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Review of the Yellagonga Regional Park water quality monitoring program 2008-2014

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FINAL REPORT

Prepared for,

Cities of Joondalup and Wanneroo

Mine Water and Environment Research Centre

Centre for Ecosystem Management

Report No. 2014-10

1. MINE WATER AND ENVIRONMENT RESEARCH CENTRE

Founded at Edith Cowan University in 2008, the Mine Water and Environment Research (MiWER) Centre is headed by A/Prof Mark Lund. The research group has a focus on mine waters; particularly pit lakes formed from open-cut mining. The group's research also extends to the ecology and rehabilitation of all inland water bodies, natural and constructed. MiWER's aim is to further understanding of freshwater science using creative, cutting-edge technologies and innovative approaches for practically improving resource sustainability and environmental condition.

MiWER is also a member of the Centre for Ecosystem Management at Edith Cowan University. More information on MiWER and our current and previous projects can be found at www.miwer.org.

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2. ACKNOWLEDGEMENTS

The support of Lara O'Neill at the City of Joondalup and Tristan Bruyn at the City of Wanneroo has been greatly appreciated. Thanks to the Cities of Joondalup and Wanneroo for funding this work. Thanks to Edith Cowan University for the provision of in-kind and infrastructure support for the project.

3. FRONTISPIECE

Plate 1: Wallubuenup Swamp in the southern section of Yellagonga Regional Park

This report should be referenced as follows.

Lund, M.A., Wyse, L., Newport, M. & Gonzalez-Pinto, J. (2014). *Review of the Yellagonga Regional Park water quality monitoring program 2008-2014.* Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2014-10, Edith Cowan University, Perth, Australia. 83pp. Unpublished report to the Cities of Joondalup and Wanneroo.

4. EXECUTIVE SUMMARY

Monitoring the water quality of surface water located within Yellagonga Regional Park has been undertaken monthly since December 2010 as part of the Yellagonga Integrated Catchment Management Plan 2009-2014. The Park contains a chain of wetlands from south of the park at Lake Goollelal through to Lake Joondalup in the north and includes Beenyup and Wallubuenup Swamps. A previous study by Lund et al (2009) provides data for 6 of the monitoring sites included in the regime and is combined into this review to be used as baseline data on which to compare. Since August 2012, monthly monitoring of 8 groundwater bores was commenced to provide a better understanding of the hydrology within the Park. In addition, the review incorporates external data retrieved from the Department of Water and Bureau of Meteorology to support the findings in this report. The focus is on the present condition of the wetland chain, underlying trends and current threats to the health of the wetlands.

A review of the existing monitoring data of both surface water and groundwater to provide:

An evaluation of the data:

- to determine whether the sites currently monitored are capturing the key elements on a spatial and temporal level;
- to identify trends and assess the significance of those trends in the context of natural seasonal occurrence versus anthropogenic impacts;
- to make an overall assessment of current threats and risks to the health of the wetlands within the park.

The Review makes several recommendations related to the value of continued monitoring, adapting the current monitoring regime based on trends reflected in the data to date, approaches to data analysis and reporting, and proposed expansion into connected environmental management concerns. The review also provides a basis on which to predict future management concerns relating to the overall health of the system.

Key issues discussed in the review include declining water levels, eutrophication, nuisance midges, acidification and heavy metals.

The following summary of recommendations is centred on targeting current and potential threats to water quality and the overall wetland ecological health to assist in future decision making processes. The recommendations are interrelated and should be considered as a collective when deciding on management strategies to address individual issues.

5. SUMMARY OF RECOMMENDATIONS

Recommendation 1.

It is recommended that the surface monitoring program be refined by removing:

- Drain Mid as it is now so regularly dry that it adds little to monitoring program.
- Lake Goollelal as it is very similar to South Lake Goollelal, but is harder to access and increasingly too dry to sample.

Recommendation 2.

It is recommended that water colour as gilvin (g_{440}) be added to the analytical program for surface monitoring, as colour might be an important explanatory factor for why algal blooms are not common in sections of the park.

Recommendation 3.

The monitoring program has worked well in terms of detecting issues within the park and is recommended to continue. The surface monitoring could be scaled back to bimonthly, while the groundwater monitoring should be continued until 3 years' worth of monthly monitoring data has been collected for all sites – at this point an assessment could be made on scaling back sampling frequency.

Recommendation 4.

It is recommended that the minimum levels of water in both lakes needed to prevent the majority of floc becoming completely dry be investigated. Once these revised minimum levels are determined, the likelihood and consequence of complete drying should be assessed and if necessary contingency plans be developed to ensure that neither Lake Joondalup nor Goollelal reach this new minimum. These plans may involve adjustments to the stormwater drainage network, aquifer recharge or direct pumping into the lakes.

Recommendation 5.

It has been previously recommended that a constructed wetland built south of Ocean Reef Rd is needed to prevent on-going enrichment of northern Lake Joondalup. It is suggested that current conditions (caused by the growth of plants across the southern part of the lake) has rendered this recommendation unnecessary at the moment. A vegetated bund built in Lake Joondalup south of Ocean Reef Rd could be considered in place of the constructed wetland. The bund essentially redirects drain water away from the Ocean Reef culvert allowing it to spend more time in the lake where a variety of natural processes will reduce the nutrient load. Vegetating the bund will enhance its nutrient removal properties and aesthetic appeal. The bund provides a backup to current functions being performed by the vegetation across South Lake Joondalup.

Recommendation 6.

The current program to upgrade stormwater outflows into the park is still important, although stormwater represents a relatively small part of the overall contribution of nutrients to the system. It is recommended that preference is given to drains in the northern section of Lake Joondalup and Lake Goollelal as these areas currently have relatively low nutrient concentrations and so are most susceptible to enrichment from stormwater. If increasing stormwater inputs is a

viable approach to increasing water depths in the lakes, then nutrient and other contaminant control will be increasingly important.

Recommendation 7.

It is recommended that a nutrient and water budget be undertaken for Lake Goollelal so that the causes of the apparent increasing nutrient concentrations can be determined.

Recommendation 8.

The overwhelming impact of drying on midge nuisance problems makes control via nutrient reductions unlikely to be successful. A major source of nutrients into the lakes is groundwater; this is very difficult and expensive to control. Unless reductions in nutrients lead to general water quality improvements that increase predators and competitors, any associated loss of algal biomass is not likely to dramatically impact on midge numbers. It is recommended that alternatives to the pesticide Abate be registered for use to control midges – this is likely to have a two-fold benefit, reducing reliance on a very old-fashioned and hard to source pesticide that has significant non-target impacts, and increased effectiveness. Pesticides such as S-Methoprene while substantially more expensive are available in a range of formulations that could provide alternative methods of treatment – such as using slow release blocks to reduce midge numbers over summer.

Recommendation 9.

The WallW bore is poorly located as it potentially shows impacts from a multitude of sources. It is recommended that better data could be obtained by replacing this bore in the monitoring program with another located further to the west (to clearly measure groundwater out of Beenyup Swamp).

Recommendation 10.

A management plan be developed and implemented in the area identified in the study by Lund et al (2013) as required by Department of Parks and Wildlife guidelines due to the confirmed presence of ASS and PASS. As part of the management plan, control options need to be investigated to mitigate on-going contamination of the Yellagonga wetlands.

Recommendation 11.

Acidification leads to high concentrations of potentially toxic metals that significantly exceed recommended trigger values. It is recommended that attempts to control metal concentrations through preventing acidification should be a high priority to protect biodiversity in the park.

6. CONTENTS

7. INTRODUCTION

7.1 YELLAGONGA REGIONAL PARK

Yellagonga Regional Park lies on the coastal limestone belt of the Swan Coastal Plain (Kinnear *et al.*, 1997) and is located in the north-west corridor of Perth approximately 20 km north of Perth's central business district. The park covers about 1,400 ha and contains a chain of wetlands beginning south of the park at Lake Goollelal through to Lake Joondalup in the north and includes Wallubuenup Swamp (divided by Woodvale Drive) and Beenyup Swamp. All the lakes are interconnected with a natural drainage line (Figure 1), where water flows northwards from the highest point of the drainage system at Lake Goollelal at ~27 m Australian Height Datum (AHD) through Wallubuenup Swamp (~19 m AHD) to Beenyup Swamp (~18 m AHD) and into Lake Joondalup at ~16 m AHD. The wetlands are nestled in an interdunal depression with a high plateau sloping to the west and generally flat to slightly undulating slopes to the east. (Kinnear *et al.*, 1997). The park is managed by the Cities of Wanneroo and Joondalup, and Department of Environment and Conservation (now Department of Parks and Wildlife) under the Yellagonga Regional Park Management Plan (Dooley *et al.*, 2003).

Urbanisation has increased surface flows into the wetlands through decreased infiltration in the catchment area (Kinnear *et al.*, 1997). This, combined with increased extraction of the Gnangara groundwater mound and steady decline in rainfall, has altered the hydrology of the wetlands. Perth's Mediterranean climate of cool wet winters and hot dry summers, ensure that most of the swamps are normally dry towards the end of summer. Although occasionally dry in the past (Hamann, 1992), since 1999 Lake Joondalup has dried annually to small pools every year. Lake Goollelal is considered a permanently inundated lake, while Wallubuenup Swamp dries annually and Beenyup Swamp dries on occasion. The trend of diminishing groundwater and recharge is the probable cause of increased soil and water acidity (Appleyard & Cook, 2004) within the park triggered by drying of the underlying sediment and subsequent oxidation.

Although the surrounds and parts of Yellagonga Regional Park have been subject to agriculture and more recently urban development, Beenyup Swamp remains highly vegetated. Upton (1996) noted stands of paperbark (*M. rhaphiophylla*) dominating the landscape, whilst a large portion of the fringing vegetation of Lake Joondalup has been replaced by lawn areas. Wallubuenup Swamp has been subject to frequent fires and no open water with most of the swamp being covered in *Typha orientalis*. February 2011 saw developers of the Chianti Estate located on the east side of Wallubuenup Swamp, begin clearing *T. orientalis* and *Populus sp*. The developers continued to spray the *T. orientalis* and *Kikuyu* until February 2012 in a bid to eradicate both weeds from the area. Lake Goollelal has properties and a public open space bounding to the water's edge but fringing vegetation generally remains in reasonable condition.

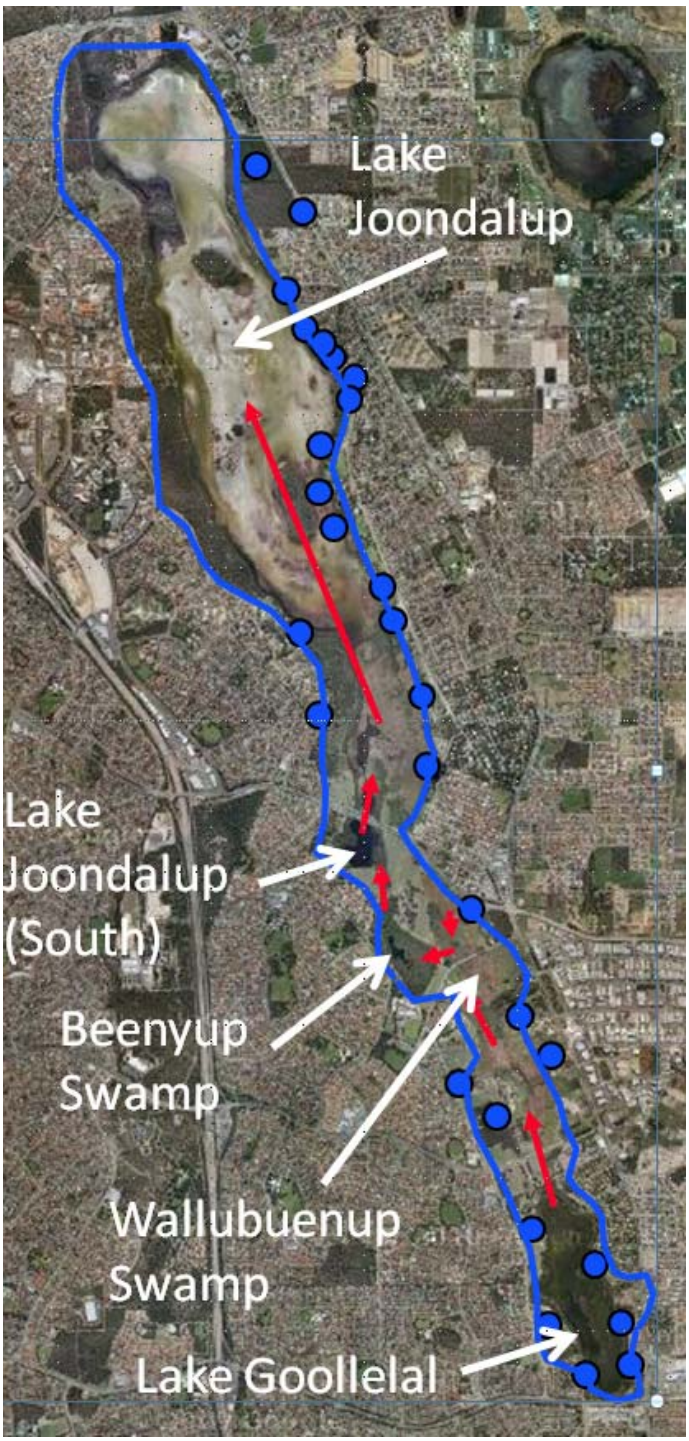


Figure 1. Direction of water flow through the Yellagonga Regional Park wetlands. Blue dots indicate drains entering the system; taken from Ove Arup & Partners (1994) and GoogleMaps (2014).

Three underlying different soil types have been identified within the Yellagonga Regional Park. These include Karakatta Sand, Spearwood Sand and Beonaddy Sand (McArthur & Bartle, 1980). Beenyup Swamp, Lake Goollelal, Lake Joondalup and Beenyup Swamp contain floc overlying peat sediments, (Bryant, 2000; Sommer, 2006; Goldsmith *et al.*, 2008) previously incorrectly described as metaphyton by Rose (1979) and Boardman (2000).

7.2 BACKGROUND TO THE REVIEW

The Cities of Wanneroo and Joondalup prepared an Integrated Catchment Management Plan (YICM) for the Yellagonga Wetlands (2009-2014). As part of the plan, a regular monitoring program for surface water quality and groundwater quality was recommended. The YICM plan concluded that combined and complete management is necessary to ensure key threatening processes to ecological integrity of the park are observed with the focus on mitigation and future improvement. Monitoring of water quality of the wetland chain is a major factor in improving the effectiveness of the management plan in terms of establishing temporal and spatial trends, reporting possible risk to environmental values, notifying of breaches in violation of water quality standards and advising of necessary action, as well as presenting an overall synopsis on the health of the wetlands within the park.

Edith Cowan University (ECU) was contracted by the Cities, to undertake water quality monitoring associated with the YICM plan. ECU were asked to review the monitoring regime and reporting components of the surface water and groundwater monitoring program to assess the accumulated data and to make recommendations for improvement. Also, the data represents four years which will give a better understanding to the trends associated with both seasonal and human influences.

7.3 SCOPE AND STRUCTURE OF THE REVIEW

An emphasis is placed on determining the physico-chemical characteristics of each site, the distribution and influence of potential contaminants, and interaction between the surface water and the superficial aquifer:

1. Review the water quality monitoring data from December 2010 – May 2014 for surface water, and August 2012 to May 2014 for groundwater, incorporating data from a previous study undertaken in 2008-2009 and data from external sources
2. Provide a synopsis of the Acid Sulphate Soil investigation undertaken in 2012
3. Evaluate the findings to identify trends and assess the significance of those trends in the context of forming a broader understanding
4. Make recommendations, as necessary, to improve the effectiveness of the current monitoring regime
5. Provide advice on the value of investigating other related areas within the park.

8. STUDY DESIGN AND METHODS

8.1 SURFACE WATER

8.1.1 DESIGN

The wetland chain comprises Lake Goollelal to the south, a permanently inundated lake at the head of the drainage system; swamps Beenyup and Wallubuenup north of Lake Goollelal and both seasonally influenced with Wallubuenup drying consistently each summer while Beenyup maintains some pools; and Lake Joondalup, situated north of the chain, which is subject to seasonal drying to small pools. The Midge Steering Committee supported a 2008/09 study of the wetland areas south of Ocean Reef Road and so neither Lakes Goollelal nor Joondalup were sampled (Lund *et al.*, 2011b). The 2008/09 study formed a useful basis for the YICM monitoring that commenced in 2010. YICM monitoring was designed to cover the entire park and so the lakes were added to the previous program and a site at Beenyup Swamp was dropped. Over the course of the study period, the number of sites has increased to provide better and more targeted coverage; in August 2011, another site at Lake Goollelal (South Lake Goollelal) and in 2012 South Culvert Inlet was added totalling 13 sites (Figure 2). The sites sampled and the frequency of sampling is shown in Table 1. Sites are sampled monthly unless considered dry (insufficient water to sample), and lake sites requiring access by canoe have to be generally >0.1 m deep for sampling and to retrieve enough sample to analyse.

Of the 13 sites, 2 are located at Lake Goollelal, 3 at Lake Joondalup and 7 within Beenyup and Wallubuenup Swamp. The site locations were selected to target inflows and outflows at each wetland to determine connectedness within the system and ascertain complexity of influence of up-gradient wetlands on down-gradient wetlands along the drainage line. To simplify the data for this review, site data has been combined together into regions from sites that are in close proximity and show relatively similar trends. These regions are listed in Table 1 and suggest a connection between sites. The analysis also showed similarities of sites are not necessarily synonymous with location and suggests there are barriers within the drainage line not previously considered. For example, Drain South and Drain Mid sites are approximately 100 metres apart, yet results suggest a lack of similarities in water properties along the drainage line.

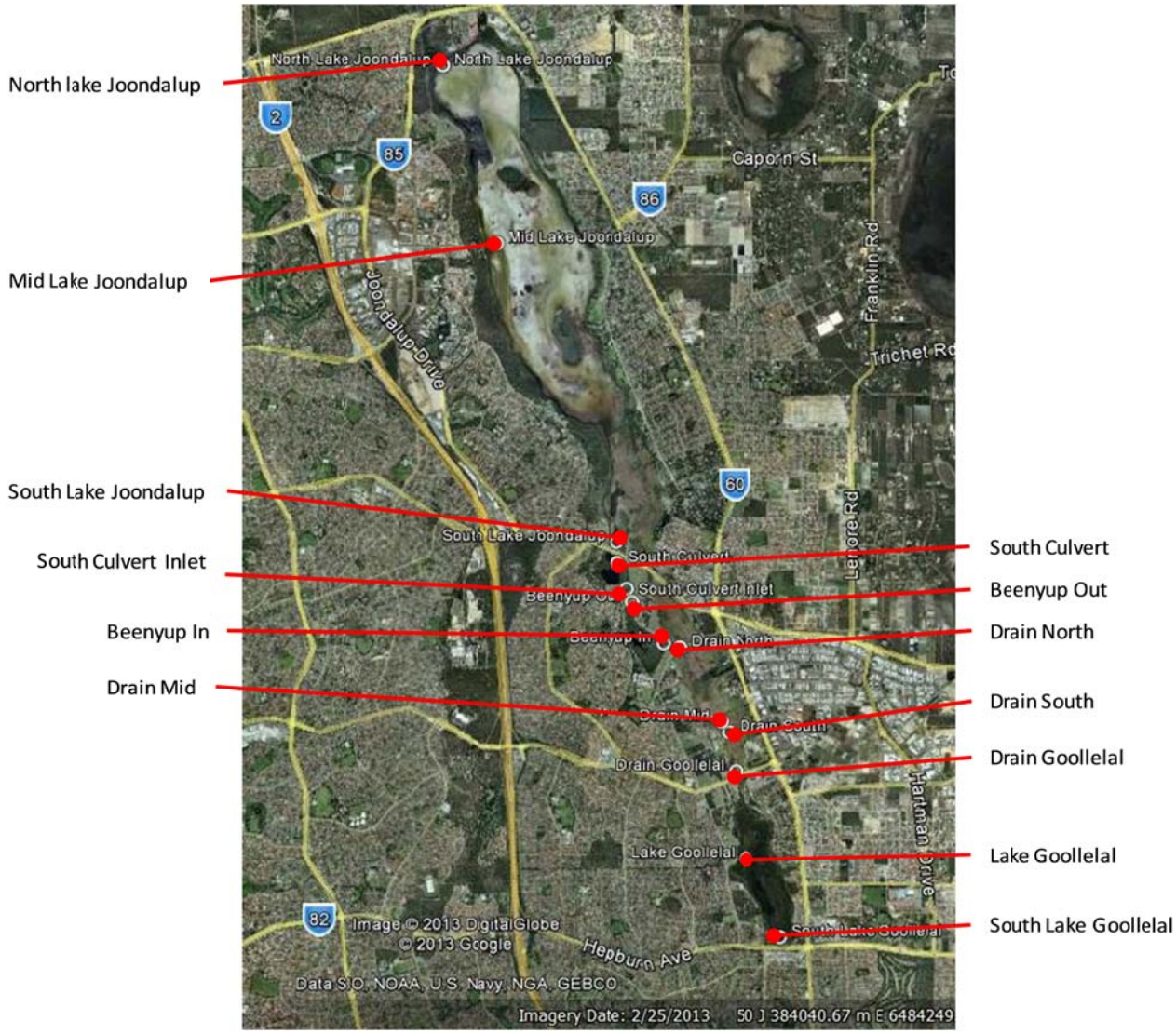


Figure 2: Aerial photograph showing the locations of the surface monitoring program for 2013/2014 (GoogleMaps) and sites combined for the ease of analysis for this review.

Table 1: Number of times each site was monitored for the duration of the project. To simplify interpretation of the data, sites were combined into regions for further analysis.

Region	Sites	Actual Times Sampled for Monitoring Year - July-June (Potential Times)					% change in sampling frequency
		2008-09 (12)	2010-11 (7)	2011-12 (12)	2012-13 (12)	2013-14 (12)	
Lake Goollelal	South Lake Goollelal	N.A.	N.A.	11	10	10	↓ 9%
	Lake Goollelal		4	12	11	10	↓ 16%
Drain South	Drain Goollelal	7	0	2	3	5	↓ 28%
	Drain South	12	2	12	7	6	↓ 50%
Drain Central	Drain Mid	12	2	7	3	4	↓ 66%
	Drain North	12	7	12	12	12	No Change
Beenyup Swamp	Beenyup In	12	7	12	12	12	No Change
	Beenyup Mid	12				N.A.	
	Beenyup Out	12	4	10	11	8	↓ 33%
	South Culvert Inlet		N.A.		6	9	N/A
South Lake Joondalup	South Culvert	N.A.	3	9	9	9	No Change
	South Lake Joondalup		3	9	9	10	↑ 10%
Lake Joondalup	Mid Lake Joondalup	N.A.	2	9	7	9	No Change
	North Lake Joondalup		2	9	7	9	No Change

Photographs of all sites are shown in Figure 3, showing the site during wet and dry times of the year.

Recommendation 1

It is recommended that the surface monitoring program be refined by removing:

- *Drain Mid as it is now so regularly dry that it adds little to monitoring program.*
- *Lake Goollelal as it is very similar to South Lake Goollelal, but is harder to access and increasingly too dry to sample.*

Lake Goollelal

a) South Lake Goollelal

October 2013 (wet)

April 2014 (dry)

b) Lake Goollelal

October 2013 (wet)

March 2014 (dry)

Drain South

c) $Drain_{Goollelal}$ (Site 5)

September 2013 (wet)

April 2014 (dry)

d) $Drain_{south}$ (Site 6)

September 2013 (wet)

April 2014 (dry)

Drain Central

e) $Drain_{mid}$ (Site 7)

October 2013 (wet)

April 2014 (dry)

f) $Drain_{north}$ (Site 4)

October 2013 (wet)

April 2014 (dry)

Beenyup

g) $Been_{in}$ (Site 3)

September 2013 (wet)

January 2014 (dry)

h) $Been_{mid}$

Winter 2009

h) $Been_{out}$ (Site 1)

September 2013 (wet)

March 2014 (dry)

South Lake Joondalup

i) South Culvert Inlet

September 2013 (wet)

April 2014 (dry)

j) South Culvert

September 2013 (wet)

April 2014 (dry)

k) South Lake Joondalup

October 2013 (wet)

April 2014 (dry)

Lake Joondalup

l) Mid Lake Joondalup
December 2013 (wet)

April 2014 (dry)

m) North Lake Joondalup
October 2013 (wet)

May 2014 (dry)

Figure 3. Photographs of the sites used in this study arranged into regions, showing seasonal changes in water regimes.

