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

Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Lake Yonderup

Hydrogeological record series

Report no. HG51
May 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 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 28 wetlands on the Swan Coastal Plain, prioritised by a combination of ecological significance, management issues and geomorphic setting.

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

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

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

Summary

Lake Yonderup is one of the 28 sites in the Perth shallow groundwater systems (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.

Falling groundwater levels in the Superficial aquifer have been attributed to decreased rainfall and resultant decreased aquifer recharge. Water levels in the lake have also decreased over time. Seasonal changes in groundwater levels in the Superficial aquifer are matched by seasonal changes in lake levels, which suggest a hydraulic link between this aquifer and the lake. This connection is possibly via karstic solution cavities close to the watertable.

From the SGS logs, locally, the aquifer has no indication of being cavernous. Rather it appears to be a primary porosity sand aquifer. The groundwater flow field around the lake is complex. Groundwater is thought to discharge to the lake on its up-gradient (eastern) side. Water quality data indicate that groundwater discharging to the lake comes from the Superficial aquifer's watertable zone.

Groundwater levels down-gradient of the lake are lower than lake levels but there is little indication from relative water levels of groundwater recharge from the lake. Indeed, vertically upward hydraulic gradients are observed between the intermediate and shallow SGS bores. It is possible that discharge of lake water into groundwater may be via localised karst solution cavities, if such cavernous limestone is present. However, the water quality data are consistent with diffuse recharge from the lake into the sand aquifer at the SGS bores.

Should a dry season dominated regime continue, it is concluded that the lake levels will be vulnerable to further decreases in groundwater levels up-gradient and down-gradient of the lake.

Lake water quality data show that for some nutrient species and various toxicants concentrations have exceeded trigger levels for south-west Australian wetlands (ANZECC & ARMCANZ 2000). Salinity has also risen steadily since 1995.

The source of sulfate enrichment in the lake is likely to be oxidation of sulfide minerals as the lake water levels drop. The absence of any downward trend in lake pH indicates that Lake Yonderup may be buffered against impacts of acidification. Lake Yonderup is not currently showing any evidence of acidification up-gradient of the lake, but high sulfates down-gradient indicate that should acidification occur, the risk of deterioration in lake water quality would be severe.

The ecological consequences of degraded hydrologic regime through declining water levels to date have been:

- degradation of lake water quality due to the concentration of nutrients, salts and ions. (At present water quality is still good. However, further water level declines will exacerbate solute concentration effects).
- shifts in wetland vegetation range and community composition since 2008
- reductions in habitat for aquatic macroinvertebrates, fish and waterbirds
- reductions in macroinvertebrate richness since 2008.

Groundwater levels are currently below the Ministerial criterion of 5.90 m AHD at the southern vegetation transect, suggesting that the vegetation at Lake Yonderup is currently experiencing some water stress. 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.

Groundwater levels will need to increase to meet the known ecological water requirements (EWRs) to protect the identified ecological values. As the lake level appears to be directly related to groundwater levels, increasing groundwater levels should restore lake levels, to meet the Ministerial criterion of an absolute summer minimum of 5.90 m AHD.

A minimum groundwater level of 5.48 m AHD at bore YDP_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.

Given predictions of a continuing drier climate (CSIRO 2009), groundwater levels are anticipated to decrease further, putting further strain on the ecological values of Lake Yonderup. External stressors (particularly from irrigation bores) may be exacerbating the drought induced decline in regional groundwater levels. This abstraction and possible impact on the hydraulic gradient requires further investigation.

If below average rainfall conditions and current abstractions persist, lake levels will not recover and irreversible ecological changes may result, with acceleration of the changes in lake condition already underway.

Given the possible hydrological connectivity of Lake Yonderup and Loch McNess (Horwitz et al. 2009a; WAWA 1995), any actions taken to restore water levels in Loch McNess would be anticipated to produce a lagged response in water levels in Lake Yonderup.

Recommendations

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

As this study has shown that lake levels are dependent upon groundwater levels and generally vary in phase with them, consideration should be given to reviewing the current management strategy for Lake Yonderup. 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 would 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.

Management Actions

- The management of Lake Yonderup should be revised to account for persistent low water levels. The acceptable levels of risk to the ecological values should be reviewed given:
    - the likely persistence of water levels below the EWRs for each ecological value
    - the ability of the ecological value to recover should groundwater return to historical levels
    - In order to meet the minimum groundwater requirements of all wetland vegetation on the southern vegetation transect, a groundwater level of 5.48 m AHD is required at bore YDP_SWC, and it is recommended that this be established as both a vegetation EWR and a Ministerial criterion
    - The minimum vegetation ecological water requirement established in this report of 4.75 m AHD should be adopted as an
    - environmental water provision for Lake Yonderup.
        - Implementation and responsibility: DoW to recognise in the next Gnangara water allocation plan.

Future Monitoring

- As there is no monitoring bore close to the northern vegetation transect it is recommended that one be established to complement the:
    - vegetation EWR
    - Ministerial criterion recommendation above.
    - As there is only limited data associated with the SGS bores, monitoring of a number of the ‘long-term’ bores should be maintained (that is bores YN6, YN7, YN11), especially if the risk bands proposed herein are used as a management tool or trigger.
    - Frequent (monthly) monitoring of groundwater static water level (SWL) should be carried out, including downstream of the lake along a given

flow path to the coast. The installation of continuous SWL recorders should be considered on bores YN7 and YN11.

- Surface water quality sampling should be continued at Lake Yonderup, with close attention paid to ammonium-N and NOx-N levels to detect any emerging problems with excess nitrogen levels
    - Implementation and responsibility: DoW to design a suitable groundwater monitoring program, that includes water chemistry sampling to inform the next Gnangara water allocation plan.

Future Investigation

- Consideration should be given to further investigation of the minimum water requirements for *B. littoralis*, as this species may have been lost from the southern vegetation transect before groundwater levels reached 5.48 m AHD.

    - Implementation and responsibility: DoW to recognise in the next Gnangara water allocation plan.

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 levels) are declining across the Gnangara Mound, and have been linked with deterioration in ecological condition and loss of biodiversity (Clark & Horwitz 2005; Froend et al. 2004a). 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. Water level declines in and around wetlands substantially increase the risks associated with acid sulfate soils (ASS) and are linked to environmental and groundwater degradation (Appleyard et al. 2006).

Lake Yonderup is a small, permanent groundwater-dependent wetland located immediately south of Loch McNess. Due to its high ecological values, Lake Yonderup is recognised as a regionally significant (System 6) conservation category wetland and is listed on the *Register of the National Estate* (Department of Water 2008b; Froend et al. 2004a). It is a relatively undisturbed wetland located in a remnant area of the Herdsman vegetation complex within the Yanchep National Park (Bush Forever site 288; WAWA 1995; Froend et al. 2004a).

Along with Loch McNess, Lake Yonderup is valued for its historically stable water regime (WAWA 1995; Froend et al. 2004a; Department of Water 2008b), with as little as 0.05 m seasonal variation in water level (Horwitz et al. 2009a).

Under Ministerial criteria, the summer absolute minimum EWR is set at 5.9 m AHD. Although water levels in Lake Yonderup have been declining steadily since 1995, the Ministerial criteria water level was met until 2003. Water levels have been declining at a rate of approximately 0.04 m/yr (Department of Water 2008b) and have largely remained below the Ministerial criteria minimum level since 2006. The recent low water levels are of significant concern for managing the ecological values of the lake (Judd & Horwitz 2009).

Comparison of lake water levels with groundwater levels (Figure 6) indicates an almost linear relationship. This supports the hypothesis proposed by Froend et al. (2004b) that ‘the wetland is entirely groundwater dependent for biophysical processes, habitat and consumptive use’. Low groundwater levels in the Yanchep groundwater area are predominantly climate driven, reflecting rainfall patterns, with some influence of land use and abstraction.

The management area review of shallow groundwater systems on the Gnangara and Jandakot mounds (McHugh & Bourke 2007) considered that the situation at Lake Yonderup was significant enough to warrant a local area hydrogeological investigation. This decision was based on the breaching of Ministerial criteria water levels each summer from 2004 to 2007, and the fact that the lake has been classified as being at severe risk of possible impact from groundwater drawdown (Froend et al. 2004b).

The management area review and the most recent review of Ministerial conditions on the Gnangara Mound (Department of Water 2008b) recommended that site-specific data be collected and analysed to determine the current status of groundwater–surface water connectivity, groundwater quality, and flow into and out of the wetland, at Lake Yonderup.

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

- upgrade the groundwater monitoring network
- improve the understanding of how Lake Yonderup functions hydrogeologically
- determine the distribution of acid sulfate soils around the lake and the their effects on water chemistry
- link the hydrogeological and chemical understanding with ecological water requirements and determine the implications for the ecological values of the lake
- identify the water and land-use issues to be addressed in the water management plan for the Gnangara Mound.

2 Background

2.1 Location and climate

Lake Yonderup is located within the Yanchep National Park, 45 km north-west of Perth CBD, on the northern part of the Swan Coastal Plain and on the Gnangara Groundwater Mound (Figure 1).

Lake Yonderup is situated in an interdunal depression within the Tamala Limestone. Loch McNess 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. The lake is 30 ha in area. There is no bathymetry available for the lake.

CALM (1999) observed that Lake Yonderup was modified by farming (market gardening and feedlots) until the 1950s and that it has been drained into channels about 3 m apart. Some of the original vegetation in the lake (sedges) was modified by the farming. Furthermore, Yanchep Beach and Wanneroo Roads cut off sections of the wetland; and road drainage 'would adversely affect water quality as a result of foreign materials washing from the road' (ibid.). Table 1 summarises the lake's attributes.

The 2005 wildfire at Yanchep National Park severely reduced vegetation cover and disturbed soil structure at Lake Yonderup.

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 rainfall station to Lake Yonderup at Wanneroo, over a 100 year period (1907–2007) shows a declining trend (Figure 2)

Table 1 Summary attributes of Lake Yonderup

Lake Yonderup	
Location (coordinates)	E: 375300, N: 6508100
Type & description of wetland or groundwater-dependent ecosystem	Permanent lake
Ecological recognition	Conservation category, Environmental Protection Policy EPP, *Register of National Estate*, System 6
Aboriginal heritage	Registered site of significance (3186)
Wetland suite	Yanchep (S.1)

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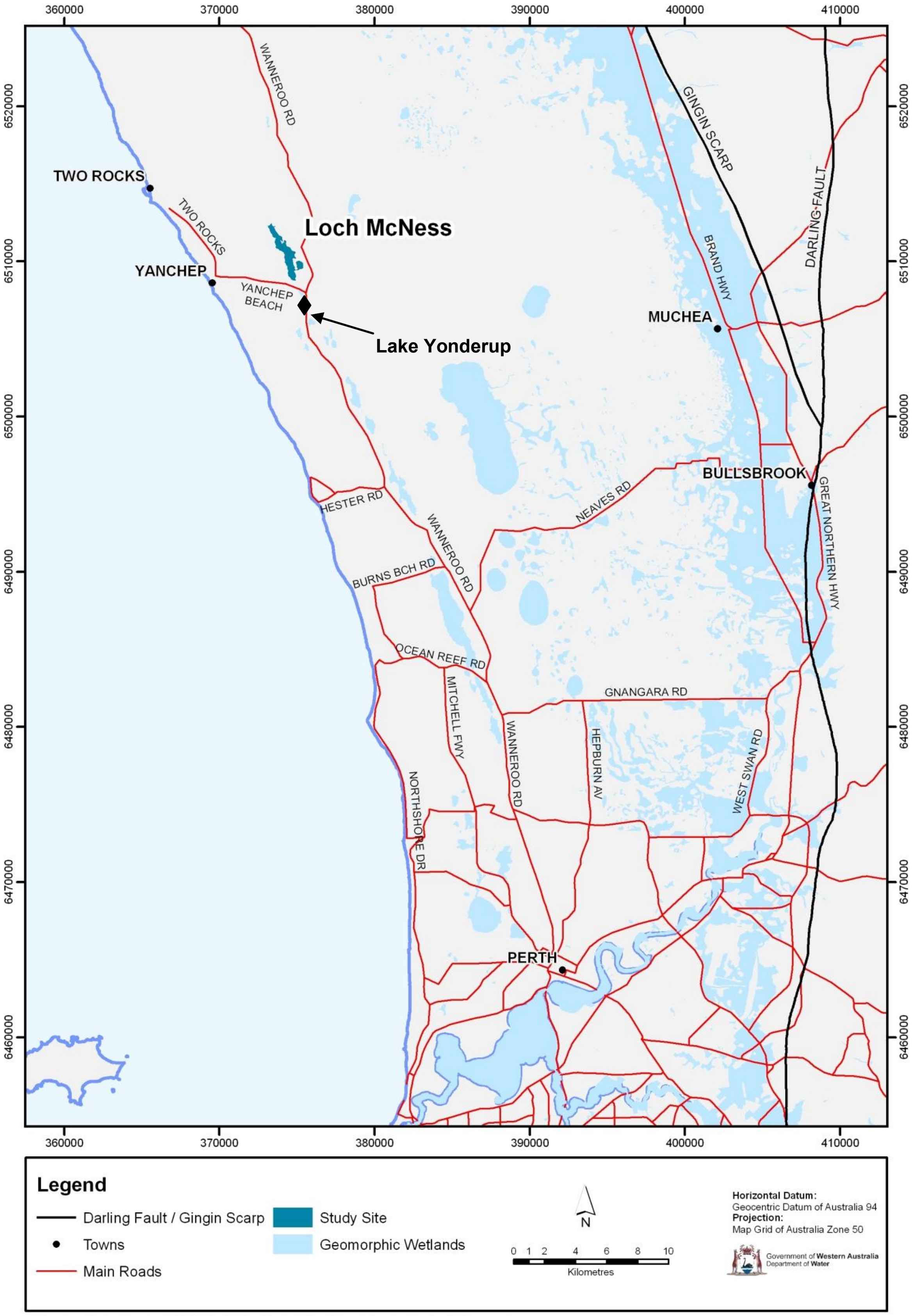

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Figure 1 Location of Lake Yonderup

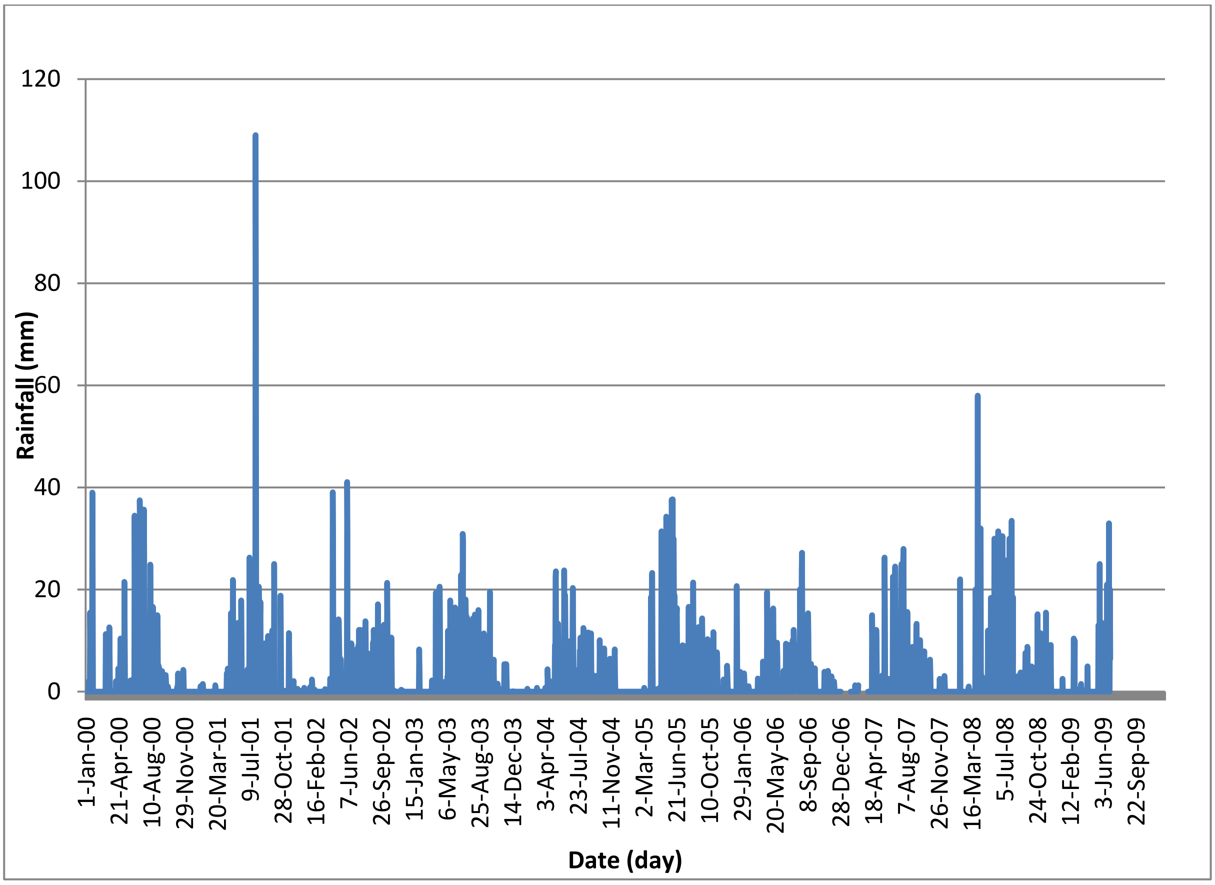

Figure 2 Monthly rainfall for Wanneroo 2000 to 2009

The annual rainfalls for each year from 2000 to 2009 are shown in Table 2. Of note is the low annual 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

2.2.1 Regional geology and geomorphology

Lake Yonderup 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 (Figure 3). The dune sands between the Swan River and the Moore River to the north, 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 overlay these. Wetlands, including Lake Yonderup, have formed where the shallow watertable in the unconfined Superficial aquifer intercepts the surface within dune swales. Where the coastal limestone occurs within the zone of fluctuation of the watertable, karst including caves has formed. Lake Yonderup is situated approximately 1 km to the south of the Yanchep cave system. Karstic limestones are reported in the area and two large cave systems occur to the south of Lake Yonderup. However, the Tamala Limestone at Yonderup would appear to be dominated by sand lithology.

The Tamala Limestone is described by Davidson (1995) as leached yellow sand and aeolian calcarenite. The calcarenite units contain numerous solution cavities, particularly in the region of watertable fluctuation. Sediments of the Quaternary Ascot Formation occur beneath the Tamala Limestone lake (see Figure 3) and are shown to occur by Davidson (1995) in areas to the west of the lake and possibly beneath the. The Ascot Formation is described as a calcarenite interbedded with sands, commonly containing glauconite and phosphatic nodules.

The Tamala Limestone is underlain in places by relatively thin sediments of the Cretaceous Lancelin Formation (Davidson 1995). The Lancelin Formation is described as a white to greenish brown glauconitic marl in the region around Guilderton, some distance to the north of the Yanchep area. Lake Yonderup is located close to the eastern edge of Cretaceous sediments where the Lancelin Formation pinches out, so it is possible that this Formation is very thinly developed or absent 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.

The Pinjar Member of the Leederville Formation lies unconformably beneath superficial sediments or the Cretaceous Lancelin Formation if present. The Pinjar

Member is approximately 50 m thick in the vicinity of the lake and consists of discontinuous interbedded sandstones, and dark grey to black siltstones and shales. Sandstone units are reported to vary from 3 m to 6 m in thickness.

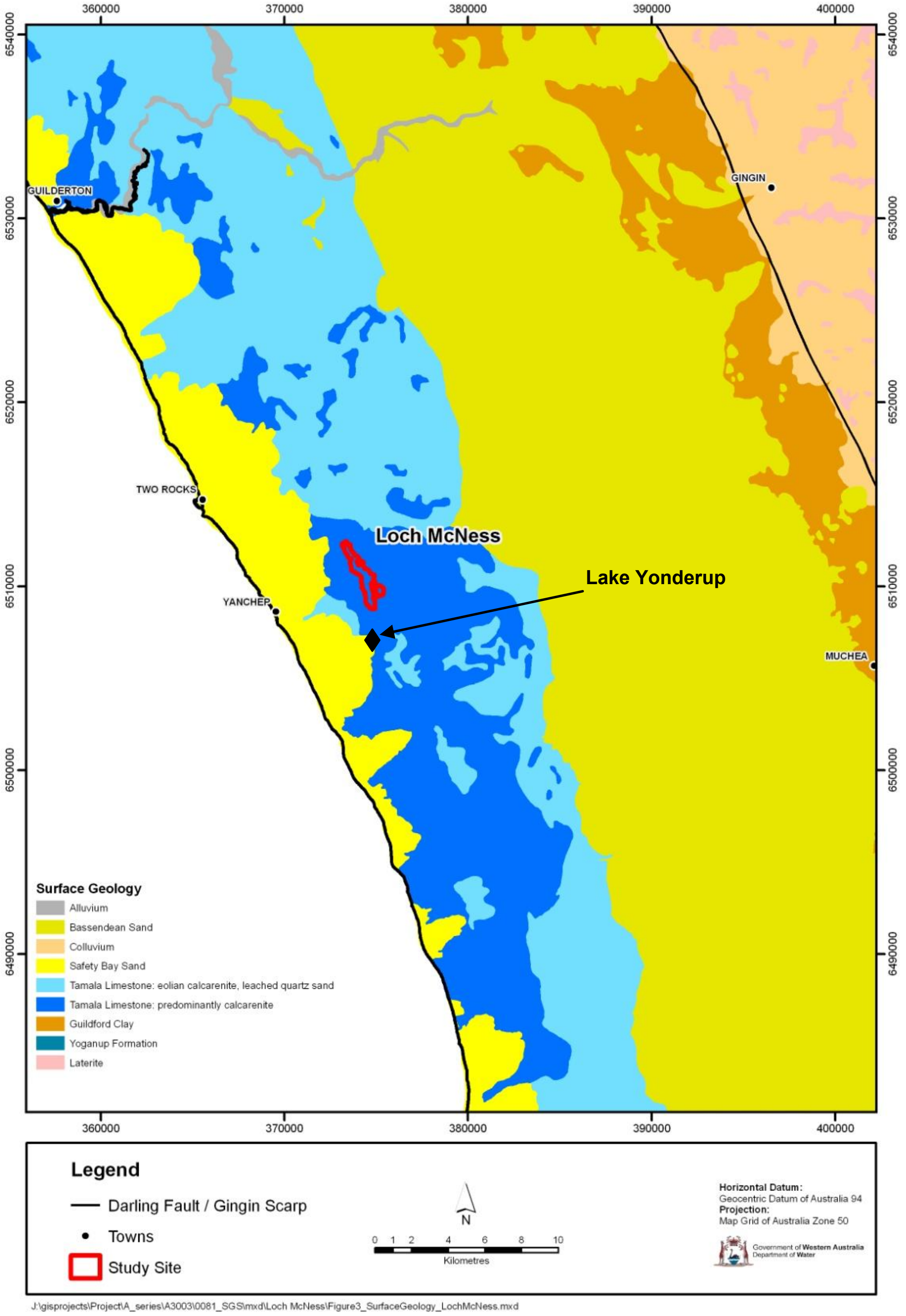

Figure 3 Generalised surface geology at Lake Yonderup

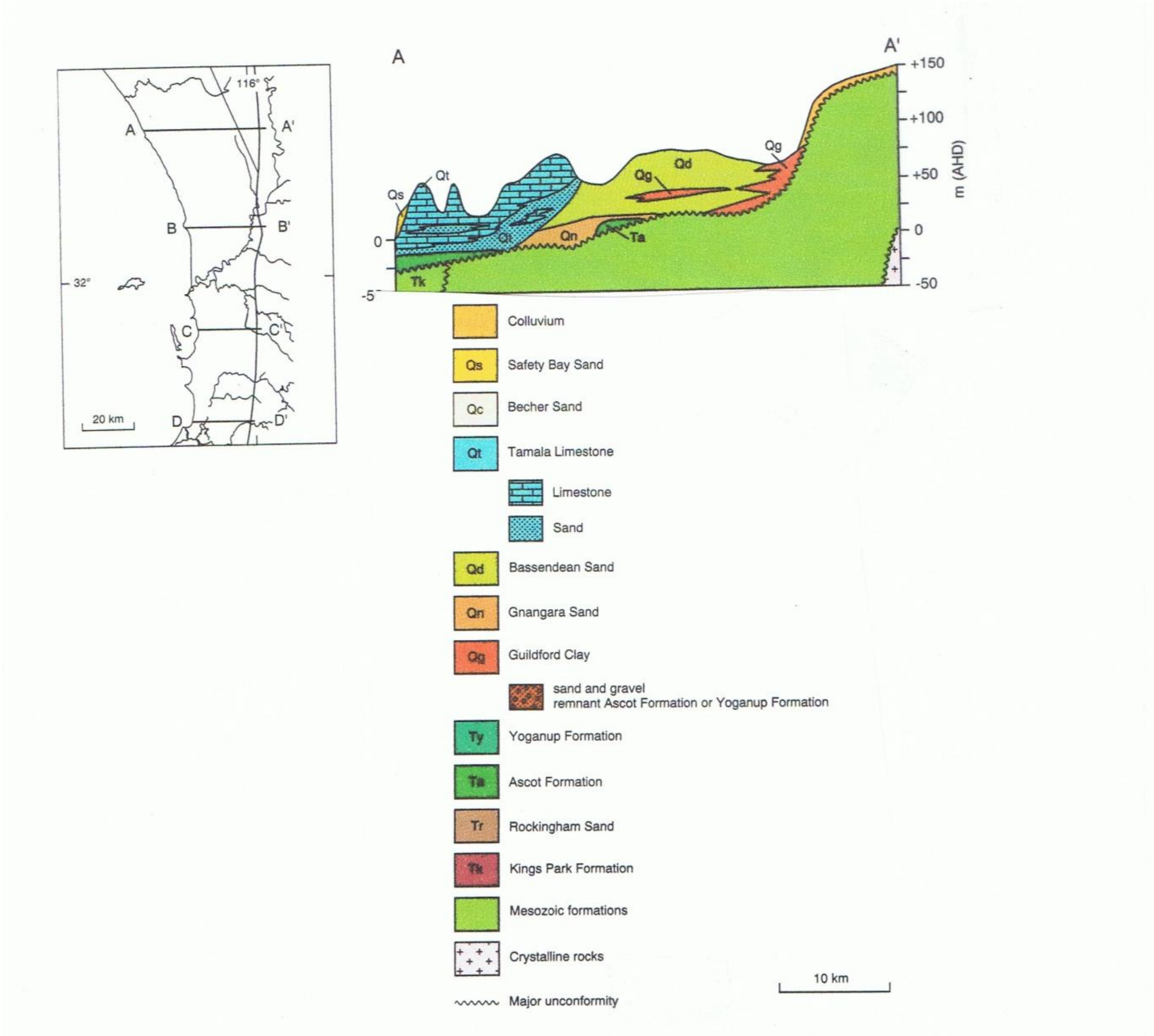

Figure 4 East-west geological cross-section through the superficial formation A-A' north of Lake Yonderup, from Davidson (1995)

2.2.2 Acid sulfate soils

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

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

The consequences that may result include:

- soil acidification
- changes of the quality of soil and water
- degradation of wetlands and water-dependant ecosystems resulting in loss of habitat and biodiversity
- reduction of soil stability and fertility
- reaction of acid surface scalds in discharge areas
- risk of long-term infrastructure damage through 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.

Lake Yonderup is at risk of acidification from the exposure of acid sulfate soils due to declining water levels in the area (McHugh & Bourke 2007; Froend et al. 2004a). Judd & Horwitz (2009) suspect that some sulfidic sediments at Lake Yonderup have been oxidised but that buffering processes may be preventing acidification of the lake.

2.3 Hydrogeology

Lake Yonderup 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 Gnangara Mound, flowing westwards beneath Lake Yonderup 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 Lake Yonderup.

Lake Yonderup 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, and it coincides with a zone of karst where caves and dolines are locally developed in the limestone, whereby streamflow and local groundwater cascades occur (Rockwater 2003).

A number of wetlands on the Swan 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 (for example, see Townley et al. 1991 and Townley & Trefry 2000). Lake Yonderup is thought to be dependent on groundwater, although Rockwater (2003) considered that Loch McNess fed water through karstic solution cavities into Lake Yonderup, and water was discharged via solution cavities back into groundwater. Krasnostein & Oldham (2004) reported that there was no likelihood of discharge of water from Loch McNess into Lake Yonderup via karstic cavities, and considered that both lakes were recharged by groundwater flows from the east. However, there is a possibility that groundwater flow in the region of Lake Yonderup is affected by local karst development, particularly at the watertable.

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 (Yesertener 2005). This lake is entirely dependent on groundwater and is thus a groundwater-dependant ecosystem which is being affected by falling groundwater levels.

Water levels in Lake Yonderup have also declined, particularly since 1987 (Rockwater 2003). This decline has caused significant reductions in the area and depth of the lake, and has exposed organic lake bed sediments. The exposure of these sediments can give rise to oxidation of sulfidic minerals within the sediments and lead to acidic conditions which impact lake water and groundwater quality (Appleyard 2005).

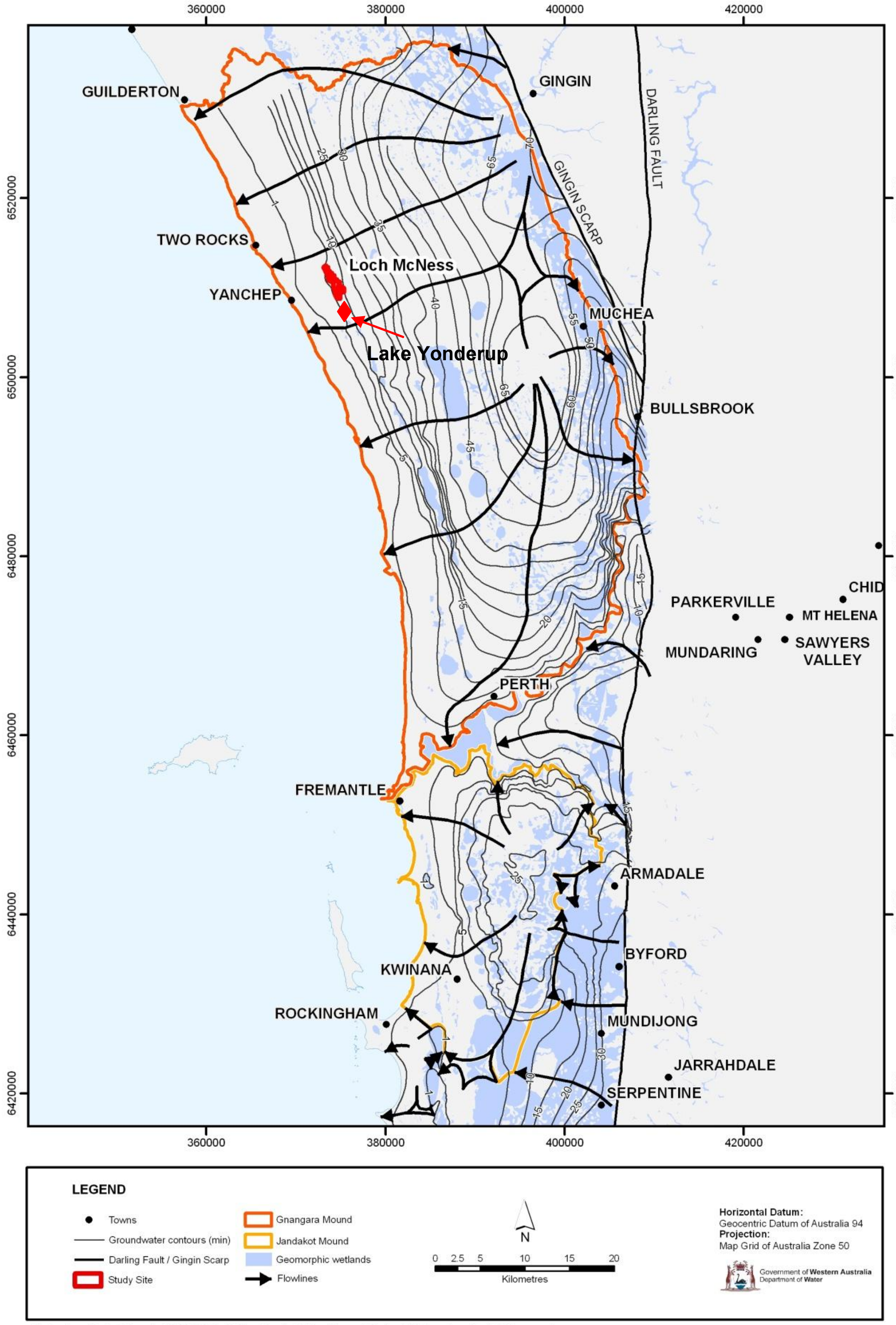

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Figure 5 Gnangara and Jandakot mounds showing flow lines

2.4 Previous studies

There have been no detailed previous hydrogeological studies at Lake Yonderup, although there have been ecological investigations carried out in relation to ecological water requirements (Froend et al. 2004a, b & c). The latter study identified Lake Yonderup as a largely undisturbed wetland with high macroinvertebrate species richness and excellent water quality, with vegetation providing a range of habitat types. It was concluded that it was likely that the wetland is entirely dependent on groundwater for biophysical processes, habitat and consumptive use. The existing summer absolute minimum water level in the lake of 5.9 m AHD was considered appropriate for maintenance of vegetation and macroinvertebrate species associated with the wetland.

Rockwater (2003) reported that the absolute minimum lake water level in summer was reached in 1995, 2001, 2002 and 2003, and that water levels in the lake have gradually declined since 1987. This varies seasonally by 0.1 m due to karst in its catchment that moderates water level variations (ibid).

There is limited information on bores up-gradient of the lake, although one bore, YN7 located ~ 70 m to the east has groundwater levels up to 2 m higher than the lake level. Lake and groundwater peak levels are reported to vary seasonally in phase. Rockwater (2003) concluded from the difference in groundwater and lake levels and their seasonal response, that there is karst control over inflow to the lake from Loch McNess to the north, and outflow via caves.

In undertaking water balance studies at Loch McNess, Bridge (1969) and Arnold (1990), reported in Krasnostein & Oldham (2004), indicate flows south from this lake to nearby caves and into Lake Yonderup. They indicate that the hydrology of Loch McNess and Lake Yonderup and the mechanisms involved in maintenance of water levels were not quantified.

The water balance study and bucket model of Krasnostein & Oldham (2004) concluded that ‘channel flow’ via caves or karstic features from Loch McNess to Lake Yonderup, as proposed by Arnold (1990) was unlikely. Krasnostein and Oldham (2004) suggested Lake Yonderup functions as a flow-through lake. Their study indicated that dye tracer studies carried out by Arnold (1990) (which showed hydraulic links between the lake and nearby caves) were a result of semi-radial groundwater flow around the lake rather than from a direct link or channel between the lake and cave.

2.5 Ecological value and significance

Environmental water provisions (EWPs) have been developed for groundwater-dependent ecosystems on the Gnangara and Jandakot Mounds (WAWA 1995). They were developed by examining the ecological water requirements of the wetlands, based on the links between groundwater and surface water levels and ecological responses (WAWA 1995; Department of Water 2008b). Where the EWPs are deemed to protect the ecological values of a wetland, they have been set as Ministerial criteria which must be complied with under the *Environmental Protection Act 1986*.

These EWPs were first set for wetlands and other groundwater-dependent ecosystems on Gnangara Mound in 1986, and were reviewed in 1995 (WAWA 1995) and again in 2004 (DoE 2004). The persistent breaching of several water level and Ministerial criteria has prompted several reviews of environmental conditions through Section 46 (*Environmental Protection Act 1986*). This report will form part of this ongoing review process.

2.5.1 Ecological values and management objectives

Lake Yonderup is a small, relatively undisturbed, permanent, groundwater-dependent wetland located immediately south of Loch McNess. It is located in a remnant area of the Herdsman vegetation complex, classified as a ‘Spearwood interdunal wetland’ within the Yanchep National Park (Bush Forever site 288; WAWA 1995; Froend et al. 2004a). Due to its high ecological value, Lake Yonderup is recognised as a regionally significant (System 6) conservation category wetland and is listed on the *Register of the National Estate* (Department of Water 2008b; Froend et al. 2004a)

Along with Loch McNess, Lake Yonderup is valued for its historically stable water regime (WAWA 1995; Froend et al. 2004a; Department of Water 2008b), with as little as 0.05 m seasonal variation in water level (Horwitz et al. 2009a).

Lake Yonderup was identified as a significant wetland under the Gnangara Mound Water Resources Environmental Review and Management Program (WAWA 1995) due to its:

- high ecological value – a result of its undisturbed nature
- rich invertebrate fauna
- excellent water quality
- undisturbed hydrologic regime and lack of seasonal variation in water level.

The environmental water provisions developed to protect these values are based on available data and understanding of the links between groundwater levels and ecological responses at Lake Yonderup. An assessment of the EWRs to protect these values led to the development of the following management objectives for Lake Yonderup (WAWA 1995):

- to maintain the environmental quality of Lake Yonderup
- to maintain its existing hydrological regime.

An absolute summer water level minimum of 5.9 m AHD was identified as sufficient to meet these management objectives and maintain the ecological values of Lake Yonderup (WAWA 1995). This water level was adopted as a Ministerial criteria (Department of Water 2008b).

In 2004, the ecological values (Froend et al. 2004a) and EWRs (Froend et al. 2004b) for Lake Yonderup were reviewed. The review found the original ecological values were still relevant and suggested that Lake Yonderup should also be valued for its vegetation community, which is largely intact and provides range of habitat types for aquatic and terrestrial fauna (Froend et al. 2004a). The review also found that the Ministerial criteria water level was sufficient for maintaining these ecological values and, thus, the current EWRs were likely to be appropriate (Froend et al. 2004b).

As the vegetation transect at the time of the review (southern transect, located 750 m south of the lake) was not influenced by surface water, the development of minimum water requirements using this transect was considered as unrepresentative of the requirements of vegetation in close proximity to Lake Yonderup (Froend et al. 2004b). The review identified that vegetation assemblages at the lake are important habitat for macroinvertebrates, and suggested vegetation EWRs (if developed) could be used as a surrogate for macroinvertebrate EWRs, especially those for emergent or littoral vegetation.

Although water levels in Lake Yonderup have been declining steadily since 1995 (Figure 6), the Ministerial criteria water level was met until 2003 (Judd & Horwitz 2009). Water levels have been declining at a rate of approximately 0.04 m/yr (Department of Water 2008b) and have largely remained below the Ministerial criteria minimum level since 2006. The recent low water levels are of extreme concern for managing the ecological values of the lake (Judd & Horwitz 2009).

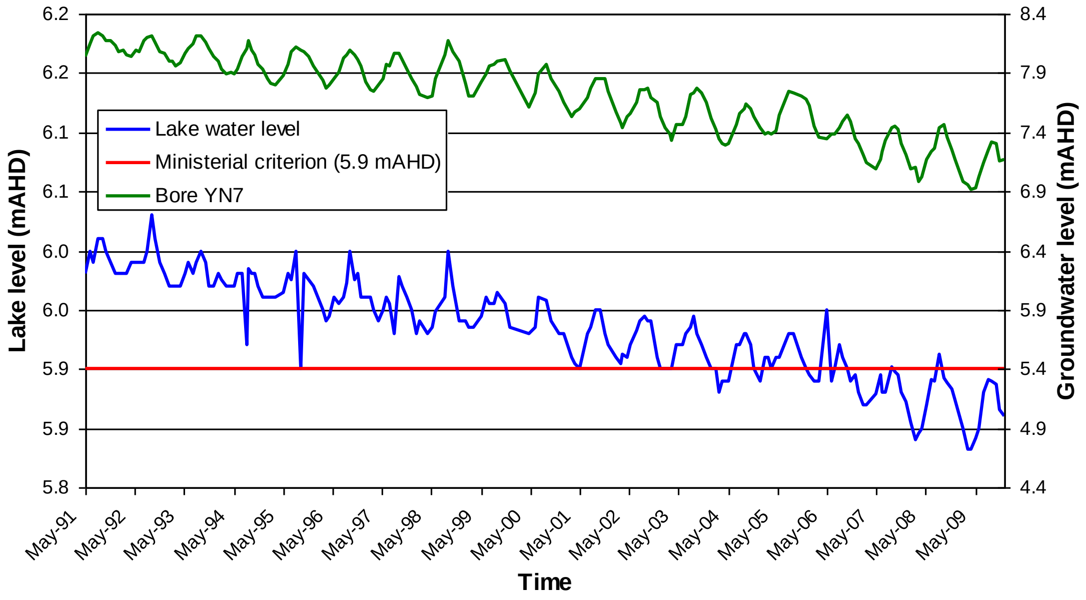

Figure 6 Water level at Lake Yonderup compared to groundwater level at bore YN7

Figure 6 shows the direct relationship between lake and groundwater levels. This supports the hypothesis proposed by Froend et al. (2004b) that ‘the wetland is entirely groundwater dependent for biophysical processes, habitat and consumptive use’. Low groundwater levels in the Yanchep groundwater area are predominantly climate-driven, reflecting rainfall patterns, with some effects from land use and abstraction.

2.5.2 Impacts of declining water levels on ecological values

A number of ecological responses to the decline in water levels at Lake Yonderup have been measured to date, with levels of response predicted to increase if low water levels persist. At present, water levels are below the currently recommended EWR of 5.9 m AHD (Department of Water 2008b) for wetland vegetation, waterbirds, macroinvertebrates, vertebrates and sediment processes.

As water levels decrease, exposed organic-rich sediment are showing signs of drying (Department of Water 2008b). Sulfidic sediments are thought to be oxidising (Judd & Horwitz 2009), a process that leads to acidification. No change in pH has been recorded in Lake Yonderup yet as the lake is thought to have a high buffering capacity (WAWA 1995) which is mitigating the effects of acidification.

As lake levels have declined, there has been increased terrestrialisation, declining condition of fringing vegetation and invasion of weed species in littoral habitats (Cullinane et al. 2009; Department of Water 2008a; Froend et al. 2004a). Overall tree health is declining in response to falling groundwater levels and the summer 2004–05 bushfires. Although one important wetland species – *Banksia littoralis* – has been lost from the southern vegetation transect, this was in response to the summer 2004–05 fires and is only indirectly linked to decreasing groundwater levels (Cullinane et al. 2009). Two other wetland species – *Melaleuca rhaphiophylla* and *Baumea juncea* –

have maintained their distribution, which has not changed from 2004–08. *Baumea juncea* and *M. rhaphiophylla* have shown some decline in condition and fragmentation across their distributions (Cullinane et al. 2009; Froend et al. 2004a).

