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Yellagonga Regional Park wetlands water quality monitoring 2017/18 report

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Prepared for,
Cities of Joondalup and Wanneroo as part of the Yellagonga Integrated Catchment Management Plan

Mine Water and Environment Research Centre

Final Report No. 2018-02

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2. ACKNOWLEDGEMENTS

The support of the Yellagonga Integrated Catchment Management team (Cities of Wanneroo and Joondalup) in funding this project is gratefully acknowledged. Particular thanks to Lara O'Neill (City of Joondalup) and Tristan Bruyn (City of Wanneroo) for their support. Thanks to Edith Cowan University for the provision of in-kind and infrastructure support for the project. The project team would also like to acknowledge the assistance of Mark Bannister at Edith Cowan University who undertook the chemical analyses at the Natural Sciences Analytical Laboratories. Finally we would like to thank the volunteers and interns who have assisted with fieldwork throughout this study.

3. FRONTISPIECE

Plate 1: Lake Goollelal in April 2018

This report should be referenced as follows.

Quintero Vasquez, M., & Lund, M.A. (2018). *Yellagonga Regional Park wetlands water quality monitoring 2017/18 report.* Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2018-02, Edith Cowan University, Perth, Australia. 62pp. Unpublished report to the Cities of Joondalup and Wanneroo.

4. EXECUTIVE SUMMARY

a) After a pilot study in 2010, which investigated the distribution of metals and nutrients within the Yellagonga Wetlands, a regular monitoring program was established. This monitoring program is also part of the Yellagonga Integrated Catchment Management plan. This monitoring program was extended to cover groundwater in 2013. Monitoring for both surface and groundwater is conducted and reported on annually. Monitoring programs have been refined over the years, with sites removed and added. A review of the monitoring data was undertaken in 2016.

b) Ten groundwater bores were sampled in 2017/18 every two months and surface water quality was sampled at 11 sites monthly June to October, December and in April. A range of physico-chemical measurements, metals and nutrients are measured. Although in previous years, ground and surface waters have been reported separately, this year the reports for 2017/18 have been combined.

c) The bores on the western side of the park show an increase in conductivity and related parameters in late summer, following evapo-concentration of solutes in the lakes.

d) High concentrations of P and N were recorded in a number of the eastern bores (particularly Mid E Joondalup), suggesting groundwater is an important source of nutrients into the northern end of Lake Joondalup..

e) All parameters recorded were compared to the ANZECC & ARMCANZ (2000) national water quality trigger values for the 95% protection of aquatic ecosystems. In 2017/2018 water quality was improved compared to previous years with only limited exceedances of guideline concentrations over slightly fewer elements (Al, As, and Zn). It appeared that groundwater was a major source of Al and Zn identified in the wetlands.

f) Sulphate to chloride and sulphate to alkalinity ratios suggest that there are acid sulphate soils within the catchment, but that natural buffering within the system is preventing low pH and high metal concentrations. The presence of acidification is also evident in the eastern bores. There is clear evidence of an ongoing trend of lower pH across the entire system as recently reported in DOW monitoring.

g) Key recommendations from the study are:
   a. to continue monitoring at the current frequency as this appears to be striking a balance between detail and cost.
   b. consideration of expanding or modifying the suite of metals/metalloids measured to better target potentially problematic elements.
   c. development of nutrient/water budgets for both Lakes Joondalup and Goollelal to better understand key sources of enrichment would assist with better targeting of management efforts to limit algal blooms. This is likely a focus of the Smart Cities project.
   d. acid sulphate soils remains an ongoing issue and further work to locate major sources would aid in their management.
   e. tracing the source of P in the drain between sites 4 and 6, as there are very high concentrations recorded on occasion.

f. a new bore is proposed for the eastern side of Lake Goollelal to assist in identification on nutrients entering the lake.

5. CONTENTS

6. INTRODUCTION

Underlying part of the Swan Coastal Plain of Western Australia, between the Darling Range fault line and Indian Ocean is the shallow unconfined aquifer of the Gnangara Mound (Appleyard and Cook 2009). The Gnangara Mound covers an area of approximately 2,200 km^2 and is the most significant water resource utilised by the population of Perth, providing up to 85% of its total domestic water requirements (Elmahdi and McFarlane 2009).

The Gnangara Mound is one component of a highly interdependent and complex hydrological system named the Gnangara groundwater system. It comprises of the Gnangara Mound, Leederville aquifer (confined and at a depth of 500 m), Yarragadee aquifer (confined and at a depth of 1000 m), rivers, wetlands (permanent and seasonal) and ocean (Wilson and Valentine 2009). Consequently it is important that the Gnangara hydrological system is maintained at a sustainable level in order to support water supply capacity, groundwater dependent ecosystems, vegetation communities and biodiversity on the Swan Coastal Plain (Wilson and Valentine 2009).

Yellagonga Regional Park occupies an area of around 1,400 ha overlying the Gnangara Mound and consists of Lake Goollelal, Wallubuenup Swamp, Beenyup Swamp, and Lake Joondalup. This interdunal chain of wetlands is a surface expression of the unconfined aquifer which flows in an east to west direction through the park (Newport et al. 2011a). Over the past thirty five years, numerous studies have been conducted around the Yellagonga wetlands, investigating nutrient enrichment, metal contamination and the presence of Acid Sulphate Soils (Congdon and McComb 1976a; Congdon 1985; Congdon 1986; Congdon and McComb 1976b; Cumbers 2004; Davis et al. 1993; Gordon et al. 1981; Khwanboonbumpen 2006; Kinnear and Garnett 1999; Kinnear et al. 1997; Lund 2003; Lund 2007; Lund et al. 2000). Nutrient and water budgets for Lake Joondalup have identified a significant quantity of water and nutrients entered Lake Joondalup via flow through from the southern portion of the Yellagonga wetlands chain (Congdon 1985; Congdon 1986; Cumbers 2004). More recently, a water quality monitoring program has found nutrient enrichment and metal contamination, which exceed ANZECC/ARMCANZ (2000) national water quality guidelines (Lund et al. 2011b; Newport et al. 2011a; Newport and Lund 2012b; Newport and Lund 2013b; Newport and Lund 2014b). An investigation in the southern section of Wallubuenup Swamp identified the presence of ASS at the $Drain_{Goollelal}$ site and this was identified as the main source of metal contamination of the lakes (Newport et al. 2011b; Newport and Lund 2013a; Newport and Lund 2014a). Monitoring of the wetlands after 2014 has revealed that metal contamination has slowly dropped to levels generally below trigger values (Gonzalez-Pinto and Lund 2015; Gonzalez-Pinto and Lund 2016; Gonzalez-Pinto et al. 2017)

The Yellagonga Integrated Catchment Management (YICM) Plan identified the need for a regular surface monitoring program for the wetlands of the Park. Regular monitoring under the YICM plan began in 2010. Newport and Lund (2012a) undertook a review of groundwater data in the vicinity of Yellagonga Regional Park - identifying a series of groundwater bores that might be suitable for regular monitoring. These bores have been supplemented with two new groundwater bores on the eastern side of Lake Goollelal and bores at Ariti Avenue and Neil Hawkins Park. In 2013, a regular monitoring program for the bores was commenced.

The purpose of this study is to report on monitoring physico-chemical parameters, nutrient levels and metal/metalloid concentrations of eleven key surface water sites along the Yellagonga Regional Park water flow path and ten bores between June 2017 and May 2018. This study aimed specifically to;

- Compare monitoring outcomes with corresponding ANZECC/ARMCANZ (2000) guideline trigger values for the 95% protection level of aquatic ecosystems, as prescribed by the management plan,
- Determine variation between surface water sites along the flow path from Lake Goollelal into North Lake Joondalup,
- Determine variation between bores north to south and east to west across the park,
- Identify variations in monitoring outcomes, driven by seasonality at surface water sites along the flow path from South Lake Goollelal into North Lake Joondalup and
- Recommend management strategies/actions and identify gaps in knowledge associated with current issues.

7. STUDY AREA

Yellagonga Regional Park lies on the coastal limestone belt of the Swan Coastal Plain 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 Department of Biodiversity, Conservation and Attractions and Cities of Wanneroo and Joondalup, 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 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 rainfall is the probable cause of increased soil and water acidity (Appleyard and Cook 2009; Appleyard et al. 2004) within the park triggered by drying of the underlying sediment and subsequent oxidation.

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

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 has 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 private properties and public open space bounding the water's edge but fringing vegetation generally remains in reasonable condition.

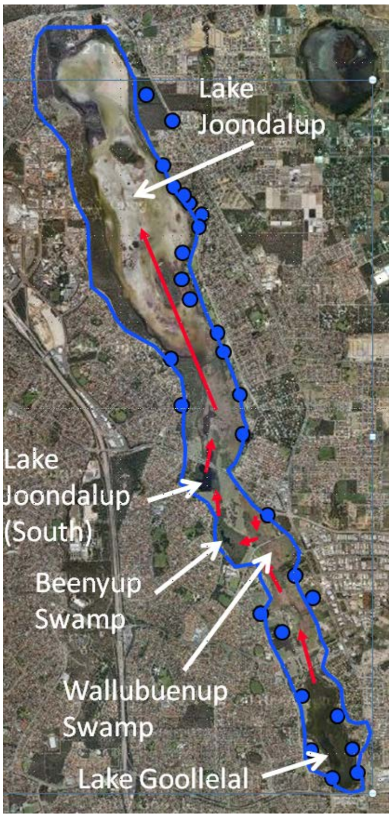


Figure 1. Direction of water flow through the Yellagonga Regional Park wetlands. Blue dots indicate drains entering the system; taken from Ove Arup & Partners (1994) and GoogleMaps (2014).

The following sites, listed from south to north within Yellagonga Regional Park surface waters, were sampled monthly from June to October, and in December 2017 and April 2018 (Figure 2 and Table 1).

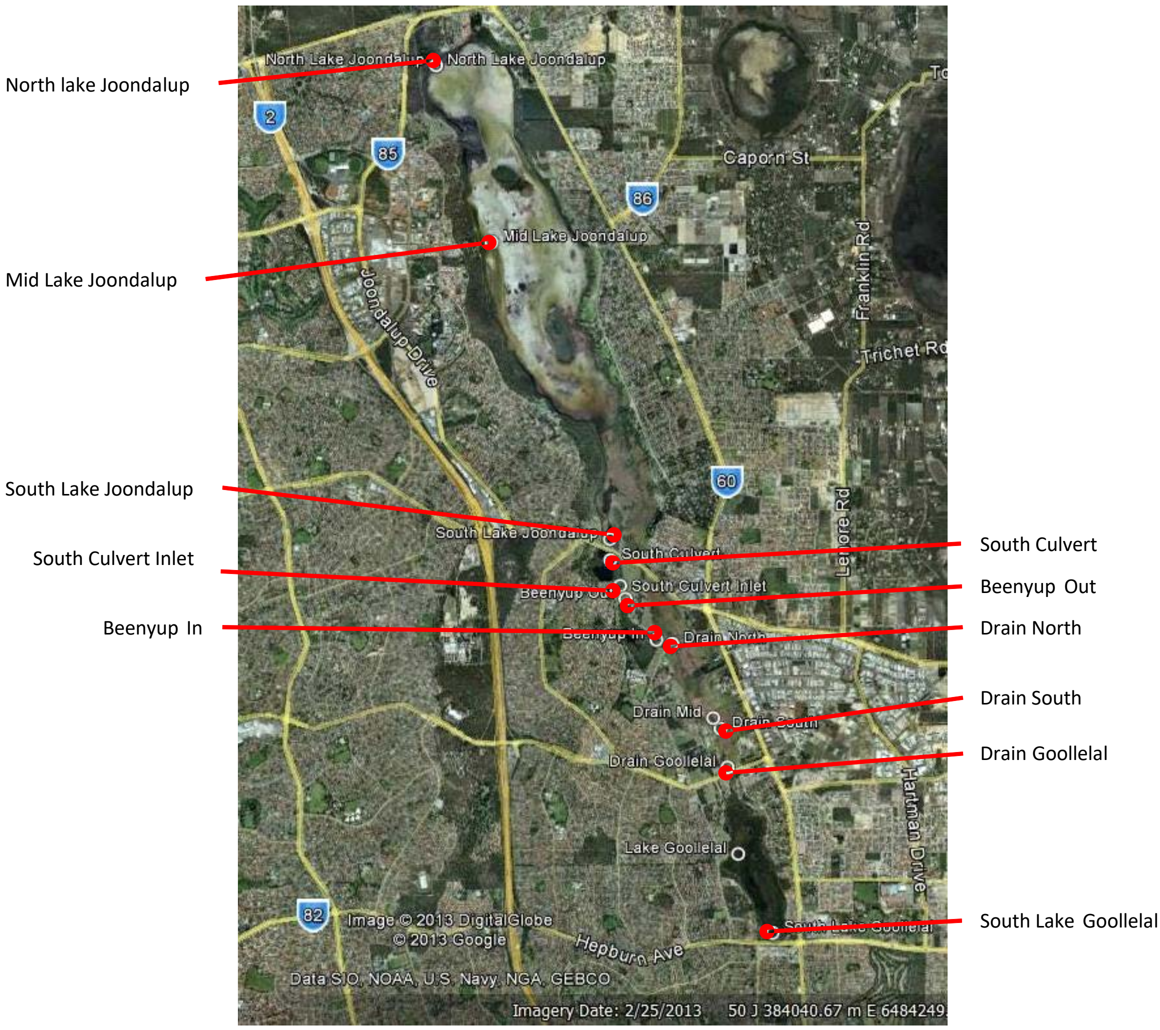


Figure 2. Locations of the eleven surface water sites in Yellagonga Regional Park (adapted from Google Earth 2013) – sites Lake Goollelal and Drain$_{Mid}$ are no longer sampled.

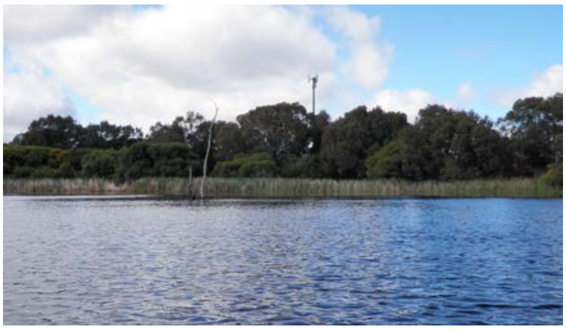
Table 1. Sampling sites for the Yellagonga Surface Monitoring. Distance south to north was determined from Google Earth and is the direct distance between sites.

Site Name	GPS Location (UTM)	Description	Distance South to North (m)
South Goollelal	50 J 0388063 6479003	Southern-most section of Lake Goollelal.	0
Goollelal	50 J 0387638 6479963	No longer sampled	1053
Drain Goollelal (Site 5)	50 J 0387489 6481019	Drain outflow from Lake Goollelal under Whitfords Ave.	2118
Drain South (Site 6)	50 J 0387399 6481490	Drain near Della Rd.	2592
Drain Mid (Site 7)	50 J 0387301 6481618	No longer sampled	2753
Drain North (Site 4)	50 J 0386796 6482519	Outflow of southern Wallubuenup Swamp into northern Wallubuenup Swamp as it flows under Woodvale Drive.	3976
Beenyup Inlet (Site 3)	50 J 0386599 6482566	Drain between Wallubuenup Swamp and Beenyup Swamp.	3976
Beenyup Outlet (Site 1)	50 J 0386214 6483064	Outflow channel from Beenyup Swamp.	4610
South Culvert Inlet	50 J 0386147 6483223	Outflow from Beenyup Swamp into the South Culvert.	4803
South Culvert	50 J 0386023 6483535	South end of Lake Joondalup separated from main body of lake by Ocean Reef Road. Tunnel runs under Ocean Reef Rd allowing water to flow from south end into main body of Lake Joondalup.	5122
South Lake Joondalup	50 J 0386016 6483793	Outflow from drain under Ocean Reef Rd into main lake water body.	5392
Mid Lake Joondalup	50 J 0384516 6487422	Neil Hawkins Park.	9314
North Lake Joondalup	50 J 0383807 6489593	The northernmost site of the study area	11587

Sites used in this study were chosen based on accessibility and representativeness of the flow path through Yellagonga Regional Park. Six sites, identified with a site number, were used in previous studies, namely Lund et al. (2011b) and Lund (2007). An additional seven sites were been added to improve understanding of changes in water quality along the flow path from south to north. After July 2014, the sites Lake Goollelal and $Drain_{mid}$ were removed from the program due to similarities to nearby sites and difficulty in accessing them. Figure 4 shows seasonal changes in water regimes at each of the eleven sites.

a) South Lake Goollelal

September 2017 (wet)



April 2018 (dry)

b) Drain$_{Goollelal}$ (Site 5)

September 2017 (wet)

April 2018 (dry)

c) Drain$_{south}$ (Site 6)

September 2017 (wet)

April 2018 (dry)

d) Drain$_{north}$ (Site 4)

September 2017 (wet)

April 2018 (dry)

e) Been$_{in}$ (Site 3)

September 2017 (wet)

April 2018 (dry)

f) Been$_{out}$ (Site 1)

September 2017 (wet)

April 2018 (dry)

g) South Culvert Inlet

September 2017 (wet)

April 2018 (dry)

h) South Culvert

September 2017 (wet)

April 2018 (dry)

i) South Lake Joondalup

September 2017 (wet)

April 2018 (dry)

j) Mid Lake Joondalup

September 2017 (wet)

April 2018 (dry)

k) North Lake Joondalup

September 2017 (wet)

April 2018 (dry)

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

Three bores are located on the eastern side of Lake Joondalup and two on the western side. There are two bores (east and west) of Wallubuenup and two eastern and one western bore around Lake Goollelal (Figure 4). The bores sampled on a bimonthly basis are listed below with their corresponding AWRC reference number or identifying number:

S.E. Goollelal – CoJ2
Mid W. Goollelal – AWRC ref: 61611870
N.E. Goollelal – CoJ1
Mid E. Wallubuenup – WN12
W. Wallubuenup – AWRC ref: 61610679
S.E. Joondalup – Ariti Avenue
Mid E. Joondalup – AWRC ref: 61610661

Mid W. Joondalup – Neil Hawkins
N.E. Joondalup – AWRC ref: 61610629
N.W. Joondalup – AWRC ref: 61611423

Figure 4. Location of the ten groundwater bores used for monthly monitoring in Yellagonga Regional Park (adapted from Google Earth 2013).

8. METHODS

8.1 SAMPLING

This report covers monthly sampling in June to October, December 2017 and April in 2018 at the eleven surface sites and bimonthly sampling of 10 bores. A surface site was considered 'dry' if the water was not deep enough to sample (<50 mm). At each bore, 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 a water sample. On each sampling occasion (surface and groundwater) the following were measured in situ at each site/bore, pH, oxidation reduction potential (ORP), conductivity, temperature, dissolved oxygen (% saturation and mg L^{-1}) were measured using a Datasonde 5a instrument or Quanta Multiprobe (both by Hydrolab, Hach). At each site, a surface water sample was also collected approximately 0.2 m below the water surface.

In the laboratory, an unfiltered aliquot (subsample) of each water sample was frozen for later determination of total nitrogen (TN[1]) 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 (NO_x-N), filterable reactive phosphorus (FRP-P), ammonia (NH_3-N) 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/MS of a range of metals (Al, As, Ca, Cd, Co, Cr, Fe, Hg, K, Mg, Mn, Na, Ni, Se, U & Zn). Alkalinity was measured on an unfiltered aliquot for each site according to the titration methodology in APHA (1999).

All analyses were performed at the School of Science 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.

8.2 DATA ANALYSIS

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.

Water quality parameters for the surface monitoring were plotted as contour plots using Surfer v15 – using time and distance north to south (see Table 1). Although sample times when the sites were dry were included in the analysis, they are not always represented on the contour plot due to the algorithm used. On the 30/7/2013, analysis for various metals was upgraded to reduce detection limits, therefore contour plots for these parameters has been restricted to post 30/7/2013.