8.1.2 MONITORING METHODS

Sampling methods have remained consistent over the years, with sampling monthly. A site was considered 'dry' if the water was not deep enough to sample (<50 mm) or deep enough to access by canoe (<100 mm). On each sampling occasion, at each site, pH, oxidation reduction potential (ORP), conductivity, temperature, dissolved oxygen (% saturation and mg L^{-1}) and turbidity were measured using a Datasonde 5a instrument. At each site, a water sample was also collected.

In the laboratory, an unfiltered aliquot (subsample) of each water sample was frozen for later determination of total nitrogen (TN) and phosphorus (TP). A filtered (0.5 µm Pall Metrigard filter paper) aliquot was then frozen for later determination of sulphate (SO_4),

chloride (Cl), nitrate/nitrite[1] (NO_x), filterable reactive phosphorus (FRP), ammonium (NH_4) and dissolved organic carbon (DOC; measured as non-purgeable organic carbon). Another filtered aliquot was acidified with nitric acid (to a pH <2 approximately 1% v/v) and then kept at 4°C for later determination by ICP-AES of a range of metals (Al, As, Ca, Cd, Co, Cr, Fe, Hg, K, Mg, Mn, Na, Ni, Se, U & Zn). In 2013/14, we introduced ICP-MS into the metal analysis for improved accuracy and low detection limits for trace metals. The ICP-MS demonstrated that previous measurements of U and Se were not correct. Unfortunately, the previous instrument at levels close to detection of these elements would report noise as positive results. Therefore all U and Se values prior to 2013/14 can be considered suspect and have been ignored in this review.

All analyses were performed at the Natural Sciences Analytical Laboratory (Edith Cowan University) as per APHA (1999). Water hardness was estimated by calculation using factors from APHA (1999) for Ca, Mg, Fe, Al, Zn, Se and Mn.

Recommendation 2.

It is recommended that water colour as gilvin (g_{440}) be added to the analytical program for surface monitoring, as colour might be an important explanatory factor for why algal blooms are not common in sections of the park.

[1] TP, TN, NH_4, NO_X and FRP are all measured as P or N i.e. FRP-P or NO_x-N

NH_4 is used to represent both ammonia and ammonium in the water.

8.2 GROUNDWATER

8.2.1 DESIGN

Newport and Lund (2012) reviewed available information on groundwater bores in the vicinity of the Yellagonga Regional Park. A total of six bores were selected as providing useful coverage for the wetlands, these were joined by two new bores provided by the City of Joondalup around Lake Goollelal (Figure 4). Monitoring commenced in August 2012 and is conducted monthly.

Figure 4: Groundwater bores monitored at Yellagonga National Park.

8.2.2 MONITORING METHODS

The analysis conducted for groundwater monitoring has been similar since the project began. At each bore on each month, the depth was measured from top of the PVC casing to water level using a dipper-T. A bailer was then used to purge each bore of three times its volume before extracting the water sample. On each occasion, pH, oxidation reduction potential (ORP), electrical

conductivity (EC), temperature and dissolved oxygen (% saturation and mg L^{-1}) were measured *in situ* using a Datasonde 5a (Hydrolab) instrument.

In the laboratory, an unfiltered aliquot of each water sample was frozen for later determination of total nitrogen (TN) and phosphorus (TP). A 0.5 µm filtered (Pall Metrigard) aliquot was then frozen for later determination of sulphate (SO_4), chloride (Cl), nitrate/nitrite (NO_x), filterable reactive phosphorus (FRP), ammonia (NH_4) and dissolved organic carbon (DOC; measured as non-purgeable organic carbon). Another filtered aliquot was acidified with nitric acid to ensure a final pH <2 (approx. 1% v/v) and then kept at 4^oC for later determination by ICP-AES for a range of metals (Al, As, Ca, Cd, Co, Cr, Fe, Hg, K, Mg, Mn, Na, Ni, Se, U & Zn). In 2013/14, we introduced ICP-MS into the metal analysis for improved accuracy and low detection limits for trace metals. The ICP-MS demonstrated that previous measurements of U and Se were not correct. Unfortunately, the previous instrument at levels close to detection for these elements would report noise as positive results. Therefore all U and Se values prior to 2013/14 can be considered suspect and have been ignored in this review. All analyses were performed at the Natural Sciences Analytical Laboratory (Edith Cowan University) as per APHA (1999).

8.3 DATA ANALYSIS

Surface water data was collated for all monitoring years and looked at inter-annual seasonal comparisons, and spatial and temporal trends using Excel, SigmaPlot and SPSS software. As previously mentioned, for the purpose of this review sites were combined for the data analysis from 13 to 6 sites – Lake Goollelal, Drain South, Drain Central, Beenyup, South Lake Joondalup, and Lake Joondalup. The analysis was conducted from July to June in line with the annual reports.

Data collated from the groundwater monitoring has been analysed in a similar way to the surface water and the results incorporated into the relevant sites to provide insight into the surface-groundwater interface. Lake Goollelal and Lake Joondalup both include 3 adjacent bores and Drain Central includes the Wallubuenup Swamp bores.

In the data analysis, concentrations that were below detection limits were assigned a value of half the detection limit and included in the calculation. This approach tends to strike a middle ground between being overly conservative and not conservative.

Recommendation 3

The monitoring program has worked well in terms of detecting issues within the park and is recommended to continue. The surface monitoring could be scaled back to bimonthly, while the groundwater monitoring should be continued until 3 years' worth of monthly monitoring data has been collected for all sites – at this point an assessment could be made on scaling back sampling frequency.

9. THE ISSUES

9.1 DRYING

Average total annual rainfall over the decades were low in the 2010s at 653.2 mm (although only 4 records), with similar records in the 1970s and 2000s at 727.2 mm and 728.5 mm respectively, with higher values in the 1980s (748.5 mm) and 1990s (790.3 mm). The average annual rainfall for Wanneroo is 804.6 mm and has only been exceeded on 3 occasions since 2000 (Figure 5).

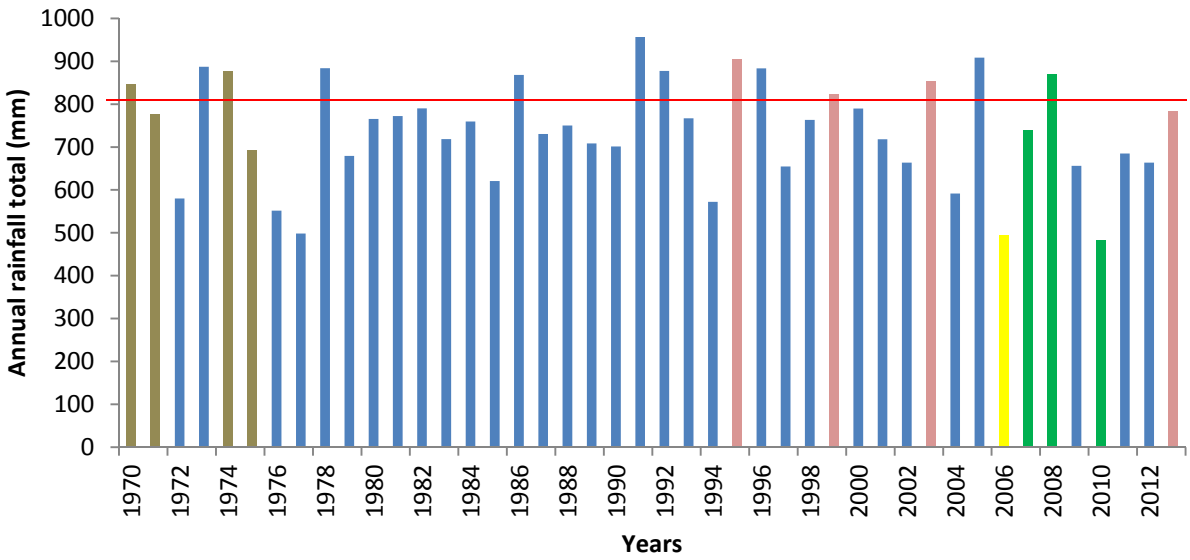


Figure 5. Total annual rainfall (mm) from 1970 to 2014, based on Wanneroo data, supplemented for missing data with the nearest closest area: Perth Airport (brown), Perth Metro (red), Tamala Park (yellow) and Mariginiup (green). Red line indicates long term average (data supplied by Bureau of Meteorology).

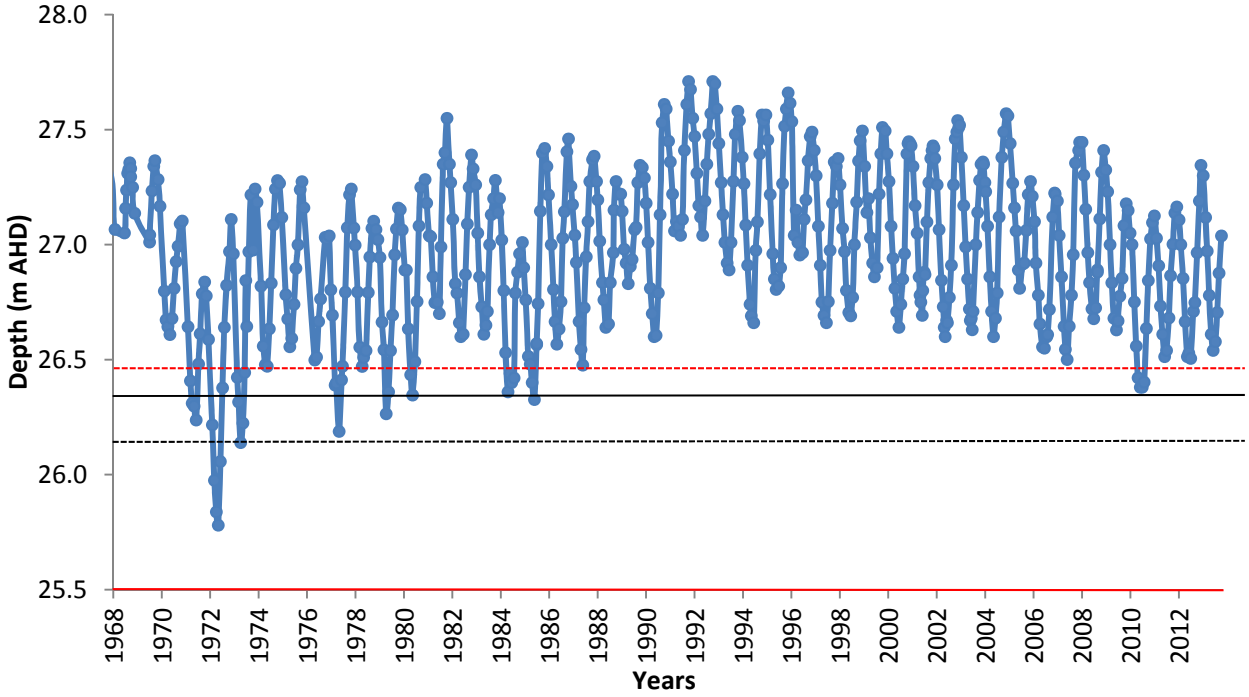
The deepest point in Lake Goollelal was estimated to be 25.47 m AHD and in Lake Joondalup at 15.54 m (Hamann, 1992). Although the lakes appear to be mainly dry at depths of 26.5 m for Lake Goollelal and 16.2 m for Lake Joondalup. There are Ministerial conditions relating to minimum water heights, these are for Lake Joondalup, a statutory preferred minimum of 16.7 m (maximum of 4 months per year) and an absolute minimum of 16.45 m. In Lake Goollelal, the preferred minimum is 26.4 m (maximum 2 months per year) and absolute minimum of 26.25 m (Dooley *et al.*, 2003). These statutory levels were finessed but not substantially altered by Froend *et al.* (2004).

Since relatively high minimum water levels in the 1990s and early 2000s, water levels have been dropping in Lake Goollelal reaching a minimum in April and May 2011 (26.38 m), which would have just breeched the preferred statutory minimum. Throughout the 1990s water levels never

were very low, whereas in 2000s there is increased frequency and length of being low (<26.6 m), March only 2003, 2005, March to April in 2008, April to May in 2012 and 2014, March to May in 2007 and 2013 and February to June in 2011. There were also low water levels in the 1970s and early 1980s, although some caution must be used with these measurements – see below.

In Lake Joondalup water levels appear to have been on a decline since 1968 with the exception of very high values during 1990-1994, so high they prompted Jarvis (1994) to drainage options to control water levels. After 1994, water levels in Lake Joondalup consistently fell below the preferred and absolute minimum statutory minimum for most of the year, reaching a minimum of <15.965 in March to May 2011 and April 2012.

a) Lake Goollelal



b) Lake Joondalup

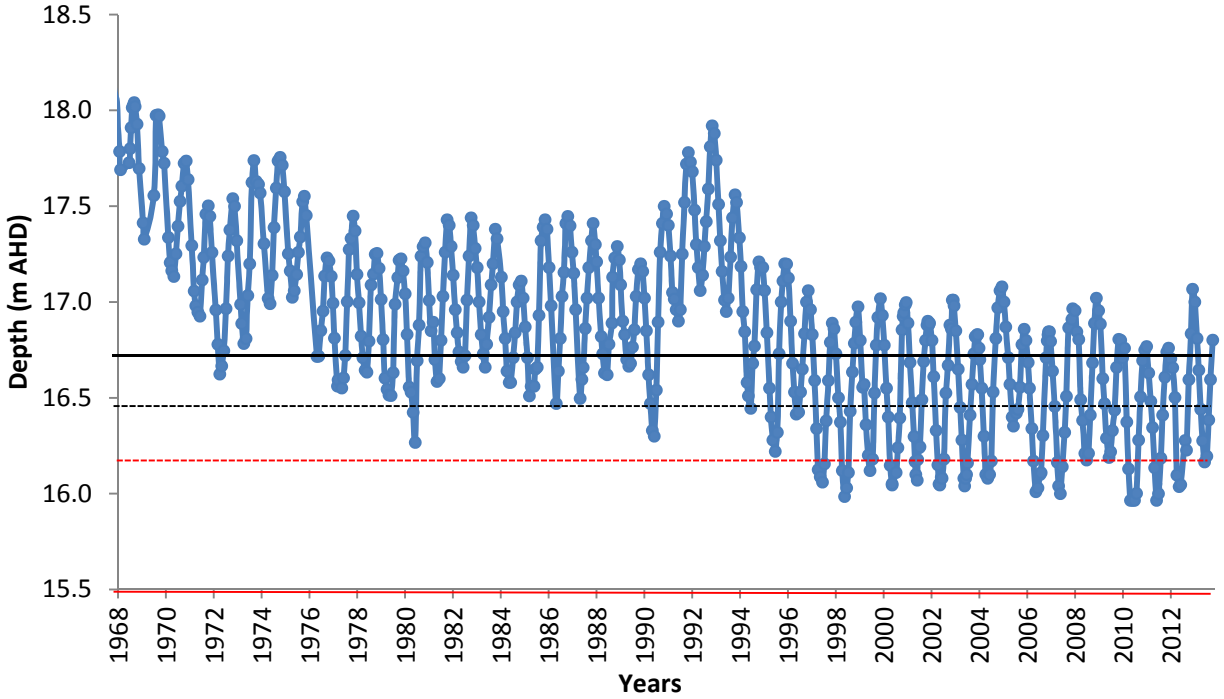


Figure 6. Height of the water surface (m AHD) in a) Lake Goollelal and b) Lake Joondalup between 1968 and present day, red line indicates deepest part of the lake (Hamann, 1992), dotted red line indicates where majority of lake is not covered with surface water, black line indicates statutory preferred minimum and dotted black the absolute minimum(Dooley *et al.*, 2003) (Data provided by the Department of Water (WA), some values converted to AHD and values marked < were assigned the value provided).

A strong and significant ($P<0.05$) correlation was found between water heights in both lakes Goollelal and Joondalup between 1969 and present (Figure 6). However, there appears to be natural groupings in the data corresponding to 1969—1976, 1977—1995 and 1996—2014, as regression lines are parallel this suggests that these differences are measurement related rather than due to a natural phenomenon. It appears that the AHD meters have been replaced or differently determined in mid-1970s and mid-1990s. The difference is significant as between the earliest and most recent data there is almost a 1 m discrepancy. It is probably reasonable to assume that the latest data is the most accurate.

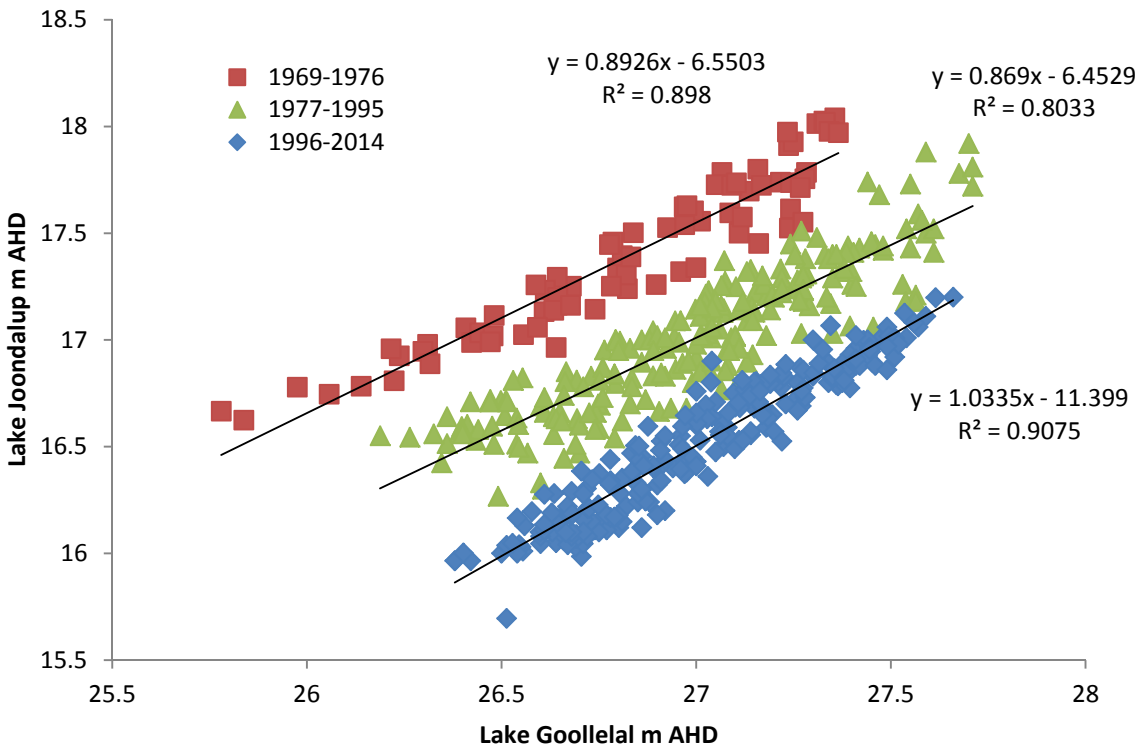


Figure 7. Scatter diagram showing relationship between the surface water heights of Lake Goollelal and Lake Joondalup, with linear regression equations, lines of best fit and R^2 values shown.

The main source of water into Lake Joondalup is direct rainfall onto the lake accounting for 3.4 to 4.3 GL (1979/80 and 2004 respectively). Sandy soils around the lake largely prevent surface runoff into the lake. Road drains around Yellagonga park create a surface water catchment of approximately 4000 ha (Ove Arup & Partners, 1994). There are 29 drains entering the park, with 17 piped outlets, 3 bubble up grates and 8 sumps (Figure 7), however Khwanboonbumpen (2006) found that for at least one piped outlet (Munderee Place, outfall no. 11) that these drains (unlike some others in Perth) do not carry groundwater and collect rainfall only from hard surfaces (e.g. roads, pavements) accounting for only 13.2% of the rainfall onto the catchment. This is reflected in the small contribution made by drains to surface inflows of 0.1 to 0.2 GL per annum (Congdon, 1985; Cumbers, 2004 respectively). The large surface area of wetlands (Beenyup and Wallubuenup) ensures that there is collection of water that flows northwards, this ensures that 0.8 GL to 1.2 GL is contributed to Lake Joondalup via the Ocean Reef culvert (Congdon, 1985; Cumbers, 2004 respectively). An estimated 81% of the water exiting Beenyup Swamp passed through the Ocean Reef culvert (Congdon, 1985), although Cumbers (2004) found only 23% transfer, her estimate was based on a few data points. Lund *et al.* (2011a) in 2009/10 in a detailed study of Beenyup Swamp found it released 1.1 GL which is more comparable with that of the 1979/80 study.

a) b)

Figure 8. Photographs of a) Outfall 2 going into Lake Joondalup via a channel, and b) Bubble up grate 2 showing indirect flow into Lake Joondalup (photographs taken from (Cumbers, 2004).

Groundwater flows from east (20 m AHD) to west (15 m AHD) across the lake. Allen (1980) (as cited in Congdon, 1985) found for nearby Lake Jandabup that outflowing groundwater only accounted for only 24% of the inflow. Lake Joondalup appears to show a similar trend to Lake Jandabup with Congdon (1985) estimating that between 1969 and 1980, groundwater contributed a nett 1.04 to 6.11 GL (mean ± sd, 2.54 ±1.27 GL) to the lake per annum. In 2004, it was estimated that there was a nett loss of 2 GL, however this is probably due to the lake increasing in volume by 2.4 GL. The lakes and swamps of the park, appear for to be perched above the water table and so only receive groundwater when its height peaks in spring and through springs. Groundwater levels have declined in the Gnangara mound over the last 20 years due to a variety of causes, this is also reflected in the groundwater around the lake (see Figure 8) which have dropped by about 1 m since the early 1980s. It is likely that the combination of lower groundwater levels and low rainfall that has seen both lakes dry out regularly in recent years.

