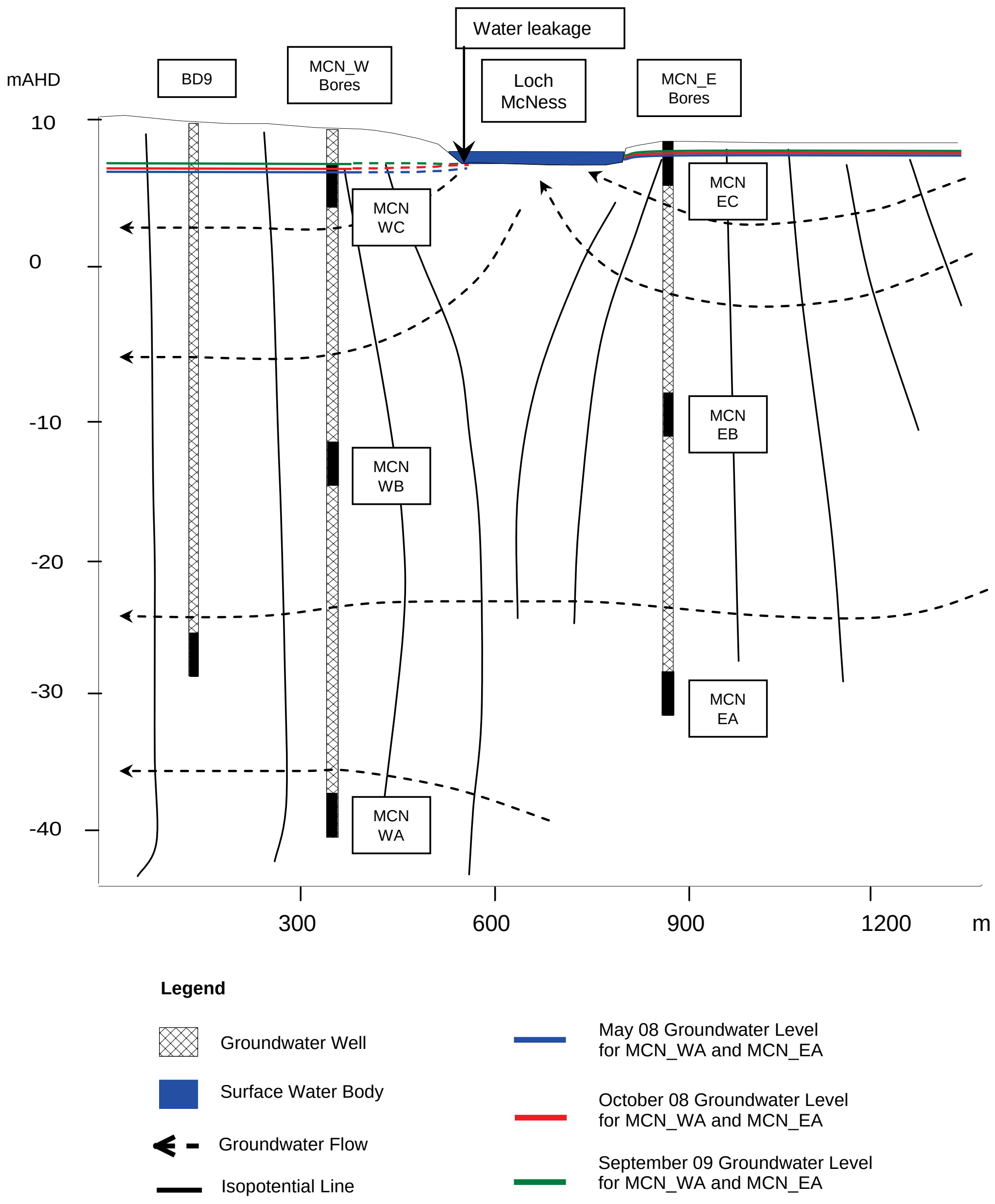


Figure 29 Watertable contours and groundwater flow paths for October 2008

Hydrogeological cross-sections for summer and winter are shown in Figure 30. These sections are approximately parallel to the groundwater flow. They represent the maximum and minimum water levels.

The vertical gradient direction of the nested piezometers within the eastern reaches of the lake indicate upward discharge (Figure 28), but the groundwater flow pattern for the western reaches of the lake is complicated by the existence of changes in the direction of the vertical gradients within the profile (Figure 29). The hydraulic head of the intermediate bore is lower than that for the shallow bore, indicating groundwater recharge in the upper part of the aquifer at this location. However, the deep bore shows groundwater levels higher than those in the intermediate bore, suggesting vertically upward gradient in the lower part of the aquifer. This suggests both downward and upward discharge is occurring in the region of the bore throughout the whole profile of the Superficial Aquifer.

The upper part of the aquifer clearly is receiving recharge from the lake, which would account for the vertically downward gradient between the shallow and intermediate bores. The vertically upward gradient in the lower part the aquifer is more difficult to account for. However, the bore logs in Table 5 show the Superficial Aquifer sitting directly on sandstone of the Leederville Formation (possible Pinjar Member). This indicates possible direct hydraulic connection between the Leederville and the superficial formation. Davidson (1995) notes the possibility of higher hydraulic heads within the Leederville compared with the Superficial Aquifer, which offers a possible explanation for the observed gradients down-gradient of the lake.



Recovered Standing Water Levels

MCN_WA	**MCN_WB**	**MCN_WC**	**Loch McNess**
May 08: 4.67 mAHD	May 08: 3.53 mAHD	May 08: 4.848 mAHD	May 08: 6.75 mAHD
Oct 08: 5.06 mAHD	Oct 08: 4.49 mAHD	Oct 08: 5.828 mAHD	Oct 08: 6.81 mAHD
Sept 09: 5.05 mAHD	Sept 09: 4.36 mAHD	Sept 09: 5.701 mAHD	Sept 09: 6.79 mAHD
MCN_EA	**MCN_EB**	**MCN_EC**	
May 08: 7.45 mAHD	May 08: 7.23 mAHD	May 08: 7.22 mAHD	
Oct 08: 7.43 mAHD	Oct 08: 7.39 mAHD	Oct 08: 7.27 mAHD	
Sept 09: 7.41 mAHD	Sept 09: 7.28 mAHD	Sept 09: 7.26 mAHD	

Figure 30 Groundwater flow paths for May and October 2008 and September 2009

6 Hydrogeochemistry

6.1 Physical and chemical characteristics

On-site physical measurements

The parameters of pH, dissolved oxygen (DO) and reduction potential (ORP) were measured on site.

Summary statistics (minimum, maximum and median) for the above parameters are shown in Table 8 for the east and west bores and for Loch McNess surface water at location 8754.

Table 8 Summary statistics for on-site measurements of pH, DO and ORP in east and west bores and Loch McNess at location 8754

Bore	**pH**			**DO mg/L**			**ORP mV**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
MCN_EA	7.58	7.79	7.67	0.17	2.11	0.48	-268	77	-37.0
MCN_EB	5.88	6.72	6.21	2.11	5.1	3.04	17	185	47.0
MCN_EC	6.88	7.37	7.02	0.93	5.01	2.70	-20	148	-2.0
MCN_WA	6.60	7.00	6.80	0.19	0.75	0.36	-110	30	23.5
MCN_WB	6.67	7.07	6.86	0.14	2.23	0.45	-125	10	4.5
MCN_WC	6.94	7.20	7.13	0.18	3.17	0.52	-125	228	-10.5
8754	7.52	8.92	8.13	3.78	11.35	7.80	-101	155	-44.0

The results are generally consistent over the time period for each bore from June 2008 to June 2009, with the possible exception of ORP measurements, which show a considerable range about the median value.

All median pH values in bores are lower than those within Loch McNess at location 8754. Bores MCN_EA, MCN_EC and MCN_WC have median pH values > 7, whilst bores MCN_EB, MCN_WA and MCN_WB have median pH values < 7, with the highest minimum value being 5.88 in MCN_EB. There is little evidence from this analysis of decreases in pH due to acid sulfate soil leaching and pyrite dissolution, unless the pH is buffered by carbonate equilibria or clay mineral buffering. The pH within the lake on occasion is somewhat outside the range recommended as trigger level in wetlands by ANZECC and ARMCANZ (2000) of 7 to 8.5, although the median value of 8.13 is well within this range. There is no indication of any trend towards lower pH within the lake at location 8754 within Loch McNess south, although there are some indications of lower observed pH values in Loch McNess north.

Dissolved oxygen concentrations are also higher in the lake compared with groundwater. Bores MCN_EA, MCN_WA, MCN_WB and MCN_WC all show the lowest median levels of < 0.5 mg/L and would appear to be anoxic. Bores MCN_EB and MCN_EC have median DO concentrations of approximately 3 mg/L and clearly are more oxygenated overall than other bores. There is little correlation between DO and ORP, although bores with low DO mostly have strongly negative ORP values at least for minimum values in Table 8. The DO and ORP data are consistent with anoxic or reducing conditions for most bores with the exception of bores MCN_EB and MCN_EC, up-gradient of the lake. The lake is strongly oxygenated (median DO of 7.8 mg/L), although some lower concentrations have been observed.

6.2 Water quality

Major cations and anions

Electrical conductivity and the concentrations of chloride, sulfate, bicarbonate, calcium and sodium in groundwater and lake water show considerable variability. This may give an indication as to the hydrology and hydrogeology of the lake system. The major ion data for the western and eastern bore clusters has been analysed using ternary (Piper) plots, using Stiff diagrams and using time-series plots. In addition, summary statistics (median, minimum and maximum values) for specific groups of analytes have been tabulated. In these tables, trigger levels for water quality in wetlands of south-west Australia (ANZECC & ARMCANZ 2000) have been compared with water quality data for the lake and bores up-gradient which contain groundwater which possibly discharges to the lake. Data from down-gradient bores have been compared against drinking water quality guidelines (NHMRC & ARMCANZ 1996) as the provision of drinking water is the highest beneficial use of the aquifer down-gradient of the lake.

Drinking water guidelines have been used to give 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 considers that any untreated waters taken from the environment is unsafe for human drinking.

The ternary plots for major cations and anions in the eastern (up-gradient) bores and Loch McNess water at Station 8754 are shown in Figure 31 and Figure 32. Of the groundwater up-gradient of the lake, the intermediate bore MCN_EB is very similar in its major ion composition to that of the lake, being relatively dominated by sodium and chloride and depleted in magnesium. The shallow bore MCN_EC and the deeper bore MCN_EA both show quite different major ion composition, being more enriched in calcium and bicarbonate than the lake and intermediate bore. It is concluded that groundwater discharging to the lake is more representative of that sampled at intermediate aquifer depths. This also suggests quite strong stratification with respect to groundwater quality within the Superficial aquifer and that groundwater at the watertable with characteristics similar to that in MCN_WC does not extend deep into the aquifer.

Most groundwater is relatively depleted in sulfate, although the shallow groundwater has the highest relative concentrations from early in the monitoring period.

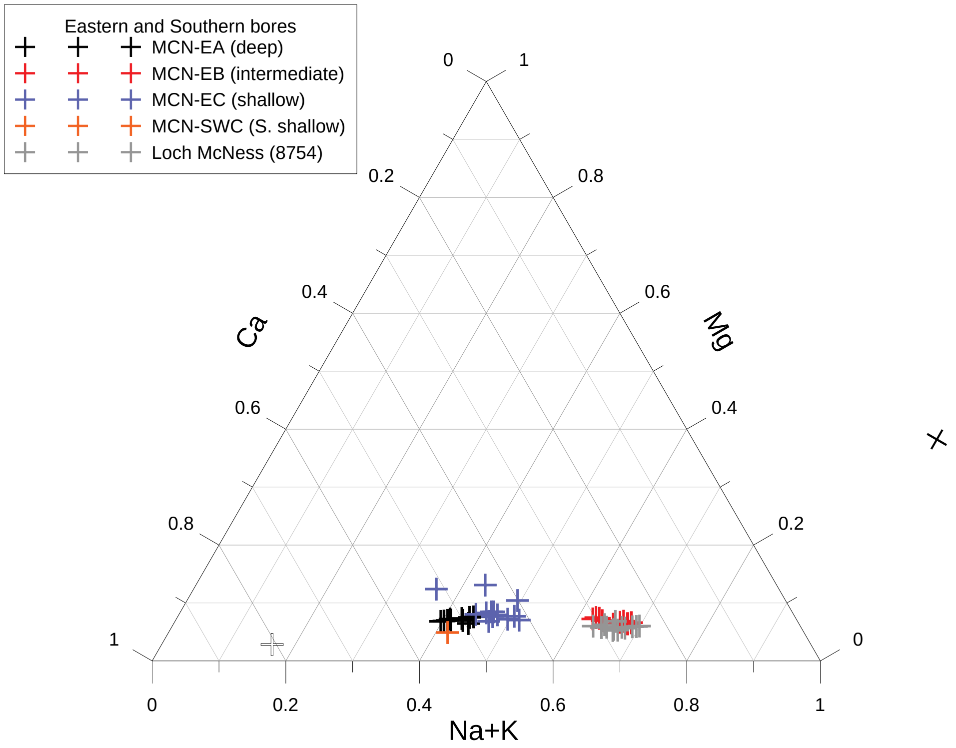


Figure 31 Ternary (Piper) plot of major cations in eastern and southern bores and in Loch McNess (8754) (data obtained from the SGS project)

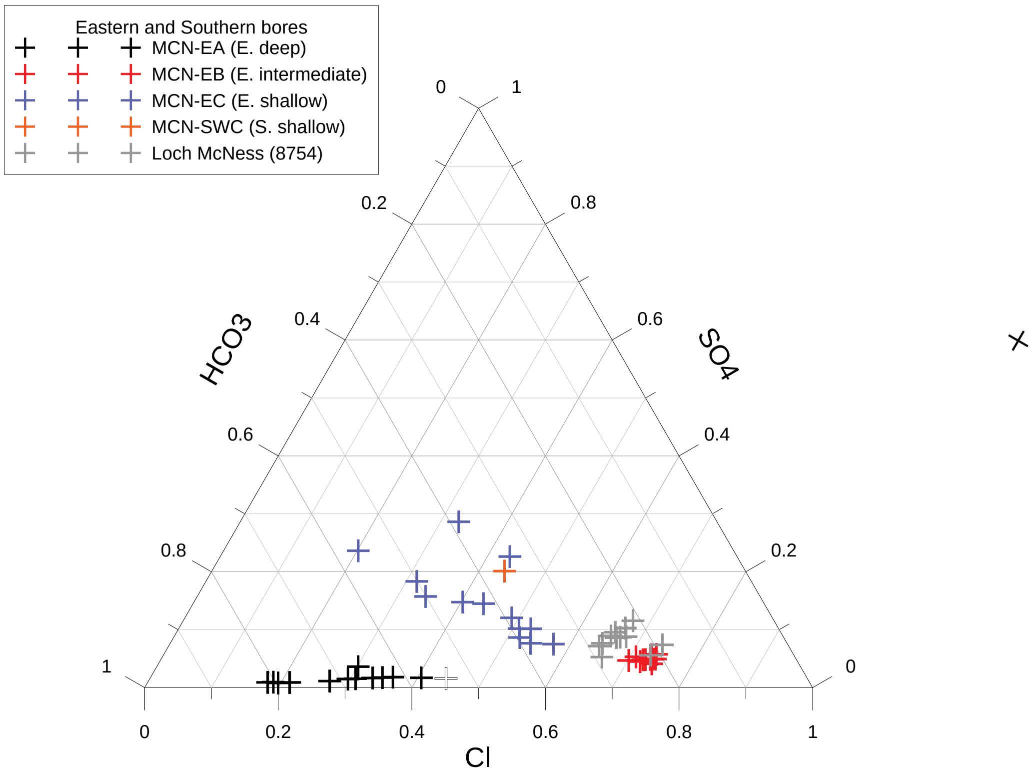


Figure 32 Ternary (Piper) plot of major anions in eastern and southern bores and in Loch McNess (8754) (data obtained from the SGS project)

Major ion compositions in the western bores down-gradient of the lake (Figure 33 and Figure 34) show deeper groundwater and the lake water relatively sodium and chloride enriched whilst shallow and intermediate bores are more calcium and bicarbonate dominant. The groundwaters are again relatively depleted in magnesium, as in the eastern bores, but shallow and deep bores show increased relative concentrations of sulfate compared with the intermediate bore.

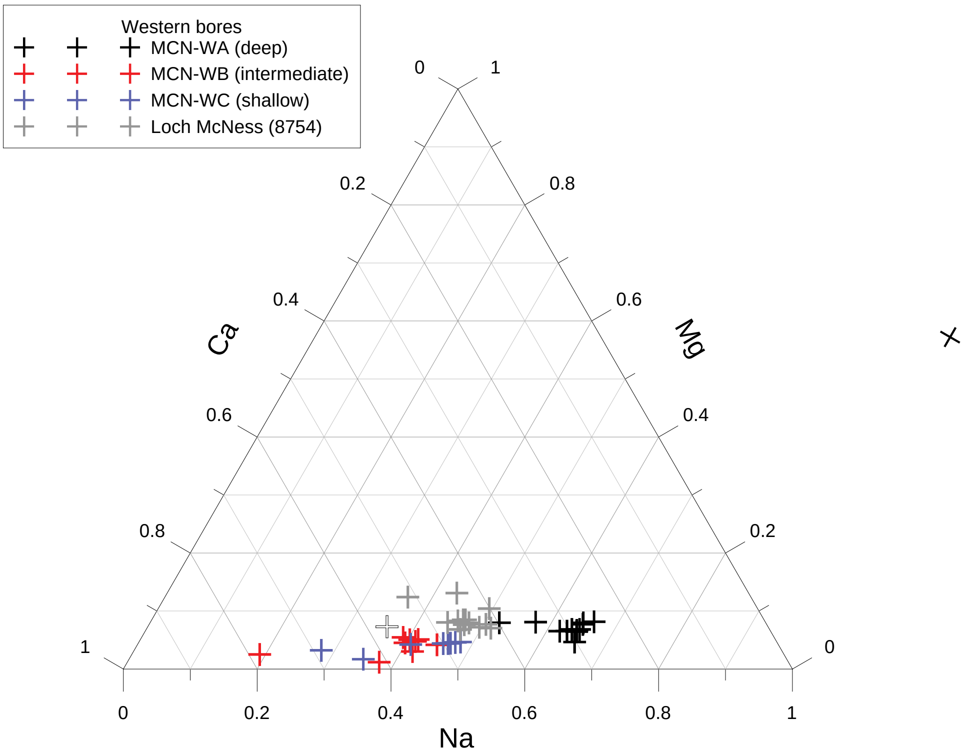


Figure 33 Ternary (Piper) plot for major cations in western and southern bores and in Loch McNess (8754) (data from the SGS project)

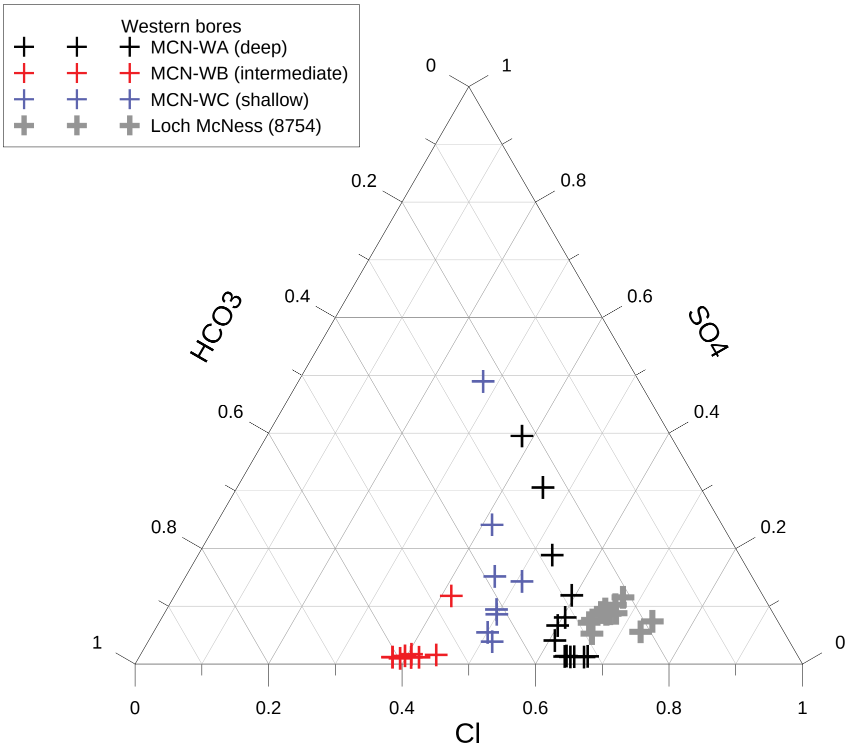


Figure 34 Ternary (Piper) plot for major anions in western and southern bores and in Loch McNess (8754) (data from the SGS project)

As indicated above, bore hydrographs suggest that lake water is discharging to a shallow watertable beneath and on the down-gradient side of the lake. Bore logs for MCN_WA indicate limestone in the upper part of the western bores (Table 5 and Figure 15), which must react with lake water increasing both calcium and bicarbonate, particularly if infiltrating lake water is affected by low-pH water from sulfide oxidation within lake sediments. The relative increases in sulfate and calcium in the shallow bore would support this explanation.

Major ion characteristics of lake water and groundwater in the Superficial aquifer are shown graphically in Stiff diagrams in Figure 35 and Figure 36. These indicate:

- a similarity in the relative concentrations of major ions between the intermediate up-gradient bore and the lake, with both being sodium chloride dominant
- considerable variability with depth in major ion composition in both up-gradient and down-gradient bores, related at least in part to lithological stratification within the aquifer
- relative enrichment of groundwater with calcium and sulfate at shallow and intermediate depths in down-gradient bores compared with lake water at location 8754 within southern Loch McNess.