[1] All nutrients are measured as the key elements ie. TN-N, TP-P, NOx-N, FRP-P and NH_3-N, but will be referred too hereafter without the –N or –P. Ammonia also includes ammonium. NOx includes both nitrate and nitrite.

9. RESULTS AND DISCUSSION

Rainfall during the period of this study (June - May) in 2017/18 totalled 707.3 mm (does not include June 2018) which was higher than in 2015/16 at 595.6 mm, 2014/15 at 651.9 mm, 2012/13 at 623.7 mm, and 2010/2011 at 433.9 mm. Lower annual rainfall (even allowing for average rainfall in June 2018) than 2011/12 at 709.5 mm, 2013/14 at 778.7 and 2016/17 at 769.4 mm (data from Bureau of Meteorology, Wanneroo and Tamala Park stations). In 2017/18, a large proportion of the rain occurred in January, with low rainfall in March to May (Figure 5).

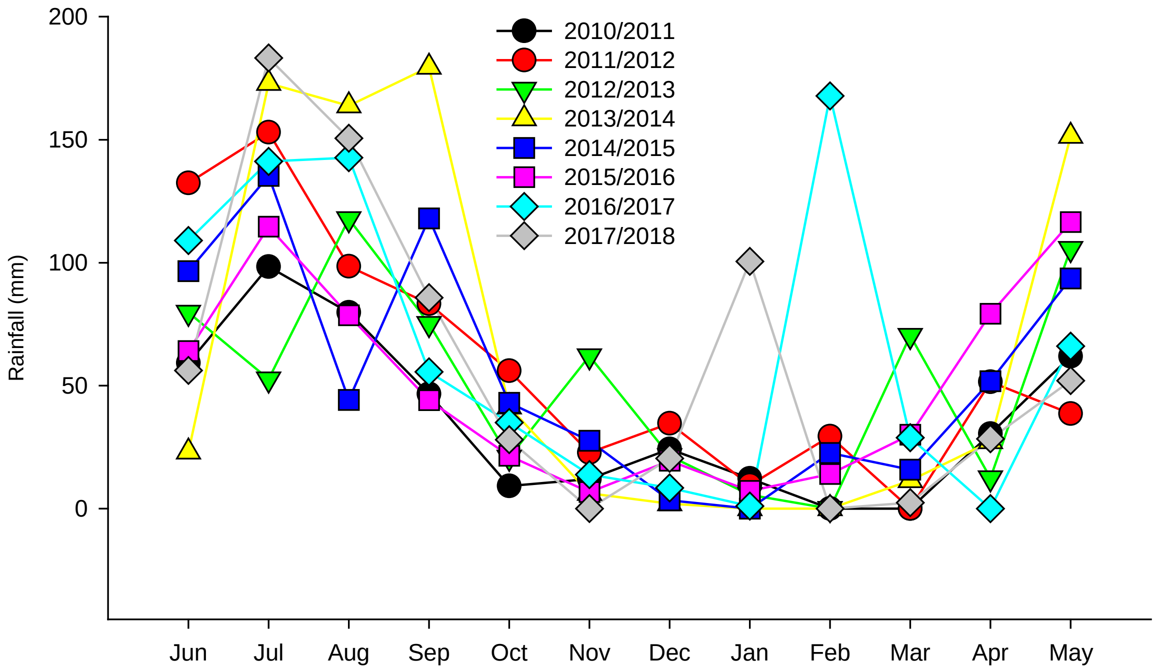


Figure 5. Monthly rainfall totals for each sampling year (June to May) 2010 onwards from data obtained from the Bureau of Meteorology, for Wanneroo and Tamala Park stations.

Water levels in Lake Joondalup cycle seasonally, however in 2011 to 2013 were particularly low. Water levels were higher in 2014 to 2015 before dropping again in 2016, good rains in 2017 saw the lake remain very wet during the normally dry period in both 2017 and 2018 (Figure 6).

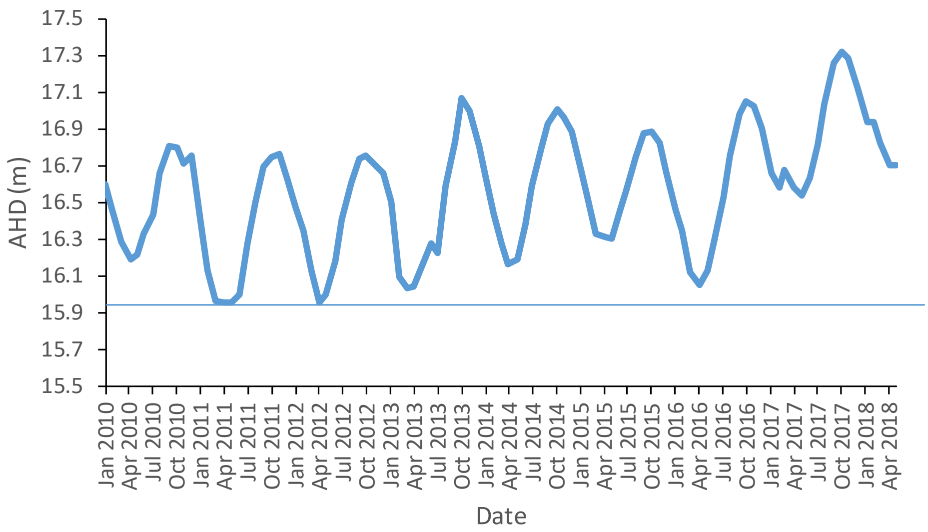


Figure 6. Water depth (AHD) of Lake Joondalup between 2010 and 2018 (horizontal line indicates the base of the AHD meter).

All surface sites were sampled throughout the study except for $Drain_{Goollelal}$ in June and December 2017 and April 2018 (Table 2).

Table 2. Occasions when sites were sampled between June 2017 and May 2018 (S= sampled).

	June	July	August	September	October	December	April
South Lake Goollelal	S	S	S	S	S	S	S
Beenyup Out (Site 1)	S	S	S	S	S	S	S
Beenyup In (Site 3)	S	S	S	S	S	S	S
Drain North (Site 4)	S	S	S	S	S	S	S
Drain Goollelal (Site 5)		S	S	S	S		
Drain South (Site 6)	S	S	S	S	S	S	S
South Culvert Inlet	S	S	S	S	S	S	S
South Culvert	S	S	S	S	S	S	S
South Lake Joondalup	S	S	S	S	S	S	S
Mid Lake Joondalup	S	S	S	S	S	S	S
North Lake Joondalup	S	S	S	S	S	S	S

Groundwater was monitored at all wells during the study period, except at Mid W Goollelal (Oct to Apr) and Mid E Wallubuenup (June) due to access issues – these have been resolved. In most of the bores (except Mid W Wallubuenup and to a lesser extent in Mid E Wallubuenup), the annual groundwater cycle can be clearly seen with minimum levels in April/May rising to peaks around October (Figure 7). Between 2013 and 2016 there was a slight trend of declining water levels but the rains in 2017 have reversed this trend at least for the moment. There was an unusual spike in water levels in N.E. Goollelal in October 2017, which cannot be easily explained.

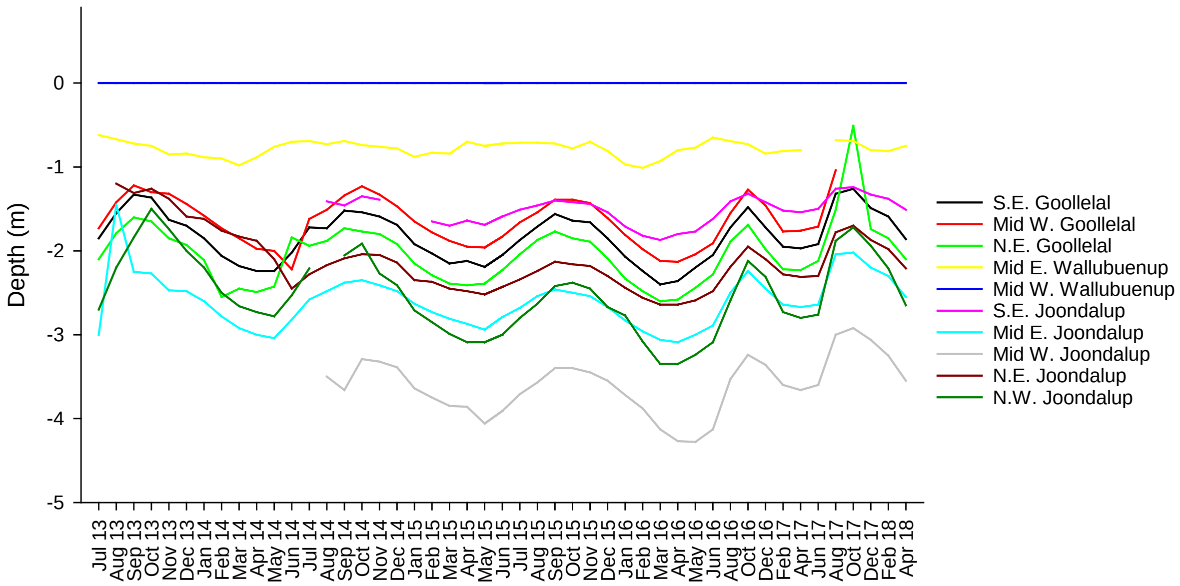
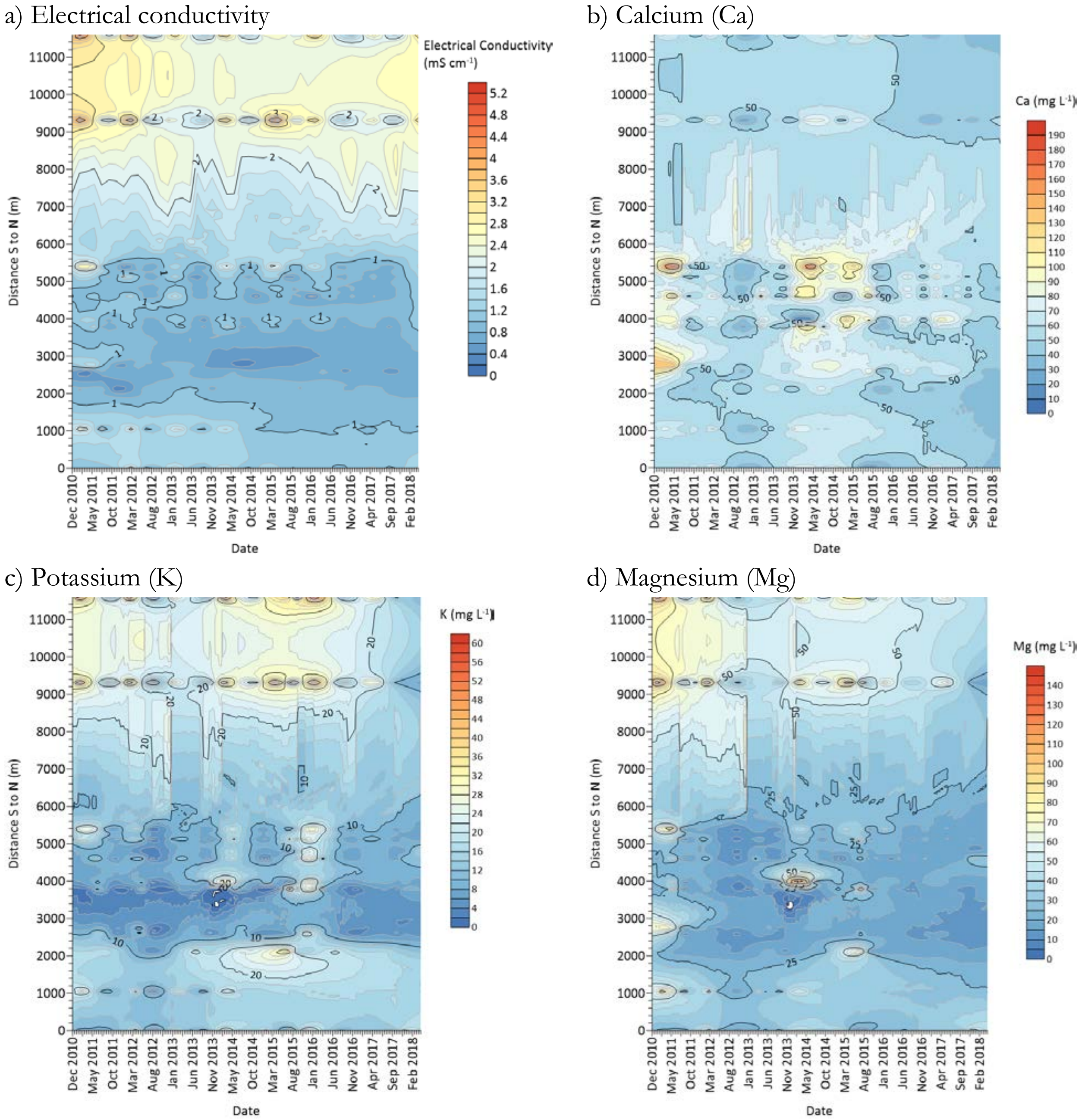


Figure 7. Depth to Water from Top of Casing (ToC) for groundwater bores for July 2013 to April 2018.

9.1 PHYSICO-CHEMISTRY

9.1.1 SURFACE WATER

The high rainfall in 2016/17 and 2017/18 reduced concentrations of common ions (K, Mg, Na and Cl) across the system (Figure 8). This slight decline in common ions was not reflected in electrical conductivity (EC) which increased slightly in 2017/18 compared to the last two years in Lake Joondalup. Evapoconcentration of solutes in the water is evident at the time of lowest water levels (summer) and is reflected in EC, and K, Mg, Na and Cl (Table 3). The greatest concentrations of these solutes tend to occur in Mid and North Lake Joondalup (Figure 8). Calcium concentrations did not reflect all the patterns seen in EC, with the lowest concentrations generally in Lake Joondalup (Mid and North). However calcium followed the strong seasonal cycle, low in winter higher in summer.


a) Electrical conductivity
Electrical Conductivity (mS cm-1)
Distance S to N (m)
Date
b) Calcium (Ca)
Ca (mg L-1)
Distance S to N (m)
Date
c) Potassium (K)
K (mg L-1)
Distance S to N (m)
Date
d) Magnesium (Mg)
Mg (mg L-1)
Distance S to N (m)
Date
Dec 2010
May 2011
Oct 2011
Mar 2012
Aug 2012
Jan 2013
Jun 2013
Nov 2013
May 2014
Oct 2014
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Jan 2016
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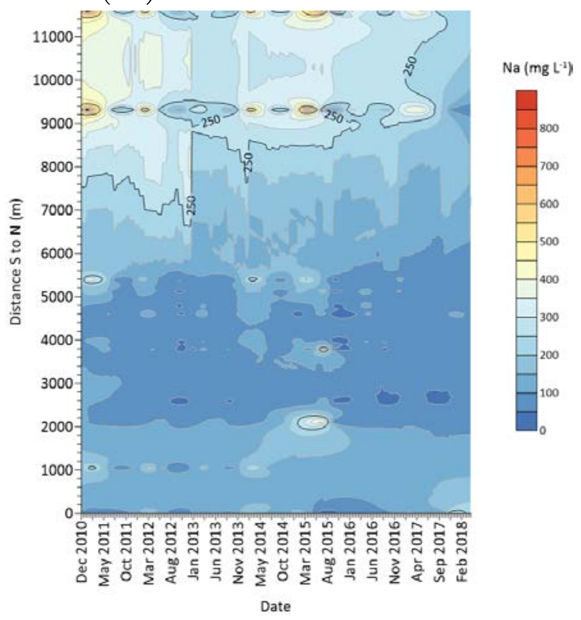
Apr 2017
Sep 2017
Feb 2018

e) Sodium (Na)



f) Chloride (Cl)

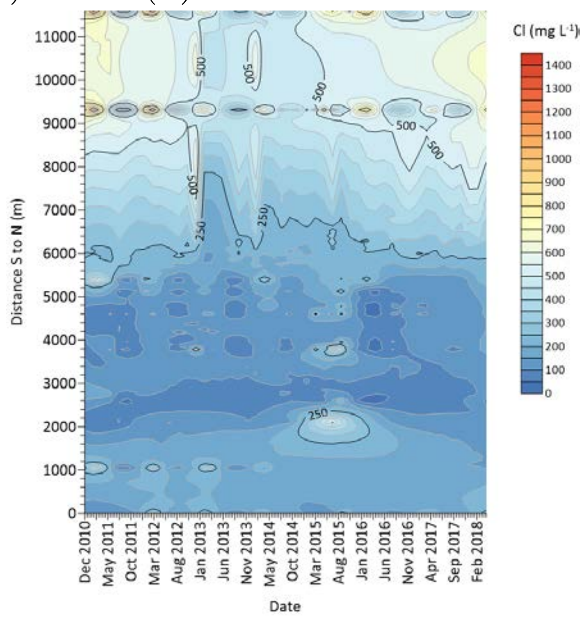


Figure 8. Changes in a) electrical conductivity, b) calcium, c) potassium, d) magnesium, e) sodium, and f) chloride over the period of monitoring at each site (June 2017- April 2018).

Table 3 Mean ±SE (range) for major solutes (in mg L^{-1}) and electrical conductivity during the study period June 2017 to April 2018

	Conductivity	Ca	K	Mg	Na
DL	mS/cm	<0.2	<0.2	<0.2	<0.2
South Lake Goollelal	1.11 ± 0.08 (0.92-1.46)	46 ± 4 (31-63)	14 ± 1 (10-21)	36 ± 4 (28-56)	156 ± 32 (92-319)
Beenyup Out (Site 1)	0.81 ± 0.06 (0.65-1.08)	51 ± 4 (43-72)	9 ± 1 (6-12)	21 ± 3 (14-32)	80 ± 7 (63-117)
Beenyup In (Site 3)	0.82 ± 0.06 (0.66-1.09)	53 ± 4 (42-75)	8 ± 0 (6-9)	17 ± 1 (14-21)	69 ± 3 (59-82)
Drain North (Site 4)	0.74 ± 0.08 (0.54-1.1)	45 ± 1 (5-136)	6 ± 0 (0-33)	15 ± 1 (1-123)	64 ± 3 (5-459)
Drain Goollelal (Site 5)	0.77 ± 0.05 (0.67-0.88)	37 ± 2 (33-42)	15 ± 1 (13-16)	17 ± 1 (15-20)	81 ± 5 (74-94)
Drain South (Site 6)	0.61 ± 0.02 (0.54-0.7)	49 ± 4 (34-65)	5 ± 1 (3-7)	13 ± 1 (12-16)	48 ± 3 (40-59)
South Culvert Inlet	0.81 ± 0.06 (0.65-1.08)	50 ± 4 (34-71)	9 ± 1 (6-15)	16 ± 1 (13-20)	67 ± 5 (44-81)
South Culvert	0.85 ± 0.07 (0.67-1.22)	53 ± 1 (44-74)	8 ± 0 (7-10)	17 ± 0 (15-21)	71 ± 1 (62-87)
South Lake Joondalup	0.9 ± 0.1 (0.71-1.46)	54 ± 4 (46-77)	8 ± 0 (7-10)	17 ± 1 (15-22)	73 ± 3 (66-90)
Mid Lake Joondalup	2.06 ± 0.26 (1.43-3.27)	42 ± 1 (34-52)	14 ± 1 (8-28)	39 ± 3 (16-67)	212 ± 17 (70-402)
North Lake Joondalup	2.15 ± 0.26 (1.47-3.28)	38 ± 1 (35-50)	16 ± 1 (9-30)	48 ± 1 (39-67)	263 ± 11 (200-412)

Water hardness was calculated for each site across the year and is shown in Figure 9. Hardness increases at sites that routinely dry, due to evapoconcentration. Hardness is associated with rainfall, with wetter years (2013, 2016 and 2017) all having lower hardness. Overall hardness ranges from moderate to extremely hard. Hardness is important as it reduces the toxicity of some metals such as Cd, Cr, Ni and Zn.