These changes have occurred despite the magnitude and rate of groundwater drawdown falling within the ‘low risk of impact’ category – 0.1 m/yr and magnitude 0.25 m for wetland species, 0.1 m/yr and 0.75 m for terrestrial species (*B. littoralis and M. rhaphiophylla*) (Department of Water 2008b). This suggests that the vegetation community of Lake Yonderup may be more sensitive to groundwater drawdown than anticipated, although the 2004–05 fire has contributed to the observed changes.

Macroinvertebrate habitats have contracted as lake levels have fallen, concentrating macroinvertebrate populations (Judd & Horwitz 2009; Sommer & Horwitz 2007; Clark & Horwitz 2005). However, the impact of declining water levels on macroinvertebrates was not detected until 2009, when there was a marked reduction in spring family richness. This change suggests that lake levels have recently reduced to such an extent that the ecology and biodiversity of Lake Yonderup has been affected (Judd & Horwitz 2009).

Despite these changes, Lake Yonderup remains one of most taxa-rich and important wetlands on the Gnangara Mound (Department of Water 2008b).

Further decline of water levels in Lake Yonderup has the potential to severely degrade the ecological values of the lake (Froend et al. 2004b). The major risks to the ecological values of the lake listed below are:

- High ecological values due to undisturbed nature:
  - The changes recorded in vegetation and macroinvertebrate communities since 2008 show that the ecology of Lake Yonderup has been disturbed by low groundwater levels. If low groundwater levels persist, the level of disturbance will increase, compromising the lake’s ecological value.
- Rich macroinvertebrate fauna:
  - Continued drying of Lake Yonderup is expected to alter the macroinvertebrate community by decreasing taxonomic richness, loss of sensitive taxa and increased abundance of tolerant taxa (Horwitz et al. 2009b). These changes will not only decrease the richness of the macroinvertebrate fauna, compromising this ecological value, but may also alter the dominant biotic processes in the lake.
- Excellent water quality:
  - The water quality in Lake Yonderup is showing signs of deterioration due to the concentration of nutrients, salts and ions. At present water quality is still good, but further water level declines will exacerbate the concentration effect. The principal threat to water quality is through acidification, which would have a toxic effect on the lake’s aquatic flora and fauna species (Horwitz et al. 2009b). Should acidification occur, the consequences would be severe.

- Undisturbed hydrologic regime and lack of seasonal variation:
    - Significant change to hydrologic regime as a result of declining water levels. This change is already underway, with water levels declining by ~ 0.13 m, and may already indicate a threshold change (Judd & Horwitz 2009). Continuing declines in lake level will cause alteration of the hydrologic regime, compromising this ecological value
- Vegetation largely intact, provides range of habitat types:
    - The wetland vegetation community at Lake Yonderup is already showing signs of water stress, with groundwater-related effects on vegetation condition and distribution recently becoming apparent (Cullinane et al. 2009). If the vegetation EWRs are not met, plants will lose vigour, further tree death will occur and species persisting at the dry extent of their known range will be lost (Horwitz et al. 2009b). Ongoing low water levels will also increase the susceptibility of vegetation communities to invasion by exotic weeds and increase the risk of fire (Froend et al. 2004a).These changes will alter the composition and distribution of the vegetation community, compromising this ecological value.

2.6 Cultural significance

Wetlands across the Swan Coastal Plain are spiritually significant to Indigenous groups (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).

Lake Yonderup is included with Loch McNess as a registered site of significance (DIA 3742) and reflects these Indigenous values. 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 signals its disappearance. It is through the activities of this Waugal that the springs which feed the lake continue to flow (McDonald et al. 2005).

As required by the *Aboriginal Heritage Act 1972* and the *Native Title Act 1993*, the Department of Water contracted an anthropologist to undertake an ethnographic survey Lake Yonderup prior to the start of drilling works. The objectives of the survey were to determine the Indigenous heritage values of the wetland area and then to conduct archaeological and ethnographic surveys as required.

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[1] A mythical water-being.

[2] According to laboratory methods guidelines (Ahern et. al. 2004), when pH_{KCl} is higher than 6.5, ANC

Near Lake Yonderup there is a cave (Yonderup Cave – DIA Site ID 3186), which has been found to be an Aboriginal burial ground (McDonald et al. 2005). Wright (2008) reported that due to the cave being some distance to the east of the proposed monitoring bores, it would not be affected by the SGS investigation's drilling activities.

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 has used a revised variable groundwater abstraction rule to set the annual groundwater allocation for the Gnangara and Jandakot mounds (DoW 2009c). 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 and water use recommendations of the Gnangara Sustainability Strategy (GSS), including the recommendation that the long-term total allocation should be reduced. The proposed statutory water management plan for Gnangara will set new allocation limits for the Yanchep groundwater area.

In response to declining groundwater levels across the Gnangara Mound, the department (Department of Water 2009c) has developed an internal policy (*Policy 4.1.1* reported in Department of Water 2009c) to limit or restrict 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–Lake Yonderup area).

WAWA (1995) stated that the environmental impacts of abstraction are considered to have been minor compared to those of urbanisation, agriculture and silviculture. However, since that time there has been a significant increase in abstraction. There are private licences in the vicinity of Lake Yonderup. Furthermore, regional groundwater levels are affected by abstraction. Figure 8 shows the drawpoints and allocations in the area around Lake Yonderup.

The possible implications to Lake Yonderup from these increases in abstraction are discussed further in Section 7.

The *Gnangara groundwater areas allocation plan* (Department of Water 2009c) 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 groundwater-dependent ecosystems, ecological condition and rate and magnitude of groundwater level change. For allocation purposes the Gnangara Mound is divided into groundwater areas and subareas. Lake Yonderup is located in the proclaimed Yanchep groundwater area and subarea (Figure 8). 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

Allocation limit	10.87 GL/yr
Licensed entitlements [1]	2.73 GL/yr
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.

Adapted from Appendix H, Department of Water 2009a.

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 they are based on:

- hydrograph trend analysis
- water balance modelling using PRAMS (Perth regional aquifer modelling system)
- CDFM (Cumulative deviation from mean rainfall)
- The protection of groundwater-dependent ecosystems including the location and condition of environmental criteria sites.

Land and water-use criteria which are currently used, or which may be used in the future, to make allocation limit decisions are based on:

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

Land surrounding Lake Yonderup, (Department of Water 2009c) which includes banksia woodland, is used for conservation purposes. 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. Significant and large Bush Forever sites are situated across the zone. These provide ecological linkages to the Yanchep National Park (Department of Water 2009b).

Pine plantations are located across the East Yanchep subarea. During the 1990s, the increasing density of pine plantations is likely to have contributed to 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’.

Because of the water use of pine plantations, the GSS 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 have lower rates of decline under native vegetation if more frequent burning is feasible (Department of Water 2009b).

3 Investigation program

3.1 Bore construction

The management area review (McHugh &Bourke 2007) recommended upgrading the groundwater monitoring network at Lake Yonderup to enable hydrogeological, hydrochemical and geochemical investigations. It was recommended that groundwater monitoring bores be installed in clusters of three, all in the Superficial aquifer. These were shallow (5 to 6 m of screen set at the watertable), intermediate (2 m of screen set approximately halfway 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. Reference to 'up-gradient' and 'down-gradient' throughout this report refers to up-hydraulic gradient and down-hydraulic gradient, unless stated otherwise.

The cluster of bores on the western (down-gradient) side of the lake was identified as YDP_West bores (YDP_WC (shallow), YDP_WB (intermediate) and YDP_WA (deep). The cluster of bores on the eastern (up-gradient) side of Lake Yonderup was identified as YDP_East bores (YDP_EC (shallow), YDP_EB (intermediate) and YDP_EA (deep). In addition to these clusters, a shallow bore was placed on the southern side of the lake and was identified as YDP_SC.

Figure 7 shows the location of these bores and Figure 8 shows these bores and other monitoring boreholes drilled during previous investigations within the region of Lake Yonderup. 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.

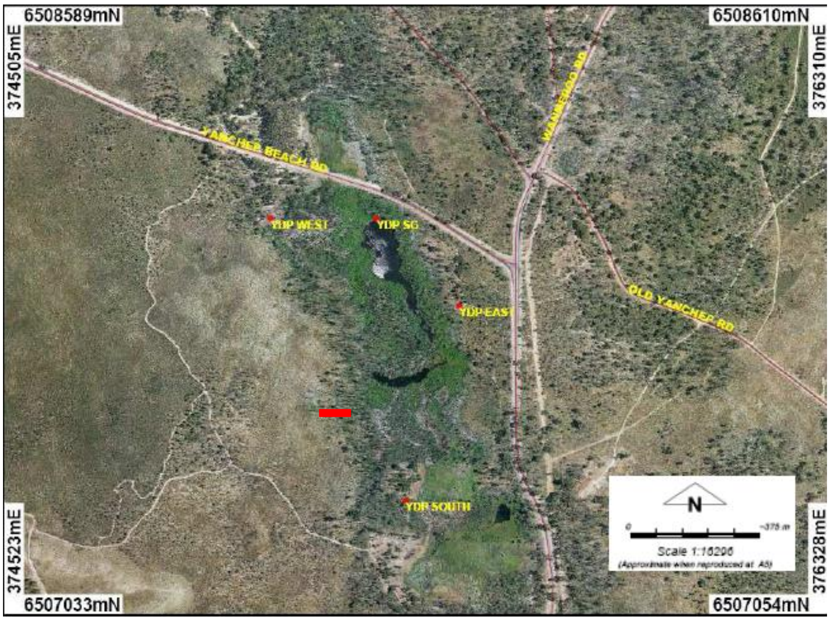


Figure 7 Location of bores used in the SGS investigation at Lake Yonderup (red line shows vegetation transect)

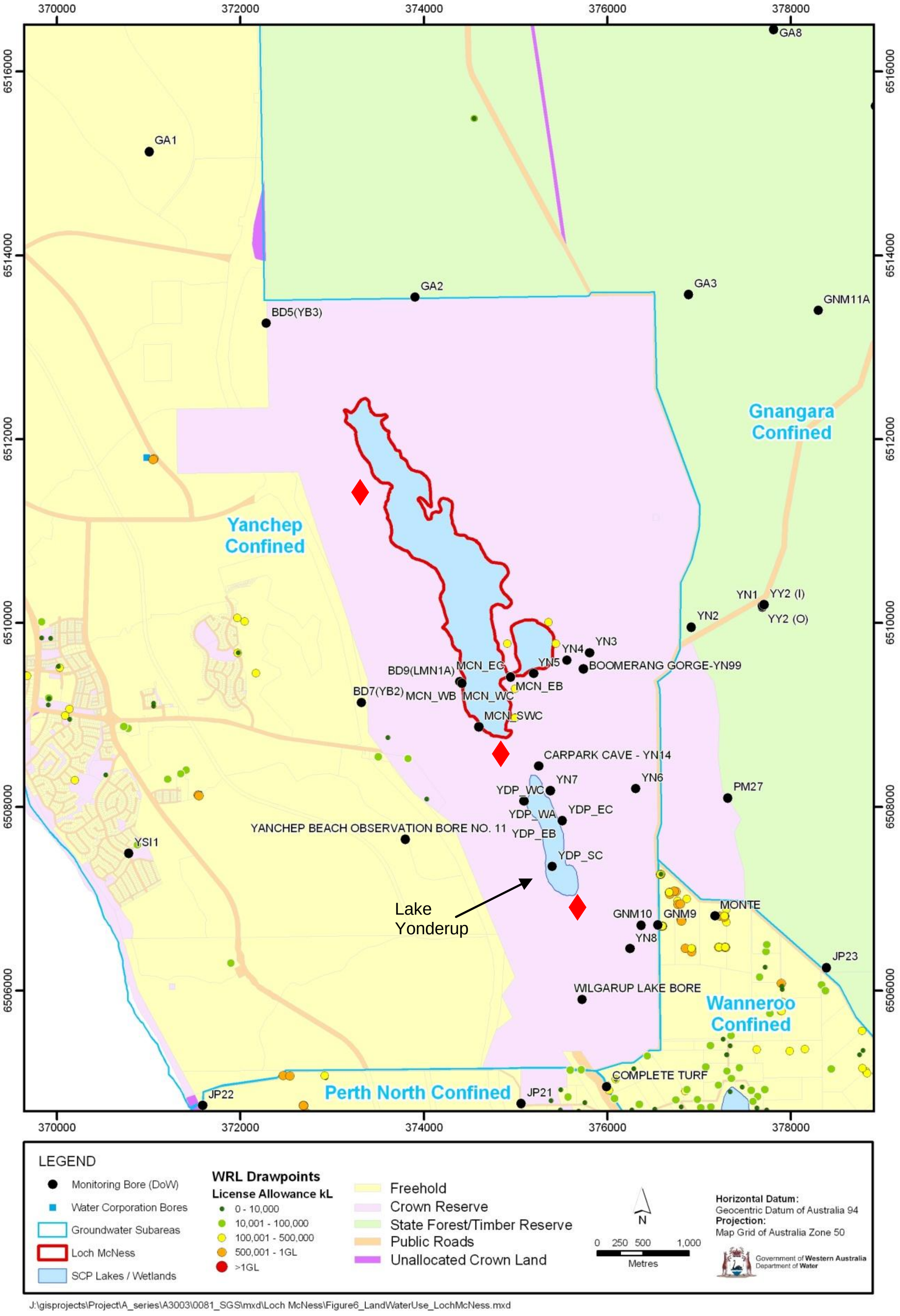


Figure 8 YDP and other bore locations in the region and allocations of Lake Yonderup (red diamonds demarcate vegetation transects)

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 consist of either steel standpipes cemented in with a height of approximately 0.5 m above ground level, or flush mount well covers which sit close to the ground surface.

Table 4 Bores involved in the SGS investigation at Lake Yonderup

Cluster bores on the eastern site Lake Yonderup (YDP_E)				
Depth	**AWRC name**	**AWRC number**	**Drilled depth mbns**	**Screen interval mbns**
Deep	YDP_EA	61611839	37	30.82–32.82
Intermediate	YDP_EB	61611838	23	20.89–22.89
Shallow	YDP_EC	61611837	9.5	1.3–7.3
Cluster bores on the western site Lake Yonderup (YDP_W)				
Depth	**AWRC name**	**AWRC number**	**Drilled depth mbns**	**Screen interval mbns**
Deep	YDP_WA	61611836	39	28.62–30.62
Intermediate	YDP_WB	61611835	20	17.87–19.87
Shallow	YDP_WC	61611834	9.5	1.5–7.5
Bore on the southern site Lake Yonderup (YDP_Sc)				
Depth	**AWRC name**	**AWRC number**	**Drilled depth mbns**	**Screen interval mbns**
Shallow	YDP_SC	61611840	6.4	0.4-6.4
Other bores within the region				
Depth	**AWRC Name**	**AWRC number**	**Drilled depth mbns**	**Screen interval mbns**
	YN6	61612105	25.59	15.51–21.51
	YN7	61612106	11.06	9.22–15.22
	YN11	61610582	12.04	14.76–16.76

Note: mbns – metres below natural surface

3.2 Acid sulfate soils testing

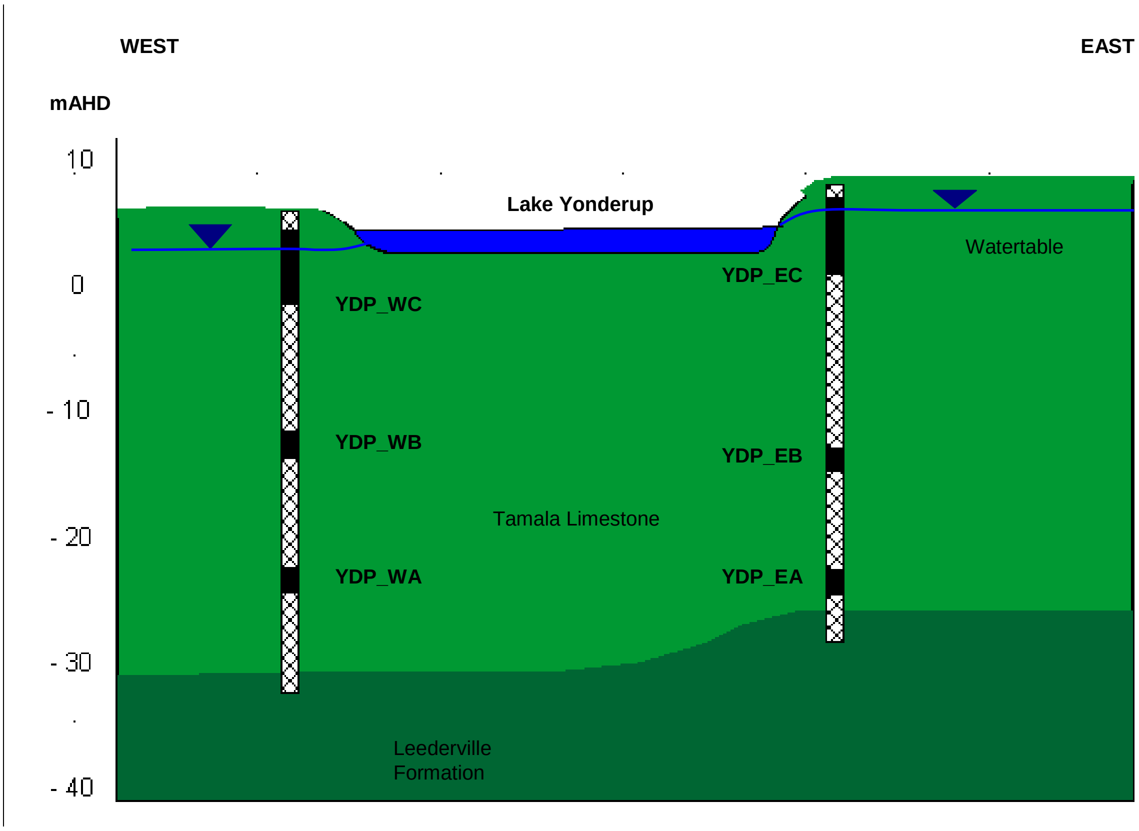
To determine the distribution and characteristics of sulfidic sediments at Lake Yonderup and the potential of these to affect groundwater quality, a study was conducted as part of the SGS investigation. Samples were collected and analysed for potential acid sulfate soils and actual acid sulfate soils according to the Department of Environment’s *Draft Investigation and Identification of acid sulfate soils guide* (DEC 2009) (see Appendix B for full methods). Field and laboratory tests were conducted on sediment recovered during drilling from SGS bores YDP_EC and YDP_WC during bore construction.

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 as extracted from the ground, or the following day. NMI used the chromium reducible sulfur suite (CRS) 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 sampling and analysis was undertaken to determine the hydrochemical characteristics of each site, the distribution and availability of potential pollutants and the interaction between the wetland and the Superficial aquifer.

Water samples were collected using low flow pumping methods as described in Appendix B. Analyses of water samples were conducted for major ions, metals, nutrients and a range of herbicides and pesticides. Figure 9 shows the location and depth of groundwater bores used for monitoring the Lake Yonderup groundwater system.



Note: vertical exaggeration is approximately 5

Figure 9 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 as such results from laboratory chemical analysis are not absolute. This uncertainty is caused by several contributing error sources, mainly precision errors and 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, also known as an ion balance, is used to check the accuracy of analytical results. The sum of positive and negative charges in the water should be equal (Appelo & Postma 2005), so the sum of the cations in solution should equal the sum of the anions:

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

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 2005). For the SGS investigation, if the electrical balance of a sample was greater than 6%, without satisfactory explanation, then the sample was left out of the analysis.

Comparing the pH measured in the laboratory with those measured in the field immediately after sampling, can indicate that a water sample has been altered by the collection, transport or storage processes. There are numerous causes for a difference in field and laboratory pH reading, and for other ‘unstable’ determinands such as dissolved oxygen (DO) and oxidation–reduction potential (ORP), including reactions involving oxidation, precipitation and release of dissolved gas. Only the on-site analyses for pH, temperature, DO and ORP were used in the data analysis reported below to avoid these problems, 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 Lake Yonderup 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 checked by calculating electrical ion balances as described above.

4 Geology

4.1 Superficial and Mesozoic formations

Borehole logs for the deep bores, YDP_EA and YDP_WA (Table 5 and Figure 10) show that the thicknesses of the superficial formation's sands and calcarenites are more than 37 m and 39 m, respectively. The location of the bores is shown in Figure 7 and Figure 8.

The bore logs indicate that the Tamala Limestone consists of stratified silty sands, sands and lesser limestones (conglomerates) in the region of Lake Yonderup. There is no obvious correlation of strata in either deep bores YDP_EA and YDP_WA located on the eastern and western sides of the lake, respectively. Only sands are observed in YDP_EA, while between 33 m and 36 m in the down-gradient bore YDP_WA the lithology recorded was 'conglomerate' (possibly this represents limestone 'kankar') (see Figure 10).

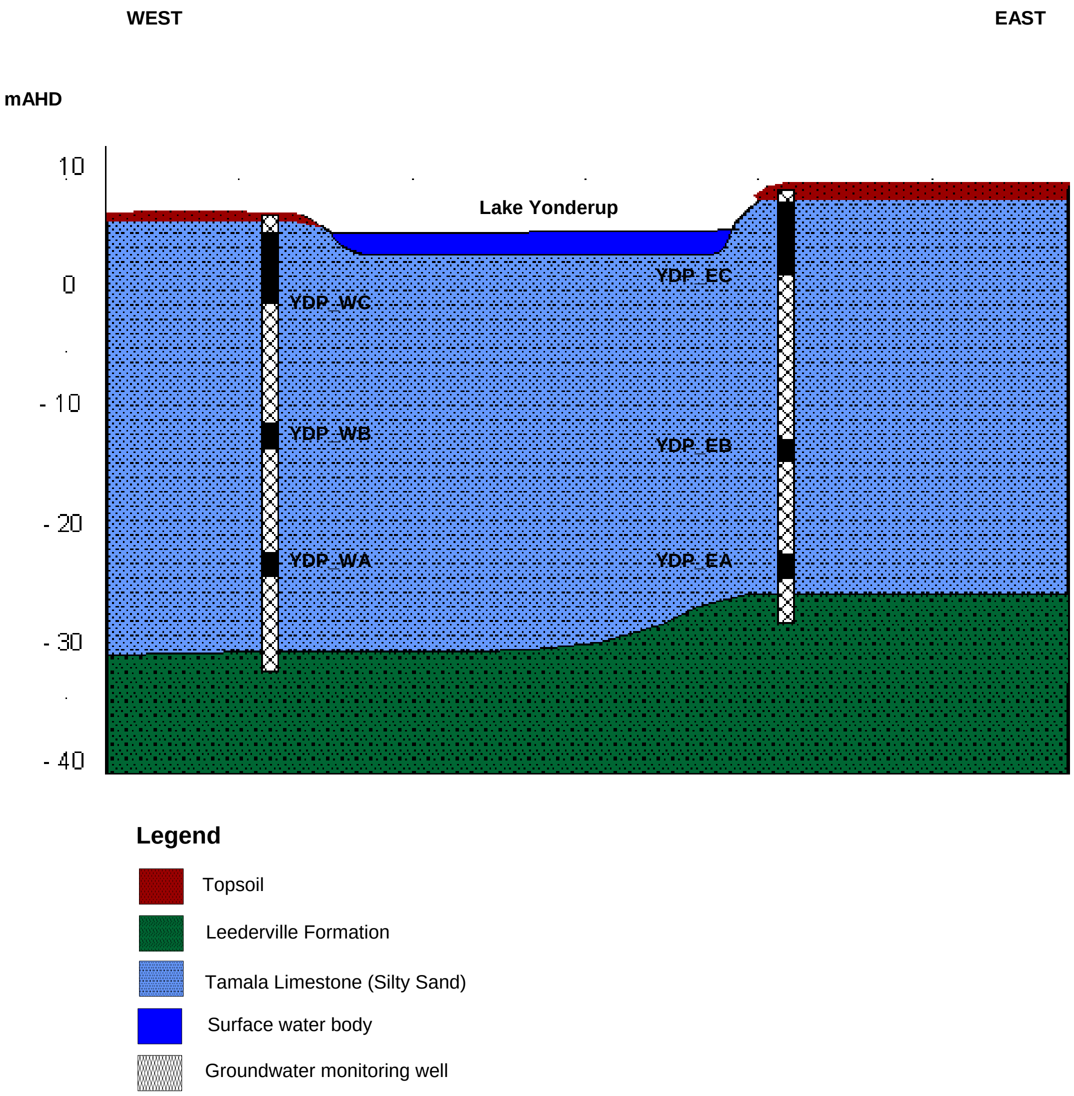
Superficial sediments (Tamala Limestone) in bores YDP_EA and YDP_WA were reported to be underlain by sandy silt of the Leederville Formation. It is possible that these are sediments of the Pinjar Member of the Leederville Formation, as the lithology more closely conforms to this formation (mudstones/siltstones and sandstones).

A bore drilled in 2004 near the former Department of Conservation and Land Management station on Yanchep Beach Road, approximately 1.5 km north-west of Lake Yonderup (Water Corporation 2004) found 22 m of sands and calcarenite underlain by black clay and sands/silts, which was interpreted as Leederville Formation, conforming closely to the description of the Pinjar Member. The Pinjar Member is reported to be 50 m thick in the vicinity of Loch McNess (Davidson 1995).

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

Bore ID	From mbns	To mbns	Formation	Code	Lithology
YDP_EA	0	1	Tamala Limestone	Qt	Topsoil and sand
	1	4	Tamala Limestone	Qt	Silty sand
	4	6	Tamala Limestone	Qt	Silty sand
	6	8	Tamala Limestone	Qt	Silty sand
	8	9	Tamala Limestone	Qt	Silty sand
	9	10	Tamala Limestone	Qt	Silty sand
	10	12	Tamala Limestone	Qt	Silty sand
	12	14	Tamala Limestone	Qt	Silty sand
	14	21	Tamala Limestone	Qt	Silty sand
	21	24	Tamala Limestone	Qt	Silty sand
	24	31	Tamala Limestone	Qt	Silty sand
	31	33	Tamala Limestone	Qt	Sand
	33	34	Tamala Limestone	Qt	Silty sand
	34	35	Tamala Limestone	Qt	Sand
	35	37	Leederville Formation	Kwl	Silty sand and black silt
YDP_WA	0	1	Tamala Limestone	Qt	Topsoil and sand
	1	2	Tamala Limestone	Qt	Sand
	2	3	Tamala Limestone	Qt	Silty sand
	3	6	Tamala Limestone	Qt	Sand
	6	7	Tamala Limestone	Qt	Silty sand
	7	10	Tamala Limestone	Qt	Sand
	10	11	Tamala Limestone	Qt	Silty sand
	11	14	Tamala Limestone	Qt	Sand
	14	18	Tamala Limestone	Qt	Silty sand
	18	20	Tamala Limestone	Qt	Silty sand
	20	27	Tamala Limestone	Qt	Silty sand
	27	29	Tamala Limestone	Qt	Silty sand
	29	31	Tamala Limestone	Qt	Silty sand
	31	32	Tamala Limestone	Qt	Silty sand
	32	33	Tamala Limestone	Qt	Silty clayey sand
	33	35	Tamala Limestone	Qt	Conglomerate
	35	36	Tamala Limestone	Qt	Conglomerate/quartz
	36	38	Tamala Limestone	Qt	Silty sand
	38	39	Leederville Formation	Kwl	Sandy silt

Note: mbns – metres below natural surface



Note: vertical exaggeration is approximately 5

Figure 10 Geological cross-section at Lake Yonderup

4.2 Lake deposits

Lake Yonderup overlies sand believed to be derived from de-calcification of the limestone, and contain chemogenic and biogenic lake deposits of peat and diatomite (Rockwater 2003).

4.3 Acid sulfate soils

4.3.1 Lake perimeter

Field and laboratory testing was carried out on three Superficial sediment cores retrieved from shallow SGS boreholes, YDP_EC, YDP_WC and YDP_SC. Laboratory analyses were conducted on eight samples including two duplicates (YDP_EC and YDP_SC) to verify the accuracy of the field results and provide better information on acid-base accounting. No samples of lake sediments were collected for ASS analysis. Full laboratory results are presented in Appendix D.

The pH_F results at YDP_WC (Figure 11) were mainly reported above 4.00 ranging from 4.22 to 7.01, except for one sample reported at 3.68 at 2.5 m. The pH_{FOX} results ranged from 2.68 to 4.58 within the upper 3.5 m of the soil profile, whereas pH_{FOX} results ranged from 5.25 to 5.45 between 4.0 m and 9.0 m. Organic materials were logged within the upper 3.5 m, which may have contributed to the low pH_{FOX} recorded. Only one sample showed a difference between pH_F and pH_{FOX} to be higher than 2.00 (at 0.1 m depth) indicating the presence of potential acid sulfate soils. The pH_{OX} results were higher than pH_{FOX}, indicating that the sample has probably undergone sulfide oxidation prior to laboratory analysis.

The pH_F results at YDP_EC (Figure 12) were above 4.00 ranging from 5.73 to 8.04 indicating an absence of potential acid sulfate soils. The pH_{FOX} results were also reported above 4, except for one sample that recorded pH_{FOX} of 3.85 at 0.2m. The pH_{OX} results reported similar value to the pH_{FOX} at the same depth of 1m.

The pH_F results at YDP_SC (Figure 13) were all above 4.00 ranging from 4.16 to 8.14, indicating the absence of potential acid sulfate soils. The pH_{FOX} results were mainly above 4.00, except for three samples at 0.9 m (2.37), 1.2 m (2.08), and 1.5 m (3.55). Two of the three samples mentioned recorded a difference between pH_F and pH_{FOX} higher than two at 1.2 m and 1.5 m, indicating the presence of potential acid sulfate soils. The pH_{OX} results were similar to the pH_{FOX} at 1.2m. However, at 0.0 m and 0.9m pH_{OX} recorded higher values than $pH_{FOX,}$ indicating that the sample has probably undergone sulfide oxidation prior to laboratory analysis.

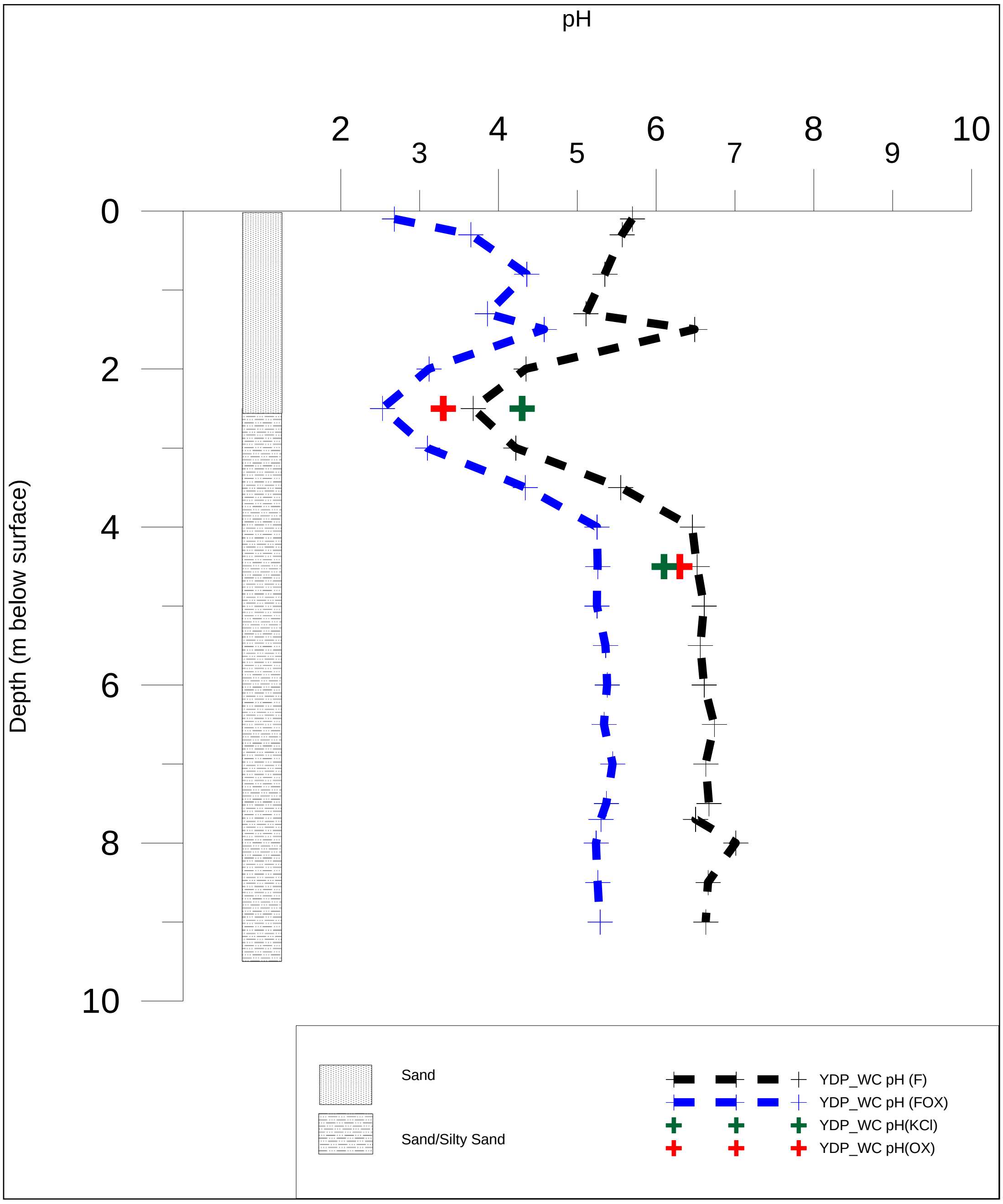


Figure 11 Natural and oxidised field pH measurements correlated with lithological units at YDP_WC

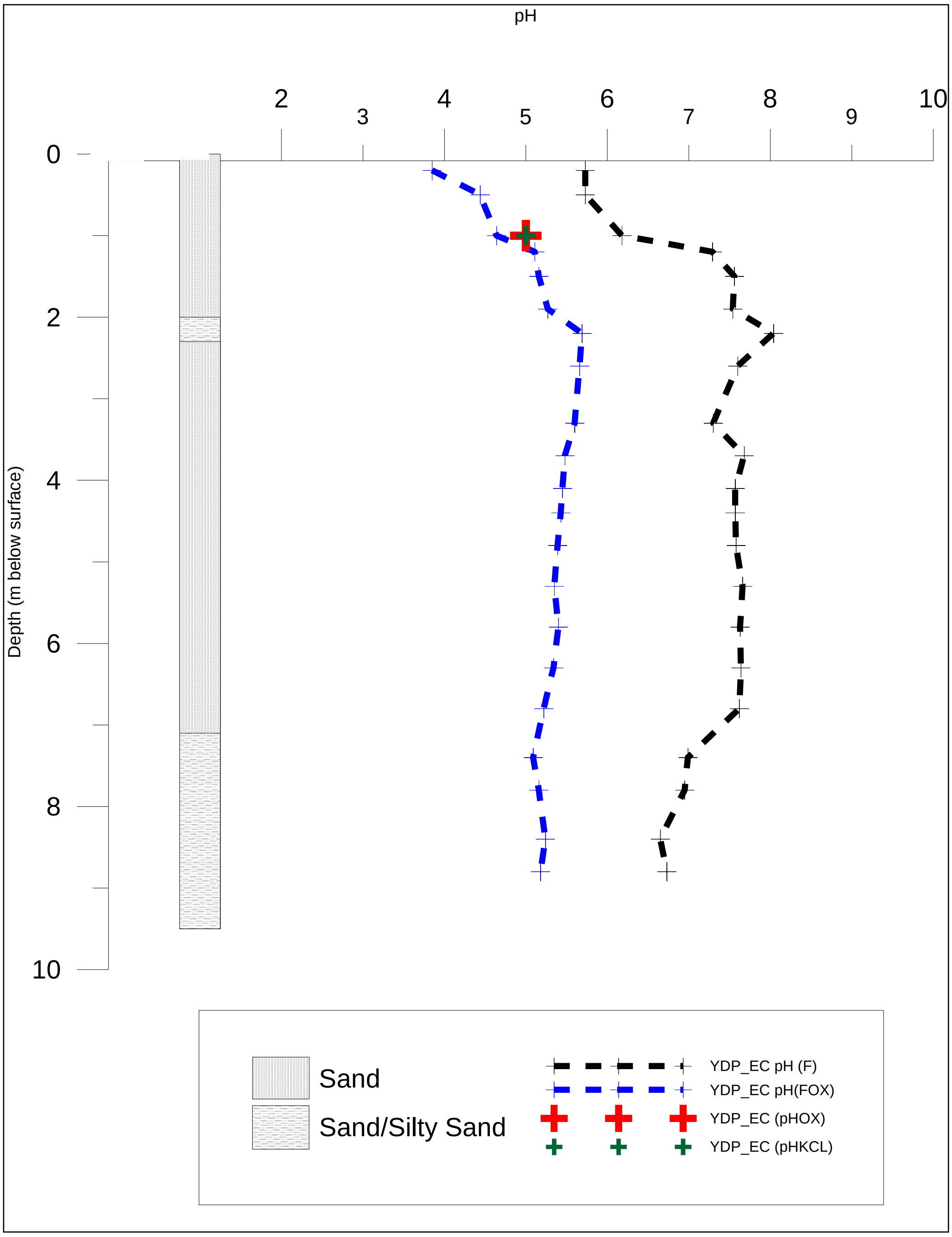


Figure 12 *Natural and oxidised pH measurements correlated with laboratory oxidised pH and lithological units at YDP_EC*

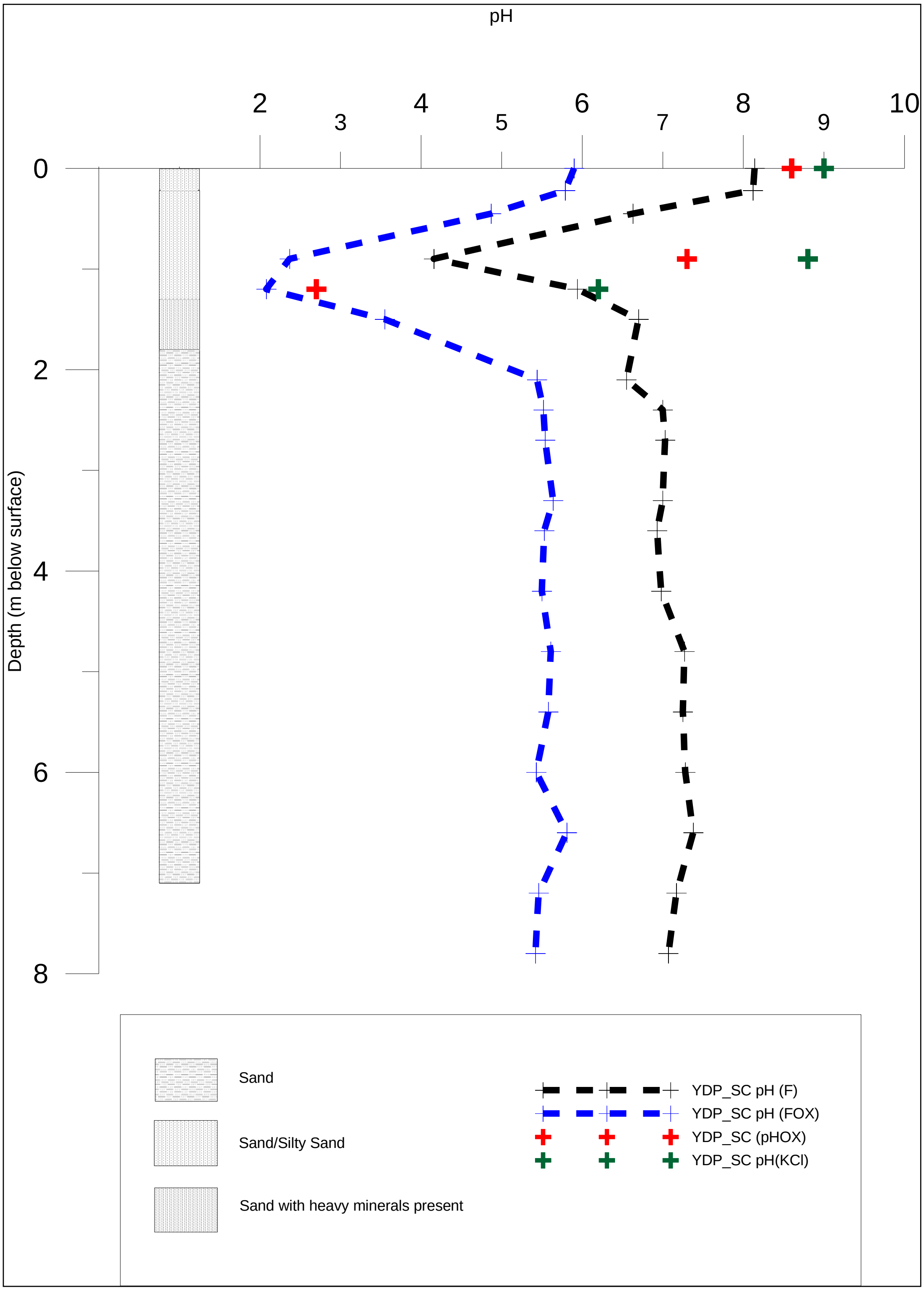


Figure 13 Natural and oxidised field pH measurements correlated with laboratory oxidised pH and lithological units at YDP_SC

The laboratory analyses were used to determine the net acidity of the sediments by measuring the effect of acid generating components of the sediments against neutralising (or basic) components. This is commonly known as acid-base accounting (ABA).

The overall equation for ABA is:

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

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

- *Actual acidity* (TAA) is the soluble and exchangeable acidity already present in the soil
- *Potential sulfidic acidity* is latent acidity that will be released if the sulfide minerals in acid sulfate soil are fully oxidised
- *Retained acidity* is the ‘less available’ fraction of the existing acidity which may be released slowly into the environment
- *Acid neutralising capacity* (ANC) is a measure of the soil’s ability to buffer acidity and resist the lowering of soil pH
- *Fineness factor* is a factor applied to the acid neutralising capacity to allow for the poor reactivity of coarser carbonate or other acid neutralising material.