The last observation could be a result of acidification caused by acid sulfate soils within those parts of the lake where sediments have been exposed to air, and where the pH of infiltrating water from the lake has been buffered by reaction with carbonate minerals in the extensive limestone identified on the down-gradient side of the lake.

The Piper and Stiff plots tend to indicate that groundwater in the Superficial aquifer is distinctly stratified, with this stratification being related in some extent to lithological stratification (e.g. leached sands as compared with limestone strata). The lake itself is strongly characteristic of groundwater from leached sands which are notably present at intermediate levels in the aquifer on the up-gradient side of the lake. This suggests that lake water being derived directly from groundwater in the upper half of the aquifer where all but groundwater close to the watertable is dominated by chloride and sodium (as sampled from the intermediate bore).

This suggests that Loch McNess displays characteristics of a flow-through lake, where groundwater discharges to the lake on the up-gradient side. However, the lake clearly now does not discharge directly into the saturated zone of the aquifer on its down-gradient side, but instead it recharges groundwater through a thin unsaturated zone presumably in part beneath the lake and on its western, down-gradient side. The lake is clearly dependent on groundwater and given the detachment of water levels in the lake and in groundwater to the west, there must be a poor hydraulic connection between the lake and groundwater in the Superficial aquifer. Lake water thus ‘perches’ on shallow lake sediments.

As indicated above there is evidence of acid sulfate leaching from lake sediments and buffering of pH by carbonate minerals in limestone observed within the upper part of the aquifer down-gradient of the lake.

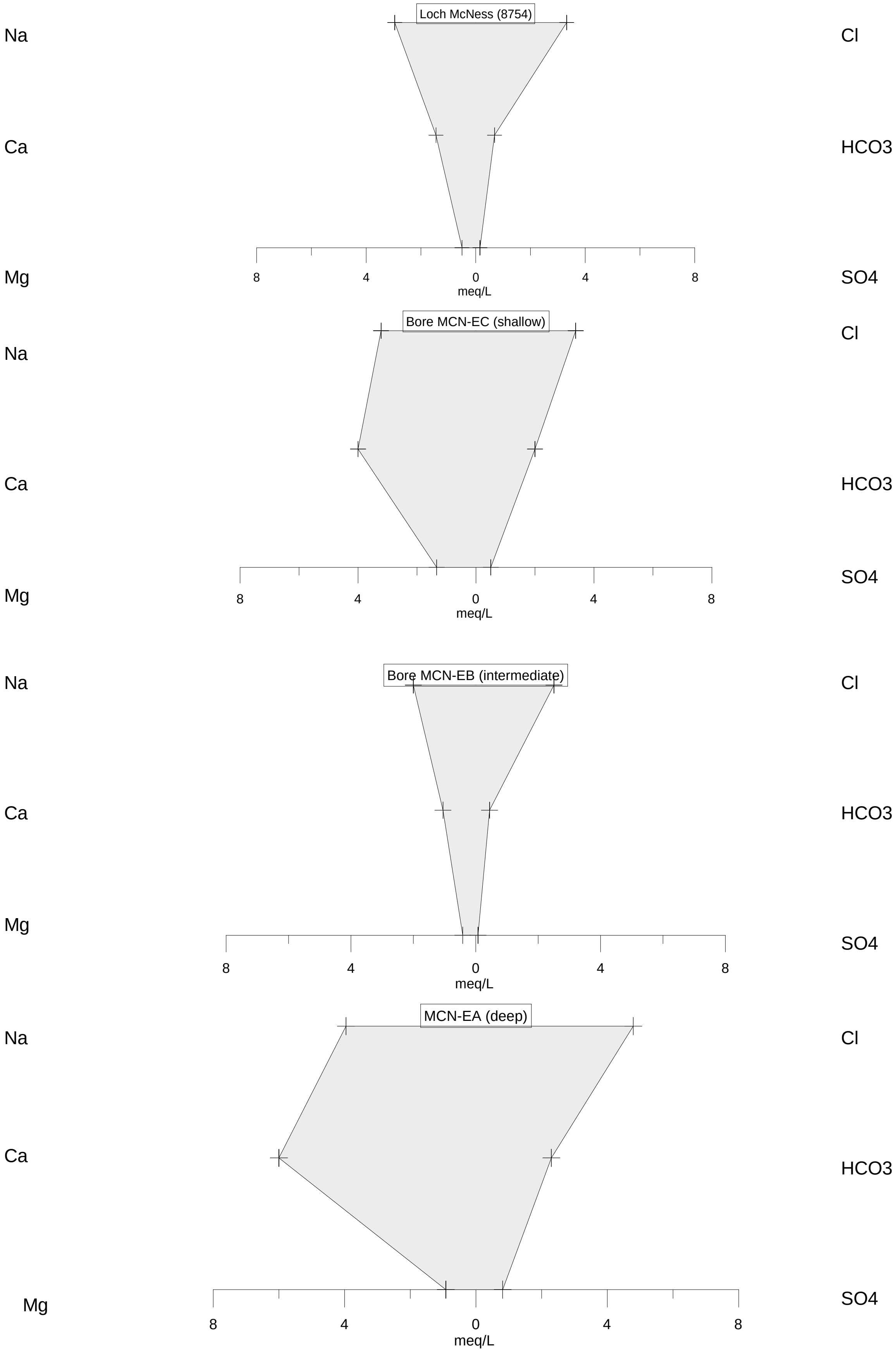


Figure 35 Representative stiff diagrams for mean cation and anion concentrations in meq/L for groundwater from eastern bores

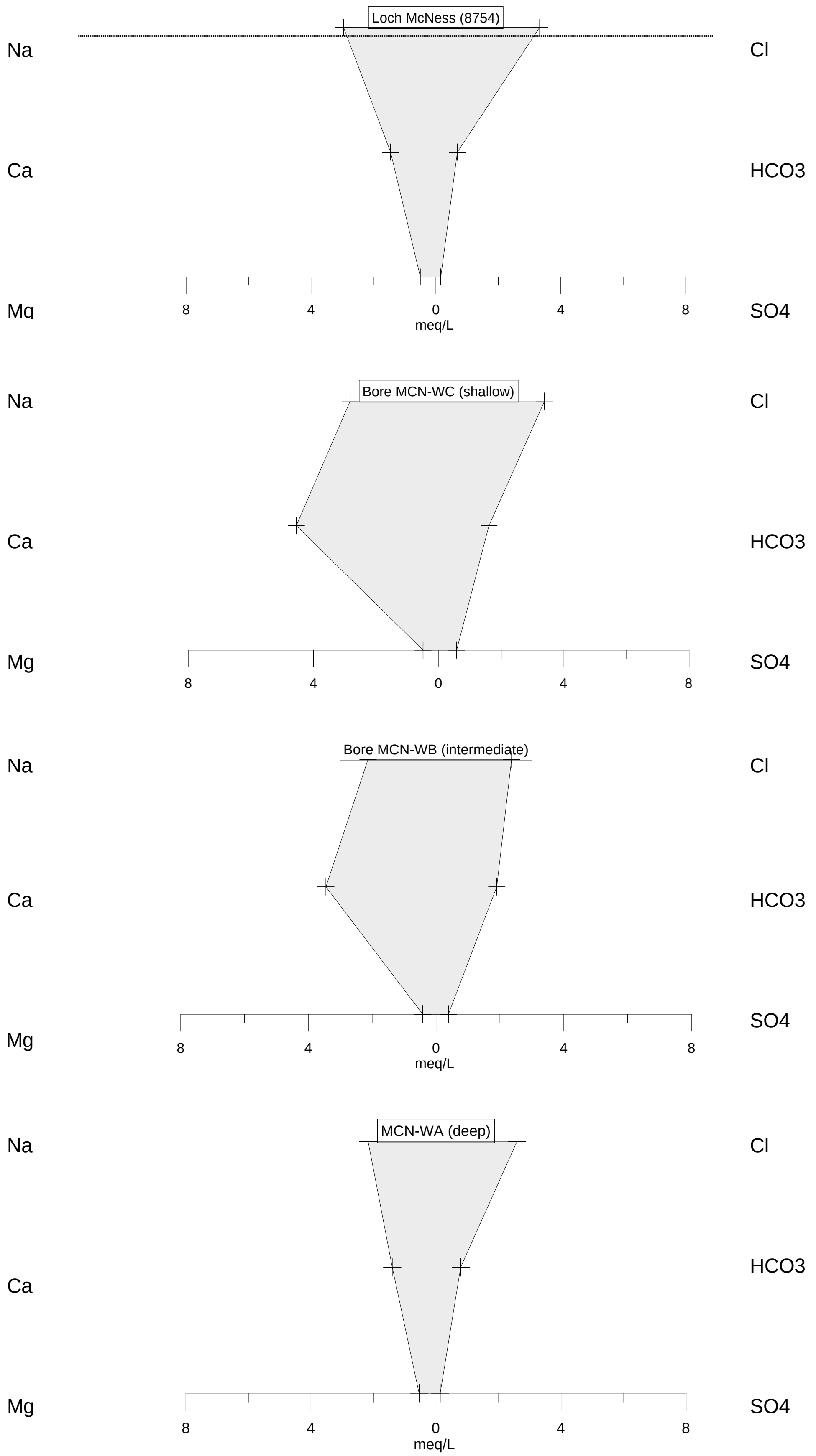


Figure 36 Representative stiff diagrams for mean cation and anion concentrations in meq/L for groundwater from western bores

Electrical conductivity and chloride

Variations over time in electrical conductivity (EC) and chloride in the lake and in eastern bores are shown in Figure 37 and Figure 38. There are clear differences in the variation over time of chloride and EC, presumably caused by differences in ionic composition of groundwater within the Superficial aquifer at different depths and relatively between groundwaters and the lake water.

The EC of lake water generally falls between those of the shallow bore and the intermediate bore over the SGS monitoring period. Chloride behaves similarly, up until the period between December 2008 and April 2009, when lake evaporation would be expected to be highest giving rise to higher concentrations of chloride as observed in Figure 38. The relationships shown in Figure 37 and Figure 38 would be consistent with Loch McNess being a flow-through lake, although the major ion characteristics shown in the Piper and Stiff diagrams suggest that groundwater of composition similar to that in the up-gradient intermediate bore are dominant in determining water quality in the lake.

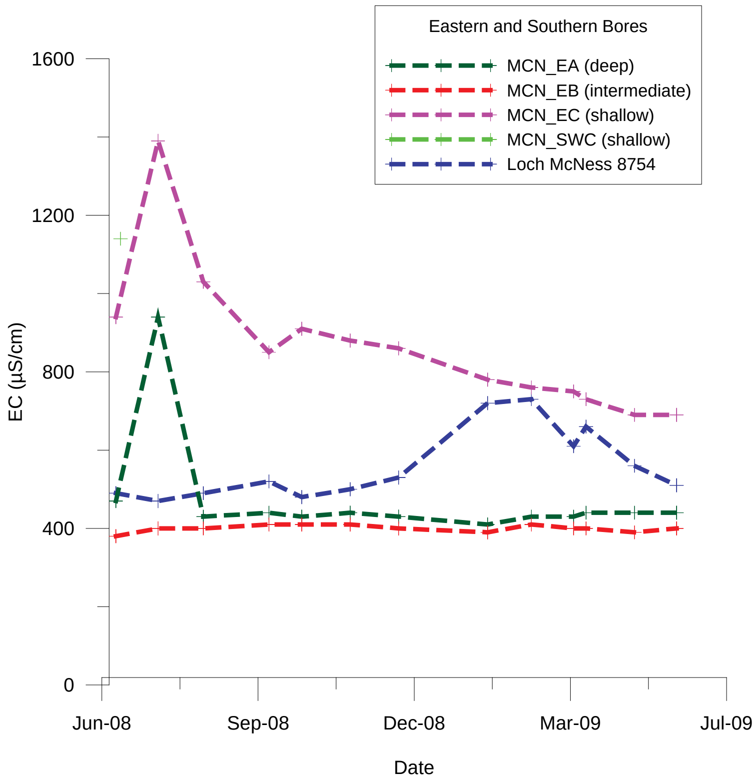


Figure 37 Variation over time of EC in eastern bores and Loch McNess.

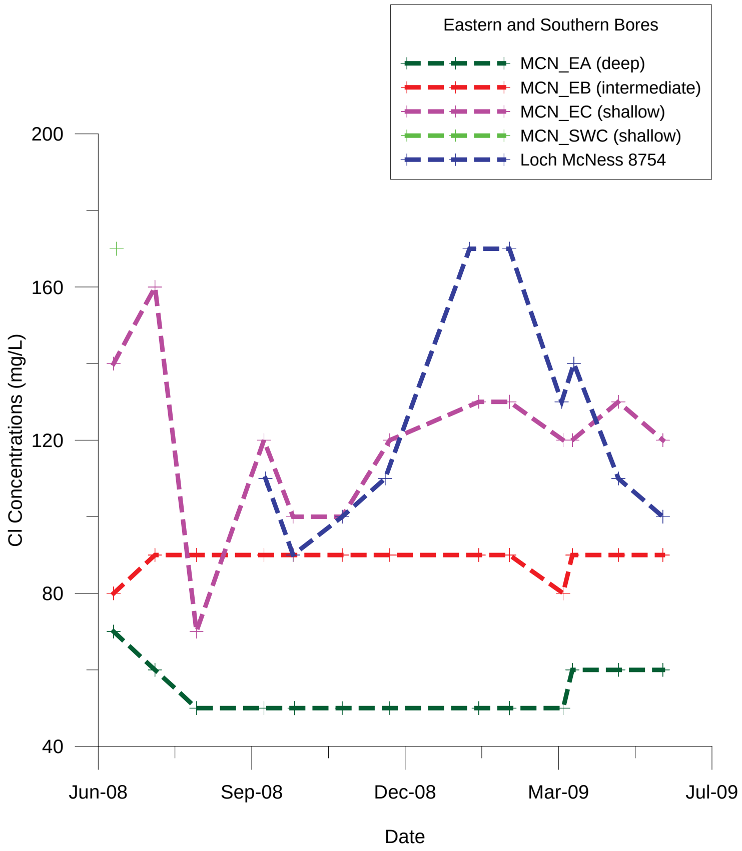


Figure 38 Variation over time of chloride in eastern bores and in Loch McNess

The variation over time of EC and chloride in Figure 39 and Figure 40 for down-gradient bores is somewhat different from that for the eastern bores. The EC of shallow and intermediate groundwater are higher than in lake water from mid to late 2008 and the concentration of chloride in the lake varies between that for chloride in intermediate and shallow groundwater. Unfortunately, access to the latter bores was affected by a bushfire in December 2008 and monitoring was not re-instated until April 2009, a critical period when evaporated lake water might have affected shallow and possibly intermediate level groundwater in the Superficial aquifer on the down-gradient side of the lake. There is an indication of higher EC and chloride in the intermediate bore in April 2009 and in the shallow bore in June 2009, once monitoring had been re-instated. This may indicate some discharge of lake water into the upper Superficial Aquifer, although again the relative ionic compositions of lake water and shallow and intermediate groundwater on the down-gradient side of the lake suggests that if this has occurred then lake water would need to have come to equilibrium with carbonate minerals after discharge back into the aquifer. The relatively rapid equilibration of groundwater from a sand aquifer with calcite from the Tamala Limestone in the Yanchep Caves (Barber 2003) indicates that this process can be quite rapid.

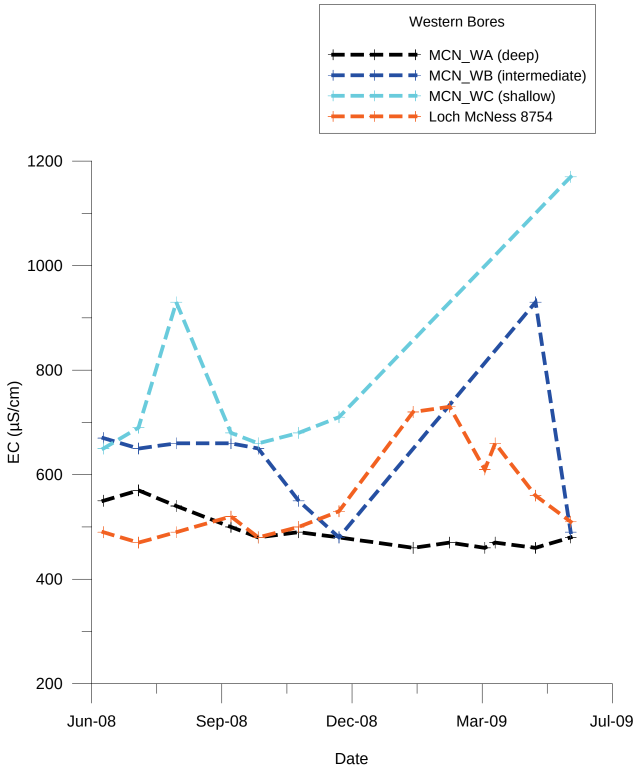


Figure 39 Variation over time of EC in western bores and Loch McNess

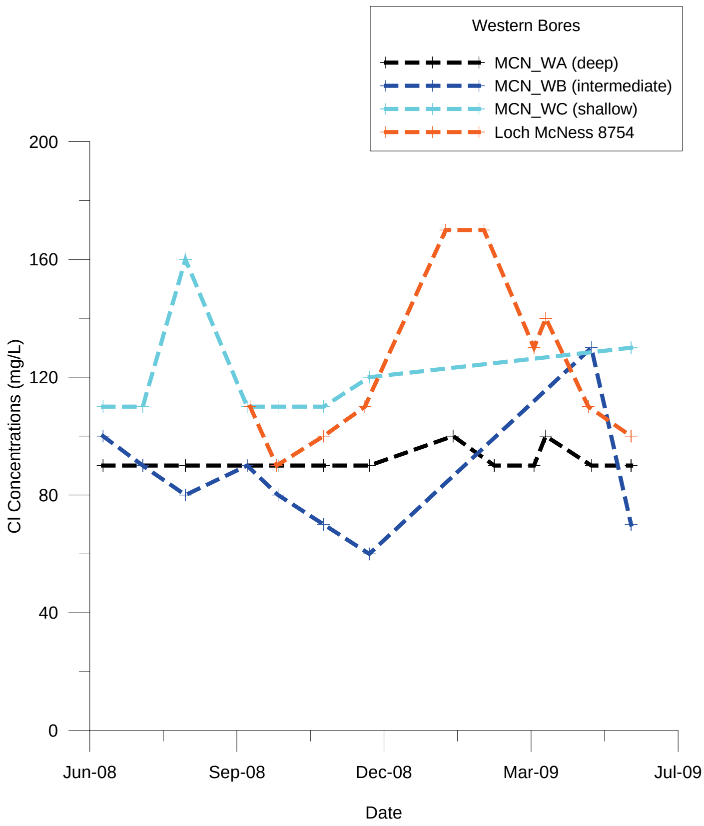


Figure 40 Variation over time of chloride in western bores and in Loch McNess

Sulfate

While sulfate is a useful indicator of redox conditions within the Superficial aquifer, it was present in relatively minor concentrations in both the groundwater and lake water at Loch McNess. To the east of the lake deep groundwater is anoxic and sulfate is mostly below detection limits (< 5 mg/L). This is indicative of sulfate reducing conditions. Intermediate groundwater immediately to the east of the lake has sulfate concentrations consistently below 10 mg/L (Figure 41), which suggests again anoxic conditions with active sulfate reduction. Higher sulfate concentrations are found in shallow groundwater to the east of the lake, being initially quite high (approximately 100 mg/L) decreasing over time to much lower concentrations by June 2009. Lake water remains reasonably constant over time (Figure 41) being closest to groundwater in the intermediate bore except for later in the monitoring period.

On the western edge of the lake (Figure 42), the intermediate bore has no detectable sulfate except in April 2009, whilst the deep bore showed reasonably high sulfate initially, which decreased to background concentrations (< 5 mg/L) by February 2009. It is not clear why this bore shows this pattern, particularly as the groundwater is anoxic and might be expected to be sulfate reducing over the whole period, in a similar manner to the up-gradient deep bore. The data thus suggests (at least for 2009) that anoxic, sulfate reducing conditions existed in the intermediate and deep parts of the Superficial aquifer.

By contrast, sulfate concentrations in the shallow bore down-gradient of the lake showed higher concentrations (approximately 100 mg/L) in June 2008, decreasing to approximately 10 mg/L to December 2008. The latter were similar to concentrations in the lake. Sulfate again showed an increase in concentration to > 100 mg/L in June 2009, with a spike in concentration in the intermediate bore in April 2009.

The apparent increase in sulfate in shallow groundwater down-gradient of the lake following the summer period (i.e. by April–June 2009) and apparent decrease over winter, could be indicative of leaching of sulfate from lake sediments or from the aquifer. This could be an indicator of leaching of sulfides when sediments are exposed to air as lake levels fall. However, analysis was made difficult by the absence of data between December 2008 and June 2009, due to the bushfire.