Table 2. Water budget for Lake Joondalup (Congdon, 1985; Cumbers, 2004; Lund *et al.*, 2011a)

	1979/80	**2004**	**2009/10**
Rainfall	3.4 GL	4.3 GL	
Surface Inflow	0.9 GL		
Southern Drain	1 GL	5.3 GL	1.1 GL (Beenyup)
O.R. Culvert	0.8 GL	1.2 GL	
Stormwater Drains	0.1 GL	0.2 GL	
Evaporation	5 GL	8.1 GL	
Net Groundwater	+0.8 GL	-2 GL	
Lake Volume		+2.4 GL	
	Congdon (1985)	Cumbers (2004)	Lund *et al* (2011)

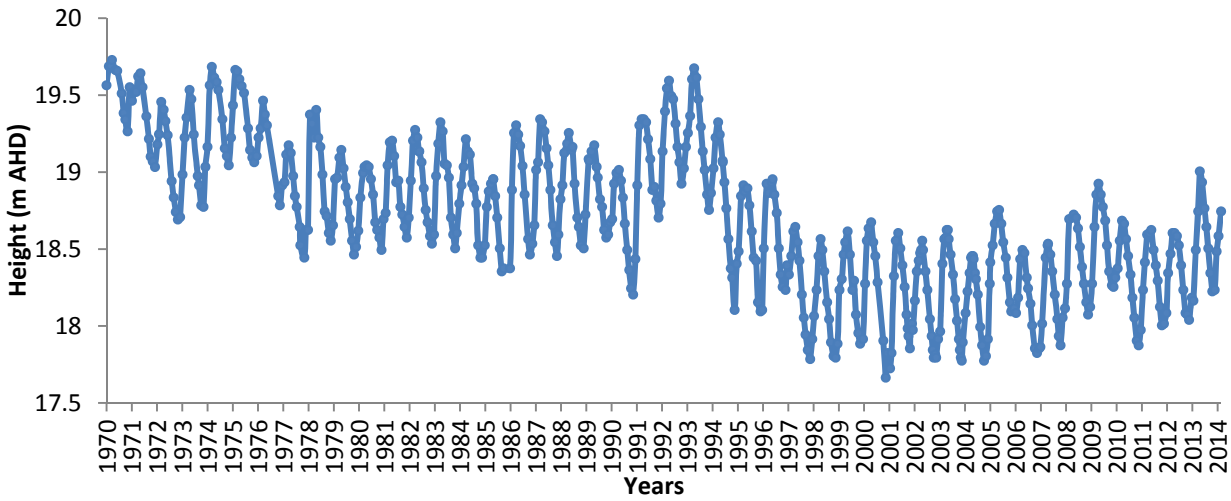


Figure 9. Groundwater heights (m AHD) recorded at JoonMidE (AWRC ref: 61610661) between 1970 and 2014 (Data provided by Department of Water)

Increasing urbanisation around the lake (as old farms are converted to urban developments) could potentially increase groundwater levels, due to reduced evapotranspiration (fewer plants) and better rain capture and transfer to the ground (roof capture) (Barron *et al.*, 2013). At JoonMidE there appears to be a generally upward trend in the minimum groundwater height since 2005, which reflects the development of Ashby. The surface catchment of Lake Joondalup was estimated to be 555,370 m^2 by Ove Arup & Partners (1994), which when combined with average annual rainfall produces approximately 0.45 GL of available stormwater runoff, suggesting that there is some potential to increase surface drainage into the lake to boost water levels.

Recommendation 4

It is recommended that the minimum levels of water in both lakes needed to prevent the majority of floc becoming completely dry be investigated. Once these revised minimum levels are determined, the likelihood and consequence of complete drying should be assessed and if necessary contingency plans be developed to ensure that neither Lake Joondalup nor Goollelal reach this new minimum. These plans may involve adjustments to the stormwater drainage network, aquifer recharge or direct pumping into the lakes.

Why? Both lakes have a layer of floc that overlies the sediment (incorrectly termed metaphyton), this a layer of primarily water and organic materials often up to 1 m deep that overlies the true sediment. The floc has a gel like consistency that has a very high nutrient binding capacity. In Lake Goollelal, the floc also contains iron pyrites (Figure 10). Currently the floc has remained wet in both lakes even at the lowest water levels, complete drying however would probably destroy the floc and cause nutrient release and loss of nutrient uptake as well as acidification in Lake Goollelal (see Section on acidification). The level at which complete drying would occur is not known exactly.

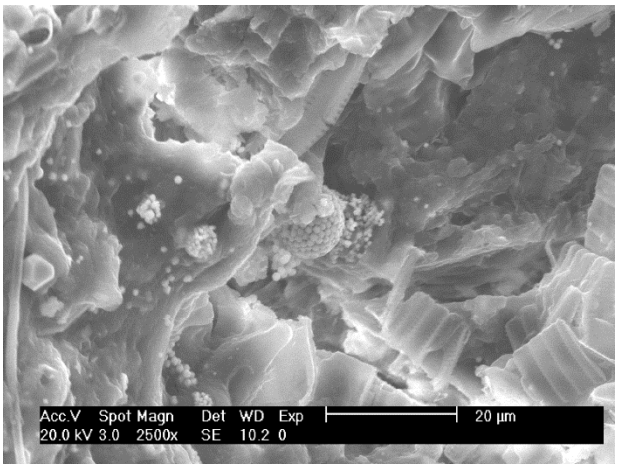


Figure 10. SEM photograph taken of Lake Goollelal floc showing crystals of iron pyrite (Photograph William Phelps)

9.2 EUTROPHICATION

A number of studies have found that Lake Joondalup is eutrophic – enriched with nutrients (Congdon & McComb, 1976; Gordon *et al.*, 1981; Congdon, 1985, 1986; Davis *et al.*, 1993; Kinnear *et al.*, 1997; Kinnear & Garnett, 1999; Lund *et al.*, 2000; Lund, 2003; Cumbers, 2004). Many of the wetlands on the Swan Coastal Plain are naturally eutrophic, as a result of their depth and history (Davis *et al.*, 1993). Lake Joondalup has become more eutrophic since European colonisation of Western Australia and the Joondalup/Wanneroo area developed for market gardening (Cumbers, 2004). In the last decade the rapid conversion of previously agricultural land around the lake to urban development has altered inflows of nutrients into the lake (Khwanboonbumpen, 2006). The main problem nutrients for eutrophication are nitrogen (N) and phosphorus (P), although it is typically P that is element of concern for freshwater systems. The main concern with eutrophication is that the nutrients encourage plant growth, initially submerged plants but as enrichment continues to benthic algae, to algal blooms and finally to blooms of cyanobacteria (which can be toxic to other organisms).

Congdon (1986) found in 1979/80 that 269 kg P and 838 kg of N entered through the Ocean Reef culvert with 3 kg of P and 39 kg of N entering through stormwater. His study estimated that 97 kg of P and 1953 kg of N entered through rainfall. Cumbers (2004) estimated that there were 24 kg of P and 471 kg of N entering the lake through rainfall, 1215 kg of P and 979 kg of N entering through the Ocean Reef culvert, 40 kg of P and 239 kg of N from stormwater (Table 3). A more detailed study of nutrient loads in Beenyup Swamp found that 1.06 GL of water was released in the year 2009/10 containing 415 kg of P and 1047 kg of N (Lund *et al.*, 2011a). Beenyup Swamp had been identified as potential source of much of the P load in the southern drain. The floc of the swamp contains very high concentrations of P (Goldsmith *et al.*, 2008), although this is partially due to the high water content of the floc which boosts concentrations measured as dry weight. Importantly,

Gunner *et al.* (2008) found that the floc did not under most conditions release much P into overlying waters. The lack of P release from suggests that the floc is in fact absorbing P from the water. Lund *et al.* (2011a) in a detailed study of inflows and outflows from Beenyup Swamp concluded that the swamp exported an additional 109 kg of P over what it received from Wallubuenup Swamp. The source of this additional P appears to be from groundwater springs. In addition, to the nutrient load from Beenyup Swamp, there appears to be an additional source of P from a groundwater spring located in the drain between the swamp and the southern part of Lake Joondalup (Helleyna, 2013). A slight increase in total P was recorded on most occasions between Beenyup out and South Culvert Inlet supporting Helleyna's (2013) finding (Figure 11). Stormwater appears not to be a major source of nutrients into Lake Joondalup, with Khwanboonbumpen (2006) finding that, overspray of fertilizers and groundwater (reticulation) onto the roads and car emissions could account for majority of nutrients in the stormwater.

Table 3. Nutrient budget for Lake Joondalup (Congdon, 1986; Cumbers, 2004; Lund *et al.*, 2011a)

	1979/80		**2004**		**2009/10**	
Rainfall	97 kg P	1953 kg N	24 kg P	471 kg N		
O.R. Culvert	269 kg P	838 kg N	1215 kg P	979 kg N	415 kg P	1047 kg N
Stormwater	3 kg P	39 kg N	40 kg P	239 kg N		
Groundwater -			360 kg P	2400 kg N		
Groundwater -			600 kg P	8400 kg N		
	Congdon (1986)		Cumbers (2004)		Lund et al (2011a)	

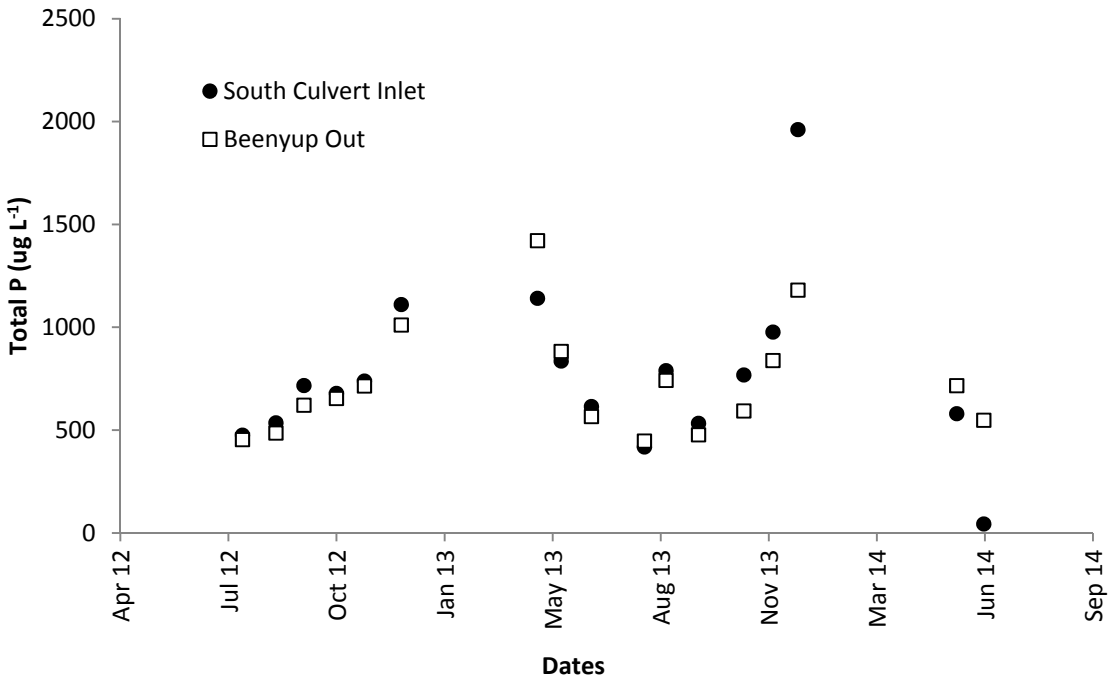


Figure 11. Comparison of Total P concentrations recorded at Beenyup outlet and at South Culvert Inlet between 2012 and 2014

Are P concentrations increasing in Lake Joondalup? According to Cumbers (2004) then there appeared to be some evidence of a slight increase from 1973 to 2001 (Figure 12), however between late 2011 and early 2012 concentrations were similar to the mid-1990s before dropping to concentrations lower than seen in the early 1970s. The large inputs from the southern drain have not substantially altered, with South Lake Joondalup still showing very high concentrations of mean 788 µg L^{-1} (201—2520 µg L^{-1}) compared to mid Lake Joondalup at 51 µg L^{-1} (<20—162 µg L^{-1})(Figure 13). The lack of apparent connection between Lake Joondalup south and mid is interesting and is probably due to the infilling of the connection between the two areas with rushes (Figure 14). The frequent drying of the lake is probably encouraging the growth and spread of *Typha orientalis*. The rushes appear to be acting in a similar way to a constructed wetland in taking up nutrients flowing northwards. Comparison of conservative chloride ions between South Lake Joondalup and mid Lake Joondalup show a substantial increase from a mean of 148 mg L^{-1} (51—574 mg L^{-1}, although the maximum was a one-off and the second highest value was 325 mg L^{-1}) compared to 449 mg L^{-1} (103—1377 mg L^{-1}). In comparison in 1992/93 Kinnear and Garnett (1999) recorded Cl concentrations of 154 mg L^{-1} (98—216 mg L^{-1}) and 328 mg L^{-1} (132—598 mg L^{-1}) respectively for south and mid Lake Joondalup indicating that in recent years the mid lake water was more salty than previously, possibly more poorly diluted by southern waters, whose flows are slowed by the growth of rushes. Given the high concentrations of nutrients in South Lake Joondalup, algal blooms would be expected to occur, however chlorophyll *a* (a surrogate measure of algae) was very similar between south and mid lake at 5 µg L^{-1} (<1—29 µg L^{-1}) versus 4 µg L^{-1}

(<1—13 µg L^{-1}) and very low. A possible explanation for the low algal biomass in the south lake is the presence of colour in the water; South Lake Joondalup has a colour of 76.7 TCU vs mid Lake Joondalup at 32.5 TCU (Storey *et al.*, 1993). Water colour (gilvin) has been found to limit algal biomass in Swan Coastal Plain wetlands (Wrigley *et al.*, 1991), with the colour of the mid-section of the lake unlikely to have any significant impact on algal growth. The stronger coloured southern section may be sufficient to reduce light penetration and chelate essential metals that might limit algal growth (Lund & Ryder, 1998). Increasing salinity or water hardness will cause colour to drop out, such as found in the northern section of the lake (Lund & Ryder, 1998).

The source of the P in northern Lake Joondalup is a combination of stormwater inputs, sediment loads and groundwater. Figure 12 shows that for the water the flow of nutrients from the south was an important source in 1999, although penetration into the northern parts of the lake was limited. Another source appears to be groundwater, as this eastern hotspot is located close to JoonMidE bore. The JoonMidE bore had average FRP concentrations of 301 µg L^{-1} (8—932 µg L^{-1}) and total P of 2047 µg L^{-1} (113—10780 µg L^{-1}). The sediment P concentration also is highest on the eastern shore indicating that it is enriched by groundwater entering the lake. Congdon (1986) suggested that the high calcium carbonate content in the sands surrounding the lake would be effective at binding P leaving the lake in groundwater. However Cumbers (2004) found relatively high concentrations of P in groundwater from a number of bores on the western side of the lake. High P concentrations in the groundwater used to supply artificial lakes such as the ECU Campus Lake and Central Park Lake are responsible for algal blooms that have occurred in these lakes. This suggested that groundwater as well as sediment represents a sink (permanent loss) of P from the lake.

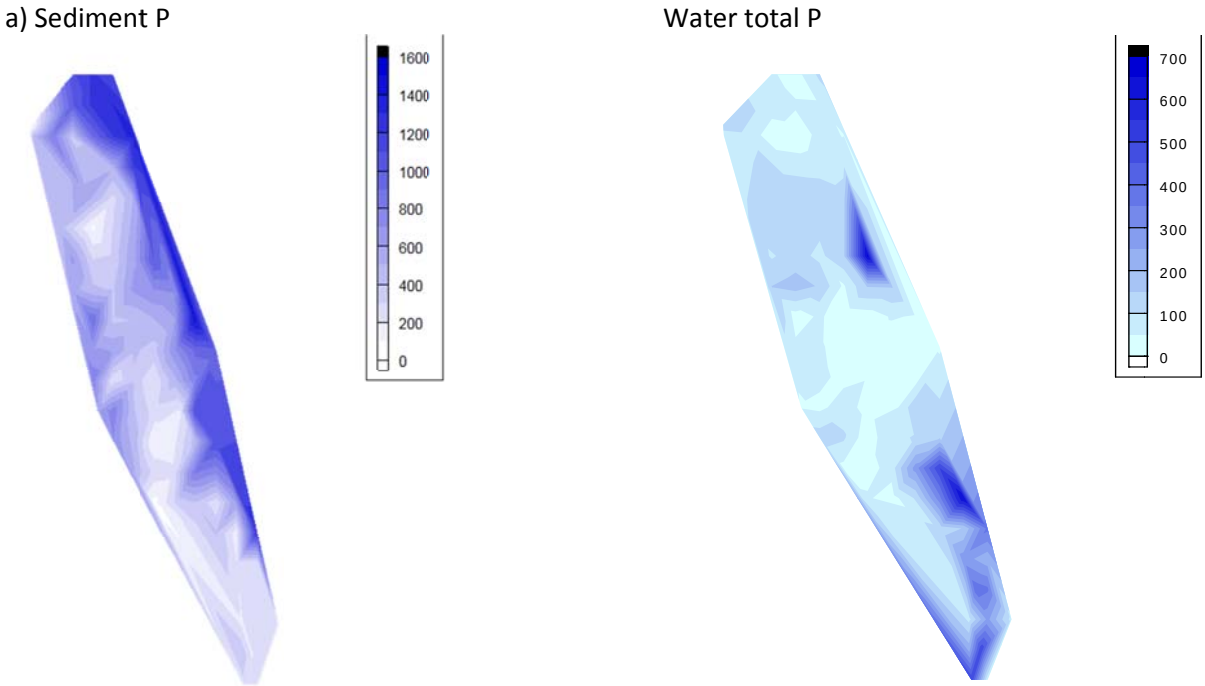


Figure 12. Contour map of a) sediment P concentrations (mg kg^{-1}) and b) water total P recorded in 1999 for Lake Joondalup (data from Lund *et al.*, 2000)

Recommendation 5

It has been previously recommended that a constructed wetland built south of Ocean Reef Rd is needed to prevent on-going enrichment of northern Lake Joondalup. It is suggested that current conditions (caused by the growth of plants across the southern part of the lake) has rendered this recommendation unnecessary at the moment.

An alternative approach: The current drain from Beenyup exits into the lake south of Ocean Reef Rd close to the Ocean Reef culvert ensuring that drain water has little chance to interact with the lake before entering the culvert. This drain water is rich in nutrients and is enriching the southern part of the lake. Given the high concentrations of nutrients, it would be expected that algal blooms would be a regular event, although water colour appears to be preventing this. It is recommended that efforts are made to limit the transfer of nutrients northwards. A low cost approach would be to construct a vegetated bund in the lake south of Ocean Reef Rd to capture the drain water and direct it through more of the lake, increasing the lakes ability to absorb nutrients. The bund would be made of sand and would simply create a physical barrier to water movement and a place to establish plants (Figure 12). Some hardening of the bund may be necessary to prevent it eroding. The performance of the bund for nutrient removal could be enhanced by encouraging growth of rushes where drain enters the lake. The bund by increasing residence time for water could encourage algal blooms in this section of the lake, but these do not appear to be an issue on the other side of Ocean Reef Rd and so are not that probable here.

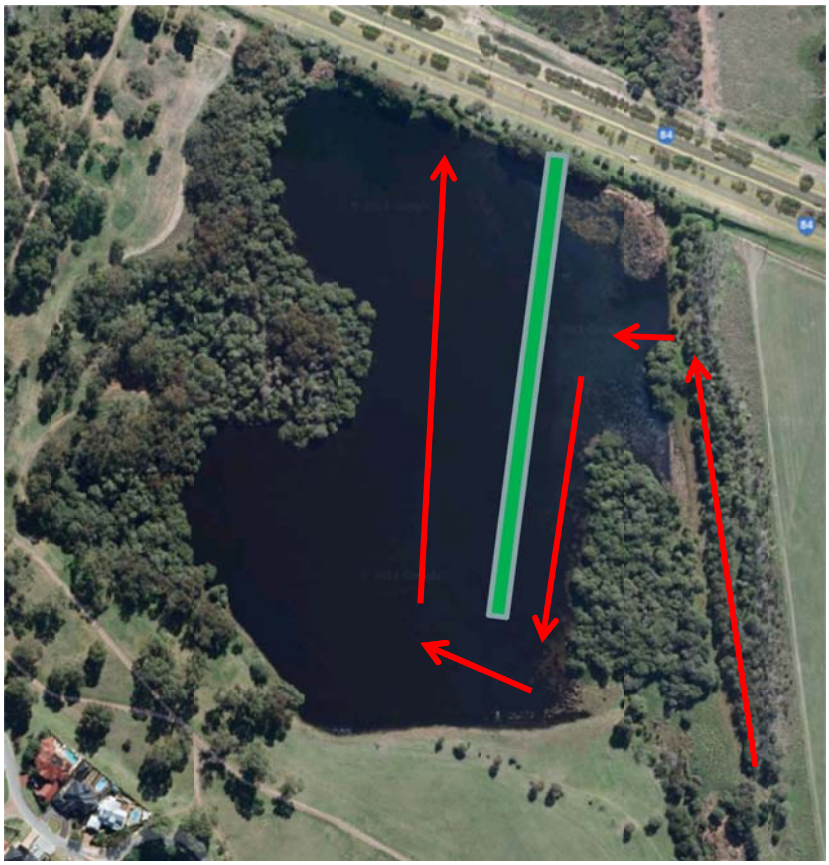
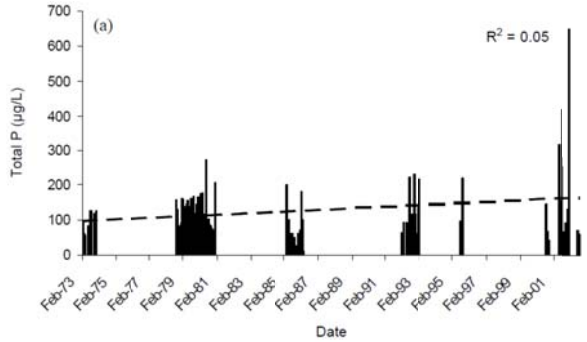


Figure 13. Lake Joondalup south of Ocean Reef Rd, showing proposed vegetated bund (green) and revised drain flow path

a) Cumbers (2004)



b) This study

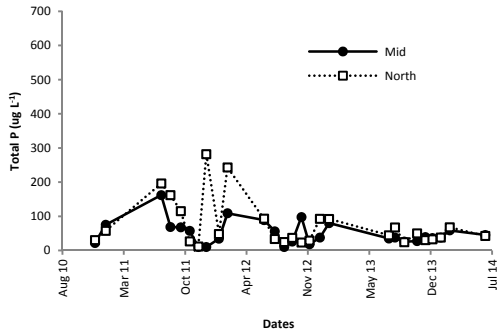


Figure 14. Total P concentrations for Lake Joondalup reported in Cumbers (2004) and b) this study

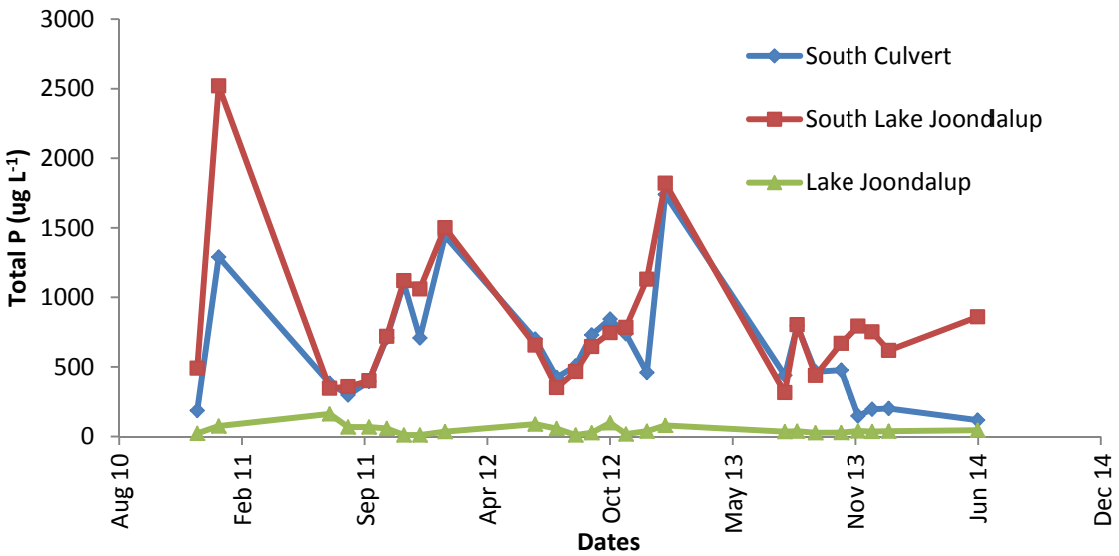


Figure 15. Comparison of Total P concentrations from the south culvert through to South Lake Joondalup and to Lake Joondalup (mid) between 2010 and 2014.

Figure 16. Aerial photographs of southern Lake Joondalup taken in January 2002 and June 2013, highlighting the growth of rushes across the divide between the southern open water and the middle of the lake (images taken from Google Earth).