Where laboratory results for sediments from Lake Yonderup showed no retained acidity or acid neutralising capacity[2] *for YDP_EC, YDP_SC (at 0.0 m and 1.2 m) and YDP_WC the acid-base accounting formula becomes:*

$$\textbf{Net acidity} = \textbf{potential sulfidic acidity} (\textbf{S}_{\textbf{cr}} \textbf{ or SPOCAS}) + \textbf{actual acidity}$$

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

Net acidity at the Lake Yonderup sites ranged from to -593 to 69 molH$^+$/t

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[2] According to laboratory methods guidelines (Ahern et. al. 2004), when pH$_{KCl}$ is higher than 6.5, ANC measurements will be required (i.e. there is ANC present), whereas when pH$_{KCl}$ is less than 6.5, TAA is measured.

Table 6 Summarised ABA for both the SPOCAS and chromium reducible sulfer suite of analyses at the Lake Yonderup site.

Both the SPOCAS and chromium ABA methods reported net acidity for two of the six samples (excluding duplicates) being above the action criteria (18.7 $molH^+/t$); (YDP_WC at 2.5 m depth and YDP_SC at 1.2 m). The highest net acidity reported by the SPOCAS method was located at the YDP_SC site and has been logged as being rich in organic materials. 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[3]. Therefore, the chromium ABA method shows samples taken from down-gradient of the lake to have higher acidity in terms of pH and net acidity content.

As indicated above, ANC values were recorded in samples from YDP_SC indicating that the sediments at this site have an inherent self-buffering capacity. This buffering is likely to be provided by carbonate minerals, given the previously reported presence of limestone in the region of the lake.

No samples of lake sediments were collected for ASS analysis. It is noted that the lake 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 the east, south and west groundwater bores and lake has been plotted in Figure 14 and Figure 15. These have been compared with the average $Cl^-:SO_4^{2-}$ ratio of seawater (7.2) (Ahern et.al. 2004).

$Cl^-:SO_4^{2-}$ ratios of less than 4 were recorded from Lake Yonderup, at YDP_SC (located toward the south of the lake), and at YDP_WB and YDP_WC (both located to the west of the lake). The results indicate that excess sulfate above that for seawater exist in the water column of the superficial sediments at Lake Yonderup, particularly in the down-gradient groundwater where it is most likely related to sulfate levels within the lake. The apparent relative depletion in sulfate in deeper Superficial aquifer bores is most likely related to sulfate reduction under anoxic conditions deeper within the aquifer (see Section 6).

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[3] SPOCAS ABA method can be subject to interferences with sulfur in organic matter and other sulfate minerals

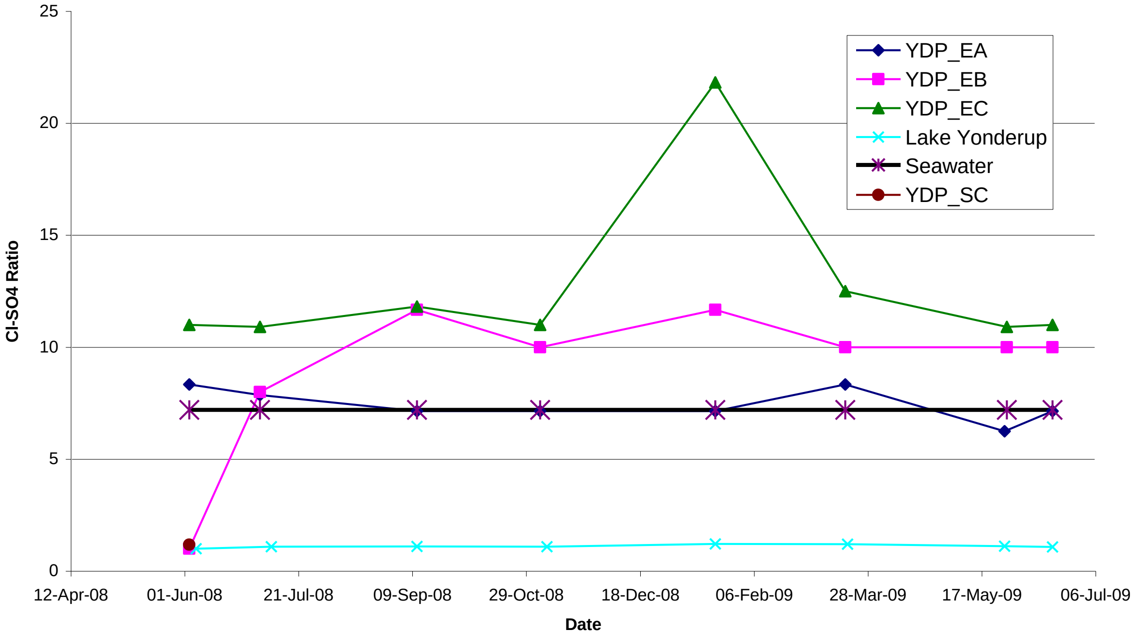


Figure 14 *Cl^-:SO_4^{2-} ratio plot for the eastern and southern bores at the Lake Yonderup site*

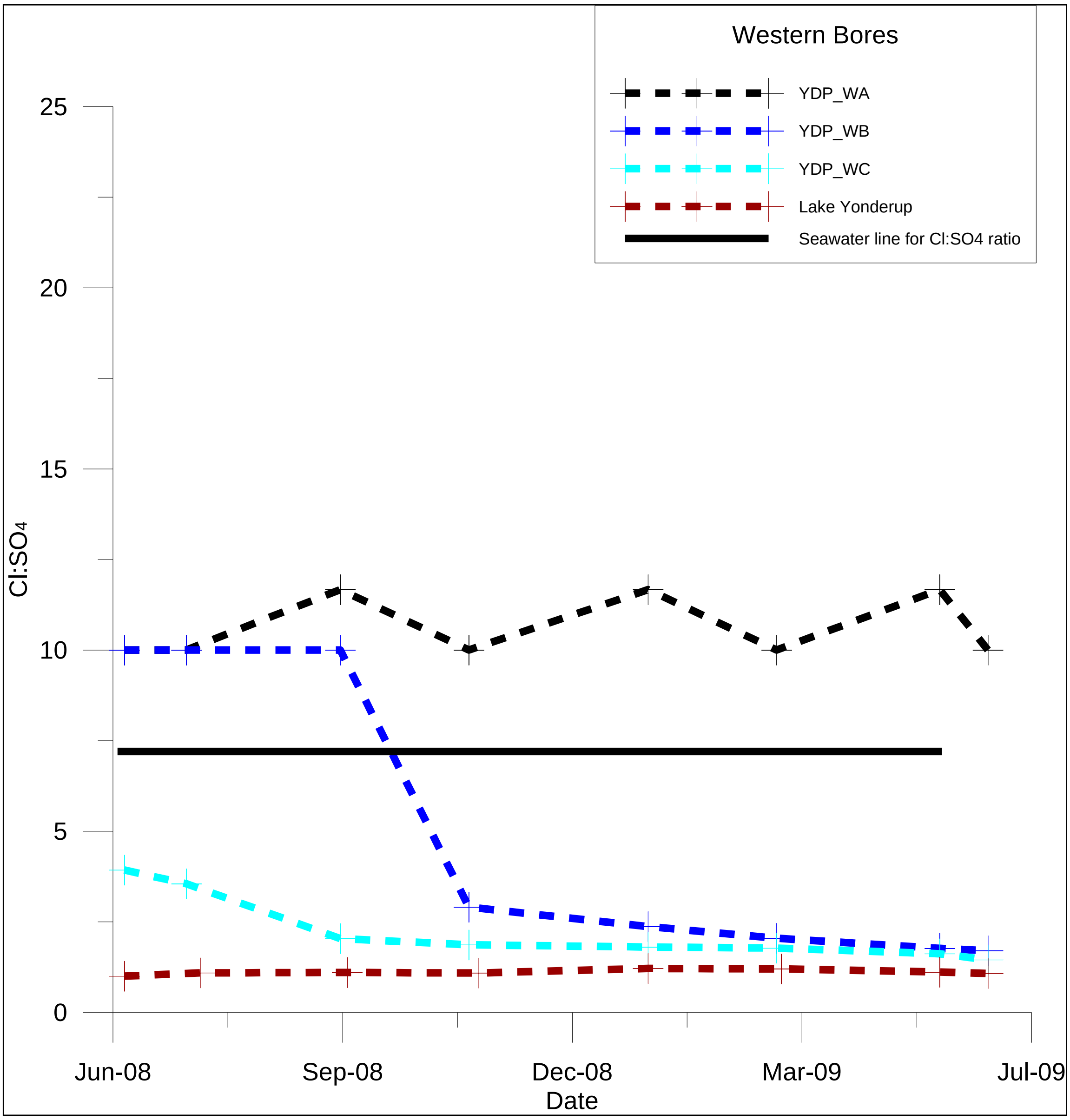


Figure 15 $Cl^-:SO_4^{2-}$ ratio at the western bores at the Lake Yonderup site

Samples from the Superficial aquifer were analysed for selected metal, metalloid and selenium concentrations (Table 6) using the analytical method NT2_49. These samples were then compared with ecological investigation levels (DEC 2010) to determine whether their concentrations pose a risk to the groundwater and environment at the Yonderup site.

The laboratory results showed that concentrations of metals for all samples were below the respective ecological investigation levels with the exception of the surface sample collected from YDP_SC which showed an elevated level of arsenic (Table 6). Cadmium and selenium were below detection limits in all samples.

Table 6 Metals and metalloids in sediment at the Lake Yonderup site

Site reference no.	**Depth m**	**Al**	**As**	**Cd**	**Cr**	**Fe**	**Mn**	**Ni**	**Se**	**Zn**	**Total solids**
		mg/kg	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**Mg/kg**	**mg/kg**	**mg/kg**	**%**
YDP_EC	1.00	5130	1.3	<0.5	25	3690	5.7	2.1	<0.5	1.0	94.5
YDP_WC	2.50	1270	4.4	<0.5	5	1210	2.1	<0.5	<0.5	0.85	69.5
YDP_WC	4.50	6000	1.3	<0.5	33	5400	7.3	2.0	<0.5	1.0	86.5
YDP_SC	0.00	2280	41.0*	<0.5	11	9090	5.9	1.2	<0.5	1.1	88.1
YDP_SC	0.90	3430	3.8	<0.5	16	2240	3.5	1.6	<0.5	3.1	85
YDP_SC	1.20	3300	2.8	<0.5	15	1420	2.9	1.7	<0.5	1.3	86.6
Ecological investigation level		na	20	3	50	na	500	60	na	200	na

na – not applicable

**This sample was above the ecological investigation level*

Increase in concentrations of sulfur (molH$^+$/t) appear to be related to the increase in concentrations of metals (Figure 16 and Figure 17) at YDP_SC. The relationships suggest that pyritic minerals present in the sediments at the site contribute to the sulfides being partially oxidised to iron oxyhydroxide minerals.

Metals at YDP_WC and YDP_EC do not appear to correlate with sulfur content in sediments (Figure 16 and Figure 17), indicating that these metals are not associated with sulfur content in the sediments at Lake Yonderup.

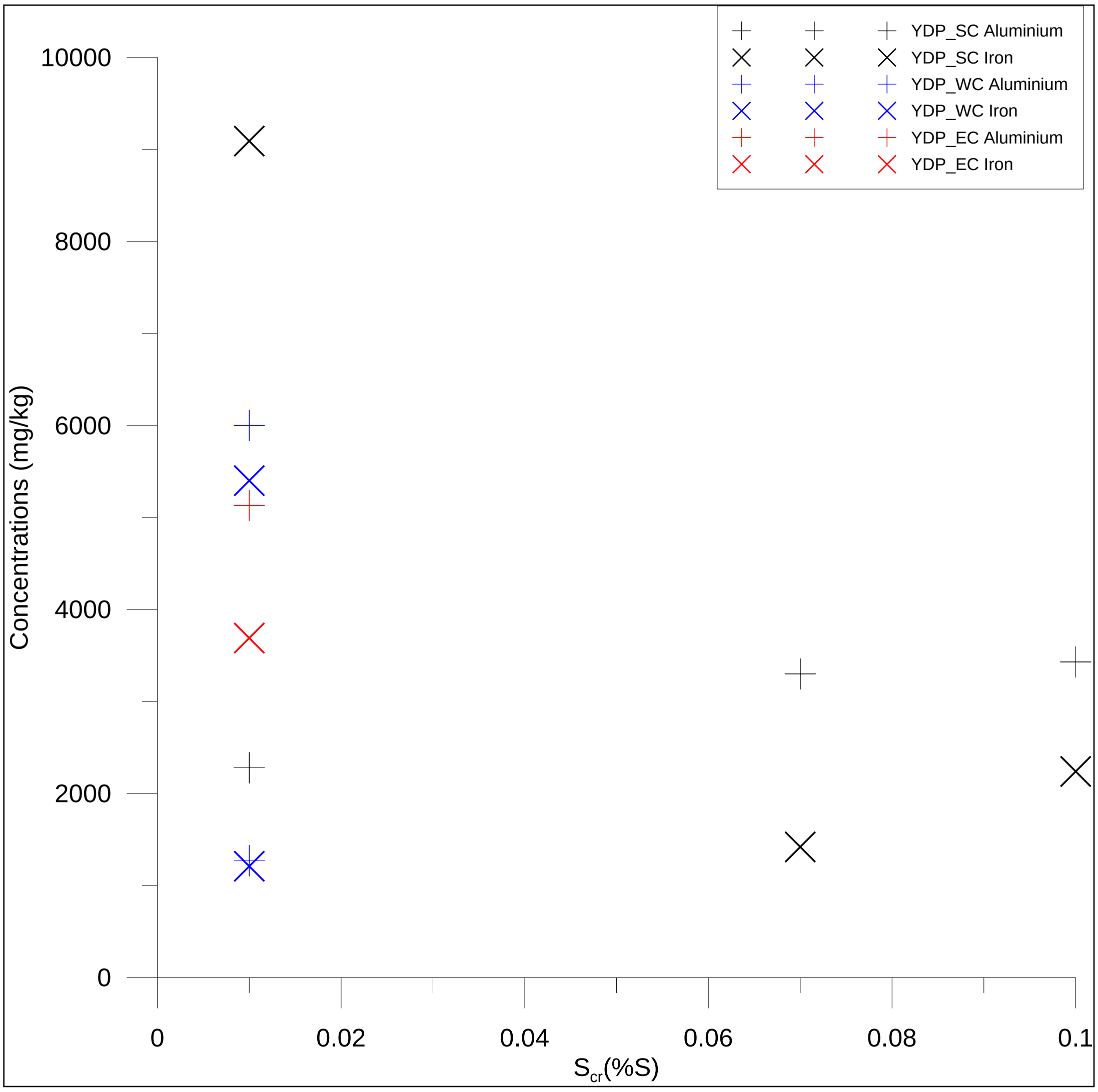


Figure 16 Plot showing the relationship between aluminium, iron and sulfur in sediments at Lake Yonderup

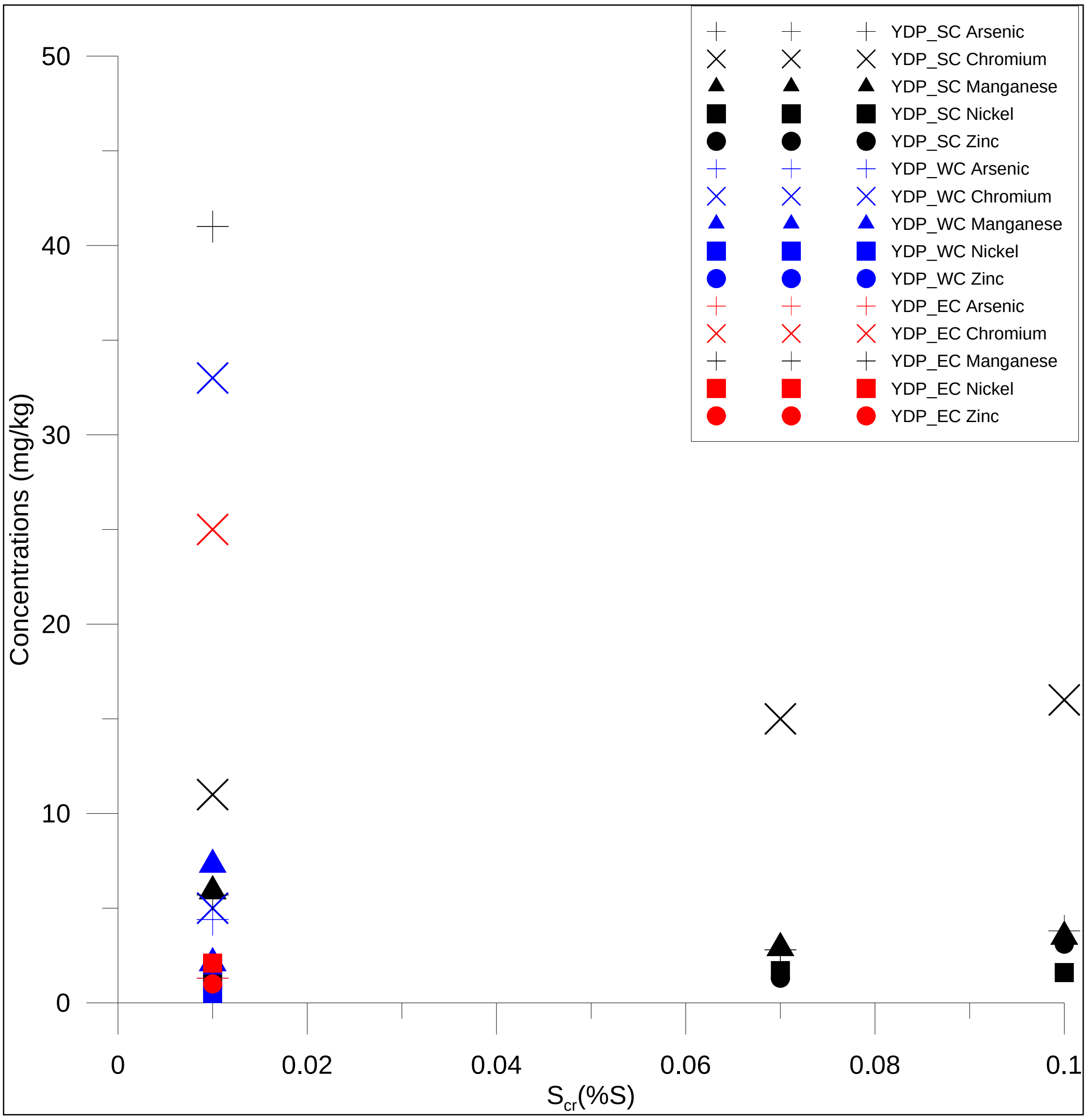


Figure 17 Plot showing the relationship between various metals and sulfur in sediments at Lake Yonderup

Overall, the results for pH, net acidity and $Cl^-:SO_4^{2-}$ ratios indicated that potential acid sulfate soils are present at Lake Yonderup. Although ANC was recognised only in shallow sediments from YDP_SC, excess sulfate above relative amounts in seawater are present in shallow groundwater of Lake Yonderup and within the lake itself. The latter is most likely related to sulfide mineral oxidation, and the absence of acid conditions within the lake and in groundwater down-gradient of the lake would suggest significant pH buffering, presumably by carbonate minerals or carbonate equilibria at Lake Yonderup. This is discussed further in Section 6.

5 Hydrogeology

5.1 Water levels

The network of bores established by Department of Water in 2008 for the SGS project together with non-SGS bores (which provide 18 years of monthly groundwater level data) were used in the analysis of lake and groundwater levels. The analysis of hydrographs and watertable contours of the region provides important information regarding the hydrology of the Superficial aquifer around Lake Yonderup.

The eastern bores (YDP_EA, YDP_EB and YDP_EC) display seasonal fluctuations over the SGS study period (April 2008 to September 2009, Figure 18). Groundwater levels for these up-gradient bores are always higher than the water level for Lake Yonderup (location 8780 to the south of Lake Yonderup). Groundwater levels for boreholes YDP_WA, YDP_WB and YDP_WC located on the western side of the lake are always lower than the lake water level measured at location 8780 (Figure 18). The water level measurement for September 2008 for YDP_WC did not reflect the normal seasonal fluctuation and may be erroneous. YDP_SC bore located on the south side of the lake shows similar water levels to YDP_WC.

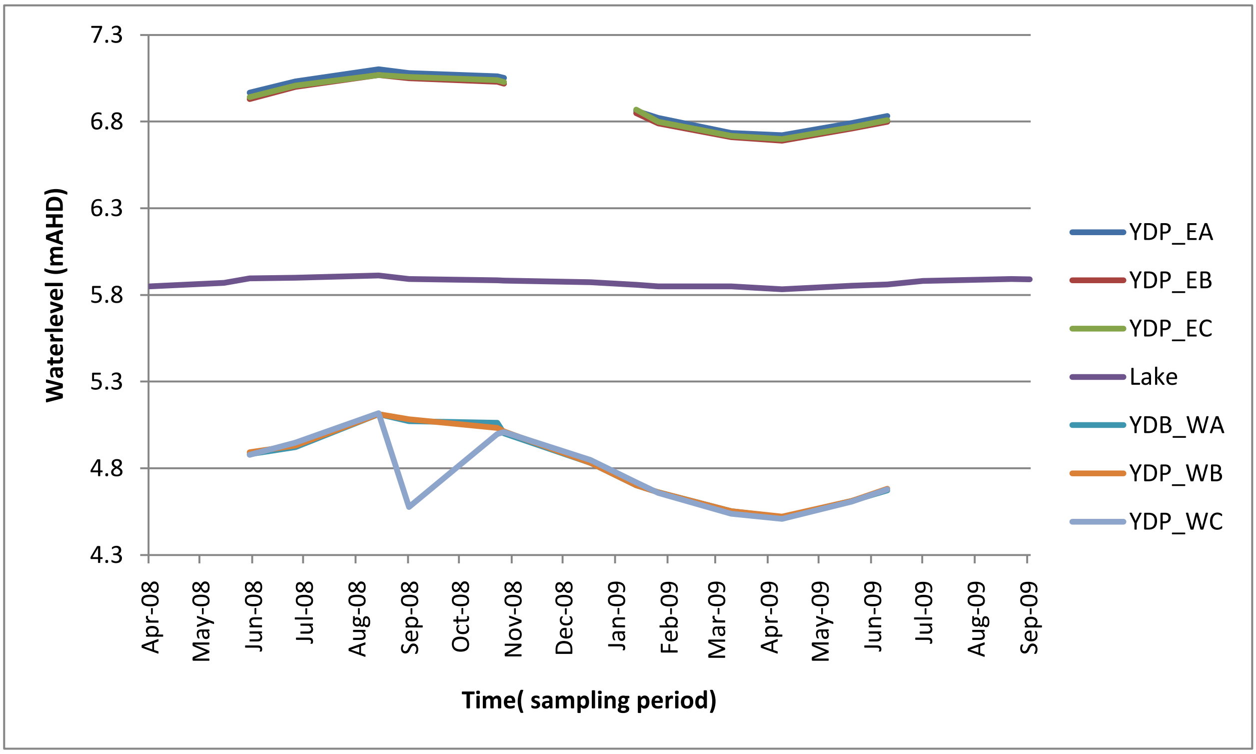


Figure 18 Hydrographs for up-gradient and down-gradient bores compared with water levels in Lake Yonderup

The lake levels and local watertables were found to vary in phase, although it was observed that heavy rainfall events affect the lake level more rapidly than the watertable. Summer minimum lake levels (Figure 18 and Figure 19) occurred in March and April. Winter maximum levels were recorded in August and September.

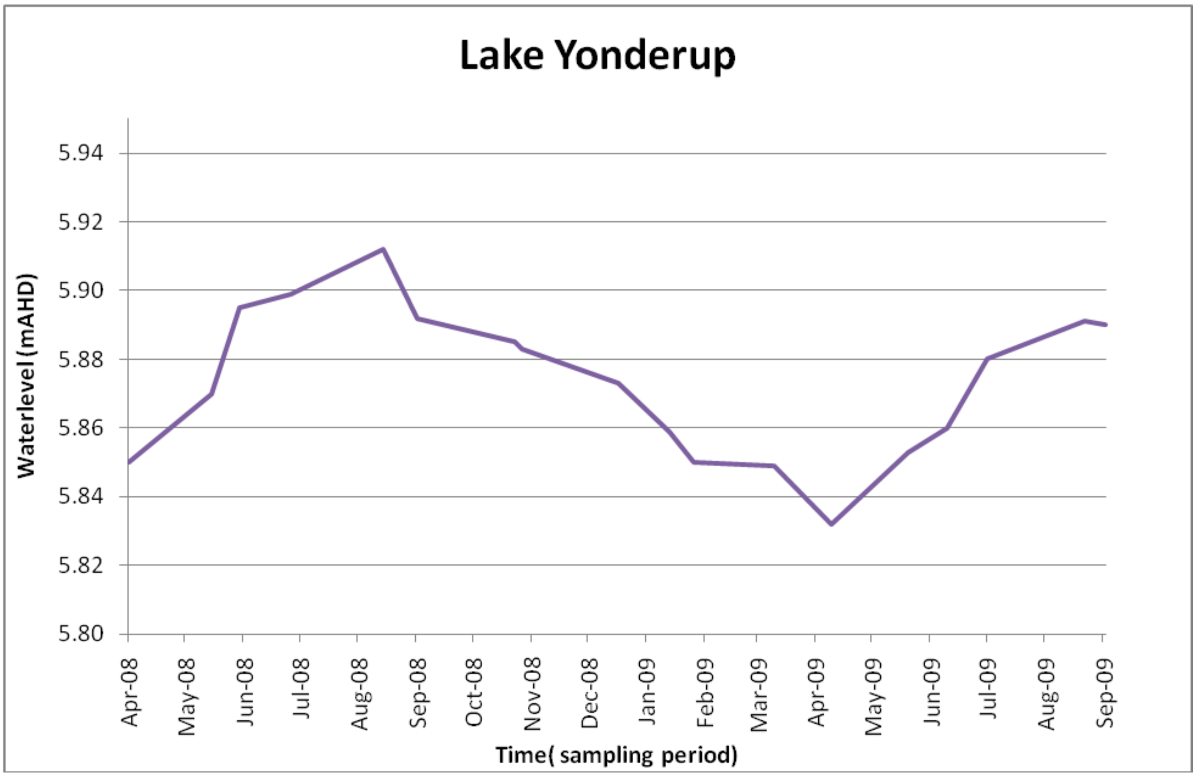


Figure 19 Hydrograph for Lake Yonderup (location 8780)

The fluctuation in hydraulic head (0.6 m) in the shallow down-gradient bore YDP_WC is matched by similar variation in the intermediate and deep down-gradient bores. The variability in heads down-gradient contrast with more subdued variability in up-gradient bores YPD_EA to YDP_EC (0.4 m) and in the lake (0.08 m) (Figure 18 and Figure 19).

The relationship between monthly water levels in the lake is spatially consistent for all other non-SGS bores (YN6 and YN7 on the up-gradient and Y11 which is situated on the down-gradient side of the lake; Figure 20 and Figure 21, respectively). Both YN6 and YN7 on the up-gradient side of the lake show steady decline in groundwater levels. However, these monitoring bores show different rates of decline (i.e. YN6 approximately 1 km up-gradient of the lake show steep decline; 13.4 m AHD in 1991 to 11.3 m AHD in 2009. YN7 closer to the lake shows a smaller but steady decline; 8.03 m AHD in 1991 to 7.13 m AHD in 2009). The decline is probably due to a decline in the annual rainfall (Figure 22) but may also be influenced by an external stressor such as pumping abstraction.

The long-term water level for Lake Yonderup is compared with monthly rainfall in Figure 22. The estimated mean lake level has declined from 6.01 m AHD to 5.86 m AHD in the last 22 years. The hydrograph shows that Lake Yonderup has a small annual water level range (Figure 19), declining very gradually over the years.

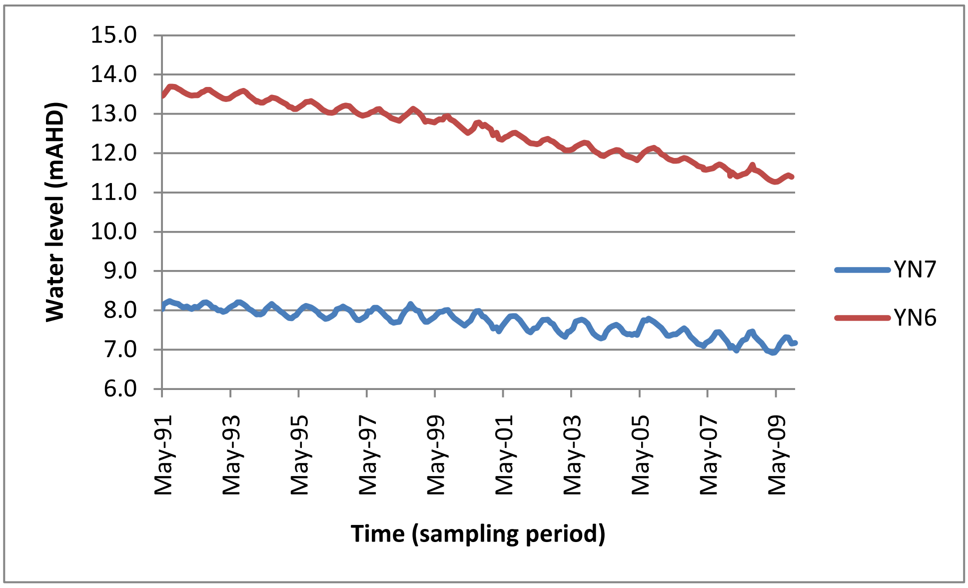


Figure 20 Hydrographs of non-SGS bores up-gradient of Lake Yonderup

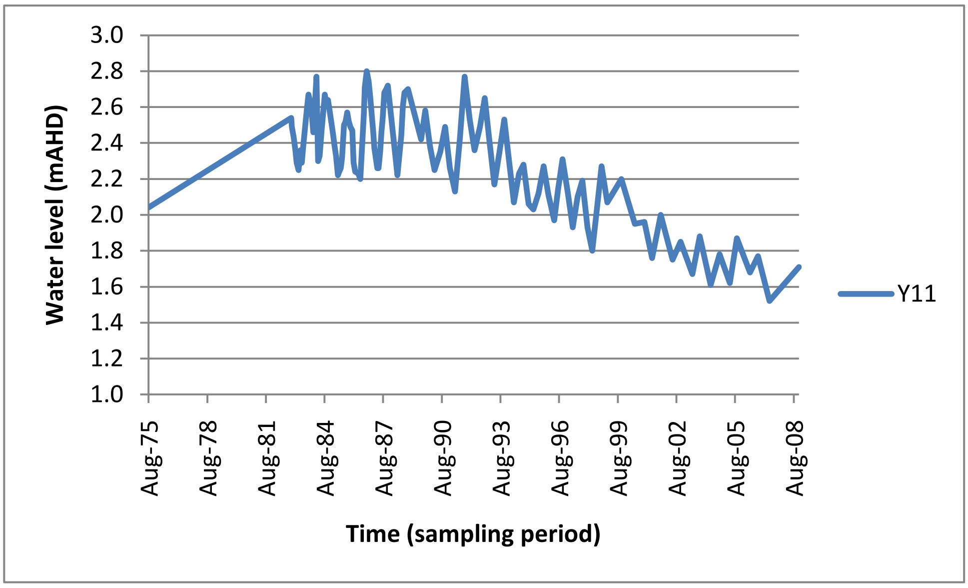


Figure 21 Hydrographs of non-SGS bore down-gradient of Lake Yonderup

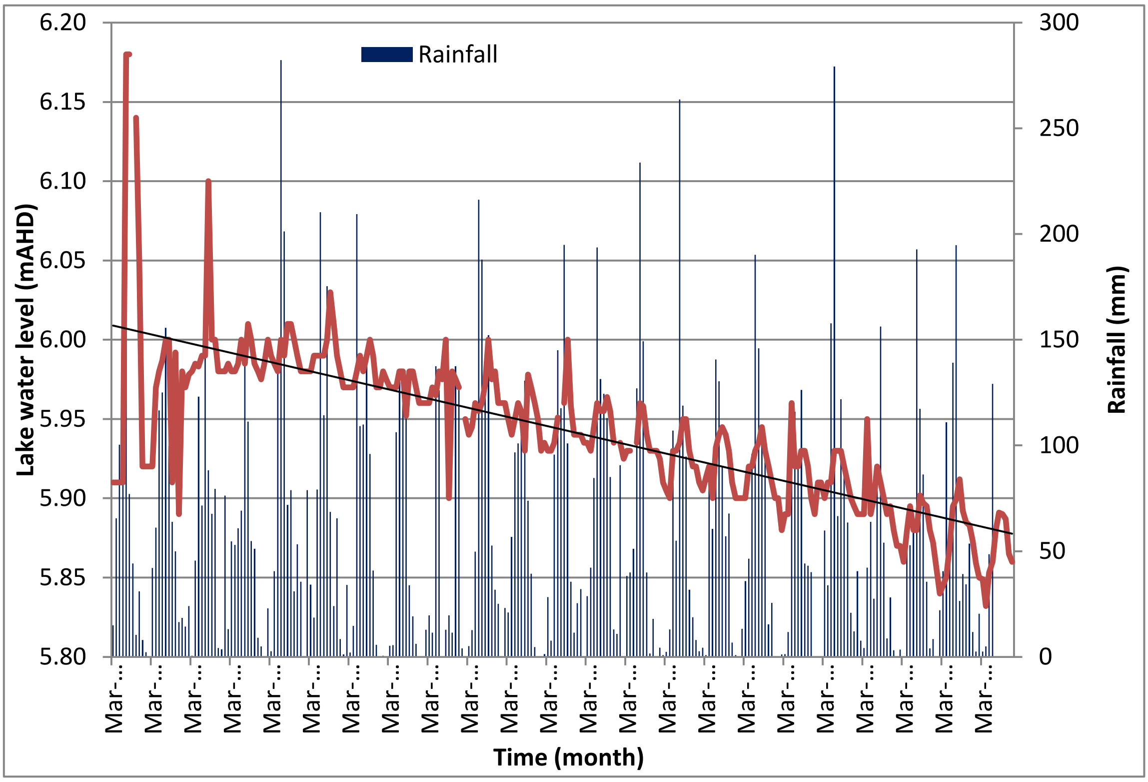


Figure 22 Lake Yonderup hydrograph for location 8780 compared with monthly rainfall 1987 to 2009. Estimated mean lake water level shown as black trend line.

5.2 Groundwater flow

The saturated thickness of the Superficial aquifer is some 30+ m in the region of Lake Yonderup and the Superficial aquifer behaves as a phreatic aquifer. Any reduction in saturated thickness will reduce the transmissivity and storage of the aquifer.

The groundwater hydraulic heads follow the topography (Figure 23), exhibiting the highest values in the east (elevation of the Gnangara Mound) and lowest in the west. Flow is indicated as being predominantly east to west. Lake Yonderup is in hydraulic connection with the regional groundwater flow system and is in a dynamic balance between topography, geology and climatic factors (Yesertener 2008). The lake generally is a minor component of the overall flow system 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 23 and Figure 24). The groundwater gradient is relatively gentle on either side of the lake.

Figure 23 shows the watertable contours for May 2008 showing groundwater flow paths, when water levels are lowest at the end of summer. At the end of winter, watertable contours (Figure 24) are similarly distributed. However, there is about a 0.2 m increase on either side of the lake, when compared to minimum (summer) levels.

A hydrogeological cross-section of summer and winter watertables is shown in Figure 25. This section is approximately parallel to groundwater flow. The winter and summer maximum and minimum water levels are shown respectively.

The groundwater level in the shallow up-gradient (eastern) bore is marginally higher than the intermediate and deep bores, and the intermediate bore is somewhat lower than the shallow and deeper parts of the aquifer (**Error! Reference source not found.** and Figure 24). Although the differences in water level between bores over time is small, this suggests an upward gradient from the intermediate bore to the shallow bore as a consequence of groundwater discharge to the lake from shallow groundwater. In contrast there is a subdued downward discharge occurring from the lower part of the Superficial aquifer to the underlying Leederville Formation, although the gradient is weak.

The groundwater flow pattern down-gradient (western side) of the lake displays minor changes in the direction of the vertical gradients within the profile during the winter and summer period. The intermediate and deep bores show groundwater levels slightly higher than those in the shallow bore in winter. However, the difference between the intermediate and deep bore water levels is insignificant (Table 7). This suggests no upward gradient in the lower part of the aquifer. The bore logs show the Superficial aquifer overlies sandstone of the Leederville aquifer (possibly the Pinjar Member). This indicates the possibility of a hydraulic connection between these aquifers. Importantly, there is no evidence of the impact on water levels in the down-gradient SGS bores from any discharge to groundwater from the lake.

Rockwater (2003) reported that ‘the difference in groundwater and lake levels and their seasonal responses appear to confirm karst control of the lake by inflow of water from Loch McNess and outflow via caves’. However, Bekesi (2007) and Krasnostein & Oldham (2004) discount any karst flow from Loch McNess towards Lake Yonderup. This suggests that a hydraulic linkage between the lakes is via natural groundwater flow within the aquifer as a whole. Part of the Lake Yonderup region would include localised karstic flow close to the watertable, although no limestone strata were recorded in any of the down-gradient SGS bores at this location.

Overall we agree with Bekesi (2007) and Krasnostein & Oldham (2004). The data indicates dominant east-west throughflow and there would be some lateral flow from lake discharge at Loch McNess, but this would be insufficient to reach Lake Yonderup. From the SGS study, the sole data supporting the hypothesis of a lack of preferred flow from Loch McNess to Lake Yonderup is the absence of limestones indicated from the bore logs.