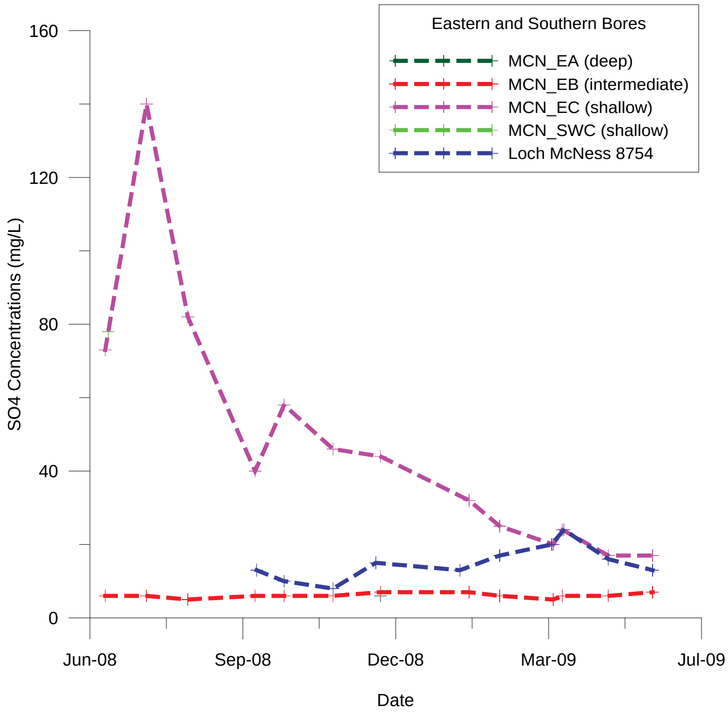


Figure 41 Variation over time of sulfate in eastern bores and Loch McNess (Note logarithmic scale for concentration axis)

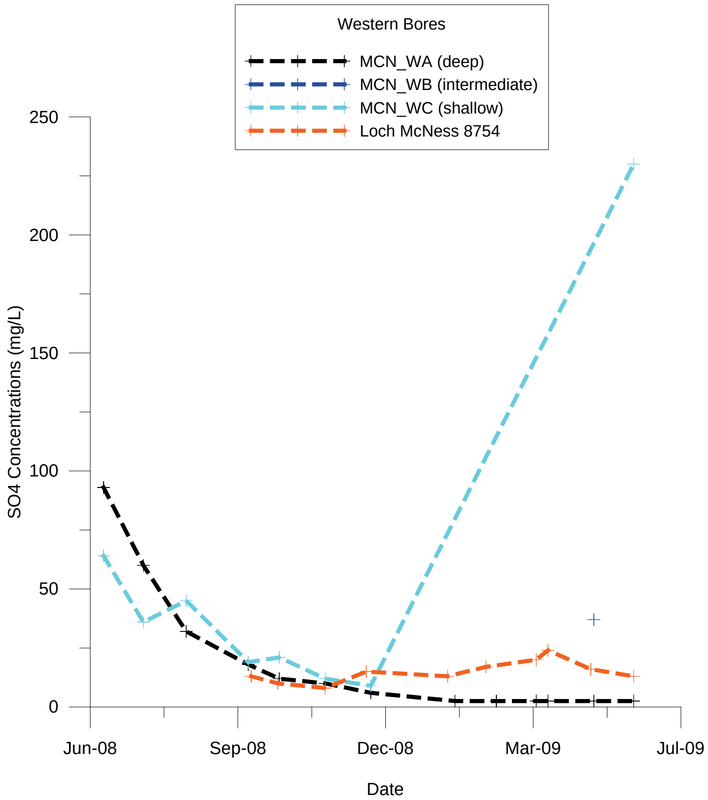


Figure 42 Variation over time of sulfate in western bores and Loch McNess, June 2008 to June 2009 (concentration axis is logarithmic).

Sodium and calcium

The concentration of sodium in the eastern (up-gradient) bores and in the lake is shown in Figure 43. Sodium shows a decrease in concentration with depth within the Superficial aquifer. Lake concentrations are generally between those of groundwater in shallow and intermediate level bores from June to December 2008 (winter), but higher than in eastern groundwater concentrations in summer, up to June 2009. Chloride concentrations follow the same pattern follows consistent with effects of water evaporation over summer.

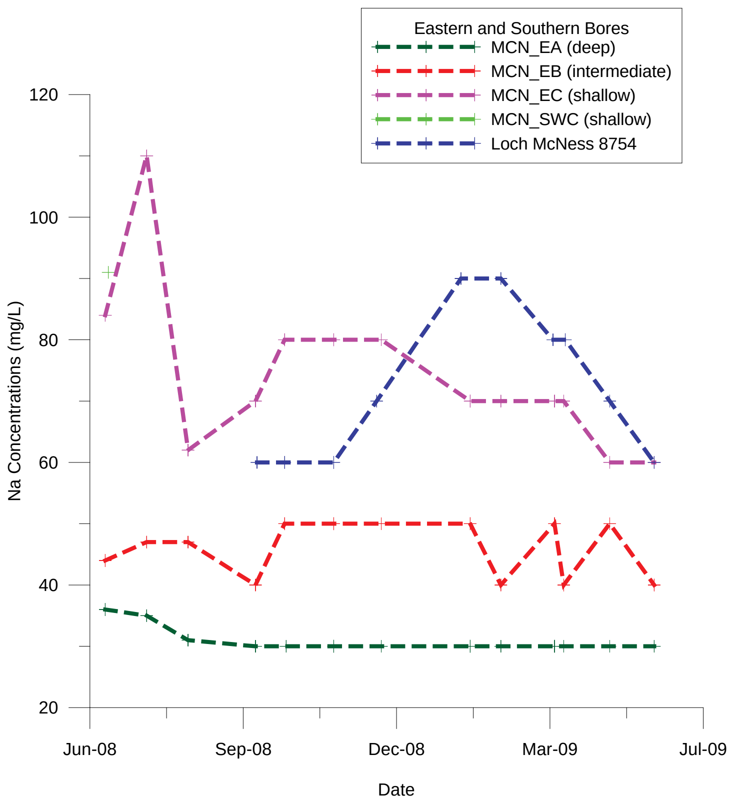


Figure 43 Variation over time of sodium in eastern bores and in Loch McNess

The sodium concentrations in the western bores are more variable, although the analysis is complicated by the absence of data for bores MCN_WB and MCN_WC in the critical period between December 2008 and April–June 2009 (i.e. the transition from summer to winter). However, there is some indication of strong increases in the concentration of sodium in shallow and intermediate groundwater in April–June 2009, following the high concentrations seen in the lake over summer. The latter data is consistent with leakage of lake water into groundwater on the western edge of the lake.

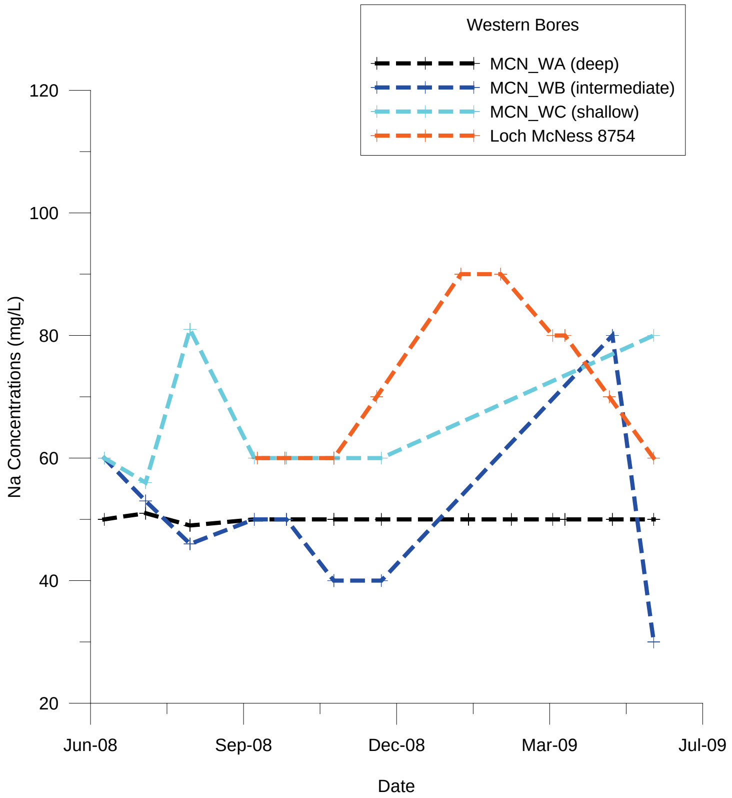


Figure 44 Variation over time of sodium in western bores and in Loch McNess

Calcium shows a distinctly different pattern to that of sodium (Figure 45 and Figure 46). In the eastern bores, calcium is highest in the shallow bore MCN_EC and to a lesser extent the deeper bore MCN_EA, with this being related to lithological and water quality stratification within the Superficial aquifer and associated with higher bicarbonate concentrations. As indicated above, the lake water and groundwater from the intermediate bore MCN_EB have much lower calcium concentrations, so it would seem that groundwater of similar composition to that in the intermediate bore is the dominant groundwater discharging into the lake.

On the down-gradient side of the lake, the shallow and intermediate bores (MCN_WB and MCN_WC) have higher calcium concentrations, with strong indications of highest levels following summer evaporation of the lake (i.e. in April and June 2009). This is consistent with lake water discharging to groundwater down-gradient of the lake, although infiltrating water must be leaching calcium from carbonate minerals below the lake to account for the increase in calcium between the lake and the western shallow and intermediate bores, unless there is significant variability in calcium concentration within the lake. Summary data on the latter from studies done by the Centre for Ecosystem Management at Edith Cowan University (Froend et al. 2004) indicate variations in calcium in rounds 26 and 27 in Loch McNess south (26–28 mg/L), close to those observed in the lake at location 8754.

The incidence of higher concentrations of calcium in June 2008 and April to June 2009 is consistent with reactions between carbonate minerals in limestone and infiltrating lake water affected by acidification over summer.

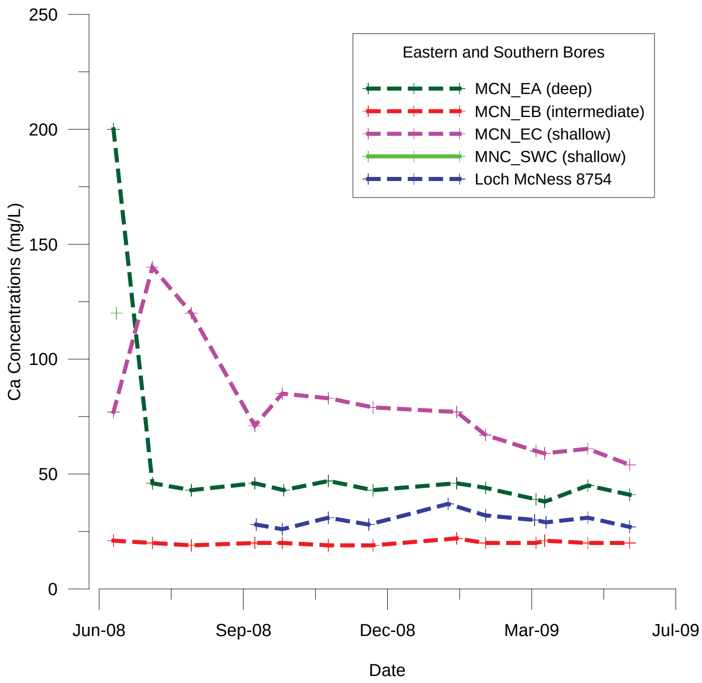


Figure 45 Variation over time of calcium in eastern bores and in Loch McNess

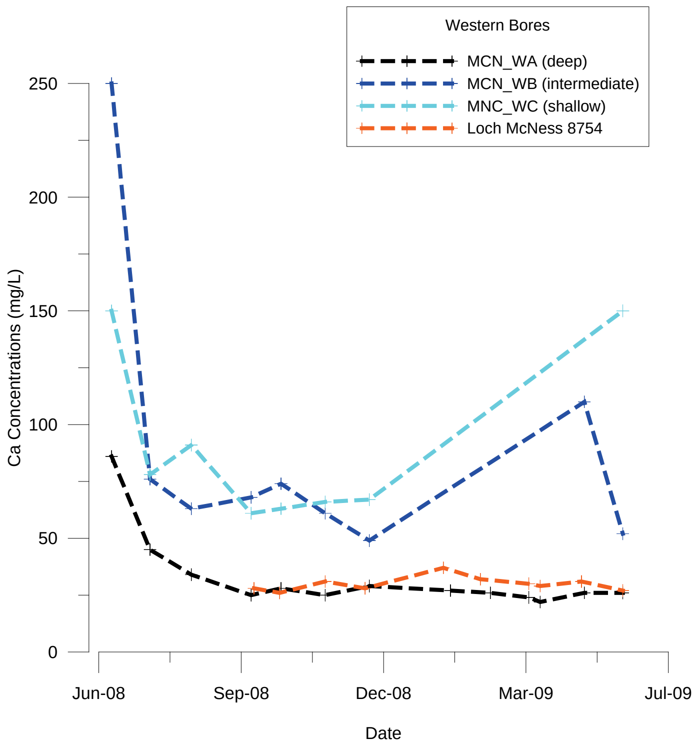


Figure 46 Variation over time of calcium in western bores and in Loch McNess

Nutrients

There is considerable variability in nitrogen species concentrations in groundwater around the site, shown by total Kjeldahl nitrogen (TKN – ammonium-N + organic N)

(Figure 47), ammonium-N and nitrate-N (Figure 48). Summary statistics for nitrogen species are shown for the east and west bores and the lake in Table 9.

The lake water is dominated by TKN, with the dominant species being organic nitrogen (ammonium-N median of only 0.02 mg/L). TKN increases in concentrations towards the end of summer (to March 2009) and then decreases (to June 2009). There is little oxidised nitrogen within the lake water at location 8754. Organic nitrogen in the lake water is assumed to be related to biomass which has developed within the lake, peaking in summer months (Figure 47).

Up-gradient of the lake in the eastern bores, groundwater at the intermediate and deep levels (MCN_EA and MCN_EB) have negligible amounts of nitrogen species, although median nitrate (NOx) in the intermediate bore is at a higher concentration than the trigger level. This contrasts with groundwater from the shallow bore MCN_EC which shows high nitrate (median 2.9 mg/L and highest value 18.0 mg/L (Figure 48)) and moderate to low levels of TKN but low ammonium-N. Shallow groundwater to the east of the lake thus has been affected by leaching of high levels of nutrients (nitrate) which have persisted, whilst the generally anoxic conditions deeper in the aquifer would have removed nitrate by denitrification, if indeed groundwater at these levels had been affected.

Table 9 Summary statistics for nitrogen species in east and west bores and in Loch McNess at location 8754

Location	**TKN mg/L**			**DON mg/L**			**Ammonium-N mg/L**			**Nitrate-N mg/L**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
MCN-EA	0.07	0.49	0.18	<0.025	0.099	0.045	0.01	**0.19**	0.03	<0.01	0.014	<0.01
MCN-EB	<0.01	0.07	0.04	<0.025	0.054	0.046	<0.01	0.02	<0.01	**0.1**	**0.17**	**0.13**
MCN-EC	0.1	**1.6**	0.14	<0.025	1.1	0.12	<0.01	0.03	0.01	**0.5**	**18**	**2.9**
MCN-WA	0.22	0.46	0.3	0.048	0.17	0.12	0.075	0.23	0.14	<0.01		
MCN-WB	0.74	1.8	1.4	0.11	0.45	0.2	**0.51**	**1.3**	**1.0**	<0.01		
MCN-WC	0.23	0.41	0.34	0.18	0.29	0.22	<0.01	0.18	0.06	<0.01	0.11	0.01
8754	0.28	1.6	0.52	0.26	1.1	0.46	<0.01	0.05	0.02	<0.01	0.02	<0.01
Trigger*		1.5 (TN)			-			0.04			0.1 (NOx)	
Drinking water guidelines		-			-			0.40			10.0	

** Trigger value for freshwater lakes and reservoirs (ANZECC & ARMCANZ 2000).*

*Exceedances in lake water and up-gradient bores highlighted in **blue**, exceedances of guideline values for down-gradient bores in **red**.*

Drinking water guideline maximum concentrations from NHMRC and NRMMC 2004.

Groundwater from the bores down-gradient of the lake on the western edge have generally low nitrogen concentrations, with negligible nitrate, but moderate concentrations of TKN (of the same order as those in the lake) and ammonium in bore MCN_WB.

Water in Loch McNess south (location 8754) shows a minor exceedance, in only one case, of the ANZECC wetland trigger levels for total nitrogen (TKN, which forms the majority of the recorded nitrogen in lake water). One maximum value for ammonium-N also marginally exceeds the trigger level.

There is potential for nitrogen contamination of lake water through discharge of nitrate enriched groundwater close to the watertable shown in the shallow up-gradient (MCN_E) bore, although this is not reflected in lake water nitrogen monitoring.

Nitrate generally in groundwater in the down-gradient bores is mostly below drinking water guideline concentrations, except for ammonium-N in groundwater at intermediate depths (Table 9).

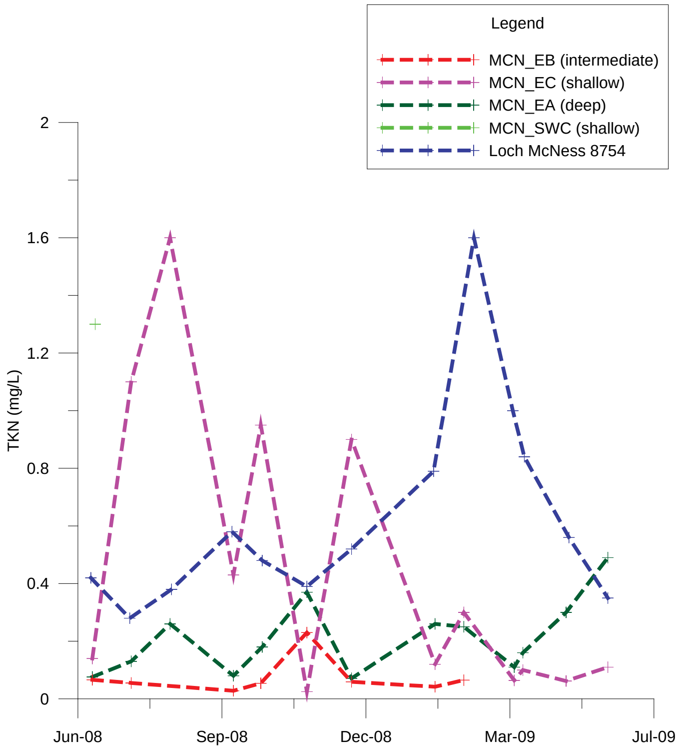


Figure 47 Variation over time in total Kjeldahl-N in eastern bores and in Loch McNess

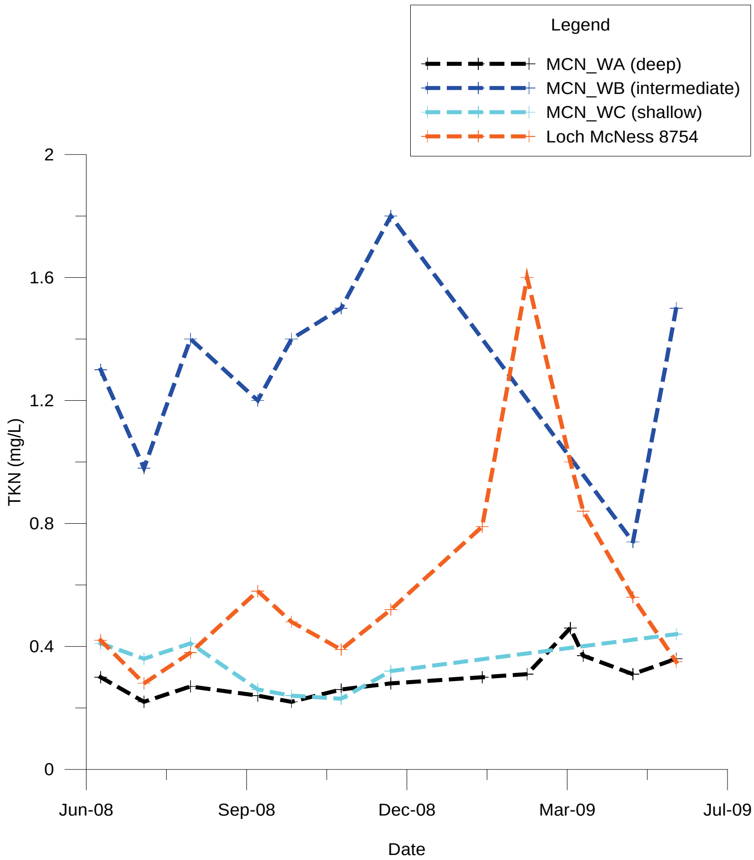


Figure 48 Variation over time in total Kjeldahl-N in western bores and in Loch McNess

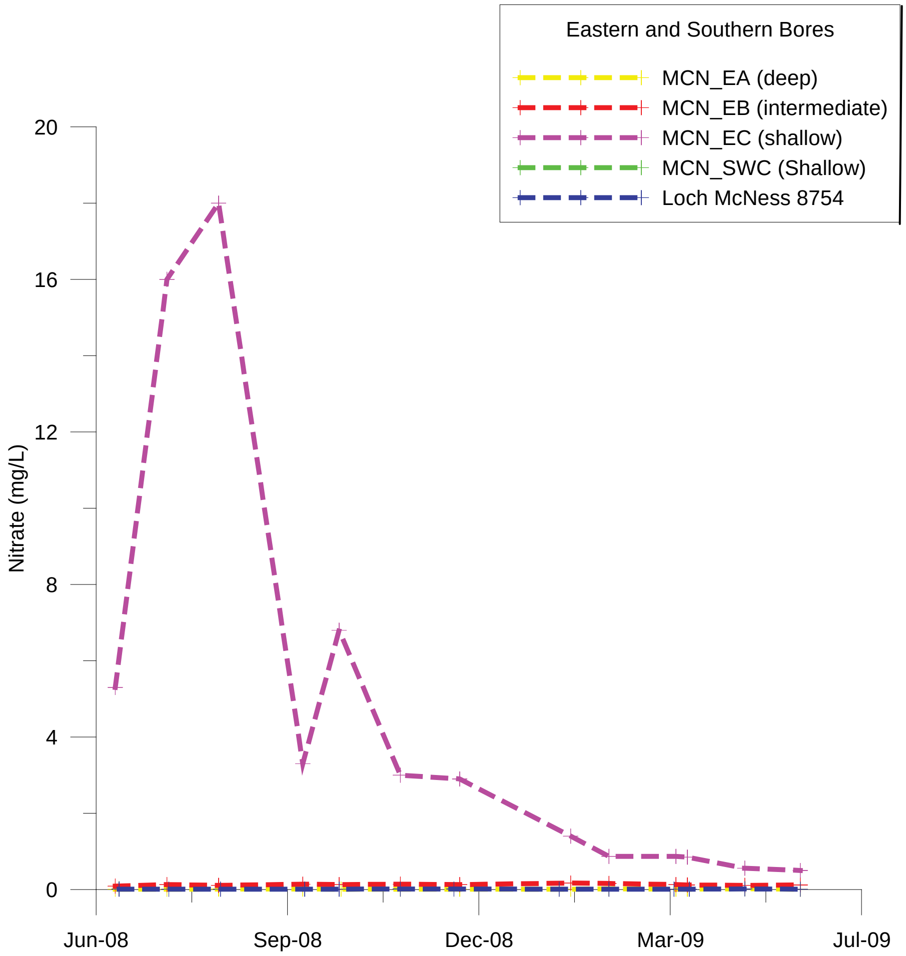


Figure 49 Variation over time in nitrate in eastern bores and in Loch McNess

Summary statistics for phosphate in groundwater and lake water at Loch McNess are shown in Table 10, and data is compared with ANZECC and ARMCANZ (2000) trigger levels for wetlands for lake water and up-gradient bores. Clearly median concentrations in lake water do not exceed trigger levels for total phosphorus or for soluble reactive phosphorus (SRP). All bores show higher median total phosphorus concentrations than in the lake water, with intermediate and deep bore showing median concentrations above the freshwater trigger level. The shallow up-gradient bore (MCN_EC) shows total phosphorus concentrations below the trigger level. Only the deep up-gradient bore (MCN_EA) shows median soluble phosphorus concentrations above the SRP trigger level.