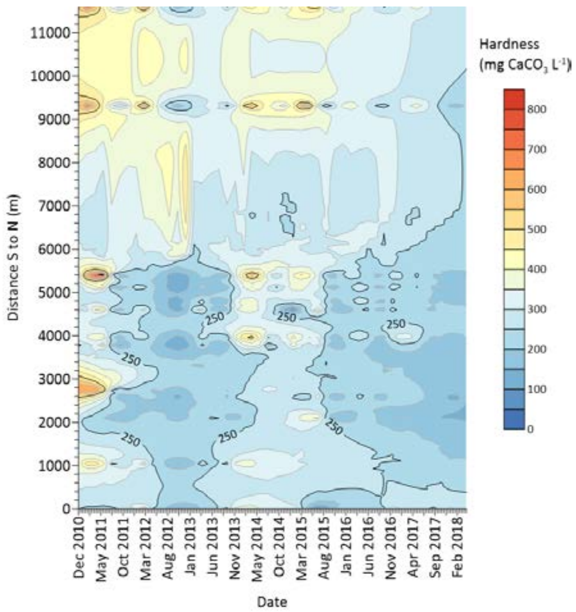


Figure 9. Calculated mean water hardness of each site for December 2010 to April 2018 (ANZECC/ARMCANZ (2000) categories: <59 mg $CaCO_3$ L^{-1} =soft, 60-119 mg $CaCO_3$ L^{-1} = moderate, 120-179 mg $CaCO_3$ L^{-1} = hard, 180-240 mg $CaCO_3$ L^{-1} = very hard and >240 mg $CaCO_3$ L^{-1} = extremely hard).

ANZECC/ARMCANZ (2000) water quality guidelines for the 95% protection of aquatic ecosystems recommend wetland pH levels between 7.0 and 8.5 pH at Mid and North Lake Joondalup remained in or above the guideline values (Figure 10). Overall there is a pattern of decreasing pH across the entire wetland system (most pronounced in the south of the park). This trend of decreasing pH has also been reported by Judd and Horwitz (2017) in their annual monitoring of Lake Joondalup. Sulphate concentrations increased slightly in Lake Joondalup in 2017/18, which may explain the increase seen in EC in Lake Joondalup.

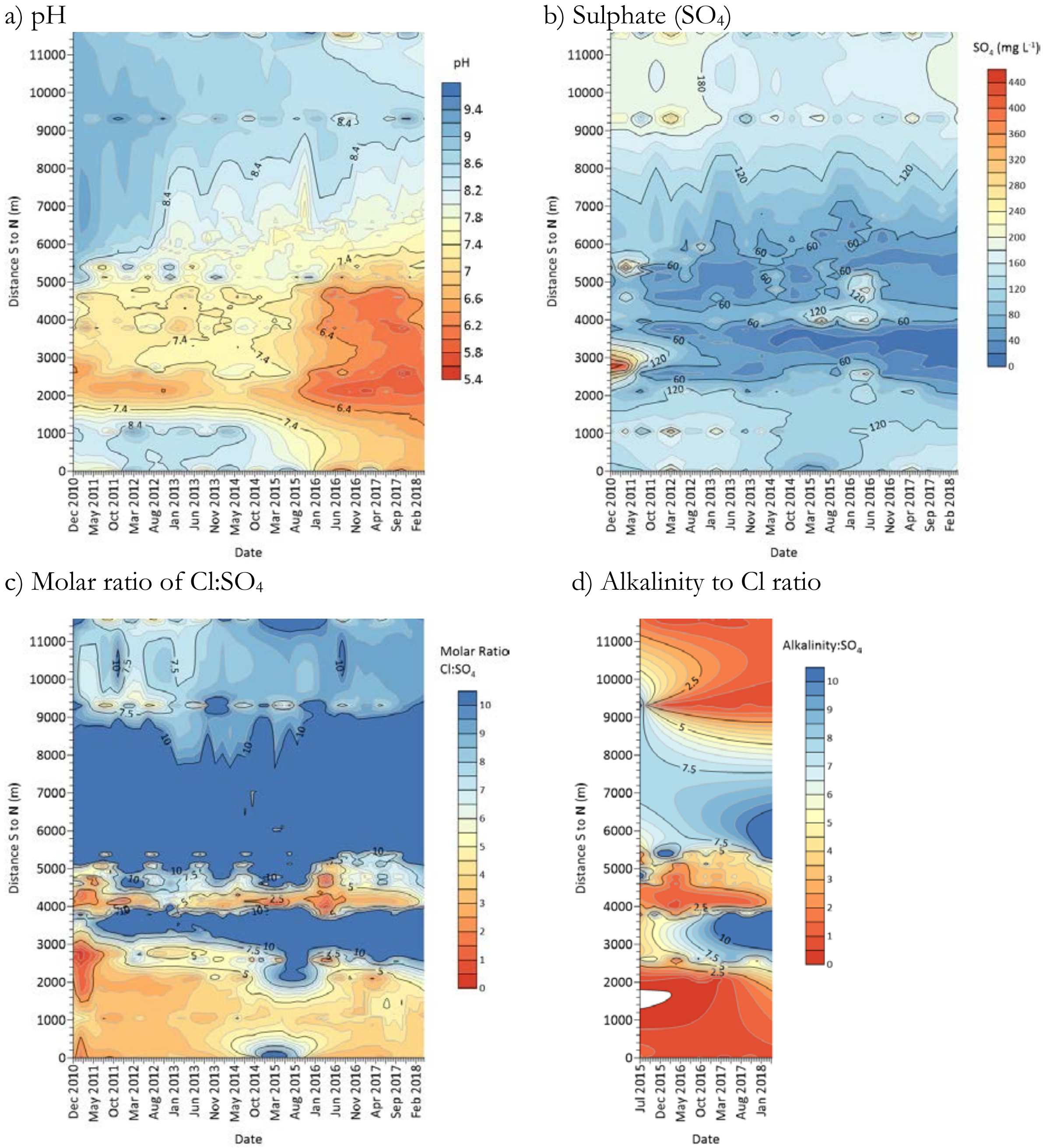


Figure 10. Changes in a) pH, and b) sulphate over the period of monitoring at each site (June 2016 – May 2017 with ANZECC & ARMCANZ (2000) trigger values for the protection of aquatic ecosystems (95%).

Chloride to sulphate molar ratios are 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 and Department of Natural Resources and Mines 2002). Best suited to saline environments, the ratio is sometimes problematic in freshwaters such as found in the Yellagonga wetlands and therefore must be treated with caution. To improve our ability to detect potential ASS, we also measured alkalinity (Table 4) as an alkalinity to sulphate ratio of <5 is considered to be a better predictor in freshwater systems

(Department of Environmental Regulation 2015). Low sulphate:chloride ratios were found on all occasions at South Lake Goollelal but only occasionally at $Beenyup_{In}$, $Drain_{Goollelal}$ and $Drain_{North}$. Alkalinity:sulphate ratios were generally low at all sites, only rising to above 5 on a few occasions between $Drain_{South}$ and South Lake Joondalup. This supports the general conclusion that there is acid sulphate soil activity within the Yellagonga catchment but currently buffering is sufficient to prevent low pH. The site around $Drain_{Goollelal}$ is known to be surrounded by ASS identified by Newport et al. (2011a). Sommer (2006) identified the presence of pyrite in the sediments of Lake Goollelal and demonstrated that on drying acidity was released. Experimentally we have investigated the likelihood of acidification following natural drying of Lake Goollelal sediment and it appears, at least initially, unlikely as we suspect that organic matter coats the pyrite preventing it from oxidising – however under prolonged drying this may not be the case. Overall despite increases in rainfall within the last couple of years, the trend towards increasing acidification appears to be ongoing especially within Lake Joondalup and Lake Goollelal.

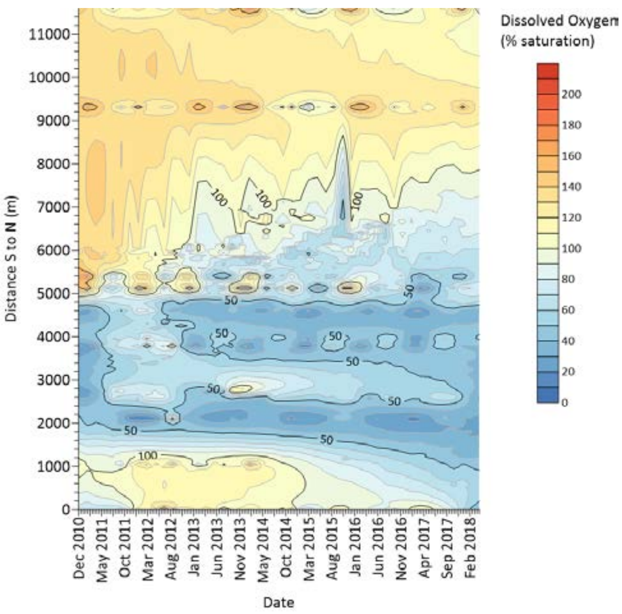
Table 4. Mean ±SE (range) for variables associated with acid sulphate soils (in mg L^{-1}) during the study period June 2017 to May 2018.

	pH	Cl^-	SO_4^{2-}	SO_4:Cl	Alkalinity	Alkalinity:SO_4	Hardness
Detection Limit		<0.5	<0.5	Molar ratio	mg$CaCO_3$ L^{-1}	Mass ratio	mg $CaCO_3L^{-1}$
South Lake Goollelal	6.49 ± 0.13 (5.97-6.84)	187 ± 17 (147-272)	150 ± 23 (101-275)	4 ± 0 (2-4)	115 ± 8 (97-140)	1 ± 0 (0-1)	264 ± 14 (230-324)
Beenyup Out (Site 1)	6.12 ± 0.09 (5.83-6.46)	120 ± 8 (100-156)	46 ± 2 (38-52)	7 ± 1 (6-10)	168 ± 15 (120-237)	4 ± 0 (3-5)	214 ± 14 (166-262)
Beenyup In (Site 3)	6.13 ± 0.12 (5.8-6.6)	118 ± 9 (95-165)	62 ± 4 (45-74)	5 ± 1 (4-8)	159 ± 14 (113-227)	3 ± 0 (2-4)	204 ± 13 (165-273)
Drain North (Site 4)	5.98 ± 0.11 (5.64-6.47)	114 ± 5 (4-538)	22 ± 4 (8-373)	17 ± 0 (0-70)	154 ± 5 (67-240)	9 ± 0 (0-15)	178 ± 6 (18-541)
Drain Goollelal (Site 5)	6.03 ± 0.17 (5.76-6.54)	122 ± 9 (106-144)	81 ± 15 (55-109)	4 ± 1 (3-5)	97 ± 20 (63-150)	1 ± 1 (1-3)	167 ± 9 (147-184)
Drain South (Site 6)	5.87 ± 0.14 (5.24-6.26)	83 ± 9 (65-133)	26 ± 3 (17-39)	9 ± 1 (6-14)	162 ± 7 (150-203)	7 ± 1 (4-9)	177 ± 11 (134-229)
South Culvert Inlet	6.34 ± 0.14 (5.81-6.82)	119 ± 8 (99-156)	46 ± 2 (38-53)	7 ± 1 (6-10)	168 ± 16 (113-240)	4 ± 0 (3-5)	193 ± 14 (151-259)
South Culvert	6.91 ± 0.15 (6.43-7.56)	127 ± 4 (105-184)	43 ± 1 (38-49)	8 ± 0 (6-10)	180 ± 8 (123-280)	4 ± 0 (3-6)	203 ± 5 (170-271)
South Lake Joondalup	7.02 ± 0.12 (6.64-7.43)	140 ± 19 (107-247)	38 ± 4 (18-45)	12 ± 4 (7-37)	187 ± 22 (133-297)	6 ± 2 (3-16)	207 ± 13 (177-283)
Mid Lake Joondalup	8.66 ± 0.24 (7.96-9.7)	482 ± 26 (324-791)	154 ± 11 (93-301)	9 ± 0 (6-10)	127 ± 3 (107-177)	1 ± 0 (0-1)	268 ± 10 (186-406)
North Lake Joondalup	8.3 ± 0.26 (7.69-9.41)	500 ± 25 (331-759)	170 ± 12 (105-343)	8 ± 0 (6-10)	132 ± 7 (107-243)	1 ± 0 (0-1)	293 ± 8 (252-400)

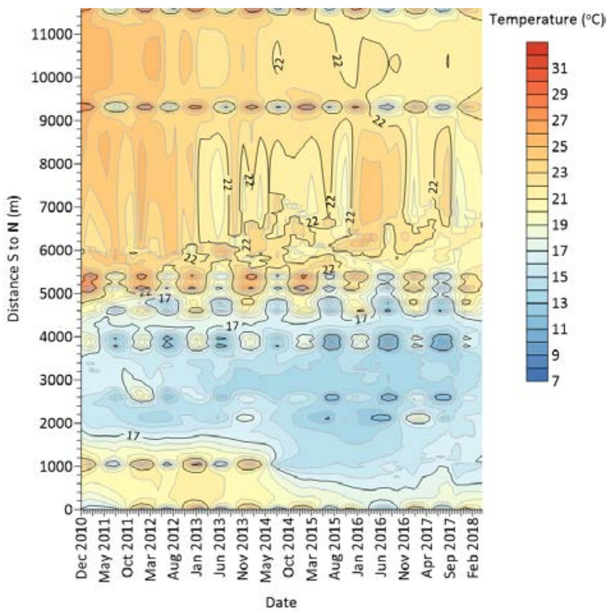
The ANZECC and ARMCANZ (2000) trigger values for dissolved oxygen are set at above 90% and below 120%. During the period of this study all sites breached trigger values, (Figure 11,

Table 5). Low dissolved oxygen levels were likely due to a lack of algae or plants and the presence of oxygen demanding sediments, common in the drain areas of the park. The lowest dissolved oxygen levels were too low to support most fish populations. Dissolved oxygen values over 100% are indicative of submerged plants or algae photosynthesising, and this is associated with Lake Joondalup, however oxygen levels have fallen in both Lake Joondalup and Lake Goollelal since 2010 possibly indicating either increased water levels or lower nutrient concentrations. ORP values are a measure of the oxidation and reduction potential within the water. The ORP values were predominantly in the oxidation region reflecting dissolved oxygen levels but appear to be generally decreasing slightly. Temperatures across the park were slightly lower in the last couple of years, as the higher rainfall has increased water depths, reducing water temperatures. Temperatures in the drains (presumably due to shading) were noticeably lower than those in the lakes. Chlorophyll *a* concentrations were generally low across the park, with occasional peaks during summer as sections of the park dry. Chlorophyll *a* concentrations have declined slightly since 2010 in both lakes, although this may be due to the increased rains in the last two years. Chlorophyll *a* is a measure of algal biomass and all the concentrations measured were relatively low. Chlorophyll a exceeded 10 µg L^{-1} on two occasions, April 2018 at South Lake Joondalup and September 2017 at $Beenyup_{Out}$ indicating likely blooms on these occasions. These blooms (<25 µg L^{-1}) were not very severe (generally considered to be >100 µg L^{-1}) and would be barely visible in the water.

a) Dissolved oxygen



b) Temperature



c) ORP d) Chlorophyll a

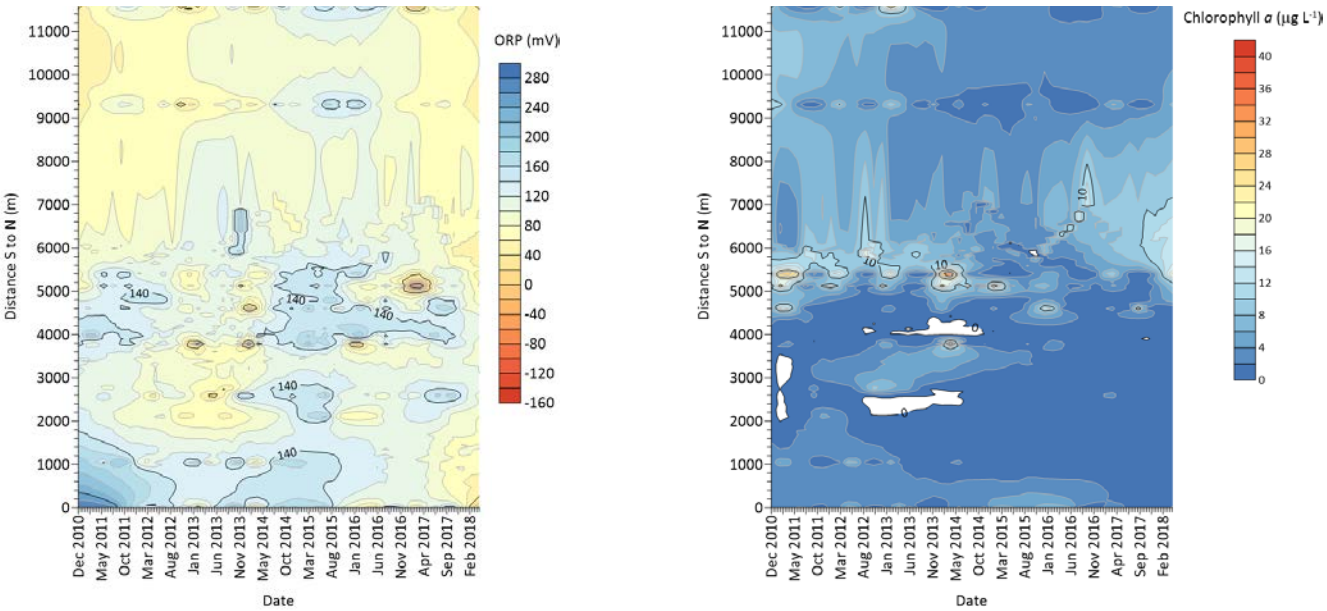


Figure 11. Changes in a) dissolved oxygen, b) temperature, c) ORP and d) Chlorophyll *a* between June 2017 and April 2018 at each site with ANZECC & ARMCANZ (2000) trigger values.

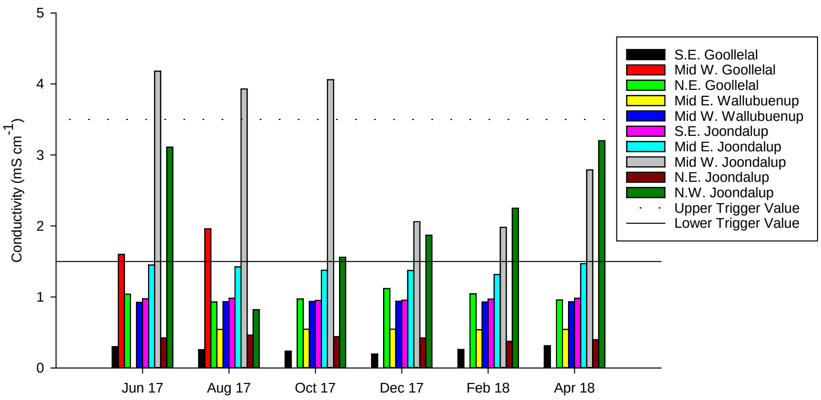
Table 5. Mean ± standard error (range) for physicochemical variables in surface waters over the study period (June 2017 – Apr 2018).