Table 7 SGS bore levels and lake water level (April 2008 to September 2009)

	YDP_WA	**YDP_WB**	**YDP_WC**	**YDP_EA**	**YDP_EB**	**YDP_EC**	**YDP_SC**	**Lake Yonderup**
	m AHD	m AHD	m AHD	m AHD	m AHD	m AHD	m AHD	m AHD
Apr-08	4.67	4.67	4.66	6.84	6.83	6.86	4.75	5.85
May-08								5.87
Jun-08	4.88	4.89	4.88	6.94	6.93	6.97	4.90	5.90
Jul-08	4.92	4.93	4.95	7.01	7.00	7.03	4.97	5.90
Aug-08	5.11	5.11	5.12	7.07	7.07	7.10	5.08	5.91
Sep-08	5.07	5.08	4.58	7.06	7.05	7.08	5.06	5.89
Oct-08	5.06	5.03	5.00	7.04	7.03	7.06	5.03	5.89
Nov-08	5.00	5.01	5.01	7.03	7.02	7.05	5.00	5.88
Dec-08	4.83	4.83	4.85					5.87
Jan-09	4.70	4.70	4.72	6.87	6.85	6.86	4.72	5.86
Feb-09	4.66	4.66	4.66	6.80	6.79	6.82	4.65	5.85
Mar-09	4.55	4.55	4.54	6.72	6.71	6.73	4.52	5.85
Apr-09	4.52	4.52	4.51	6.70	6.69	6.72	4.49	5.83
May-09	4.61	4.61	4.61	6.77	6.76	6.79	4.62	5.85
Jun-09	4.67	4.68	4.68	6.81	6.80	6.83	4.68	5.86
Jul-09								5.88
Aug-09								5.89
Sep-09	5.05	5.06	5.14	7.02	7.01	7.04	5.02	5.89

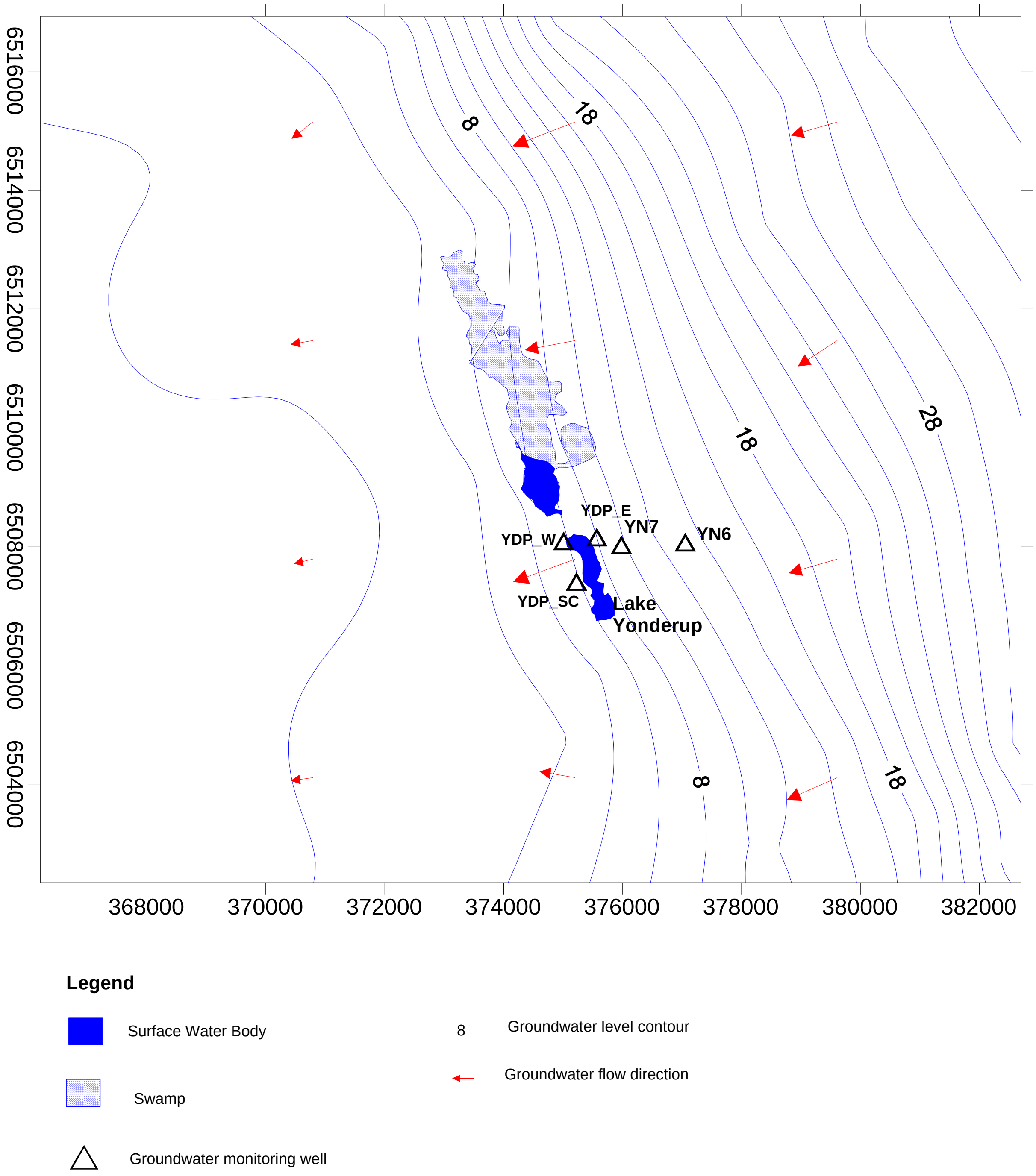


Figure 23 *Watertable contours for May 2008 showing groundwater flow paths for Lake Yonderup*

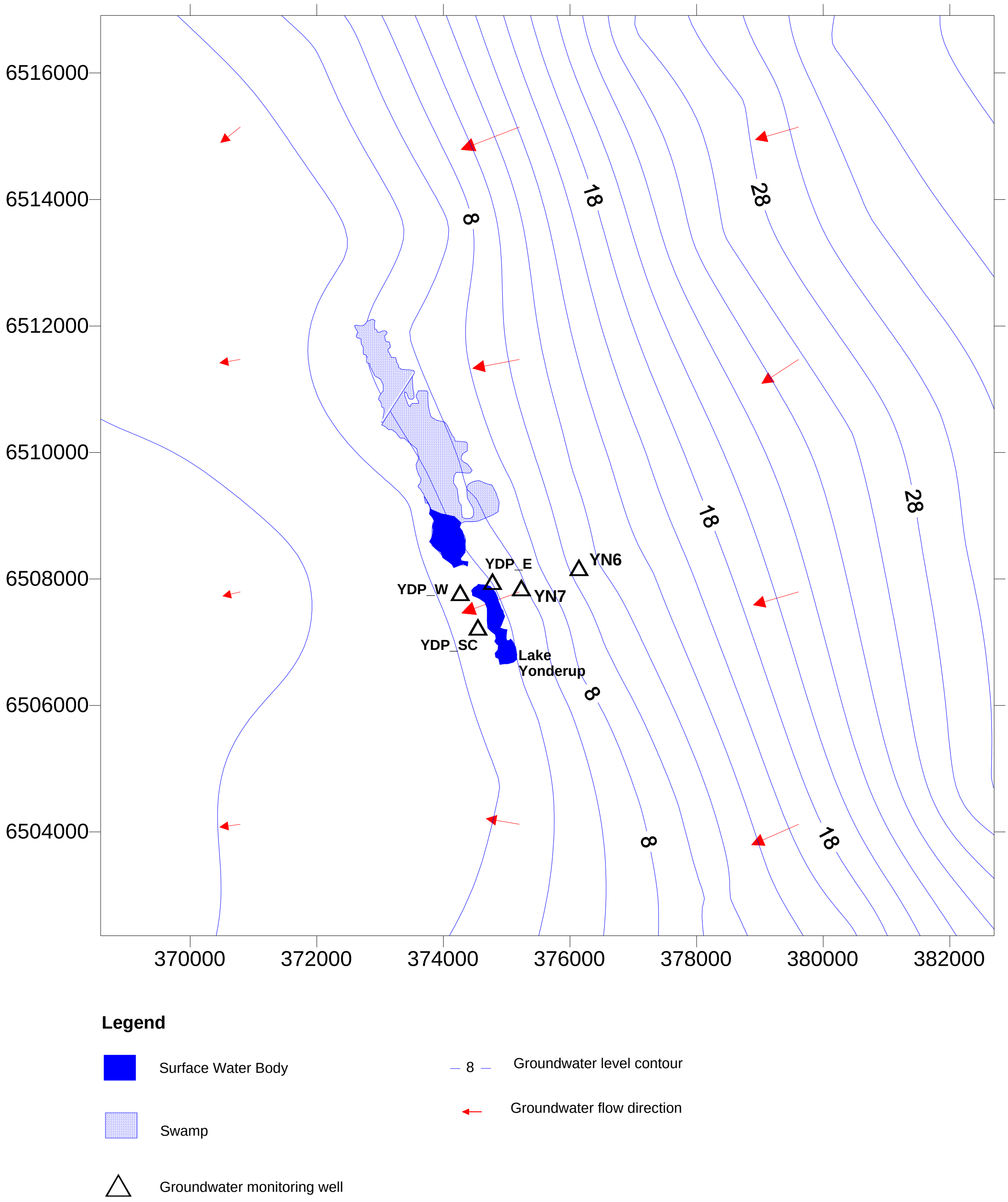
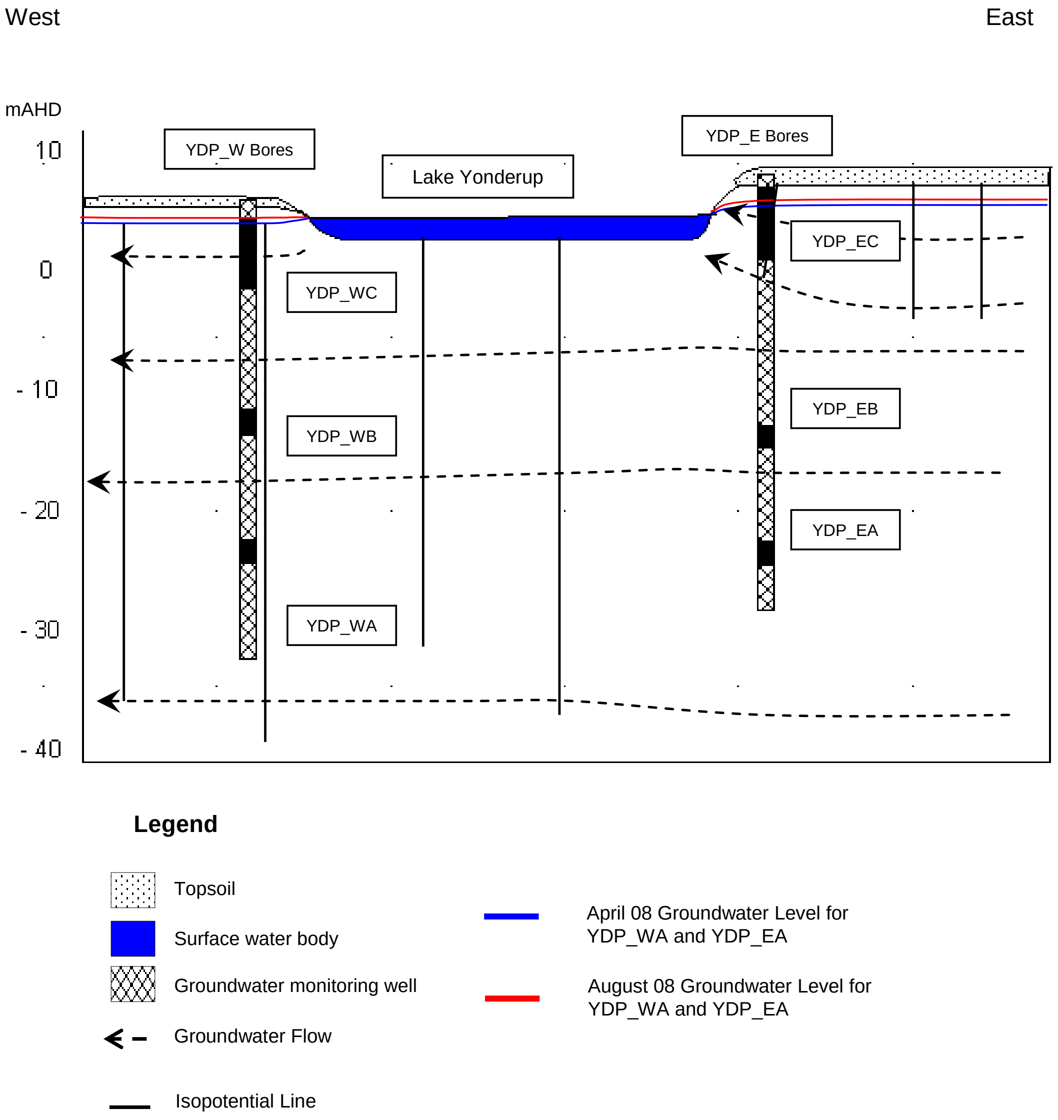


Figure 24 Watertable contours for October 2008 showing groundwater flow paths for Lake Yonderup



Standing Water Levels

YDP_WA	**YDP_WB**	**YDP_WC**	**YDP_EA**
Apr 08: 4.67 mAHD	Apr 08: 4.67 mAHD	Apr 08: 4.66 mAHD	Apr 08: 6.84 mAHD
Aug 08: 5.11 mAHD	Aug 08: 5.11 mAHD	Aug 08: 5.12 mAHD	Aug 08: 7.07 mAHD
YDP_EB	**YDP_EC**	**YDP_SC**	**Lake Yonderup**
Apr 08: 6.83 mAHD	Apr 08: 6.9 mAHD	Apr 08: 4.75 mAHD	Apr 08: 5.85 mAHD
Aug 08: 7.07 mAHD	Aug 08: 7.10 mAHD	Aug 08: 5.08 mAHD	Aug 08: 5.90 mAHD

Figure 25 Groundwater flow paths for Lake Yonderup

Pertinent interpretations from the preceding discussion and the conceptual model (Figure 25) follow:

- the watertable is a subdued replica of landscape
- Lake Yonderup receives groundwater through its eastern reaches and rainfall, and loses water through evaporation and minimal groundwater discharge from its western reaches
- there is a throughflow continuum given the, essentially, vertical isopotentials at the western bore
- there is little apparent leakage through lake sediments which are presumably of low hydraulic conductivity
- the hydrograph of Lake Yonderup shows that the small fluctuation in lake levels (winter high to summer low only 0.08 m; monthly fluctuation 0.01 to 0.02 m) indicates that Lake Yonderup is a permanent feature which is supported by the local groundwater flow system, although further lowering of the watertable up-gradient of the lake suggests that the status of the lake is vulnerable to watertable recession over time.

6 Hydrogeochemistry

6.1 Physical and chemical characteristics

6.1.1 On-site physical measurements (pH, DO, ORP)

Summary statistics (minima, maxima and median values) for pH, dissolved oxygen and oxidation–reduction potential are shown in Table 8 for YDP east and west bores and for Lake Yonderup at location 8780.

Table 8 Summary statistics for on-site measurements of pH, DO and ORP in east and west YDP bores and in Lake Yonderup at location 8780

Sampling location	**pH**			**DO mg/L**			**ORP mV**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
YDP_EA	6.8	7.3	6.9	0.6	6.5	0.8	-9	151	9
YDP_EB	6.2	6.7	6.3	0.8	4.2	3.1	22	168	38
YDP_EC	6.9	7.2	7.0	4.7	8.0	5.9	-16	134	-3
YDP_WA	7.0	7.2	7.1	1.5	2.8	2.1	-20	211	-6
YDP_WB	6.3	6.9	6.4	4.1	5.5	4.7	11	196	35
YDP_WC	6.2	6.6	6.4	4.1	8.3	5.3	24	168	36
Lake Yonderup 8780	6.8	7.8	7.3	6.2	9.8	7.2	-56	195	-10

The pH within Lake Yonderup falls below the lower limit trigger level of 7.0 to 8.5 in south-west Australia wetlands set by ANZECC/ARMCANZ (2000). This is in contrast to the situation at Loch McNess where the median lake pH is within the range. The pH of groundwater in the shallow bore YDP_WC is slightly lower than that in the lake while groundwater at an intermediate level in the Superficial aquifer (bore YDP_EB) has a somewhat lower pH than at shallower depths.

The concentration of dissolved oxygen decreases with depth overall in the aquifer (see median concentrations). The shallow bores, YDP_EC and YDP_WC, and Lake Yonderup water are both well oxygenated, whilst the deep bore YDP_EA is mostly anoxic. Oxidation–reduction potentials show little relationship to dissolved oxygen.

6.2 Water quality

6.2.1 Major cations and anions

Concentrations of electrical conductivity (EC), chloride, sulfate, bicarbonate, calcium and sodium in groundwater and lake water show considerable variability within the region of Lake Yonderup. The major ion data has been analysed using ternary (Piper) plots, Stiff diagrams and time-series plots for the western and eastern bore clusters and compared with lake water quality. 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 for bores up-gradient which contain groundwater which may discharge to the lake. Drinking water quality guidelines (NHMRC–NRMMC 2004) have been compared with data from down-gradient bores, as provision of drinking water is the most significant beneficial use of the aquifer down-gradient of the lake.

Drinking water guidelines were also 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.

Piper diagrams for major cations in the lake and up-gradient groundwater are shown in Figure 26. Sodium and calcium are relatively more abundant in both surface water and groundwater, while magnesium is depleted, as at nearby Loch McNess. Groundwater at intermediate depths is somewhat richer in sodium than other cations.

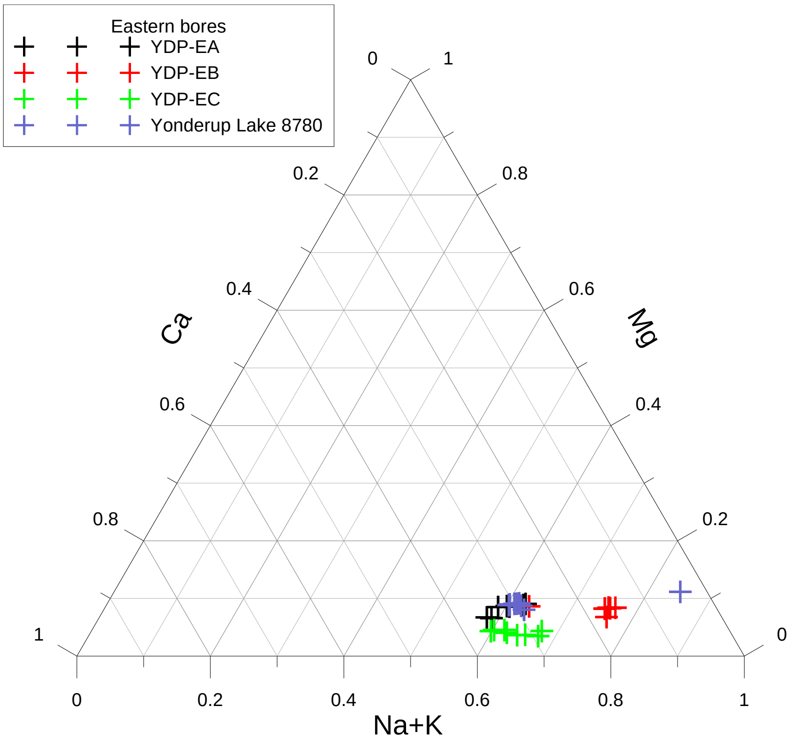


Figure 26 Ternary (Piper) plot of major cations in eastern bores and in Lake Yonderup (8780) (data obtained from the SGS project)

The major anion plots in Figure 27 show that the lake is much richer in sulfate than any of the groundwater up-gradient of the lake. The source of the sulfate in the lake is likely to be oxidation of sulfide minerals as the lake water levels drop. The absence of any obvious trend downwards in lake pH (Table 8) indicates that, as at Loch McNess, Lake Yonderup may be well buffered against the effects of acidification.

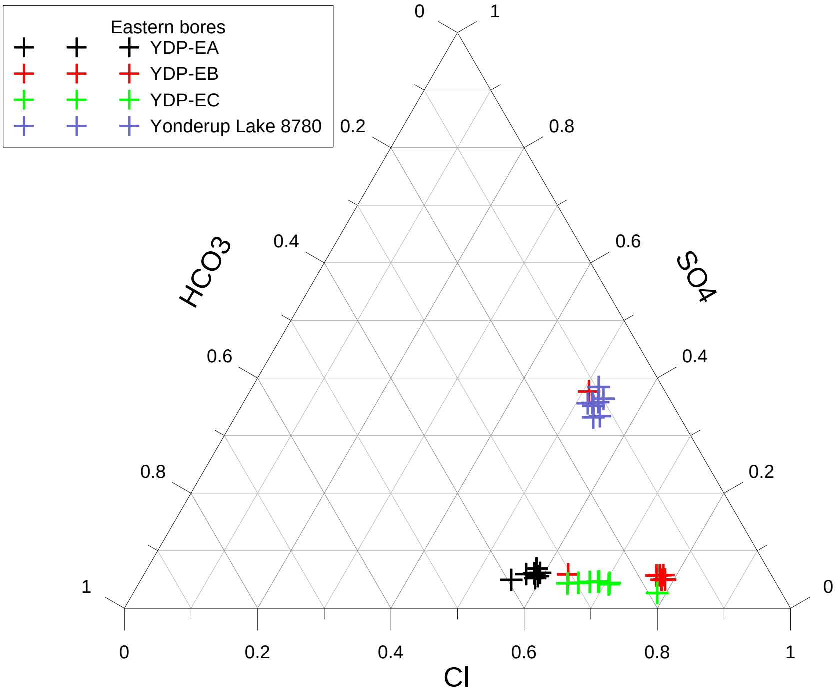


Figure 27 Ternary (Piper) plot of major anions in eastern bores and in Lake Yonderup (8780) (data obtained from the SGS project)

Down-gradient of the lake at the YDP_W bores, lake water is richer in calcium than shallow and intermediate level groundwater, and magnesium is again relatively depleted in all groundwater and surface water (Figure 28). Groundwater at shallow and intermediate depths has relatively more sodium than calcium compared with lake water and the deep bore. This contrasts with the situation at Loch McNess where lake water was relatively rich in sodium and groundwater more dominated by calcium.

Overall, lake water is richer in sulfate than groundwater, although shallow groundwater down-gradient of the lake shows a trend towards sulfate enrichment (Figure 29).

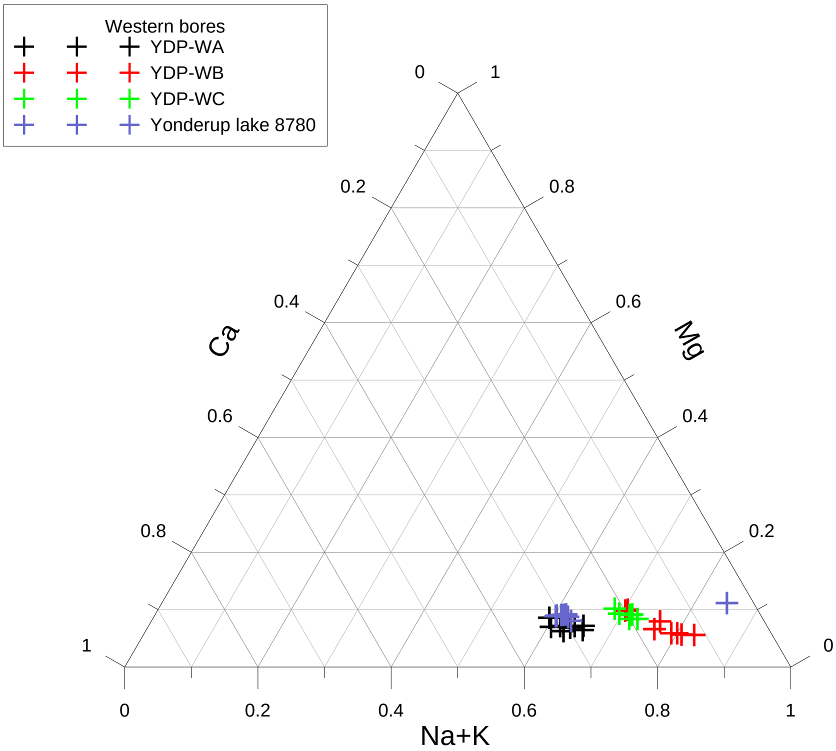


Figure 28 Ternary (Piper) plot for major cations in western and southern bores and in Lake Yonderup (87580) (data from the SGS project)

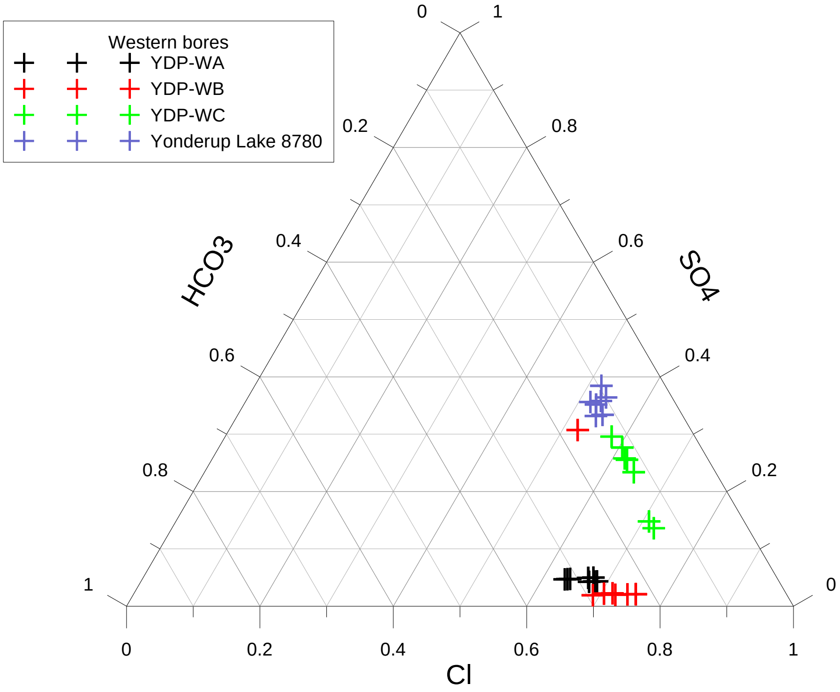


Figure 29 Ternary (Piper) plot for major anions in western and southern bores and in Lake Yonderup (8780) (data from the SGS project)

Stiff diagrams are shown in Figure 30 and Figure 31 comparing the major ions in lake water with up-gradient and down-gradient groundwater from the YDP bores respectively.

The lake water is richer in sulfate than groundwater, as noted in the Piper diagrams. However, major ions in shallow up-gradient groundwater are similar to those in the lake with the exception of sulfate, which suggests that groundwater with composition similar to that in the shallow bore YDP_EC is contributing most groundwater discharge to the lake.

At Loch McNess, groundwater was considered to be discharging to the lake from the upper half of the aquifer, based on water compositions in the lake and the Superficial aquifer at different depths. Townley et al. (1991) indicated on the basis of modelling of flow-through lakes that those lakes with narrow width normal to the direction of groundwater flow as at Lake Yonderup received groundwater from shallow depths. In contrast, lakes like Loch McNess which were of somewhat greater width normal to groundwater flow lines received more extensive groundwater discharge from greater depths within the aquifer. The modelling would thus seem to be consistent with what is observed at both Lake Yonderup and Loch McNess.

Down-gradient of the lake, the Stiff diagrams show a significant contrast between lake water and groundwater (*Figure 31*), with the lake being richer in both sulfate and calcium. From major ion composition, there is little obvious evidence of the effects of lake water discharge to groundwater on the down-gradient side of the lake.

Discharge from the western reaches of Lake Yonderup to groundwater is considered to be diffuse, possibly with minor amounts leaking from the lake floor into groundwater. This increases the sulfate and possibly nitrate concentration in groundwater in the western SGS bores above that observed in the eastern SGS bores.

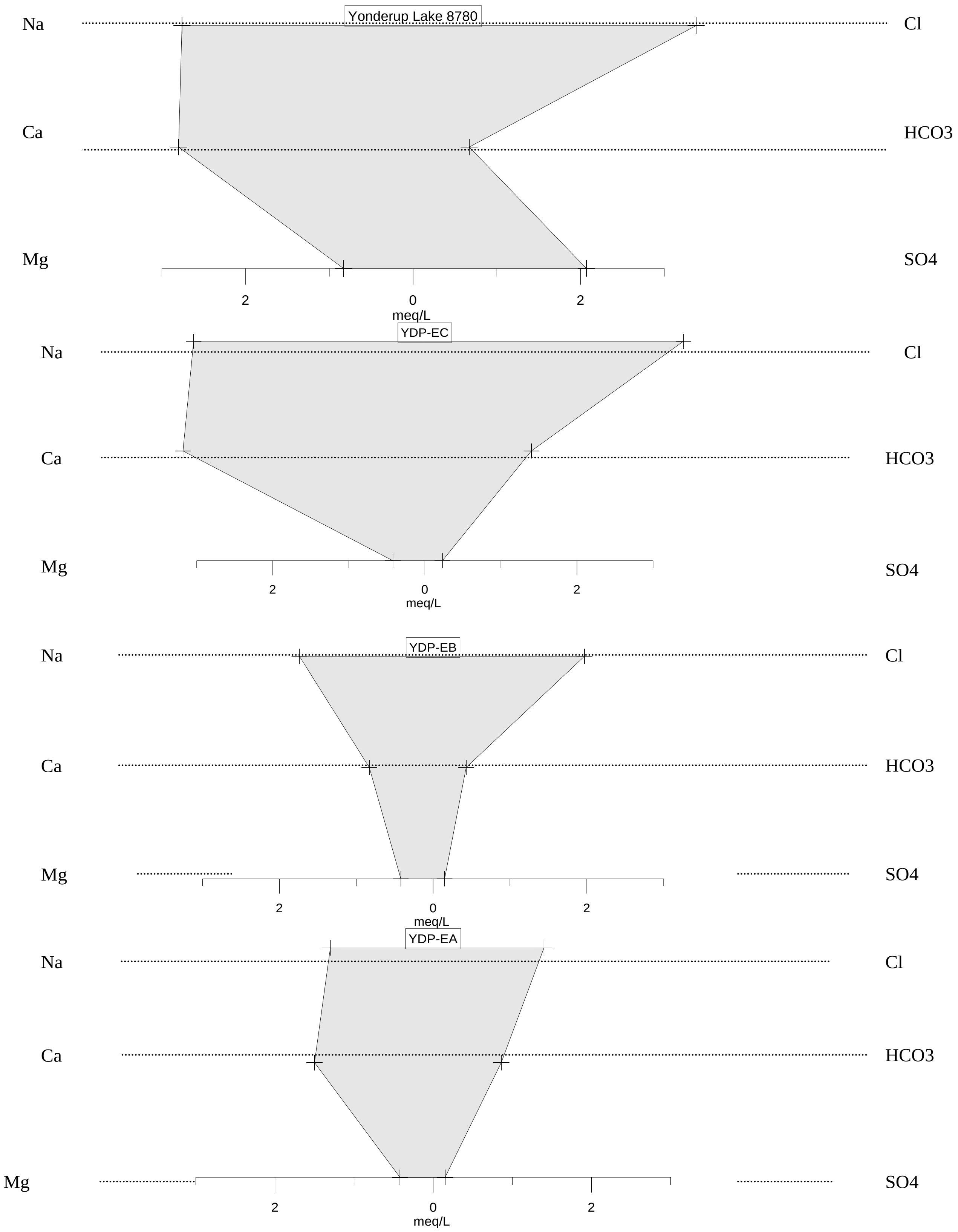


Figure 30 Representative Stiff diagrams for mean cation and anion concentrations in meq/L for groundwater from eastern bores

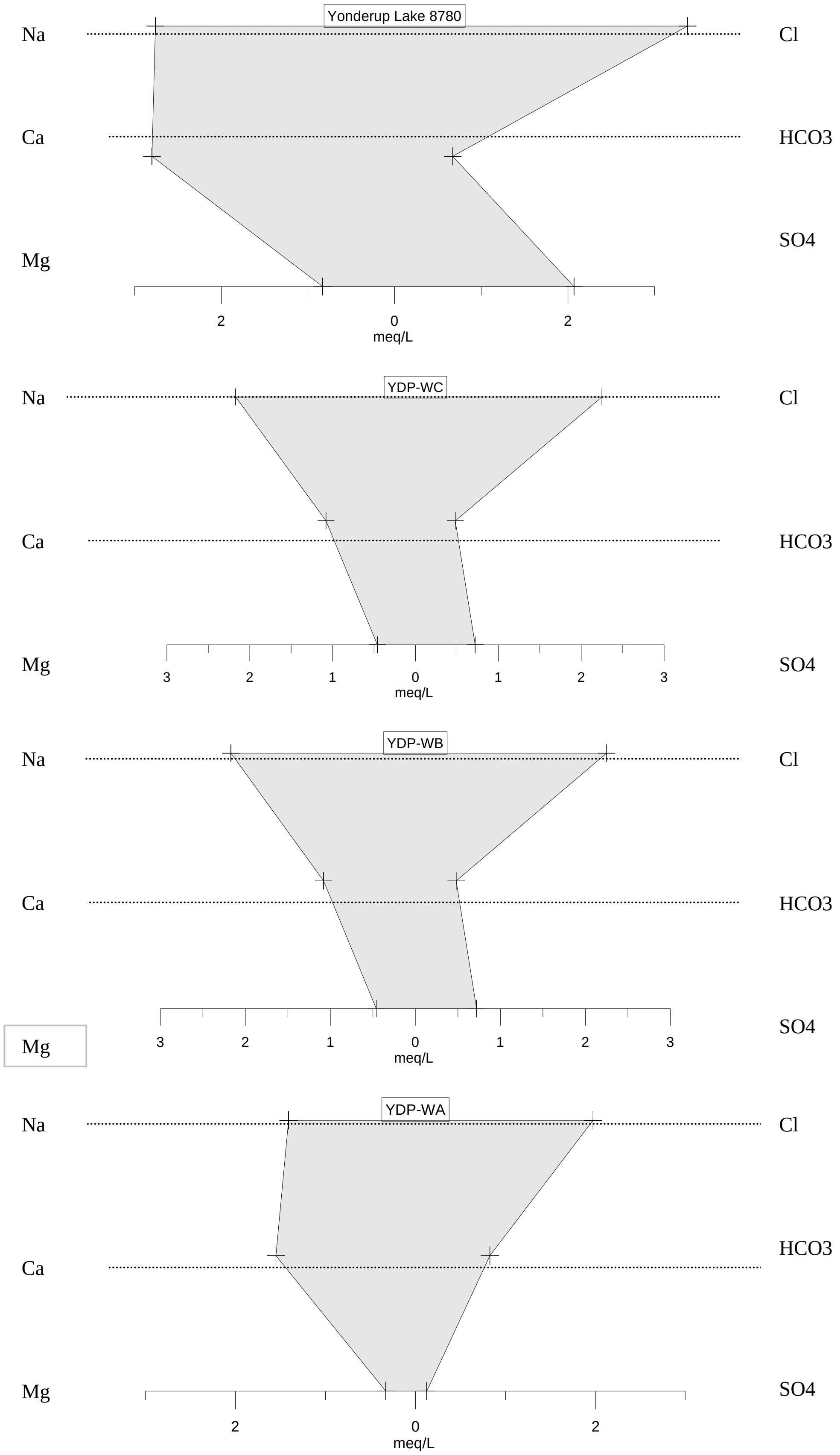


Figure 31 *Representative Stiff diagrams for mean cation and anion concentrations in meq/L for groundwater from western bores*

6.2.2 Electrical conductivity and chloride

Variations over time in electrical conductivity and chloride in the lake and in eastern bores are shown in Figure 32 and Figure 33.

The up-gradient shallow bore YDP_EC shows the closest EC to that of Lake Yonderup, again indicating that shallow groundwater only is discharging to the lake (Figure 32). The same relationships are shown by chloride (Figure 33).

On the down-gradient side of the lake, the EC of lake water is slightly higher than that of groundwater in the shallow bore YDP_WC, but higher than in groundwater deeper within the aquifer (Figure 34).

The concentration of chloride in lake water is higher than in groundwater at intermediate and deep bores YDP_WB and YDP_WA, respectively. Groundwater at shallow depths is slightly higher than that in lake water over most of the SGS monitoring period.

The time series plots indicate that concentrations remain steady at the majority of monitoring locations over the study period. The only exception to this is the significant increase in chloride at YDP_EC that occurred in February 2009. Following this peak reading the chloride readings steadily decrease towards mid 2009. The elevation in chloride observed in YDP_EC could be causing the increase in chloride beginning to occur in the lake water towards the end of the observation period (Figure 35).

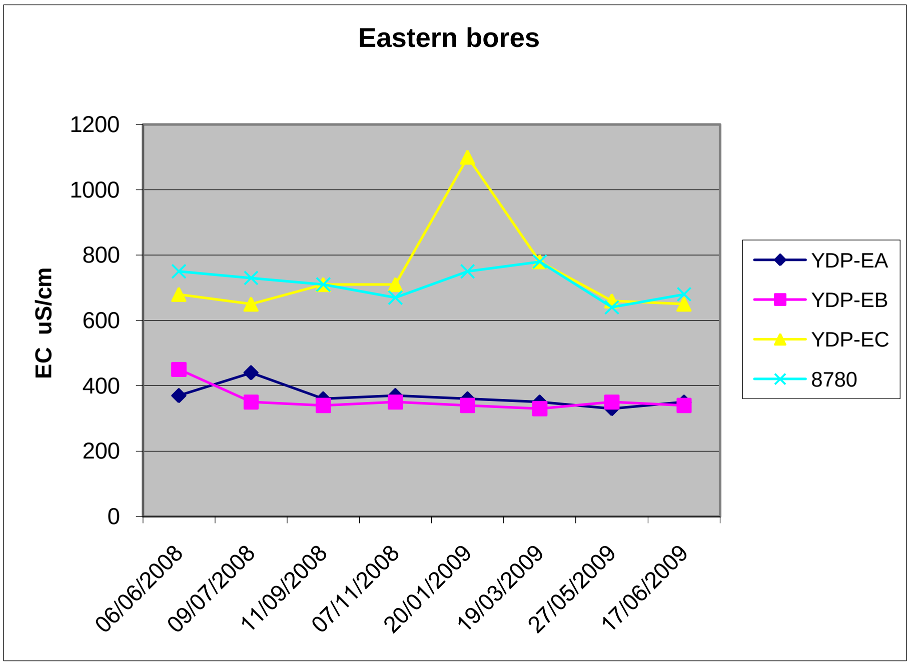


Figure 32 Variation of EC for eastern bores and Lake Yonderup

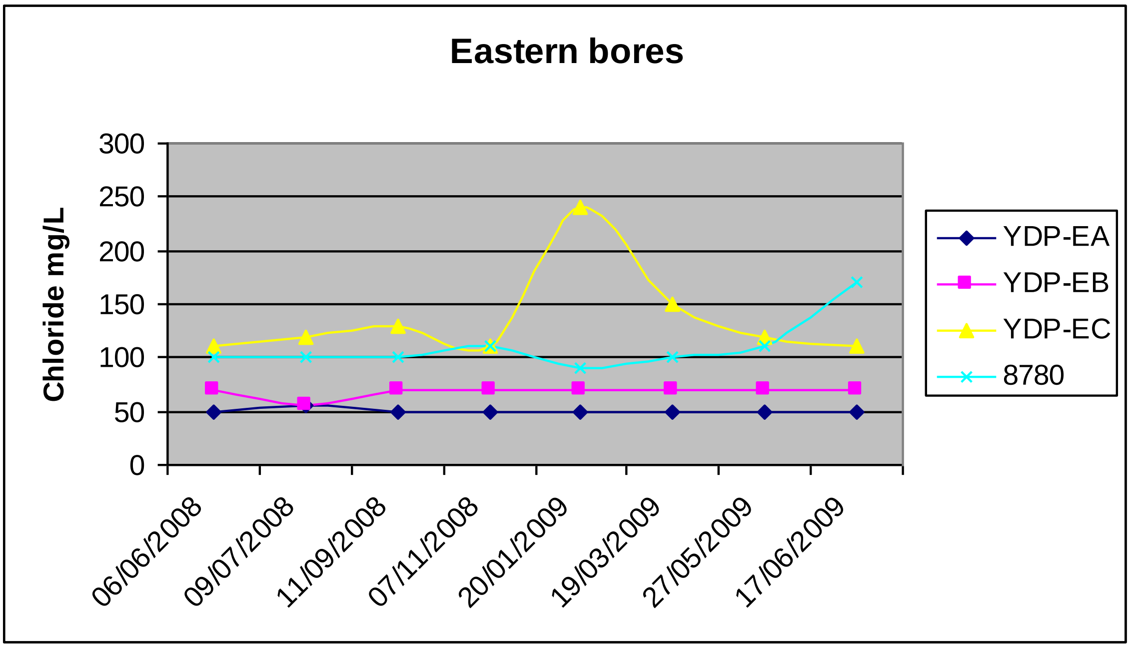


Figure 33 *Variation in chloride for eastern bores and Lake Yonderup*

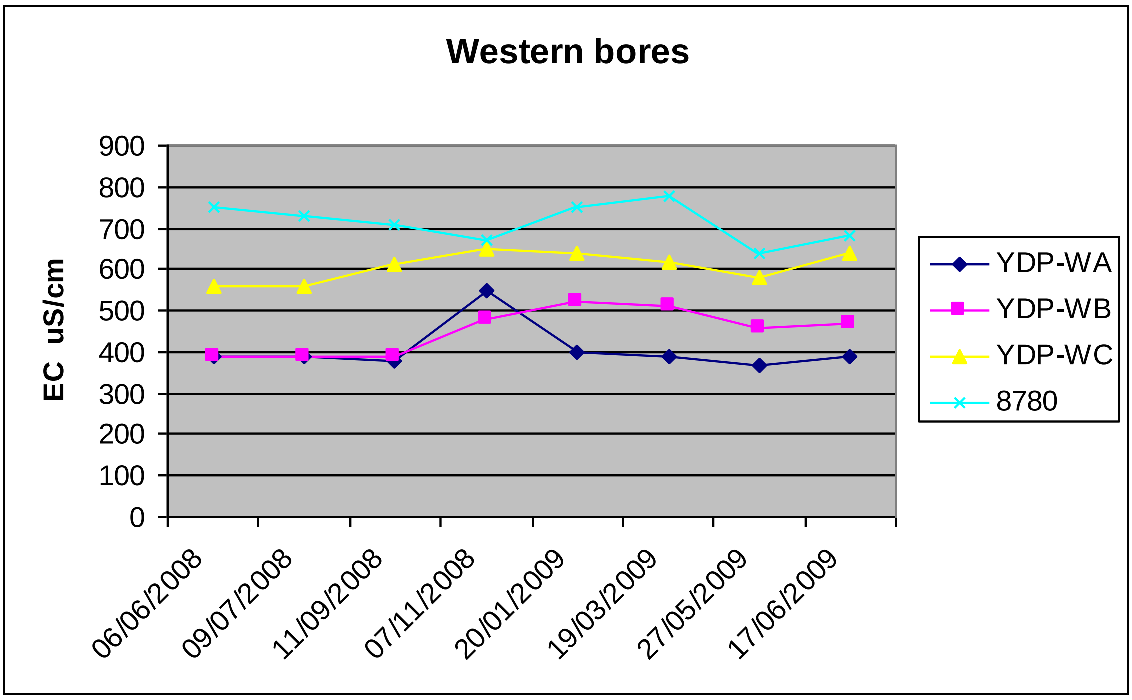


Figure 34 *Variation in EC for western bores and Lake Yonderup*

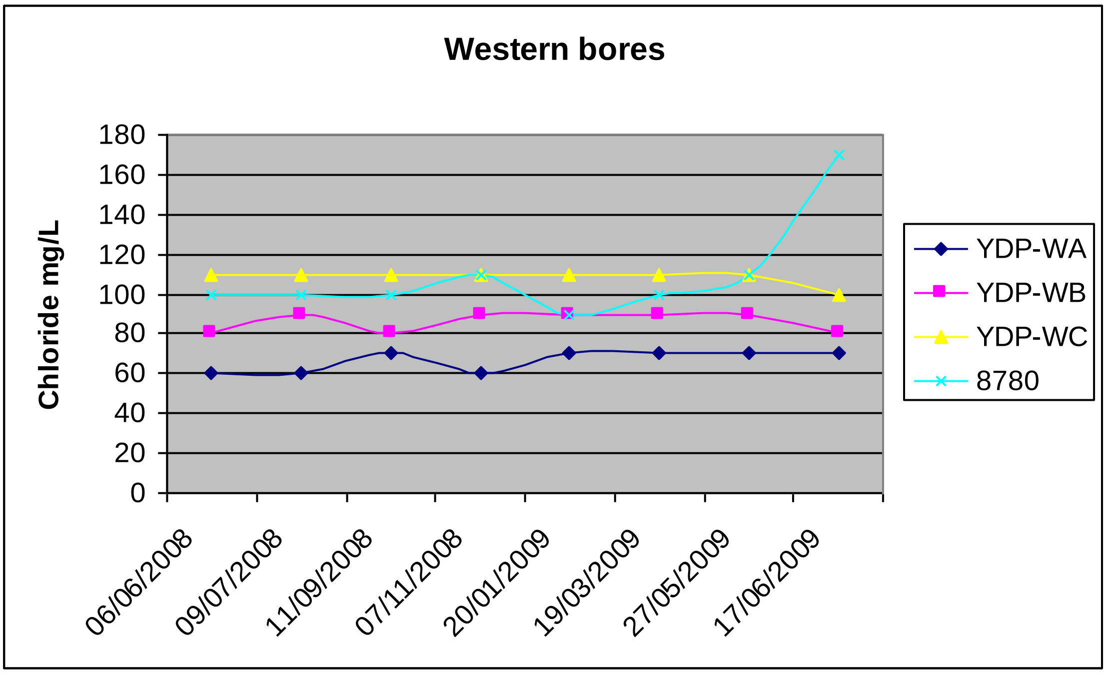


Figure 35 Variation in chloride for western (down-gradient) bores and Lake Yonderup

6.2.3 Sulfate

Figure 36 shows time-course variation for sulfate in the lake and groundwater. This emphasises the sulfate enrichment of the lake relative to groundwater, with one sample from the intermediate bore showing an elevated concentration early in the SGS study. Sulfate enrichment in the lake indicates that oxidation of sulfide minerals may be occurring as a consequence of discharge of groundwater to the lake. Acidification may result as groundwater discharges through lake sediments, or from processes within the lake and lake sediments.