All groundwater phosphorus concentrations are above the levels found in surface water in the lake, which have consistently remained below trigger levels.

Table 10 Summary of total and reactive soluble phosphate species in groundwater in east and west bores and in Loch McNess at location 8754.

Location		**Total P mg/L**			**SRP mg/L**	
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**
MCN_EA	0.078	0.61	0.33	0.016	0.069	0.032
MCN_EB	0.039	2.1	0.13	<0.005	0.038	0.015
MCN_EC	<0.005	0.025	0.011	<0.005	0.006	<0.005
MCN_WA	0.043	0.12	0.061	<0.005	0.063	<0.005
MCN_WB	0.035	0.17	0.066	<0.005	0.027	0.022
MCN_WC	0.028	0.17	0.08	<0.005	0.036	0.031
8754	<0.01	0.035	0.016	<0.005	0.012	<0.005
Trigger value *		0.06			0.03	

** Trigger values are ANZECC and ARMCANZ (2000) concentrations for wetlands*

Exceedances are shown in blue

Minor and trace metals and metalloids

Summary statistics for a number of metals and metalloids are shown in Table 11, which also shows the exceedances of the freshwater trigger levels for wetlands (ANZECC & ARMCANZ 2000). It is noteworthy that lake water shows exceedances of freshwater wetland trigger concentrations only for boron (one high concentration) and cadmium (one high concentration) over the SGS monitoring period.

There are a number of metals and metalloids which exceed wetland trigger levels and drinking water guideline maximum concentrations in groundwater from the up-gradient and down-gradient bores.

Groundwater up-gradient of the lake shows exceedances of wetland trigger levels for median concentrations of arsenic, chromium, nickel and zinc in MCN_EA and MCN_EB, whilst bore MCN_EC shows exceedances for median concentrations for chromium and zinc. There is one elevated concentration of cadmium in each of the bores MCN_EA and MCN_EB.

Metal and metalloid concentrations in MCN bores down-gradient and to the west of the lake were also assessed against drinking water guideline maximum concentrations (NHMRC & ARMCANZ 1996). Arsenic and soluble iron median concentrations exceed the guideline for all three MCN_W bores, whilst the maximum concentration of chromium and nickel exceed the guideline in bores MCN_WA and MCN_WB.

Drinking water guidelines have been used to give 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 considers that any untreated waters taken from the environment is unsafe for human drinking.

From the available data there appears to be a relationship between anoxic conditions in groundwater and elevated concentrations of soluble iron and arsenic and possibly other metals. The metal contamination does not affect the lake water quality and there is no evidence which supports acidification being a cause of increased arsenic or iron in groundwater.

Table 11 Minor metals and metalloids in groundwater and lake water at Loch McNess

Location	Al mg/L			As mg/L			B mg/L			Cd mg/L			Cr mg/L		
	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.	Median
MCN-EA	0.012	0.300	0.0240	0.003	0.073	0.0170	0.0150	0.079	0.0335	<0.0001	0.0006	<0.0001	0.002	0.081	0.024
MCN-EB	0.006	0.150	0.0110	<0.001	0.013	0.0030	0.0120	0.0420	0.0220	<0.0001	0.0005	<0.0001	<0.001	0.069	0.007
MCN-EC	<0.005	0.029	0.0090	<0.001	**0.002**	<0.0010	0.0160	0.0630	0.0320	<0.0001	0.0001	<0.0001	<0.001	0.010	0.002
MCN-WA	0.007	0.022	0.0160	**0.022**	**0.081**	**0.0290**	0.0150	**0.7800**	0.0460	<0.0001	0.0003	0.0001	<0.001	0.002	0.001
MCN-WB	0.006	0.032	0.0180	0.005	**0.029**	**0.0080**	0.0110	0.0710	0.0310	<0.0001	0.0004	<0.0001	<0.001	**0.099**	0.009
MCN-WC	0.006	0.012	0.0065	**0.011**	**0.050**	**0.0205**	0.0140	0.0850	0.0275	<0.0001	<0.0001	<0.0001	<0.001	0.001	<0.001
8754	0.007	0.018	0.011	<0.001	0.004	0.001	0.011	0.5200	0.0185	<0.0001	0.0006	<0.0001	<0.001	0.001	<0.001
Trigger value*		0.0550			0.013**			0.3700			0.0002			0.001	
Drinking water guidelines		0.2000			0.007			0.3000			0.0020			0.050	

*** value for As(III) shown. Trigger level for As(IV) is 0.024 mg/L.*

** Trigger values are ANZECC and ARMCANZ (2000) concentrations for toxicants in wetlands*

Exceedances of trigger levels for lake water and up-gradient bores are in blue, exceedances of trigger levels for down-gradient bores are in red.

Table 12 Minor metals and metalloids in groundwater and lake water at Loch McNess – continued

Location	Fe (sol) mg/L			Mn mg/L			Ni mg/L			Zn mg/L		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
MCN_EA	0.080	**1.300**	**0.360**	0.023	**0.150**	0.056	0.002	0.049	0.014	0.002	0.430	0.027
MCN_EB	0.005	0.120	0.027	0.002	0.440	0.013	0.001	0.024	0.003	0.002	0.150	0.026
MCN_EC	0.007	0.046	0.011	0.003	0.025	0.007	<0.001	0.003	0.002	0.001	0.055	0.010
MCN_WA	**1.700**	**4.600**	**2.200**	0.054	**0.140**	0.063	0.005	**0.028**	0.011	0.005	0.100	0.034
MCN_WB	0.190	**3.800**	**0.410**	0.012	0.100	0.024	0.002	0.015	0.004	0.002	0.036	0.006
MCN_WC	**2.000**	**7.800**	**2.350**	0.007	0.060	0.020	<0.001	0.001	<0.001	0.002	0.160	0.008
8754	0.028	0.160	0.071	0.004	0.014	0.006	<0.001	<0.001	<0.001	<0.001	0.010	0.004
Trigger value*	-			-			0.011			0.008		
Drinking water guidelines		0.300			0.100			0.020			3.000	

** Trigger values are ANZECC and ARMCANZ (2000) concentrations for toxicants in wetlands.*

Exceedances of trigger levels for lake water and up-gradient bores are in blue, exceedances of trigger levels for down-gradient bores are in red.

Herbicides and pesticides

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

6.3 Summary of trigger level breeches

Table 13 Summary of trigger level breeches

	Trigger levels – wetlands south-west Australia – ANZECC and ARMCANZ (2000)
pH	Lake samples for 8754 (Loch McNess south) are above the trigger level of pH 8.5. All up-gradient bores are below this level but the low pH does not affect lake water quality. There is evidence of acid sulfate soil activity in the lake sediments, but carbonate buffering from high lake pH and possibly carbonate minerals in the upper part of the aquifer buffers acidity from sulfide oxidation.
Total N	Median lake TN below trigger level but maximum observed concentration marginally exceeds trigger level towards end of summer. Shallow up-gradient bore grossly exceeds TN trigger level from high nitrate, but this is not carried through to the lake in discharged groundwater .
NH4-N	Median lake concentration below trigger level, but maximum observed concentration slightly above trigger level. Median concentration in up-gradient bores well below trigger level.
NOx	Median lake concentration well below the trigger level. Shallow up-gradient bore shows high concentrations, but other up-gradient bores depleted in nitrate possibly from denitrification.
TP	Median lake concentration below trigger level. Up-gradient deeper bores are above trigger level median shallow bore is well below trigger level.
FRP	Median lake SRP well below trigger level, and only deep up-gradient bore has median level above trigger level.

	Trigger levels – toxicants in freshwater ANZECC and ARMCANZ (2000)	Drinking water guidelines (as main beneficial use) NHMRC and ARMCANZ (1996)
Al	Concentrations in the lake below trigger levels.	All concentrations below guideline concentrations.
As	All lake concentrations below trigger level. Deep up-gradient bore median level above trigger. Maximum levels in shallow and intermediate bores above trigger level.	All median concentrations in down-gradient bores above guideline. Median level in deep up-gradient bore above guideline. Groundwater typically has arsenic above guideline value where conditions are reducing for iron solubilisation.
B	One lake level concentration slightly above trigger level. Groundwaters well below trigger level apart from one sample in shallow down-gradient bore.	Most groundwaters well below guideline level. Bore MCN-WC has unusually high concentration in one sample.
Cd	Lake water exceeds trigger level for one sample, at similar concentration to groundwater in up-gradient deep and intermediate bores.	Groundwater in down-gradient bores well below guideline level.
Cr	Median lake water concentration well below trigger level but median level in up-gradient bores all above trigger.	Groundwater in down-gradient bores well below guideline level.

	Trigger levels – toxicants in freshwater ANZECC and ARMCANZ (2000)	Drinking water guidelines (as main beneficial use) NHMRC and ARMCANZ (1996)
Ni	Lake concentrations well below trigger level, but up-gradient deep bore median level exceeds trigger, and maximum concentration in intermediate bore is above trigger level.	Deep down-gradient bore marginally exceeds guideline value. Deep up-gradient bore median value exceeds guideline and maximum concentration in intermediate up-gradient bore exceeds guideline
Zn	Lake water maximum observed concentration close to trigger level. Up-gradient median concentrations are all above trigger value.	All concentrations below guideline concentrations.
Fe	N/A	Median concentrations in all down-gradient bores exceed guideline value.
Mn	N/A	Maximum concentration in shallow down-gradient bore exceeds guideline value.

7 Processes and interactions between surface water and groundwater

Analysis of the local hydrogeology at Loch McNess allows an interpretation of hydrogeochemical processes and surface water–groundwater interactions to be made. These interactions are shown conceptually in Figure 50. Previously, Loch McNess could be classified as a ‘flow-through lake’, with a connection to the regional groundwater flow system of the Gnangara Mound. However, certain fundamental changes have occurred to the surface water–groundwater interactions and the hydrochemistry at the lake and its surroundings. These changes have implications for how the site should be managed.

The following sections discuss what has been learnt through this project.

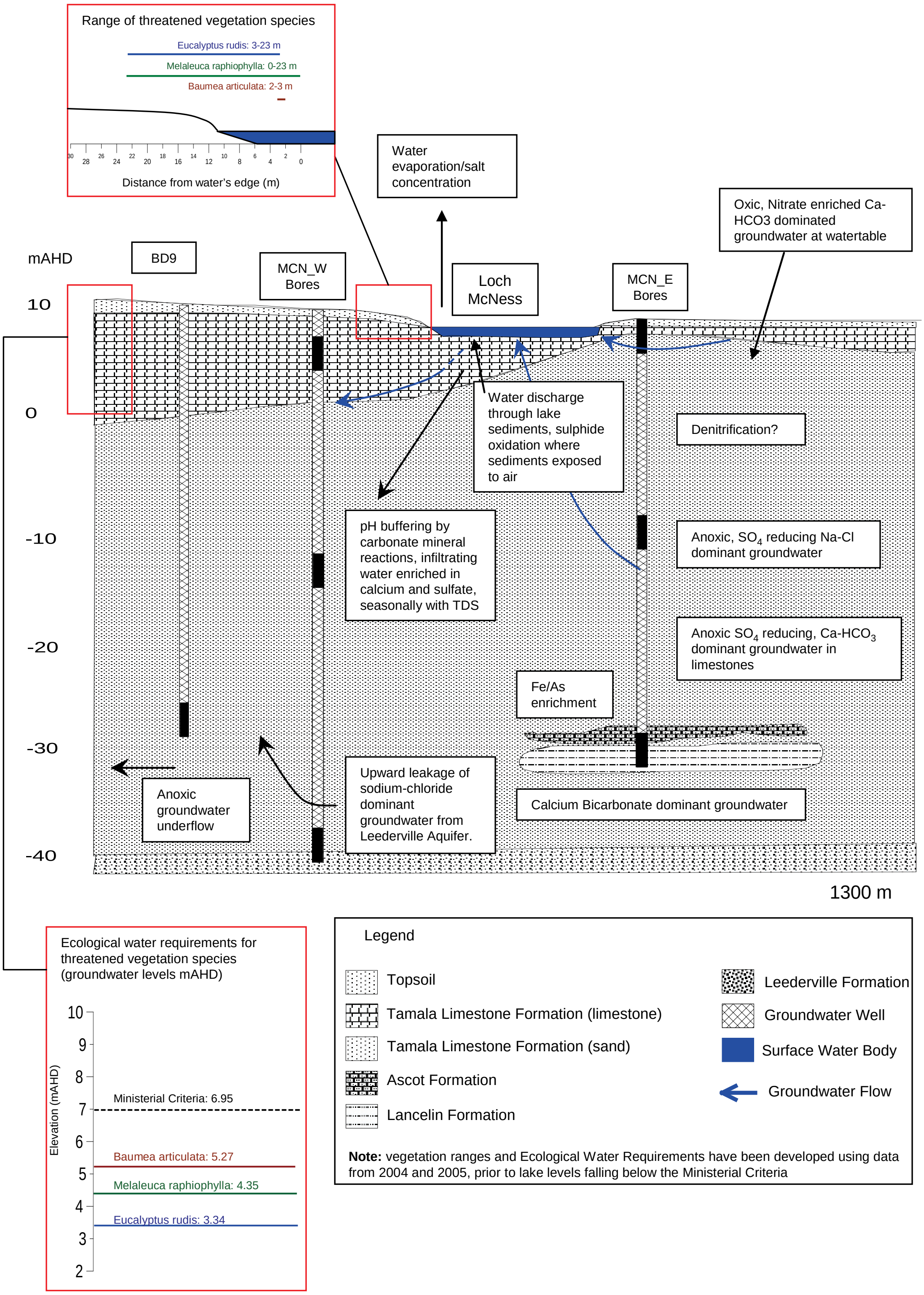


Figure 50 Conceptual diagram of geochemical processes and EWRs for groundwater-dependent systems at Loch McNess

7.1 Groundwater hydrology

Loch McNess is in hydraulic connection with the regional groundwater flow system via the Superficial aquifer. Lake and groundwater levels are defined by a dynamic balance between topography, hydrogeology and varying climate, and probably groundwater abstraction and land use, too. Loch McNess is a lake which is dependent on groundwater for its existence.

This study has found that the lake levels and local watertable vary in phase (with normal 'phase-delay' and 'signal' attenuation of the watertable). Summer minima occur in March and April, whilst winter maxima occur in August and September. Fluctuations in heads down-gradient contrast with the much more subdued variability in up-gradient bores (and in the lake).

Loch McNess had a semi-stable water level and small annual water level range (~ 0.1 m) until late 2006. Prior to 2006, groundwater levels were lower than in the lake on its down-gradient side, although these rebounded seasonally and showed higher levels than in the lake, which presumably allowed lake levels to remain remarkably constant over time. However, there has been a steady decline in groundwater and lake levels over time since the early 1990s up until 2006.

Since 2006, the water level in the lake has declined to 6.70 m AHD (from a maximum of 7.05 m), preceded by a rapid decrease in groundwater levels on the down-gradient side of the lake (bore BD9). There is a correlation between the marked decline in groundwater levels on the down-gradient side of the lake and, following a short lag period, by a slower decline in lake levels which stabilise somewhat after 2007–08, but still show a seasonal variation from historic data. The relationship between low rainfall in 2006 and continuation of groundwater levels lower than in the lake on its down-gradient side, indicates that there is a new hydrologic regime operating and the relationship between lake and groundwater levels is now different to what it was. Thus, Loch McNess has changed from a lake with flow-through characteristics to one where lake water on the western edge of the lake has become detached from groundwater and any discharge to groundwater from the lake or lake sediments is by leakage through what is assumed to be a partially saturated zone on the western edge of the lake.

There is a vertical groundwater flow component (upward leakage) on the eastern side of the lake, which indicates groundwater discharge to the lake. This weak upward head on the eastern side indicates mainly flow into and below the lake from the Superficial aquifer. Water quality characteristics suggest groundwater within the upper half of the aquifer discharges into the lake with predominant composition similar to that observed in the intermediate depth bore to the east of the lake.

The groundwater flow pattern on the western side of the lake is more complex. Here there is a marked recharge (strong head differential) component to the intermediate groundwater from the shallow groundwater that receives recharge from the lake. Conversely there is an upward gradient from the 'deeper' aquifer. This suggests upward leakage is occurring locally in the Superficial Aquifer where it directly overlies sandstone of the Leederville Formation (possible Pinjar Member) indicating hydraulic connection between these two aquifers.

Bekesi (2007 unpublished) analysed the groundwater hydrology and found:

- a change in groundwater gradient ‘across the lake and environs’, from the up-gradient side of the lake (steeper gradient of 0.0057) compared with down-gradient (gentler gradient of 0.0007) explained by facies change
- down-gradient (west of lake) lies the Tamala Limestone, which is a dual porosity transmissive aquifer that may be sensitive to water level changes
- up-gradient (east of lake) lies the moderately transmissive sands (presumably Spearwood Sands)
- small but increasing gradients (down-gradient) in summer of 2006 (gradient = 0.0036 in September 2006 and 0.0048 in December 2006)
- down-gradient from Loch McNess, the hydraulic gradient increased locally by about one-third within a short time after 2006
- up-gradient of Loch McNess, the hydraulic gradient has decreased as groundwater levels have receded, giving less inflow of groundwater to the lake system
- there is a southern groundwater flow component (lake to caves flow) perpendicular to the ‘regional’ gradient; between bore YN7 and the lake. The hydraulic gradient is half that of 1995.

The decline in regional groundwater levels up-gradient cause less groundwater inflow to Loch McNess. In addition, the more transmissive limestone down-gradient from the lake locally show significantly increased gradient and hence increased outflow from the lake. More outflow coupled with less inflow causes the decline in Loch McNess water levels. Hence, further decline in lake levels can be expected unless groundwater levels increase upstream of Loch McNess through increased recharge.

The cause of the lower inflow up-gradient is not clear. Furthermore it is hard to visualise a change in the hydraulic character of this phreatic aquifer (less inflow – more outflow). There may be downstream stressors (abstraction bores, land use, drainage) that are increasing the gradient downstream by flow capture. If this is the reason, water levels in Loch McNess may recover if the stressors can be identified and moderated.

Figure 13 shows licensed allocations for Water Corporation production bores and private bores west of Loch McNess. Although licensed for 1.5 GL/a, there has been zero draw from bores YB6 and YB7, and on average between 0.25 GL/a and 0.35 GL/a are abstracted from bore YB4. As not all private bores are metered, it is not possible to know the total abstraction from them. However, it appears that most abstraction immediately to the west of the lake is coming from the golf course and the cave supplementation bore (54 ML/a). Adrian Peck, (pers. comm.) noted that there are horticultural developments to the south-east of Loch McNess that may affect groundwater levels close to Loch McNess. The possible effects of these abstractions on the hydraulic gradient require further investigation.

7.2 Groundwater chemistry

Major ion hydrochemistry suggests that:

- stratification with respect to groundwater quality within the Superficial aquifer is related to some extent to lithological stratification (i.e. leached sands as compared with limestone strata)
- east (up-gradient) of the lake:
  - Groundwater discharges directly to the lake and emanates from the upper half of the Superficial aquifer where groundwater characteristically is of similar composition to that observed in the intermediate bore (sodium and chloride enriched and depleted in magnesium).
  - Shallow groundwater has been affected by leaching of high levels of nutrients (nitrate). Bore MCN_EC seems to be affected by a source of nitrate to the east of the lake.
- west (down-gradient) of the lake:
  - Observed relative increase in sulfate and calcium in shallow groundwater following summer (i.e. by April–June 2009) and apparent decrease over winter, is consistent with oxidation of acid sulfate soils and/or sulfides and release of sulfate and acidification of infiltration water from lake sediments as lake levels fall, and buffering of pH by reaction between infiltrating water and carbonate minerals in extensive limestone strata in the upper part of the aquifer.
  - The effects of evaporation of lake water over summer increases the concentrations of chloride and sodium, and these carry through to the groundwater at shallow and intermediate depths, consistent with lake discharge to groundwater.