Recommendation 6

The current program to upgrade stormwater outflows into the park is still important, although stormwater represents a relatively small part of the overall contribution of nutrients to the system. It is recommended that preference is given to drains in the northern section of Lake Joondalup and Lake Goollelal as these areas currently have relatively low nutrient concentrations and so are most susceptible to enrichment from stormwater. If increasing stormwater inputs is a viable approach to increasing water depths in the lakes, then nutrient and other contaminant control will be increasingly important.

Since 1998, Lake Joondalup has dried every summer, whereas it had dried previously on a number of occasions but not for years in succession (Hamann, 1992). This has led to regular nuisance midge problems that were initially attributed to releases of nutrients from the sediments upon re-flooding after drying contributing to algal blooms. This no longer appears to be likely, as experiments by Wong (2003) and Sommer (2006) have shown that despite high nutrient concentrations in the floc, nutrients are not released upon re-wetting provided the floc does not become totally dry. Flocs tend to occur in wetlands that are permanent, and while they can survive occasional drying (no surface water, but not completely dry), severe drying is likely to see them destroyed and with that substantial release of nutrients.

Lake Goollelal has been studied much less than Lake Joondalup and few data are available. In 1999, the lake was sampled between July and November; concentrations of total P were on average 23 µg L^{-1} (10—98 µg L^{-1}) (Lund *et al.*, 2000). In the 2010s concentrations appear to have substantially increased to an average of 101 µg L^{-1} (<20—1680 µg L^{-1}), although most of this increase is tied to a few high concentrations occurring in June 2012 and 2014, and January 2011. These peaks correspond to similar peaks in FRP; interestingly the 2012 peak was not replicated at South Lake Goollelal indicating a localised event, although the 2014 event occurred at both sites (Figure 16). Removing these one-off peaks reduces the average to 41 µg L^{-1} which still supports an increase in the P concentrations over the last 15 years. There are two very high concentrations of total P recorded in South Lake Goollelal, as they are not accompanied by increases in FRP and are not replicated in Lake Goollelal samples they may simply be due to algae caught in the sample. The source of the P appears to be groundwater from the south-east side (GoolSE) of the lake, which had FRP concentrations on average 23 µg L^{-1} (11—42 µg L^{-1}) compared to the north-east bore (GoolNE) where the average was 9 µg L^{-1} (1—17 µg L^{-1}). Concentrations of total P in both bores were very high on occasion reaching 1750 and 9220 µg L^{-1} for GoolNE and GoolSE respectively

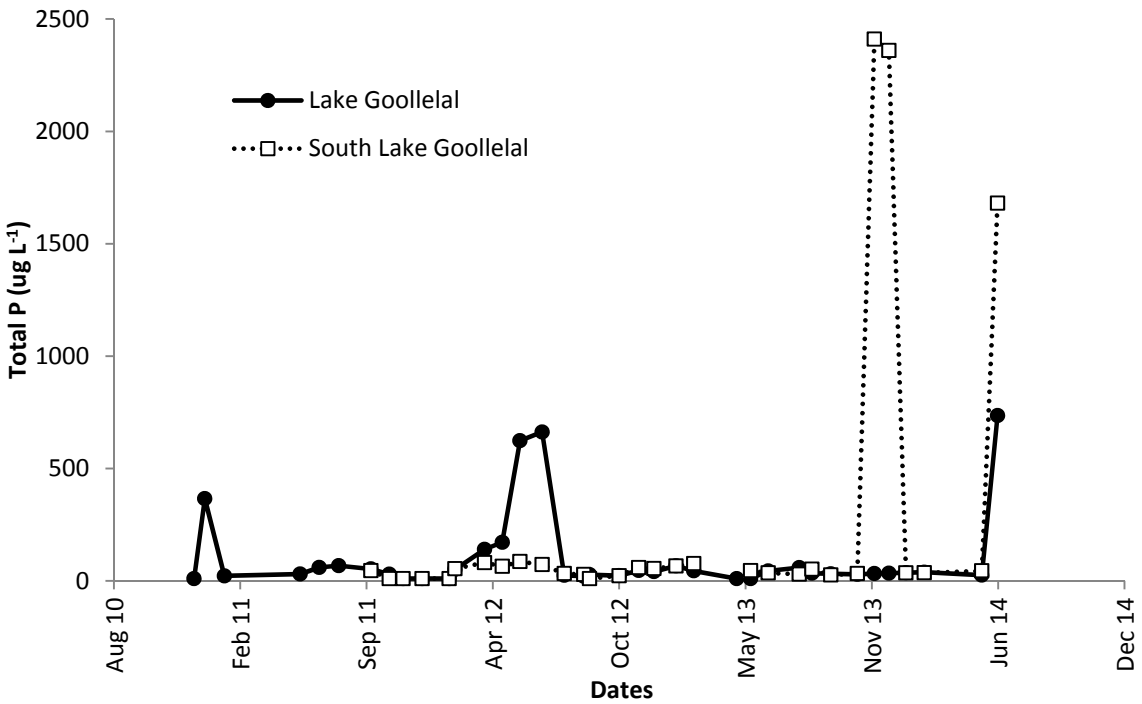


Figure 17. Total P concentrations in Lake Goollelal (from two sites) between 2010 and 2014.

Recommendation 7.

It is recommended that a nutrient and water budget be undertaken for Lake Goollelal so that the causes of the apparent increasing nutrient concentrations can be determined.

9.3 NUISANCE MIDGES

Lake Joondalup has nuisance midge problems for many years. Nuisance midges belong to the Chironomidae and are small flies about the size of mosquitos. Unlike mosquitos, midges do not bite and in Australia are not known to cause any negative health effects, although in other countries they have been known to cause allergenic reactions in susceptible people (Ali, 1991). As larvae midge live in the sediments of lakes. Midge larvae feed in many different ways, some are predatory, and most others feed on algae or bacteria. Anecdotal evidence suggests that in Western Australia, the main nuisance species can be associated with algal blooms (although this seems limited to artificial habitats – such as drains) or in most natural lakes occur in numbers that are not strongly correlated to algal biomass – suggesting they are feeding on bacteria. Indeed, the low algal biomass in both Lakes Goollelal and Joondalup would support this latter suggestion. Despite this suggestion, there does appear to be a link between eutrophication and nuisance plagues of midge. A possible explanation for this is eutrophication impacts on sensitive taxa effectively removing a range of sensitive predators and competitors that normally regulate midge

populations. Under this scenario, midge would be expected to be a problem on occasion and at specific times of year (some species tend to emerge only at specific times of the year). Davis *et al*. (2002) using a modelling approach showed that drying of the lake resulted in warmer water the following season (due to the shallowness), which stimulated midge growth (as per Suffell, 2002; Roberts, 2003). Davis *et al*. (2002) reported that pesticide treatments for controlling midges in Lake Joondalup occurred in 1981, 1985, 1986, 1991, 1996 and 1998 onwards. These treatments all follow particularly dry years, with the exception of the 1985 and 1986 treatments. It is likely that the recent rise in midge problems at Lake Goollelal is a combination of increasing eutrophication and more frequent and severe drying.

Recommendation 8

The overwhelming impact of drying on midge nuisance problems makes control via nutrient reductions unlikely to be successful. A major source of nutrients into the lakes is groundwater; this is very difficult and expensive to control. Unless reductions in nutrients lead to general water quality improvements that increase predators and competitors, any associated loss of algal biomass is not likely to dramatically impact on midge numbers. It is recommended that alternatives to the pesticide Abate be registered for use to control midges – this is likely to have a two-fold benefit, reducing reliance on a very old-fashioned and hard to source pesticide that has significant non-target impacts, and increased effectiveness. Pesticides such as S-Methoprene while substantially more expensive are available in a range of formulations that could provide alternative methods of treatment – such as using slow release blocks to reduce midge numbers over summer.

9.4 ACIDIFICATION OF THE WETLANDS

9.4.1 BACKGROUND

Acid sulphate soil (ASS) is the term used to describe soils and sediments containing oxidising iron sulphides, predominately iron pyrites (Department of Environment, 2003). In an anaerobic (no oxygen) environment these iron sulphide rich sediments remain benign (referred to as Potential ASS or PASS). However when exposed to an oxygenated environment, chemical and biological processes cause the oxidation of the sulphides resulting in the production of sulphuric acid. The acidity can cause metals in surrounding geologies to dissolve. When the buffering capacity of the receiving environment is exceeded heavy metal/metalloid contamination and acidification occur (Department of Environment and Conservation, 2013). Disturbance and exposure of PASS has the potential to convert it to ASS and lead to contamination of soil, water and air, causing harm to human health and ecological integrity e.g. loss of biodiversity, riparian vegetation, water quality deterioration, groundwater contamination, corrosion of infrastructure, and in humans skin irritation and respiratory problems (National Working Party on Acid Sulfate Soils, 2000).

Fifty six years ago, it was acknowledged that ASS were present in Australia (Sammut *et al.*, 1996). Twenty six years ago, concern was raised in relation to the potential impacts of ASS after it was found to be responsible for the occurrence of massive fish kills in Tweed River, NSW (Sammut *et al.*, 1996). More recently it has been estimated that there are 40 000 km^2 of pyritic sediments in coastal regions of Australia (National Working Party on Acid Sulfate Soils, 2000). In response to the multi-dimensional threat that ASS potentially poses, there are National and State level legislation, polices and guidelines detailing how ASS should be investigated, identified, managed and treated (Department of Environment and Conservation, 2013).

The Swan Coastal Plain, situated on the Western Australian coastline is of particular concern for ASS. The organically, pyritic rich sediments of lands that were historically wetlands and existing groundwater dependant wetlands present massive sources of potential ASS (Appleyard *et al.*, 2004). The two main activities threatening the release of ASS sources into wetland ecosystems on the northern Swan Coastal Plain is urban development and draw down from groundwater extraction (Appleyard *et al.*, 2004). Further compounding the effect of draw down from groundwater extraction has been a series of below average rainfall years over the last couple of decades (Bureau of Meteorology), reducing recharge of the superficial aquifer. These circumstances led to the drying event of Lake Jandabup in the late 1990s causing acidification and consequential loss of ecological integrity (Sommer & Horwitz, 2001). Another example of ASS exposure on the Swan Coastal Plain is Spoonbill Reserve in the City of Stirling, where urban development caused acidification of groundwater and resulted in risk to human health from metal exposure (Hinwood *et al.*, 2006; Lund *et al.*, 2010). Figure 18 is a broad scale indication of identified risk areas of ASS within Yellagonga Park.

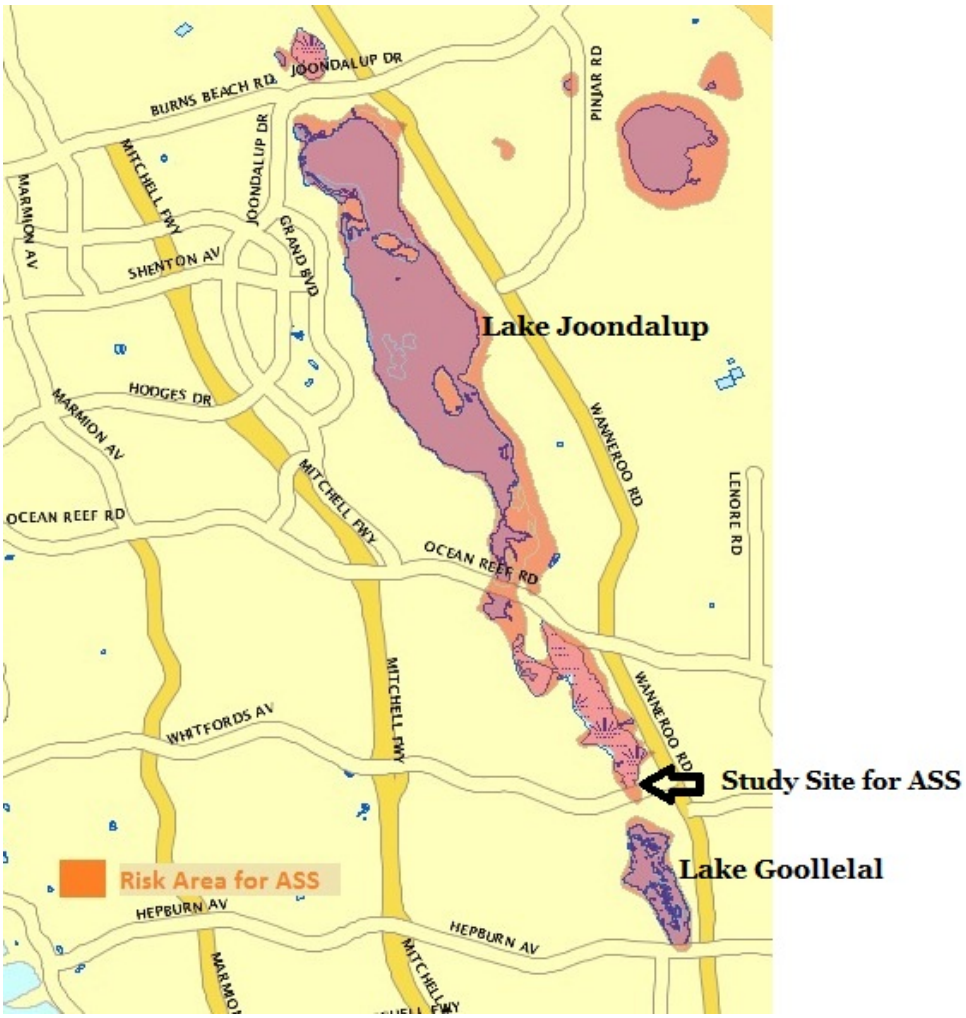


Figure 18. ASS risk area map adapted from Landgate Geocentric Datum of Australia (created 20 May 2014 from landgate.wa.gov.au) with ASS study site noted.

9.4.2 WATER ACIDIFICATION

Disturbance of ASS within the drainage system may lead to increased occurrence of acidification of the wetlands. Drainage paths as seen here are cause for concern due to the location of PASS and ASS. Chloride to sulphate molar ratios is commonly used to indicate the presence of acid sulphate soils (ASS). Oxidation of metal sulphides (typically pyrites) into sulphuric acid, increasing sulphate relative to conservative chloride ions, which results in low molar ratios. A molar ratio of four or less is considered a good indicator of ASS contamination (Department of Local Government and Planning & Department of Natural Resources and Mines, 2002). Figure 36 illustrates seasonal acidification events based on $Cl:SO_4$ ratios as described above. Drain South has the lowest ratio in autumn 2011 at <1.5, this site shows an acidification event from winter 2008, peaking in autumn 2011 and subsequent recovery to ratios above 4 by spring 2011. This event was also reflected in low ratios at Drain Central, Beenyup and South Lake Joondalup possibly caused by waters flowing northwards from Drain South. Between winter 2011 and summer 2013/14 Lake Goollelal had

consistently low Cl:SO_4 ratios. Low water levels during the summer at Lake Goollelal appear to allow for some acidification of the sediments, however the acid appears to be neutralised by the natural buffering in the system. pH was lowest in Lake Goollelal between September and November each year dropping from summer highs of >8.5 to just over 7.5.

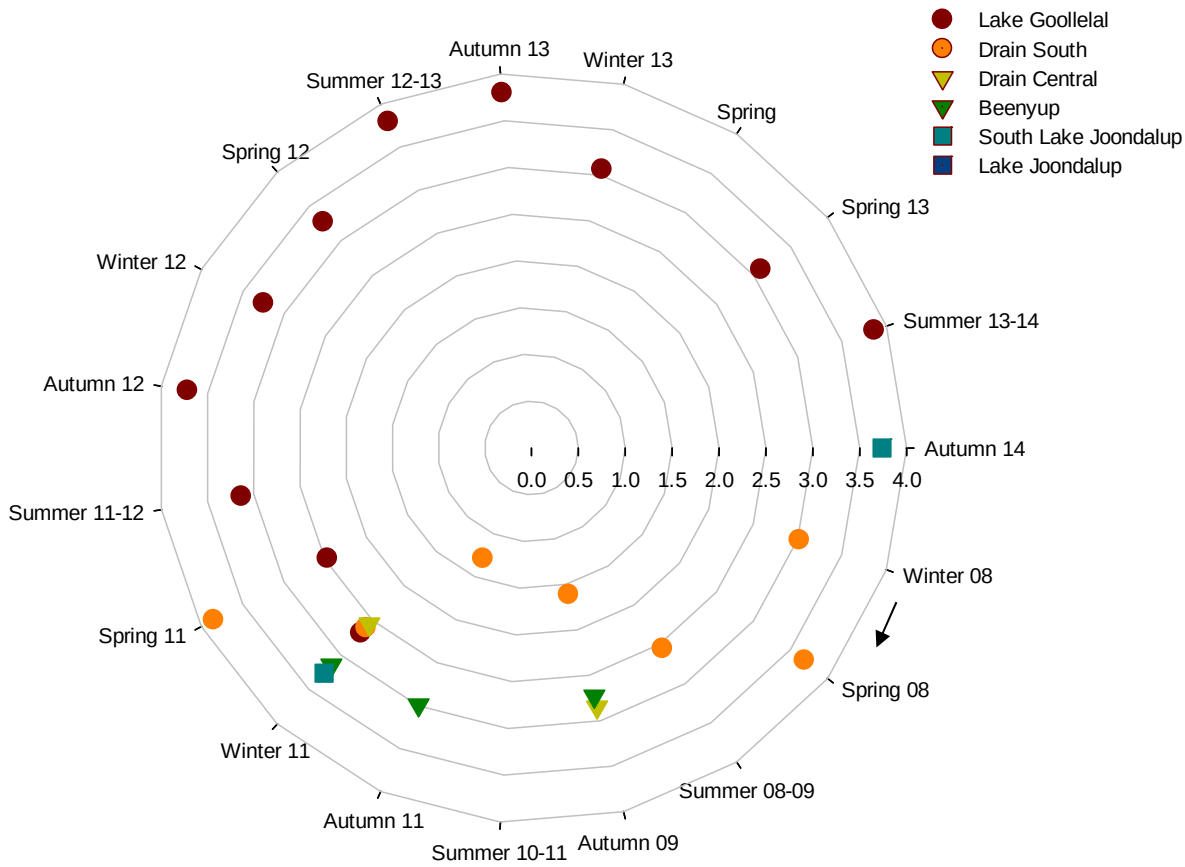


Figure 19. Radar plot showing all Cl:SO_4 molar ratios <4 only, of regions in Yellagonga Park from Winter 2008 to Autumn 2014. Seasons were grouped Summer - December to February, Autumn - March to May, Winter - June to August and Spring - September to November.

Another explanation of the low Cl:SO_4 ratio in Lake Goollelal is that it is not due to drying of the sediments but is primarily due to inflowing groundwater. In Figure 20, water from GoolNE and GoolSE bores clearly shows very low ratios, particularly in the NE, as the water passes through the lake, the ratio increases and is generally slightly higher at GoolMidW. GoolNE bore also has comparatively low pH, with the majority of measurements below pH 6, with GoolSE with substantially higher pH, all above 6.5. The groundwater outflow of the lake, as measured at GoolMidW has a pH that typically falls between the two other bores.

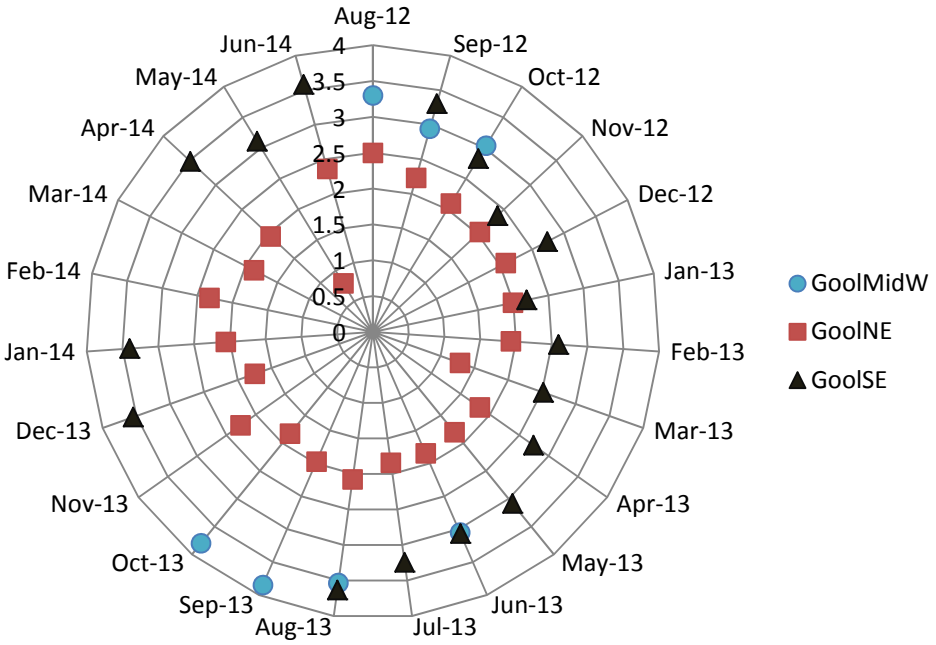


Figure 20. Radar plot showing all Cl:SO_4 molar ratios <4 only, of bores GoolMidW, GoolNE and GoolSE over the monitoring period Aug 2012 to Jun 2014.

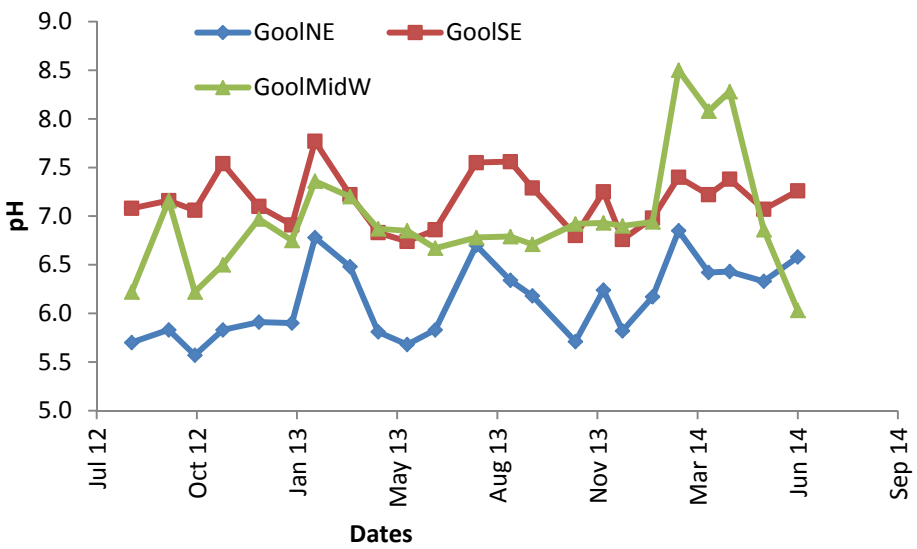


Figure 21. pH in bores around Lake Goollelal between 2012 and 2014

At Wallubuenup Swamp, the eastern bore (WallE) had no signs of acidity. However, the western bore (WallW) had very low Cl:SO_4 ratios typically <1.5. Suggesting acidity was being generated in the swamp (Figure 22). The WallW bore is not very usefully located as it is difficult to isolate the source of the water in the bore, is it from Wallubuenup or Beenyup Swamp or the nearby sump.

Recommendation 9

The WallW bore is poorly located as it potentially shows impacts from a multitude of sources. It is recommended that better data could be obtained by replacing this bore in the monitoring program with another located further to the west (to clearly measure groundwater out of Beenyup Swamp).