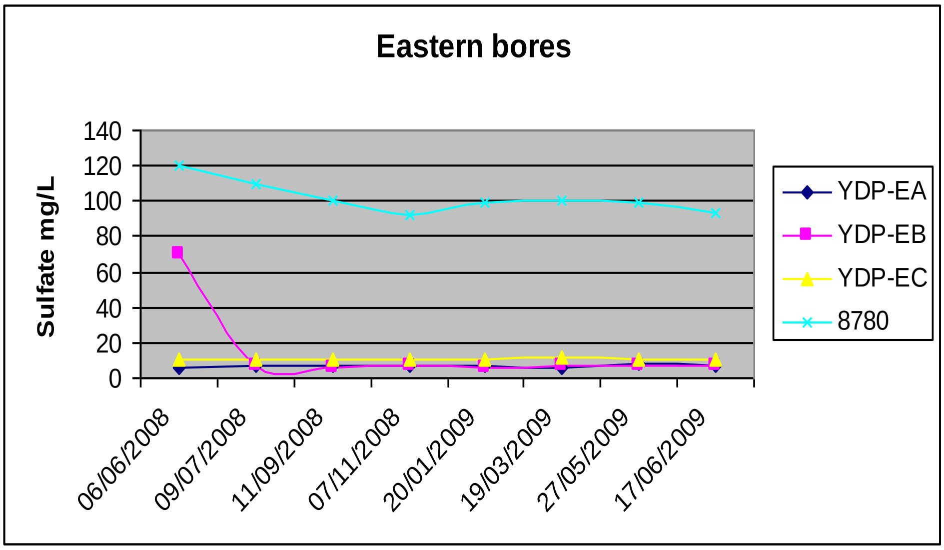


Figure 36 Time-course variation in sulfate concentration in groundwater from the eastern bores and Lake Yonderup

Figure 37 shows that lake water is significantly richer in sulfate than groundwater down-gradient of the lake. Sulfate concentrations have been steadily increasing in the shallow and intermediate down-gradient bores since mid 2008.

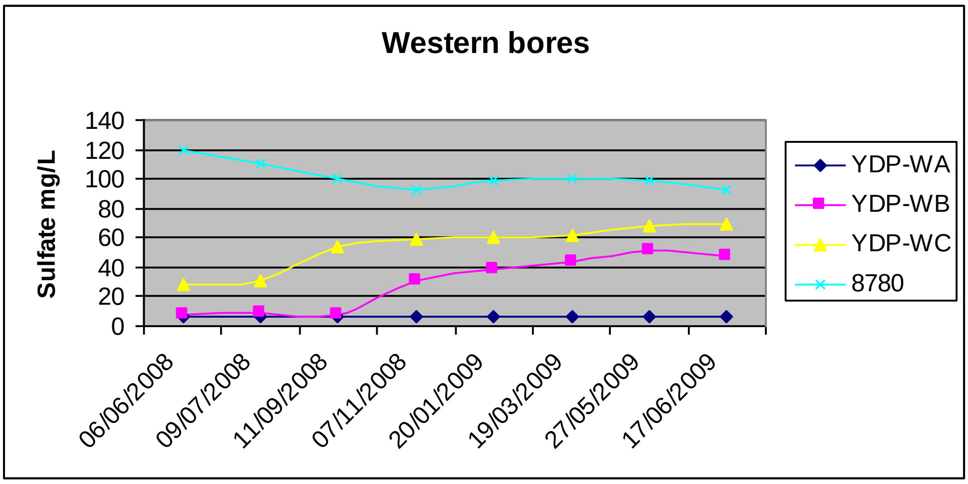


Figure 37 Time-course variation in sulfate concentration in groundwater from the western bores and Lake Yonderup

6.2.4 Sodium and calcium

Sodium and calcium concentrations in shallow groundwater up-gradient of the lake are similar to those within the lake (Figure 38 and Figure 40), both being higher than concentrations deeper within the aquifer. This relationship is complementary to that observed for other ions and physical parameters and is consistent with groundwater discharge to the lake being derived from relatively shallow groundwater east of the lake.

Concentrations of sodium in lake water over the SGS monitoring period are similar to those at shallow depths down-gradient of the lake (Figure 39). As indicated in Figure 41, lake water is richer in calcium than groundwater immediately down-gradient of the lake. This supports the conclusion that there is little evidence of discharge of lake water into groundwater in the area of the western SGS bores.

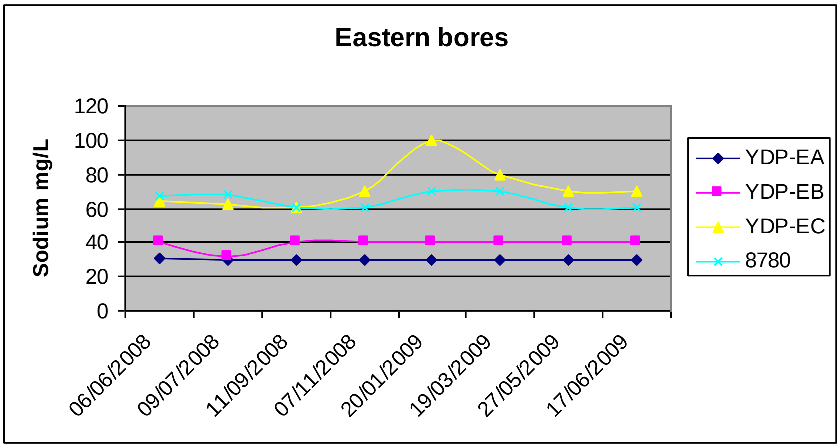


Figure 38 *Time-course variation of sodium concentration in groundwater in eastern YDP bores and Lake Yonderup*

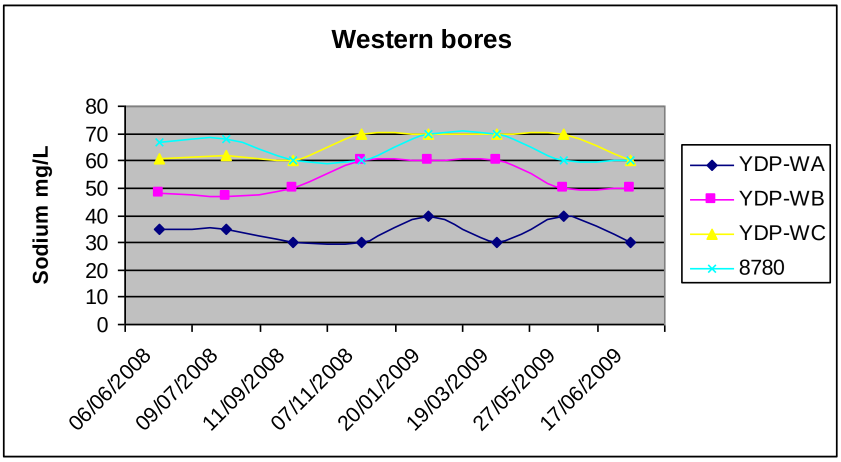


Figure 39 *Time-course variation of sodium concentration in groundwater in western YDP bores and Lake Yonderup*

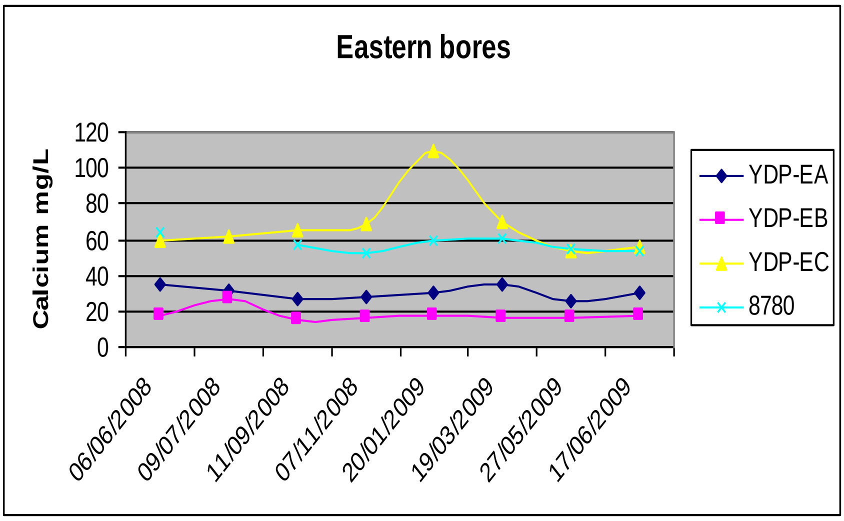


Figure 40 *Time-course variation of calcium concentration in groundwater in eastern YDP bores and Lake Yonderup*

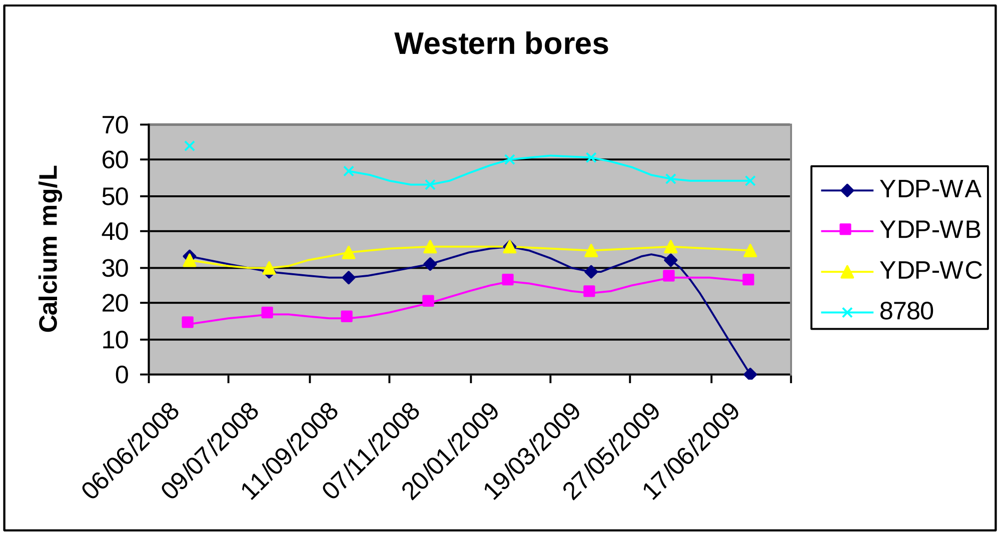


Figure 41 Time-course variation of calcium concentration in groundwater in western YDP bores and Lake Yonderup

6.2.5 Nutrients

Summary statistics for nitrogen and ammonia in groundwater and lake water are shown in Table 9 and time-course variations for total nitrogen (TN) and nitrate (total oxidised nitrogen) are shown in Figure 42, Figure 43, Figure 44 and Figure 45. Lake water is dominated by total Kjeldahl nitrogen (TKN), with most of this being organic nitrogen. In contrast, groundwater is richer in nitrate (oxidised nitrogen) with generally lesser amounts of TKN (organic nitrogen).

Nitrate in groundwater up-gradient and down-gradient of the lake exceed the trigger levels for wetlands in south-west Australia. Ammonium was detected above the trigger value of 0.04 mg/L at YDP_EB (0.1 mg/L) and in the lake water sample (8780) at 0.08 mg/L. YDP_WB (0.3 mg/L) and YDP_WC (0.3 mg/L) both recorded ammonia at 0.3 mg/L. Groundwater immediately down-gradient of the lake shows no concentrations of ammonium or nitrate above the drinking water guidelines.

Table 9 Summary statistics for nitrogen species in groundwater in east and west YDP bores and in Lake Yonderup at location 8780

	Total nitrogen mg/L			**Total Kjeldahl nitrogen mg/L**			**Ammonium-N mg/L**			**Nitrate-N mg/L**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
YDP_EA	<0.025	0.14	0.67	<0.025	0.11	0.06	<0.01	<0.01	<0.01	<0.01	0.03	0.02
YDP_EB	0.06	0.22	0.1	<0.025	0.12	0.09	<0.01	0.1**	<0.01	<0.01	0.1**	0.05
YDP_EC	0.06	0.7	0.3	<0.025	0.11	<0.025	<0.01	<0.01	<0.01	0.05	0.59**	0.29**
YDP_WA	<0.025	0.18	0.11	0.04	0.13	0.05	<0.01	<0.01	<0.01	<0.01	0.66	0.04
YDP_WB	0.2	0.77	0.35	<0.025	0.44	0.09	<0.01	0.03	<0.01	0.13	0.33	0.28
YDP_WC	0.14	0.52	0.35	0.06	0.26	0.08	<0.01	0.03	<0.01	0.1	0.3	0.22
8780	0.14	0.45	0.24	0.16	0.45	0.25	<0.01	0.08**	<0.01	<0.01	0.043	<0.01
Trigger*		1.5			–			0.04			0.1 (NOx)	
Drinking water guidelines		–			–			0.4			10	

** Trigger value for south-west Australia wetlands (ANZECC & ARMZANZ 2000)*

***Exceedances in lake water and up-gradient bores*

Drinking water guideline maximum concentrations from (NHMRC–NRMMC, 2004)

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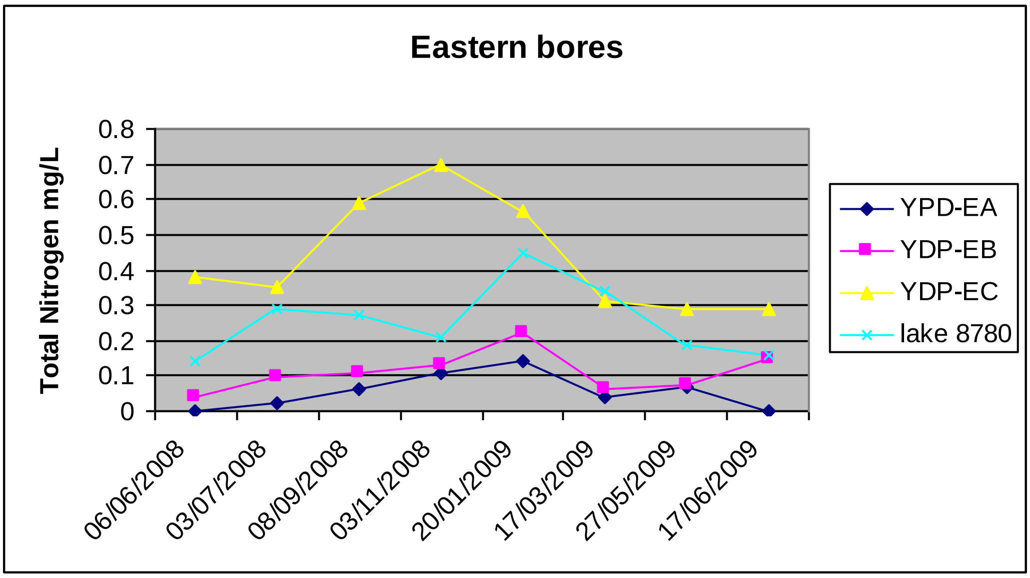


Figure 42 Time-course variation in total Kjeldahl nitrogen concentration in groundwater in eastern YDP bores and Lake Yonderup

Total nitrogen in up-gradient bores shows higher concentrations in shallow groundwater than in the lake and in groundwater lower in the aquifer (Figure 42). Most of this nitrogen in shallow groundwater is nitrate which shows a similar pattern to TN over the monitoring period for the shallow bore YDP_EC (Figure 44).

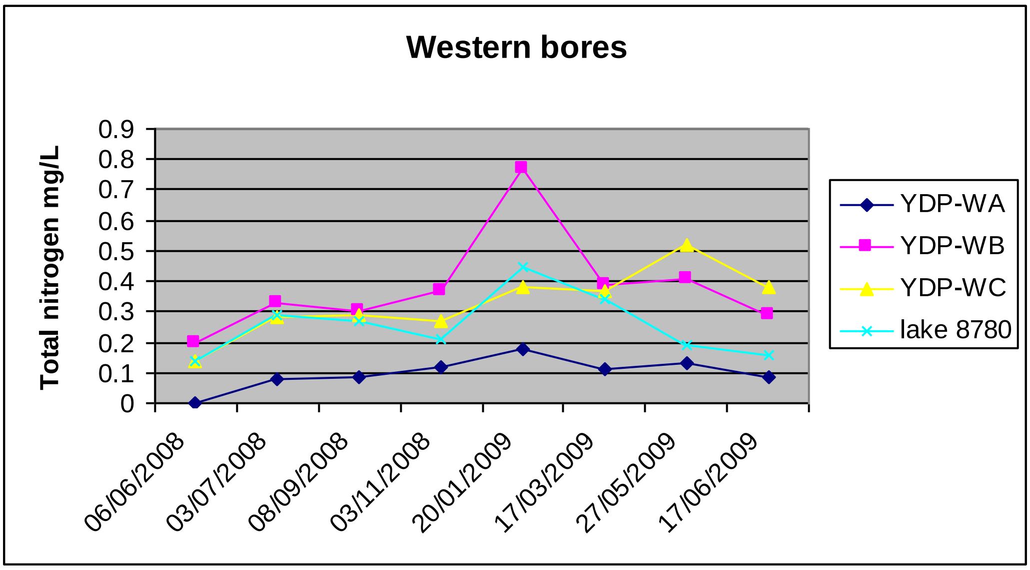


Figure 43 Time-course variation in total Kjeldahl nitrogen concentration in groundwater in western YDP bores and Lake Yonderup

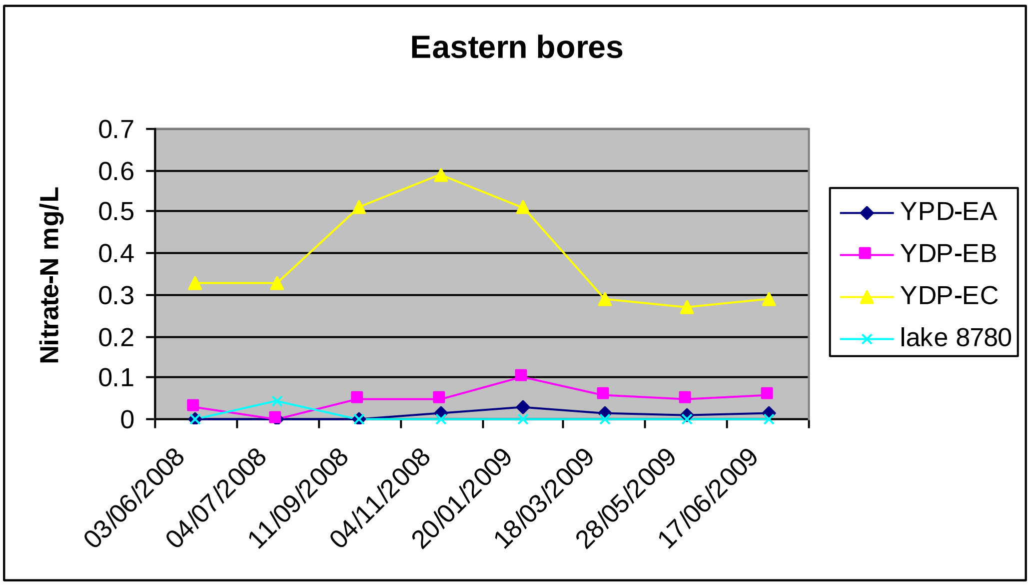


Figure 44 Time-course variation in nitrate concentration in groundwater in eastern, up-gradient YDP bores and Lake Yonderup

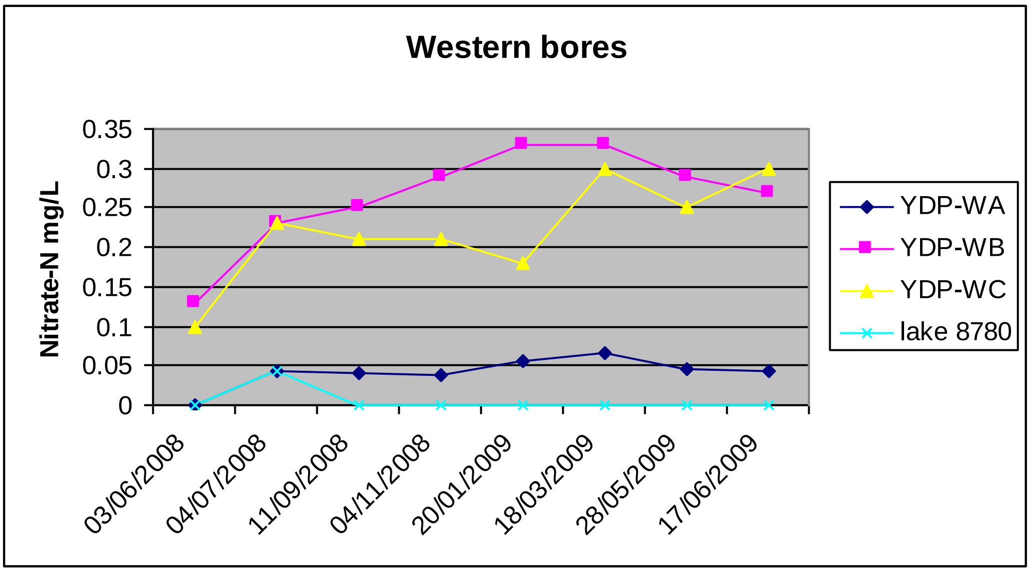


Figure 45 Time-course variation in nitrate concentration in groundwater in western, down-gradient YDP bores and Lake Yonderup

Total nitrogen in down-gradient bores is shown in Figure 43, and nitrate in groundwater from these bores is shown in Figure 45. TN in the lake is similar in concentration over time to that in shallow and intermediate bores down-gradient of the lake, although TN in the lake is mainly organic nitrogen (Table 9) and that in groundwater is mainly nitrate (Figure 45). Data for other ions in the western SGS bores suggest little evidence of lake water discharge to groundwater down-gradient of the lake. Hence nitrate at shallow and intermediate levels most likely has a source other than the lake. If the lake is causing high nitrogen in groundwater on its western down-gradient side, then there must be transformation of organic nitrogen to ammonium-N and nitrification of ammonium to nitrate taking place beneath the lake.

Summary statistics (minima, maxima and median concentrations) for total phosphorus (TP) and soluble reactive phosphorous (SRP) are shown in Table 10, where these are compared with trigger concentrations for south-west Australian wetlands (ANZECC & ARMCANZ 2000) for Lake Yonderup and up-gradient groundwater.

Table 10 Summary statistics for total and reactive soluble phosphate species in groundwater in east and west YDP bores and in Lake Yonderup at location 8780

		Total-P mg/L			**SRP mg/L**	
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**
YDP_EA	0.12**	0.68**	0.26**	0.069**	0.098**	0.081**
YDP_EB	0.018	0.25**	0.043	<0.005	0.01	<0.005
YDP_EC	0.006	0.25**	0.01	<0.005	0.01	<0.005
YDP_WA	0.12	0.37	0.17	0.053	0.089	0.074
YDP_WB	0.088	1.7	0.145	0.018	0.043	0.041
YDP_WC	0.009	0.055	0.013	<0.005	0.008	<0.005
Lake Yonderup 8780	0.012	0.018	0.016	<0.005	0.013	<0.005
Trigger value *		0.06			0.03	

** Trigger values are south-west Australia wetlands (ANZECC & ARMCANZ 2000)*

***Exceedances of trigger values*

Up-gradient bores show TP levels in excess of trigger levels, as do down-gradient monitoring points at YDP_WA and YDP_WB. Soluble reactive phosphorus is likewise present in concentrations above the trigger level in the deep bore up-gradient of the lake reporting a maximum of 0.098 mg/L and also at YDP_WA and YDP_WB. The lake showed no concentrations in excess of the trigger level over the SGS monitoring period.

6.2.6 Minor and trace metals and metalloids

Summary statistics (minima, maxima and median values) for minor and trace metals and metalloids are shown in Table 11 for data collected in the SGS study. Data for lake concentrations and up-gradient groundwater are compared with trigger levels for toxicants in south-west Australia wetlands (ANZECC & ARMCANZ 2000), and data for down-gradient bores are compared with drinking water guideline maximum concentrations in raw water (NHMRC–NRMMC 2004) since drinking water is the most significant beneficial use down-gradient of the lake.

Lake water showed no exceedances of trigger levels over the SGS monitoring period. Some groundwater up-gradient of the lake did show concentrations above the trigger level, mainly deeper in the Superficial aquifer. Thus at the base of the aquifer (bore YDP_EA), all concentrations for chromium and maximum and median concentrations for zinc are above relevant trigger levels shown in Table 11. The intermediate bore (YDP_EB) exceeded chromium, whilst zinc showed median and maximum levels above the trigger. At shallow depths (bore YDP_EC, which contributes most discharge to the lake), chromium and zinc were again observed above the trigger level shown in Table 11.

Down-gradient of Lake Yonderup, groundwater at intermediate levels (bore YDP_WB) showed one maximum concentration above the drinking water guideline for chromium and nickel. Median and maximum concentrations were above the guideline for arsenic, although the median arsenic level was close to the guideline value (Table 11). Groundwater at shallow depth (bore YDP_WC) showed no concentrations above drinking water guidelines.

6.2.7 Herbicides and pesticides

Samples were analysed for 41 herbicides and pesticides, twice in winter 2008, once in summer 2009 and once in winter 2009. Results are below the 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.

Table 11 Summary statistics for minor metals and metalloids in groundwater and lake water at Lake Yonderup

		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**
YDP_EA	<0.005	0.031	0.015	0.001	0.007	0.002	<0.01	0.026	0.017	<0.0001	0.003*	<0.0001	0.002*	0.062*	0.006*
YDP _EB	<0.005	0.011	0.01	<0.001	0.005	<0.001	<0.01	0.013	<0.01	<0.0001	<0.0001	<0.0001	<0.001	0.019*	<0.001
YDP _EC	0.006	0.017	0.009	<0.001	0.001	<0.001	0.01	0.019	0.016	<0.0001	<0.0001	<0.0001	0.001	0.002*	0.001
YDP _WA	0.007	0.041	0.008	0.002	0.005	0.003	<0.01	0.086	0.02	<0.0001	0.0001	<0.0001	0.002	0.016	0.007
YDP _WB	<0.005	0.058	0.011	0.007	0.088[#]	0.008[#]	<0.01	0.057	0.027	<0.0001	0.0005	<0.0001	0.002	0.52[#]	0.01
YDP _WC	<0.005	0.01	<0.005	<0.001	0.002	<0.001	0.012	0.041	0.018	<0.0001	<0.0001	<0.0001	<0.001	0.009	0.002
Lake Yonderup 8780	<0.005	0.009	<0.005	<0.001	<0.001	<0.001	<0.01	0.13	<0.01	<0.0001	<0.0001	<0.0001	<0.001	0.001	<0.001
Trigger level*		0.055			0.013^			0.37			0.0002			0.001	
Drinking water guidelines[#]		0.2			0.007			0.3			0.002			0.05	

** Trigger level for south-west Australia wetlands (ANZECC & ARMCANZ 2000) and their exceedances*

[#] *Drinking water guideline concentrations (NHMRC–NRMMC 2004)and their exceedances*

^Value for As(III) shown; trigger level for As(IV) is 0.024 mg/L

Table 11 (continued)

	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**
YDP_EA	0.033	0.019	0.08	0.009	0.067	0.017	0.001	0.006	0.002	0.001	0.12*	0.017*
YDP_EB	0.009	0.072	0.032	0.001	0.009	0.003	<0.001	0.005	<0.001	0.005	0.062*	0.015*
YDP_EC	0.009	0.044	0.002	<0.001	<0.001	<0.001	<0.001	0.008	<0.001	0.001	0.014*	0.006
YDP_WA	0.009	0.063	0.03	0.005	0.052	0.015	0.003	0.006	0.003	0.003	0.055	0.015
YDP_WB	0.007	0.15	0.03	0.001	0.048	0.002	0.001	0.035#	0.002	0.004	0.081	0.018
YDP_WC	<0.005	0.036	0.018	0.001	0.009	0.004	<0.001	0.002	<0.001	<0.001	0.035	0.012
Lake Yonderup 8780	0.007	0.030	0.013	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.006	0.003
Trigger level*		-						0.011			0.008	
Drinking water guidelines#		0.3						0.02			3	

** Trigger level for south-west Australia wetlands (ANZECC & ARMCANZ 2000) and their exceedances*

#Drinking water guideline concentrations (NHMRC–NRMMC 2004)and their exceedances

^Value for As(III) shown; trigger level for As(IV) is 0.024 mg/L

6.3 Summary of trigger level breaches

Table 12 Summary of trigger level breaches

	Wetlands trigger levels – ANZECC & ARMCANZ (2000)
pH	All lake pH values were within the recommended range of 7.0 to 8.5 (overall range 7.3-7.9), and all groundwater up-gradient of the lake showed similar pH values below the recommended range.
TN	Lake concentrations were below the trigger level; with most TN being organic N. TN in groundwater was below the trigger level.
NH_4-N	Ammonium was detected above the trigger value of 0.04 mg/L at YDP_EB (0.1 mg/L) and in the lake water sample (8780) at 0.08 mg/L. YDP_WB(0.3 mg/L) and YDP_WC(0.3 mg/L) both recorded ammonia at 0.3 mg/L.
NO_x	Nitrate in groundwater up-gradient of the lake exceeded the trigger levels for wetlands in south-west Australian wetlands.
TP	Up-gradient bores showed TP levels in excess of trigger levels, as did down-gradient monitoring points at YDP_WA and YDP_WB.
SRP	Soluble reactive phosphorus was present in concentrations above the trigger level in the deep bore up-gradient of the lake, reporting a maximum 0f 0.098 mg/L and also at YDP_WA and YDP_WB. The lake showed no concentrations in excess of the trigger level over the SGS monitoring period.

	'Toxicants' in wetlands trigger levels ANZECC & ARMCANZ (2000)	**Drinking water guidelines as main beneficial use NHMRC–NRMMC (2004)**
Al	Concentrations in the lake and up-gradient groundwater were below trigger levels	All concentrations were below guideline concentrations.
As	All lake and groundwater concentrations were below trigger levels.	Median concentrations in down-gradient intermediate bore (YDP_WB) were above guidelines, all other maximum concentrations in down-gradient groundwater were below guidelines.
B	All lake and groundwater concentrations were below trigger level.	All concentrations were below guideline concentrations.
Cd	All lake and groundwater concentrations were below trigger level, except for one maximum concentration in deep bore YDP-EA, not considered to be contributing significantly to discharge to the lake.	Groundwater in down-gradient bores were below guideline levels.
Cr	All lake concentrations were below trigger level. Deep up-gradient bore YDP-EA showed median concentration above trigger level, and one maximum level in each of bores YDP-EB and –EC were above trigger level. Latter concentrations in shallow bore were not considered significant in groundwater discharge to the lake.	Groundwater in down-gradient bores generally well below guideline level, but one maximum concentration exceeded the guideline in the intermediate bore, YDP-WB reported at 0.52 mg/L.
Ni	Lake concentrations and groundwater were well below trigger levels.	YDP_WB (deep) reported a maximum concentration in above the guideline.
Zn	All lake concentrations were below trigger level; median concentrations at intermediate and deep aquifer levels exceeded trigger levels and one maximum concentration at shallow depth exceeded trigger level. Latter not considered significant.	All concentrations were below guideline levels.

Fe	N/A	Median concentrations in all down-gradient bores exceeded guideline levels.
Mn	N/A	Maximum concentration in shallow down-gradient bore exceeded guideline level.

7 Processes and interactions between surface water and groundwater

Analysis of the local hydrogeology at Lake Yonderup allows an interpretation of hydrogeochemical processes and surface water–groundwater interactions to be made. These are shown conceptually in Figure 46. Lake Yonderup has been classified as being groundwater-dependent, with connection to the regional groundwater flow system of the Gnangara Mound. Flow of groundwater into the lake is largely from the region at shallow depths close to the watertable, possibly through karst solution features which may be developed to the east of the lake. These characteristics have implications for how the site should be managed.

Pertinent observations follow from Figure 46:

- Groundwater up-gradient of the lake was of similar geochemical character to that at intermediate and deep levels in down-gradient bores, suggesting groundwater underflow beneath the lake at intermediate and deep aquifer levels.
- Lake water was richer in sulfate and calcium than down-gradient groundwater, indicating effects of sulfide mineral oxidation and carbonate mineral buffering within lake sediments, as lake pH remains stable.
- There were low levels of nitrogen(predominantly nitrate), influent to the lake at shallow depths, occasional single maximum values in lake of ammonium and nitrate above trigger levels, but with predominant form of nitrogen in the lake being TKN (being principally organic nitrogen, given low ammonium-N).
- There was some evidence of increase in sulfate in groundwater at shallow depths down-gradient of the lake. This is most likely due to a combination of diffuse infiltration (low level discharge) of sulfate enriched lake water and by in situ processes such as sulfide mineral oxidation or acidification as groundwater discharges through lake sediments.

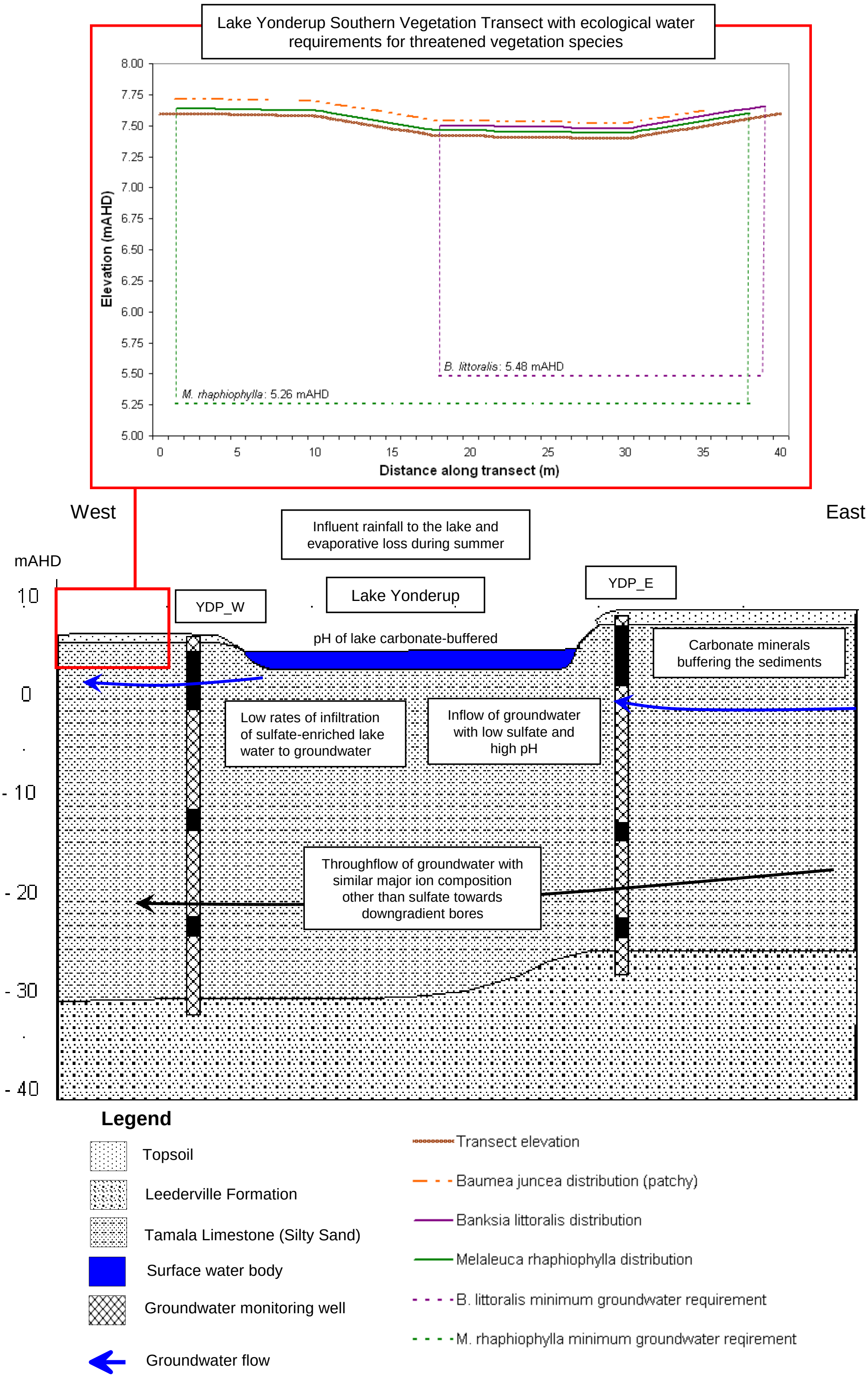


Figure 46 Conceptual diagram of geochemical processes and EWRs for groundwater-dependent systems at Lake Yonderup

7.1 Groundwater hydrology

Lake Yonderup is in hydraulic connection with the regional groundwater flow system via the Superficial aquifer. Lake and in particular, groundwater levels are determined by a dynamic balance between topography, hydrogeology, climate variation, groundwater abstraction and land use. Lake Yonderup is a lake which is entirely dependent on groundwater for its existence.

This study has found that the lake levels and local watertables vary in phase (with normal 'signal' attenuation of the watertable). Summer minima occur in March and April, while 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). The lack of any phase lag between lake and groundwater levels suggests a strong hydraulic linkage between the lake and the aquifer, possibly via karst solution cavities at or close to the watertable. Lake Yonderup has a semi-stable water level and small annual water level range (~ 0.08 m). There has been a steady decline in groundwater and lake levels over time, at least since the early 1990s.

There is a subdued vertical groundwater flow component (upward leakage) on the eastern side of the lake between the intermediate and shallow SGS bores, which indicates groundwater discharge to the lake from the Superficial aquifer. The similarity in water quality characteristics between lake water and groundwater from the shallow up-gradient bore suggests that only groundwater close to the watertable discharges into the lake. There is some evidence of a very small, downward hydraulic gradient between the intermediate and deep bores, although this is not considered to affect the hydrogeology significantly.

The groundwater flow pattern on the western side of the lake is more complex. Here there is little evidence of discharge of lake water into the sands of the Tamala Limestone, with no clear and consistent hydraulic gradient between the different bores and some indication of a very low upward hydraulic gradient between the intermediate and shallow down-gradient bores. Although this gradient is very weak it may suggest outflow from the lake towards YDP_Wb.

The lack of substantial evidence of discharge of the lake back into the aquifer is problematic given that lake levels are higher than groundwater levels in the western bores. Water quality data – high sulfate concentrations in the lake and much lower concentrations in shallow groundwater – supports the conclusion that there is little discharge into the aquifer,. The concentration of sulfate in the shallow down-gradient bore is still significantly higher than in up-gradient bores, indicating some low-level discharge of lake water into the underlying sands.

It is concluded that on the basis of the strong hydraulic connection between the lake and aquifer (from synchronous water level changes), that there may be localised karst features which dominate inflow to the lake, although there were no indications of limestone lithologies in the SGS bores. The evidence of low discharge of lake water back into groundwater also indicates that lake sediments may have low hydraulic conductivity and water losses by evaporation in the lake may come close to balancing groundwater inflow and any direct accession of water from rainfall to the lake.

The latter is important, and indicates that given the strong hydraulic connection, possibly via karst features, that the lake is vulnerable to continued decreases in groundwater levels.

The cause of the decrease in groundwater levels up-gradient is uncertain, although Yesertener (2008) concluded from modelling that decreasing rainfall and lower recharge were mainly responsible for falling groundwater levels on the Gnangara Mound. There may be stressors (abstraction bores, land use, drainage) that are decreasing groundwater levels downstream by flow capture, given that down-gradient bores show increased variability in water levels compared with up-gradient bores. This requires further investigation.

The licensed allocations for Water Corporation production bores and private bores in the Lake Yonderup area have been shown earlier in Figure 8, in Section 2.7. Within a 2 km radius there are approximately two drawpoints due north of Lake Yonderup, one due west (the cave supplementation bore abstracting 54 ML/yr) and a cluster of irrigation bores (10 or so with a total licensed allocation of some 1.2 GL/yr) for horticulture south-east of the lake. The irrigation bores are situated in the northern extremity of the Carabooda irrigation area. As not all private bores are metered, it is not possible to know the total abstraction from these private bores.

7.2 Groundwater chemistry

Major ion hydrochemistry suggests that:

- east (up-gradient) of the lake:
    - groundwater discharges directly to the lake, emanating from a region close to the watertable in the Superficial aquifer where groundwater characteristically is of similar composition and salinity to that observed in the shallow bore, except for sulfate.
    - lake water becomes enriched in sulfate as shallow groundwater discharges into the lake through acidified sediments, presumably from oxidation of sulfides within lake sediments beneath the lake.
    - lake pH (6.8 to 7.8) was mostly within the recommended range for wetlands in south-west Australia (7.0 to 8.5), There was no evidence of acidification of lake water from sulfide oxidation in sediments and pH values have remained around this range since 1995. It is considered likely that carbonate minerals in lake sediments or lake water alkalinity are sufficient to buffer the lake pH by carbonate buffering (see Stumm and Morgan 1996) and negate the effects of sulfide oxidation and water acidification.
    - as indicated above, ANC values were recorded in samples from YDP_SC which indicate that the sediments at this site have an inherent self-buffering capacity. This buffering is likely to be provided

by carbonate minerals given the presence of limestone in the region of the lake.

- groundwater west down-gradient) of the lake:
    - shallow groundwater shows similar EC, chloride and sodium to that in the lake and in up-gradient groundwater. However, lake water contains approximately twice the concentration of sulfate than shallow groundwater down-gradient, and groundwater deeper in the aquifer is somewhat depleted in sulfate. This suggests that discharge of lake water into groundwater within the sands of the Tamala Limestone at the location of the western bores is diffuse and probably small, particularly given the location of the bores close to the lake edge.
    - organic nitrogen (TKN) is the dominant nitrogen species in lake water, while nitrate is dominant in groundwater. There are higher concentrations of nitrate in down-gradient, shallow bores than in up-gradient bores, which suggests some additional source of nitrogen in groundwater below the lake. If the nitrogen is derived from diffuse lake discharge as is sulfate, then the predominant organic nitrogen would have to have been transformed to ammonium-N and nitrified to give nitrate in groundwater. There is little impact of this on groundwater quality as concentrations are below drinking water guidelines.