	Temperature °C	Dissolved Oxygen (mgL^{-1})	Dissolved Oxygen %	ORP mV	Chlorophyll *a* ug L^{-1}
South Lake Goollelal	17.1 ± 1.7 (12.1-24.8)	7.9 ± 1 (3.3-10.4)	81 ± 9 (36-102)	107 ± 26 (-15-174)	0.9 ± 0.5 (0.1-3)
Beenyup Out (Site 1)	15.3 ± 1.5 (11-21.9)	4.1 ± 0.3 (3.1-5.4)	41 ± 3 (33-54)	149 ± 15 (85-178)	3.6 ± 3.4 (0.1-24)
Beenyup In (Site 3)	12.4 ± 1.3 (8.4-18.5)	5.8 ± 0.5 (3.8-7.8)	54 ± 3 (41-67)	144 ± 13 (103-180)	0.1 ± 0 (0.1-0.3)
Drain North (Site 4)	12.1 ± 1.3 (8.3-18.2)	5.4 ± 0.5 (3.6-6.9)	50 ± 3 (38-59)	121 ± 10 (83-142)	0.2 ± 0.1 (0.1-0.4)
Drain Goollelal (Site 5)	13.8 ± 0.9 (11.8-16.1)	3.9 ± 0.4 (3-4.8)	38 ± 4 (31-47)	113 ± 9 (89-132)	0.1 ± 0.1 (0.4-0.2)
Drain South (Site 6)	12.7 ± 1.1 (9.4-17.6)	6.2 ± 0.7 (2.4-7.3)	58 ± 6 (24-70)	154 ± 13 (88-195)	0.2 ± 0.1 (0.1-0.4)
South Culvert Inlet	16 ± 1.8 (11.1-24.9)	5.7 ± 0.2 (4.7-6.9)	58 ± 2 (51-70)	132 ± 13 (68-170)	1.6 ± 0.8 (0.1-5.5)
South Culvert	17.7 ± 1.9 (12.3-26.2)	5.5 ± 0.7 (2.6-7.4)	59 ± 8 (26-86)	103 ± 9 (55-131)	2.1 ± 1.2 (0.1-8.6)
South Lake Joondalup	17.4 ± 1.7 (12.4-24.7)	5.6 ± 0.6 (3-7.8)	57 ± 5 (36-73)	106 ± 12 (35-129)	3.2 ± 2.8 (0.1-20.3)
Mid Lake Joondalup	18.7 ± 1.8 (13.1-26.6)	11.6 ± 0.4 (10.2-12.9)	126 ± 6 (116-162)	74 ± 9 (46-104)	2 ± 1.1 (0.1-6.8)
North Lake Joondalup	18.5 ± 1.8 (12.8-26.2)	11 ± 0.9 (6.7-14.5)	120 ± 12 (78-181)	85 ± 10 (31-106)	1.5 ± 0.8 (0.1-4.7)

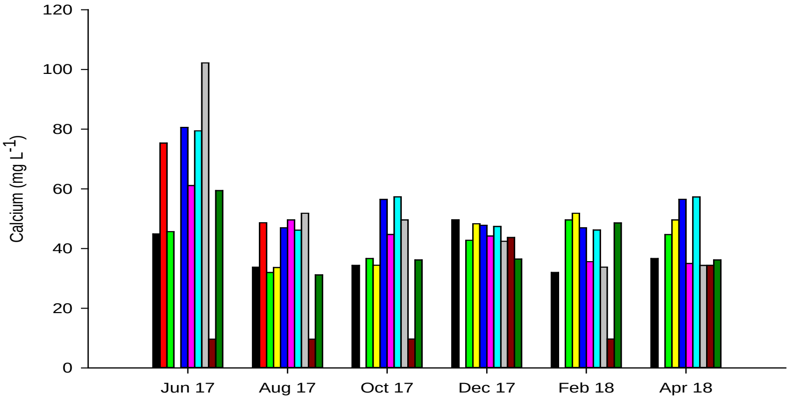
9.1.2 GROUNDWATER

The conductivity followed a trend of typically higher values in western bores compared to eastern ones, the only exception was Mid W Wallubuenup (Figure 8. and Table 6). The seasonal drying and evapoconcentration of salts in the lakes is reflected in the western bores. In Mid W Joondalup, peak EC occurs in June to October, dropping in December and February – this reflects the delay due to slow groundwater movement compared to changes seen in the lakes. In N.W. Joondalup the peak EC is in June and April and trough in August. The main ion contributing to the high EC in western bores is Cl, which shows very similar peaks and troughs. Calcium concentrations were generally highest in June, but while lower varied little after that, the exception was N.E. Joondalup which had peaks in December and April. Cycles were similar for Na, Mg and K which were similar to that of conductivity and Cl, with the exception of high values in Mid E Wallubuenup in February and April. Trends were similar to previous years.

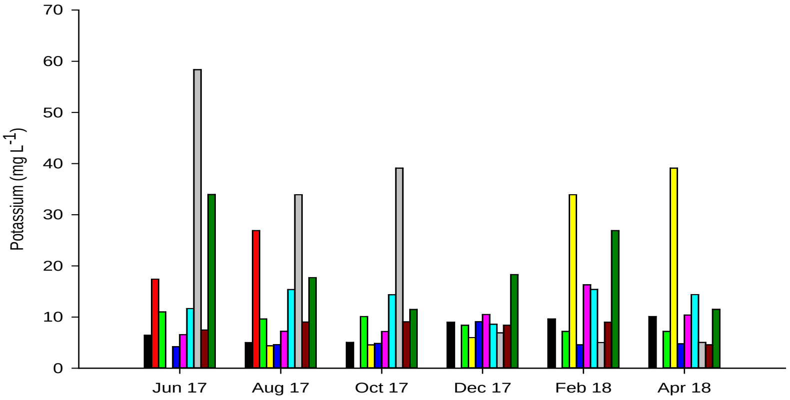
a) Electrical conductivity



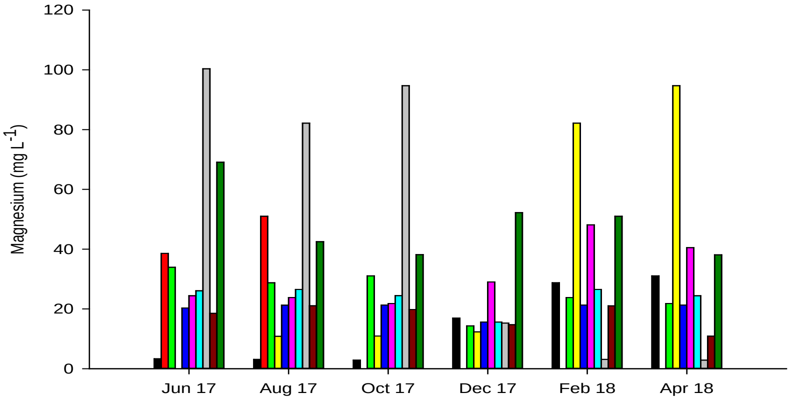
b) Calcium (Ca)



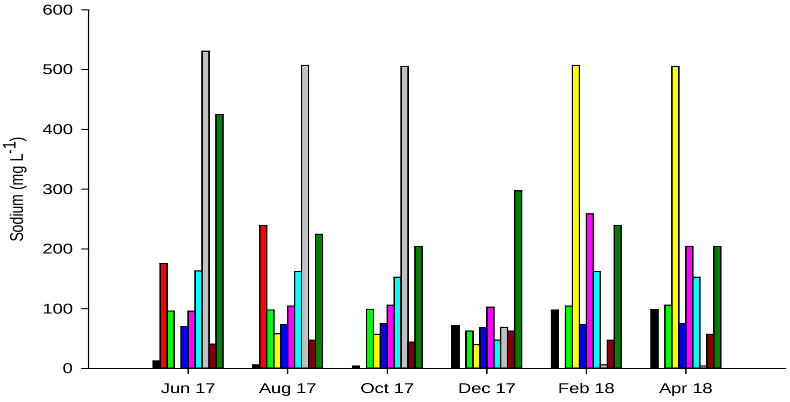
c) Potassium (K)



d) Magnesium (Mg)



e) Sodium (Na)



f) Chloride (Cl^-)

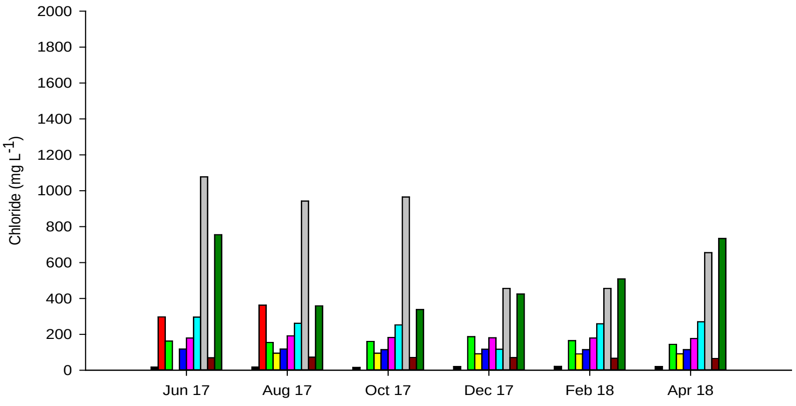


Figure 12. Changes in a) electrical conductivity, b) calcium, c) potassium, d) magnesium, e) sodium and f) chloride over the period of monitoring at each site (June 2017 – April 2018).

Table 6 Mean ± standard error (range) for common solutes during the monitoring period June 2017 to April 2018 (all in mg L^{-1})

	Ca	K	Mg	Na
DL	<0.2	<0.2	<0.2	<0.2
S.E. Goollelal	38.6 ± 2.9 (32-49.6)	7.5 ± 0.9 (5-10.1)	14.3 ± 5.4 (2.9-31.1)	48.5 ± 18.8 (4.1-98.6)
Mid W. Goollelal	62 ± 13.4 (48.6-75.3)	22.2 ± 4.7 (17.4-26.9)	44.8 ± 6.2 (38.6-51)	207.2 ± 31.7 (175.5-239)
N.E. Goollelal	41.9 ± 2.6 (32-49.6)	8.9 ± 0.6 (7.2-11)	25.6 ± 2.9 (14.3-33.9)	94.2 ± 6.5 (62.5-105.8)
Mid E. Wallubuenup	43.6 ± 3.9 (33.7-51.8)	17.6 ± 7.8 (4.4-39.1)	42.2 ± 19 (10.8-94.7)	233.5 ± 111.4 (40-507)
W. Wallubuenup	55.9 ± 5.3 (47-80.6)	5.4 ± 0.8 (4.2-9.1)	20.2 ± 0.9 (15.6-21.3)	72.6 ± 1.1 (68.3-74.9)
S.E. Joondalup	45 ± 4 (35-61.1)	9.7 ± 1.5 (6.6-16.3)	31.3 ± 4.3 (21.8-48.1)	145.1 ± 28.2 (95.8-258.6)
Mid E. Joondalup	55.7 ± 5.2 (46.2-79.4)	13.3 ± 1.1 (8.6-15.4)	23.9 ± 1.7 (15.6-26.5)	140 ± 18.6 (47.4-163.2)
Mid W. Joondalup	5.2 ± 4.3 (33.8-102.2)	1.1 ± 3.7 (5-58.4)	1.7 ± 7.9 (2.9-100.3)	18.6 ± 44.7 (4.1-530.7)
N.E. Joondalup	19.5 ± 6.3 (9.7-43.7)	7.9 ± 0.7 (4.6-9.1)	17.7 ± 1.7 (10.9-21)	49.8 ± 3.4 (40.8-62.6)
N.W. Joondalup	41.4 ± 1.8 (31.2-59.4)	20 ± 1.5 (11.5-34)	48.5 ± 2 (38.1-69.1)	265.6 ± 14.2 (204-424.8)

Calculated hardness of water samples from the bores are shown in Figure 13. Hardness was very similar to 2016/2017. Despite the higher rainfall in 2016 and 2017, this does not seem to have had a large effect on reducing hardness. Hardness was highest in western bores, reflecting evapo-concentration of solutes passing through the lake.

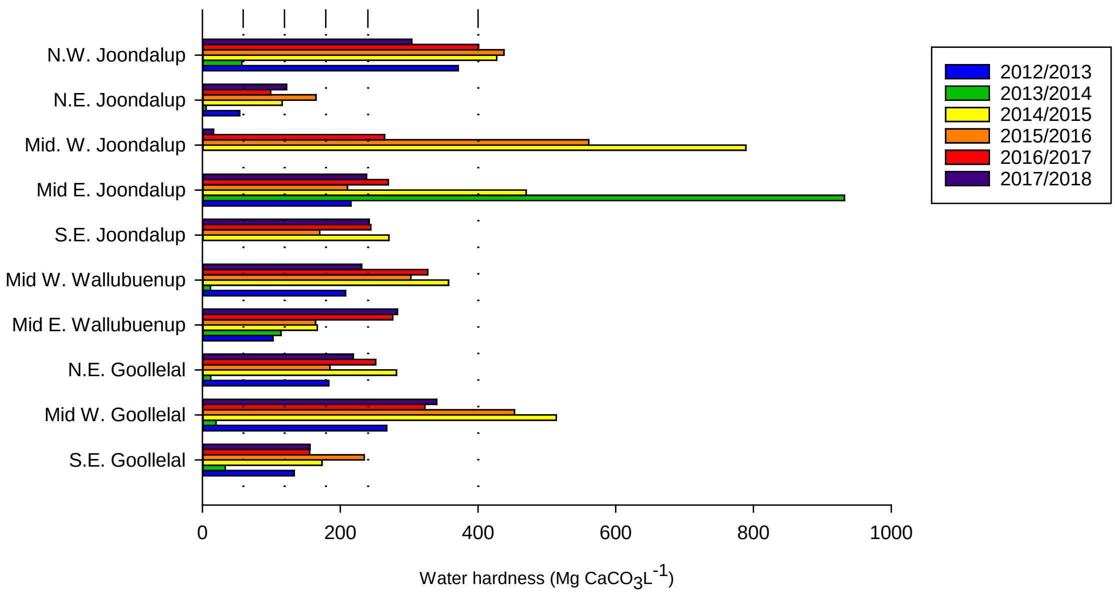
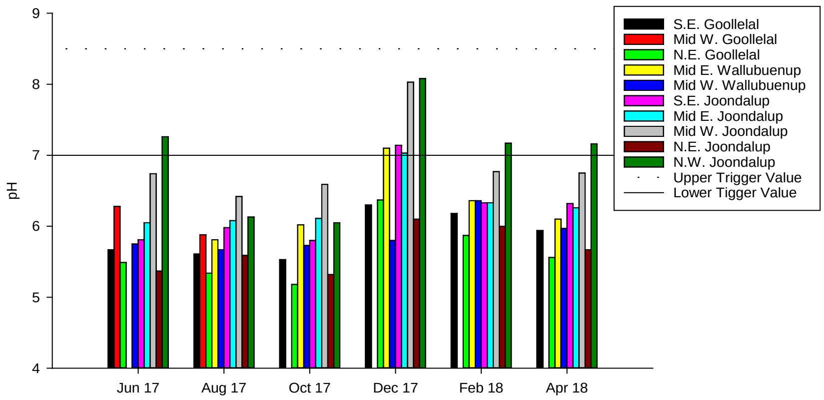


Figure 13. Calculated mean water hardness for the period of monitoring at each bore (June 2017 – April 2018) with ANZECC & ARMCANZ (2000) categories indicated.

pH of the groundwater ranged from slightly acid 5 to <7, the lowest values were in N.E. Goollelal as in previous years and was highest in December to February (Figure 10). Overall pH at all sites was relatively constant across the year varying by <2 units. pH was highest in Western bores excluding Mid W Wallubuenup. Sulphate concentrations were generally highest in the western sites (Mid W. Joondalup, N.W. Joondalup and Mid W. Goollelal).

a) pH



b) Sulphate (SO_4)

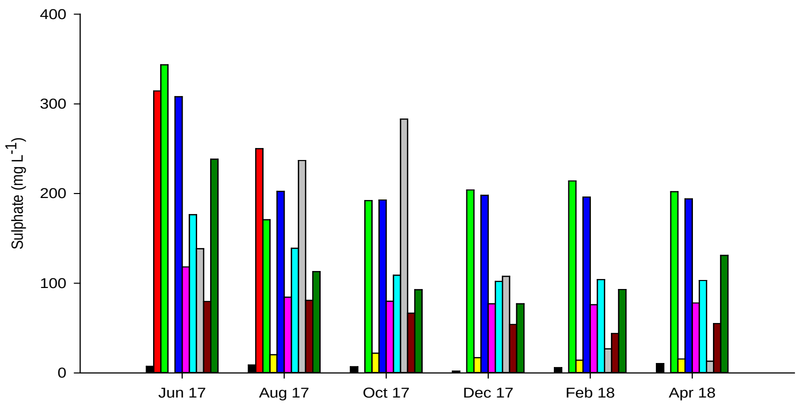
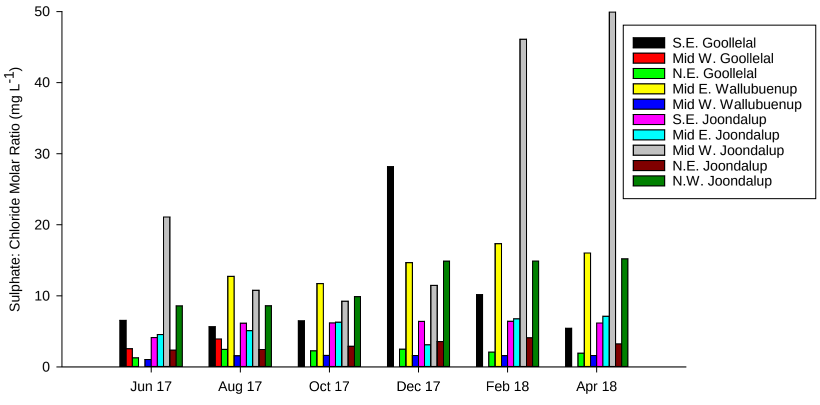


Figure 14. Changes in a) pH and b) sulphate over the period of monitoring at each bore (June 2017 – April 2018 with ANZECC & ARMCANZ (2000) trigger values for the protection of aquatic ecosystems (95%).

Ratios of sulphate to chloride and alkalinity to chloride indicated the possible presence of ASS contamination at N.E. Goollelal, W. Wallubuenup, S.E. Joondalup, Mid E. Joondalup, and N.E. Joondalup (Table 7), although pH was not <5 or aluminium concentrations >1 mg L^{-1}, these sites had some very high iron concentrations. Overall, there is suggestion that oxidation of acid sulphate soils is occurring within the catchment, but not all criteria are met to confirm this is occurring (Department of Environmental Regulation 2015). N.E. and N.W. Joondalup also have indicative alkalinity to sulphate ratios but do not have high Fe concentrations (Figure 15).

a) Sulphate: Chloride Ratio



b) Alkalinity: Chloride Ratio

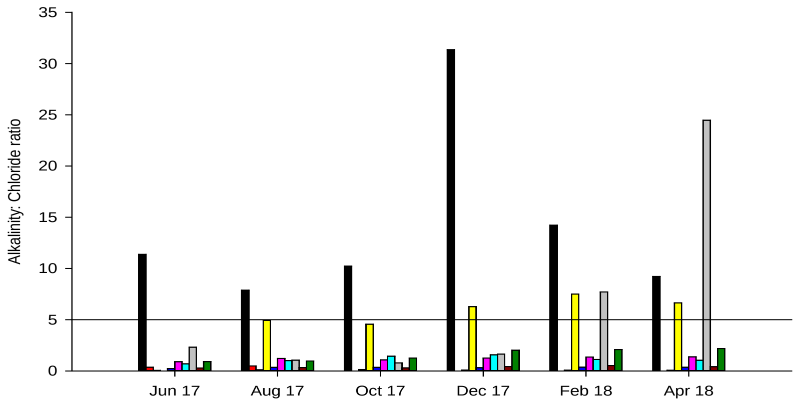


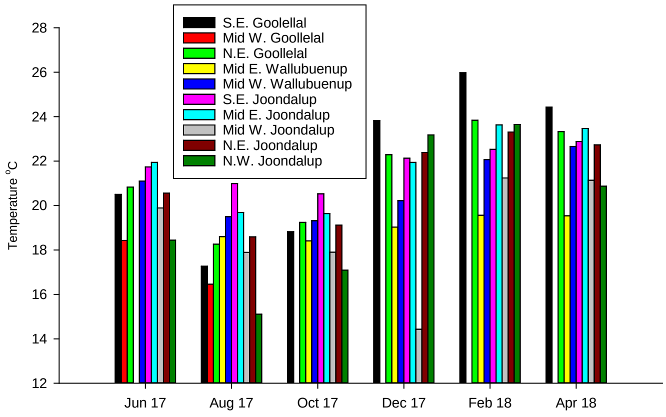
Figure 15. Ratios of Sulphate to Chloride and Alkalinity to Chloride in groundwater bores sampled between June 2017 and April 2018.