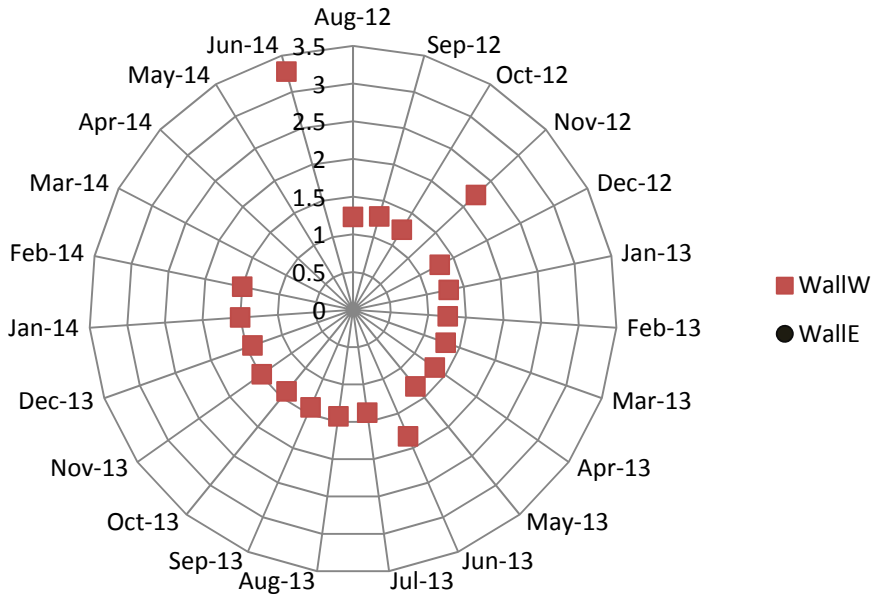


Figure 22. Radar plot showing all Cl:SO_4 molar ratios <4 only, of bores WallW and WallE over the monitoring period Aug 2012 to Jun 2014.

Lake Joondalup bores on the eastern side show only one time where Cl:SO_4 ratios dropped below 4 for JoonMidE, however in the JoonNE most sample occasions had ratios <4. In JoonNE, the ratio was lowest between September 2012 and April 2013 at around 2 (Figure 23). On the western side, only one record of ratios <4 was recorded.

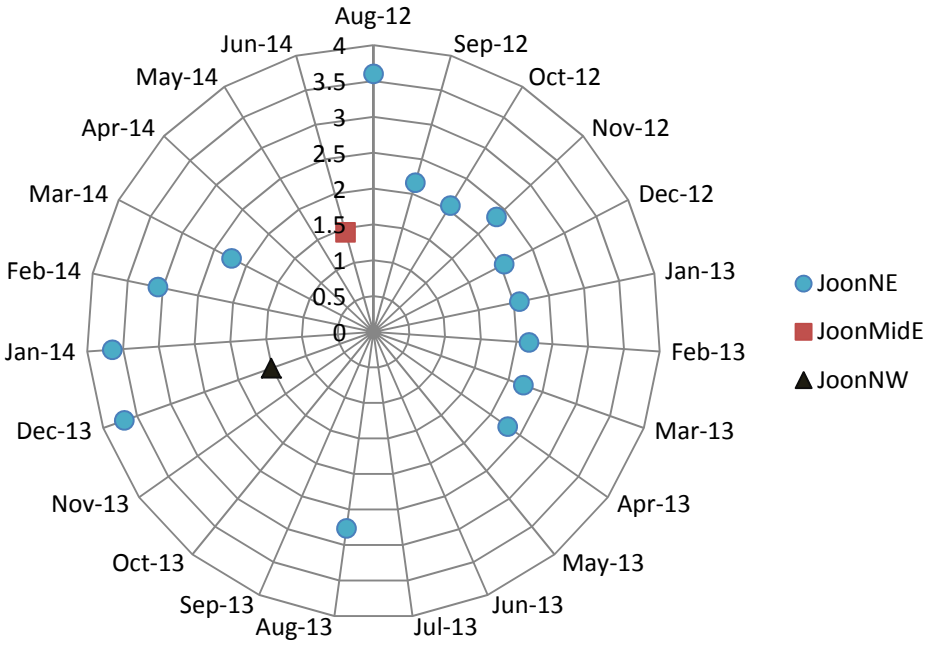


Figure 23. Radar plot showing all Cl:SO_4 molar ratios <4 only, of bores JoonE, JoonMidE and JoonNW over the monitoring period Aug 2012 to Jun 2014.

These results suggest that there is acidification of ASS occurring to the north-east of Lake Joondalup, where there is a large area of ASS known to occur (see Figure 18). Developments in Tapping or the pine forest could be responsible for the acidification, although given the slow rate of movement for groundwater it is possible that the acidification occurred a distance away several years ago and has only just reached the bore. The high limestone content of this area ensures that no acidity is detectable and that few metals are problematic.

Chloride is a conservative ion (not normally involved in biological processes) and so is very useful to understand the impact of evaporation on water bodies. Chloride concentrations should vary directly in response to evapo-concentration of the water. Correlations at combined sites between conductivity, temperature and chloride against water depth are shown in Table 2. The significant correlations between depth and chloride across all sites clearly show evapo-concentration occurs across the year. Temperature was only correlated at a couple of sites to depth, as it is highly variable depending on the time of day sampled and can be strongly influenced by shading. Conductivity includes parameters other than chloride and this can be seen in the absence of correlations with depth in the two drain sites. This suggests that other processes are releasing ions into the water that influence conductivity. It is likely that these two sites are showing the impacts of acid sulphate soils leaching metals into the water.

Table 4: Relationship between seasonal water level fluctuations and conductivity concentrations, temperature and chloride concentrations at each of the sites.

	Seasonal (Depth) effect		
Site	**Conductivity**	**Temperature**	**Cl**
Lake Goollelal	**		**
Drain South			*
Drain Central		*	*
Beenyup Swamp	**	**	*
Sth Lake Joondalup	**		**
Lake Joondalup	**		**

** P < 0.01
* P < 0.05

9.4.3 INVESTIGATION INTO ASS

The evidence of acidification around Drain South prompted an investigation into ASS within the park in October 2010 and April 2011 (Stage 1), focussed on the immediate surrounds of the channel linking Lake Goollelal and Wallubuenup Swamp. The likelihood of ASS had been identified in previous Yellagonga Regional Park water monitoring programs due to high metal concentrations, indicative ratios of sulphate to chloride and low pH. Using static net acidity generation tests (NAG), potential ASS was identified just north of Whitfords Ave (Figure 35) but not south. A more detailed investigation was recommended and subsequently commenced (Stage 2).

In Stage 2 soil profiles to a depth of 1.5 m were collected over a hectare. Soil strata were identified and then a combined sample from each stratum were analysed as per Department of Parks and Wildlife recommendations (pH_{ox}, SPOCAS, S_{cr}) and a range of metals. Stage 2 identified a majority of the area sampled as being ASS contaminated, with levels sufficiently high as to trigger the need for an ASS management plan. It was recommended that further work be undertaken to determine and map deposits of ASS within this section of Yellagonga Regional Park. The next stage (3), a series of four piezometers (down to 1.5 m) were installed around the known source of ASS, to confirm that metals and low pH from these sources were entering the wetland via groundwater (Figure 36). Production of a contour map of the area affected by ASS and beyond provided an illustration of possible ASS pockets that may be located in the area and how groundwater moved through the soils toward the channel. Six soil profiles were collected (to a depth of 1.5 m) to confirm that the ASS edges had been located.

The extent of the ASS identified in Stages 1 and 2 appears to be limited to the floodplain around site Drain Goollelal. There is evidence of ASS in groundwater, however this appears to be

generated at a distance from the drain and is neutralised before it reaches the drain. The western piezometer sample was observed high in P that warrants further investigation.

The study found that the area that had previously been sampled in Stages 1 and 2 represented the critical ASS areas that were most likely responsible for poor water quality seen in the Yellagonga wetlands monitoring studies. The area appeared to be limited to the extent of the floodplain (as demarcated by the presence of *Typha orientalis*). The extent of the area northwards is still unknown although it appears to have stopped by site Drain Central. It is possible that the construction of Whitfords Avenue may have been responsible for the disturbance of relocation of ASS that has become a problem at Drain Goollelal. The groundwater sampling confirms that there are traces of ASS impacts above the *T. orientalis* as determined through $Cl:SO_4$ ratios. A possible explanation, is that the low ratios of $Cl:SO_4$ are caused by ASS much higher in the landscape (as per GoolNE bore), that are being neutralised by limestone in the catchment. The neutralisation causes many of the metals to precipitate out simply leaving high sulphate in the waters close to Drain South.

Figure 24. Locations of soil profiles for Stage 2, Drain Goollelal and Drain South, and piezometers installed for Stage 3 of the assessment of ASS; road to the south is Whitfords Avenue, adapted from Google Earth.

The results confirm the extent of ASS and PASS in the area and under the Department of Environment and Conservation Guidelines this should trigger the development of a management plan for the area. Options for remediation/management of the site also need to be developed.

Recommendation 10

A management plan be developed and implemented in the area identified in the study by Lund et al (2013) as required by Department of Parks and Wildlife guidelines due to the confirmed presence of ASS and PASS. As part of the management plan, control options need to be investigated to mitigate on-going contamination of the Yellagonga wetlands.

9.5 METAL CONTAMINATION

The toxicity of certain metals including cadmium, nickel and zinc is reduced with increasing water hardness (which is primarily determined by concentrations of Ca, Mg and also Se, Fe, Al, Zn and Mn). Generally the waters of the park are hard ranging to extremely hard. In 2010/11, hardness was at its highest, whereas in 2012/13 it was low (Figure 25). There were minor changes in Ca between sites when all data were combined, with slightly higher Mg concentrations in Lakes Goollelal and Joondalup compared to the other sites (Figure 26). Direct comparison of changes over time between Lakes Goollelal and Joondalup for both Ca and Mg show moderate correlations between ions within each lake (Goollelal r^2=0.65; Joondalup r^2=0.54), with a moderate correlation for Mg between both lakes (r^2=0.65) but weak for Ca (r^2=0.27). To determine if these relationships were related to evapo-concentration, they were compared with Cl (Figure 27) with Lake Goollelal showing Mg was poorly correlated to Cl (r^2=0.29) but Ca was not correlated; in contrast Lake Joondalup Ca was poorly correlated to Cl (r^2=0.24) and Mg strongly correlated (r^2=0.77). These correlations show that there were strong seasonal trends in both Ca and Mg driven primarily by evapo-concentration, but this relationship was much weaker for Ca than Mg. Although Ca is used in a range of biological processes, the lack of correlations might reflect release of Ca as a result of acidification and subsequent neutralisation by calcium carbonate (Jeziorski *et al.*, 2008).

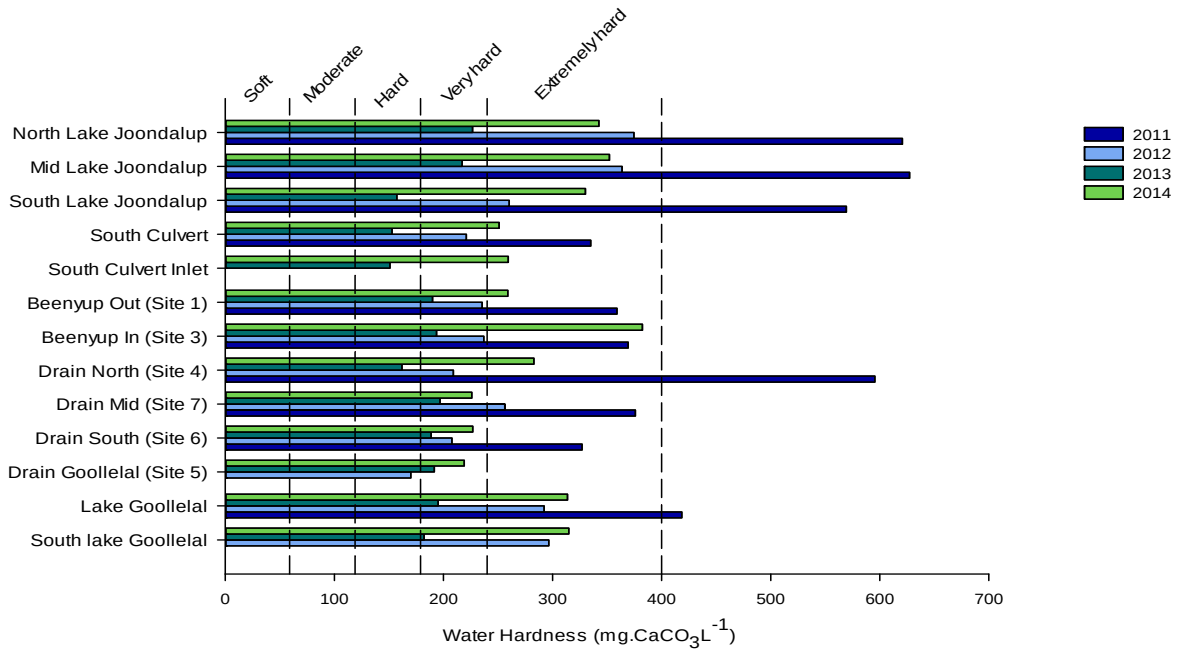


Figure 25. Calculated mean water hardness of each site for the consecutive years of monitoring (2011-2014), with ANZECC/ARMCANZ (2000) categories indicated.

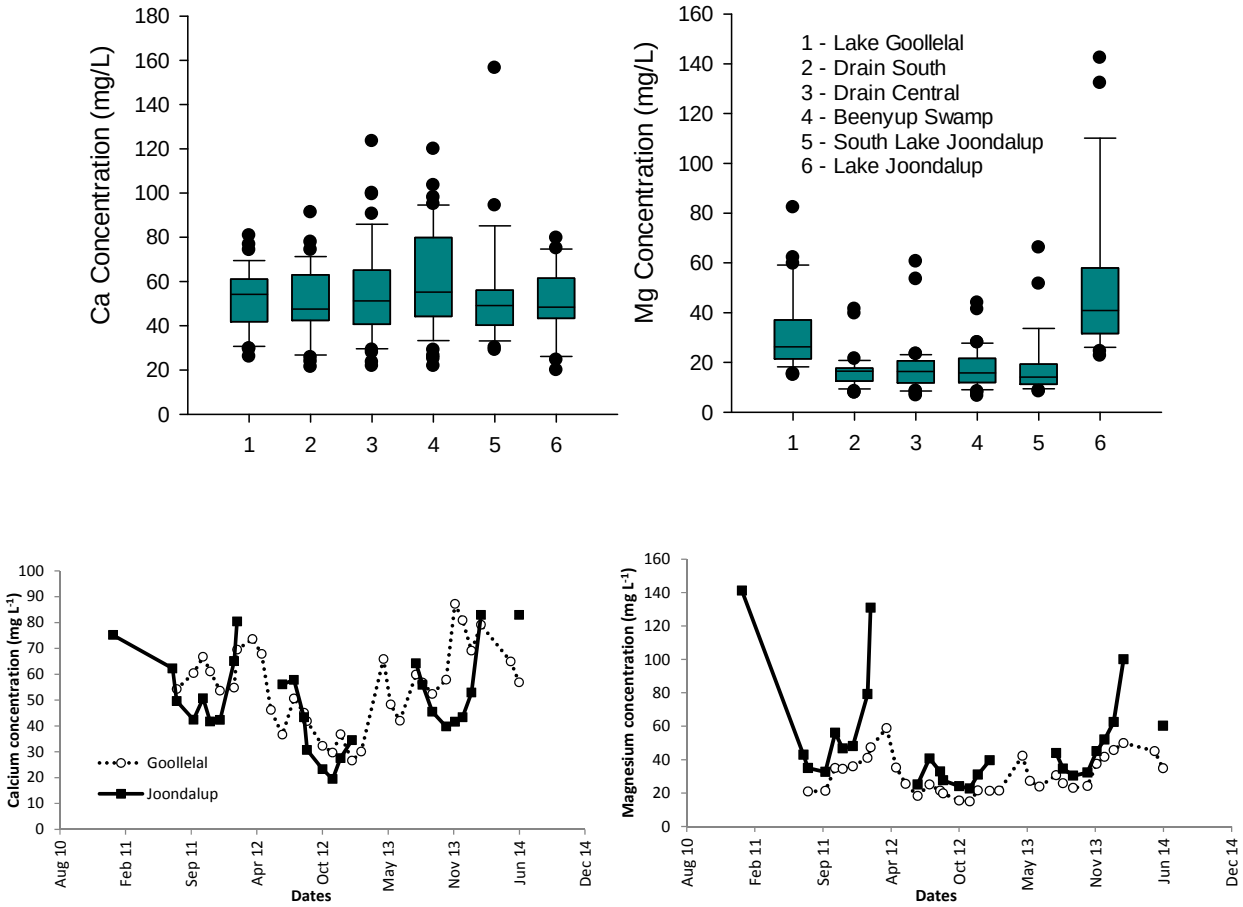


Figure 26. Box plots for some of calcium and magnesium at each site and changes in concentrations in Lake Goollelal and Lake Joondalup over the monitoring period 2010-2014.

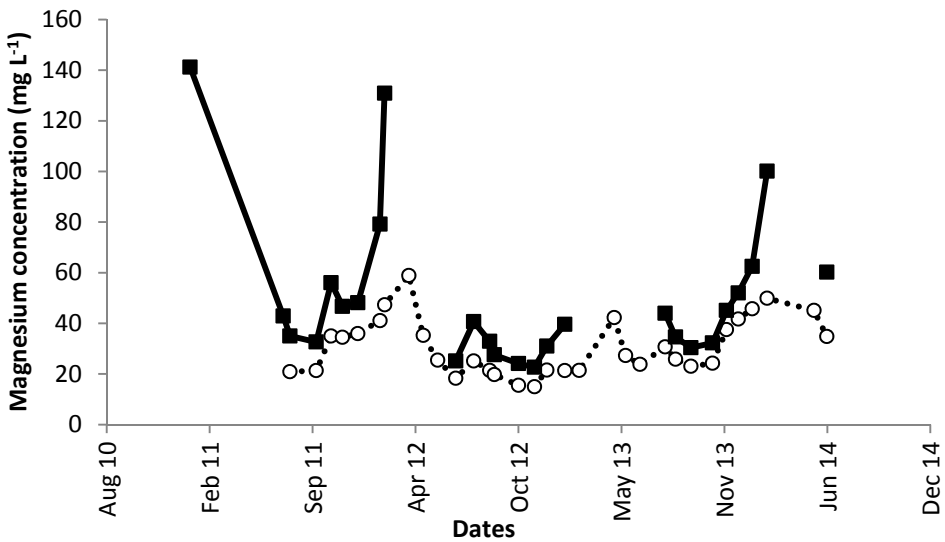


Figure 27. Chloride concentrations from Lakes Goollelal and Joondalup between 2010 and 2014

Metals are naturally found in surface waters as well as being a sign of contamination (e.g stormwater drainage) or as a result of acidification. To assess whether metal concentrations pose any risks to the ecosystem, comparison to ANZECC/ARMCANZ (2000) guidelines can be useful. Values exceeding the guidelines are a risk to organisms found in the wetlands. The guidelines recommend that exceedances need to be investigated closely to determine the consequences of these metal concentrations. In Table 5, the exceedances recorded for metals with trigger values known for the 95% protection of aquatic ecosystems are shown. A 95% level of protection was chosen to represent the urban and disturbed nature of much of the park. For some metals such as Cd, Cr and Hg, the detection limits of analysis used were higher than the trigger values and so these have been flagged as possible exceedances of the trigger values. However with better detection limits in 2013/14 only Hg was found to actually exceed the trigger value in that year, but all three metals had concentrations well above the triggers (see Table 6). Metals such as Co, Ca, Fe, K, Mg, Mn and Na either don't have trigger values or are considered to be safe. Aluminium and As frequently exceeded the guidelines, in all years except 2013/14 where there were only 2 exceedances for each metal. Aluminium was highest in 2012/13, whereas As had the highest peak value in 2011/12 but the highest average in 2009/10. In 2013/14 there might have been exceedances of Se and U, although this could simply be due to a couple of high detection limits. Nickel had the most exceedances in 2011/12 with a peak value of 0.106 mg L^{-1}, which is less than the highest harness corrected trigger value. Zinc frequently exceeded trigger values in all years. At the time of the acidification event at Drain South, metal concentrations rose to high levels but appear to have generally recovered to levels below trigger values in 2013/14. Occasional spikes of Al, As, Hg and Zn still occur and therefore may not be solely due to acidification.

Long-lived organisms such as turtles can accumulate metals and suffer chronic toxic effects. Although little is known about metal toxicity in turtles, two dead turtles (*Chelodina oblonga*) collected from Lake Goollelal in March 2010 were analysed for metals and Mg, Hg and Cu were just above minimum reportable levels, while Co and Cr were higher in one animal, As, Cd, Ni, and Pb were below reportable levels (Department of Environment and Conservation). Given that most of highest metal concentrations were detected north of Lake Goollelal, these concentrations in turtles might be much higher in other parts of the park.

Recommendation 11.

Acidification leads to high concentrations of potentially toxic metals that significantly exceed recommended trigger values. It is recommended that attempts to control metal concentrations through preventing acidification should be a high priority to protect biodiversity in the park.

Table 5. Exceedance of ANZECC/ARMCANZ (2000) water quality guidelines for the 95% protection of aquatic ecosystems for metals and metalloids recorded in this study (Number exceeding trigger value and in brackets number exceeding detection limit (all in 2014)).

Metal/ Metalloid (mg L^{-1})	ANZECC/ ARMCANZ (2000) Trigger Value	2009/10	2010/11	2011/12	2012/13	2013/14
Aluminium (Al)	0.055	3 (27)	16 (25)	17 (99)	94 (111)	2
Arsenic (As)	0.013 - 0.024*	23 (36)	(0)**	15 (21)	8 (27)	2
Calcium (Ca)	—	(78)	(36)	(149)	(121)	0
Cadmium (Cd)	0.0009—0.0030[H]	23 (23)**	6 (6)**	57 (57)**	61 (70)**	0
Cobalt (Co)	ID	(10)	(36)	(39)	(41)	0
Chromium (Cr)	ID - 0.004*	9 (9)**	1(1)**	34 (34)**	44 (44)**	0
Iron (Fe)	ID	(78)	(31)	(121)	(104)	0
Mercury (Hg)	0.0006 - ID*	5 (5)**	(0)	2 (2)	12 (120)	2
Potassium (K)	—	(78)	(36)	(122)	(120)	0
Magnesium (Mg)	—	(78)	(36)	(122)	(121)	0
Manganese (Mn)	1.9	(53)	(26)	(75)	(48)	0
Sodium (Na)	—	(78)	(36)	(122)	(121)	0
Nickel (Ni)	0.047—0.146[H]	4 (11)	(0)	20 (58)	5 (44)	0
Selenium (Se)						2[#]
Uranium (U)	0.005[+]					1[#]
Zinc (Zn)	0.034—0.106[H]	20 (20)**	22 (25)	59 (60)	9 (14)	5

[H] Range of values (over all years) corrected for hardness (increases trigger) as per ANZECC/ARMCANZ (2000), hardness calculated from mean values of collected data for Ca, Mg, Sr, Fe, Al, Zn and Mn.

* Range for As III and V, Cr III and VI, and Hg inorganic and methyl.

** Detection limit was greater than the trigger value, therefore a conservative assessment assumes that all values potentially exceeded trigger values, however this may not have been the case.

ID Insufficient data to derive a reliable trigger value.

— No trigger provided in ANZECC/ARMCANZ (2000)

\+ Low reliability, interim working level as prescribed in ANZECC/ARMCANZ (2000)

\# Concentrations were BDL due to an increase in the limit of recording as a result of dilution.