There appears to be a relationship between anoxic conditions in groundwater and elevated concentrations of soluble iron and arsenic and possibly other metals and metalloids. These elevated concentrations, particularly of arsenic, require further investigation, although metal contamination is not affecting the lake water quality at present.

Bore hydrographs support the hypothesis that lake water discharges to shallow groundwater on the western edge of the lake. Here, the watertable is hydraulically detached from the lake on its western edge as lake levels have dropped, and acidification of water in lake sediments would seem to have increased the concentration of sulfate in the lake and in groundwater down-gradient of the lake.

There is little evidence of decreases in pH due to acidification in lake sediments, in the lake or in groundwater on the western edge of the lake. The buffering of pH by lake water alkalinity and by carbonate mineral dissolution is clearly effective in maintaining steady pH levels. However, some incidences of lower pH values in lake water in Loch McNess north suggest that alkalinity may not be as effective a buffering agent within these parts of the lake where water depth is much shallower and where leaching of acid sulfate soils is occurring.

7.3 Summary of findings on processes and interactions

In summary, Loch McNess, whilst previously described as a ‘flow-through lake’, recently has become permanently disconnected from the groundwater flow system on its down-gradient (western) side. Groundwater discharge into the lake on its eastern (up-gradient) side has continued but is somewhat decreased. Most recently, the lake appears to be recharging groundwater through a thin, unsaturated zone presumably in part beneath the lake on its western (down-gradient) side. The lake is clearly dependent on groundwater and given the detachment of water levels in the lake and in groundwater to the west, there must be a poor hydraulic connection between the lake and groundwater in the Superficial aquifer. Lake water thus ‘perches’ on shallow lake sediments on the western edge.

Detailed monitoring of groundwater levels over time, in bore BD9 particularly, have been instrumental in defining changes in the hydrogeological system around the lake. More frequent (monthly) monitoring of groundwater and lake levels including downstream of the lake along a given flow path to the coast is recommended in future. The installation of continuous water level recorders should be considered on bores BD7 and BD9.

Loch McNess south (the largest area of open water within the Loch McNess system) has been the main focus of this study, given its importance. However, it would appear that Loch McNess north is more vulnerable to the changed hydrological regime. It is a significantly shallower surface water system so the effects on water quality, such as lower pH, increased salinity, increased nutrient peaks and possible eutrophication, are likely to occur more rapidly. It is recommended that, if possible, a similar drilling investigation and monitoring be carried out at Loch McNess north to monitor this more vulnerable system.

8 Implications for ecological values and management recommendations

8.1 Monitoring infrastructure

The new monitoring bore associated with the southern vegetation transect recommended for implementation by the Department of Water (2008a) is now in place (MCN_SWC) and has been recording data since June 2008. As the northern vegetation transect is considered to be less representative, no monitoring bore has been established there. However, as the threatened plant *Baumea articulata* is still present at this site (recorded as part of 2008 vegetation survey) but has not been recorded at the southern vegetation transect since 2005, consideration should be given to establishing a bore associated with this transect and ensuring that vegetation monitoring is continued at this site. In addition, installing this second bore would allow comparison and better data resolution for groundwater-vegetation links, as well as providing improve monitoring of vegetation changes related to groundwater depth.

As there has been only limited data collected from the MCN bores, it is also recommended that monitoring of a number of the long term bores is maintained (i.e. YN3, YN5, BD7, BD9), especially if the risk bands proposed in Section 8.3 are used as a management tool or trigger.

Further, we recommend that the suitability of all monitoring bores is reviewed after five years of data collection to ensure that they provide the data necessary to assess ecological changes. After five years, the dataset collected should be sufficient to assess the effectiveness of the existing bores for monitoring purposes and to identify if any further infrastructure is required or whether the monitoring frequency of some bores needs to be changed.

8.2 Ecological implications

The following consequences of falling water levels to date are expected to worsen should lake levels remain below the Ministerial Criteria level of 6.95 m AHD:

- degradation of water quality, particularly in North Loch McNess
- significant reductions in macroinvertebrate richness
- significant shifts in wetland vegetation range and community composition
- decline in vegetation health
- some terrestrialisation of wetland areas
- some encroaching of fringing vegetation into the lake basin
- reductions in habitat for aquatic macroinvertebrates, fish and waterbirds.

Water level and water quality are considered to be the most immediate threats to the ecological values of Loch McNess, which historically had a relatively constant water level and good water quality. Extremely low surface water levels have significantly reduced the amount of habitat available to wetland plants and aquatic fauna (invertebrates, fish and waterbirds), with effects on the health of wetland plants and the richness of macroinvertebrate communities already apparent.

Continuing declines in water level will increase the risk of acidification of the lake as decreasing lake water levels give increased oxidation of sulfide minerals within lake sediments. Although pH values below 7.0 – the minimum guideline value for wetlands in south-western Australia for the protection of aquatic ecosystems (ANZECC & ARMCANZ 2000) naturally occur in Loch McNess, the frequency and magnitude of these occurrences has increased since 2006, with a record minimum pH of 6.32 recorded in 2008. Although not a direct threat at this time, the effects of acidification are potentially devastating if pH values continue to decrease, particularly in Loch McNess north. Prolonged exposure to pH levels below 6.0 are detrimental to wetland biota, resulting in a loss of diversity and abundance, as well as altering nutrient and ion absorption capacities. Permanent subsurface saturation is required to prevent acidification (Horwitz et al. 2009).

Deteriorating water quality will affect aquatic fauna values at the site by reducing habitat suitability. Although nutrient levels are below guideline values (ANZECC & ARMCANZ 2000), with the exception of some short-term exceedances, they are showing an increasing trend, elevating the risk of eutrophication. Eutrophication in Loch McNess north is considered a serious risk (Froend et al. 2004a) which would threaten the pristine designation of this area. Studies have shown that for the Swan Coastal Plain Wetlands, as nutrient levels increase macroinvertebrate richness decreases, rare taxa are lost and the abundance of tolerant species increases (Growns et al. 1992).

The source of excess nutrients in Loch McNess is uncertain, given the location of the wetland within the Yanchep National Park, although run-off from the nearby Yanchep pine plantation may be a contributing factor. Nutrients may also reach the lake through groundwater inflows, as nutrients are able to move freely through sandy strata of the Swan Coastal Plain (Growns et al. 1992). Nutrient levels will increase as water levels decrease due to a combination of concentration and the release of nutrients previously stored in lake sediments through increasing sediment re-suspension in shallow waters. Increasing nutrient levels will support elevated algal growth, potentially leading to algal blooms.

A number of possible ecological responses to persistent low water levels in have been described in Appendix 5 of *A summary of investigations into ecological water requirements of groundwater-dependent ecosystems in the South West groundwater area* (Department of Water 2006). Of these, the likely effects of persistent low water levels on the identified ecological values of Loch McNess are:

- change in overall condition from an undisturbed wetland to a disturbed state, due to:
    - severe reductions in rates of primary production and nutrient cycling in response to drying

  - severe disruptions to food chains due to loss of ecologically sensitive species and changes to nutrient availability (including changes linked to decreasing pH)
  - measurable destabilisation of wetland sediments due to increasing re-suspension of sediments as a result of lower water levels, as well as drying and erosion of exposed lake sediments
  - substantial changes to water quality beyond the natural limits of variation – particularly increasing nutrient levels, increasing conductivity and decreasing pH – leading to significant changes in the ecological community including the loss of sensitive aquatic fauna species
- reductions in diversity and abundance of current rich aquatic fauna through:
  - large reductions (> 50 % reduction in both vertebrate and macroinvertebrate abundance due to reduction in food and/or habitat availability (as result of drying)
  - reduction in quantity and quality of available water bird habitat due to low water levels
- change in vegetation communities and availability of associated habitat types, through:
  - increasing rates of territorialisation and encroachment of xeric species into wetland habitats, reducing quality and extent of wetland vegetation
  - significant changes in vegetation condition through substantial dieback in overstorey species, loss of density and cover in understorey species and reductions in vegetation height and diameter in response to declining groundwater levels.

If a critical threshold in groundwater level decline has been reached, ecosystems dependent upon stable water levels may never recover fully from the lake level decline. The magnitude of the decline in groundwater levels coupled with forecasts for a drier climate, suggests that a return to historic water levels is unlikely. Consequently, lake levels may remain below the Ministerial Criteria level for the foreseeable future and the ecological character of Loch McNess will shift further towards that of a marsh or wooded swamp, to the detriment of wetland values and communities.

Ecological water requirements

Although the current ecological water requirements and Ministerial Criteria appear to be appropriate for maintaining the identified ecological values associated with Loch McNess, the current Ministerial Criteria does not take into account the linkage between groundwater levels and lake levels. Given the long-term decline in groundwater levels and likely persistence of dry conditions, the Ministerial Criteria should be revised to better manage the risks to Loch McNess of persistent low water levels.

Examination of the results of the vegetation surveys from 2004 to 2008 (Bertuch et al. (2004), Rogan et al. (2006), Pettit et al. (2007), Boyd et al. (2008), Cullinane et al. (2009)) has shown that the Loch McNess vegetation community has responded to decreasing water levels and the bushfire in the summer of 2004 (Figure 51). Of the three threatened plant species present, *Melaleuca raphiophylla*'s range has remained similar, while *Eucalyptus rudis* has shown a shift in its range (increased up and downslope from 2004–05 to 2008 (Figure 51). While *Baumea articulata* survived the bushfire of 2004, it has not been recorded in association with the southern vegetation transect since 2005 (although it is still recorded in association with the northern transect).

As a groundwater monitoring bore has been established at the southern vegetation transect, minimum groundwater levels, set as ecological water requirements, for vegetation can be established for the southern vegetation transect using the mean water depth of common wetland species (as described by Loomes (2000) and cited in Froend et al. (2004b)). Application of this approach for determining the minimum water requirements for vegetation identifies the following minimum requirements:

- *Baumea articulata* – 5.27 m AHD
- *Eucalyptus rudis* – 4.35 m AHD
- *Melaleuca rhaphiophylla* – 3.34 m AHD

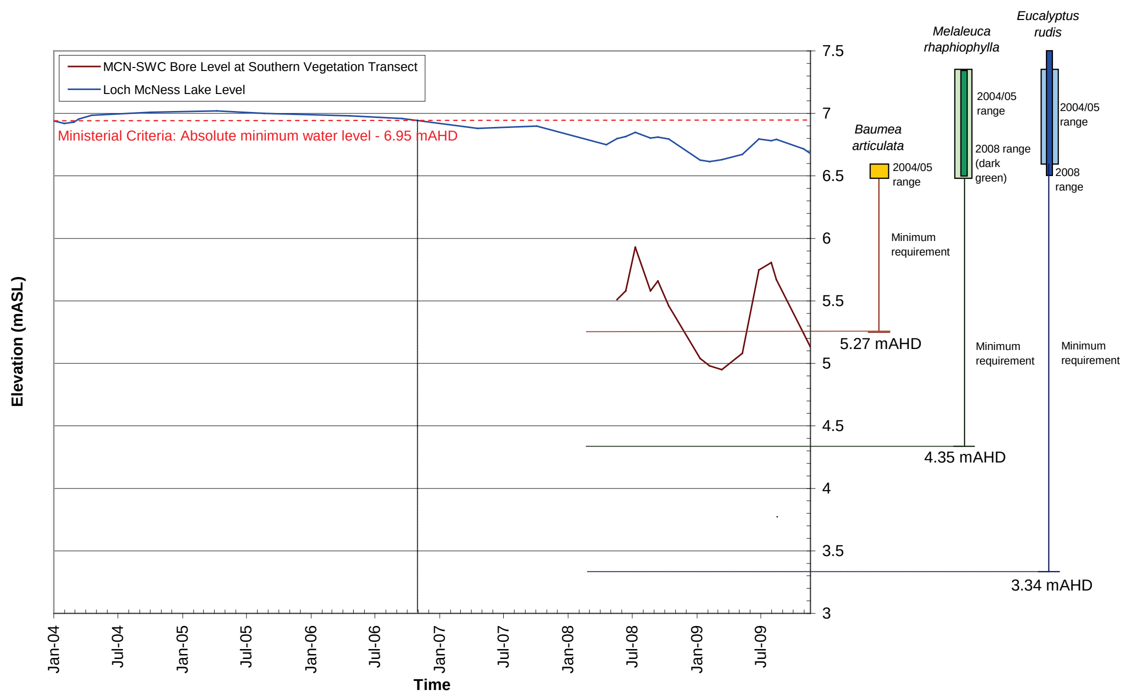


Figure 51 Relationship between vegetation, lake and groundwater levels (MCN_SWC bore)

In developing the minimum requirements, the range of each species from 2004–05 was used (Figure 51). This time period was selected as the lake level at that time was above the established Ministerial Criteria and *B. articulata* was present. The shift in range for *E. rudis* from 2004–05 to 2008 may be a response to the 2004 bushfire (decreased competition and increased habitat availability up and downslope) and declining water levels (resulting in a downslope shift), thus the 2008 range should not be used to develop ecological water requirements as it may over-estimate the depth to which roots may establish in order to access groundwater since changes in vegetation range are expected before the species reach their critical threshold (or minimum requirement).

In order to meet the minimum groundwater requirements of all wetland vegetation on the southern vegetation transect, a groundwater level of 5.27m AHD is required at bore MCN_SWC, and it is recommended that this is established as both a vegetation EWR and a Ministerial Criterion. Monitoring of bore MCN_SWC since 2008 (Figure 51) indicates that groundwater levels have fluctuated below this minimum level over summer 2008 and 2009, supporting the proposed minimum requirement for *B. articulata* (as *B. articulata* has not been recorded from this site since 2005) and the use of 5.27m AHD as a vegetation EWR and Ministerial Criterion.

Figure 52 provides a conceptual model of changes in hydrology and groundwater with a decline in lake level and the subsequent effects on vegetation. Figure 52(a) shows the interactions when groundwater levels are at or above the existing Ministerial Criterion (minimum water level of 6.95 m AHD). At this surface water level, the lake is a flow-through system and all key vegetation types are expected to extend their roots down to the saturated groundwater zone below the lake and/or unsaturated zone.

With reduced surface water levels (Figure 52b), while the groundwater level still remains connected along the eastern and northern shore (up-gradient), it becomes partially disconnected on the western and southern shore (down-gradient). As the lake level moves down the shore away from the fringing and riparian vegetation and the groundwater levels receded, the size of unsaturated zone increases between the vegetation and groundwater table (up and down gradient). As a result, shallow rooted species such as *B. articulata* can become disconnected from both the surface water and saturated groundwater table, thus becoming reliant on the unsaturated zone. Other, deeper rooted species such as *M. raphiophylla* and *E. rudis* are able to maintain contact with the saturated groundwater zone. However, they may also show signs of stress due to the increase in the unsaturated zone and reduction in root mass in direct contact with the saturated groundwater zone.

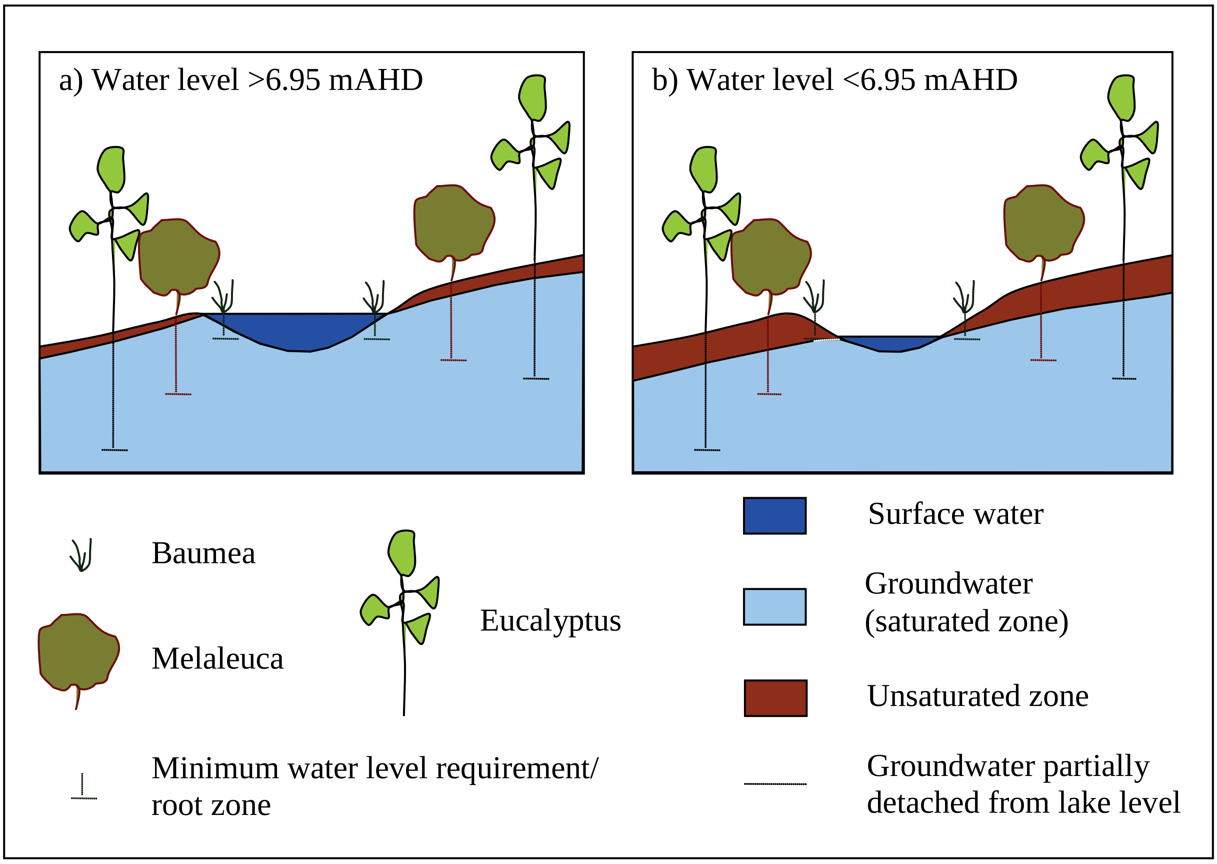


Figure 52 Conceptual model of changes in hydrology and the vegetation

Baumea articulata has not been recorded at the southern transect since 2005 and it is suspected that changes in surface and groundwater hydrology placed it under stress, leading to its loss from the southern vegetation transect. If the watertable has become partially detached from the lake level down-gradient, then hydrological changes may have resulted in *B. articulata* becoming reliant on water from the unsaturated zone and unable to persist at this transect. As the groundwater has remained connected to the lake level upslope, *B. articulata* is still able to reach the saturated groundwater zone and persist in these areas (hence its presence within the northern vegetation transect).

Consideration should be given to further investigation of the minimum water requirements for *B. articulata* at Loch McNess, as this species may have been lost from the southern vegetation transect before groundwater levels reached 5.27m AHD (minimum water requirement calculated using the methodology from Loomes (2000) as cited in Froend et al. 2004b). As the minimum requirements are meant to be based on low risk '(based on' means in water depth ranges rather than absolute minimums), then it could be expected that *B. articulata* would have been present at the site more recently than 2004–05.

It is anticipated that if groundwater levels continue to fall and/or remain below 5.27m AHD, more significant shifts in the vegetation community will occur as groundwater levels approach the minimum requirements for other species (*E. rudis* and *M. rhapiophylla*). Continued reduction in groundwater levels (due to groundwater abstraction and reduced rainfall) will further increase the size of the unsaturated zone and reduce the root mass in direct contact with the saturated zone. This will increase the stress levels to these species and lead to a decline in vegetation health (e.g. reduced growth), canopy reduction and the early death of species. The greater the depth of the watertable, the more sensitive vegetation species will be to changes.

As this study has shown that lake levels are dependent upon groundwater levels and generally vary in phase, consideration should be given to reviewing the current management strategy for Loch McNess. Until the historic hydrologic regime can be restored, lake levels will remain low and the Ministerial Criteria water level will continue to be breached. An alternative management approach could involve the development of critical groundwater thresholds or risk bands that link to declining lake level in conjunction with the use of EWRs and Ministerial Criteria. This approach is discussed in detail in Section 8.3 – Management Recommendations.

Land and water use

In order to maintain the ecological values and meet the water management objectives of Loch McNess, water levels in the lake will need to increase to levels above the Ministerial Criteria absolute minimum (6.95 m ASL).

Unfortunately, due to climate forecasts predicting increasingly dry conditions (CSIRO 2009), water levels are unlikely to return to the Ministerial Criteria level in the foreseeable future. Although climate has been identified as the major cause of groundwater decline in the Gnangara Mound (Department of Water 2008b), the only viable management approach to improve groundwater levels is by reducing the impacts of land and water use.

Assessments undertaken by the Department of Water (2008b) found that climate and abstraction account for the majority of groundwater declines in the Yanchep area (-0.6 m and -0.4 m respectively at bore YN3).

Although the effects of land use on water levels in the Yanchep groundwater area appear to be minimal (Department of Water 2008b), good land management practices may improve groundwater levels. Total abstraction in the Yanchep Groundwater Area is estimated at less than 0.5 GL/yr, with the greatest impact on lake levels related to abstraction immediately west of the lake for golf course use and cave supplementation. Reducing abstraction from these sources may help to increase groundwater levels down-gradient of the lake, supporting the re-establishment of the lake's flow-through hydrologic regime.