Table 7 Mean ± standard error (range) for chloride, sulphate, chloride to sulphate ratios, alkalinity, alkalinity to chloride ratios and hardness in bores during the monitoring period June 2017 to April 2018

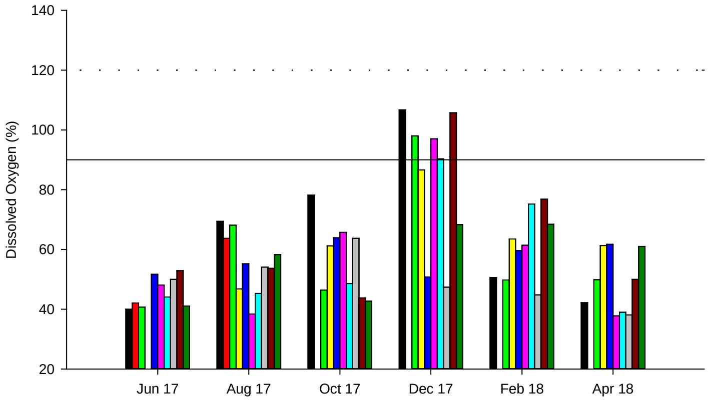
	Cl^- mg L^{-1}	SO_4^{2-} mg L^{-1}	Cl^-:SO_4^{2-} molar ratio	Alkalinity mg $CaCO_3$ L^{-1}	Alkalinity: SO_4^{2-} ratio	Hardness mg $CaCO_3$ L^{-1}
DL	<0.5	<0.5				
S.E. Goollelal	19.4 ± 0.9 (16.4-22)	6.9 ± 1.2 (2-10.5)	10.4 ± 3.6 (5.4-28.2)	77.8 ± 5 (63.3-96.7)	14 ± 3.6 (7.9-31.4)	156 ± 22 (97-220)
Mid W. Goollelal	330.1 ± 32.9 (297.2-363)	282.3 ± 32.2 (250.2-314.5)	3.2 ± 0.7 (2.6-3.9)	118.3 ± 5 (113.3-123.3)	0.4 ± 0.1 (0.4-0.5)	340 ± 7 (333-347)
N.E. Goollelal	162.3 ± 5.8 (144-187)	221.1 ± 25.2 (170.8-343.7)	2.1 ± 0.2 (1.3-2.5)	19.4 ± 1.8 (13.3-26.7)	0.1 ± 0 (0.1-0.1)	219 ± 13 (166-265)
Mid E. Wallubuenup	93 ± 0.9 (91-95.4)	17.8 ± 1.4 (14.2-21.9)	14.5 ± 1 (11.7-17.3)	103.3 ± 1.5 (100-106.7)	6 ± 0.5 (4.6-7.5)	283 ± 86 (129-514)
W. Wallubuenup	116.4 ± 0.7 (115-118.5)	215.3 ± 18.6 (192.8-308)	1.5 ± 0.1 (1-1.6)	68.9 ± 1.4 (63.3-73.3)	0.3 ± 0 (0.2-0.4)	231 ± 15 (189-295)
S.E. Joondalup	182 ± 2 (177-191.4)	85.5 ± 6.7 (76.1-118.1)	5.9 ± 0.4 (4.1-6.4)	100.6 ± 3.2 (86.7-106.7)	1.2 ± 0.1 (0.9-1.4)	242 ± 12 (202-287)
Mid E. Joondalup	242.8 ± 25.9 (117-296.2)	122.1 ± 12.3 (101.8-176.4)	5.5 ± 0.6 (3.1-7.1)	133.9 ± 8.9 (106.7-160)	1.1 ± 0.1 (0.7-1.6)	238 ± 16 (183-307)
Mid W. Joondalup	25.9 ± 45.5 (456-1077.5)	12.3 ± 18.2 (13.1-283.1)	0.6 ± 8.2 (9.2-135.7)	8.9 ± 9.9 (176.7-320)	0.1 ± 1.5 (0.8-24.5)	16 ± 41 (98-669)
N.E. Joondalup	69.7 ± 1.1 (66-73.1)	63.4 ± 6.1 (44.3-80.9)	3.1 ± 0.3 (2.4-4.1)	23.3 ± 0.9 (20-26.7)	0.4 ± 0 (0.3-0.5)	122 ± 11 (101-170)
N.W. Joondalup	520.1 ± 30.7 (338.5-755.2)	124.2 ± 9.8 (77.4-238.4)	12 ± 0.6 (8.6-15.2)	180 ± 11.1 (110-286.7)	1.6 ± 0.1 (0.9-2.2)	304 ± 12 (248-433)

Water temperatures varied by approximately 6 °C at each site over the year, highest in summer and lowest in winter (Figure 16, Table 8). Dissolved oxygen was measured in all bores at >30% saturation. Despite low dissolved oxygen concentrations, ORP was generally >0 mV across the year for eastern sites (except Mid E. Wallubuenup, S.E. Joondalup), while western sites had very low ORP, generally <-100 mV, (except for Mid W Wallubuenup). These low ORP values despite the presence of oxygen indicated chemical processes rather than oxygen as the driver for ORP changes.

a) Temperature



b) Dissolved Oxygen



c) ORP

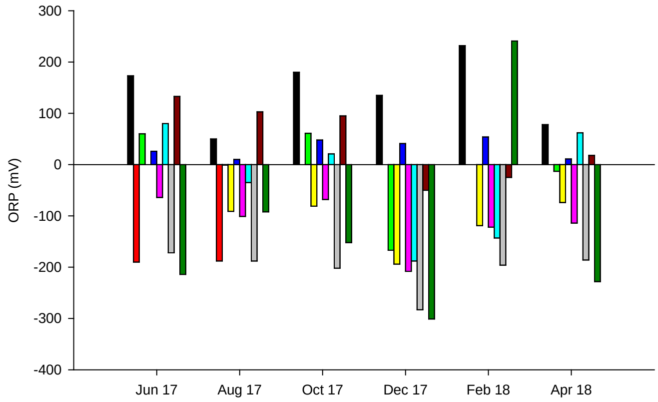


Figure 16. Variation throughout groundwater monitoring period for a) temperature, b) dissolved oxygen, c) ORP and d) depth to water between June 2017 and April 2018 at each bore.

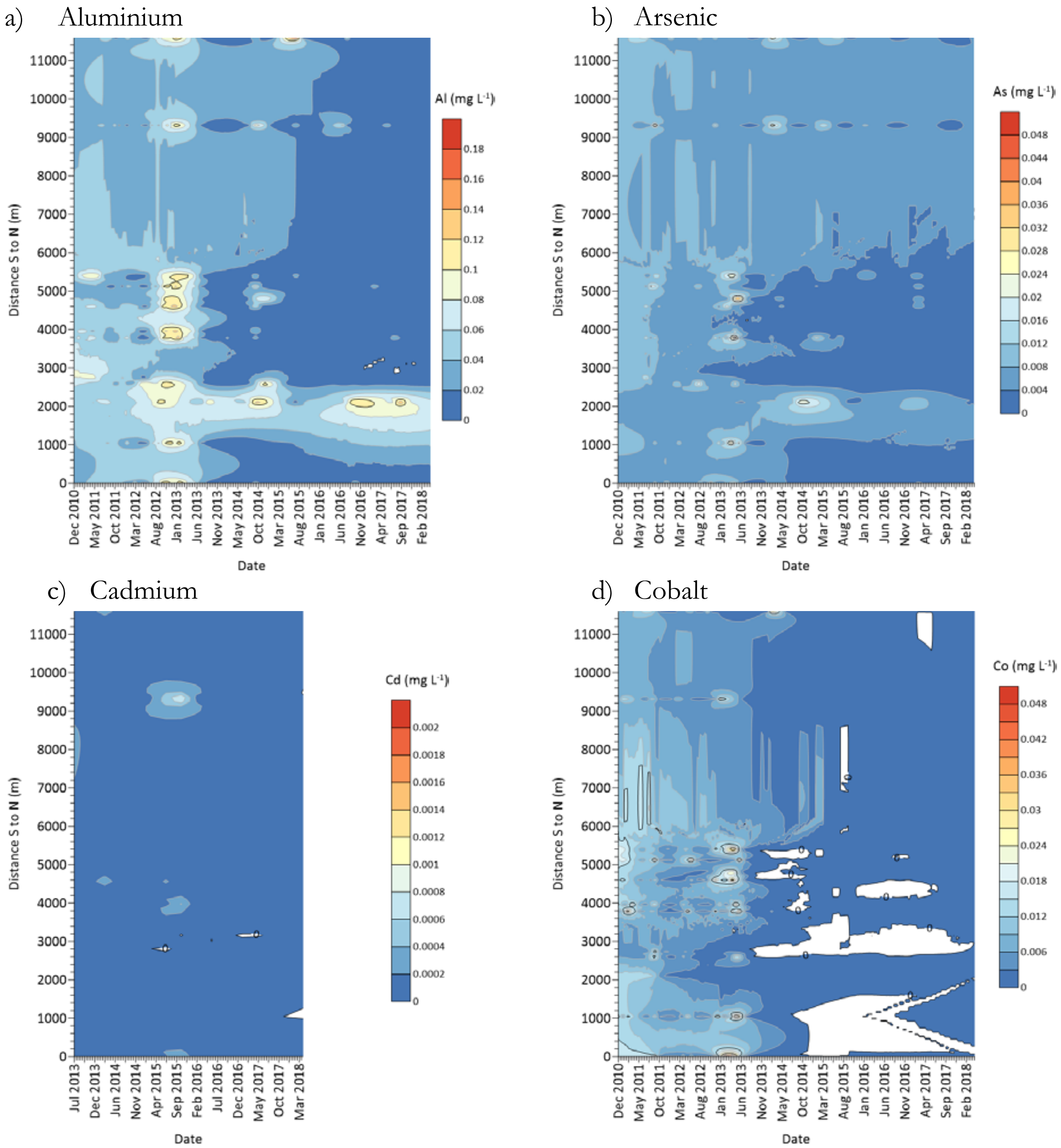
Table 8. Mean ± standard error (range) for physico-chemical variables over the monitoring period for groundwater bores (June 2017- April 2018)

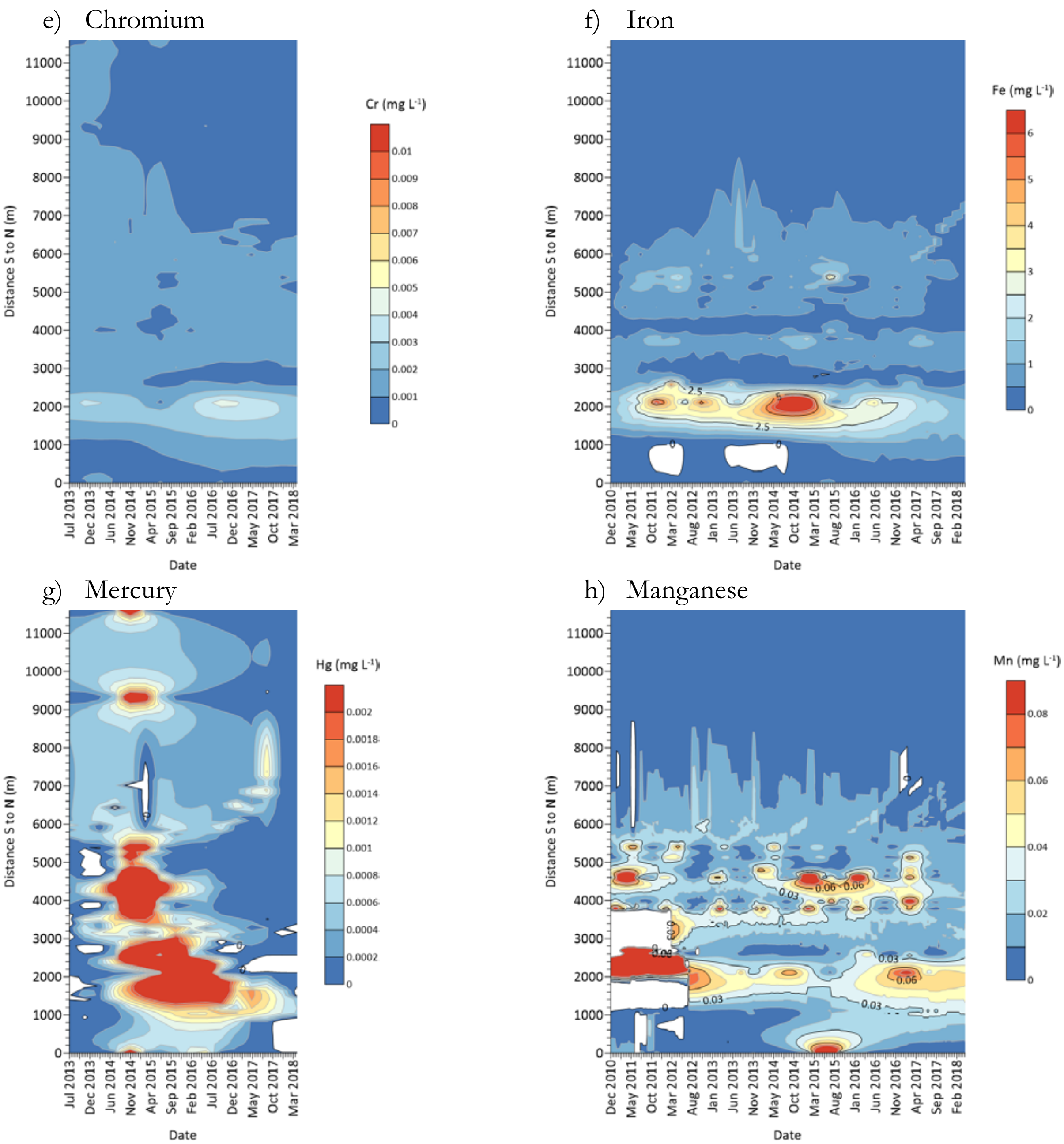
	Temperature (°C)	Conductivity (mS cm^{-1})	Dissolved Oxygen (mg L^{-1})	Dissolved Oxygen (%)	pH	ORP (mV)
Goollelal SE	26	0.26	4.1	50.6	6.18	232
Goollelal Mid W	17.4 ± 1 (16.5-18.4)	1.78 ± 0.18 (1.6-1.96)	5.1 ± 1.2 (3.9-6.2)	52.9 ± 10.8 (42.1-63.7)	6.08 ± 0.2 (5.88-6.28)	-189 ± 1 (-190--188)
Goollelal NE	18.3	0.93	6.4	68.1	5.34	-1
Wallubuenup Mid E	19 ± 0.2 (18.4-19.6)	0.54 ± 0 (0.54-0.55)	5.9 ± 0.6 (4.4-8)	63.9 ± 6.4 (46.8-86.6)	6.28 ± 0.22 (5.81-7.1)	-112 ± 22 (-194--74)
Wallubuenup W	20.8 ± 0.6 (19.3-22.7)	0.93 ± 0 (0.92-0.94)	5.1 ± 0.2 (4.6-5.8)	57.2 ± 2.2 (50.8-63.9)	5.88 ± 0.1 (5.67-6.36)	32 ± 8 (10-54)
Joondalup SE	21.8 ± 0.4 (20.5-22.9)	0.97 ± 0.01 (0.95-0.98)	5.1 ± 0.8 (3.2-8.4)	58.1 ± 9.1 (37.8-97)	6.23 ± 0.21 (5.8-7.14)	-113 ± 21 (-208--64)
Joondalup Mid E	21.7 ± 0.7 (19.6-23.6)	1.4 ± 0.02 (1.32-1.47)	5.2 ± 0.9 (3.3-9.2)	57.1 ± 8.4 (39-90.3)	6.31 ± 0.15 (6.05-7.03)	-34 ± 45 (-188-80)
Joondalup Mid W	18.7 ± 1.1 (14.4-21.2)	3.17 ± 0.42 (1.98-4.18)	4.5 ± 0.4 (3.4-5.9)	49.7 ± 3.6 (38.1-63.7)	6.88 ± 0.24 (6.42-8.03)	-205 ± 16 (-283--172)
Joondalup NE	21.1 ± 0.8 (18.6-23.3)	0.42 ± 0.01 (0.38-0.46)	5.6 ± 0.8 (4-9.1)	63.8 ± 9.5 (43.8-105.7)	5.68 ± 0.13 (5.32-6.1)	46 ± 31 (-50-133)
Joondalup NW	19.7 ± 1.4 (15.1-23.7)	2.14 ± 0.38 (0.82-3.2)	5.1 ± 0.4 (3.8-6)	56.6 ± 4.9 (41.1-68.4)	6.98 ± 0.31 (6.05-8.08)	-124 ± 79 (-301-241)

10. METALS AND METALLOIDS

10.1.1 SURFACE WATERS

In accordance with the ANZECC and ARMCANZ (2000) guidelines, corrections to trigger values based on site specific water hardness were calculated for cadmium, nickel and zinc (see Table 9). Figure 17 shows the seasonal changes in measured metal and metalloid concentrations since 2010 in the park. During this year, only Al and Zn exceeded the trigger values on some occasions, which is the least exceedances since 2010 in numbers of parameters and concentrations. High levels of Al can be associated with acid sulphate soils, however concentrations were below the 1 mg L^{-1} normally considered indicative (Department of Environmental Regulation 2015). Aluminium contamination is acutely and chronically toxic to fish, amphibians, invertebrates and phytoplankton (ANZECC & ARMCANZ, 2000). Mercury concentrations dropped well below the trigger values this year. As Cd, Cr and U are well below trigger values and show little variability, it might be worth removing them from the monitoring schedule and replacing them with other potentially deleterious metals such as B, Cu, and Pb.


a) Aluminium
b) Arsenic
c) Cadmium
d) Cobalt
Distance S to N (m)
Date
Al (mg L-1)
As (mg L-1)
Cd (mg L-1)
Co (mg L-1)


e) Chromium
Cr (mg L-1)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Distance S to N (m)
Date
Jul 2013
Dec 2013
Jun 2014
Nov 2014
Apr 2015
Sep 2015
Feb 2016
Jul 2016
Dec 2016
May 2017
Oct 2017
Mar 2018
f) Iron
Fe (mg L-1)
6
5
4
3
2
1
0
2.5
Dec 2010
May 2011
Oct 2011
Mar 2012
Aug 2012
Jan 2013
Jun 2013
Nov 2013
May 2014
Oct 2014
Mar 2015
Aug 2015
Jan 2016
Jun 2016
Nov 2016
Apr 2017
Sep 2017
Feb 2018
g) Mercury
Hg (mg L-1)
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
h) Manganese
Mn (mg L-1)
0.08
0.06
0.04
0.02
0
0.03
0.06
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0

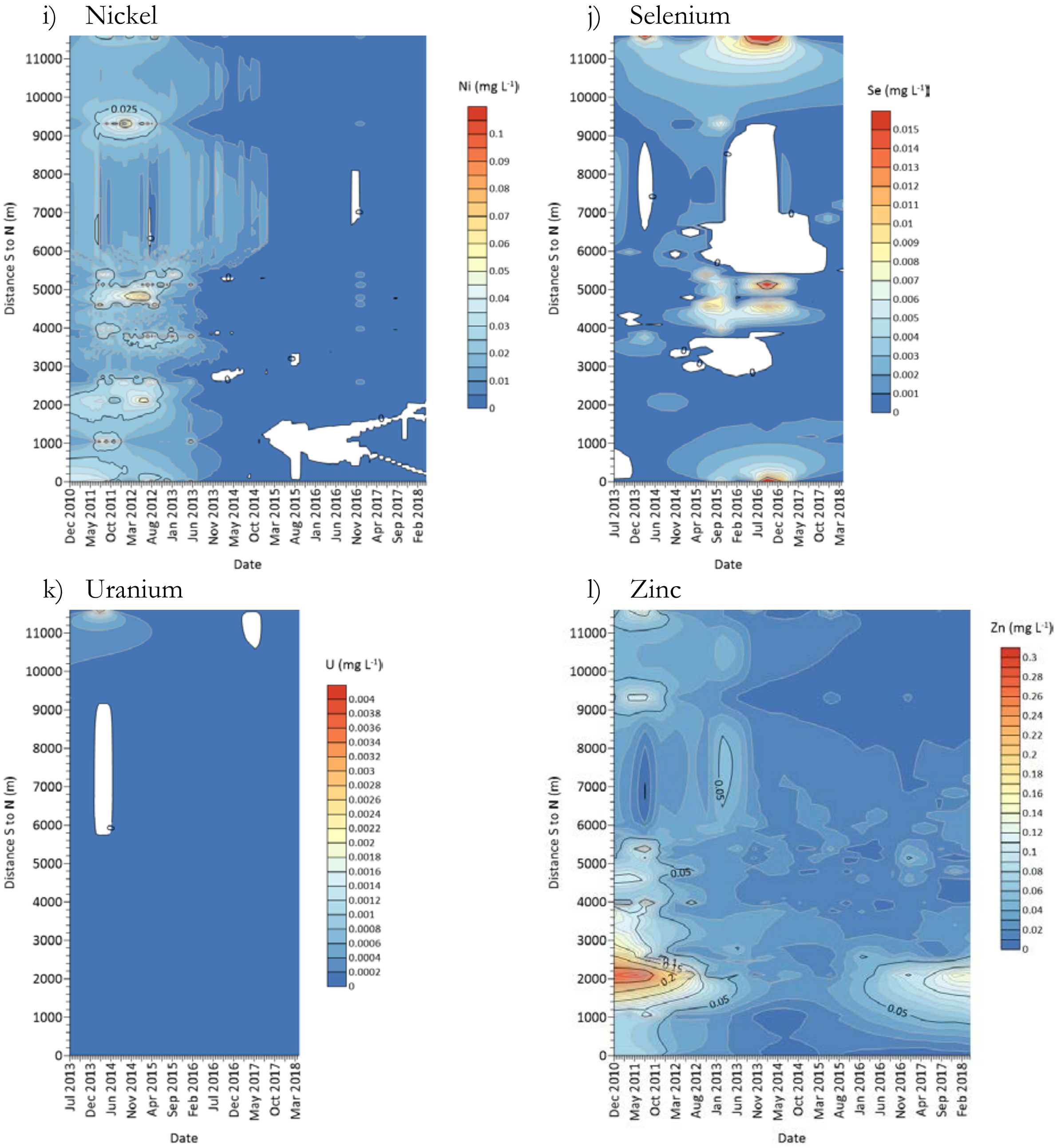


Figure 17. Metals and metalloid concentrations between June 2017 and April 2018 in Yellagonga wetlands.