Table 6. Mean ± se (maximum value) concentrations of selected metals recorded across all sites in each sampling year

Metal/ Metalloid (mg L^{-1})	2009/10	2010/11	2011/12	2012/13	2013/14
Aluminium (Al)	0.03±0.003 (0.07)	0.065 ± 0.005 (0.11)	0.037 ± 0.003 (0.11)	0.08 ± 0 (0.14)	0.012 ± 0.001 (0.12)
Arsenic (As)	0.04±0.004 (0.11)	<0.02	0.007 ± 0.00 (0.35)	0.01 ± 0 (0.05)	0.0037 ± 0.0003 (0.03)
Calcium (Ca)	42.4±2.3 (96.0)	87.26 ± 7.49 (216.8)	56.597 ± 2.067 (216.8)	45.0 ± 1.46 (114.1)	65.2 ± 2.9 (197.2)
Cadmium (Cd)	0.04±0.004 (0.08)	0.008 (0.012)	0.0043 ± 0.0003 (0.019)	0.01 ± 0 (0.03)	0.0001 ± 0 (0.0006)
Cobalt (Co)	0.04±0.007 (0.08)	0.02 ± 0.0003 (0.035)	0.0066 ± 0.0004 (0.029)	0.01 ± 0 (0.05)	0.0006 ± 0.0003 (0.03)
Chromium (Cr)	0.04±0.007 (0.06)	<0.005 (0.008)	0.007 ± 0.0005 (0.028)	0.01 ± 0 (0.05)	0.0013 ± 0 (0.0034)
Iron (Fe)	0.63±0.12 (9.2)	0.56 ± 0.09 (1.47)	1.1 ± 0.39 (7.42)	0.53 ± 0.07 (6.1)	0.48 ± 0.05 (3.05)
Mercury (Hg)	0.08±0.009 (0.11)	<0.05	0.026 ± 0.001 (0.172)	0.04 ± 0.01 (0.79)	0.0003 ± 0 (0.0007)
Potassium (K)	4.9±0.4 (18.81)	17.36 ± 3.89 (52.12)	11.90 ± 1.46 (48.03)	7.13 ± 0.51 (29.01)	13.23 ± 0.91 (59)
Magnesium (Mg)	14.3±0.8 (31.79)	58.44 ± 9.77 (143.5)	28.35 ± 4.23 (133.60)	17.15 ± 0.75 (44.75)	33.18 ± 2.6 (122.86)
Manganese (Mn)	0.04±0.004 (0.12)	0.083 ± 0.023 (0.37)	0.029 ± 0.011 (0.179)	0.02 ± 0 (0.15)	0.02 ± 0 (0.09)
Sodium (Na)	64.7±3.5 (150.7)	235 ± 62.4 (811.9)	124.8 ± 22.82 (653.7)	89.08 ± 4.54 (287.3)	134.89 ± 9.68 (622.21)
Nickel (Ni)	0.04±0.006 (0.08)	<0.02	0.026 ± 0.002 (0.106)	0.02 ± 0 (0.09)	0.001 ± 0.0001 (0.007)
Selenium (Se)					0.001 ± 0.0003 (0.025)
Uranium (U)					0.0024 ± 0.0005 (0.05)
Zinc (Zn)	0.09±0.01 (0.23)	0.107 ± 0.012 (0.19)	0.082 ± 0.017 (0.304)	0.03 ± 0 (0.2)	0.019 ± 0.002 (0.08)

Wangara sump collects surface runoff from the Wangara industrial area and directs it to a sump for storage and evaporation. This sump is located close to the eastern edge of Wallubuenup Swamp. There is provision for the sump to overflow into Wallubuenup Swamp if water levels get too high, although the authors have never seen this occur since 2010. In 2010, Ms J. Gill (as part of Masters Project) sampled the soils between the sump and Wallubuenup Swamp as shown in Figure 28. At all sites she found Hg (<2 µg g^{-1}), Se (<5 µg g^{-1}), U (<5 µg g^{-1}) below detection and As mainly below detection (<2 µg g^{-1}) with one value of 2.6 µg g^{-1} and Cd also below detection (<1 µg g^{-1}) with a few positive measurements reaching 11.3 µg g^{-1} (not at site G). Chromium reached 91 µg g^{-1}, Ni 27 µg g^{-1} and Zn reached 1206 µg g^{-1} (although most values were <200 µg g^{-1}). Davis *et al.* (1993) found much higher concentrations of As in Lake Goollelal sediments, but much lower levels of Zn (17-18 µg g^{-1}). Colwell's P (a measure of readily available P) was <30 mg kg^{-1} at all sites except A1 (52 mg kg^{-1}) and F (146 mg kg^{-1}). Only the two higher values would be considered to be enriched. Therefore there doesn't appear to be evidence of significant contamination of the swamp by surface runoff from the sump.

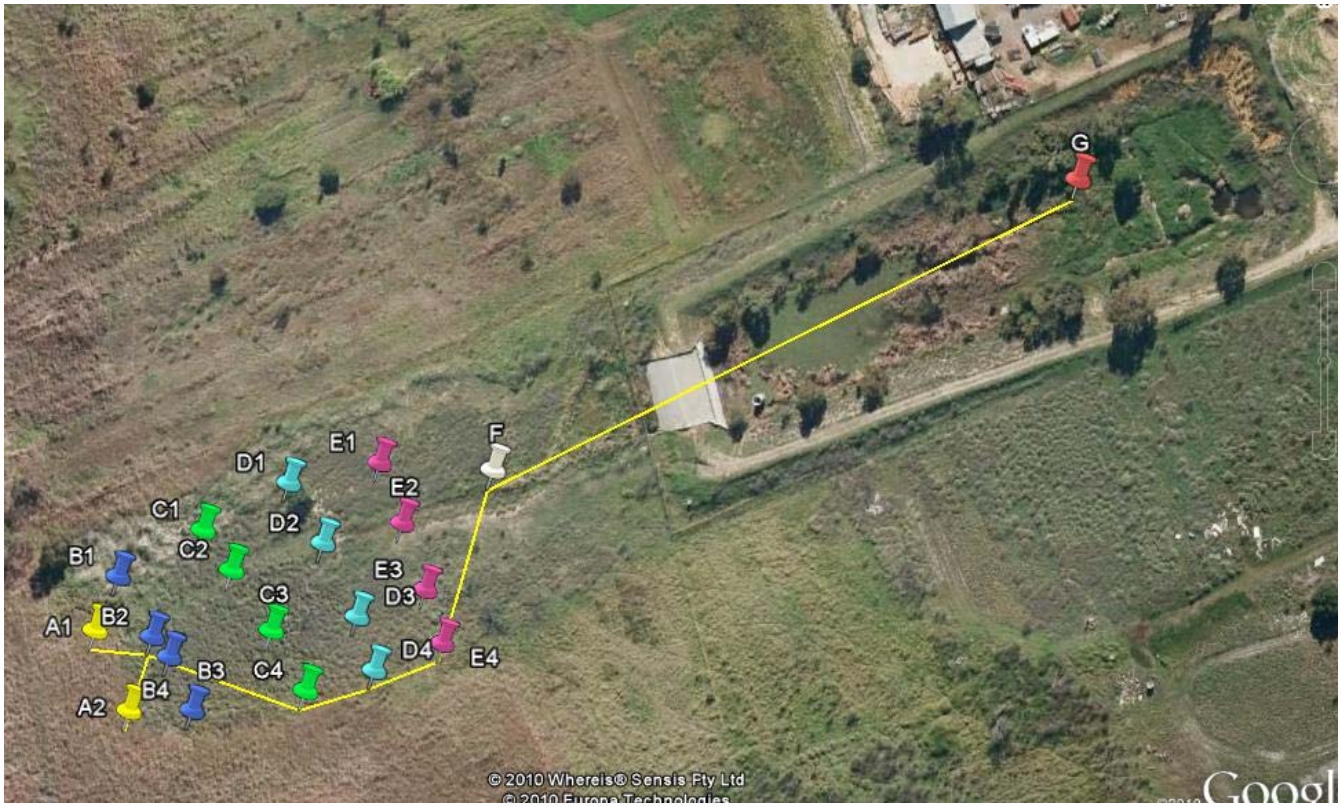


Figure 28. Soil sampling sites in the downstream flow of any overflow or seepage from Wangara Sump (photograph from Google Earth 2010)

10. CONCLUSIONS

Yellagonga Park contains a chain of wetlands from south of the park at Lake Goollelal through to Lake Joondalup in the north and includes Beenyup and Wallubuenup Swamps. Monitoring of the water quality of surface water located within Yellagonga Regional Park has been undertaken monthly since December 2010 as part of the Yellagonga Integrated Catchment Management Plan 2009-2014. A previous study by Lund et al (2009) provides data for 6 of the monitoring sites included in the regime and is combined into this. Since August 2012, monthly monitoring of 8 groundwater bores was commenced to provide a better understanding of the hydrology within the Park. In addition, the review incorporates external data retrieved from the Department of Water and Bureau of Meteorology to support the findings in this report. The focus was on the present condition of the wetland chain, underlying trends and current threats to the health of the wetlands.

The reviewed aimed:

- to determine whether the sites currently monitored are capturing the key elements on a spatial and temporal level;
- to identify trends and assess the significance of those trends in the context of natural seasonal occurrence versus anthropogenic impacts;
- to make an overall assessment of current threats and risks to the health of the wetlands within the park.

The current monitoring program appears to be suitable for understanding key elements on spatial and temporal scales. In the surface monitoring, some simplification of the current program is warranted but groundwater monitoring is recommended to continue in its current forms, expanded to include two new bores provided by the Cities. Key issues for the park are declining water levels, eutrophication, nuisance midges, acidification and heavy metals. Of these, declining water levels caused by over-abstraction of groundwater or climate change is the most significant driver of issues in the park, driving midge problems and acidification. Eutrophication remains an underlying problem but currently tackling the issue will provide minimal benefits to the wetland chain.

It is clear from the review that the current management focus needs to move to managing declining water levels. This review contains several recommendations that seek to aid this focus. The future value of the park is dependent on management actions taken now, as complete drying of either Lake Joondalup or Lake Goollelal may lead to irreversible damage to the wetland ecosystem.

11. REFERENCES

Ali, A. (1991). Perspectives on management of pestiferous Chironomidae (Diptera), an emerging global problem. *Journal of the American Mosquito Control Association* 7: 260-281.

Allen, A. D. (1980). *The hydrogeology of Lake Jandabup, Swan Coastal Plain, W.A.* Annual Report 1979.

ANZECC/ARMCANZ (2000). *Australian and New Zealand guidelines for fresh and marine water quality, Volume 2. Aquatic ecosystems - rationale and background Information*. Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

APHA (1999). Standard methods for the examination of water and wastewater. 20th edn, American Public Health Association, American Water Works Association, Water Environment Federation, Washington DC, USA. 1,220pp.

Appleyard, S.; Wong, S.; Willis-Jones, B.; Angeloni, J. & Watkins, R. (2004). Groundwater acidification caused by urban development in Perth, Western Australia: source, distribution, and implications for management. *Australian Journal of Soil Research* 42: 579-585.

Barron, O. V.; Barr, A. D. & Donn, M. J. (2013). Effect of urbanisation on the water balance of a catchment with shallow groundwater. *Journal of Hydrology* 485: 162-176.

Boardman, L. (2000). *Metaphyton in Lake Joondalup*. 4th Year project Bachelor of Engineering (Environmental), University of Western Australia, Perth, Australia. 82pp.

Bryant, T. (2000). *The release of phosphorus from wetland sediment: A study of Lake Joondalup.* Third Year Environmental Management Project Report Edith Cowan University, Perth.

Congdon, R. A. (1985). *The water balance of Lake Joondalup*. Bulletin 183. Western Australian Department of Conservation and Environment, Lib Bk.

Congdon, R. A. (1986). *Nutrient loading and phytoplankton blooms in Lake Joondalup, Wanneroo, Western Australia*. Technical Series 6. Department of Conservation and Environment, Western Australia, Lib Copy Q574.52632209941 Con.

Congdon, R. A. & McComb, A. J. (1976). The nutrients and plants of Lake Joondalup, a mildly eutrophic lake experiencing large seasonal changes in volume. *Journal of the Royal Society of Western Australia* 59: 14-23.

Cumbers, M. (2004). *Improving nutrient management at Lake Joondalup, Western Australia, through identification of key sources and current trajectories,* Honours thesis, Edith Cowan University, Perth.

Davis, J. A.; McGuire, M.; Robson, B. & Lund, M. A. (2002). Predicting wetland response to nutrient enrichment: modelling temperature, algal blooms and nuisance midge swarms. *Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie {Verh. int. Ver. Limnol.}* 28: 635-340.

Davis, J. A.; Rosich, R. S.; Bradley, J. S.; Growns, J. E.; Schmidt, L. G. & Cheal, F. (1993). Wetland classification on the basis of water quality and invertebrate community data. Water Authority of Western Australia and the Western Australian Department of Environmental Protection, Perth. 242pp.

Department of Environment (2003). *General Guidance on Managing Acid Sulphate Soils*. Department of Environment (WA), Perth, Western Australia. 23pp.

Department of Environment and Conservation (2013). *Identification and investigation of acid sulfate soils and acidic landscapes*. Department of Environment and Conservation, 82pp.

Department of Local Government and Planning & Department of Natural Resources and Mines (2002). *State Planning Policy 2/02 Guideline: Planning and Managing Development involving Acid Sulfate Soils*. Indooroopilly Brisbane, QLD, Australia.

Dooley, B.; Bowra, T.; Cluning, D. & Thompson, P. (2003). *Yellagonga Regional Park: management plan, 2003-2013*. Perth.

Froend, R.; Loomes, R.; Horwitz, P.; Bertuch, M.; Storey, A. & Bamford, M. (2004). *Study of ecological water requirements on the Gnangara and Jandakot Mounds under Chapter 46 of the Environmental Protection Act. Task 2: Determination of ecological water requirements*. 239pp.

Goldsmith, K.; Lund, M. A. & McCullough, C. D. (2008). *Nutrient Loading in Sediment of Beenyup Swamp (Yellagonga Regional Park)*. MiWER/Centre for Ecosystem Management, Perth. 32pp.

Gordon, D. M.; Finlayson, C. M. & McComb, A. J. (1981). Nutrients and phytoplankton in three shallow freshwater lakess of different trophic status in Western Australia. *Australian Journal of Marine and Freshwater Research* 32: 541-553.

Gunner, R.; Lund, M. & McCullough, C. (2008). *Factors controlling the release of sediment-bound phosphorus from a seasonal wetland (Beenyup Swamp)*. Report Mine Water and Environment Research/Centre for Ecosystem Management, Perth. 32pp.

Hamann, J. A. (1992). *Lake level changes within the Yellagonga Regional Park: A historical perspective,* Honours thesis, Edith Cowan University, Perth.

Helleyna, F. (2013). *Investigation of the potential for a constructed wetland at South Lake Joondalup*. Research Student Report Series 60pp.

Hinwood, A. L.; Horwitz, P.; Appleyard, S.; Barton, C. & Wajrak, M. (2006). Acid sulphate soil disturbance and metals in groundwater: Implications for human exposure through home grown produce. *Environmental Pollution* 143: 100-105.

Jarvis, B. (1994). *Management of lake water levels in the north west corridor*. Report. Water Authority, Perth.

Jeziorski, A.; Yan, N. D.; Paterson, A. M.; DeSellas, A. M.; Turner, M. A.; Jeffries, D. S.; Keller, B.; Weeber, R. C.; McNicol, D. K.; Palmer, M. E.; McIver, K.; Arseneau, K.; Ginn, B. K.; Cumming, B. F. & Smol, J. P. (2008). The Widespread Threat of Calcium Decline in Fresh Waters. *Science* 322: 1374-1377.

Khwanboonbumpen, S. (2006). *Sources of nitrogen and phosphorus in stormwater drainage from established residential areas and options for improved management,* Ph.D. thesis, Edith Cowan University, Perth.

Kinnear, A. & Garnett, P. (1999). Water chemistry of the wetlands of the Yellagonga Regional Park, Western Australia. *Journal of the Royal Society of Western Australia* 82: 79-85.

Kinnear, A.; Garnett, P.; Bekle, H. & Upton, K. (1997). *Yellagonga wetlands: A study of the water chemistry and aquatic fauna*. Edith Cowan University, Perth. Got copy.

Lund, M.; McCullough, C. & Newport, M. (2011a). *Nutrient and metal loads in and out of Beenyup Swamp*. Unpublished report to City of Wanneroo, City of Joondalup and Department of Environment and Conservation 20011-15. Mine Water and Environment Research Centre/Centre for Ecosystem Management, Perth. 55pp.

Lund, M. A. (2003). *Monitoring Program of the Cities of Joondalup and Wanneroo: A Review*. Report No. 2003-02. Centre for Ecosystem Management, Edith Cowan University, Perth.

Lund, M. A.; Brown, S. & Lee, G. (2000). *Controlling midges at Lake Joondalup and Lake Goolelall*. Report 2000-10. Centre for Ecosystem Management, Edith Cowan University, Perth. My report.

Lund, M. A.; McCullough, C. D. & Galeotti, D. (2010). Remediation of water quality and macroinvertebrate communities in an urban artificial lake affected by acid sulphate soils. *Verhandlungen der Internationalen Vereinigung für Limnologie* 32: 1,373-1,378.

Lund, M. A.; McCullough, C. D.; Somesan, N.; Edwards, L. & Reynolds, B. (2011b). *Yellagonga wetlands nutrient and metal study*. 2009-15. City of Wanneroo, City of Joondalup and Department of Environment and Conservation, Perth, Western Australia. 43pp.

Lund, M. A. & Ryder, D. S. (1998). Can artificially generated gilvin (g440 m^{-1}, Gelbstoff) be used as a tool for lake restoration. *Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie* 26: 731-735.

McArthur, W. M. & Bartle, G. A. (1980). *landforms and soils as an aid to urban planning in the Perth metropolitan north west corridor, Western Australia*. CSIRO, Melbourne.

National Working Party on Acid Sulfate Soils (2000). *National Strategy for the Management of Coastal Acid Sulfate Soils*. Wollongbar, NSW, Australia. 39pp.

Newport, M. & Lund, M. A. (2012). *Review of Yellagonga Regional Park wetlands groundwater data*. CEM Report 2012-14. Mine Water and Environment Research Centre/Centre for Ecosystem Management, Perth, Australia. 160pp.

Ove Arup & Partners (1994). *Yellagonga Regional Park Drainage Study*. Perth.

Roberts, M. (2003). *Investigation into the population dynamics and key life history characteristics of non-biting midge (Diptera: Chironomidae) which can be utilised to improve nuisance control at Lake Joondalup, Western Australia,* Honours thesis, Edith Cowan University, Perth.

Rose, T. W. (1979). *Periphyton and metaphyton in Lake Joondalup,*thesis, University of Western Australia,

Sammut, J.; White, I. & Melville, M. D. (1996). Acidification of an estuarine tributary in eastern Australia due to drainage of acid sulphate soils. *Marine and Freshwater Research* 47: 669-684.

Sommer, B. (2006). *Drying and re-wetting of organic wetland sediments: Biogeochemistry and implications for wetland management,* Ph.D. thesis, Edith Cowan University, Perth.

Sommer, B. & Horwitz, P. (2001). Water quality and macroinvertebrate response to acidification following intensified summer droughts in a Western Australian wetland. *Marine and Freshwater Research* 52: 1015-1021.

Storey, A. W.; Vervest, R. M.; Pearson, G. B. & Halse, S. A. (1993). Waterbird usage of wetlands on the Swan Coastal Plain. Water Authority of Western Australia and the Western Australian Department of Environmental Protection, Perth. 168pp.

Suffell, K. (2002). *Improving management of nuisance midges (Diptera: Chironomidae) in Perth (Western Australia) wetlands based on their responses to temperature and sediment type,* Honours thesis, Edith Cowan University, Perth.

Wong, V. (2003). *Metaphyton and phosphorus dynamics at Lake Joondalup, Western Australia,* Honours thesis, University of Western Australia, Perth.

Wrigley, T. J.; Rolls, S. W. & Davis, J. A. (1991). Limnological features of coastal-plain wetlands on the Gnangara Mound, Perth, Western Australia. *Australian Journal of Marine and Freshwater Research* 1991: 761-773.

12. APPENDICES

12.1 LAKE GOOLLELAL

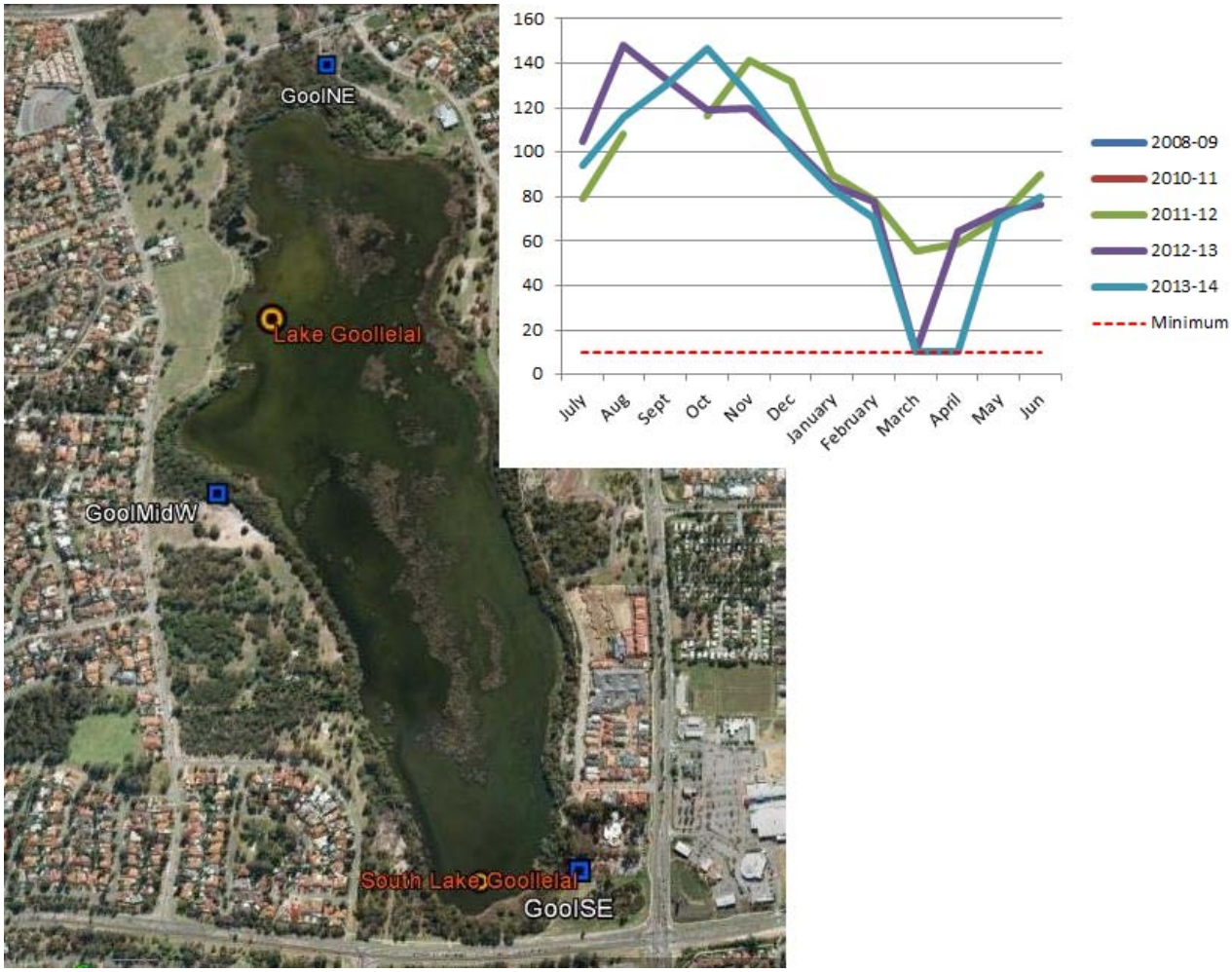


Figure 29. Aerial map of the two combined sites at Lake Goollelal (GoogleMaps) and adjacent bores GoolSE, GoolMidW and GoolNE with comparison of inter-annual water levels (July-June), threshold level of 10cm when sampling did not occur.