There has been some deterioration in lake water quality since 1995, shown by increases in EC from ~400 to 500 µS/cm to the current level of ~650 to 750 µS/cm (Froend et al. 2004) as water levels recede in the lake. However, the EC in the shallow up-gradient bore in 2008–09 was similar to that in the lake, so it is concluded that groundwater discharging to the lake has largely contributed to the increase in salinity in the lake.

Nutrients show some variability, although the incidence of ‘spikes’ of TKN and organic nitrogen is not showing a tendency to increase over time.

Analysis of available SGS water quality data indicates that water quality in Lake Yonderup is currently good, although some changes in water chemistry were recorded in 2008–09, suggesting that low water levels are starting to affect water quality (Judd & Horwitz 2009). Analysis suggests that nutrient (Figure 48) and salinity (Figure 47) levels are increasing in response to declining water levels, but the recorded changes have been minor and no water quality guidelines (DEC 2010) have been breached. Data collected to date does not show any evidence of reduction in buffering capacity (Figure 49), suggesting that Lake Yonderup is not currently at risk of acidification, despite low water levels.

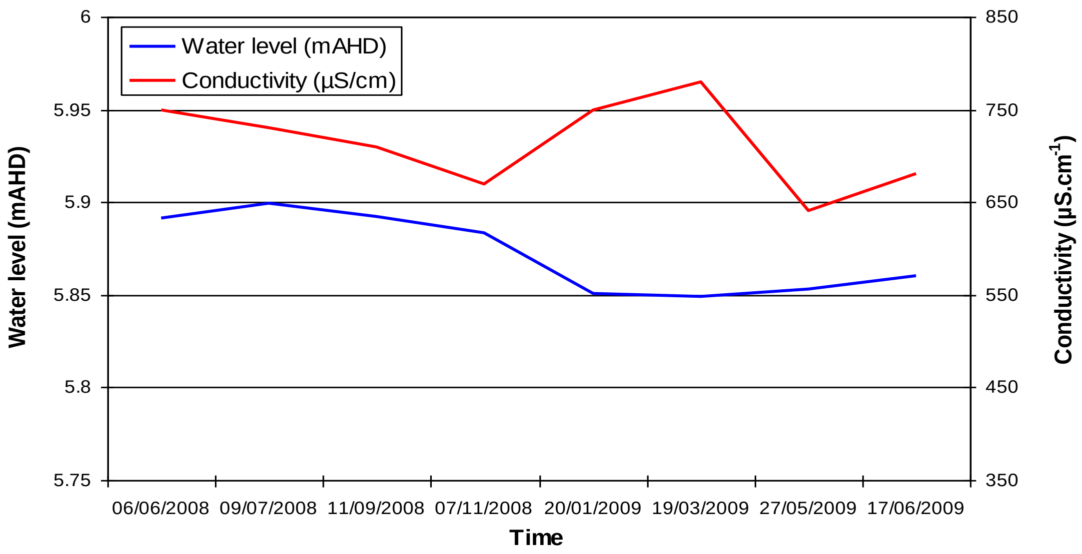


Figure 47 Relationship between water level and electrical conductivity (salinity) in Lake Yonderup

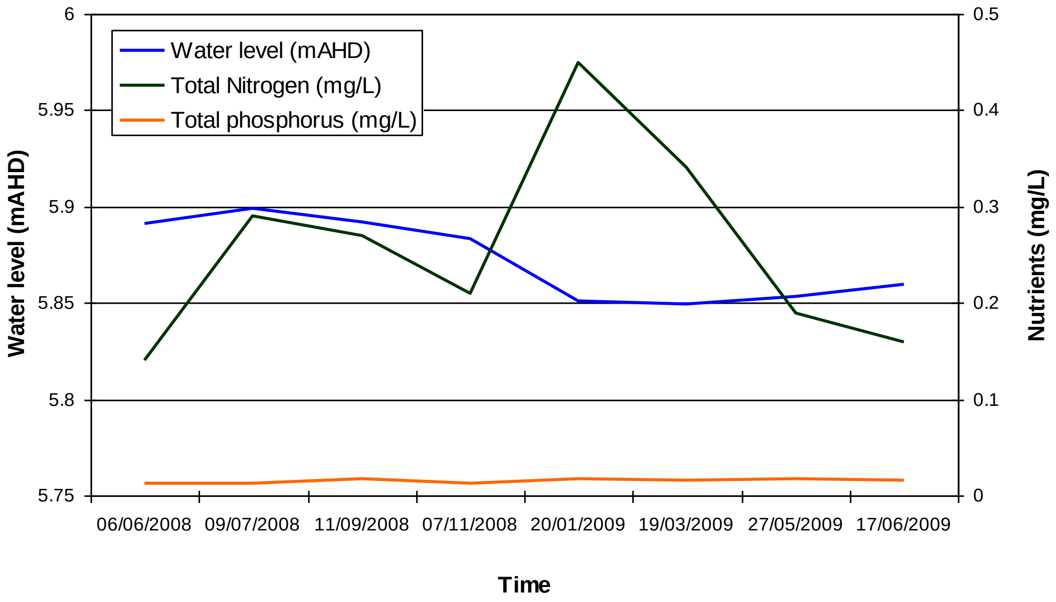


Figure 48 Relationship between decreasing water level and increasing nutrient (nitrogen and phosphorus) levels in Lake Yonderup

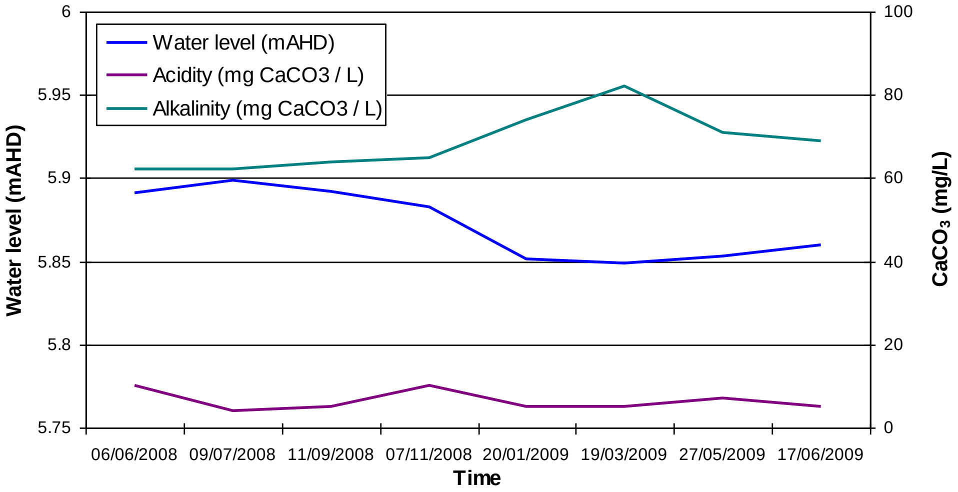


Figure 49 Relationship between water level and buffering capacity (alkalinity and acidity) in Lake Yonderup

7.3 Conclusion and recommendations

Whilst Lake Yonderup has maintained its hydrologic regime as a groundwater-dependent ‘flow-through lake’, the lake levels are highly vulnerable to further decreases in groundwater levels both up-gradient and down-gradient of the lake. Declining groundwater levels may result in it becoming ‘perched’ unless measures are taken to redress its water balance.

Groundwater flow into the lake on its eastern (up-gradient) side comes from the watertable zone, and has continued at a somewhat decreased discharge rate. At the western (down-gradient) side the lake recharges groundwater through a combination of low discharge via the watertable and through a thin, unsaturated zone presumably in part beneath the lake. Notwithstanding inflows to the lake from down-gradient groundwater, water losses by evaporation in the lake may come close to balancing groundwater inflow to the lake and any direct accession of water from rainfall.

Townley et al. (1991) indicated on the basis of modelling of flow-through lakes that those lakes with narrow width normal to the direction of groundwater flow as at Lake Yonderup received groundwater from shallow depths. In contrast, lakes like Loch McNess which were of greater width normal to groundwater flow lines received more extensive groundwater discharge from greater depths within the aquifer. The modelling would thus seem to be consistent with what has been observed from the SGS study at Lake Yonderup (and Loch McNess).

Detailed monitoring of groundwater levels over time in bore YN7 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 surface water level recorders should be considered on bores YN7 and YN11.

8 Implications for ecological values and management recommendations

8.1 Monitoring infrastructure

With the recent addition of a new monitoring bore (YDP_SC) associated with the already existing vegetation transect and the establishment of a second, northern vegetation transect, the monitoring infrastructure for Lake Yonderup has been improved. However, consideration should be given to establishing a monitoring bore associated with the northern vegetation transect. This vegetation transect is closer to Lake Yonderup and could be used to set vegetation EWRs for the lake (which could also act as surrogates for macroinvertebrate EWRs). As the southern transect is 750 m from the lake it is not considered representative of vegetation assemblages for the lake and thus not suitable for establishment of vegetation EWRs (Froend et al. 2004b).

Installing a bore associated with the northern vegetation transect would allow comparison and better data resolution for defining links between groundwater and vegetation, as well as providing improved tracking of, and confidence in, vegetation changes related to changes in groundwater depth.

As there is only limited data associated with the YDP bores, it is recommended that monitoring of the long-term bores YN7 and YN11 be maintained.

Further, it is recommended that the suitability of all monitoring bores be 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

Hydrologic regime is the ecological value at most immediate threat due to low groundwater levels. Changes to the hydrologic regime also have the greatest impact on other ecological values of Lake Yonderup.

A reduction in family richness occurred in spring 2009 (Judd & Horwitz 2009) suggesting that lake levels have recently reduced to such an extent that the ecology and biodiversity of Lake Yonderup is being affected (Judd & Horwitz 2009). The vegetation community of Lake Yonderup may be more sensitive to groundwater drawdown than anticipated, although the 2004–05 fire has contributed to the observed changes.

Lake Yonderup is entirely dependent on groundwater for maintaining its hydrology, biophysical processes, habitats and biological communities (Froend et al. 2004b). Water level declines to date have not yet had a significant impact on the ecological values of the lake, but if groundwater levels continue to decline the hydrological regime of the lake will alter. Falling water levels will have an adverse effect on water quality, sediment stability, macroinvertebrate richness and aquatic habitat availability. Salinity, nutrient and ion levels in the lake will increase due to concentration as a result of evaporation.

Wind re-suspension of lake sediments will increase as water levels fall, leading to the release of nutrients into the water column. This, together with the concentration effect (concentration of nutrients increases as water levels decrease) and nutrient enriched groundwater inflows, may cause nutrient levels to increase enough to trigger summer algal blooms.

The combined effects of concentration and exposure of lake sediments will increase the risk of acidification on Lake Yonderup. Although the lake currently shows no signs of acidifying, sufficient sulfidic sediments are present at the site to trigger acidification as these sediments are oxidised. Exposure of lake sediments due to falling water levels could release sufficient acids to overcome the natural buffering capacity of Lake Yonderup, harming aquatic flora and fauna. Permanent subsurface saturation is required to prevent acidification (Horwitz et al. 2009a).

The degrading of water quality by concentration, eutrophication and/or acidification will permanently reduce Lake Yonderup’s previously excellent water quality, which in turn will alter the macroinvertebrate richness as sensitive taxa are lost and more tolerant taxa increase in abundance. The macroinvertebrate community will also be altered due to changes in the quality and availability of habitats as lake levels fall. Falling water levels will also affect the habitat available to fish and waterbirds, and will decrease the value of Lake Yonderup as a waterbird refuge during dry periods.

A single breach of the trigger value for south-west Australia wetlands (ANZECC & ARMZANZ 2000) was observed from surface water sampling undertaken at Lake Yonderup, with ammonium-N reported at 0.078 mg/L on one occasion, exceeding the trigger value of 0.04 mg/L. As this breach was a single incident, with ammonium levels declining back to historical levels on the next sampling occasion, it is not considered to be ecologically significant. If further breaches of the ammonium trigger value occur in the future there may be some cause for concern. Elevated ammonium-N will lead to an increase in NOx-N as the ammonia is converted to nitrite then to nitrate. This process then increases the concentration of ecologically available nitrogen, leading to elevated total nitrogen values and possibly triggering algal blooms. It is recommended that surface water quality sampling be continued at Lake Yonderup, with close attention paid to ammonium-N and NOx-N levels to detect any emerging problems with excess nitrogen levels. As Lake Yonderup has been identified as a flow-through system the breaches highlighted in the up-gradient bores may also be significant for lake water quality in the future. Further monitoring of the system (particularly at YDP_EC) will be required in order to understand this potential impact.

The ecological consequences will be greatest if groundwater levels continue to decline, with the possibility of triggering the worst case scenario of Lake Yonderup becoming a seasonally inundated sumpland or a seasonally waterlogged dampland (Froend et al. 2004b). The historically stable hydrologic regime of Lake Yonderup would be lost and the Ministerial criterion will continue to be breached, with serious implications for the ecological values of the lake. Changes in ecological condition would include degradation of water quality and reductions in flora and fauna condition and diversity. This would affect the ecological values of the lake so severely as to be unrecoverable.

If the rate of groundwater decline can be slowed or stabilised, the damage to the ecological values of Lake Yonderup will be less. The ecosystem should be capable of partial to full recovery should water levels return to historic levels, with the amount of recovery depending on the duration and extent of water levels below the identified EWRs.

8.2.1 Ecological water requirements

Currently the Ministerial water level criteria (5.9 m AHD) is used as a surrogate ecological water requirement for vegetation, macroinvertebrates, vertebrates and sediment processes, and is considered to be appropriate by Froend et al. (2004b). To date, no specific EWRs for vegetation have been developed, although if developed they could be used as a surrogate for a macroinvertebrate EWR due to the close relationship between vegetation and macroinvertebrate habitats.

Until recently, no groundwater monitoring bore was associated with the southern vegetation transect, which is located 750 m south of Lake Yonderup (Section 7, Figure 46). Instead, water level data was obtained from bores at some distance (70 m) from the transect. Consequently, the groundwater levels used may not accurately reflect groundwater levels at the vegetation transect (Froend et al. 2004c). A new bore (YDP_SC) was installed at the southern vegetation transect in April 2008 to overcome this limitation. A second, northern vegetation transect was established in 2007 (Cullinane et al. 2009) to provide additional vegetation data closer to the lake and overcome the limitation identified by Froend et al. (2004b).

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)) indicates that the distribution of species with elevation has not changed significantly since 2004, with the exception of *Banksia littoralis* which was not recorded after the 2004-05 bushfire (Figure 50).

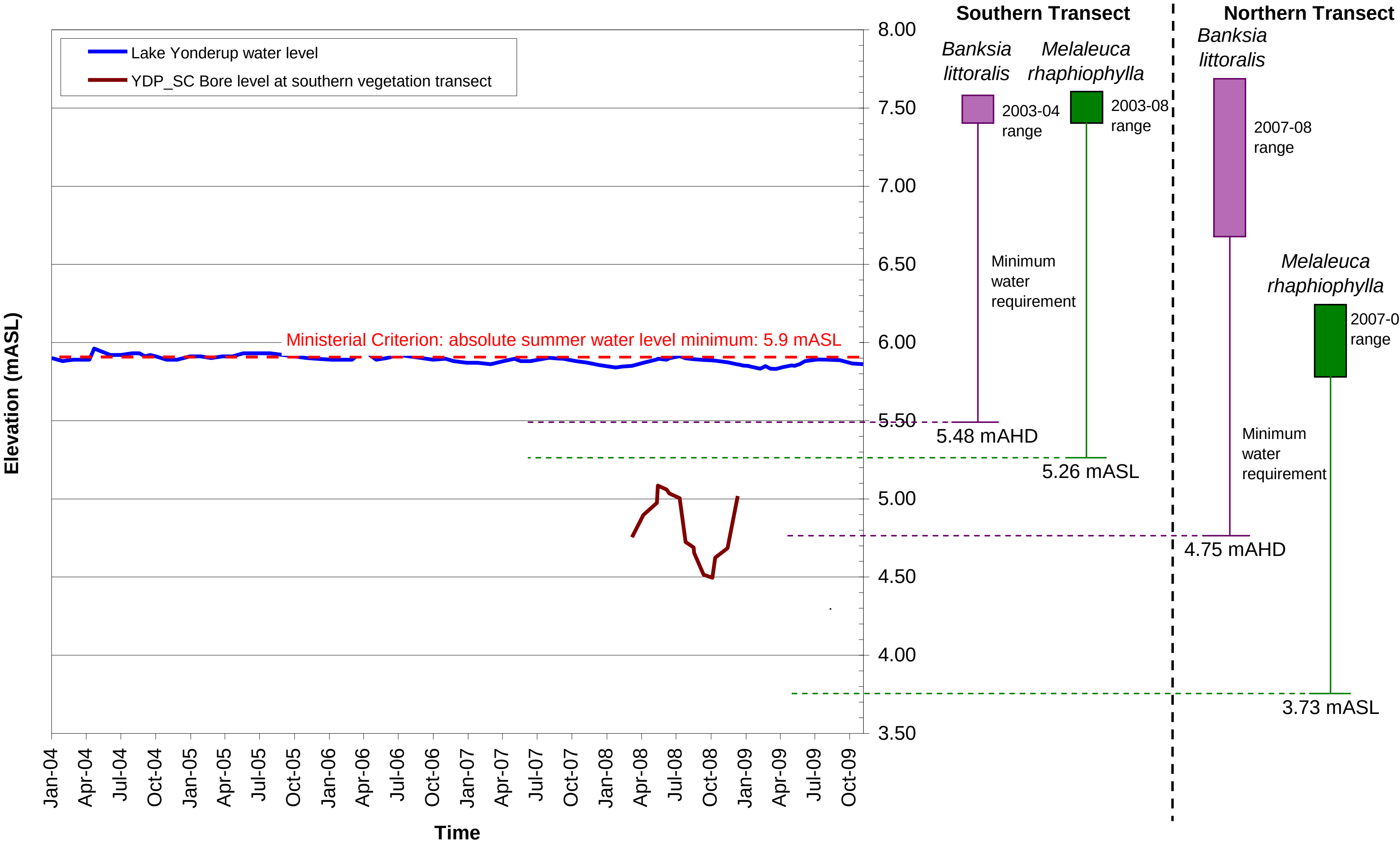


Figure 50 Relationship between vegetation distributions, lake levels and groundwater levels (bore YDP_SC)

Of the three most significant wetland plant species present, *B. juncea* has shown fragmentation of its range, *M. rhaphiophylla* has maintained its distribution and *B. littoralis* has been lost from the southern transect entirely.

As a groundwater monitoring bore has been established at the southern vegetation transect, minimum groundwater levels (EWRs) for *M. rhaphiophylla* and *B. littoralis* can be established for this transect using the mean water depth as described by Loomes (2000), cited in Froend et al. (2004b):

- *Banksia littoralis* – 5.48 m AHD
- *Melaleuca rhaphiophylla* – 5.26 m AHD

In developing the minimum requirements, the range of each species from 2004–08 was used. It is noted that *B. littoralis* has not been recorded at the site since 2004. In order to meet the known minimum groundwater requirements for wetland vegetation, a groundwater level of 5.48 m AHD would be required at bore YDP_SC. While this level could be established as both a vegetation EWR and a Ministerial criterion, there are concerns over the distance of this vegetation transect from Lake Yonderup (as raised by Froend et al. 2004b).

Monitoring of bore YDP_SC since 2008 indicates that groundwater levels are currently below the minimum requirements at the southern vegetation transect (Figure 50), suggesting that the vegetation is currently experiencing some level of water stress. The relationship between lake level and groundwater levels at bore YDP_SC is not yet clear as there is insufficient data available for this bore.

Analysis of vegetation data from the northern transect provided the following minimum groundwater levels (EWRs) for *M. rhaphiophylla* and *B. littoralis* using the method described by Loomes (2000), cited in Froend et al. (2004b):

- *Banksia littoralis* – 4.75 m AHD
- *Melaleuca rhaphiophylla* – 3.73 m AHD

As shown in Figure 50, these minimum levels are below the groundwater level recorded at the southern site. As there is no groundwater bore in the vicinity of the northern vegetation transect it is recommended that one is established so that both a vegetation EWR and a Ministerial criterion can be established for Lake Yonderup.

8.2.2 Land and water use

Assessments undertaken by the Department of Water (2008c) 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). At Lake Yonderup, modelling shows that climate change is the major cause of falling groundwater levels, responsible for decreases of 0 to 1 m (PRAMS models) to 1.1 m (CDFM models), with much smaller effects due to abstraction and land use (Department of Water 2008b). Table 13 summarises these conclusions.

With climate forecasts predicting increasingly dry conditions (CSIRO 2009), low groundwater levels are likely to persist and water levels in Lake Yonderup are anticipated to remain low. Consequently, although climate has been identified as the major cause of groundwater decline in the Gnangara Mound (Department of Water 2008c), the only viable management approach to improve groundwater levels is reducing the impact of land and water use.

Table 13 Factors affecting groundwater levels at bore 6162565 (Lake Yonderup staff gauge)

Model	**Factor**	**Extent of change in groundwater levels m**
CDFM	Abstraction (local private use)	–0.3
	Land use	Low
	Climate	–1.1
PRAMS	Base case	0 to 1
	Climate	0 to 1
	Water corporation abstraction	No change
	Private abstraction	No change
	Pine plantations	+ 0 to 1
	Native vegetation	+ 0 to 1

Source: Department of Water 2004a

Although the impacts of land use on water levels in the Yanchep groundwater area appear to be minimal (Department of Water 2008c), good land management practices may improve groundwater levels. Total abstraction in the Yanchep groundwater area, including private use, is estimated at approximately 2.7 GL/yr, with the greatest impact on lake levels related to abstraction immediately north of the lake and north-west of the lake for cave supplementation. Some impact may be caused by pumping for irrigation south-east of the lake. Reducing abstraction from these sources may help to increase both lake and groundwater levels.

Additional groundwater recharge could be provided by managing land use within the Yanchep groundwater area. The land uses affecting groundwater recharge related to water levels at Lake Yonderup are native vegetation (Yanchep National Park) and the Yanchep pine plantation (Department of Water 2008b). 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 (2008c) provide details on the effects of pine plantation management on groundwater levels. Under current contractual arrangements, pine plantations (*Pinus pinaster*) on the Gnangara Mound are scheduled to be cleared between 2002 and 2027 (Brown et al. 2009). The recommendation by Ranjan et al. (2009) to replace cleared pine plantations with annual grasslands should be implemented to improve groundwater recharge once forestry activities have ceased.

Changes to plantation management practices, including thinning, accelerated clearing and replacement with alternative species, may significantly reduce the impacts of pine forestry on groundwater levels and may contribute to increases in groundwater levels (Department of Water 2008c). To maximise groundwater recharge for Lake Yonderup, the move from pines to grasslands should be accelerated in the East Yanchep plantation area. In the interim, existing plantations should be managed to increase recharge by thinning established plantations. Increasing the fallow area to 30% to 42 % of the total plantation area should reduce water uptake sufficiently to negate the negative impacts of maturing pines on groundwater levels (URS Forestry 2008). The phasing out of *P. pinaster* should also be encouraged in the Yanchep plantation where possible, with replacement by alternative forestry species with lower water requirements (URS Forestry 2009).

A combination of reduced abstraction and improved forestry 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 Lake Yonderup and postpone the onset of severe, irreversible ecological changes. If groundwater levels can be increased to pre-2004 levels, lake levels should be restored sufficiently to meet the Ministerial criterion levels in the majority of years, preventing further ecological damage and possibly reversing the current decline in ecological condition.

8.3 Management recommendations

In order to meet the water management objectives of Lake Yonderup, groundwater levels will need to increase. As lake level is directly related to groundwater level, increasing groundwater levels will also restore lake levels, although the extent of groundwater increase required to meet the Ministerial criteria absolute summer minimum (5.90 m AHD) cannot be determined from the available data. Meeting this criterion would meet the ecological water requirements for maintaining lake water quality, sediments and aquatic fauna (Froend et al. 2004b).Given predictions of a continuing drier climate (CSIRO 2009), groundwater levels are anticipated to decrease further, putting further strain on the ecological values of Lake Yonderup.

The impacts of low groundwater levels on the ecological values of Lake Yonderup can be somewhat reduced through management actions taken to reduce the volume of abstraction in the Yanchep groundwater area and to manage surrounding land uses to maximise groundwater recharge. This would slow the rate of groundwater decline, decreasing the risk and severity of ecological impacts. However, restoring lake levels to meet the Ministerial criterion may not be possible due to the dominant influence of rainfall on groundwater levels.

Consequently, the management of Lake Yonderup should be revised to account for persistent low water levels. The acceptable levels of risk to the ecological values should be reviewed given the likely persistence of water levels below the EWRs for each ecological value, and the ability of the ecological value to recover should groundwater return to historical levels.

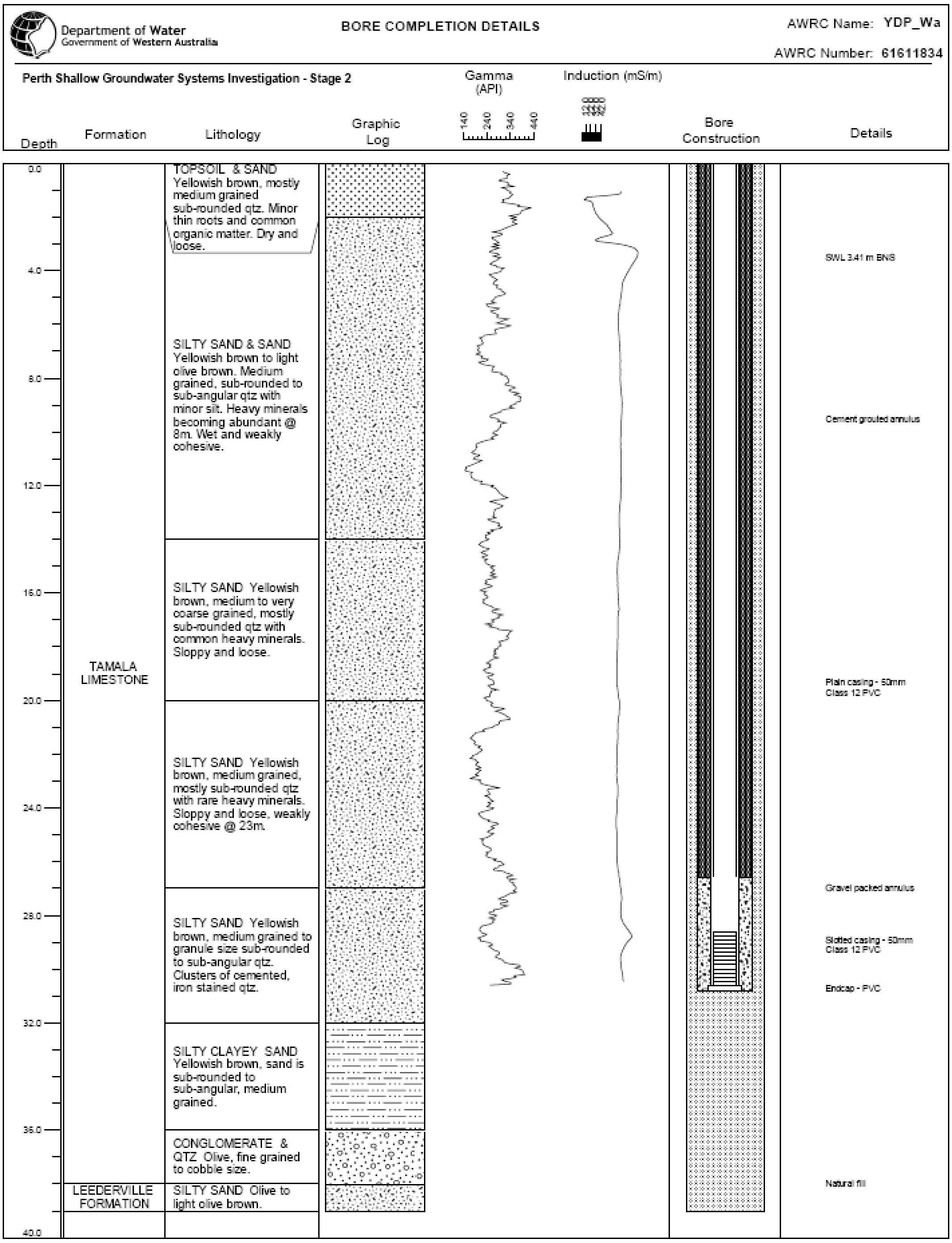
Based on our assessment of the EWRs of wetland vegetation species at Lake Yonderup, a water level of 5.48 m AHD at Bore YDP_SC should be sufficient to maintain the vegetation community at the southern transect within an acceptable level of risk based on the method described by Loomes (2000), cited in Froend et al. (2004b). However, this transect is not considered to be representative of vegetation close to the lake as it is not influenced by lake water. While the northern transect is located closer (with a minimum water level of 4.75 m AHD required to maintain the vegetation community), there is no monitoring bore associated with this site. As the vegetation community determines the fauna to a large extent (Froend et al. 2004b), protecting the vegetation should also help to preserve the macroinvertebrate, waterbird and terrestrial fauna associated with lake, despite low lake levels. Thus the adoption of the minimum vegetation EWR established in this report (4.75 m AHD) as an environmental water provision for Lake Yonderup is recommended, in addition to maintaining the existing EWRs and Ministerial criteria.

Given the hydrological connectivity of Lake Yonderup and Loch McNess (Horwitz et al. 2009a; WAWA 1995), any actions taken to restore water levels in Loch McNess would be expected to produce a lagged response in water levels in Lake Yonderup.

Consideration should be given to further investigation of the minimum water requirements for *B. littoralis*, as this species may have been lost from the southern vegetation transect before groundwater levels reached 5.48 m AHD. Note, however that this loss may have been in response to the summer 2004–05 fires and only indirectly linked to decreasing groundwater levels.

Appendices

Appendix A — Construction diagrams



Department of Water
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BORE COMPLETION DETAILS

AWRC Name: **YDP_Wa**
AWRC Number: **61611834**

Perth Shallow Groundwater Systems Investigation - Stage 2

TAMALA LIMESTONE

TOPSOIL & SAND Yellowish brown, mostly medium grained sub-rounded qtz. Minor thin roots and common organic matter. Dry and loose.

SILTY SAND & SAND Yellowish brown to light olive brown. Medium grained, sub-rounded to sub-angular qtz with minor silt. Heavy minerals becoming abundant @ 8m. Wet and weakly cohesive.

SILTY SAND Yellowish brown, medium to very coarse grained, mostly sub-rounded qtz with common heavy minerals. Sloppy and loose.

SILTY SAND Yellowish brown, medium grained, mostly sub-rounded qtz with rare heavy minerals. Sloppy and loose, weakly cohesive @ 23m.

SILTY SAND Yellowish brown, medium grained to granule size sub-rounded to sub-angular qtz. Clusters of cemented, iron stained qtz.

SILTY CLAYEY SAND Yellowish brown, sand is sub-rounded to sub-angular, medium grained.

CONGLOMERATE & QTZ Olive, fine grained to cobble size.

LEEDERVILLE FORMATION

SILTY SAND Olive to light olive brown.

Drilled by:	Great Southern Drilling	Northing (Z50):	6508046.73	Screens (m BNS):	28.62 - 30.62
Date drilled:	4/1/08	Easting (Z50):	375094.63	SWL (m BNS):	3.41
Logged by:	Josephine Searle	Surface (m AHD):	7.43	EC (mS/m):	34200
Aquifer:	Superficial	Drill depth (m BNS):	39	pH:	7.5

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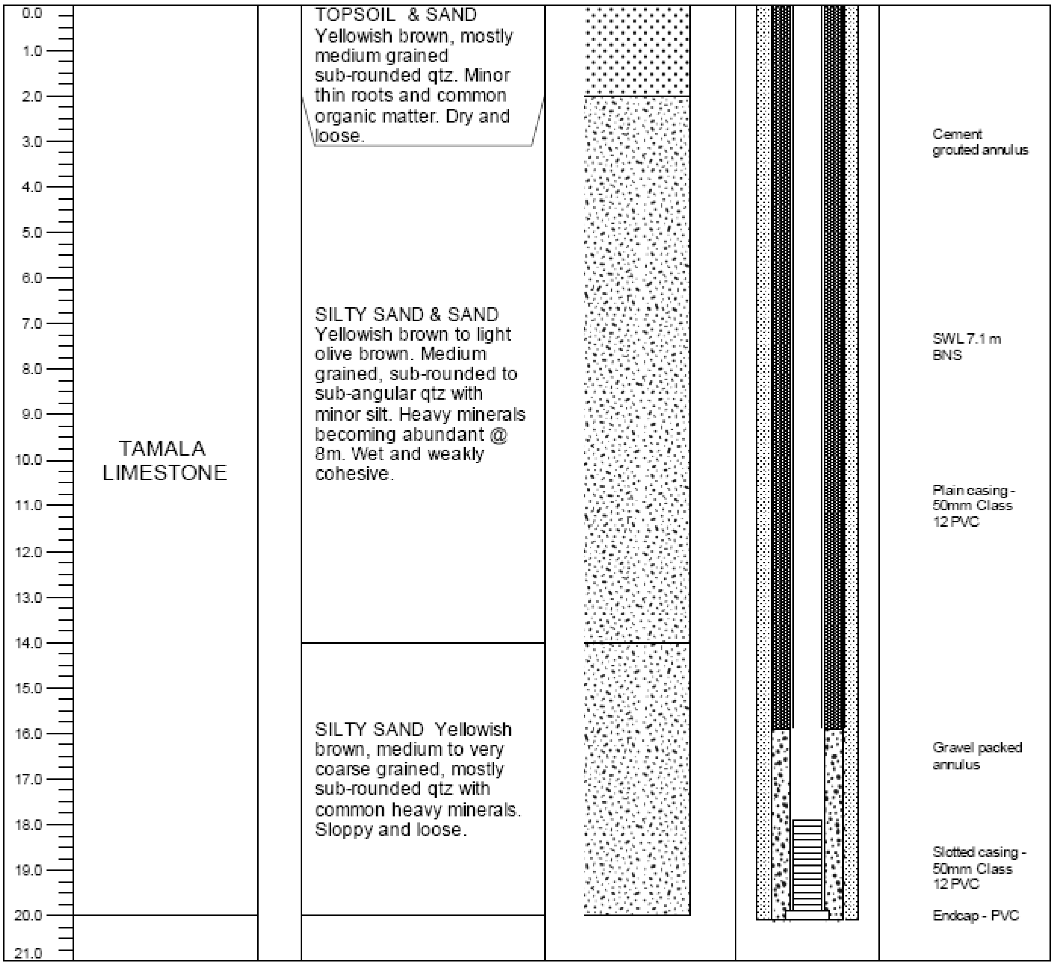
Government of **Western Australia**

BORE COMPLETION DETAILS

AWRC Name: **YDP_Wb**
AWRC Number: **61611835**

Perth Shallow Groundwater Systems Investigation - Stage 2

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



TAMALA LIMESTONE

TOPSOIL & SAND Yellowish brown, mostly medium grained sub-rounded qtz. Minor thin roots and common organic matter. Dry and loose.

SILTY SAND & SAND Yellowish brown to light olive brown. Medium grained, sub-rounded to sub-angular qtz with minor silt. Heavy minerals becoming abundant @ 8m. Wet and weakly cohesive.

SILTY SAND Yellowish brown, medium to very coarse grained, mostly sub-rounded qtz with common heavy minerals. Sloppy and loose.

Cement grouted annulus

SWL 7.1 m BNS

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

Drilled by:	Great Southern Drilling	Northing (Z50):	6508046.81	Screens (m BNS):	17.87 - 19.87
Date drilled:	4/8/08	Easting (Z50):	375093.64	SWL (m BNS):	7.1
Logged by:	Josephine Searle	Surface (m AHD):	7.42	EC (uS/m):	34700
Aquifer:	Superficial	Drill depth (m BNS):	20	pH:	7.1

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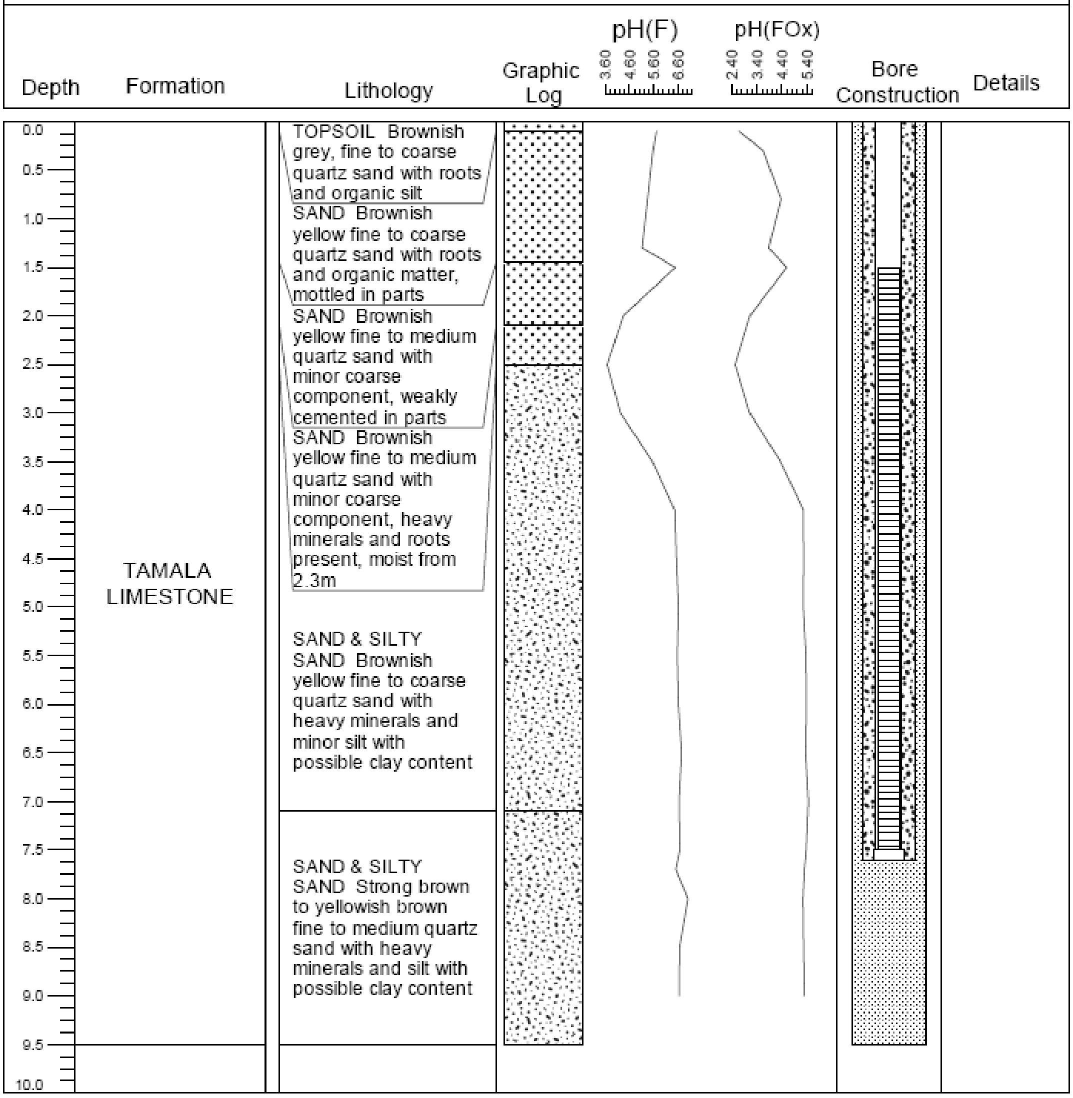
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **YDP_Wc**
AWRC Number: **61611836**

Perth Shallow Groundwater Systems Investigation - Stage 2



TOPSOIL Brownish grey, fine to coarse quartz sand with roots and organic silt

SAND Brownish yellow fine to coarse quartz sand with roots and organic matter, mottled in parts

SAND Brownish yellow fine to medium quartz sand with minor coarse component, weakly cemented in parts

SAND Brownish yellow fine to medium quartz sand with minor coarse component, heavy minerals and roots present, moist from 2.3m

SAND & SILTY SAND Brownish yellow fine to coarse quartz sand with heavy minerals and minor silt with possible clay content

SAND & SILTY SAND Strong brown to yellowish brown fine to medium quartz sand with heavy minerals and silt with possible clay content

Drilled by:	Great Southern Drilling	Northing (Z50):	6508047.03	Screens (m BNS):	1.49 - 7.49
Date drilled:	4/8/08	Easting (Z50):	375091.65	SWL (m BNS):	6.8
Logged by:	Josephine Searle	Surface (m AHD):	7.37	EC (uS/m):	49300
Aquifer:	Superficial	Drill depth (m BNS):	9.5	pH:	6.8

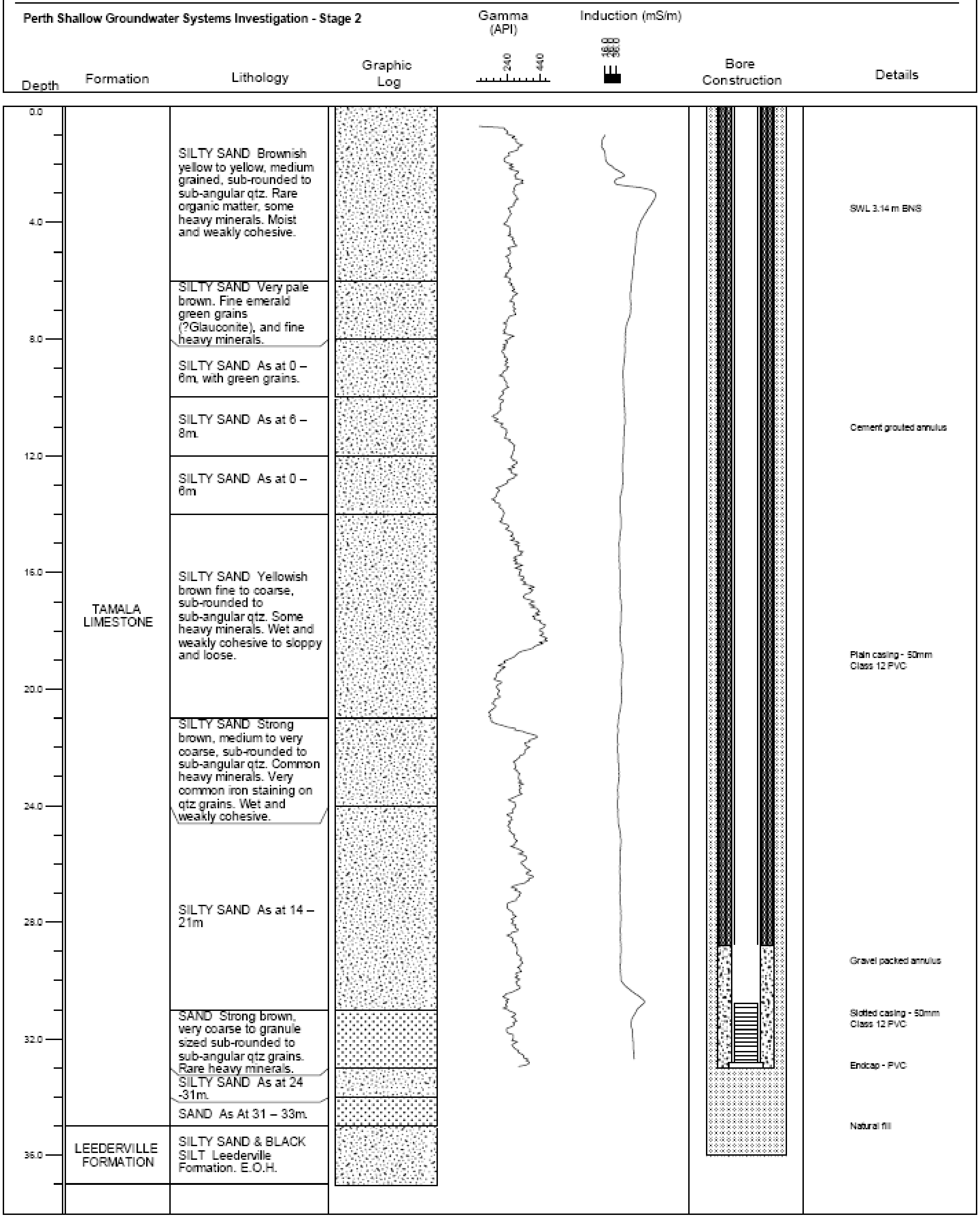
Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **YDP_Ea**
AWRC Number: **61611837**

Perth Shallow Groundwater Systems Investigation - Stage 2

Formation	Lithology
TAMALA LIMESTONE	SILTY SAND Brownish yellow to yellow, medium grained, sub-rounded to sub-angular qtz. Rare organic matter, some heavy minerals. Moist and weakly cohesive.
	SILTY SAND Very pale brown. Fine emerald green grains (?Glauconite), and fine heavy minerals.
	SILTY SAND As at 0 – 6m, with green grains.
	SILTY SAND As at 6 – 8m.
	SILTY SAND As at 0 – 6m
	SILTY SAND Yellowish brown fine to coarse, sub-rounded to sub-angular qtz. Some heavy minerals. Wet and weakly cohesive to sloppy and loose.
	SILTY SAND Strong brown, medium to very coarse, sub-rounded to sub-angular qtz. Common heavy minerals. Very common iron staining on qtz grains. Wet and weakly cohesive.
	SILTY SAND As at 14 – 21m
	SAND Strong brown, very coarse to granule sized sub-rounded to sub-angular qtz grains. Rare heavy minerals.
	SILTY SAND As at 24 -31m.
	SAND As At 31 – 33m.
LEEDERVILLE FORMATION	SILTY SAND & BLACK SILT Leederville Formation. E.O.H.