Table 9. Exceedances of ANZECC/ARMCANZ (2000) water quality trigger values for 95% protection of aquatic ecosystems for metals and metalloids recorded in this study between June 2017 and April 2018

Metal/Metalloid (mg L^{-1})	ANZECC/ ARMCANZ (2000) Trigger Value	Detection Limit	Mean ± se (maximum value)	No. exceeding detection limit (No. exceeding trigger value)
Aluminium (Al)	0.055	<0.0005	0.014 ± 0.003 (0.169)	74 (3)
Arsenic (As)	0.013 - 0.024*	<0.00001	0.0025 ± 0.0001 (0.0065)	74 (0)
Calcium (Ca)	—	<0.2	47.56 ± 1.22 (77.07)	74 (0)
Cadmium (Cd)	0.0011 – 0.0016^H	<0.00001	0.00004 ± 0 (0.00021)	58 (0)
Cobalt (Co)	ID	<0.00002	0.0001 ± 0 (0.0011)	74 (0)
Chromium (Cr)	ID - 0.006^H	<0.00005	0.0012 ± 0.0001 (0.0035)	74 (0)
Iron (Fe)	ID	<0.0005	0.41 ± 0.05 (1.98)	74 (0)
Mercury (Hg)	0.0006 - ID*	<0.00002	0.000028 ± 0.000006 (0.000214)	13 (0)
Potassium (K)	—	<0.2	10.02 ± 0.58 (30.03)	74 (0)
Magnesium (Mg)	—	<0.2	23.69 ± 1.58 (67.18)	74 (0)
Manganese (Mn)	1.9	<0.00005	0.01 ± 0 (0.06)	74 (0)
Sodium (Na)	—	<0.2	108.62 ± 9.79 (411.99)	74 (0)
Nickel (Ni)	0.0480 – 0.0687^H	<0.00005	0.0004 ± 0.0001 (0.0016)	30 (0)
Selenium (Se)	0.011	<0.00005	0.0003 ± 0 (0.001)	71 (0)
Uranium (U)	0.005+	<0.00002	0.00001 ± 0 (0.00007)	14 (0)
Zinc (Zn)	0.0350 – 0.05^H	<0.00025	0.016 ± 0.003 (0.157)	72 (7)

H Value corrected for hardness (increases trigger) as per ANZECC/ARMCANZ (2000), hardness calculated from mean values of collected data for Ca, Mg, Se, 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 10. Mean ± standard error (range) for selected metals (in µg L^{-1}) over the 12 month study period (June 2017 – April 2018). Figure marked < were below detection.

	Al	As	Cd	Co	Cr	Fe
DL	>0.5	>0.01	>0.01	>0.02	<0.05	<0.01
South Lake Goollelal	7.6 ± 1.3 (2.8-12.1)	2.5 ± 0.2 (2-3.5)	0.031 ± 0.008 (<0.01-0.055)	0.154 ± 0.017 (0.075-0.2)	0.678 ± 0.057 (0.455-0.854)	109.2 ± 21.2 (35-191.3)
Beenyup Out (Site 1)	8.2 ± 1 (2.6-10.7)	2.2 ± 0.1 (1.8-2.3)	0.032 ± 0.008 (<0.01-0.06)	0.1 ± 0.007 (0.074-0.129)	1.253 ± 0.061 (1.079-1.474)	381.6 ± 25.6 (274.6-491.9)
Beenyup In (Site 3)	9.9 ± 1 (6.9-13.5)	1.8 ± 0.1 (1.3-2.3)	0.04 ± 0.01 (<0.01-0.081)	0.129 ± 0.022 (0.054-0.24)	1.325 ± 0.078 (1.072-1.704)	452 ± 36.8 (324.5-617.9)
Drain North (Site 4)	14.3 ± 2 (2.4-138)	1.7 ± 0.3 (0.9-52)	0.042 ± 0.207 (0.003-22)	0.117 ± 0.47 (<0.02-47)	1.625 ± 0.306 (0.134-30)	951.2 ± 25.1 (3.5-2134.7)
Drain Goollelal (Site 5)	95.9 ± 25.4 (51.3-168.8)	4.9 ± 0.7 (3.3-6.5)	0.046 ± 0.005 (0.036-0.06)	0.94 ± 0.081 (0.784-1.146)	2.998 ± 0.184 (2.611-3.493)	1464.1 ± 262.1 (784.7-1920.7)
Drain South (Site 6)	12.6 ± 0.6 (10.3-14.6)	1.5 ± 0.1 (1.2-1.6)	0.062 ± 0.026 (<0.01-0.214)	0.074 ± 0.006 (0.054-0.099)	0.922 ± 0.065 (0.796-1.294)	240.9 ± 49.8 (129.6-521.5)
South Culvert Inlet	9.8 ± 0.7 (7.1-12.4)	2.1 ± 0.1 (1.8-2.4)	0.047 ± 0.014 (0.005-0.118)	0.101 ± 0.004 (0.087-0.118)	1.302 ± 0.07 (1.081-1.501)	376.9 ± 26 (273.5-505.4)
South Culvert	7.9 ± 0.5 (3.3-14.8)	2.4 ± 0.1 (1.6-3.6)	0.048 ± 0.008 (<0.01-0.166)	0.111 ± 0.005 (0.068-0.19)	1.189 ± 0.036 (0.866-1.526)	422 ± 12.9 (353.3-618.4)
South Lake Joondalup	7 ± 1 (1.6-10.4)	2.5 ± 0.3 (1.6-3.7)	0.045 ± 0.019 (<0.01-0.155)	0.109 ± 0.009 (0.09-0.156)	1.195 ± 0.081 (0.89-1.486)	483.4 ± 28.8 (396.2-586.8)
Mid Lake Joondalup	10 ± 1.3 (1.2-29.5)	3.7 ± 0.2 (2.6-5.9)	0.03 ± 0.005 (<0.01-0.103)	0.051 ± 0.002 (0.037-0.083)	0.633 ± 0.012 (0.474-0.725)	45.9 ± 5.1 (15.6-112.4)
North Lake Joondalup	9.7 ± 0.5 (3.9-16.2)	3.7 ± 0.2 (2.7-6.1)	0.013 ± 0.002 (<0.01-0.04)	0.057 ± 0.002 (0.039-0.087)	0.669 ± 0.021 (0.376-0.827)	49.9 ± 7 (15.4-146.7)

Table 10 cont.

DL	Hg >0.02	Mn >0.05	Ni >0.05	Se >0.05	U >0.02	Zn <0.05
South Lake Goollelal	0.04 ± 0.03 (<0.02-0.2)	5.26 ± 1.33 (1.37-9.88)	0.29 ± 0.14 (<0.05-0.94)	0.24 ± 0.03 (0.09-0.38)	0.027 ± 0.008 (<0.02-0.069)	5.2 ± 1.04 (0.13-9.04)
Beenyup Out (Site 1)	0.04 ± 0.03 (<0.02-0.21)	12.93 ± 2.31 (7.38-23.88)	0.35 ± 0.16 (<0.05-1.06)	0.25 ± 0.06 (0.14-0.58)	0.01 ± 0 (<0.02)	8.16 ± 1.09 (3.05-11.1)
Beenyup In (Site 3)	0.04 ± 0.03 (<0.02-0.19)	14.83 ± 2.67 (7.24-26.64)	0.41 ± 0.18 (<0.05-1)	0.27 ± 0.02 (0.18-0.37)	0.024 ± 0.005 (<0.02-0.045)	11.23 ± 0.89 (8.06-14.25)
Drain North (Site 4)	0.03 ± 4.45 (0-785.18)	14.47 ± 2.25 (0.71-270.8)	0.41 ± 0.98 (<0.05-90)	0.29 ± 1.86 (<0.05-222)	0.009 ± 5.744 (<0.02-333.692)	22.39 ± 2.15 (0.13-256)
Drain Goollelal (Site 5)	0.01 ± 0 (<0.02)	40.64 ± 7.25 (27.29-55.84)	0.03 ± 0 (<0.05)	0.83 ± 0.08 (0.61-1)	0.016 ± 0.004 (<0.02-0.024)	98.86 ± 25.24 (55.25-156.7)
Drain South (Site 6)	0.03 ± 0.02 (<0.02-0.17)	10.23 ± 3.27 (5.2-29.49)	0.4 ± 0.2 (<0.05-1.43)	0.22 ± 0.04 (0.08-0.44)	0.013 ± 0.002 (<0.02-0.025)	21.86 ± 5.34 (11.52-51.56)
South Culvert Inlet	0.03 ± 0.02 (<0.02-0.13)	12.19 ± 1.67 (8.24-20.68)	0.41 ± 0.19 (<0.05-0.98)	0.2 ± 0.04 (<0.05-0.32)	0.01 ± 0 (<0.02)	15.73 ± 5.26 (2.11-45.24)
South Culvert	0.03 ± 0.01 (<0.02-0.12)	13.7 ± 0.82 (9.7-26.32)	0.41 ± 0.07 (<0.05-1.15)	0.17 ± 0.01 (<0.05-0.31)	0.011 ± 0.001 (0.005-0.025)	8.55 ± 0.37 (4.99-12.62)
South Lake Joondalup	0.02 ± 0.01 (<0.02-0.09)	13.33 ± 1.98 (9.2-24.53)	0.48 ± 0.22 (<0.05-1.27)	0.18 ± 0.04 (0.07-0.34)	(<0.02)	12.71 ± 3.07 (8.03-30.75)
Mid Lake Joondalup	0.02 ± 0 (<0.02-0.03)	1.15 ± 0.05 (0.95-2)	0.49 ± 0.09 (<0.05-1.61)	0.25 ± 0.02 (0.11-0.51)	0.012 ± 0.001 (<0.02-0.025)	1.69 ± 0.14 (0.32-2.87)
North Lake Joondalup	0.01 ± 0 (<0.02-0.03)	1.01 ± 0.04 (0.53-1.31)	0.38 ± 0.07 (<0.05-1.3)	0.21 ± 0.03 (<0.05-0.68)	0.011 ± 0 (<0.02-0.014)	8.43 ± 2.22 (0.13-43.27)

10.1.2 GROUNDWATERS

The number of samples from all the bores that exceeded ANZECC & ARMCANZ (2000) guidelines for the protection of aquatic ecosystems are shown in Table 3. It should be noted that these guidelines were not designed for groundwater, but assuming that this groundwater discharges into the lake then it provides an indicator of potential issues. Aluminium, As, and Zn all had concentrations that on occasion were higher than guideline levels (often by an order of magnitude) indicating potential problems for the lakes. Interestingly, in 2015/16, Cd and Hg were also problematic but this is not the case in 2016/17 or this year. Aluminium, and Zn concentrations were particularly problematic with over 25% of samples exceeding guidelines. The low pH in the bores would increase the toxicity of Al which is most toxic around pH 4.5-5. All the metals detected at high concentrations were also identified as problematic in the Yellagonga surface water monitoring program, suggestive that a major source might be groundwater.

Table 11. Exceedances of ANZECC & ARMCANZ (2000) water quality trigger values for 95% protection of aquatic ecosystems for metals and metalloids recorded in this study between June 2017 and April 2018.

Metal/Metalloid (mg L^{-1})	ANZECC/ ARMCANZ (2000) Trigger Value	Detection Limit	Mean ± se (maximum value)	No. exceeding detection limit (No. exceeding trigger value)
Aluminium (Al)	0.055	<0.0005	0.038 ± 0.005 (0.186)	55 (11)
Arsenic (As)	0.013 - 0.024*	<0.00001	0.0052 ± 0.001 (0.0367)	55 (3)
Calcium (Ca)	—	<0.2	44.42 ± 2.24 (102.19)	55 (0)
Cadmium (Cd)	0.0011 – 0.0016[H]	<0.00001	0.00006 ± 0.00001 (0.00029)	44 (0)
Cobalt (Co)	ID	<0.00002	0.0002 ± 0 (0.0019)	55 (0)
Chromium (Cr)	ID - 0.006[H]	<0.00005	0.0015 ± 0.0001 (0.0051)	55 (0)
Iron (Fe)	ID	<0.0005	1.11 ± 0.28 (7.22)	55 (0)
Mercury (Hg)	0.0006 - ID*	<0.00002	0.00002 ± 0 (0.00009)	24 (0)
Potassium (K)	—	<0.2	13.04 ± 1.49 (58.36)	55 (0)
Magnesium (Mg)	—	<0.2	30.68 ± 3.17 (100.33)	55 (0)
Manganese (Mn)	1.9	<0.00005	0.01 ± 0 (0.05)	55 (0)
Sodium (Na)	—	<0.2	147.23 ± 19.06 (530.66)	55 (0)
Nickel (Ni)	0.0480 – 0.0687[H]	<0.00005	0.0011 ± 0.0001 (0.0043)	37 (0)
Selenium (Se)	0.011	<0.00005	0.0004 ± 0 (0.0018)	53 (0)
Uranium (U)	0.005+	<0.00002	0.00005 ± 0.00001 (0.00026)	43 (0)
Zinc (Zn)	0.0350 – 0.05[H]	<0.00025	0.111 ± 0.009 (0.389)	55 (47)

H Value corrected for hardness (increases trigger) as per ANZECC/ARMCANZ (2000), hardness calculated from mean values of collected data for Ca, Mg, Se, Fe, Al, Zn and Mn.
* Range for As III and V, Cr III and VI, and Hg inorganic and methyl.
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)

Table 12. Mean ± standard error (range) for selected metals over the June 2017 to April 2018 monitoring period with ANZECC & ARMCANZ (2000) water quality trigger values for 95% protection of aquatic ecosystems for metals and metalloids for reference (all in µg L^{-1}).

	Al	As	Cd	Co	Cr	Fe
DL	<0.5	<0.01	<0.01	<0.02	<0.05	<0.5
Trigger Value	>55	>13-24	>0.3-1.7[H]	ID	ID-4*	ID
S.E. Goollelal	25 ± 7 (12-60)	2.3 ± 0.3 (1.6-3)	0.08 ± 0.02 (0.03-0.17)	0.17 ± 0.02 (0.11-0.22)	0.79 ± 0.04 (0.69-0.97)	81.5 ± 22.9 (35.1-159.1)
Mid W. Goollelal	104 ± 81 (23-186)	7.3 ± 1.2 (6-8.5)	0.07 ± 0.03 (0.04-0.1)	0.39 ± 0.33 (0.06-0.72)	1.34 ± 0.39 (0.94-1.73)	142.5 ± 41.9 (100.5-184.4)
N.E. Goollelal	50 ± 14 (16-111)	1.1 ± 0.2 (0.5-1.8)	0.11 ± 0.03 (0.03-0.25)	0.24 ± 0.02 (0.18-0.31)	0.75 ± 0.05 (0.62-0.99)	4579.7 ± 1019.5 (209.7-7222)
Mid E. Wallubuenup	25 ± 5 (15-45)	12.7 ± 1.6 (8.2-17.3)	0.03 ± 0.01 (<0.01-0.06)	0.14 ± 0.01 (0.1-0.18)	3.26 ± 0.17 (2.81-3.74)	69.1 ± 16.2 (24.7-108.3)
W. Wallubuenup	12 ± 3 (5-26)	1.8 ± 0.2 (1.2-2.3)	0.11 ± 0.03 (0.04-0.23)	0.09 ± 0.01 (0.06-0.14)	2.2 ± 0.18 (1.52-2.78)	4659.4 ± 432.6 (2950-5827)
S.E. Joondalup	30 ± 5 (20-49)	1.2 ± 0.1 (1-1.3)	0.04 ± 0.01 (<0.01-0.11)	0.12 ± 0.03 (0.06-0.27)	0.68 ± 0.02 (0.61-0.78)	63.7 ± 20.6 (14.9-127.2)
Mid E. Joondalup	46 ± 16 (17-102)	1.6 ± 0.1 (1.5-1.9)	0.04 ± 0.02 (<0.01-0.14)	0.81 ± 0.23 (0.38-1.87)	0.87 ± 0.06 (0.71-1.07)	140.6 ± 38.5 (37.8-271.2)
Mid W. Joondalup	16 ± 5 (41-105)	0.1 ± 1.7 (10.3-36.7)	0.02 ± 0 (<0.01-0.01)	0.23 ± 0.01 (0.09-0.31)	0.06 ± 0.19 (2.03-5.14)	38.5 ± 21.1 (77.9-418.3)
N.E. Joondalup	20 ± 5 (12-43)	1.3 ± 0.1 (1-1.6)	0.1 ± 0.04 (0.03-0.29)	0.1 ± 0.01 (0.05-0.14)	0.91 ± 0.04 (0.78-1.01)	150.7 ± 15.6 (100.5-202.7)
N.W. Joondalup	32 ± 3 (15-61)	3.6 ± 0.2 (2.5-5.7)	0.03 ± 0 (<0.01-0.07)	0.12 ± 0.01 (0.05-0.27)	1.21 ± 0.04 (0.89-1.44)	173.7 ± 9.5 (113.5-244.4)

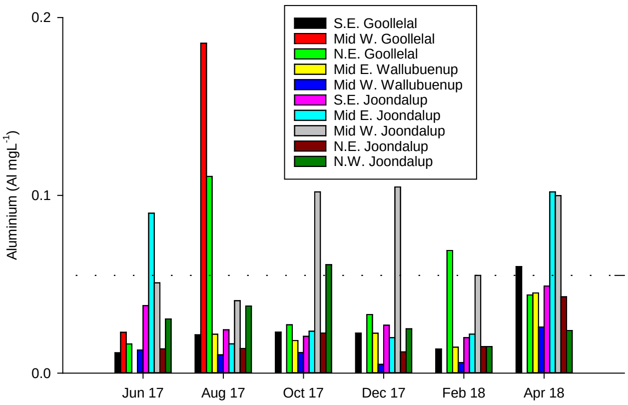
Table 12. cont.