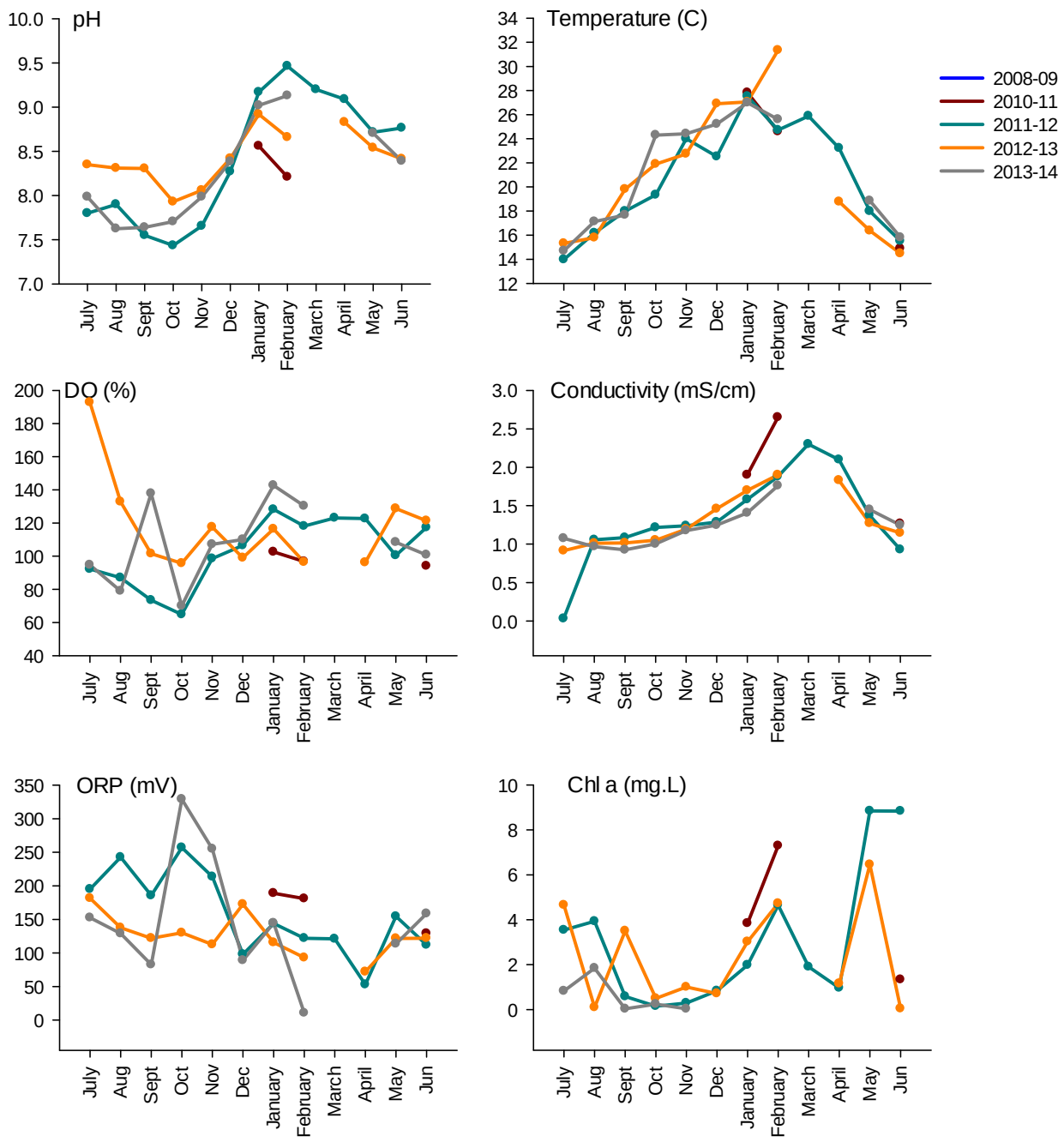


Figure 30. Inter-annual comparison of physico-chemical parameters for surface water at Lake Goollelal over the monitoring period from July to June.

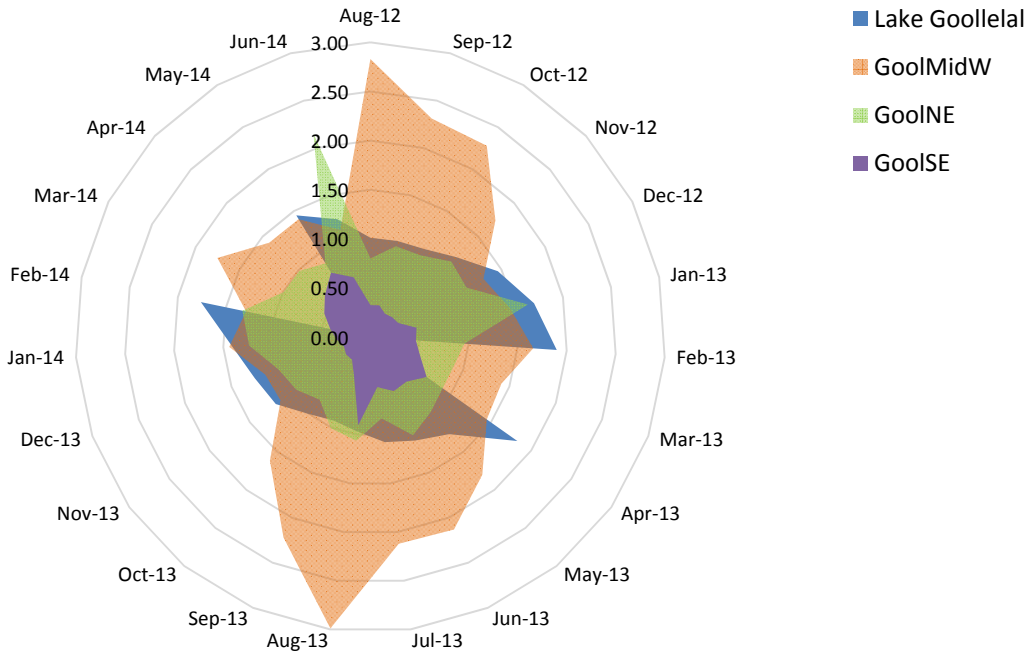


Figure 31. Radar plot showing electrical conductivity in water samples from Lake Goollelal and adjacent bores GoolMidW, GoolNE and GoolSE from August 2012 to June 2014.

12.2 DRAIN SOUTH

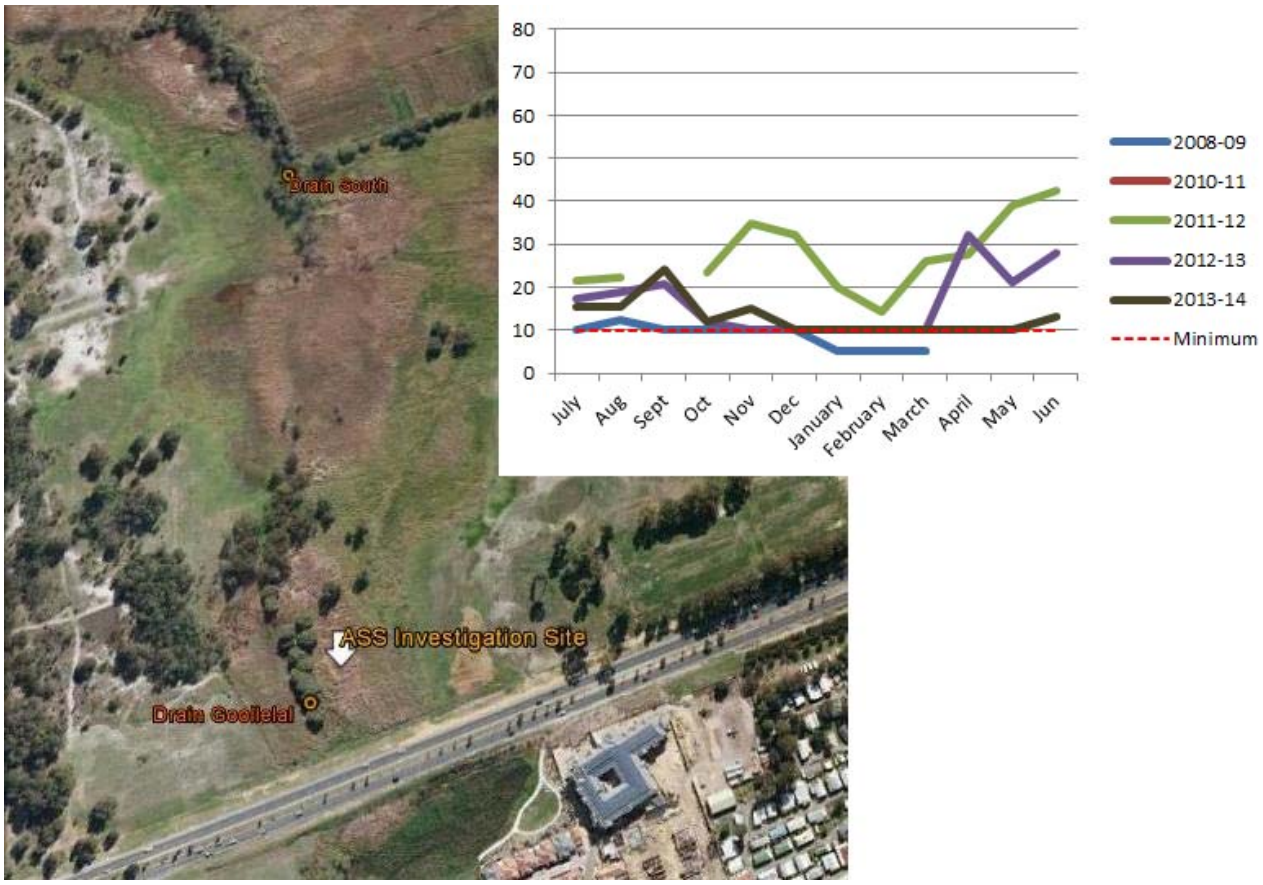


Figure 32. Aerial map of the two combined sites at Drain South (GoogleMaps) with comparison of inter-annual water levels (July-June), threshold level of 10cm when sampling did not occur.

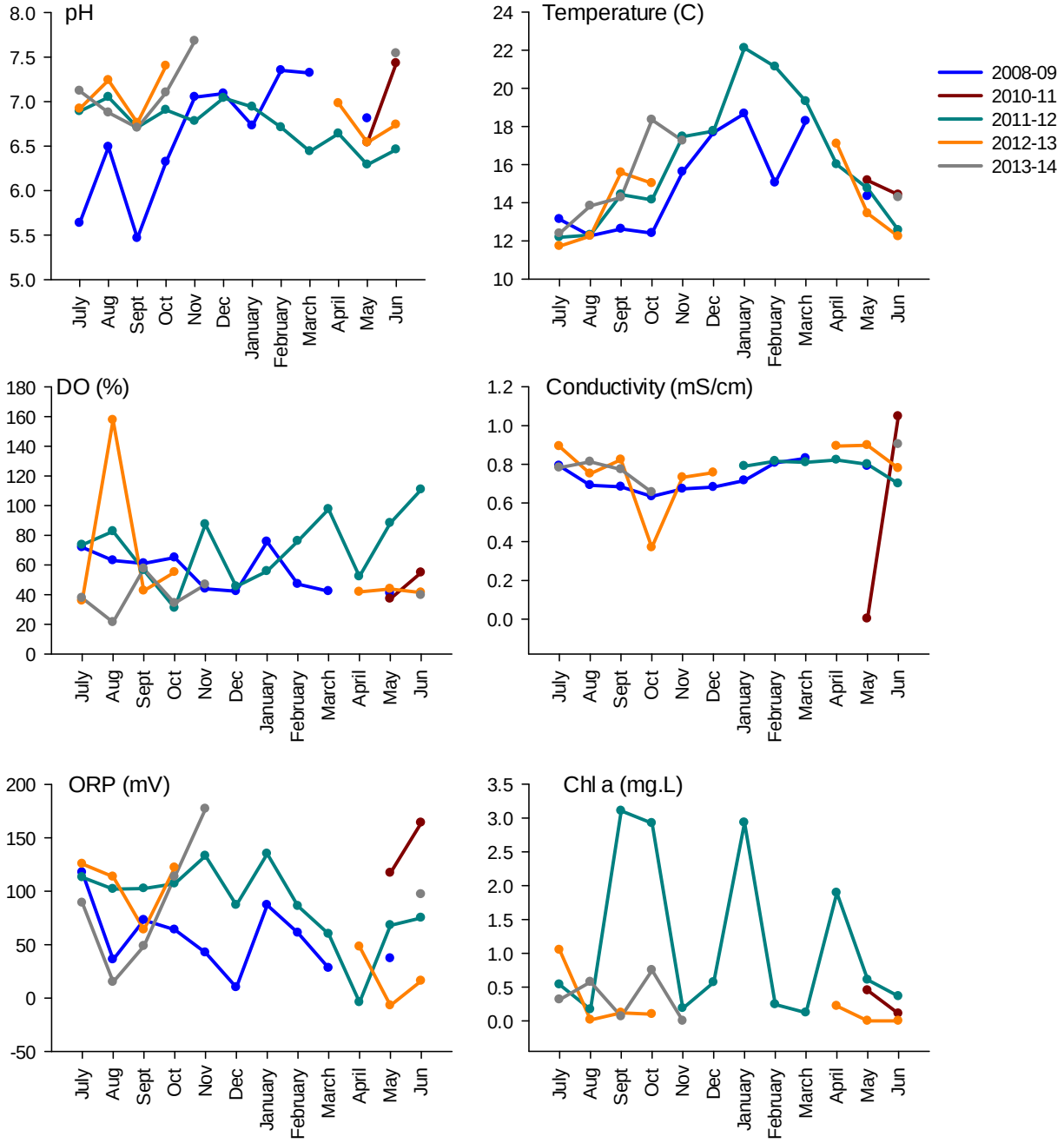


Figure 33. Inter-annual comparison of physico-chemical parameters for surface water at Drain South over the monitoring period from July to June.

12.3 DRAIN CENTRAL

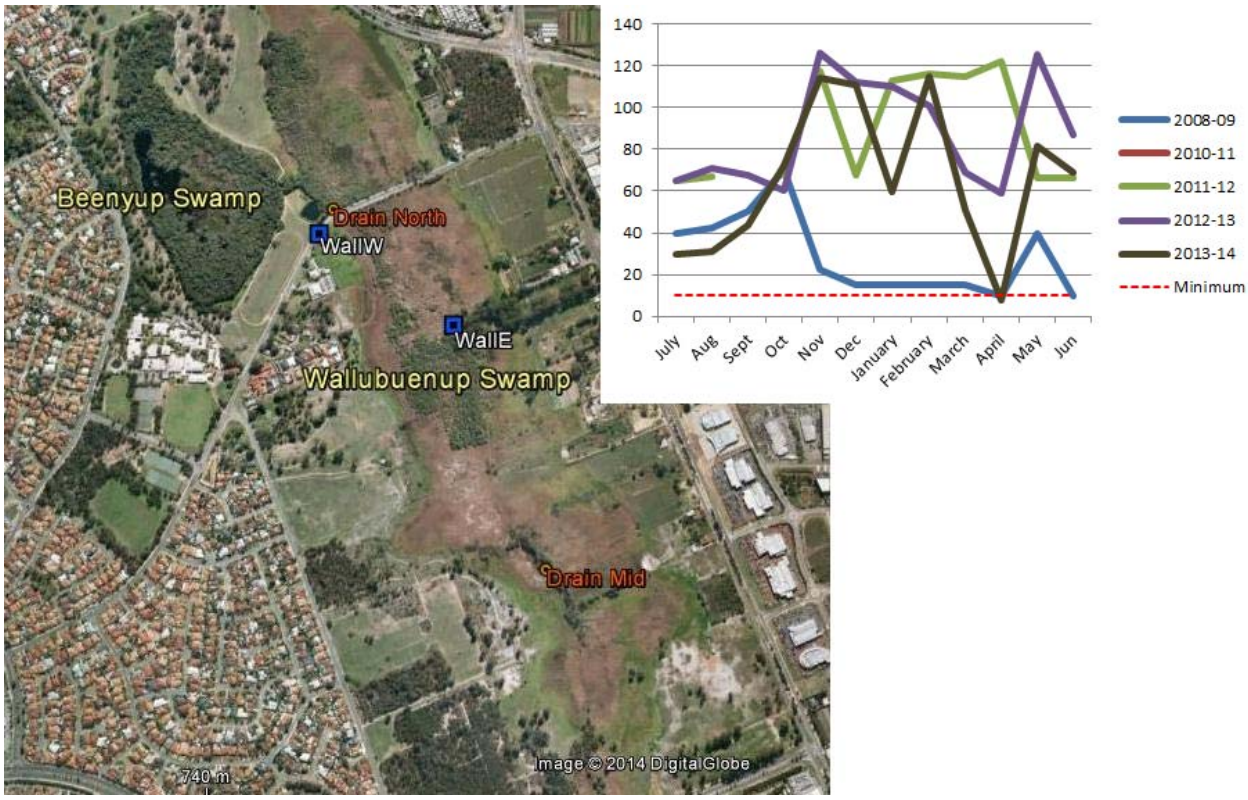


Figure 34. Aerial map of the two combined sites at Drain Central (GoogleMaps), adjacent bores WallW and WallE with comparison of inter-annual water levels (July-June), threshold level of 10cm when sampling did not occur.

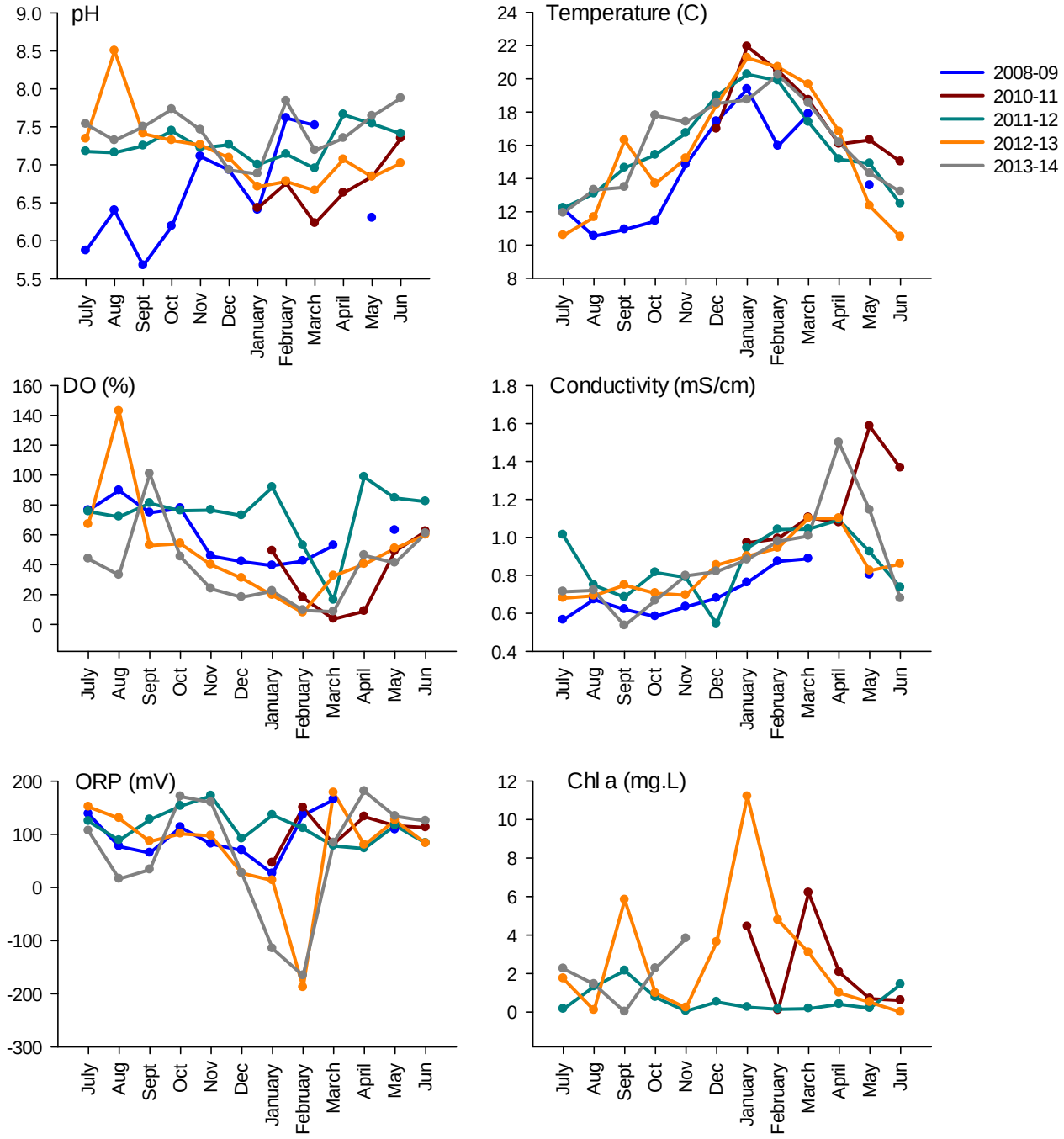


Figure 35. Inter-annual comparison of physico-chemical parameters for surface water at Drain Central over the monitoring period from July to June.

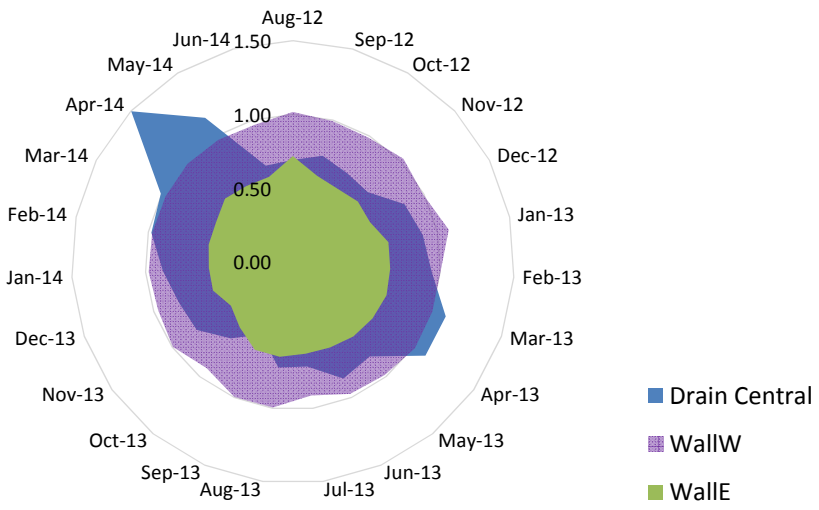


Figure 36. Radar plot showing hydraulic conductivity in water samples from Drain Central and adjacent bores WallW and WallE from August 2012 to June 2014.