Drilled by:	Great Southern Drilling	Northing (Z50):	6507835.74	Screens (m BNS):	30.82 - 32.82
Date drilled:	4/2/08	Easting (Z50):	375508.66	SWL (m BNS):	3.14
Logged by:	Josephine Searle	Surface (m AHD):	9.34	EC (mS/m):	34000
Aquifer:	Superficial	Drill depth (m BNS):	37	pH:	7.7

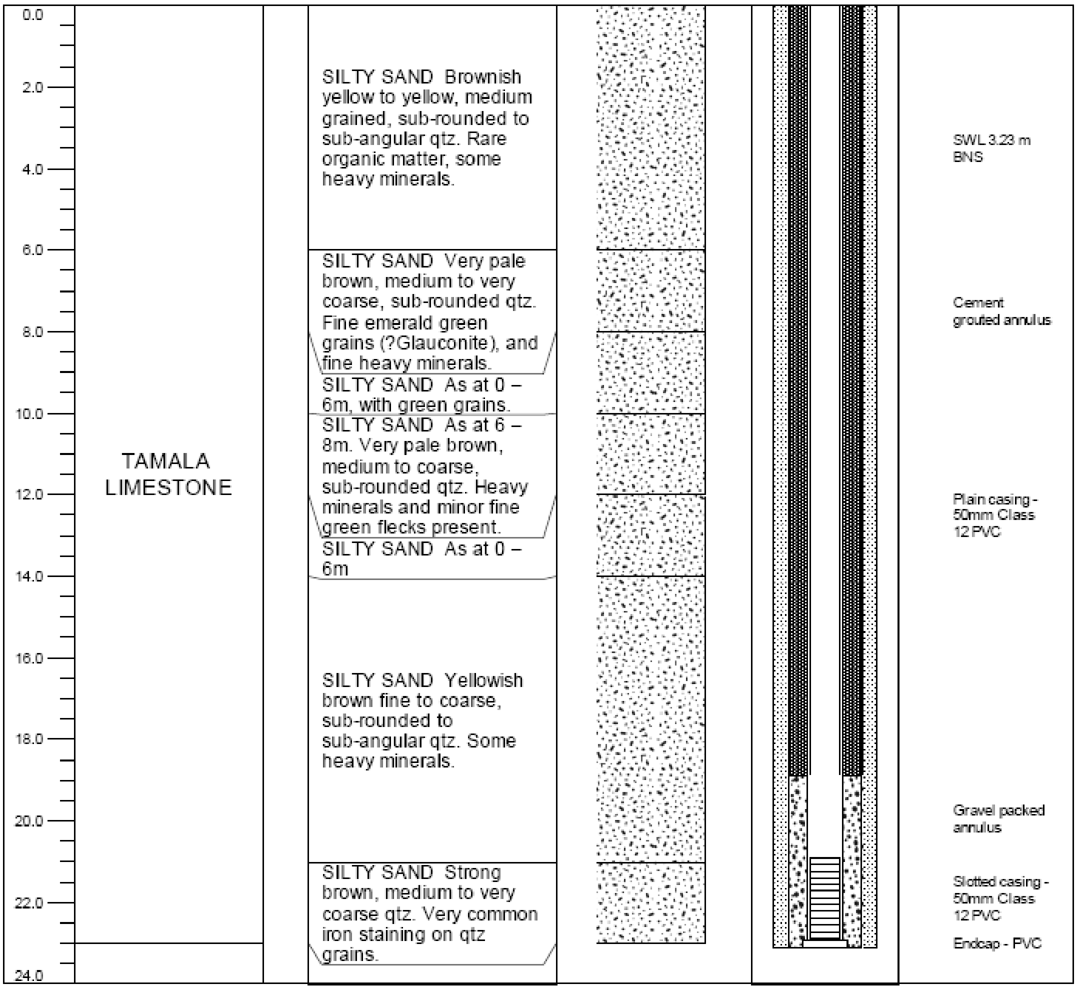
Department of **Water**
Government of **Western Australia**

BORE COMPLETION DETAILS

AWRC Name:	**YDP_Eb**
AWRC Number:	**61611838**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Formation	Lithology	Graphic Log	Bore Construction	Details



SILTY SAND Brownish yellow to yellow, medium grained, sub-rounded to sub-angular qtz. Rare organic matter, some heavy minerals.

SILTY SAND Very pale brown, medium to very coarse, sub-rounded qtz. Fine emerald green grains (?Glauconite), and fine heavy minerals.

SILTY SAND As at 0 – 6m, with green grains.

SILTY SAND As at 6 – 8m. Very pale brown, medium to coarse, sub-rounded qtz. Heavy minerals and minor fine green flecks present.

SILTY SAND As at 0 – 6m

SILTY SAND Yellowish brown fine to coarse, sub-rounded to sub-angular qtz. Some heavy minerals.

SILTY SAND Strong brown, medium to very coarse qtz. Very common iron staining on qtz grains.

SWL 3.23 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

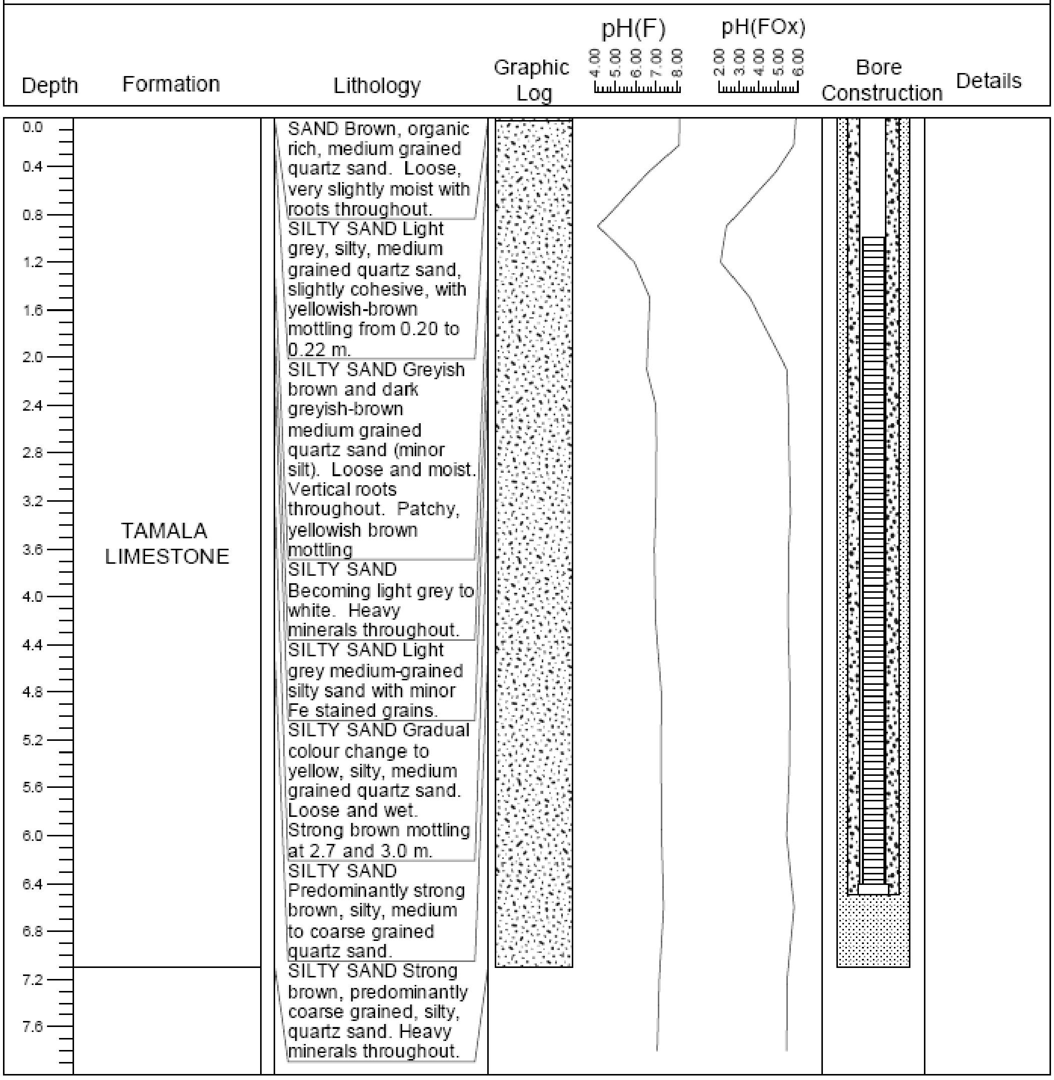
Drilled by:	Great Southern Drilling	Northing (Z50):	6507835.89	Screens (m BNS):	20.89 - 22.89
Date drilled:	4/8/08	Easting (Z50):	375509.62	SWL (m BNS):	3.23
Logged by:	Josephine Searle	Surface (m AHD):	9.34	EC (uS/m):	6750
Aquifer:	Superficial	Drill depth (m BNS):	23	pH:	7.8

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **YDP_Sc**
AWRC Number: **61611840**

Perth Shallow Groundwater Systems Investigation - Stage 2



SAND Brown, organic rich, medium grained quartz sand. Loose, very slightly moist with roots throughout.

SILTY SAND Light grey, silty, medium grained quartz sand, slightly cohesive, with yellowish-brown mottling from 0.20 to 0.22 m.

SILTY SAND Greyish brown and dark greyish-brown medium grained quartz sand (minor silt). Loose and moist. Vertical roots throughout. Patchy, yellowish brown mottling

SILTY SAND Becoming light grey to white. Heavy minerals throughout.

SILTY SAND Light grey medium-grained silty sand with minor Fe stained grains.

SILTY SAND Gradual colour change to yellow, silty, medium grained quartz sand. Loose and wet. Strong brown mottling at 2.7 and 3.0 m.

SILTY SAND Predominantly strong brown, silty, medium to coarse grained quartz sand.

SILTY SAND Strong brown, predominantly coarse grained, silty, quartz sand. Heavy minerals throughout.

Drilled by:	Great Southern Drilling	Northing (Z50):	6507336.72	Screens (m BNS):	1 - 7
Date drilled:	4/21/08	Easting (Z50):	375398.8	SWL (m BNS):	2.29
Logged by:	Sandie McHugh	Surface (m AHD):	6.27	EC (uS/m):	21300
Aquifer:	Superficial	Drill depth (m BNS):	7.1	pH:	7.1

Appendix B — Sampling methods and analysis

Groundwater sampling methodology

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

Low flow bladder pump and water quality procedures

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

Results are recorded on a Field Observation Form for submission to 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 are collected by wading close to installed staff gauges, flushing bottles three times with lake water and filling from 10cm below the surface. *In situ* field parameters and surface water levels were also recorded.

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

Field pH testing methods

After Ahern et al. (1998), modified from the Department of Environment and Conservation (2006).

Field pH testing

Before sampling:

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

Field pH_F and pH_{FOX} testing

1. Take ½ teaspoon of sediment sample approximately every 25 cm or when a lithology change is noted (whichever is lesser), noting the depth of the sample.
2. Place into beaker used for pH_F tests and add 12 ml of water from a clean syringe (marked pH_F) to make a 1:5 soil:water solution and shake well.
3. Take another ½ teaspoon sized sample of sediment from the same place as the previous sample used for the pH_F measurement, and place into a beaker used for measuring pH_{FOX}.
4. Add 12 ml of pH adjusted 30% hydrogen peroxide using a second syringe (marked H_{FOX}) to make a 1:5 soil:peroxide solution, and shake well.
5. Repeat above steps until entire core has been sampled.
6. Shake all beakers well and leave for approximately 1 hour (during which time logging of cores can be done).

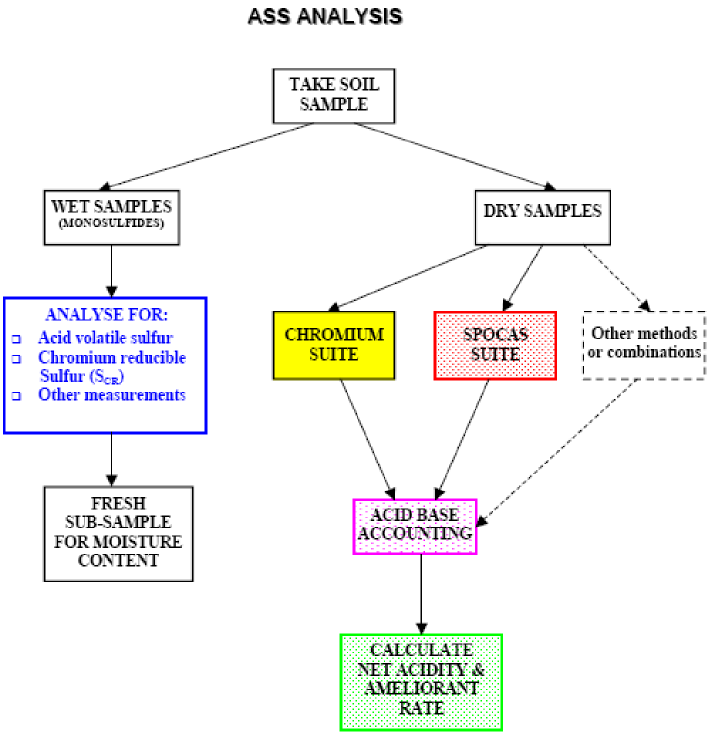
7. Regularly shake (i.e. every 5 to 10 minutes) all beakers to ensure maximum amount of sediment goes into solution.
8. After 1 hour record pH_F and H_{FOX} readings, taking all pH_F measurements first (to ensure no contamination with peroxide and also to allow maximum time for peroxide to react with the sediments). Clean pH probe with distilled water between each reading.
9. Dispose of solutions into an appropriate container (although hydrogen peroxide rapidly decomposes to water and oxygen so is not harmful to the environment) and thoroughly clean all beakers, syringes and other equipment using Decon (detergent) and water.

Laboratory methods

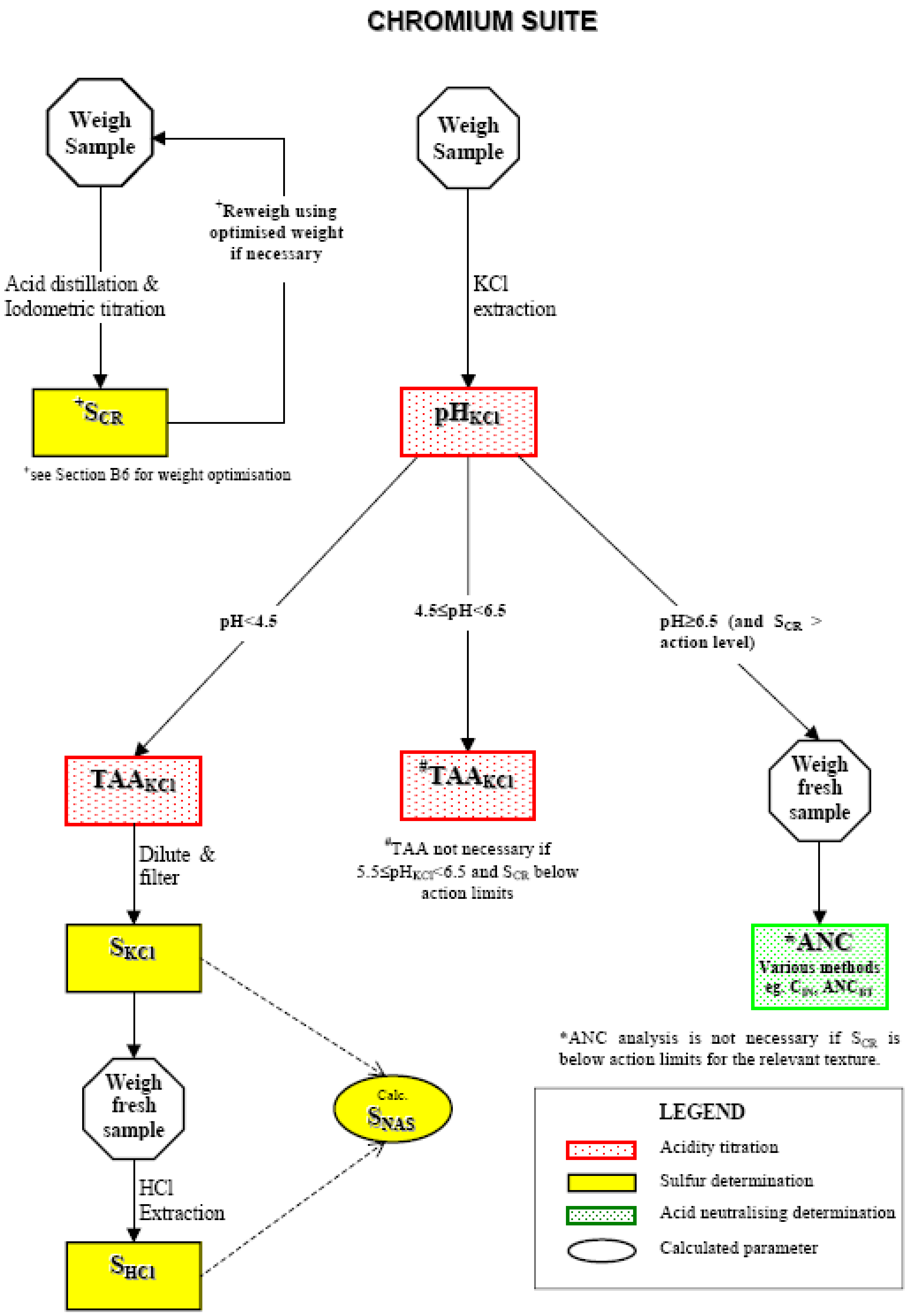
After Ahern et al. 2004.

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

The metal and metalloids samples were prepared and digested with HNO_3/HCl at 100^{o}C for two hours and diluted prior to analysis. The concentrations of acid extractable elements in sediments were determined by 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.

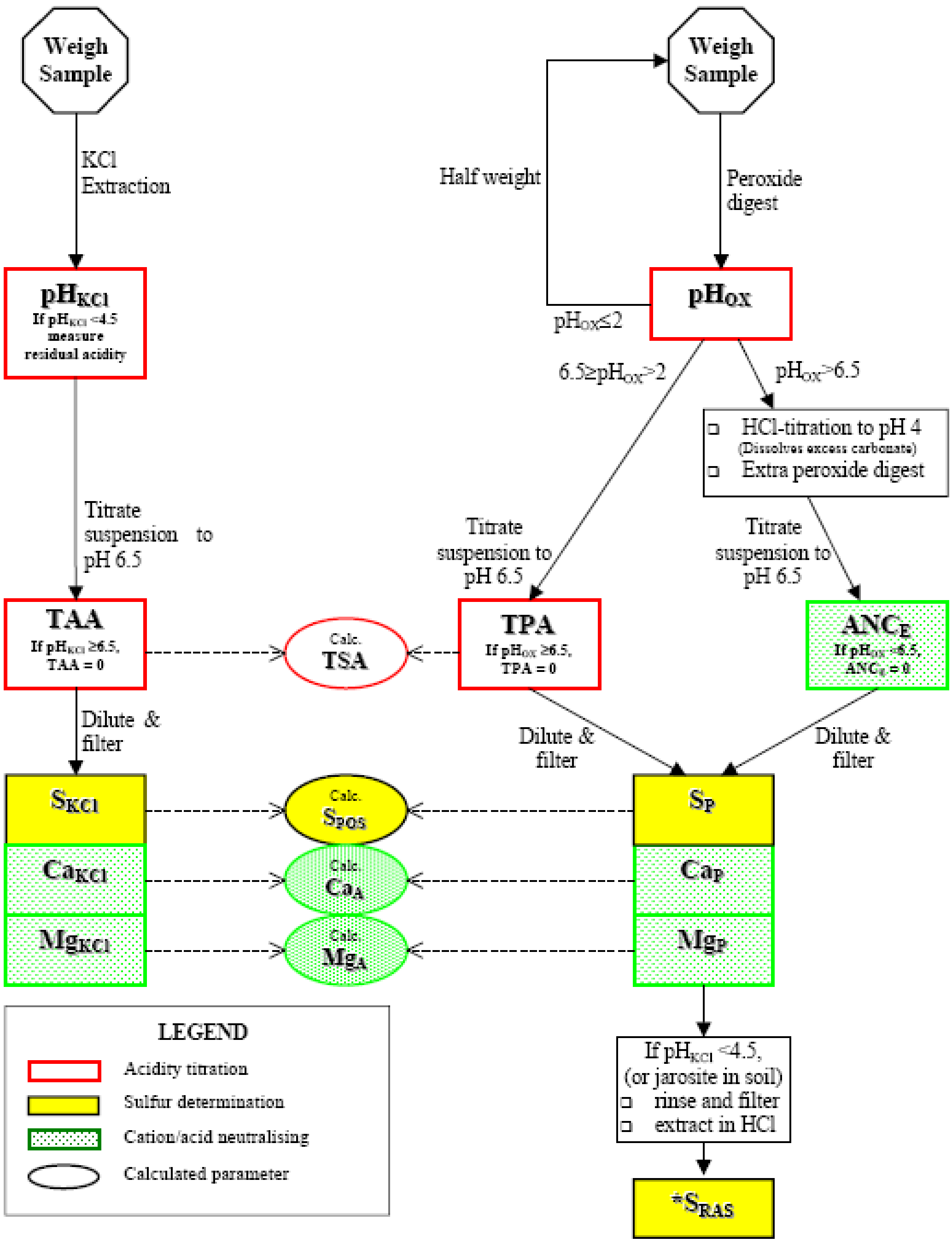


Flow diagram for overall methods used in the quantitative analyses of acid sulfate soils (from Ahern et al. *1998).*



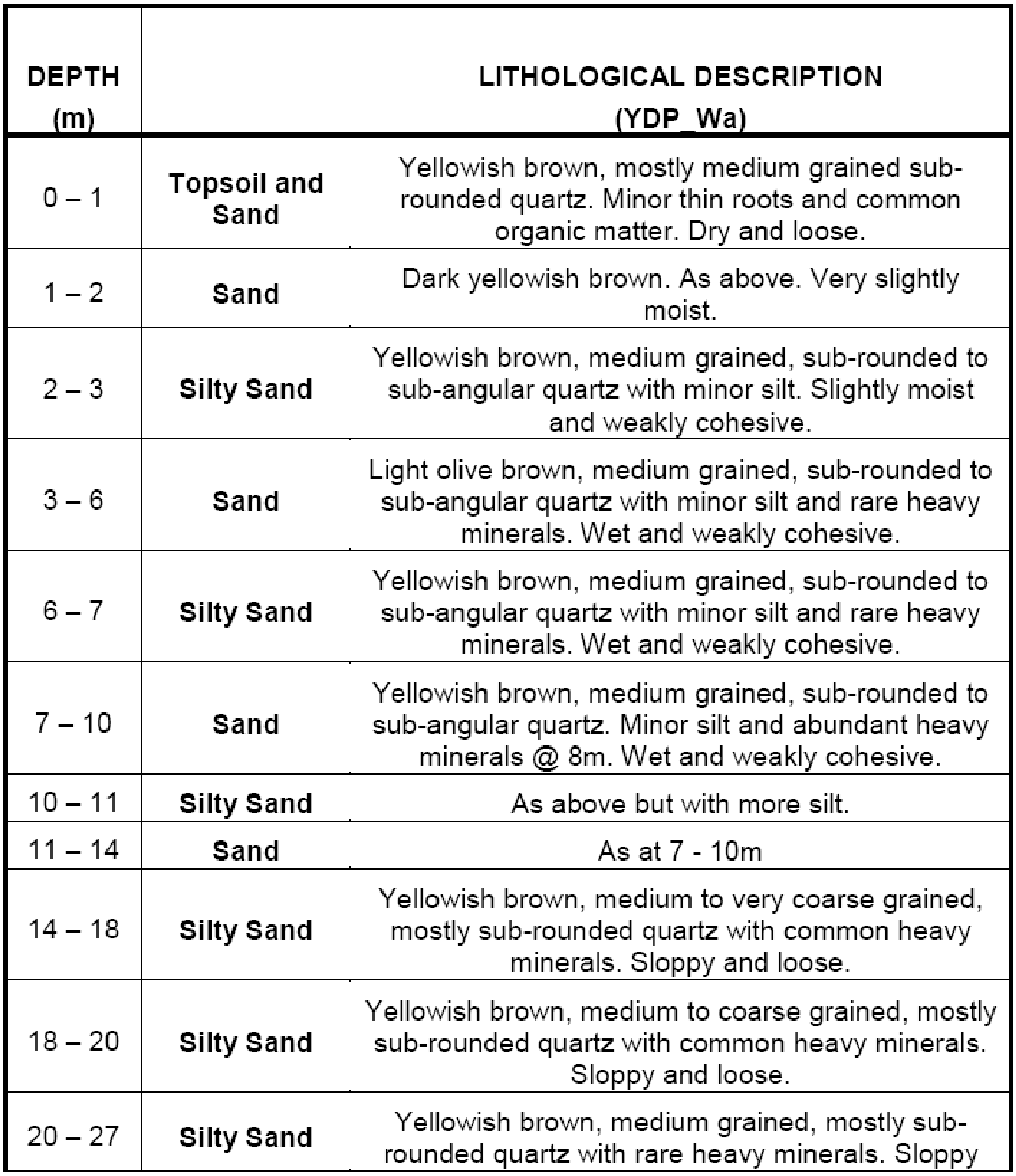
Flow diagram of steps involved using the chromium suite (from Ahern et al. *1998).*

SPOCAS: FLOW DIAGRAM

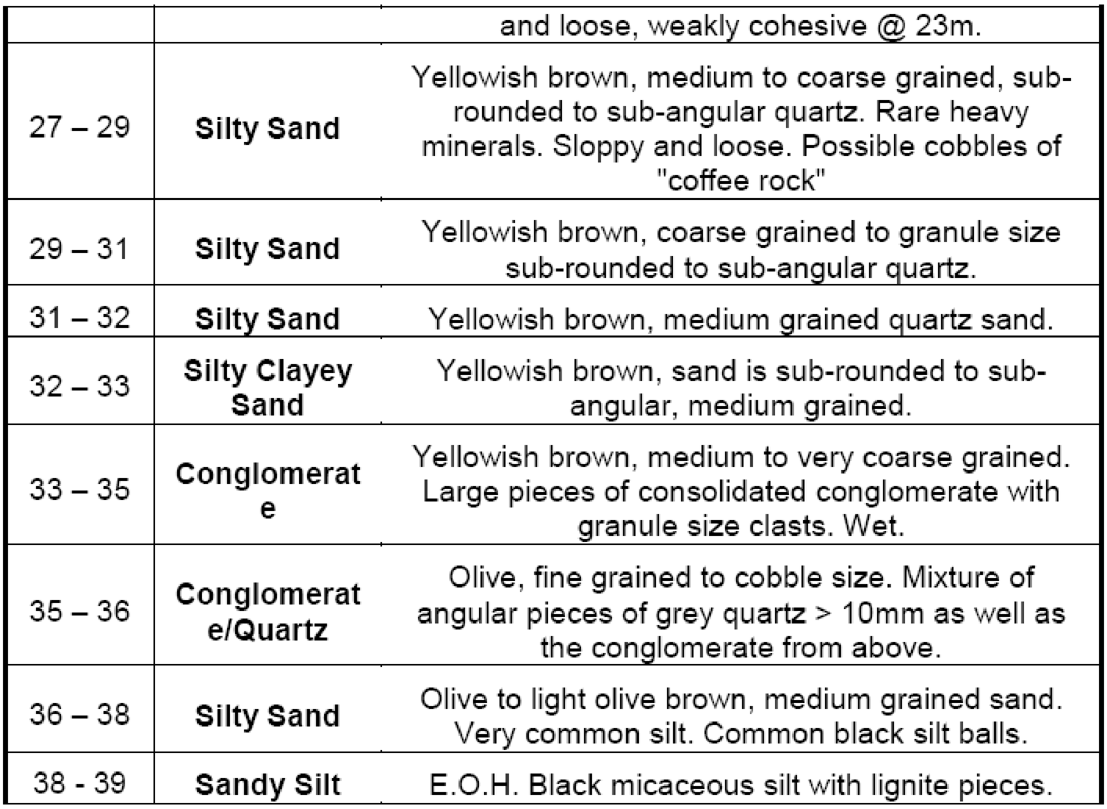


Flow diagram of steps involved in analysis using the SPOCAS suite (from Ahern et al. *1998).*

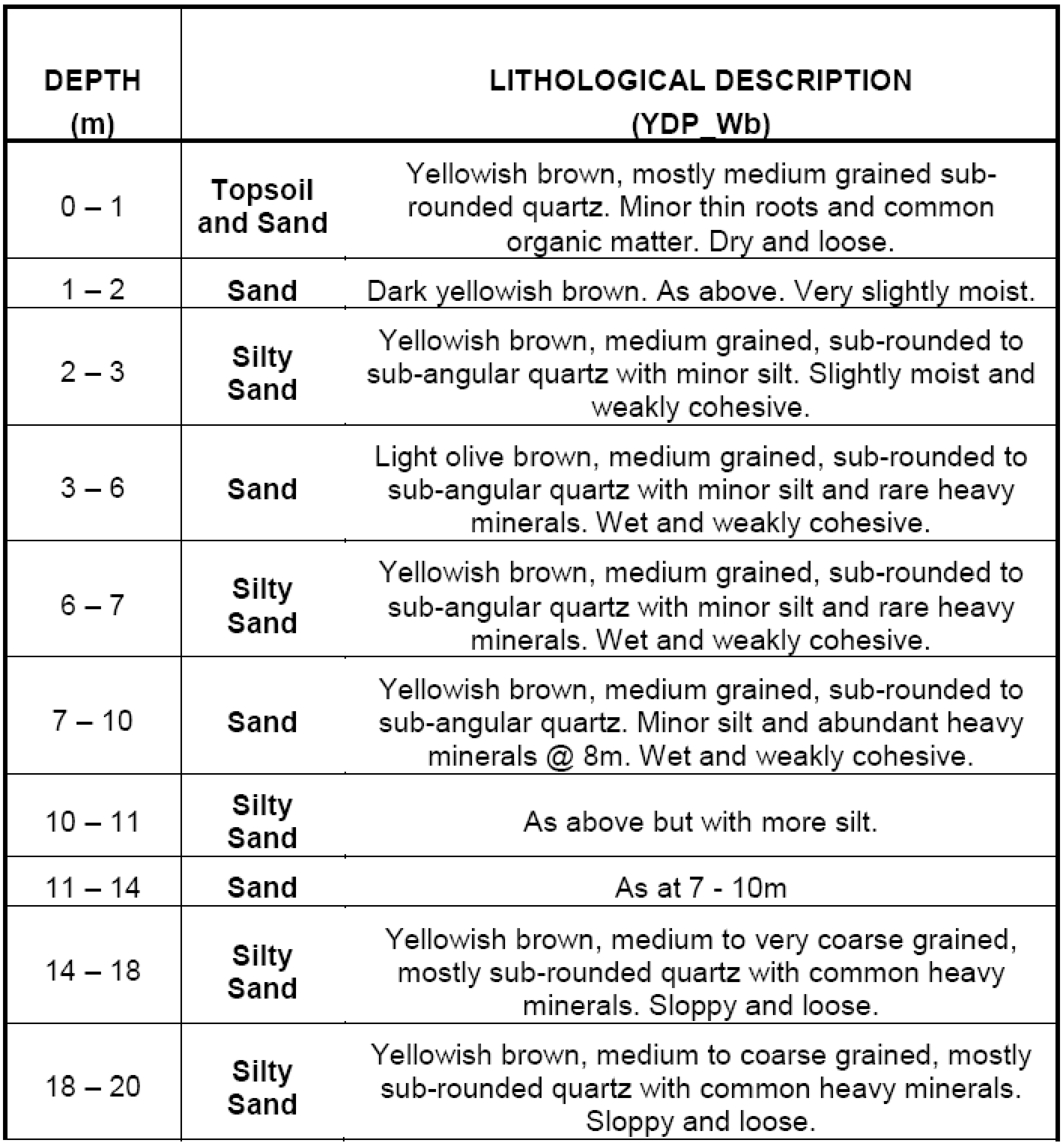
Appendix C — SGS investigation bore lithology logs



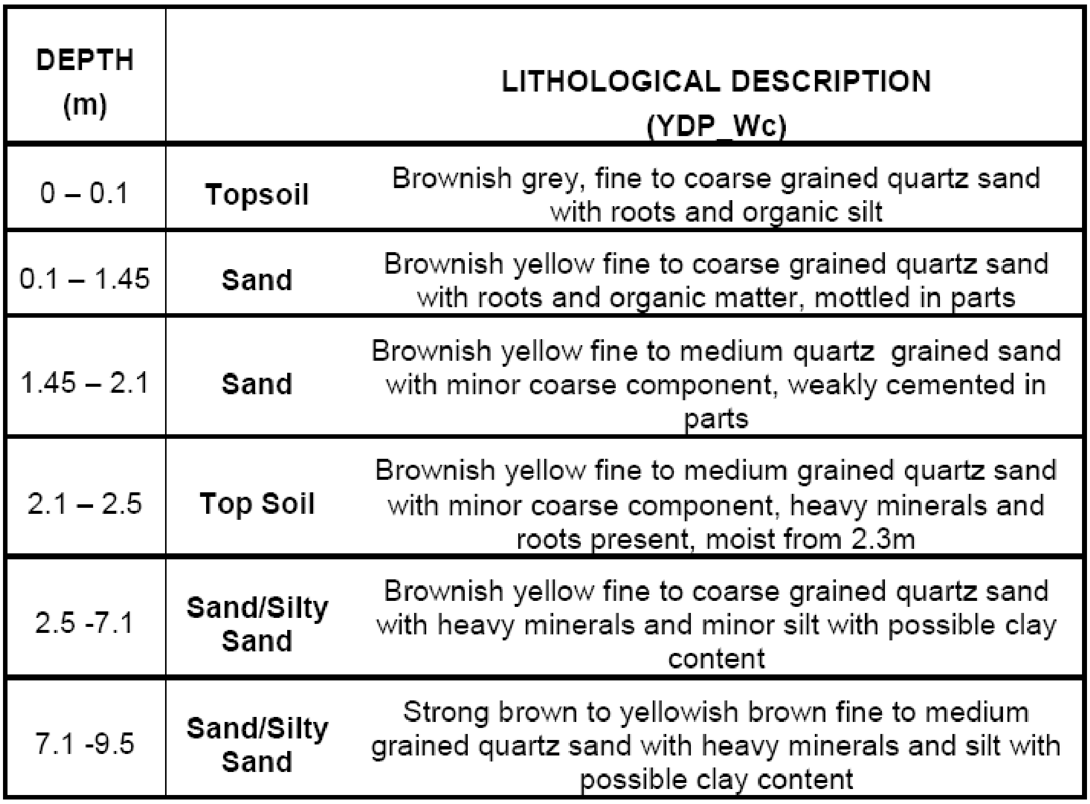
DEPTH (m)	LITHOLOGICAL DESCRIPTION (YDP_Wa)	
0 – 1	**Topsoil and Sand**	Yellowish brown, mostly medium grained sub-rounded quartz. Minor thin roots and common organic matter. Dry and loose.
1 – 2	**Sand**	Dark yellowish brown. As above. Very slightly moist.
2 – 3	**Silty Sand**	Yellowish brown, medium grained, sub-rounded to sub-angular quartz with minor silt. Slightly moist and weakly cohesive.
3 – 6	**Sand**	Light olive brown, medium grained, sub-rounded to sub-angular quartz with minor silt and rare heavy minerals. Wet and weakly cohesive.
6 – 7	**Silty Sand**	Yellowish brown, medium grained, sub-rounded to sub-angular quartz with minor silt and rare heavy minerals. Wet and weakly cohesive.
7 – 10	**Sand**	Yellowish brown, medium grained, sub-rounded to sub-angular quartz. Minor silt and abundant heavy minerals @ 8m. Wet and weakly cohesive.
10 – 11	**Silty Sand**	As above but with more silt.
11 – 14	**Sand**	As at 7 - 10m
14 – 18	**Silty Sand**	Yellowish brown, medium to very coarse grained, mostly sub-rounded quartz with common heavy minerals. Sloppy and loose.
18 – 20	**Silty Sand**	Yellowish brown, medium to coarse grained, mostly sub-rounded quartz with common heavy minerals. Sloppy and loose.
20 – 27	**Silty Sand**	Yellowish brown, medium grained, mostly sub-rounded quartz with rare heavy minerals. Sloppy



		and loose, weakly cohesive @ 23m.
27 – 29	**Silty Sand**	Yellowish brown, medium to coarse grained, sub-rounded to sub-angular quartz. Rare heavy minerals. Sloppy and loose. Possible cobbles of "coffee rock"
29 – 31	**Silty Sand**	Yellowish brown, coarse grained to granule size sub-rounded to sub-angular quartz.
31 – 32	**Silty Sand**	Yellowish brown, medium grained quartz sand.
32 – 33	**Silty Clayey Sand**	Yellowish brown, sand is sub-rounded to sub-angular, medium grained.
33 – 35	**Conglomerate**	Yellowish brown, medium to very coarse grained. Large pieces of consolidated conglomerate with granule size clasts. Wet.
35 – 36	**Conglomerate/Quartz**	Olive, fine grained to cobble size. Mixture of angular pieces of grey quartz > 10mm as well as the conglomerate from above.
36 – 38	**Silty Sand**	Olive to light olive brown, medium grained sand. Very common silt. Common black silt balls.
38 - 39	**Sandy Silt**	E.O.H. Black micaceous silt with lignite pieces.



DEPTH (m)	LITHOLOGICAL DESCRIPTION (YDP_Wb)	
0 – 1	**Topsoil and Sand**	Yellowish brown, mostly medium grained sub-rounded quartz. Minor thin roots and common organic matter. Dry and loose.
1 – 2	**Sand**	Dark yellowish brown. As above. Very slightly moist.
2 – 3	**Silty Sand**	Yellowish brown, medium grained, sub-rounded to sub-angular quartz with minor silt. Slightly moist and weakly cohesive.
3 – 6	**Sand**	Light olive brown, medium grained, sub-rounded to sub-angular quartz with minor silt and rare heavy minerals. Wet and weakly cohesive.
6 – 7	**Silty Sand**	Yellowish brown, medium grained, sub-rounded to sub-angular quartz with minor silt and rare heavy minerals. Wet and weakly cohesive.
7 – 10	**Sand**	Yellowish brown, medium grained, sub-rounded to sub-angular quartz. Minor silt and abundant heavy minerals @ 8m. Wet and weakly cohesive.
10 – 11	**Silty Sand**	As above but with more silt.
11 – 14	**Sand**	As at 7 - 10m
14 – 18	**Silty Sand**	Yellowish brown, medium to very coarse grained, mostly sub-rounded quartz with common heavy minerals. Sloppy and loose.
18 – 20	**Silty Sand**	Yellowish brown, medium to coarse grained, mostly sub-rounded quartz with common heavy minerals. Sloppy and loose.