,	Hg	Mn	Ni	Se	U	Zn
DL	<0.02	<0.05	<0.05	<0.05	<0.02	<0.05
Trigger Value	>0.6-ID*	>1.9	>18.1-88.5[H]	>11	>5[+]	>13.2-64.3[H]
S.E. Goollelal	0.024 ± 0.009 (<0.01-0.065)	2.1 ± 0.4 (0.5-3)	1.47 ± 0.42 (0.03-2.59)	0.261 ± 0.035 (0.154-0.363)	0.063 ± 0.013 (0.036-0.124)	102.8 ± 4.5 (85.8-117.5)
Mid W. Goollelal	0.051 ± 0.041 (<0.01-0.091)	4.4 ± 2.3 (2.1-6.8)	0.64 ± 0.62 (0.03-1.26)	0.229 ± 0.188 (0.041-0.417)	0.006 ± 0.004 (<0.001-0.01)	37.5 ± 8.2 (29.3-45.7)
N.E. Goollelal	0.028 ± 0.011 (<0.01-0.08)	11.8 ± 0.9 (9-15.6)	0.93 ± 0.31 (0.03-1.88)	0.258 ± 0.063 (0.084-0.52)	0.015 ± 0.005 (<0.001-0.036)	234.7 ± 36.8 (128.7-388.8)
Mid E. Wallubuenup	0.013 ± 0.003 (<0.01-0.027)	8.8 ± 0.8 (7.1-11.2)	0.79 ± 0.36 (0.03-1.92)	0.754 ± 0.155 (0.372-1.202)	0.122 ± 0.011 (0.099-0.161)	121.9 ± 5.8 (107.6-137.3)
W. Wallubuenup	0.018 ± 0.006 (<0.01-0.044)	25.8 ± 1.6 (20.9-31.5)	0.86 ± 0.32 (0.03-1.99)	0.15 ± 0.038 (<0.05-0.283)	0.046 ± 0.004 (0.037-0.062)	131.4 ± 9.7 (111.6-173.3)
S.E. Joondalup	0.025 ± 0.007 (<0.01-0.048)	15.7 ± 1.2 (11.7-20.6)	1.15 ± 0.61 (0.03-4.02)	0.254 ± 0.041 (0.133-0.398)	0.042 ± 0.006 (0.026-0.067)	142.4 ± 8.7 (118.1-168.7)
Mid E. Joondalup	0.019 ± 0.007 (<0.01-0.052)	32.4 ± 6.8 (14.4-51)	1.66 ± 0.64 (0.03-4.3)	0.428 ± 0.028 (0.359-0.535)	0.089 ± 0.008 (0.066-0.115)	120.7 ± 6 (106.6-139.2)
Mid W. Joondalup	0.007 ± 0.005 (<0.01-0.092)	6.8 ± 0.6 (2.1-12.3)	0.64 ± 0.18 (0.03-2.84)	0.028 ± 0.056 (0.068-1.064)	0.008 ± 0.015 (0.032-0.261)	6 ± 4.6 (33.1-98.5)
N.E. Joondalup	0.022 ± 0.009 (<0.01-0.065)	3.1 ± 0.1 (2.7-3.3)	0.67 ± 0.25 (0.03-1.64)	0.229 ± 0.048 (0.112-0.443)	0.012 ± 0.002 (0.006-0.021)	53.9 ± 4.2 (42.5-66.8)
N.W. Joondalup	0.026 ± 0.004 (<0.01-0.069)	5.9 ± 0.6 (3.3-12.4)	0.92 ± 0.14 (0.03-2.32)	0.766 ± 0.092 (0.392-1.794)	0.025 ± 0.002 (0.01-0.042)	49.4 ± 1.5 (33.6-61.1)

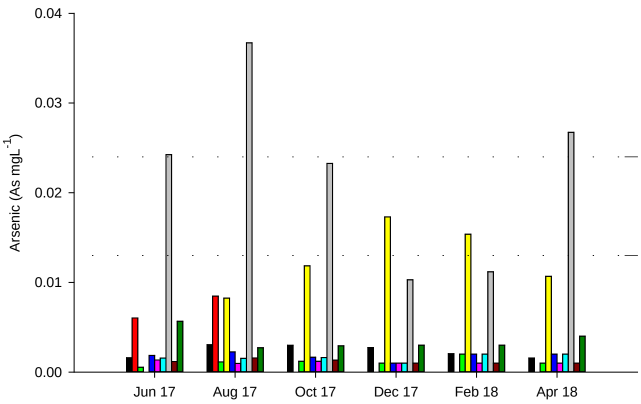
H Value corrected for hardness (increases trigger) as per ANZECC/ARMCANZ (2000), hardness calculated from mean values of collected data for Ca, Mg, Se, Fe, Al, Zn and Mn.
* Range for As III and V, Cr III and VI, and Hg inorganic and methyl.
ID Insufficient data to derive a reliable trigger value.
+ Low reliability, interim working level as prescribed in ANZECC/ARMCANZ (2000)

Figure 18 shows metal concentrations where the metal exceeded ANZECC/ARMCANZ guidelines for protection of freshwater ecosystems. Figure 18a shows high Al concentrations associated with bores likely contaminated by ASS. Arsenic only exceeded the upper guideline at Mid W Joondalup, but exceeded the lower guideline a number of times at Mid E Wallubuenup. The two guideline values for As relate to the specific form (which was not measured here). Arsenic is often associated with ASS, but this does not appear to be the case here (Figure 18b). The source of Zn is unknown but potentially toxic levels are found in all bores (Figure 18c).

a) Aluminium



b) Arsenic



c) Zinc

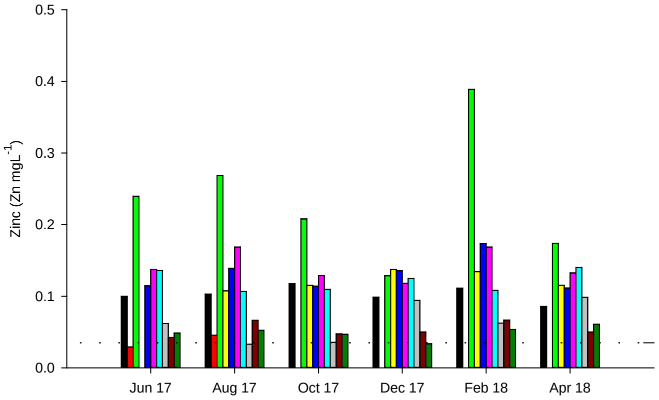


Figure 18. Metal concentrations for groundwater samples taken between June 2017 and April 2018 for all sites sampled. Dotted lines indicate the ANZECC & ARMCANZ (2000) trigger value ranges for the protection of aquatic ecosystems (95%).

10.2 NUTRIENTS

10.2.1 SURFACE WATERS

Dissolved organic C concentrations were typical of Swan Coastal Plain wetlands and tended to increase slightly northwards (Figure 19). Concentrations of DOC were high throughout most of the park in April 2017 before declining in the southern part of the park during this year. The drivers of DOC concentrations are not currently known.

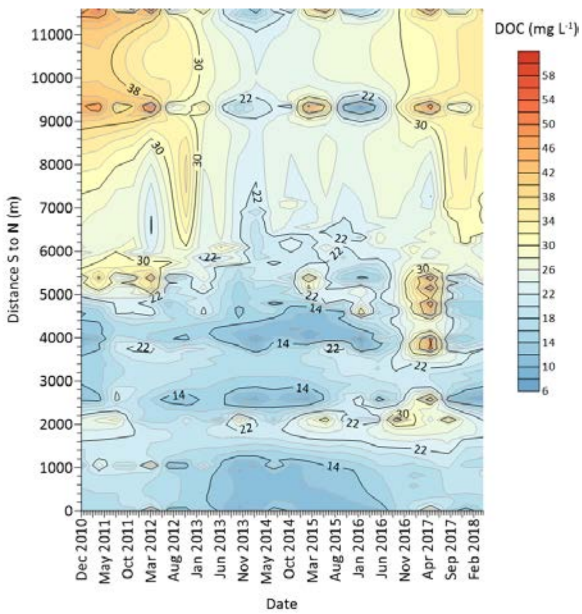


Figure 19. Dissolved organic C concentrations across the park between 2010 and 2018.

Total phosphorus concentrations (Figure 20) exceeded the 60 µg L^{-1} ANZECC & ARMCANZ (2000) water quality guidelines for the 95% protection of aquatic ecosystems, at all sites except North Lake Joondalup and South Lake Goollelal where exceedances were uncommon. (Table 13). Another important feature of phosphorus in the Yellagonga system was the high proportion of FRP (often exceeding 50% of the total). This is suggestive of significant groundwater inputs from catchments low in limestone (which would normally bind the FRP). The highest Total P concentrations occur in the south drains (sites 4-6). Interestingly the high Total P concentrations seen at the south drains in the last couple of years were not reflected in FRP concentrations suggesting that were associated with algal blooms (although the Chlorophyll *a* concentrations do not support this) or other particulates in the water.

The results show that Beenyup Swamp continues to export small amounts of P (particularly as FRP) as recorded by Lund et al. (2011a). The South Culvert inlet and South Culvert had slightly higher P concentrations compared to $Beenyup_{out}$ which fits with that seen previously, where there appeared to be a source of P (assumed to be groundwater) between $Beenyup_{out}$ and the Culvert. Phosphorus declines from South Lake Joondalup to North/Mid Lake Joondalup, suggesting either: rapid uptake by the Lake Joondalup sediment, or the thick rushes between as the South Lake Joondalup site and Mid Lake Joondalup.

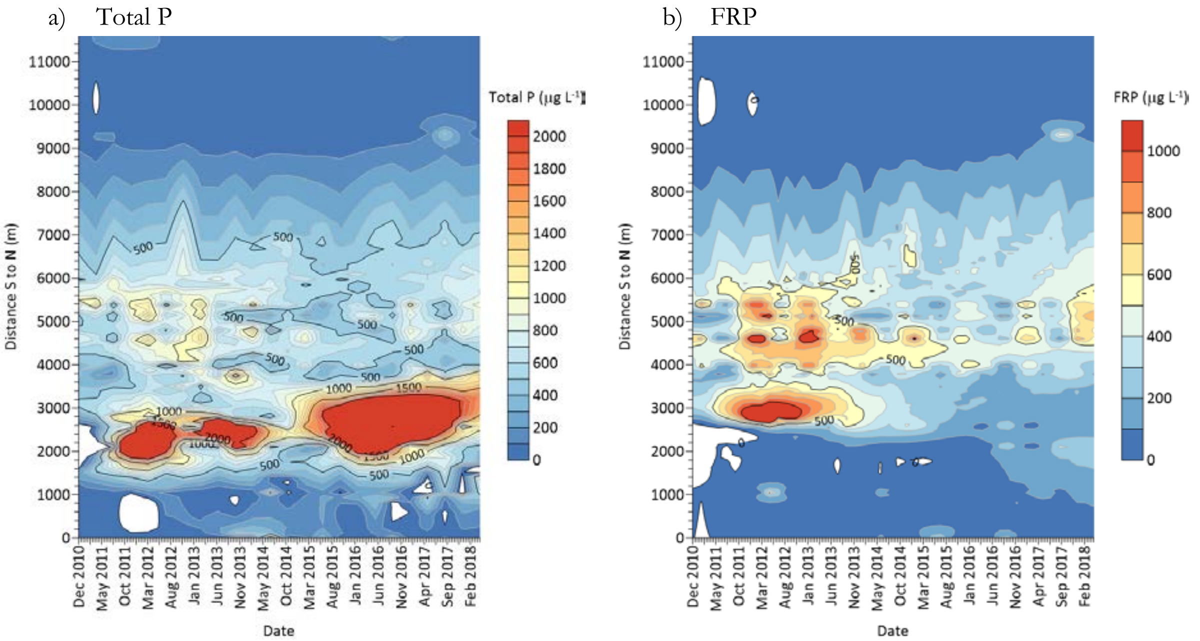


Figure 20. Total P and FRP concentrations across the park between 2010 and 2018.

Total N concentrations commonly exceeded the recommended ANZECC & ARMCANZ guidelines of 1500 µg L^{-1} (Figure 21 & Table 13), particularly during spring. Total N concentrations appear to be declining in Lakes Joondalup and Goollelal from the highs in 2010 and 2011. The majority of the excessive N was in the form of organic N and is most likely associated with particulates of organic matter in the water. Algae and submerged plants probably generate these organic matter particulates in Lake Joondalup accounting for the high concentrations seen there. As seen for Total P there were high concentrations of Total N at sites 4-6. Relatively low concentrations of NOx and NH_3 were recorded throughout the system. Unlike recorded in Lund et al (2011a) there was no strong evidence of nitrogen export from Beenyup.

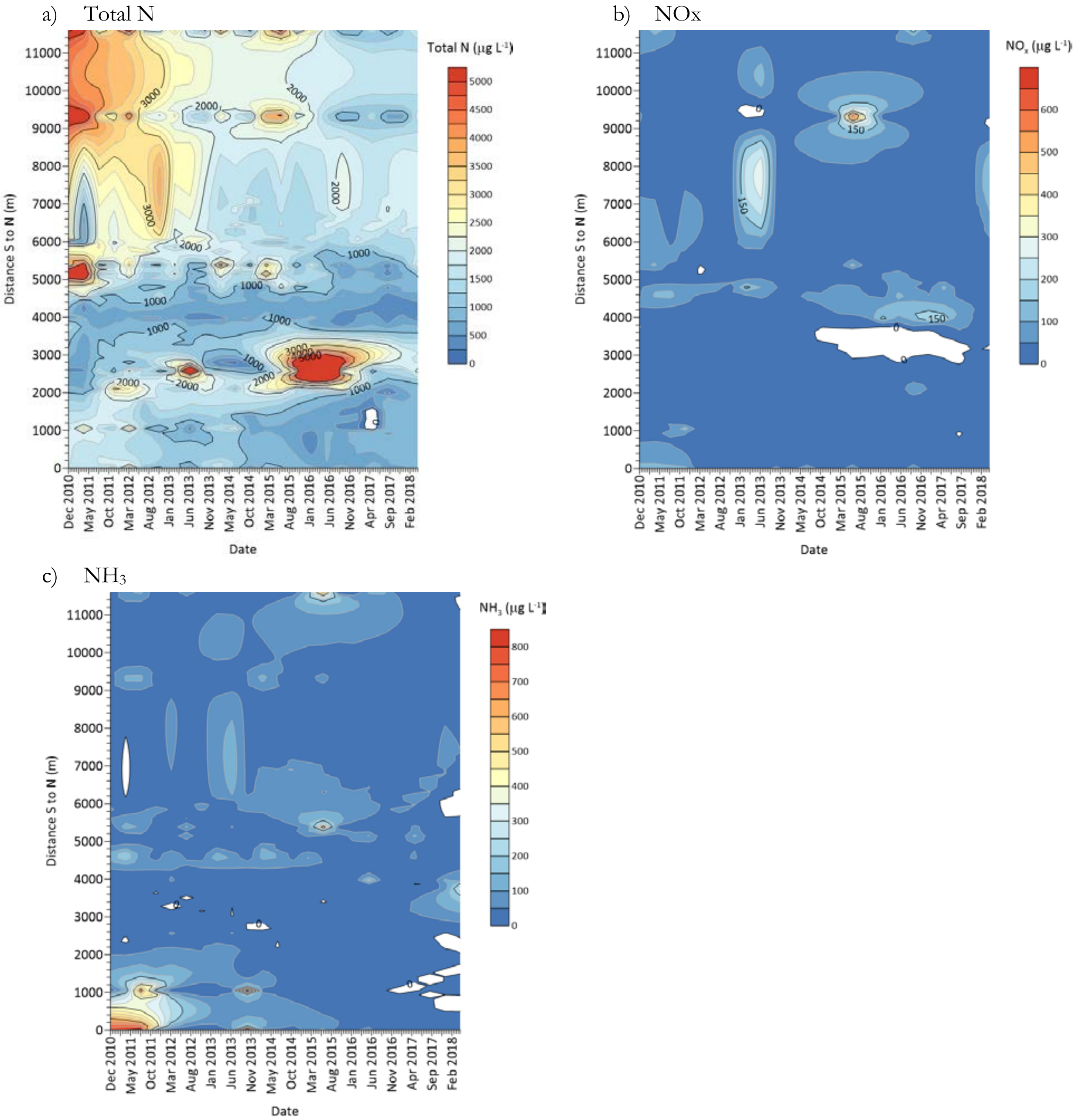


Figure 21. Concentrations of Total Nitrogen, NOx and NH_3 across the park between 2010 and 2018.

Table 13. Mean ± s.e. (range) for nutrients in water recorded at each study site over the course of the monitoring period (June 2017 - April 2018)

	NH_3-N	NOx-N	Total N	Organic N	FRP-P	Total P	Organic P	DOC
	µg.L^{-1}	µg.L^{-1}	µg.L^{-1}	µg.L^{-1}	µg.L^{-1}	µg.L^{-1}	µg.L^{-1}	mg.L^{-1}
DL	>3	>2	>50		>2	>20		>0.5
South Lake Goollelal	33 ± 29 (<3-204)	9 ± 5 (3-37)	741 ± 127 (192-1140)	699 ± 113 (187-997)	50 ± 12 (14-89)	72 ± 16 (28-136)	22 ± 5 (8-47)	18.1 ± 2.7 (10.9-33.7)
Beenyup Out (Site 1)	12 ± 8 (<3-62)	35 ± 22 (2-150)	490 ± 96 (<50-830)	443 ± 83 (<50-664)	338 ± 114 (64-861)	429 ± 107 (89-924)	91 ± 41 (20-337)	21.5 ± 5.9 (12.8-56.5)
Beenyup In (Site 3)	28 ± 18 (<3-119)	77 ± 32 (8-240)	426 ± 101 (<50-744)	321 ± 89 (<50-569)	302 ± 38 (123-408)	402 ± 38 (220-511)	101 ± 37 (20-279)	20.5 ± 4.8 (11.8-47.4)
Drain North (Site 4)	50 ± 11 (<3-2520)	68 ± 3 (<2-298)	587 ± 39 (<50-4450)	470 ± 37 (<50-4369)	299 ± 19 (3-2420)	821 ± 37 (10-6000)	522 ± 30 (0-5627)	23.1 ± 0.5 (2.2-56.5)
Drain Goollelal (Site 5)	<3 (<3)	4 ± 2 (<2-8)	329 ± 159 (<50-669)	323 ± 159 (<50-664)	265 ± 65 (73-366)	1207 ± 409 (473-2190)	942 ± 465 (107-2117)	27.9 ± 4.5 (16.5-37.9)
Drain South (Site 6)	2 ± 1 (<3-7)	4 ± 2 (<2-16)	1271 ± 360 (187-2520)	1265 ± 358 (186-2497)	112 ± 8 (93-153)	1462 ± 616 (358-4820)	1350 ± 619 (205-4719)	14.8 ± 4.8 (8.6-43.3)
South Culvert Inlet	7 ± 5 (<3-37)	34 ± 23 (<2-155)	859 ± 273 (76-2260)	817 ± 276 (<50-2258)	377 ± 86 (173-808)	799 ± 222 (334-2035)	422 ± 241 (20-1854)	20.8 ± 5.3 (14.1-52.8)
South Culvert	37 ± 10 (<3-178)	18 ± 3 (2-65)	563 ± 43 (202-1010)	508 ± 43 (121-1004)	430 ± 30 (156-793)	479 ± 32 (204-862)	49 ± 5 (5-93)	23 ± 2.2 (14.3-57.8)
South Lake Joondalup	28 ± 11 (3-82)	13 ± 4 (3-26)	710 ± 230 (208-2010)	669 ± 235 (146-2005)	394 ± 79 (158-690)	495 ± 111 (166-932)	101 ± 48 (8-340)	24.8 ± 5.2 (14.2-53.9)
Mid Lake Joondalup	21 ± 3 (3-51)	16 ± 2 (4-44)	855 ± 102 (111-1960)	818 ± 102 (104-1950)	260 ± 34 (20-570)	320 ± 38 (40-639)	60 ± 9 (5-165)	31.6 ± 1.8 (21.7-56.4)
North Lake Joondalup	7 ± 1 (<3-20)	3 ± 0 (<2-5)	990 ± 83 (442-1880)	981 ± 83 (419-1870)	48 ± 3 (18-72)	63 ± 3 (29-86)	15 ± 1 (6-32)	29.7 ± 1.9 (16.1-54.7)

The highest DOC concentrations were found in water leaving Lake Joondalup at N.W. Joondalup, Mid W. Joondalup and Mid W. Goollelal (Figure 22). The western Joondalup concentrations were highest in June. This pattern is almost identical to that seen for EC (Figure 8.), and therefore probably an evapoconcentration effect.