Reducing groundwater abstraction throughout the Gnangara Mound aquifers, including the Yanchep Groundwater Area, is also anticipated to slow the rate of decline in groundwater levels (Ranjan et al. 2009). Groundwater abstraction from the Gnangara Mound is predominantly for outdoor use as part of the public water supply, with some agricultural and horticultural use, but little water is obtained from the Yanchep Groundwater Area for abstraction purposes (Department of Water 2008b).

Additional groundwater recharge could be provided by managing land use within the Yanchep Groundwater Area. The land uses affecting Loch McNess are native vegetation (Yanchep National Park) and the Yanchep pine plantation (Department of Water 2008a). As the native vegetation is protected by the national park, the only option for managing land use to improve water levels is through changes to pine forestry practices.

Analyses conducted by the Department of Water (2008b) provide details on the effects of pine plantation management on groundwater levels. Changes to plantation management practices can significantly reduce the effects of pine forestry on groundwater levels and have the potential to contribute to increases in groundwater levels (Department of Water 2008b). Current management of the vegetation in the Yanchep Groundwater Area to maximise groundwater recharge should continue, following the recommendations in Department of Water (2008a; 2008b) and Brown et al. (2009).

A combination of reduced abstraction and land use management would, at the least, help to slow the rate of groundwater decline (Ranjan et al. 2009). Slowing the rate of decline would reduce the ecological stress on Loch McNess and deferring severe, irreversible ecological changes. If groundwater levels can be increased to pre-2006 levels, further ecological damage would be prevented and the current decline in ecological condition would be reversed.

8.3 Management recommendations

The identified ecological values of Loch McNess are being degraded because water levels are persisting below the Ministerial Criterion. In addition, development of a vegetation EWR (5.27m AHD) and analysis of relevant bore data, indicate that the recommended minimum requirement to maintain vegetation communities has been exceeded over summer since July 2008 (Figure 51). Low lake levels have resulted from groundwater levels falling below the threshold level required to maintain the lake's hydrological regime. As Loch McNess is entirely dependent on groundwater for its existence, increasing groundwater levels is essential for ensuring the future of this ecologically significant wetland.

It is advised that groundwater use is significantly reduced, particularly from bores down-gradient of the lake, in line with the Department of Water Policy 4.1.1 (Department of Water 2009b) in order to restore groundwater levels to those required to protect the ecological values of Loch McNess.

A minimum groundwater level of 5.27m AHD at bore MCN_SWC would appear to be sufficient to maintain the connection between the vegetation and groundwater (although further investigation of the minimum water requirements for *B. articulata* is recommended). Groundwater abstraction and land use in the Yanchep Groundwater Area should be managed with the aim of maintaining groundwater above this level.

If the maintenance of the historic hydrologic regime is desired, a minimum groundwater level of 7.0 m AHD at bore BD9 would appear to be sufficient to restore the connection between the lake and groundwater. Restoring this connection would assist in returning lake levels above the Ministerial Criterion (in combination with increased rainfall).

Although reducing abstraction and changing land management practices will improve groundwater levels, these actions alone may not be sufficient to restore the lake's hydrologic regime, due to the significant effect of low rainfall, attributed to climate change, on groundwater levels. Lake levels may not be able to be restored for many years, if at all. Therefore it is imperative that, until hydrological connectivity can be restored, management of Loch McNess focuses on reducing the risks associated with low lake levels. A 'risk band' management approach is proposed for future management, along with the use of identified EWRs.

As groundwater levels were in decline before the lake level (especially at bores located away from the lake such as BD7), provision of risk bands relating to groundwater level in addition to identified EWRs may assist in the management of Loch McNess by defining groundwater levels which are consider to be of low, medium or high risk to the stability of lake water levels, and thus the ecological values of the lake. A preliminary assessment based on the data provided in Figure 6 suggests potential groundwater risk bands could be as outlined in Table 15 and Figure 53. These bands have been determined based on:

- changes in the lake hydrograph (e.g. start of decline in 1999 to levels approaching the Ministerial Criterion)
- changes in the rate of change in groundwater levels (i.e. for YN3 and B7)
- significant changes in groundwater level and rate of change in lake level (in 2006).

At present the risk band limits (as defined in Table 15) are based on two bores located away from the lake, due the length of record available and their ability to reflect regional changes that are not as obvious at bores immediately associated with Loch McNess. Over time the risk bands should be adjusted to incorporate bore MCN_SWC and the vegetation EWR. Froend et al. (2004b) identified the following rates and magnitudes of decline and the associated risks for vegetation.

Table 14 Risk bands suggested by Froend et al. (2004b)

Risk band	Rate of decline m/year	Magnitude of decline m
Low	0.1	0.25
Medium	0.1 to 0.2	0.25 to 0.50
High	0.2 to 0.3	0.50 to 0.70

As more data becomes available from bore MCN_SWC, rates of change could be analysed and correlated to the identified risk bands and EWRs, including identifying potential changes in soil moisture and effects on phreatophytic vegetation.

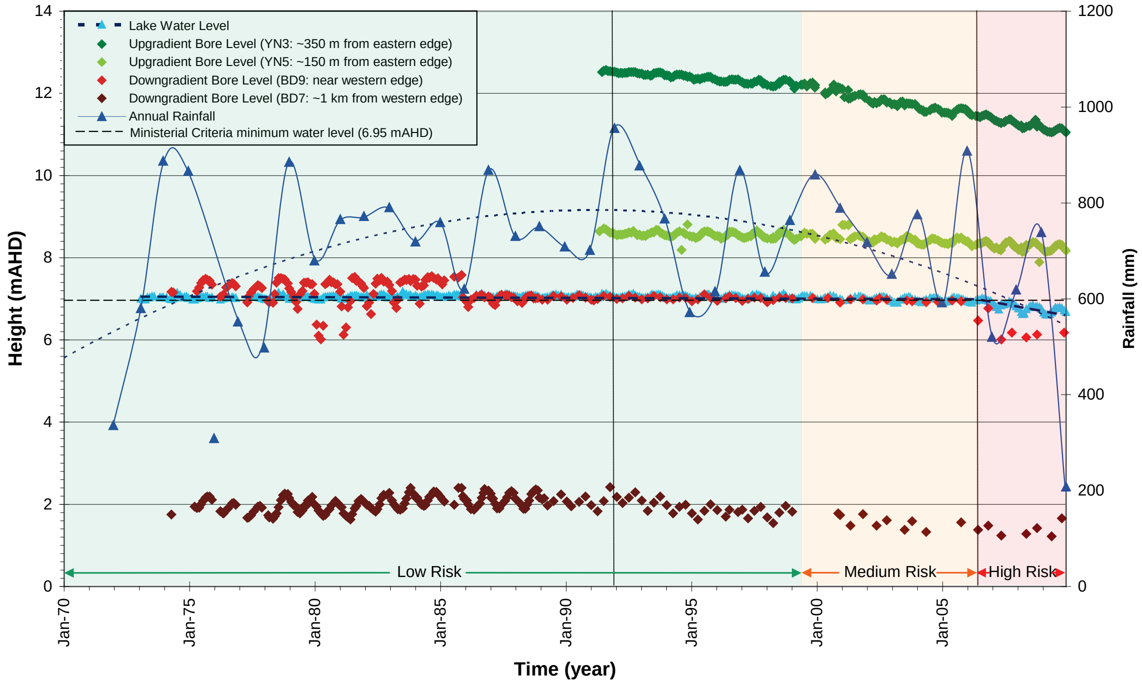


Figure 53 Potential groundwater risk bands for management (dashed line is rainfall trend line)

Table 15 Potential groundwater risk bands for management

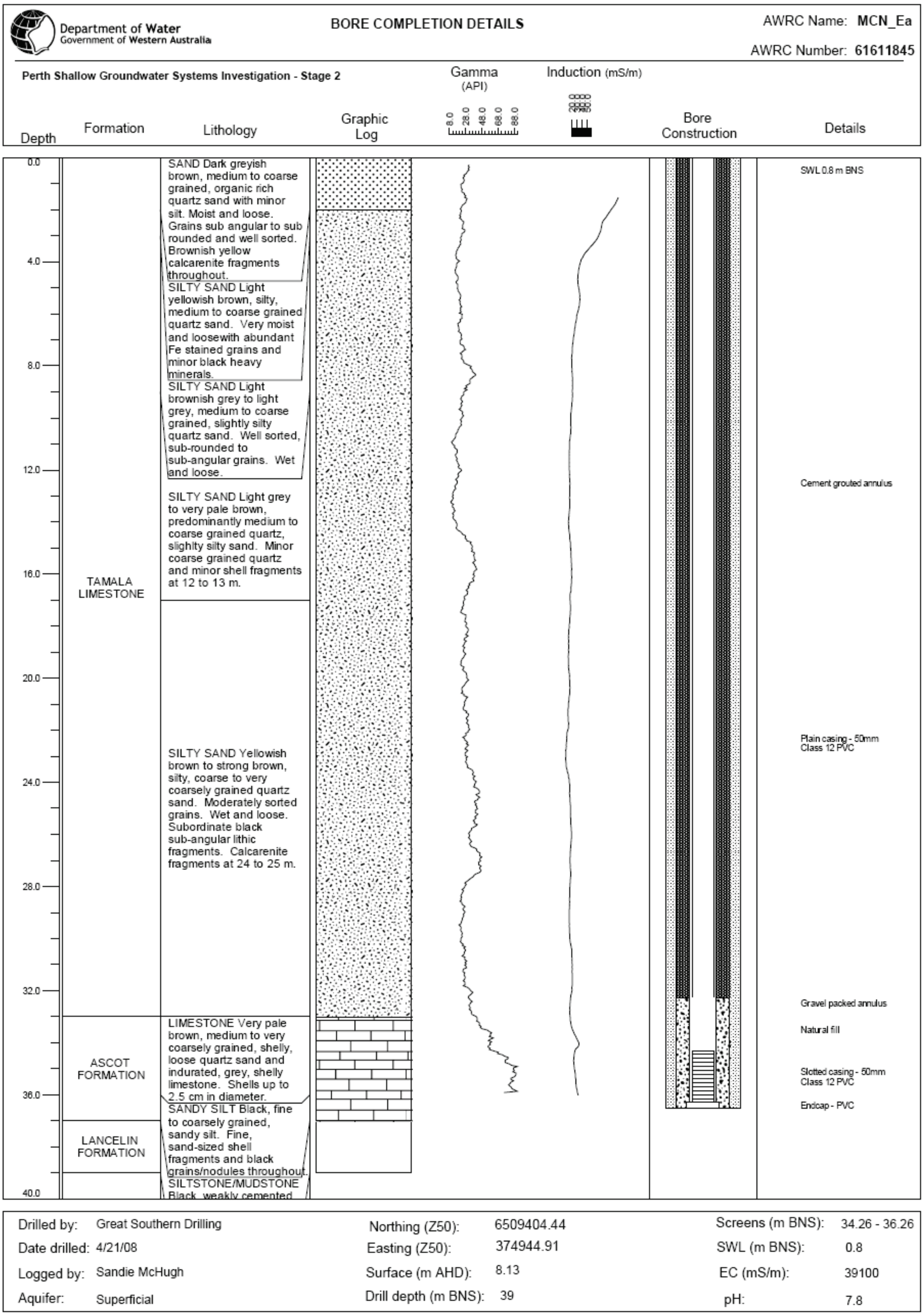
Risk band	Justification	Bore level YN3 m AHD	Bore level BD7 m AHD
Low	• Lake level above Ministerial Criterion • Ecological values maintained • Watching brief for monitoring and management	>12.3	>1.7
Medium	• Lake level approaching and/or occasionally below Ministerial Criterion • Ecological values showing some indications of change • Active surveillance required and management of surface and groundwater levels where possible, to reduce decline in groundwater levels	12.3 to 11.4	1.7 to 1.4

Risk band	Justification	Bore level YN3 m AHD	Bore level BD7 m AHD
High	• Lake level below Ministerial Criterion • Changes in the ecological character of Loch McNess occurring (changes in vegetation extent and condition, changes in macroinvertebrate communities) • Action required to manage surface and groundwater levels where possible, to reduce decline in groundwater levels and maintain ecological health • May require on-ground works to minimise effects on ecosystems where possible when lake levels decline (e.g. active weed management)	<11.4	<1.4

Future monitoring work at Loch McNess should include detailed assessments of the relationship between lake and groundwater levels and the associated ecological responses. This work will help to improve the conceptual understanding of the influence of groundwater levels on ecological condition and the refinement of the risks of persistent low-rainfall conditions to the ecological values of Loch McNess, supporting effective management of this ecologically-significant wetland in a significantly drier future climate.

Appendices

Appendix A — Construction diagrams



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BORE COMPLETION DETAILS

AWRC Name:	**MCN_Eb**
AWRC Number:	**61611846**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Formation	Lithology	Graphic Log	Bore Construction	Details

Depth: 0.0, 2.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0, 18.0, 20.0, 22.0, 24.0

Formation: TAMALA LIMESTONE

Lithology:

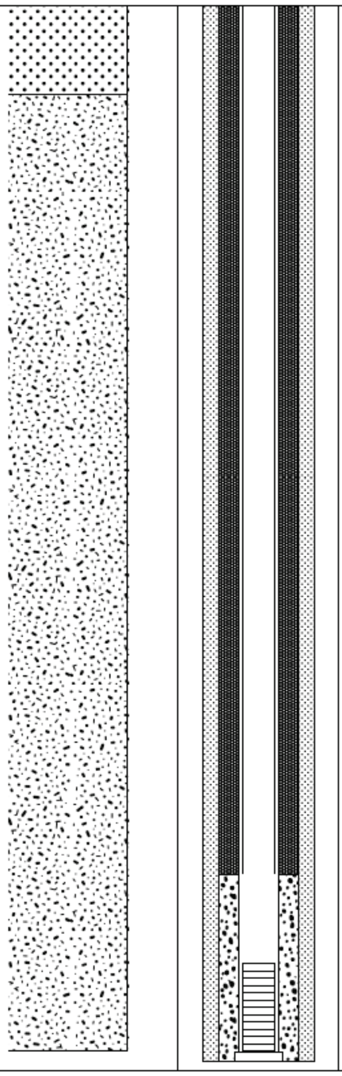
SAND Dark greyish brown, medium to coarse grained, organic rich quartz sand with minor silt. Moist and loose. Grains sub angular to sub rounded and well sorted. Brownish yellow calcarenite fragments throughout.

SILTY SAND Light yellowish brown, silty, medium to coarse grained quartz sand. Very moist and loosewith abundant Fe stained grains and minor black heavy minerals.

SILTY SAND Light brownish grey to light grey, medium to coarse grained, slightly silty quartz sand. Well sorted, sub-rounded to sub-angular grains. Wet and loose.

SILTY SAND Light grey to very pale brown, predominantly medium to coarse grained quartz, slighlty silty sand. Minor coarse grained quartz and minor shell fragments at 12 to 13 m.

SILTY SAND Yellowish brown to strong brown, silty, coarse to very coarsely grained quartz sand. Moderately sorted grains. Wet and loose. Subordinate black sub-angular lithic fragments. Calcarenite fragments at 24 to 25 m.



Details:

SWL 0.98 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

Drilled by:	Great Southern Drilling	Northing (Z50):	6509403.31	Screens (m BNS):	21.55 - 23.55
Date drilled:	4/21/08	Easting (Z50):	374944.91	SWL (m BNS):	0.98
Logged by:	Sandie McHugh	Surface (m AHD):	8.15	EC (uS/m):	36000
Aquifer:	Superficial	Drill depth (m BNS):	23.55	pH:	6.5

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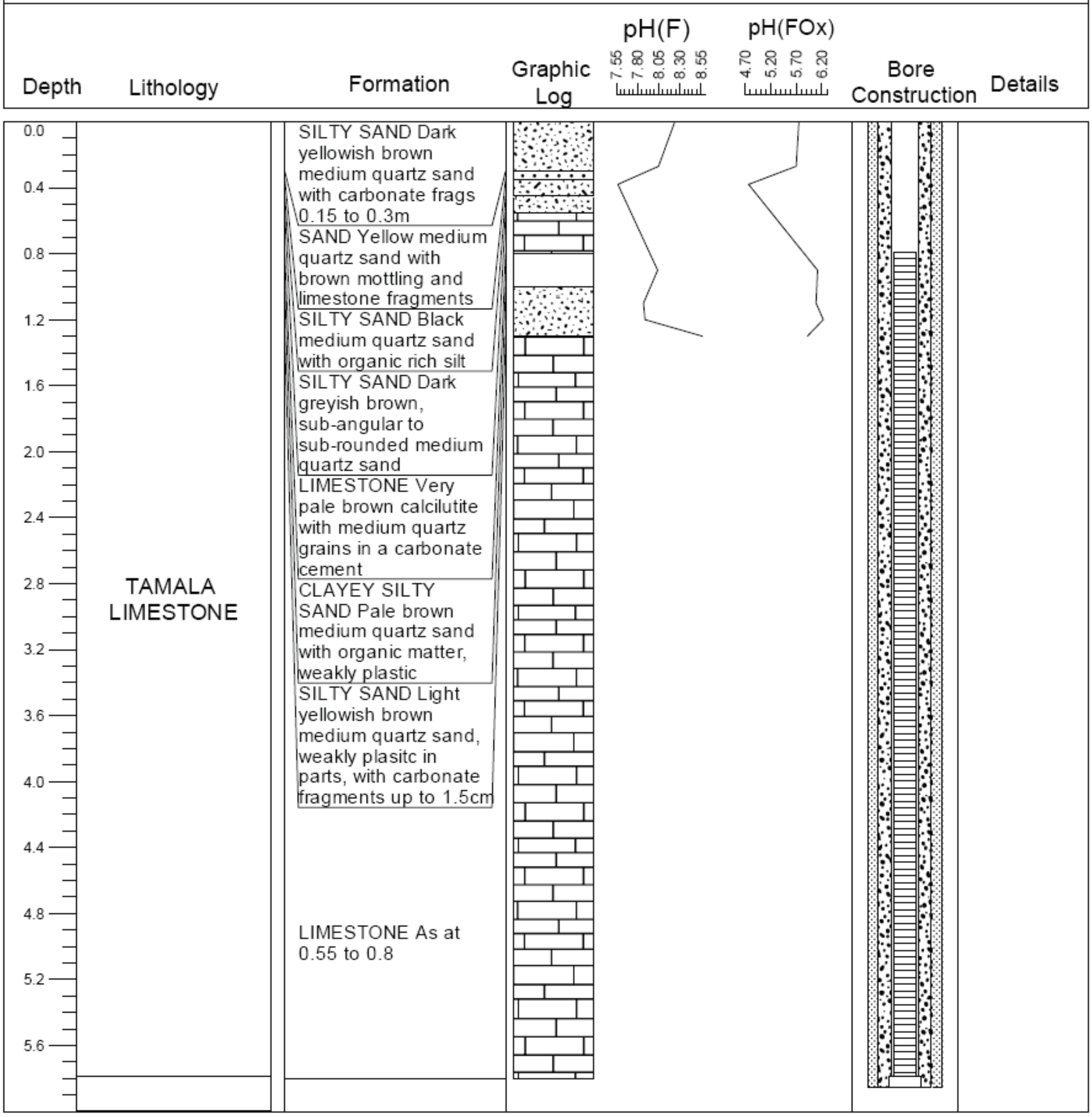
BORE COMPLETION DETAILS

AWRC Name: **MCN_Ec**
AWRC Number: **61611847**

Perth Shallow Groundwater Systems Investigation - Stage 2



Drilled by:	Great Southern Drilling	Northing (Z50):	6509401.69	Screens (m BNS):	0.79 - 5.79
Date drilled:	4/21/08	Easting (Z50):	374944.91	SWL (m BNS):	1.02
Logged by:	Sarah Bourke	Surface (m AHD):	8.17	EC (uS/m):	108300
Aquifer:	Superficial	Drill depth (m BNS):	5.79	pH:	7.3

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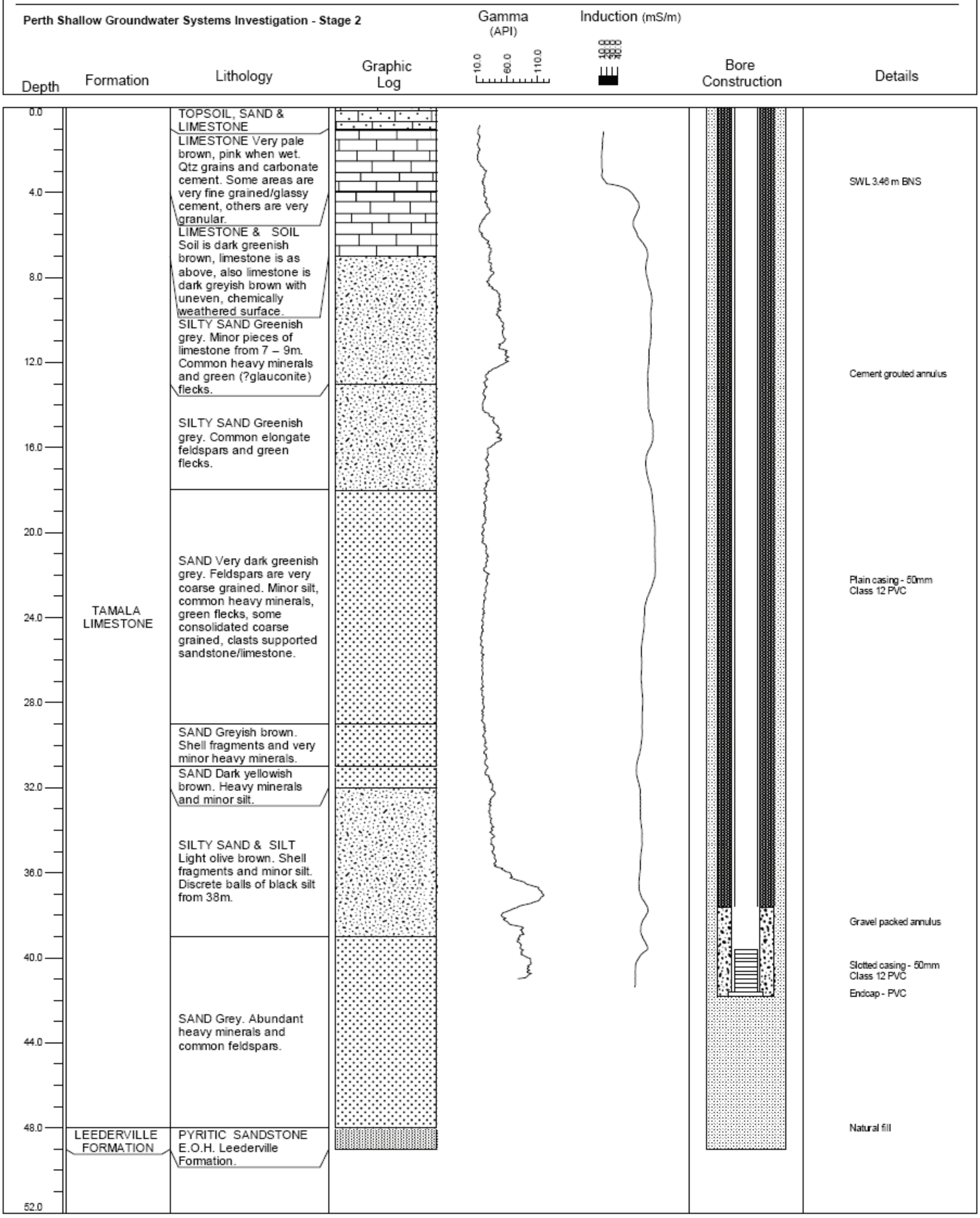
BORE COMPLETION DETAILS

AWRC Name: **MCN_Wa**
AWRC Number: **61611841**



Drilled by:	Great Southern Drilling	Northing (Z50):	6509330.19	Screens (m BNS):	39.61 - 41.61
Date drilled:	4/7/08	Easting (Z50):	374417.53	SWL (m BNS):	3.46
Logged by:	Josephine Searle	Surface (m AHD):	9.12	EC (mS/m):	54900
Aquifer:	Superficial	Drill depth (m BNS):	49	pH:	6.6

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BORE COMPLETION DETAILS

AWRC Name:	**MCN_Wb**
AWRC Number:	**61611842**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Lithology	Formation	Graphic Log	Bore Construction	Details

Depth: 0.0, 2.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0, 18.0, 20.0, 22.0, 24.0, 26.0, 28.0, 30.0

Lithology: TAMALA LIMESTONE

Formation:

TOPSOIL, SAND & LIMESTONE Yellowish brown. Common organic matter.