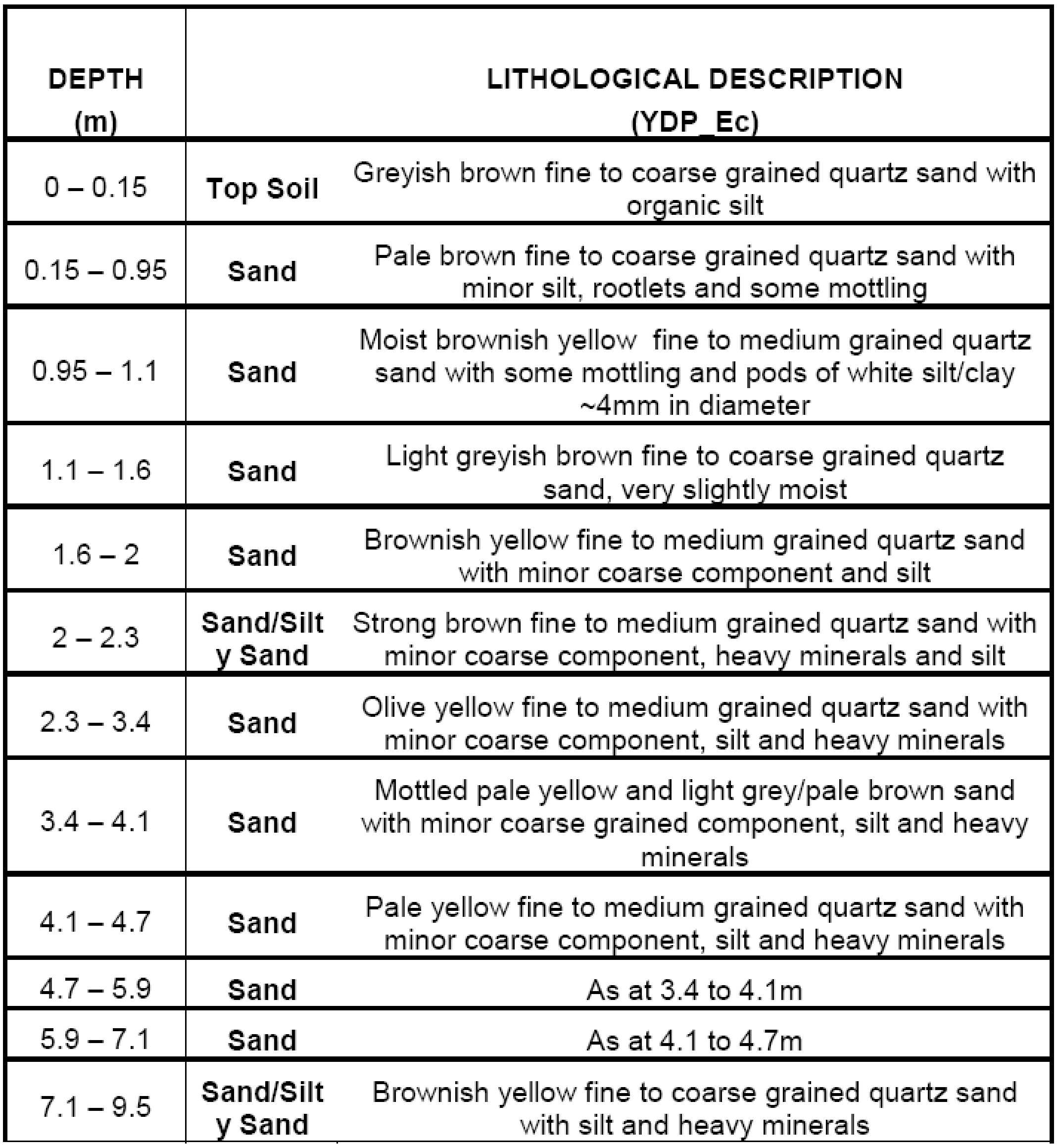


DEPTH (m)	**LITHOLOGICAL DESCRIPTION (YDP_Wc)**	
0 – 0.1	**Topsoil**	Brownish grey, fine to coarse grained quartz sand with roots and organic silt
0.1 – 1.45	**Sand**	Brownish yellow fine to coarse grained quartz sand with roots and organic matter, mottled in parts
1.45 – 2.1	**Sand**	Brownish yellow fine to medium quartz grained sand with minor coarse component, weakly cemented in parts
2.1 – 2.5	**Top Soil**	Brownish yellow fine to medium grained quartz sand with minor coarse component, heavy minerals and roots present, moist from 2.3m
2.5 -7.1	**Sand/Silty Sand**	Brownish yellow fine to coarse grained quartz sand with heavy minerals and minor silt with possible clay content
7.1 -9.5	**Sand/Silty Sand**	Strong brown to yellowish brown fine to medium grained quartz sand with heavy minerals and silt with possible clay content

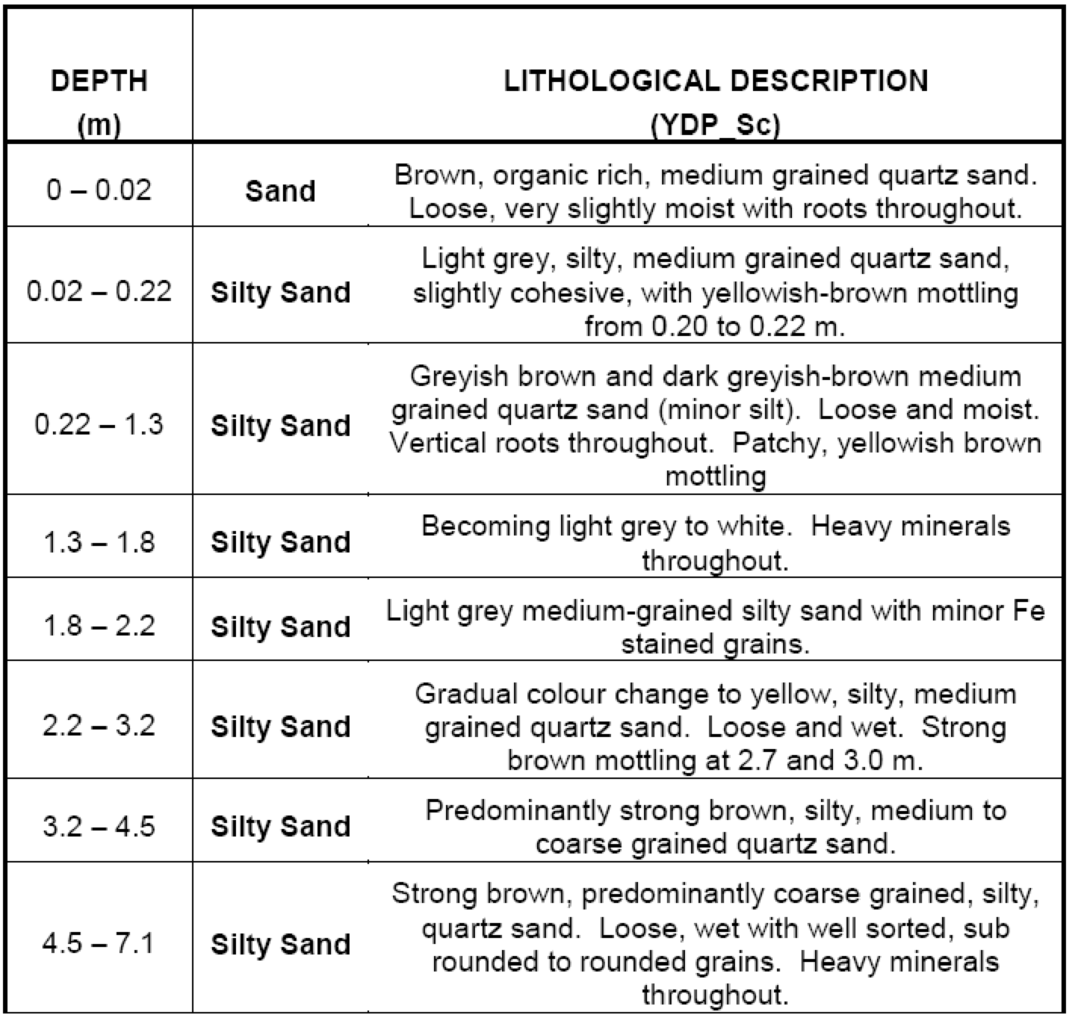
DEPTH (m)	**LITHOLOGICAL DESCRIPTION (YDP_Ea)**	
0 – 1	**Topsoil and Sand**	Brownish yellow, medium to coarse grained, sub-rounded quartz. Some organic matter. Very slightly moist, very weakly cohesive.
1 - 4	**Silty Sand**	Brownish yellow, medium grained, sub-rounded to sub-angular quartz. Rare organic matter, some heavy minerals. Moist and weakly cohesive.
4 - 6	**Silty Sand**	Yellow, coarse to medium grained, sub-rounded to sub-angular quartz. Rare organic matter, some heavy minerals. Wet and cohesive.
6 - 8	**Silty Sand**	Very pale brown, medium to very coarse grained, sub-rounded quartz. Fine emerald green grains (?Glauconite), and fine heavy minerals. Wet and cohesive.
8 – 9	**Silty Sand**	As @ 1 - 4m. Green (?Glauconite) flecks.
9 - 10	**Silty Sand**	Yellow, medium grained quartz with green flecks. Sloppy and loose.
10 - 12	**Silty Sand**	Very pale brown, medium to coarse grained, sub-rounded quartz. Heavy minerals and minor fine green flecks present. Wet and weakly cohesive.
12 - 14	**Silty Sand**	Brownish yellow, medium grained, sub-rounded to sub-angular quartz. Some heavy minerals. Wet and weakly cohesive.
14 - 21	**Silty Sand**	Yellowish brown fine to coarse grained, sub-rounded to sub-angular quartz. Some heavy minerals. Wet and weakly cohesive to sloppy and loose.

21 - 24	**Silty Sand**	Strong brown, medium to very coarse grained, sub-rounded to sub-angular quartz. Common heavy minerals. Very common iron staining on quartz grains. Wet and weakly cohesive.
24 - 31	**Silty Sand**	Yellowish brown fine to medium grained, sub-rounded (to sub-angular) quartz. Some heavy minerals. Wet and weakly cohesive. Becoming coarser grained at base.
31 – 33	**Sand**	Strong brown, very coarse grained to granule sized sub-rounded to sub-angular quartz grains. Rare heavy minerals. Wet and weakly cohesive.
33 – 34	**Silty Sand**	As @ 28 - 31m
34 - 35	**Sand**	As @ 31 - 33m
35 - 37	**Silty Sand and Black Silt**	E.O.H.

DEPTH (m)	**LITHOLOGICAL DESCRIPTION (YDP_Eb)**	
0 – 1	**Topsoil and Sand**	Brownish yellow, medium to coarse grained, sub-rounded quartz. Some organic matter. Very slightly moist, very weakly cohesive.
1 - 4	**Silty Sand**	Brownish yellow, medium grained, sub-rounded to sub-angular quartz. Rare organic matter, some heavy minerals. Moist and weakly cohesive.
4 - 6	**Silty Sand**	Yellow, coarse to medium grained, sub-rounded to sub-angular quartz. Rare organic matter, some heavy minerals. Wet and cohesive.
6 - 8	**Silty Sand**	Very pale brown, medium to very coarse grained, sub-rounded quartz. Fine emerald green grains (?Glauconite), and fine heavy minerals. Wet and cohesive.
8 – 9	**Silty Sand**	As @ 1 - 4m. Green (?Glauconite) flecks.
9 - 10	**Silty Sand**	Yellow, medium grained quartz with green flecks. Sloppy and loose.
10 - 12	**Silty Sand**	Very pale brown, medium to coarse grained, sub-rounded quartz. Heavy minerals and minor fine green flecks present. Wet and weakly cohesive.
12 - 14	**Silty Sand**	Brownish yellow, medium grained, sub-rounded to sub-angular quartz. Some heavy minerals. Wet and weakly cohesive.
14 - 21	**Silty Sand**	Yellowish brown fine to coarse grained, sub-rounded to sub-angular quartz. Some heavy minerals. Wet and weakly cohesive to sloppy and loose.
21 – 23	**Silty Sand**	Strong brown, medium to very coarse grained, sub-rounded to sub-angular quartz. Common heavy minerals. Very common iron staining on quartz grains. Wet and weakly cohesive.



DEPTH (m)	LITHOLOGICAL DESCRIPTION (YDP_Ec)	
0 – 0.15	**Top Soil**	Greyish brown fine to coarse grained quartz sand with organic silt
0.15 – 0.95	**Sand**	Pale brown fine to coarse grained quartz sand with minor silt, rootlets and some mottling
0.95 – 1.1	**Sand**	Moist brownish yellow fine to medium grained quartz sand with some mottling and pods of white silt/clay ~4mm in diameter
1.1 – 1.6	**Sand**	Light greyish brown fine to coarse grained quartz sand, very slightly moist
1.6 – 2	**Sand**	Brownish yellow fine to medium grained quartz sand with minor coarse component and silt
2 – 2.3	**Sand/Silty Sand**	Strong brown fine to medium grained quartz sand with minor coarse component, heavy minerals and silt
2.3 – 3.4	**Sand**	Olive yellow fine to medium grained quartz sand with minor coarse component, silt and heavy minerals
3.4 – 4.1	**Sand**	Mottled pale yellow and light grey/pale brown sand with minor coarse grained component, silt and heavy minerals
4.1 – 4.7	**Sand**	Pale yellow fine to medium grained quartz sand with minor coarse component, silt and heavy minerals
4.7 – 5.9	**Sand**	As at 3.4 to 4.1m
5.9 – 7.1	**Sand**	As at 4.1 to 4.7m
7.1 – 9.5	**Sand/Silty Sand**	Brownish yellow fine to coarse grained quartz sand with silt and heavy minerals



DEPTH (m)	LITHOLOGICAL DESCRIPTION (YDP_Sc)	
0 – 0.02	**Sand**	Brown, organic rich, medium grained quartz sand. Loose, very slightly moist with roots throughout.
0.02 – 0.22	**Silty Sand**	Light grey, silty, medium grained quartz sand, slightly cohesive, with yellowish-brown mottling from 0.20 to 0.22 m.
0.22 – 1.3	**Silty Sand**	Greyish brown and dark greyish-brown medium grained quartz sand (minor silt). Loose and moist. Vertical roots throughout. Patchy, yellowish brown mottling
1.3 – 1.8	**Silty Sand**	Becoming light grey to white. Heavy minerals throughout.
1.8 – 2.2	**Silty Sand**	Light grey medium-grained silty sand with minor Fe stained grains.
2.2 – 3.2	**Silty Sand**	Gradual colour change to yellow, silty, medium grained quartz sand. Loose and wet. Strong brown mottling at 2.7 and 3.0 m.
3.2 – 4.5	**Silty Sand**	Predominantly strong brown, silty, medium to coarse grained quartz sand.
4.5 – 7.1	**Silty Sand**	Strong brown, predominantly coarse grained, silty, quartz sand. Loose, wet with well sorted, sub rounded to rounded grains. Heavy minerals throughout.

Appendix D — Acid sulfate soils laboratory and field results

Borehole ID	Soil texture	Field pH				
		Depth m	pH_F	pH_{FOX}	Δ pH	Reaction
YDP_Ec	light brown f to c qtz sand	0.20	5.73	3.85	-1.88	None
YDP_Ec	f to c qtz sand pale brown	0.50	5.73	4.44	-1.29	None
YDP_Ec	f to m qtz sand. Moist	1.00	6.18	4.64	-1.54	None
YDP_Ec	compacted f to qtz sand light brown	1.20	7.29	5.11	-2.18	None
YDP_Ec	as above, rootlets	1.50	7.56	5.16	-2.40	None
YDP_Ec	brownish yellow f to m qtz sand	1.90	7.54	5.27	-2.27	None
YDP_Ec	salty brown f to m qtz sand	2..2	8.04	5.69	-2.35	None
YDP_Ec	olive yellow f to m qtz sand	2.60	7.60	5.66	-1.94	None
YDP_Ec	as above	3.30	7.30	5.60	-1.70	None
YDP_Ec	mottled L grey / yellow f to m qtz sand	3.70	7.68	5.48	-2.20	None
YDP_Ec	pale yellow f to m qtz sand	4.10	7.57	5.45	-2.12	Slight
YDP_Ec	as above	4.40	7.57	5.43	-2.14	None
YDP_Ec	pale yellow f to m qtz sand	4.80	7.58	5.39	-2.19	None
YDP_Ec	as above	5.30	7.66	5.35	-2.31	None
YDP_Ec	as above	5.80	7.63	5.40	-2.23	None
YDP_Ec	as above	6.30	7.64	5.34	-2.30	None
YDP_Ec	as above	6.80	7.62	5.22	-2.40	None
YDP_Ec	brownish yellow f to c silty qtz sand	7.40	6.99	5.09	-1.90	None
YDP_Ec	as above	7.80	6.95	5.16	-1.79	None
YDP_Ec	as above	8.40	6.65	5.24	-1.41	None
YDP_Ec	as above	8.80	6.73	5.18	-1.55	None
YDP_Wc	Brown Grey top soil F to C Qtz w/ Org silt	0.10	5.70	2.68	-3.02	Slight
YDP_Wc	Orange F to C Qtz sand w/ rootlets and OM	0.30	5.57	3.65	-1.92	Slight

Borehole ID	**Soil texture**	**Field pH**				
		Depth m	**pH_F**	**pH_{FOX}**	**Δ pH**	**Reaction**
YDP_Wc	as above	0.80	5.35	4.36	-0.99	Slight
YDP_Wc	light orange / brown f to m qtz sand	1.30	5.11	3.86	-1.25	Slight
YDP_Wc	compacted dark orange mottled f to m qtz sand	1.50	6.49	4.58	-1.91	Moderate
YDP_Wc	Dark orange f to m qtz sand	2.00	4.35	3.12	-1.23	None
YDP_Wc	Orange / light brown f to m qtz sand	2.50	3.68	2.53	-1.15	None
YDP_Wc	as above with minor OM	3.00	4.22	3.10	-1.12	None
YDP_Wc	Orange F to C Qtz sand w/ rootlets and OM	3.50	5.55	4.34	-1.21	None
YDP_Wc	as above	4.00	6.46	5.25	-1.21	None
YDP_Wc	orange f to m qtz sand, minor cs	4.50	6.52	5.26	-1.26	None
YDP_Wc	as above	5.00	6.61	5.25	-1.36	None
YDP_Wc	as above	5.50	6.56	5.36	-1.20	None
YDP_Wc	as above	6.00	6.61	5.38	-1.23	None
YDP_Wc	as above	6.50	6.74	5.34	-1.40	None
YDP_Wc	as above	7.00	6.63	5.45	-1.18	None
YDP_Wc	f to m qtz sand, yellowish brown	7.50	6.67	5.37	-1.30	None
YDP_Wc	Strong brown f to m silty qtz sand	7.70	6.50	5.30	-1.20	Slight
YDP_Wc	f to m qtz sand, yellow	8.00	7.01	5.24	-1.77	None
YDP_Wc	as above , silty yellowish brown	8.50	6.66	5.26	-1.40	Slight
YDP_Wc		9.00	6.63	5.29	-1.34	None
YDP_Sc	Brown organic rich qtz sand	-	8.14	5.90	-2.24	Vigorous
YDP_Sc	light grey qtz sand	0.22	8.12	5.79	-2.33	slight
YDP_Sc	grey brown m qtz sand org rich in parts	0.45	6.63	4.87	-1.76	Slight
YDP_Sc	as above	0.90	4.16	2.37	-1.79	Slight
YDP_Sc	as above	1.20	5.94	2.08	-3.86	Volcanic

Borehole ID	Soil texture	Field pH				
		Depth m	pH_F	pH_{FOX}	Δ pH	Reaction
YDP_Sc	L grey m qtz sand	1.50	6.70	3.55	-3.15	Slight
YDP_Sc	yellow m qtz sand	2.10	6.55	5.44	-1.11	Slight
YDP_Sc	as above	2.40	7.00	5.52	-1.48	Slight
YDP_Sc	as above	2.70	7.03	5.54	-1.49	Slight
YDP_Sc	strong brown silty sand	3.30	7.00	5.64	-1.36	Slight
YDP_Sc	strong brown silty qtz sand	3.60	6.93	5.53	-1.40	Slight
YDP_Sc	as above	4.20	6.98	5.50	-1.48	Slight
YDP_Sc	as above	4.80	7.27	5.61	-1.66	Slight
YDP_Sc	as above	5.40	7.25	5.58	-1.67	Slight
YDP_Sc	as above	6.00	7.28	5.43	-1.85	Slight
YDP_Sc	as above	6.60	7.38	5.81	-1.57	Slight
YDP_Sc	as above	7.20	7.17	5.46	-1.71	Slight
YDP_Sc	Yellow silty m / c qtz sand	7.80	7.07	5.42	-1.65	Slight

Client sample number	ANC $_E$ Excess acid neutralising capacity % $CaCO_3$	pH $_{KCl}$ pH of KCl extract	TAA Titratable actual acidity $molH^+/t$	TPA Titratable peroxide acidity $molH^+/t$	TSA (calc) Titratable sulfidic acidity $molH^+/t$	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
Limit of reporting	<0.05		<1	<1	<1	<0.1	<0.1	<0.01	<0.01
200709991		4.3	20	16	<1	<0.1	<0.1	0.01	<0.01
200709991		4.3	21	15	<1	<0.1	<0.1	0.02	<0.01
200709992		6.1	<1	<1	<1	<0.1	<0.1		
200709993		5.5	<1	<1	<1	<0.1	<0.1		

Client sample number	Net acidity as % S	Alternative calculation Net acidity as % S	Net acidity as $molH^+/t$	Alternative calculation Net acidity as $molH^+/t$	Soil Bulk density t/m^3
200709991	0.04	0.04	25	25	1
200709992	0.05	0.05	30	30	1
200709993	0	0	0	0	1
	0	0	0	0	1

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
Limit of reporting		<0.05		<1	<1	<1	<0.1	<0.1	<0.01
W08/08469	200803550	14	9.0	<1	<1	<1	6.3	<0.1	
W08/08470	200803551	0.75	8.8	<1	<1	<1	0.2	<0.1	
W08/08470-D	200803551	0.59	8.7	<1	<1	<1	0.4	<0.1	
W08/08471	200803552		6.2	<1	69	68	<0.1	<0.1	
W08/08472	200803553		3.9	7	3	<1	<0.1	<0.1	<0.01
W08/08473	200803554		4.0	4	<1	<1	<0.1	<0.1	<0.01
W08/08474	200803555		5.3	1	<1	<1	<0.1	<0.1	

NMI lab number	Client sample number	Net acidity	Alternative calculation	Net acidity	Alternative calculation			Soil		Alternative calculation
			Net acidity		Net acidity	Fineness factor	Safety factor	Bulk density	Liming rate for ag lime	Liming rate for ag lime
		as % S	as % S	as mol H^+/ t	as mol H^+/ t			t/ m^3	kg $CaCO_3$/ t	kg $CaCO_3$/ t
Limit of reporting										
8469	200803550	0.04	0.04	25	25	1.5	1.5	1.0	1.9	1.9
8470	200803551	0.05	0.05	30	30	1.5	1.5	1.0	2.4	2.4
8470-D	200803551	0.00	0.00	0	0	1.5	1.5	1.0	0.0	0.0
8471	200803552	0.00	0.00	0	0	1.5	1.5	1.0	0.0	0.0

Site ref no.	**Date collected**	**Aluminium**	**Arsenic**	**Cadmium**	**Chromium**	**Iron**	**Manganese**
		mg/kg	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**	**mg/kg**
		NT2_49	NT2_49	NT2_49	NT2_49	NT2_49	NT2_49
YDP_SC	08-Apr-08	2280	41	<0.5	11	9090	5.9
YDP_SC	08-Apr-08	3430	3.8	<0.5	16	2240	3.5
YDP_SC	08-Apr-08						
YDP_SC	08-Apr-08	3300	2.8	<0.5	15	1420	2.9
LXA_WC	09-Apr-08	12	<0.5	<0.5	<0.5	23	<0.5
LXA_WC	09-Apr-08	7.6	<0.5	<0.5	<0.5	16	<0.5
LXA_WC	09-Apr-08	3.9	<0.5	<0.5	<0.5	11	<0.5

Site ref no.	**Date collected**	**Nickel**	**Selenium**	**Zinc**	**Total solids**	**ANC bt as $CaCO_3$**	**ANC e as $CaCO_3$**	**pH $_{KCl}$**	**pH ox**	**Scr**
		mg/kg	**mg/kg**	**mg/kg**	**%**	**%**	**%**			**%**
Limit of reporting						<0.05				<0.01
YDP_SC	08-Apr-08	1.2	<0.5	1.1	88.1		14	9	8.6	<0.01
YDP_SC	08-Apr-08	1.6	<0.5	3.1	85	1.4	0.75	8.8	7.3	0.1
YDP_SC	08-Apr-08					0.9	0.59	8.7	7.5	0.1
YDP_SC	08-Apr-08	1.7	1.8	1.3	86.6			6.2	2.7	0.07
LXA_WC	09-Apr-08	<0.5	<0.5	1.9	98.8			3.9	3.7	<0.01
LXA_WC	09-Apr-08	<0.5	<0.5	0.84	99.3			4	3.3	<0.01
LXA_WC	09-Apr-08	<0.5	<0.5	0.65	88.3			5.3	4.5	<0.01

Site Ref No.	**TAA**	**TPA**	**TSA (calc)**	**$\mathrm{Ca_{A}}$ (calc)**	**$\mathrm{Ca_{KCl}}$**	**$\mathrm{Ca_{P}}$**	**$\mathrm{Mg_{A}}$ (calc)**	**$\mathrm{Mg_{KCl}}$**	**$\mathrm{Mg_{P}}$**	**$\mathrm{S_{HCl}}$**	**$\mathrm{S_{KCl}}$**	**$\mathrm{S_{NaS}}$ (calc)**	**$\mathrm{S_{P}}$**	**$\mathrm{S_{POS}}$ (calc)**
	molH/t	**molH/t**	**molH/t**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Limit of reporting	<1	<1	<1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01
YDP_SC	<1	<1	<1	6.3	0.3	6.6	<0.1	<0.1	<0.1		<0.01		WL28 1-23D	WL28 1-23E
YDP_SC	<1	<1	<1	0.2	0.2	0.4	<0.1	<0.1	<0.1		0.02		0.03	0.02
YDP_SC	<1	<1	<1	0.4	0.2	0.6	<0.1	<0.1	<0.1		0.02		0.16	0.14
YDP_SC	<1	69	68	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		0.02		0.18	0.15
LXA_WC	7	3	<1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01	<0.01	0.13	0.11
LXA_WC	4	<1	<1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01
LXA_WC	1	<1	<1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		<0.01		<0.01	<0.01
													<0.01	<0.01

Site ref no.	Date collected	Aluminium mg/kg	Arsenic mg/kg	Cadmium mg/kg	Chromium mg/kg	Iron mg/kg	Manganese mg/kg	Nickel mg/kg	Selenium mg/kg	Zinc mg/kg
61611836	12-Mar-08	1270	1.3	<0.5	5	1210	2.1	<0.5	<0.5	0.85
61611836	12-Mar-08									
61611836	12-Mar-08	6000	4.4	<0.5	33	5400	7.3	2	<0.5	1
61611839	12-Mar-08	5130	1.3	<0.5	25	3690	5.7	2.1	<0.5	1

Site ref no.	Date collected	Total solids	pH $_{KCl}$	pH ox	S $_{Cr}$	TAA	TPA	TSA (calc)	Ca $_{A}$ (calc)	Ca $_{KCl}$	Ca $_{P}$
		%			%	molH/t	molH/t	molH/t	%	%	%
Limit of reporting					<0.01	<1	<1	<1	<0.1	<0.1	<0.1
61611836	12-Mar-08	69.5	4.3	3.3	<0.01	20	16	<1	<0.1	<0.1	<0.1
61611836	12-Mar-08		4.3	3.3	<0.01	21	15	<1	<0.1	<0.1	<0.1
61611836	12-Mar-08	86.5	6.1	6.3	<0.01	<1	<1	<1	<0.1	<0.1	<0.1

Site ref no.	Date collected	Mg_{A} (calc) %	Mg_{KCl} %	Mg_{P} %	S_{HCl} %	S_{KCl} %	S_{NaS} (calc) %	S_{P} %	S_{POS} (calc) %
Limit of reporting		<0.1	<0.1	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01
61611836	12-Mar-08	<0.1	<0.1	<0.1	0.04	0.02	0.01	0.02	<0.01
61611836	12-Mar-08	<0.1	<0.1	<0.1	0.04	0.02	0.02	0.02	<0.01
61611836	12-Mar-08	<0.1	<0.1	<0.1		<0.01		<0.01	<0.01
61611839	12-Mar-08	<0.1	<0.1	<0.1		<0.01		<0.01	<0.01

Shortened forms

ABA	Acid-base accounting
AHD	Australian height datum
ANC	Acid neutralising capacity
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agricultural and Resource Management Council of Australia and New Zealand
bns	Below natural surface (below ground level)
CALM	Former Department of Conservation and Land Management
CRS	Chromium reducible sulfur suite of analyses
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DIA	Department of Indigenous Affairs
EC	Electrical conductivity
EWP	Environmental water provision
EWR	Ecological water requirement
NHMRC	National Health & Medical Research Council
NRMMC	Natural Resource Management Ministerial Council
PRAMS	Perth regional aquifer modelling system
SGS	Shallow groundwater systems
SPOCAS	Suspension peroxide oxidation combined acidity and sulfur suite of analyses
SRP	Soluble reactive phosphorus
TAA	Titratable actual acidity
TDS	Total dissolved salts
TPA	Titratable peroxide acidity

TSA	Titratable sulfidic acidity
WAWA	Water Authority of Western Australia

Glossary

Abstraction	The withdrawal of water from any water resource.
Acid buffering capacity	A measure of the resistance to changes in pH following the addition of an acid.
Acid neutralising capacity	A measure of the soil's ability to buffer acidity and resist the lowering of soil pH.
Acid sulfate soils	Naturally occurring, these are soils containing significant quantities of reduced sulfur (pyrite and other sulfides). When these soils are disturbed the reduced sulfur is oxidised resulting in the release of acidity and often toxic metals.
Acidification	The process by which soil, or water becomes more acidic (decreasing pH).
Actual acidity	The soluble and exchangeable acidity already present in the soil.
Algal blooms	The rapid excessive growth of algae, generally caused by high nutrient levels and favourable conditions. Can result in water column deoxygenation when the algae die.
Alkalinity	A measure of a solution's ability to resist changes in pH due to the addition of an acid. In natural waters this usually relates to the amount of bicarbonate, carbonate and hydroxide compounds present in the water.
Allocation limit	The volume of water set aside for annual licensed use.
Aquifer	A geological formation or group of formations able to receive, store and/or transmit large amounts of water.
Bore	A narrow, normally vertical hole drilled into a geological formation to monitor or withdraw groundwater from an aquifer (*see also* Well).
Buffer	A solution which resists changes in pH when a small amount of strong acid or base are added
Buffering capacity	*see* Acid-buffering capacity.

CDFM	‘Cumulative deviation from the mean’ – a technique for evaluating rainfall patterns.
Confined aquifer	A permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability, the hydraulic head being higher than the upper surface of the aquifer.
Confining bed	Sedimentary bed of very low hydraulic conductivity.
Contaminants	A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful effects to humans or the environment.
Dissolution	The process of dissolving a solid to produce a solution.
Drawdown	The difference between the elevation of the initial piezometric surface and its position after pumping or gravitational drainage.
Ecological water requirement	The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk).
Eutrophication	An excess of nutrients (nitrogen and phosphorus) in an ecosystem, often resulting in excessive primary production.
Evapotranspiration	The combined loss of water by evaporation and transpiration. Includes water evaporated from the soil surface and water transpired by plants.
Fault	A fracture in rocks or sediments along which there has been an observable displacement.
Fineness factor	A factor applied to the acid neutralising capacity to allow for the poor reactivity of coarser carbonate or other acid neutralising material.
Flux	Flow
Formation	A group of rocks or sediments that have certain characteristics in common, were deposited about the same geological period, and that constitute a convenient unit for description.

Groundwater	Water that occupies the pores within the rock or soil profile.
Groundwater-dependent ecosystem	An ecosystem that depends on groundwater for its existence and health.
Hydraulic	Pertaining to water motion.
Hydraulic gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction.
Ion	An atom which has lost or gained electrons and therefore carries an electrical charge.
Leach	Remove soluble matter by percolation of water.
Metalloid	An element whose properties are between those of metals and non-metals.
Neutralisation	The chemical reaction in which an acid and a base react to produce salt and water.
Oxidation	A process resulting in the loss of electrons from a chemical species accompanied by an increase in oxidation state. This process does not necessarily require the presence of oxygen.
pH	The negative logarithm of the concentration of hydrogen ions.
Potential sulfidic acidity	The latent acidity that will be released if the sulfide minerals in acid sulfate soil are fully oxidised.
Redox potential	In aqueous solutions, the reduction potential is the tendency of the solution to either gain or lose electrons and is measured in volts (V), millivolts (mV), or Eh (1 Eh = 1 mV mV). Because the absolute potentials are difficult to accurately measure, reduction potentials are defined relative to the standard hydrogen electrode which is arbitrarily given potential of 0.00 V.
Reduction	A process resulting in the gain of electrons by a chemical species accompanied by a decrease in oxidation state.

Retained acidity	The ‘less available’ fraction of the existing acidity which may be released slowly into the environment.
Salinity	A measure of the concentration of total dissolved solids in water. 0–500 mg/L fresh 500–1500 mg/L fresh to marginal 1500–3000 mg/L brackish > 3000 mg/L saline
Scarp	A line of cliffs (steep slopes) produced by faulting or by erosion.
Stressor	An agent, condition or other stimulus that causes stress to an organism or ecosystem.
Sulfate reduction	In the aquatic environment, the microbially catalysed process which converts sulfate to sulfide.
Surficial	Pertaining to the surface.
Toxicity	The degree to which a substance is able to damage an exposed organism.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Transpiration	The loss of water vapour from a plant, mainly through the leaves.
Trigger level	Concentrations of key indicators, above or below which there is a risk of adverse biological effects.
Unconfined aquifer	A permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure.
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.
Well	An opening in the ground made or used to obtain access to underground water. This includes soaks, wells, bores and excavations.

References

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

——, Stone, Y, & Blunden B 1998, *Acid sulphate soils assessment guidelines*, Published by the Acid Sulphate Soil Management Advisory Committee, Wollonbar, New South Wales.

ANZECC & ARMCANZ 2000, *Australian and New Zealand guidelines for Fresh and marine water quality. Volume 1: the guidelines*, Australian and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Appelo & Postma 2005, *Geochemistry, groundwater and pollution*, 2nd edn, A.A. Balkema Publishers, Leiden, The Netherlands.

Appleyard, SJ 2005, Acidification of the Superficial aquifer in the Perth region: Causes, distribution and information gaps, Progress report no. 3, unpublished discussion paper, Department of Environment, Perth.

Arnold, J 1990, *Jenny Arnold's Perth wetlands resource book, Environmental Protection Authority*, Perth.

Bekesi G, 2007, *Loch McNess Notes 17 May 2007*, Internal, Department of Water

Bertuch, M, Loomes, R & Froend, R 2004, *Wetland vegetation monitoring 2004 – survey of Gnangara wetlands*, report to the Department of Environment, Report no. 2004 – 15, Centre for Ecosystem Management, Edith Cowan University, Joondalup, Western Australia.

Bourke 2008, *Bore completion report for the shallow groundwater system investigation stage,* Department of Water, Perth.

Boyd, T, Loomes, R & Froend, R 2008, *Wetland vegetation monitoring 2007 – survey of Gnangara wetlands*, report to the Department of Environment, Report no. 2008 – 01, Centre for Ecosystem Management, Edith Cowan University, Joondalup, Western Australia.

Bridge, P 1969, 'Reports of trips to Wanneroo-Yanchep caves', *West Caver*, 9(6), pp. 124–5.

Brown PH, Sonneman T & Kinloch J 2009, *Ecological linkages within the pine plantation on the Gnangara groundwater system: A report to the Gnangara Sustainability Strategy*; Department of Environment and Conservation, Perth.

CALM 1999, *Yanchep National Park management plan 1989–1999*, Management Plan no.14, Department of Conservation and Land Management, Perth.

Clark JD & Horwitz P 2005, *Final annual report for the wetland macroinvertebrate monitoring program of the Gnangara Mound project – Spring 2004 to Summer*

2005, Report no. 2005, Centre for Ecosystem Management, Edith Cowan University, Joondalup, Western Australia.

Clifton C and Evans R 2001, ‘A framework to assess the environmental water requirements of groundwater dependent ecosystems’, *Proceedings of the Third Australian Stream Management Conference* (Eds Rutherford I, Sheldon F, Brierley G & Kenyon C) Brisbane, pp. 149–55.

CSIRO 2009, *Groundwater yields in south-west Western Australia: A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project*; CSIRO Water for a Healthy Country Flagship, Australia.

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

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

Department of Environment 2004, *Section 46 review of environmental conditions on management of the Gnangara and Jandakot Mounds. Stage 1: proposal for changes to conditions*, Resource Management Division, Department of Environment, Perth.

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

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

Department of Water 2006, *A summary of investigations into ecological water requirements of groundwater-dependent ecosystems in the South West groundwater areas*; Department of Water, Perth.

—— 2008a, Gnangara groundwater areas. Water management plan. Draft for public comment. Perth. WA, Australia.

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

——2008c, *Assessment of the declining groundwater levels in the Gnangara Groundwater Mound*, Department of Water, Perth.

——2009a, *Bore completion report for the shallow groundwater system investigation stage 2*,Department of Water, Perth.

——2009b, *Gnangara Sustainability Strategy Appendix 1 – Gnangara groundwater system zone plans*, Department of Water, Perth.

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

Fältmarsch, RM, Åström, ME & Vuori, KM 2008, ‘Environmental risks of metals mobilised from acid sulfate soils in Finland: a literature review’, *Boreal Environmental Research* 13, pp. 444–56.

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

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

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

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

Horwitz P, Sommer B & Hewitt P 2009b, ‘Chapter Five: wetlands – changes, losses and gains’ in Wilson B & Valentine E (Eds) 2009, *Biodiversity values and threatening processes on the Gnangara groundwater systems*, Department of Environment and Conservation, Perth.

——, Sommer B & Froend R 2009a, ‘Chapter four: wetlands and groundwater-dependent ecosystems’ in Wilson B & Valentine E (Eds) 2009, *Biodiversity values and threatening processes on the Gnangara groundwater systems*, Department of Environment and Conservation, Perth.

Indian Ocean Climate Initiative 2002, *Climate variability and change in south-west Western Australia,* Indian Ocean Climate Initiative Panel, Perth.

Judd S & Horwitz P 2009, *Annual report for the wetland macroinvertebrate monitoring program of the Gnangara Mound environmental monitoring project – Spring 2008 to Summer 2009*, Centre for Ecosystem Management, Edith Cowan University, Joondalup, Western Australia.

Krasnostein, AL & Oldham, CE 2004, ‘Predicting wetland water storage’, *Water Resources Research*, Vol. 40.

McArthur, WM and Bettenay, E 1960, *The development and distribution of soils of the Swan Coastal Plain, Western Australia*, CSIRO Soil Publication 16.

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

McHugh, SL & Bourke, SA 2007, *Management area review: shallow groundwater systems on Gnangara and Jandakot mounds, HG25*, Department of Water, Perth.

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

Pettit, N, Loomes, R & Froend, R 2007, *Wetland vegetation monitoring 2006 – survey of Gnangara wetlands*, report to the Department of Environment, Report no. 2007 – 03, Centre for Ecosystem Management, Edith Cowan University, Joondalup, Western Australia.

Ranjan R, Tapsuwan S, Elmahdi A & Kaczan D 2009, *Analysis of land and water use scenarios for the Gnangara groundwater system*, CSIRO: Water for a Healthy Country National Research Flagship, Canberra.

Rockwater 2003, *Report for the investigation of groundwater–wetland water level relationships study, Gnangara & Jandakot mounds*, Rockwater Pty Ltd, report for Department of Environment, Perth.

Rogan, R, Loomes, R & Froend, R 2006, *Wetland vegetation monitoring 2005 – survey of Gnangara wetlands*, report to the Department of Environment, Report no. 2006 – 01, Centre for Ecosystem Management, Edith Cowan University, Joondalup, Western Australia.

Sommer B & Horwitz P 2007, *Annual report for the wetland macroinvertebrate monitoring program of the Gnangara Mound environmental monitoring project – Spring 2006 to Summer 2007*, Report no. 2007/07, Centre for Ecosystem Management, Edith Cowan University, Joondalup, Western Australia.

Stumm, W & Morgan, J.J 1996, Aquatic Chemistry, Chemical Equilibria and Rates in Natural Waters, 3rd ed. John Wiley & sons, New York.

Townley, LR & Trefry, MG 2000, ‘Surface water–groundwater interaction near shallow circular lakes: Flow geometry in three dimensions’, *Water Resources Research* Vol. 36, No. 4, pp. 935–49.

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

URS Forestry 2008, *Assessment of silvicultural regimes for softwood plantations established on the Gnangara Mound,* final report to Forest Products Commission, URS Australia Pty Ltd, Lexia, Western Australia.

—— 2009, *Gnangara groundwater system plantation species assessment,* final report to Forest Products Commission, URS Australia Pty Ltd, Lexia, Western Australia.

Water Corporation 2004, *Yanchep National Park; Groundwater recharge to cave systems : Construction, development and pump-testing of Yanchep Cave bore 3/04*, Water Corporation, Perth.

Water Authority of Western Australia 1995, *Review of proposed changes to environmental conditions: Gnangara Mound water resources* (*section 46),* Water Authority of Western Australia, Perth.

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

—— 2008, *Indigenous heritage survey, metropolitan area Indigenous groups, Loch McNess – Wagardu – Yanchep National Park*, *Department of Water – Perth Shallow Groundwater Systems Project*, Department of Water, Perth.

Yesertener, C 2005, 'Impacts of climate, land and water use on declining groundwater levels in the Gnangara Groundwater Mound, Perth, Australia', *Australian Journal of Water Resources*, vol.8, pp. 143–52.

—, C 2008, *Assessment of the declining groundwater levels in the Gnangara Groundwater Mound, HG14*, Department of Water, Perth.

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