12.4 BEENYUP

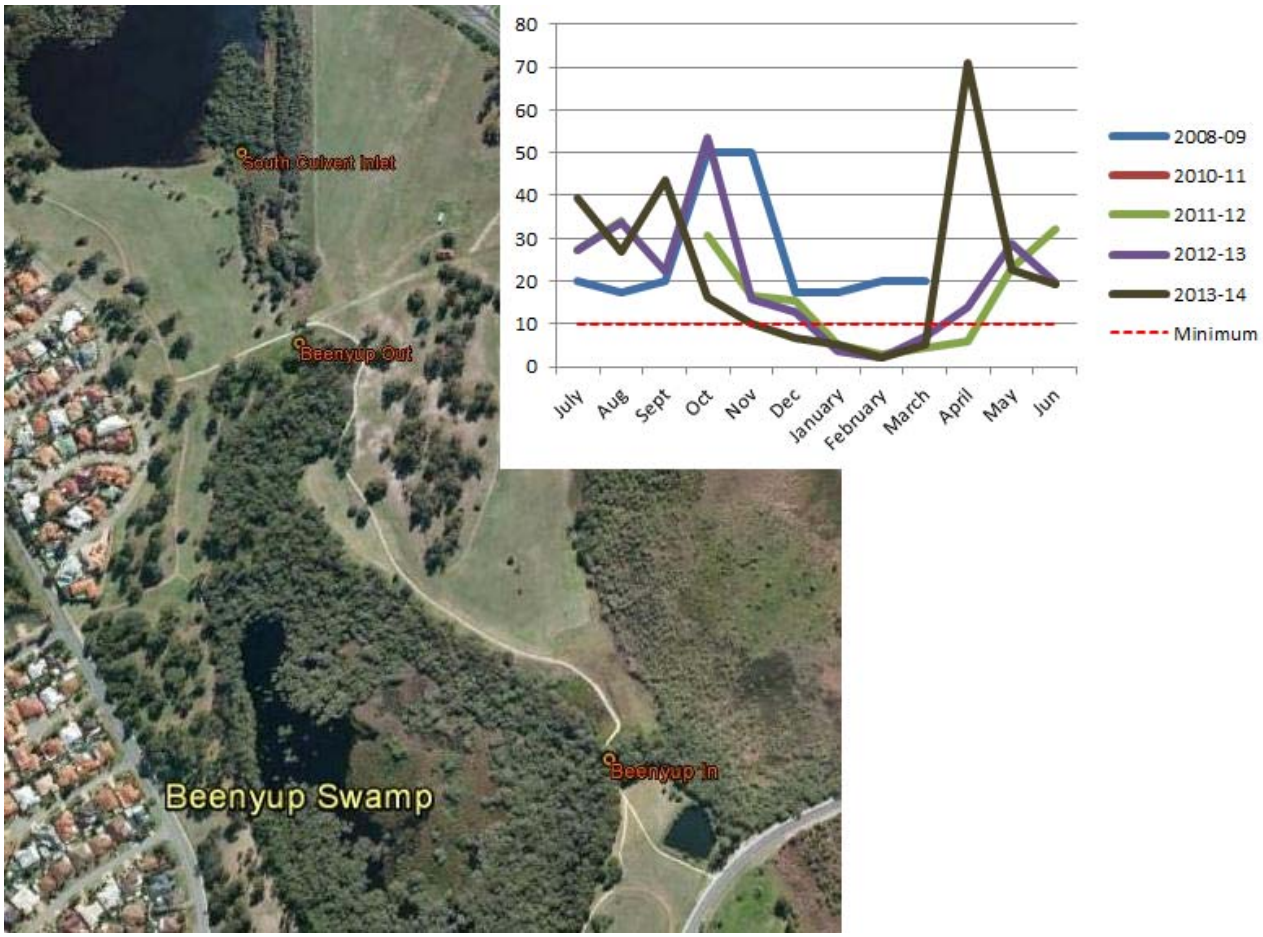


Figure 37. Aerial map of the two combined sites at Beenyup Swamp (GoogleMaps) with comparison of inter-annual water levels (July-June), threshold level of 10cm when sampling did not occur.

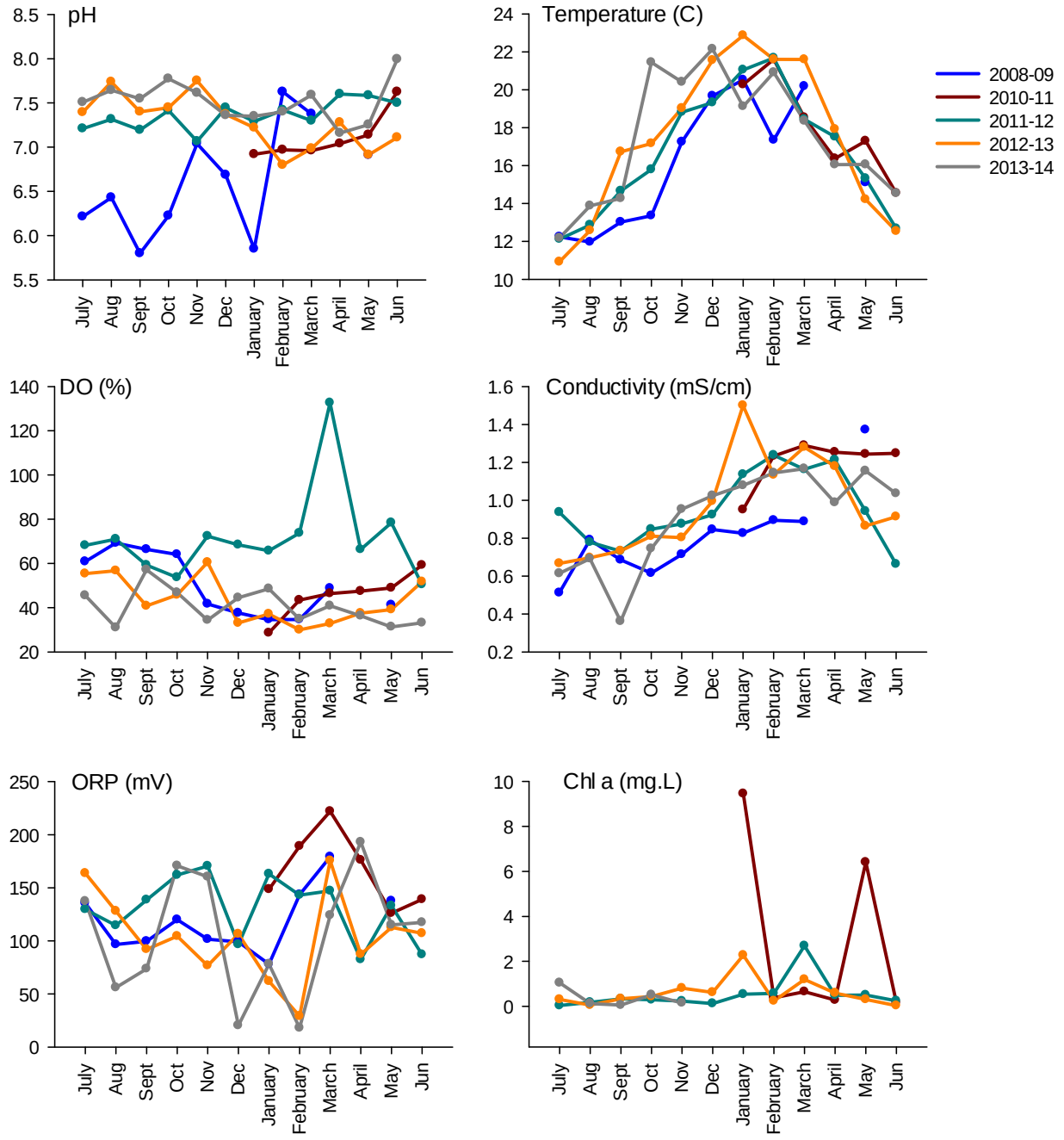


Figure 38. Inter-annual comparison of physico-chemical parameters for surface water at Beenyup Swamp over the monitoring period from July to June.

12.5 SOUTH LAKE JOONDALUP

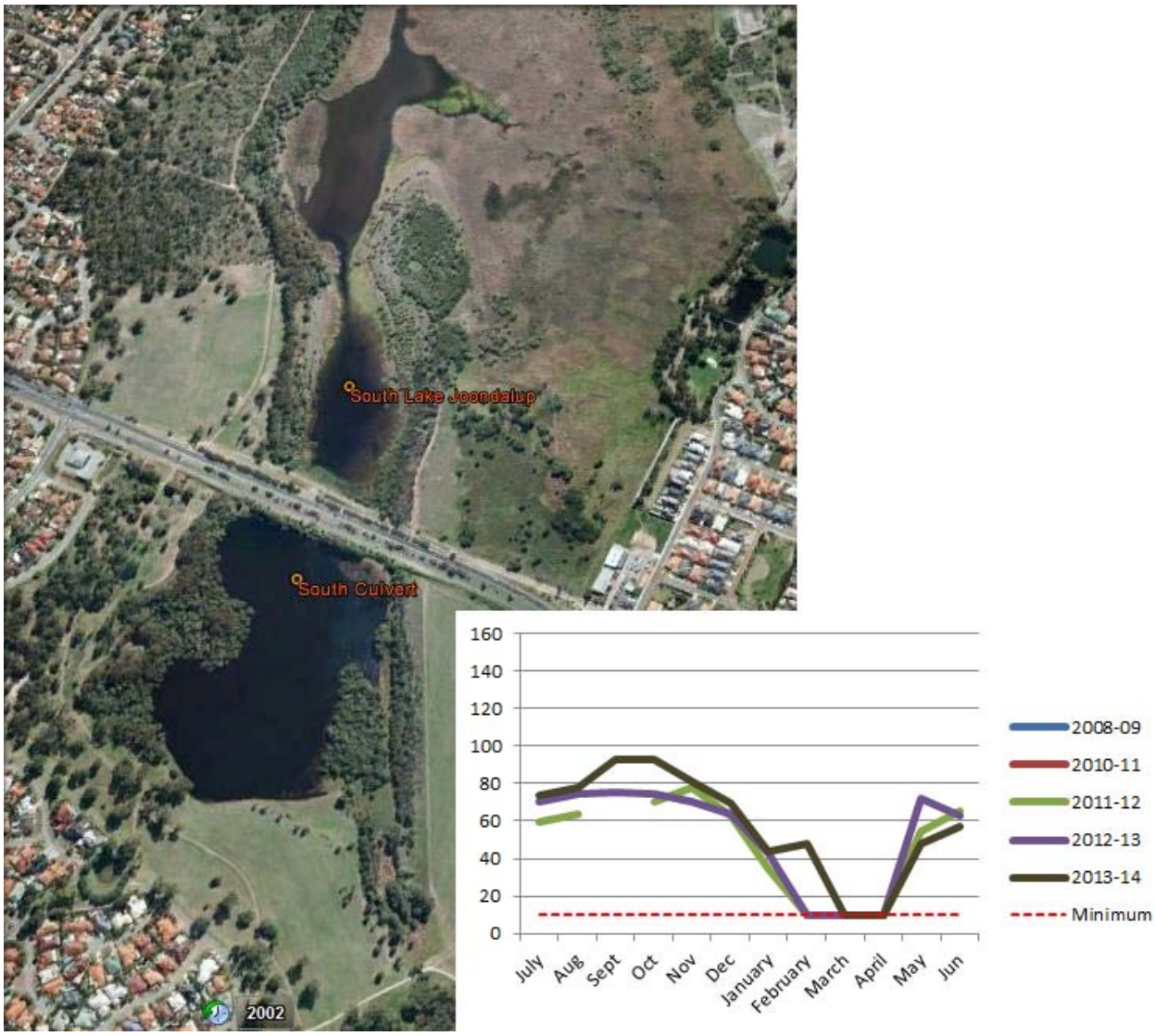


Figure 39. Aerial map of the two combined sites at South Lake Joondalup (GoogleMaps) with comparison of inter-annual water levels (July-June), threshold level of 10cm when sampling did not occur.

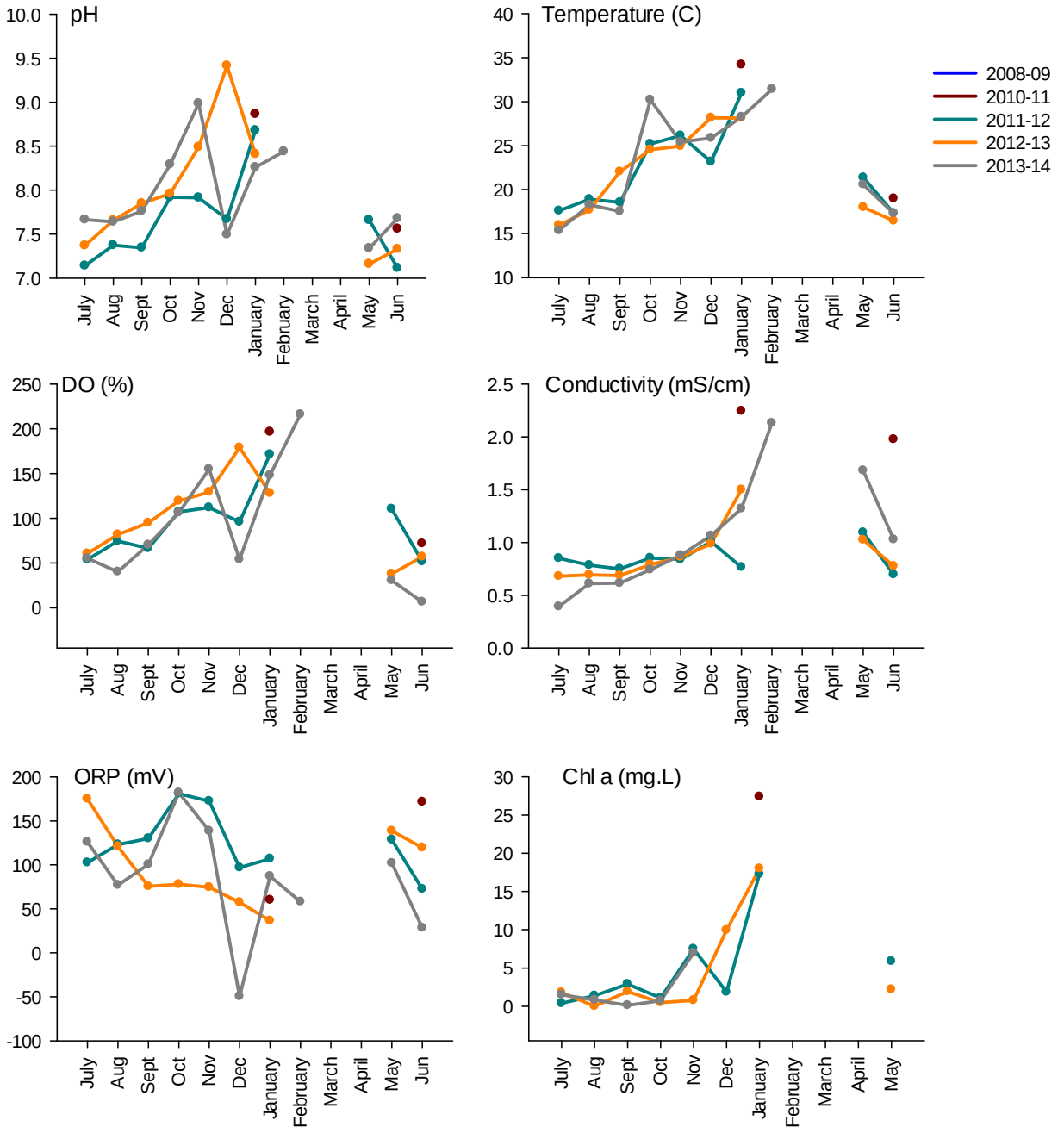


Figure 40. Inter-annual comparison of physico-chemical parameters for surface water at South Lake Joondalup over the monitoring period from July to June.

12.6 LAKE JOONDALUP

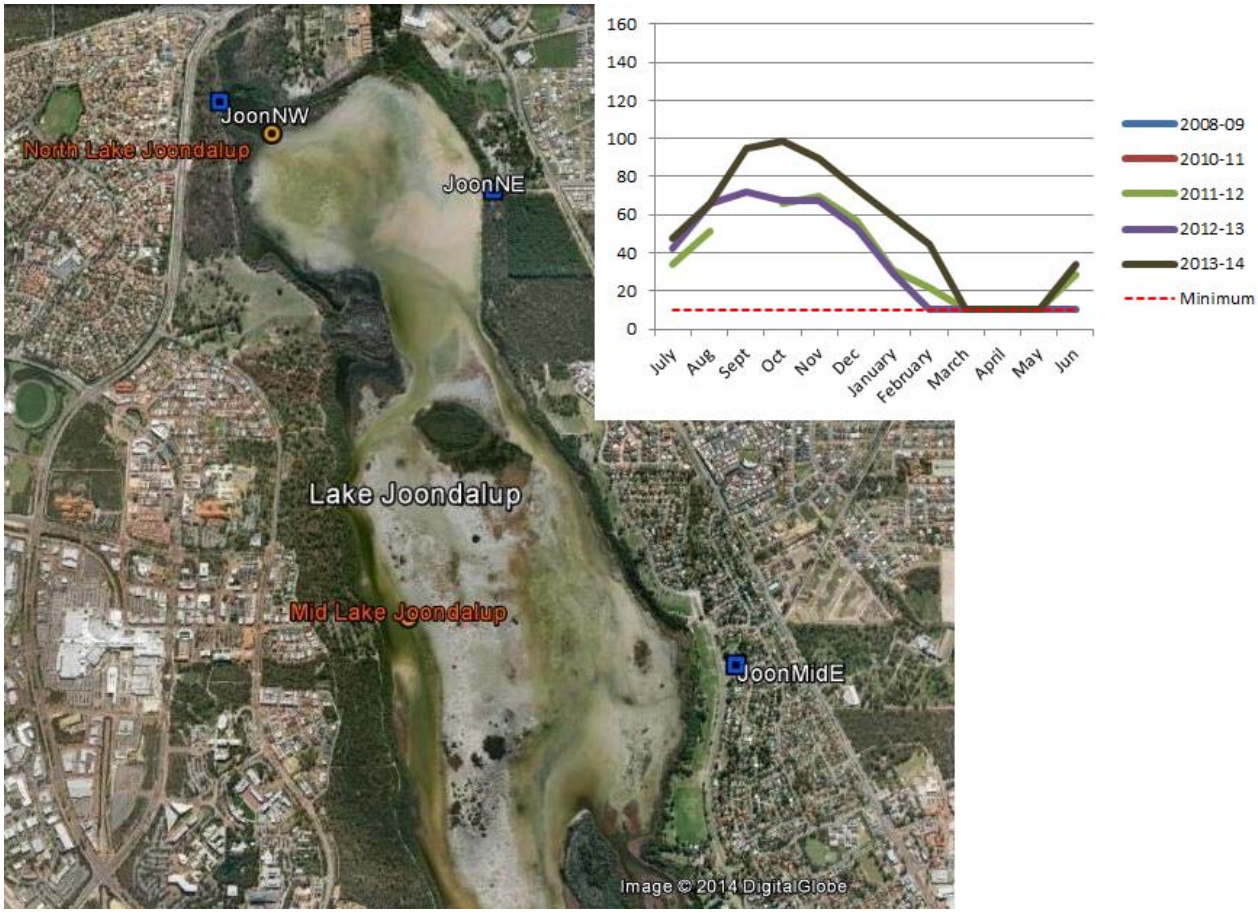


Figure 41. Aerial map of the two combined sites at Lake Joondalup (GoogleMaps) and adjacent bores JoonMidE, JoonNW and JoonNE with comparison of inter-annual water levels (July-June), threshold level of 10cm when sampling did not occur.

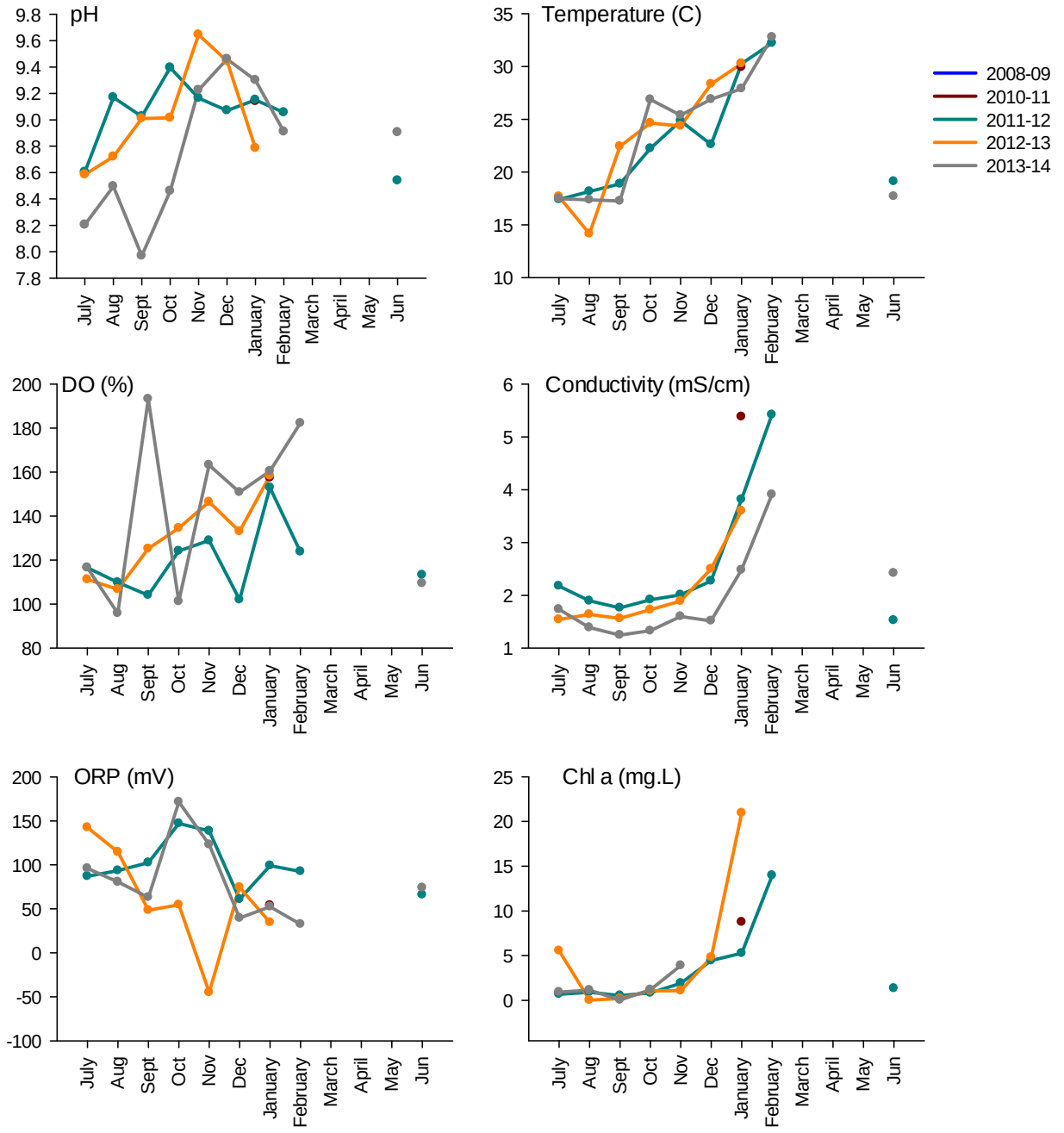


Figure 42. Inter-annual comparison of physico-chemical parameters for surface water at Lake Joondalup over the monitoring period from July to June.

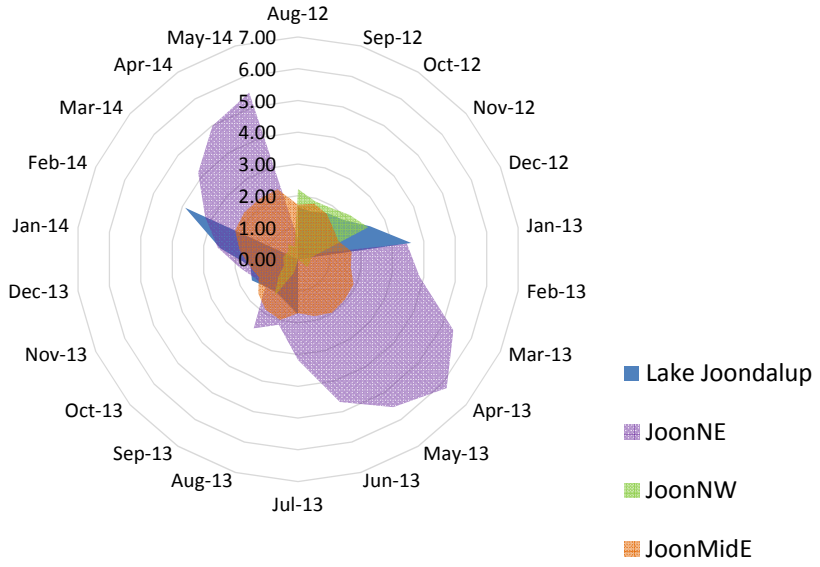


Figure 43. Radar plot showing hydraulic conductivity in water samples from Lake Joondalup and adjacent bores JoonE, JoonMidE and JoonNW from August 2012 to June 2014.