LIMESTONE Very pale brown, pink when wet. Qtz grains and carbonate cement. Some areas are very fine grained/glassy cement, others are very granular. Dry consolidated rock.

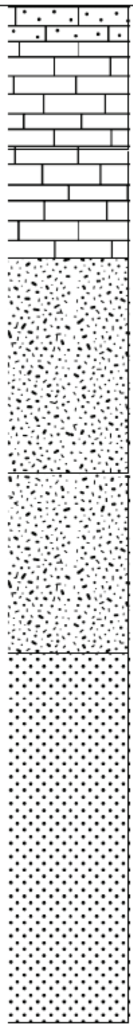
LIMESTONE & SOIL Soil is dark greenish brown, limestone is as above, also limestone is dark greyish brown with uneven, chemically weathered surface. Moist sandy soil, loose, wet from 6m. Possibly a cave/hole as the drill dropped almost a metre.

SILTY SAND Greenish grey. Minor pieces of limestone from 7 – 9m. Common heavy minerals and green (?glauconite) flecks.

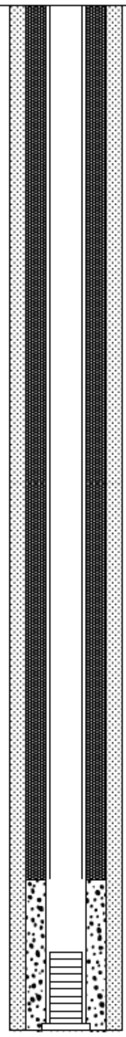
SILTY SAND Greenish grey. Common elongate feldspars and green flecks.

SAND Very dark greenish grey. Minor silt, common heavy minerals, green flecks, some consolidated coarse grained, clasts supported sandstone/limestone.

Graphic Log:



Bore Construction:



Details:

SWL 5.46 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

Drilled by:	Great Southern Drilling	Northing (Z50):	6509332.17	Screens (m BNS):	26.26 - 28.26
Date drilled:	4/21/08	Easting (Z50):	374416.38	SWL (m BNS):	5.46
Logged by:	Josephine Searle	Surface (m AHD):	9	EC (uS/m):	70300
Aquifer:	Superficial	Drill depth (m BNS):	28.26	pH:	7.2

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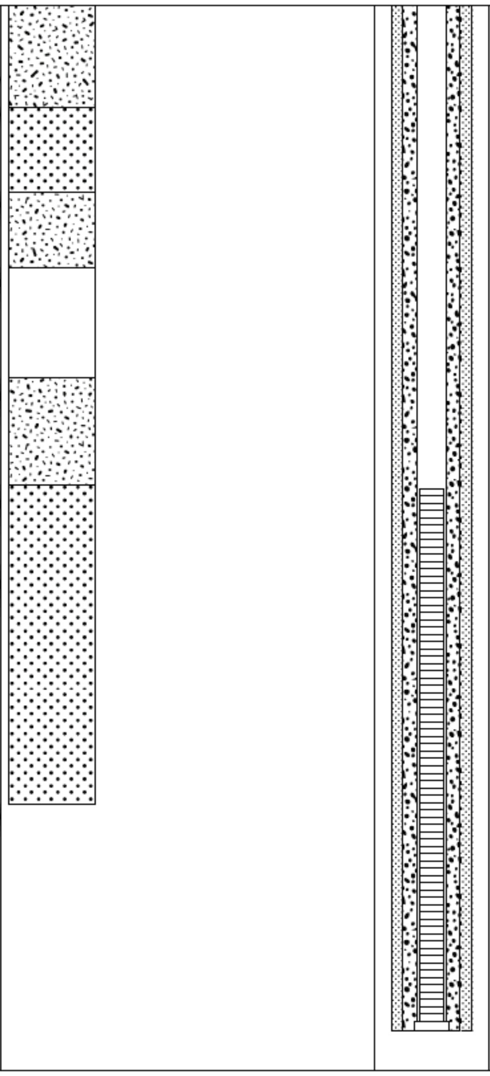
BORE COMPLETION DETAILS

AWRC Name: **MCN_Wc**
AWRC Number: **61611843**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Formation	Lithology
0.0–1.5	TAMALA LIMESTONE	SILTY SAND Dark greyish brown, organic rich, medium to coarsely grained quartz sand. Roots throughout.
1.5–2.9	TAMALA LIMESTONE	SILTY SAND Very pale brown, silty, medium grained quartz sand with minor clay component.
2.9–5.0	TAMALA LIMESTONE	SAND Brownish yellow to brown, medium to coarsely grained quartz sand with minor silt and clay. Fe mottling throughout and orange stained quartz grains common.
5.0–6.5	TAMALA LIMESTONE	SILTY SAND Light brownish grey, silty, medium to coarsely grained quartz sand. Abundant heavy minerals
6.5–8.2	TAMALA LIMESTONE	LIMESTONE/SILTY SAND Light grey cemented, partly sandy limestone. Friable in parts, loose, calcareous silty sand in parts.
8.2–9.7	TAMALA LIMESTONE / –	SILTY SAND Greenish grey, silty, medium to coarsely grained quartz sand, heavy minerals throughout.
9.7–10.8		SAND Light grey to white, coarse to very coarsely grained, quartz sand.
10.8–12.0		SAND Light grey medium to coarse grained quartz sand with minor silt

Graphic Log | pH(F) 4.40 6.40 8.40 | pH(FOx) 2.40 4.40 6.40 8.40 | Bore Construction | Details



Drilled by:	Great Southern Drilling	Northing (Z50):	6509331.18	Screens (m BNS):	5 - 11
Date drilled:	4/21/08	Easting (Z50):	374418.03	SWL (m BNS):	4.06
Logged by:	Sandie McHugh	Surface (m AHD):	8.89	EC (uS/m):	68200
Aquifer:	Superficial	Drill depth (m BNS):	11.45	pH:	7.2

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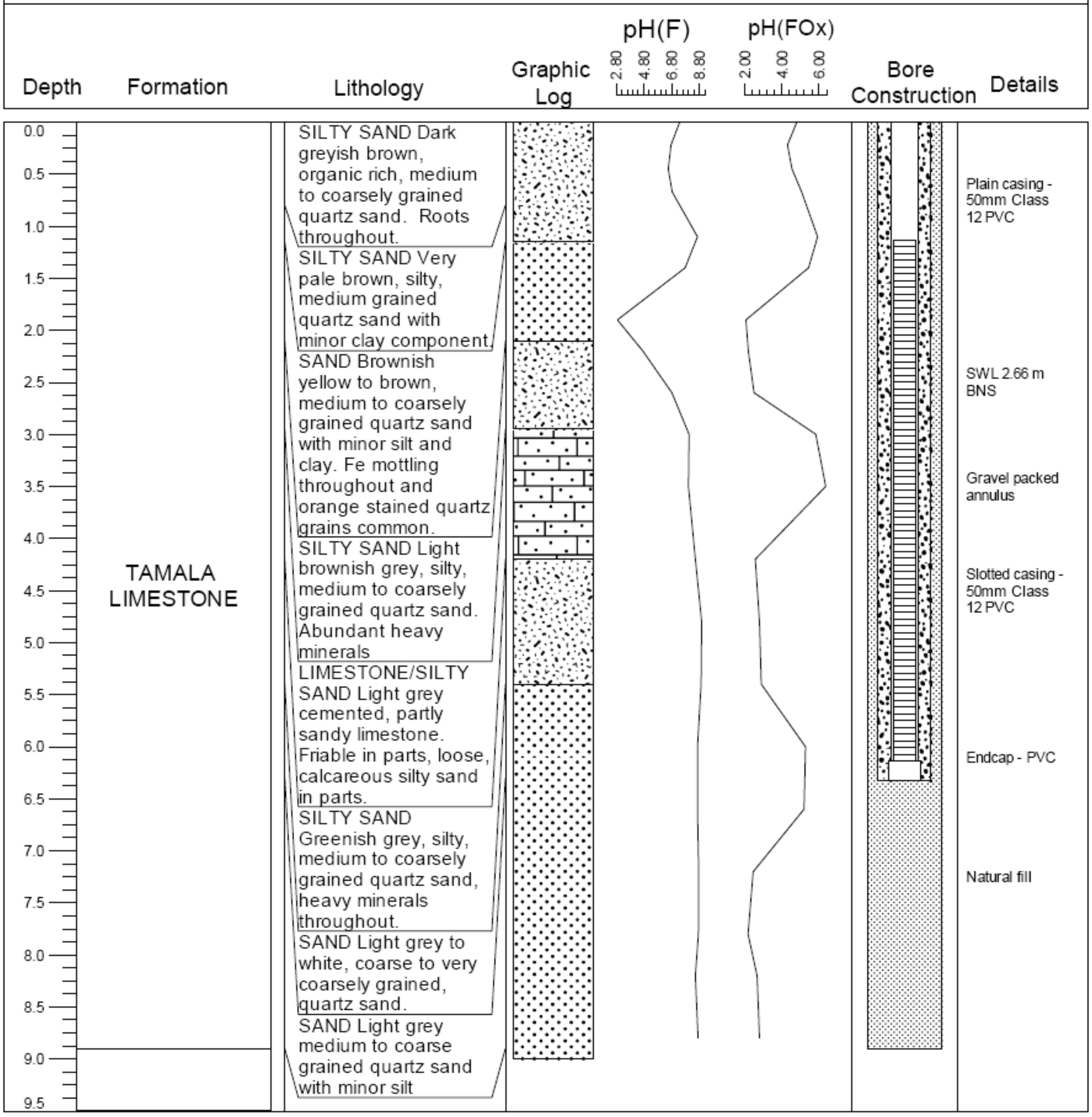
BORE COMPLETION DETAILS

AWRC Name: **MCN_SWc**
AWRC Number: **61611844**

Perth Shallow Groundwater Systems Investigation - Stage 2



Drilled by:	Great Southern Drilling	Northing (Z50):	6508857.46	Screens (m BNS):	1.13 - 6.13
Date drilled:	4/21/08	Easting (Z50):	374597.41	SWL (m BNS):	2.66
Logged by:	Sandie McHugh	Surface (m AHD):	7.69	EC (uS/m):	94100
Aquifer:	Superficial	Drill depth (m BNS):	6.13	pH:	7.3

Appendix B — Sampling methods and analysis

Groundwater sampling methods

Water samples were collected using low flow pumping methods. The low flow sampling technique provides a low stress, low impact, minimal drawdown purging method of groundwater sampling. The pump is lowered to the screened interval and the bore is 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 reduces the aeration or degassing of samples collected. It also minimises the disturbance within the water well column and surrounding materials, 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.
- Decontaminate all instrumentation and equipment (i.e. pumping equipment, hoses, and standing water level recorders) prior to and after sampling at each site location. Decontamination is conducted by first rinsing with a mixture of Decon-910® and Perth scheme water. A second thorough rinse is performed using just Perth Scheme water, and then a final very thorough rinse is conducted using the standard laboratory purchased deionised water.
- Use new (disposable) air and water tubing for each sampling event.
- Ensure water quality meters are functional and calibrated.
- Dip bore for groundwater level and record.
- Identify screen depth from records and lower low flow bladder pump to midway between screened interval. If sampling a shallow bore (full length screen) lower pump to 0.5 m below groundwater level.
- Connect air tubing to air supply.
- Connect water outlet tubing to instrument flow cell.
- Apply air to pump, adjust air supply and discharge time to commence pumping.
- Note other field observations such as unusual sample colour, presence of large quantities of particulate matter and smell.
- Measure the in situ field parameters pH, conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell. Record measurements every 5 minutes until the parameters stabilise then record the final reading.

Results are recorded 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.

Surface water parameters were collected by wading close to installed staff gauges, flushing bottles three times with lake water and filling from 10 cm below the surface. In situ field parameters and surface water levels were also recorded.

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

Field pH testing methods

[After Ahern et al*.* (1998), modified from the Department of Environment (2006)].

Field pH testing

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

Field pH_F and pH_{FOX} testing

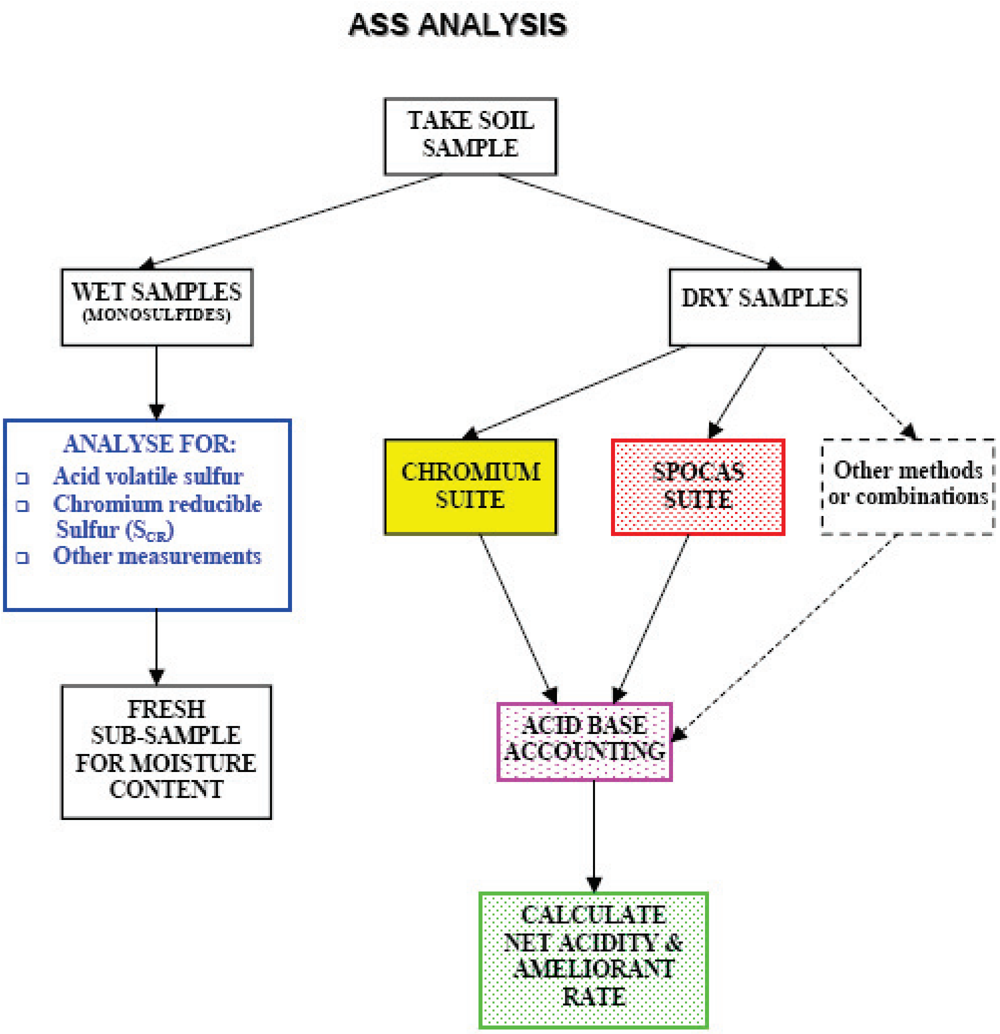
- Take ½ teaspoon sized sample of sediment approximately every 25 cm or when a lithology change is noted (whichever is lesser), noting the depth of the sample.
- Place into beaker used for pH_F tests and add 12 ml of water from a clean syringe (marked pH_F) to make a 1:5 soil:water solution and shake well.
- 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}.
- 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.
- Repeat above steps until entire core has been sampled.
- Shake all beakers well and leave for approximately 1 hour (during which time logging of cores can be done).

- Regularly shake (i.e. every 5 to 10 minutes) all beakers to ensure maximum amount of sediment goes into solution.
- After 1 hour record 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.
- Dispose of solutions into an appropriate container (although hydrogen peroxide rapidly decomposes to water and oxygen so is not harmful to the environment) and thoroughly clean all beakers, syringes and other equipment using Decon (detergent) and water.

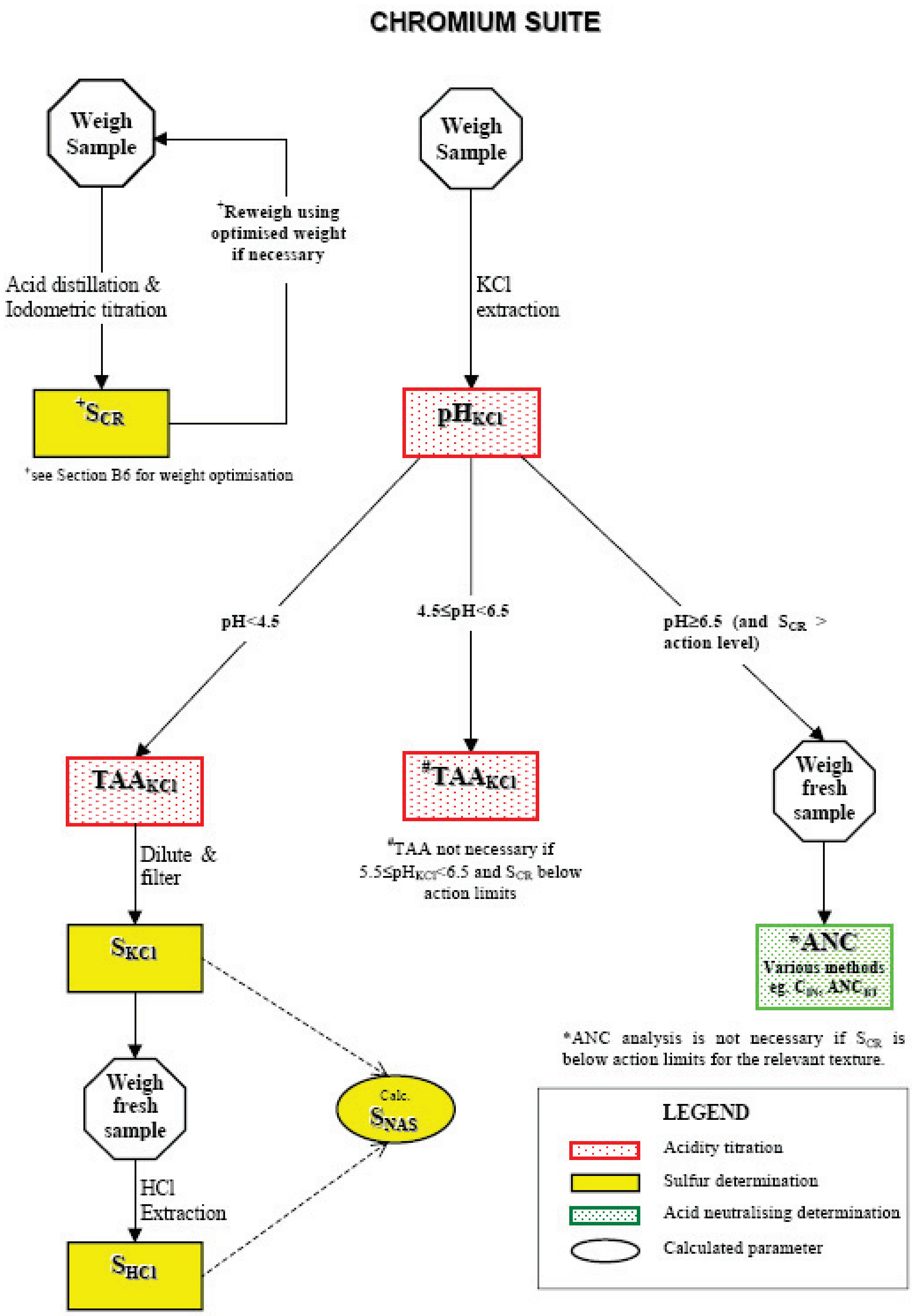
Laboratory methods

(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).

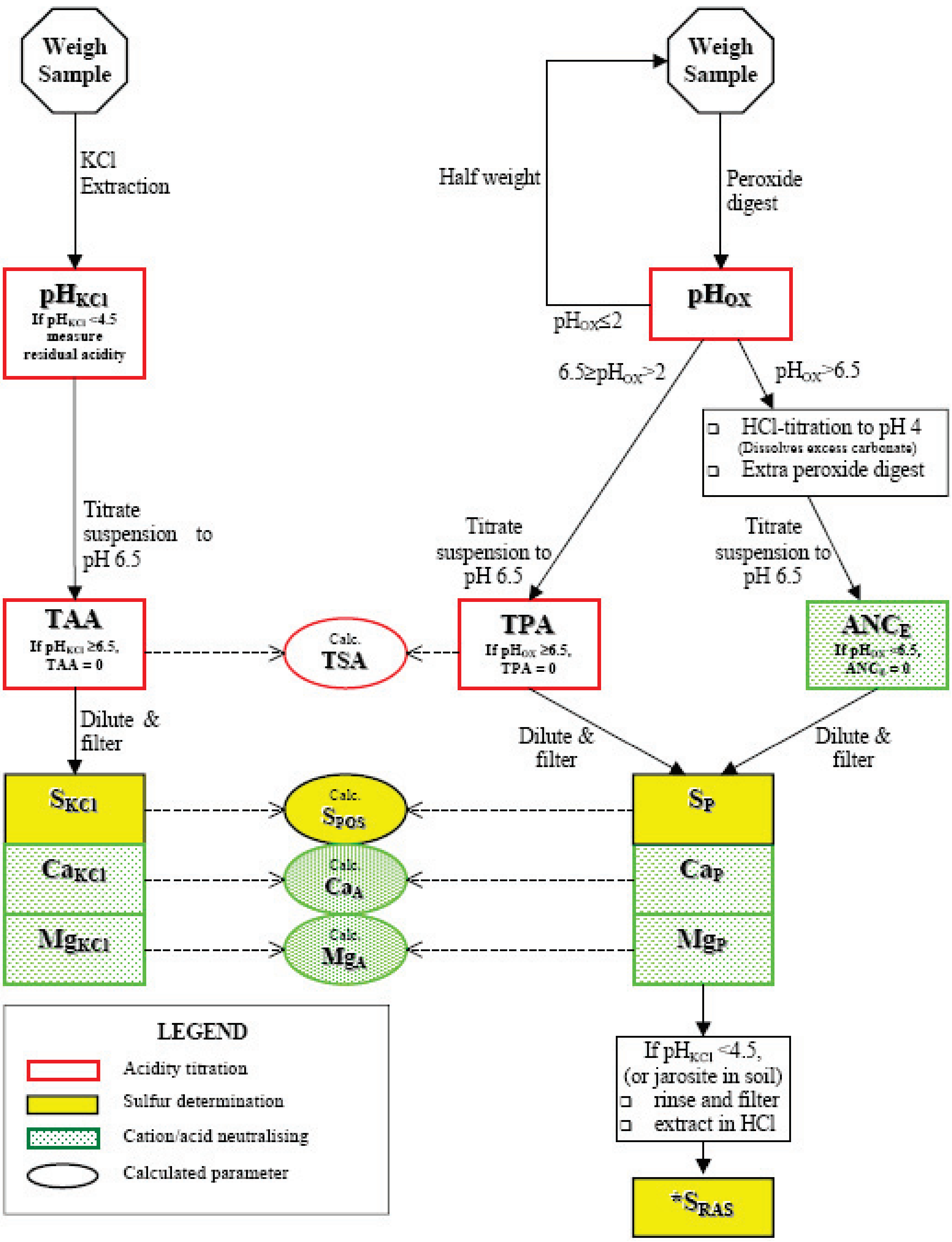


Flow diagram for overall methods used in the quantitative analyses of acid sulfate soils. (From Ahern et al. 1998)



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)

The metal and metalloid samples were prepared and digested with HNO_3/HCl at 100 ^oC for two hours and diluted prior to analysis. The concentrations of acid extractable elements in sediments were determined by an inductively coupled plasma mass spectrometer (ICPMS) and inductively coupled plasma atomic emission spectrometer (ICPAES) depending on the concentrations and detection limits required. Anomalously high concentrations which may have been due to matrix interferences were cross checked once more using ICPMS.

Appendix C — SGS investigation bore lithology logs

DEPTH (m)	LITHOLOGICAL DESCRIPTION (MCN_Ea)	
0 – 2	**Sand**	Dark greyish brown, medium to coarse grained, organic rich quartz sand with minor silt. Moist and loose. Grains sub angular to sub rounded and well sorted. Brownish yellow calcarenite fragments throughout.
2 – 3	**Silty Sand**	Light yellowish brown, silty, medium to coarse grained quartz sand. Very moist and loosewith abundant Fe stained grains and minor black heavy minerals.
3 – 9	**Silty Sand**	Light brownish grey to light grey, medium to coarse grained, slightly silty quartz sand. Well sorted, sub-rounded to sub-angular grains. Wet and loose.
9 – 17	**Silty Sand**	Light grey to very pale brown, predominantly medium to coarse grained quartz, slighlty silty sand. Minor coarse grained quartz and minor shell fragments at 12 to 13 m.
17 – 33	**Silty Sand**	Yellowish brown to strong brown, silty, coarse to very coarsely grained quartz sand. Moderately sorted grains. Wet and loose. Subordinate black sub-angular lithic fragments. Calcarenite fragments at 24 to 25 m.
33 – 36	**Limestone**	Very pale brown, medium to very coarsely grained, shelly, loose quartz sand and indurated, grey, shelly limestone. Shells up to 2.5 cm in diameter.
36 – 37	**Sandy Silt**	Black, fine to coarsely grained, sandy silt. Fine, sand-sized shell fragments and black grains/nodules throughout.
37 - 39	**Siltstone/ Mudstone**	Black, weakly cemented siltstone. Very slightly moist.

DEPTH (m)	LITHOLOGICAL DESCRIPTION (MCN_Eb)	
0 – 2	**Sand**	Dark greyish brown, medium to coarse grained, organic rich quartz sand with minor silt. Moist and loose. Grains sub angular to sub rounded and well sorted. Brownish yellow calcarenite fragments throughout.
2 – 3	**Silty Sand**	Light yellowish brown, silty, medium to coarse grained quartz sand. Very moist and loosewith abundant Fe stained grains and minor black heavy minerals.
3 – 9	**Silty Sand**	Light brownish grey to light grey, medium to coarse grained, slightly silty quartz sand. Well sorted, sub-rounded to sub-angular grains. Wet and loose.
9 – 17	**Silty Sand**	Light grey to very pale brown, predominantly medium to coarse grained quartz, slighlty silty sand. Minor coarse grained quartz and minor shell fragments at 12 to 13 m.
17 – 23.55	**Silty Sand**	Yellowish brown to strong brown, silty, coarse to very coarsely grained quartz sand. Moderately sorted grains. Wet and loose. Subordinate black sub-angular lithic fragments. Calcarenite fragments at 24 to 25 m.

DEPTH (m)	LITHOLOGICAL DESCRIPTION (MCN_Ec)	
0 – 0.35	**Silty Sand**	Yellow medium quartz sand with brown mottling and limestone fragments
0.35 - 0.45	**Silty Sand**	Black medium grained quartz sand with organic rich silt
0.45 – 0.55	**Silty Sand**	Dark greyish brown, sub-angular to sub-rounded medium grained quartz sand
0.55 – 0.8	**Limestone**	Very pale brown calcilutite with medium grained quartz grains in a carbonate cement
0.8 – 1	**Clayey Silty Sand**	Pale brown medium grained quartz sand with organic matter, weakly plastic
1 – 1.3	**Silty Sand**	Light yellowish brown medium grained quartz sand, weakly plasitc in parts, with carbonate fragments up to 1.5cm
1.3 – 5.79	**Limestone**	As at 0.55 to 0.8

DEPTH (m)	LITHOLOGICAL DESCRIPTION (MCN_Wa)	
0 – 1	**Topsoil, Sand & Limestone**	Yellowish brown, medium to coarse grained, sub-rounded to sub-angular quartz sand. Common organic matter. Dry and loose.
1 – 4	**Limestone**	Very pale brown, pink when wet. Medium grained sub-rounded to sub-angular quartz grains and carbonate cement. Some areas are very fine grained/glassy cement, others are very granular. Dry consolidated rock.
4 – 5	**Soil & Limestone**	Soil is dark greenish brown, limestone is as above. Moist sandy soil, loose. Possible a cave/hole as the drill dropped almost a metre.
5 – 6	**Soil & Limestone**	Soil as above, limestone is dark greyish brown with uneven, chemically weathered surface. Soil is moist, sandy and loose.
6 – 7	**Limestone**	Greyish brown as above. Wet.
7 – 9	**Silty Sand**	Greenish grey, coarse to fine grained, grain size decreasing with depth. Sub-rounded to sub-angular. Minor pieces of limestone. Common heavy minerals and green (?glauconite) flecks. Wet and weakly cohesive.
9 – 13	**Silty Sand**	As above. Grain size medium to fine grained. No limestone pieces.
13 – 18	**Silty Sand**	Greenish grey, coarse grained sub-rounded, mostly spherical quartz. Common elongate feldspars and green flecks. Wet.

18 – 24	**Sand**	Very dark greenish grey. Medium to coarse grained quartz, feldspars are very coarse grained. Sub-rounded to sub-angular. Minor silt, common heavy minerals, some consolidated coarse grained, clasts supported sandstone/limestone.
24 – 29	**Sand**	Light greenish grey to greenish grey. Medium grained to granular sub-rounded quartz. Minor silt, green flecks and heavy minerals.
29 – 31	**Sand**	Greyish brown, medium to coarse grained, sub-rounded to angular quartz. Shell fragments and very minor heavy minerals.
31 – 32	**Sand**	Dark yellowish brown, coarse grained to granular, sub-angular to angular quartz. Heavy minerals and minor silt.
32 – 38	**Silty Sand**	Light olive brown, medium grained to granular, well rounded to angular quartz. Shell fragments and minor silt.
38 – 39	**Silt And Silty Sand**	Very dark brown, medium to very coarse grained, well rounded to angular quartz. Discrete balls of black silt.
39 – 48	**Sand**	Grey, medium to pebble sized, mostly very coarse grained. Sub-rounded to angular, moderately spherical to elongate. Abundant heavy minerals and common feldspars.
48 - 49	**Pyritic Sandstone**	E.O.H

DEPTH (m)	LITHOLOGICAL DESCRIPTION (MCN_Wb)	
0 – 1	**Topsoil, Sand & Limestone**	Yellowish brown, medium to coarse grained, sub-rounded to sub-angular quartz sand. Common organic matter. Dry and loose.
1 – 4	**Limestone**	Very pale brown, pink when wet. Medium grained sub-rounded to sub-angular quartz grains and carbonate cement. Some areas are very fine grained/glassy cement, others are very granular. Dry consolidated rock.
4 – 5	**Soil & Limestone**	Soil is dark greenish brown, limestone is as above. Moist sandy soil, loose. Possible a cave/hole as the drill dropped almost a metre.
5 – 6	**Soil & Limestone**	Soil as above, limestone is dark greyish brown with uneven, chemically weathered surface. Soil is moist, sandy and loose.
6 – 7	**Limestone**	Greyish brown as above. Wet.
7 – 9	**Silty Sand**	Greenish grey, coarse to fine grained, grain size decreasing with depth. Sub-rounded to sub-angular. Minor pieces of limestone. Common heavy minerals and green (?glauconite) flecks. Wet and weakly cohesive.
9 – 13	**Silty Sand**	As above. Grain size medium to fine grained. No limestone pieces.
13 – 18	**Silty Sand**	Greenish grey, coarse grained sub-rounded, mostly spherical quartz. Common elongate feldspars and green flecks. Wet.
18 – 24	**Sand**	Very dark greenish grey. Medium to coarse grained quartz, feldspars are very coarse grained. Sub-rounded to sub-angular. Minor silt, common heavy minerals, some consolidated coarse grained, clasts supported sandstone/limestone.
24 – 28.6	**Sand**	Light greenish grey to greenish grey. Medium grained to granular sub-rounded quartz. Minor silt, green flecks and heavy minerals.

DEPTH (m)	LITHOLOGICAL DESCRIPTION (MCN_Wc)	
0 – 1	**Topsoil, Sand and Limestone**	Yellowish brown, medium to coarse, sub-rounded to sub-angular quartz sand. Common organic matter. Dry and loose.
1 – 4	**Limestone**	Very pale brown, pink when wet. Medium grained sub-rounded to sub-angular quartz grains and carbonate cement. Some areas are very fine grained/glassy cement, others are very granular. Dry consolidated rock.
4 – 5	**Soil and Limestone**	Soil is dark greenish brown, limestone is as above. Moist sandy soil, loose. Possible a cave/hole as the drill dropped almost a metre.
5 – 6	**Soil and Limestone**	Soil as above, limestone is dark greyish brown with uneven, chemically weathered surface. Soil is moist, sandy and loose.
6 – 7	**Limestone**	Greyish brown as above. Wet.
7 – 9	**Silty Sand**	Greenish grey, coarse to fine, grain size decreasing with depth. Sub-rounded to sub-angular. Minor pieces of limestone. Common heavy minerals and green (?glauconite) flecks. Wet and weakly cohesive.
9 – 11.45	**Silty Sand**	As above. Grain size medium to fine. No limestone pieces.

DEPTH (m)	LITHOLOGICAL DESCRIPTION (MCN_SWc)	
0 – 0.8	**Silty Sand**	Dark greyish brown, organic rich, medium to coarsely grained quartz sand. Roots throughout. Well sorted, sub rounded to sub angular grains. Loose and dry.
0.8 – 1.15	**Silty Sand**	Very pale brown, silty, medium grained quartz sand with minor clay component. Slightly cohesive and moist.
1.15 – 1.7	**Sand**	Brownish yellow, medium to coarsely grained quartz sand with minor silt and clay. Generally loose, more cohesive in parts. Fe mottling throughout and orange stained quartz grains common.
1.7 – 2.1	**Sand**	Brown, medium to coarsely grained quartz sand with minor silt and Fe stained grains. Loose and moist.
2.1 – 2.95	**Silty Sand**	Light brownish grey, silty, medium to coarsely grained quartz sand. Abundant heavy minerals
2.95 – 4.2	**Limestone /Silty Sand**	Light grey cemented, partly sandy limestone. Friable in parts, loose, calcareous silty sand in parts.
4.2 – 5.4	**Silty Sand**	Greenish grey, silty, medium to coarsely grained quartz sand, loose, wet, heavy minerals throughout.
5.4 – 6.3	**Sand**	Light grey to white, coarse to very coarsely grained, quartz sand. Grains well sorted and rounded.
6.3 – 8.9	**Sand**	Light grey medium to coarse grained quartz sand with minor silt

Appendix D – Acid sulfate soils laboratory and field results

Borehole ID	Soil texture	Field pH				Reaction
		Depth m	pH_F	PH_{FOX}	Δ pH	
MCN_SWC	Top soil, m to c qtz sand	0.0	7.38	4.79	-2.59	
MCN_SWC	brown org rich sand	0.2	6.76	4.29	-2.47	
MCN_SWC	as above	0.5	6.56	4.54	-2.02	
MCN_SWC	as above	0.7	6.84	5.05	-1.79	
MCN_SWC	pale yellow silty qtz sand	1.1	8.66	5.91	-2.75	
MCN_SWC	yellow brown silty qtz sand	1.4	7.78	5.43	-2.35	
MCN_SWC	gry brown sand & silt	1.9	2.89	2.05	-0.84	Moderate
MCN_SWC	L grey silty sand	2.2	4.74	2.18	-2.56	Volcanic
MCN_SWC	as above	2.6	6.82	2.49	-4.33	Volcanic
MCN_SWC	sandy	3.0	8.06	5.81	-2.25	Slight
MCN_SWC	as above	3.5	8.01	6.35	-1.66	Slight
MCN_SWC	green grey cs qtz sand	4.2	8.52	2.56	-5.96	Volcanic
MCN_SWC	as above	4.8	8.97	2.78	-6.19	Volcanic
MCN_SWC	as above	5.4	8.92	2.88	-6.04	Moderate
MCN_SWC	L grey to white cs qtz sand	6.0	8.67	5.26	-3.41	
MCN_SWC	L grey m to cs qtz sand	6.6	8.67	5.18	-3.49	Slight
MCN_SWC	as above	7.2	8.74	2.44	-6.30	Slight
MCN_SWC	as above	7.8	8.72	2.17	-6.55	Moderate
MCN_SWC	L grye m to cs qtz sand	8.2	8.52	2.65	-5.87	Slight
MCN_SWC	as above	8.8	8.70	2.78	-5.92	Slight
MCN_EC	brown top soil	0.0	8.24	5.75	-2.49	Slight
MCN_EC	brown org rich m to c qtz sand	0.3	8.05	5.70	-2.35	Slight
MCN_EC	dk brown org rich qtz sand	0.4	7.57	4.77	-2.80	Slight
MCN_EC	grey silty sand	0.9	8.04	6.12	-1.92	Moderate
MCN_EC	brown clayey silty sand. Carbonate frags	1.1	7.87	6.09	-1.78	Moderate
MCN_EC	yellowish brown silty sand. Carbonate frags	1.2	7.89	6.23	-1.66	Moderate
MCN_EC	yellow qtz sand	1.3	8.57	5.92	-2.65	Moderate

NMI lab number	Client sample number	ANC $_E$ Excess acid neutralising capacity % $CaCO_3$	pH $_{KCl}$ pH of KCl extract	TAA Titratable actual acidity mol H^+/ t	TPA Titratable peroxide acidity mol H^+/ t	TSA (calc) Titratable sulfidic acidity mol H^+/ t	Ca $_A$ (calc) Reacted Ca % Ca	Mg $_A$ (calc) Reacted Mg % Mg	S_{NAS} (calc) Retained acidity % S	S $_{POS}$ (calc) Potential sulfidic acidity % S
W08/08128	200803542		8.7	<1	1	1	<0.1	<0.1		
W08/08129	200803543	2.4	9.2	<1	<1	<1	1.9	<0.1		
W08/08130	200803544	13	9.3	<1	<1	<1	6.1	0.1		
W08/08130-D	200803544	13	9.4	<1	<1	<1	5.9	0.1		
W08/08131	200803545		3.1	53	55	2	<0.1	<0.1	<0.01	<0.01
W08/08132	200803546		5.3	3	69	66	<0.1	<0.1		
W08/08133	200803547		6.1	1	100	100	<0.1	<0.1		
W08/08134	200803548		8.2	<1	7	7	<0.1	<0.1		
Limit of reporting		<0.05		<1	<1	<1	<0.1	<0.1	<0.01	<0.01

NMI lab number	Client sample number	Net acidity % S	Net acidity % S Alternative calculation	Net acidity mol H^+/ t	Net acidity mol H^+/ t Alternative calculation	Fineness factor	Safety factor	Soil bulk density t/ m^3	Liming rate for ag lime kg $CaCO_3$/ t	Liming rate for ag lime kg $CaCO_3$/ t Alternative calculation
W08/08128	200803542	0.001	0	1	0	1.5	1.5	1	0	0.0
W08/08129	200803543	-0.513	-1	-102	-632	1.5	1.5	1	-8	-49.4
W08/08130	200803544	-2.777	-3	-555	-2084	1.5	1.5	1	-43	-163.0
W08/08130-D	200803544	-2.777	-3	-555	-2018	1.5	1.5	1	-43	-157.8
W08/08131	200803545	0.085	0	53	53	1.5	1.5	1	4	4.1
W08/08132	200803546	0.005	0	3	3	1.5	1.5	1	0	0.2
W08/08133	200803547	0.002	0	1	1	1.5	1.5	1	0	0.1
W08/08134	200803548	0.007	0	5	0	1.5	1.5	1	0	0.0

Shortened forms

ABA	Acid–base accounting
CRS	chromium reducible sulfur
DO	Dissolved oxygen
DON	Dissolved Organic Nitrogen
EC	Electrical conductivity
EWR	Ecological water requirement
m AHD	Elevation relative to Australian height datum
mBNS	Metres below natural surface
NMI	National Measurement Institute
PRAMS	Perth regional aquifer modelling system
SPOCAS	Suspension peroxide oxidation combined acidity and sulfur
SRP	Soluble reactive phosphorus
WAWA	Water Authority of Western Australia
WIN	Water Information Network database

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