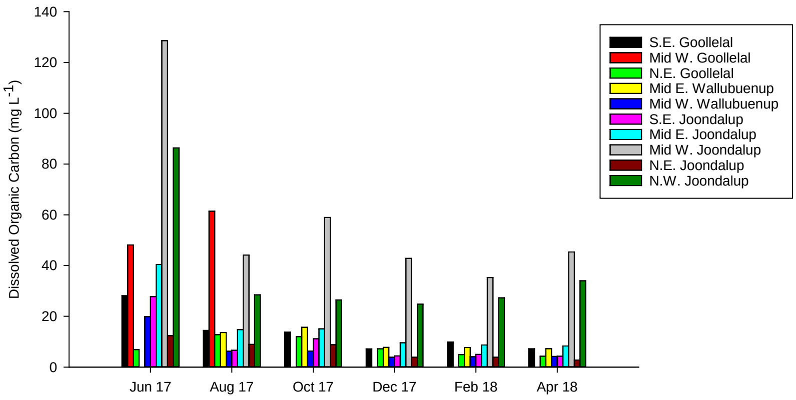


Figure 22. Dissolved organic C concentrations recorded in groundwater bores from June 2017 to April 2018.

In 2016/17 concentrations of Total P and fractions were higher than in 2015/16 in almost all cases. However, the pattern of P concentrations across the bores was almost identical to that of 2014/15. Mid E Joondalup had the highest concentrations of FRP exceeding 100 µg L^{-1}, in most months and highest concentrations of Total P in all months sampled. All sites were dominated by organic P (probably inorganic particulates, as the analysis does not discriminate between organic and inorganic forms). S.E. Goollelal, Mid E. Wallubuenup and Mid E. Joondalup were consistently high in P suggesting that these bores were sources of P in wetland system. These sites also had high P concentrations in previous years. The N.W. Joondalup bore was usually higher in P than N.E. Joondalup and was the only western site besides Mid W Joondalup site that showed significant P levels. High P concentrations in the western bores of Lake Joondalup are important as a P loss mechanism from the lake.

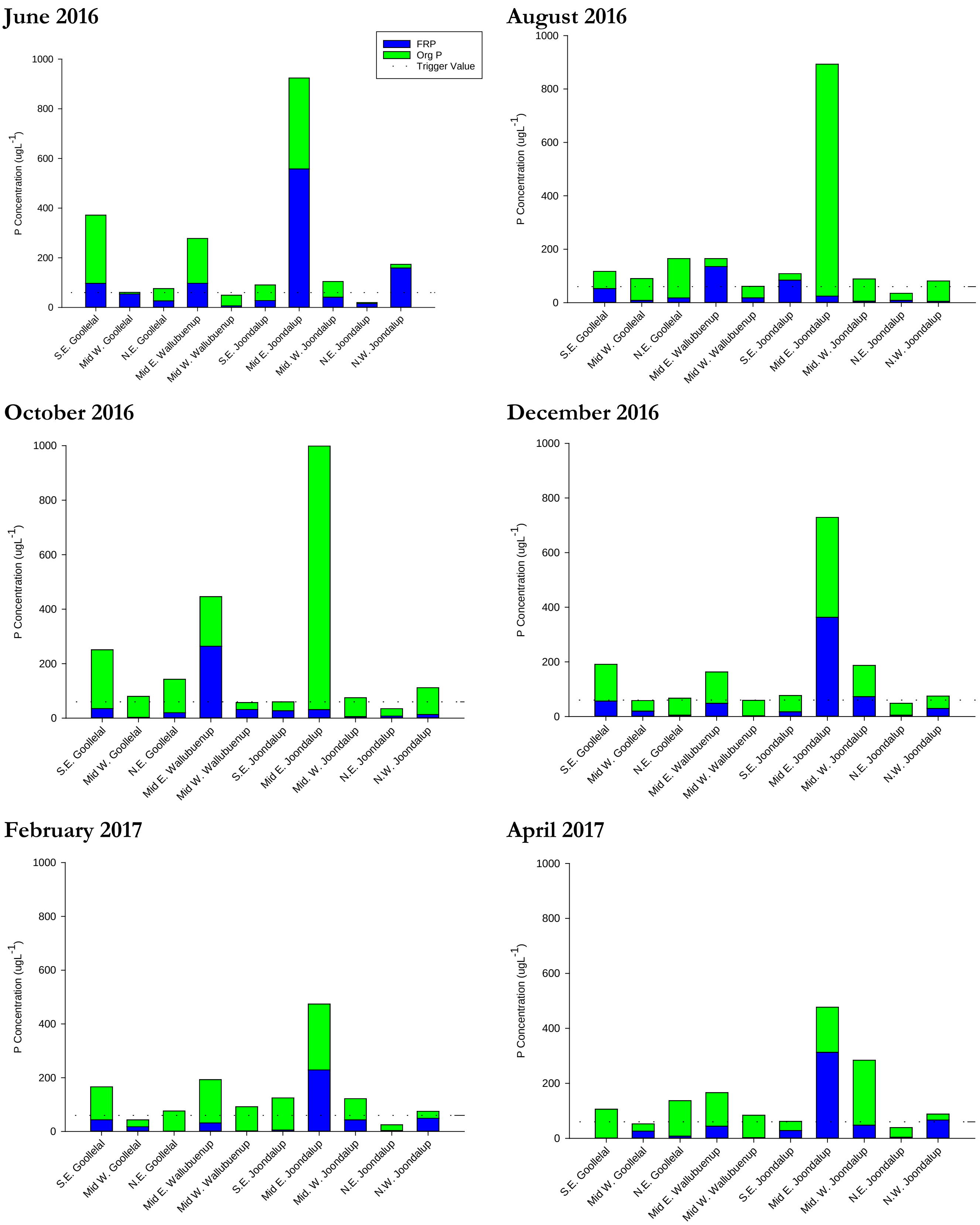
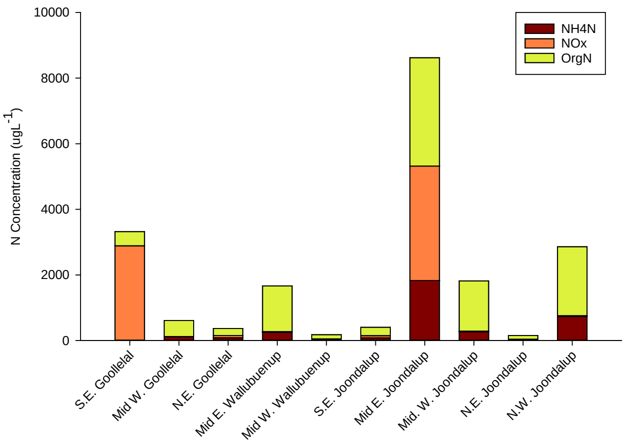


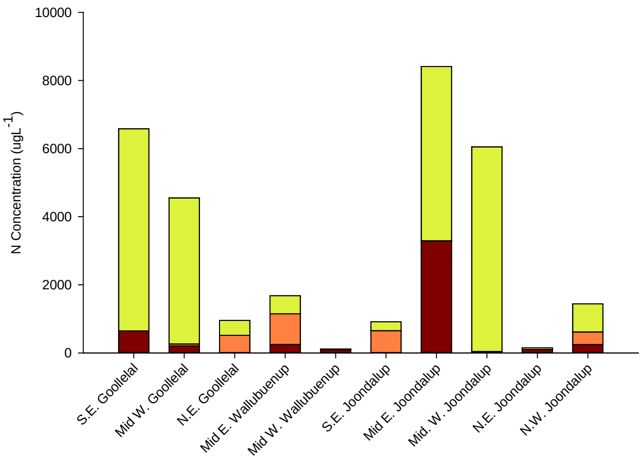
Figure 23. Breakdown of total phosphorus into chemical fractions (organic P and FRP) recorded in groundwater at each bore between June 2017 and April 2018 with the ANZECC & ARMANZ (2000) trigger value for total phosphorus shown.

Nitrogen concentrations in the groundwater were dominated by organic N (the analysis used does not discriminate between organic and inorganic forms), most probably N associated with colloidal particles between June and October. Mid E. Joondalup, Mid W Joondalup and S.E. Goollelal consistently had very high NOx concentrations. High concentrations of NOx at Mid E. Joondalup may be from the former landfill areas on the eastern side of Lake Joondalup and fertiliser use on lawns. At S.E. Goollelal the high NOx may be from septic tanks east of Kingsley or a legacy of former agricultural activities on the eastern side of the lakes. Occasional spikes of NH_4 are seen in eastern bores. Similar patterns were seen in nitrogen in bores in previous years.

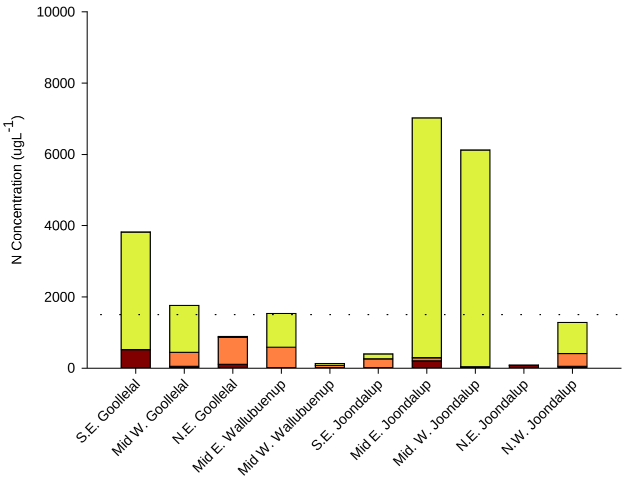
June 2016



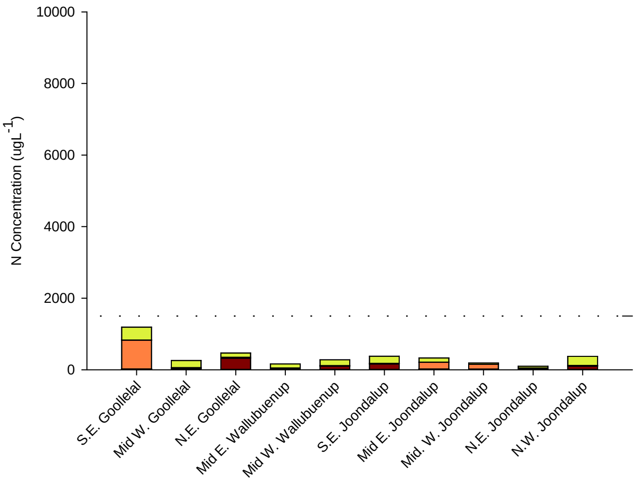
August 2016



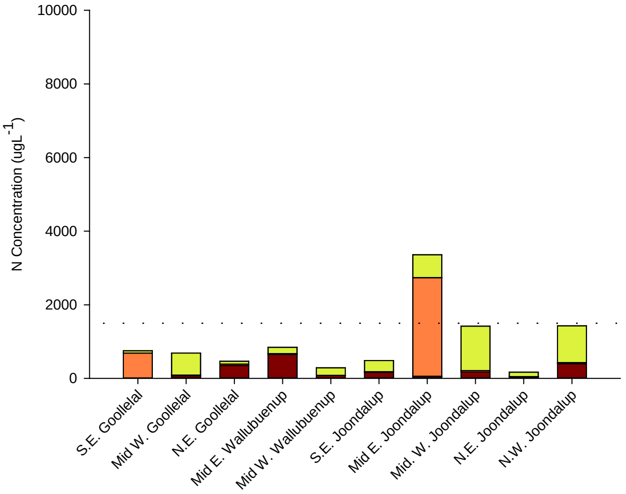
October 2016



December 2016



February 2017



April 2017

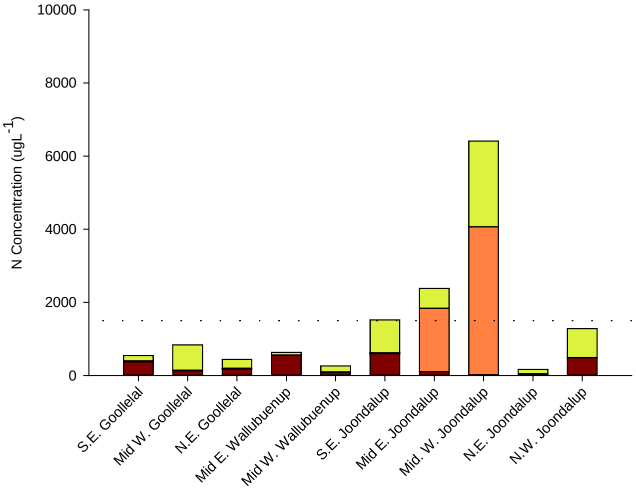


Figure 24. Breakdown of total nitrogen into chemical fractions (organic nitrogen, nitrate/nitrite (NO_x) and ammonium (NH_4)) recorded in groundwater at each bore between June 2017 and April 2018 with the ANZECC & ARMANZ (2000) trigger value for total nitrogen.

Table 14. Mean ± s.e. (range) for nutrients in water recorded at each bore over the course of the monitoring period (June 2017- April 2018), concentrations recorded as < were below the detection limit (DL).

	NH_4-N µg L^{-1}	NO_x-N µg L^{-1}	TN µg L^{-1}	FRP-P µg L-1	TP µg L^{-1}	DOC µg L^{-1}
DL	<3	<2	<50	<2	<20	<0.5
S.E. Goollelal	91 ± 54 (5-275)	1268 ± 554 (13-2810)	2122 ± 616 (395-3940)	47 ± 14 (13-109)	243 ± 62 (58-420)	13.4 ± 3.2 (7.2-28.1)
Mid W. Goollelal	123 ± 35 (87-158)	9 ± 4 (5-14)	1337 ± 197 (1140-1534)	41 ± 3 (39-44)	58 ± 1 (57-60)	54.8 ± 6.7 (48.1-61.4)
N.E. Goollelal	271 ± 48 (142-394)	33 ± 12 (6-87)	620 ± 120 (287-1060)	26 ± 10 (5-58)	114 ± 14 (77-163)	8 ± 1.5 (4.3-12.8)
Mid E. Wallubuenup	296 ± 70 (126-451)	465 ± 446 (10-2250)	2091 ± 473 (812-3700)	82 ± 33 (17-165)	154 ± 29 (63-218)	10.4 ± 1.8 (7.2-15.7)
W. Wallubuenup	138 ± 42 (90-348)	292 ± 189 (6-1130)	765 ± 306 (228-1780)	262 ± 158 (7-781)	497 ± 246 (74-1420)	7.4 ± 2.5 (3.9-19.9)
S.E. Joondalup	82 ± 29 (<3-152)	19 ± 6 (<2-40)	548 ± 110 (164-965)	32 ± 9 (12-62)	161 ± 79 (67-556)	9.9 ± 3.7 (4.3-27.8)
Mid E. Joondalup	49 ± 38 (3-239)	1580 ± 545 (10-3050)	3863 ± 1453 (287-8700)	161 ± 71 (21-478)	532 ± 194 (37-1290)	16.1 ± 5 (8.3-40.4)
Mid W. Joondalup	38 ± 20 (<3-298)	545 ± 191 (6-2780)	1453 ± 132 (1800-3960)	71 ± 10 (48-178)	194 ± 7 (154-255)	5 ± 5.8 (35.3-128.6)
N.E. Joondalup	195 ± 117 (<3-643)	25 ± 3 (11-31)	561 ± 246 (114-1740)	35 ± 17 (5-92)	145 ± 74 (<20-490)	6.8 ± 1.6 (2.8-12.4)
N.W. Joondalup	314 ± 60 (5-829)	12 ± 1 (3-25)	1435 ± 135 (365-2370)	57 ± 5 (33-96)	101 ± 7 (57-173)	37.9 ± 4 (24.8-86.4)

11. CONCLUSION

In conclusion, this monitoring study found that there is ongoing evidence of possibly active acid sulphate soils throughout much of the park. However despite this, water quality was better than previously seen in the monitoring, with lower concentrations of most nutrients and metals. This apparent dichotomy is explained by natural neutralisation of acidity preventing high metal concentrations. Further, there has been good (close to average) rainfall in 2016 and 2017 which might be simply diluting the metals and effects of acidification. Despite the lack of apparent impact on water quality, it is noted that pH seems to be dropping over time very slowly a phenomena also noted by DOW monitoring (Michael Hammond, DOW, pers. comm.). There remains a real risk that at some point the natural ability of the wetland system to buffer incoming acidity may be lost or severely reduced leading to significant problems. Active acid sulphate soils are an ongoing problem for the wetland system and currently our understanding of the location of the soils is limited. A detailed ASS mapping exercise across the park and Wanneroo catchment would allow the extent of the problem to be understood and then managed.

This year only aluminium and zinc (as in previous years) was a significant problem (exceeding guideline values), with occasional high values of arsenic. Overall, exceedances of trigger values were lower than in previous years – aided by the high water levels. Neither mercury nor selenium, which had previously been identified as a cause of concern were problematic in 2017/18.

Physical parameters and nutrients also exceeded ANZECC & ARMCANZ (2000) national water quality guidelines for the protection of aquatic ecosystems (95%) throughout the flow path of Yellagonga waters on occasion. Nutrient patterns followed those of previous years, indicating high levels of enrichment up until Mid Lake Joondalup. Nutrient levels were generally lower than previous years, possibly due to dilution by the high rainfall. The wetlands remain a complex system of interacting pressures, namely drying, acidification and eutrophication. The current monitoring program provides ongoing warning of major trends within the wetland system.

Ten bores (4 western, 6 eastern) were sampled for a broad range of physico-chemical parameters, nutrient and metal/metalloid concentrations between June 2017 and April 2018. All the western bores showed a strong evapo-concentration effect for conductivity and related solutes reflecting changes in the nearest lake. There was evidence that certain bores such as Mid E. Joondalup and both eastern Goollelal bores tended to be highly contaminated with aluminium and zinc - it appears that groundwater was a source of Al identified in the surface water of the wetlands. High concentrations of P and N were recorded in a number of the eastern bores (particularly Mid E Joondalup and both Lake Goollelal bores), suggesting groundwater is an important source of nutrients into both lakes. It is likely that landfill around the edge of Lake Joondalup, former agricultural practices or lawn fertilization are responsible for the contamination of these eastern bores. The high level of contamination seen in Mid E. Joondalup bore is reflected in the water of the northern section of Lake Joondalup but the size and volume of Lake Joondalup means that contamination is heavily diluted. The monitoring of the groundwater bores is starting to show areas of likely contamination of the Yellagonga wetlands, but also shows contaminants leaving the wetland system (particularly P). The bores show evidence of oxidised acid sulphate soils with very low sulphate to chloride/alkalinity ratios, however in 2016/17 pH decreased suggesting that several sites are contaminated by ASS.

12. RECOMMENDATIONS

1. It is recommended that the monitoring program continue for 2018/19 with a minor adjustment in metals measured – replacing Cd, Cr and U with B, Cu, and Pb. The metals Cd, Cr and U are well below guideline trigger values and have been since accurate ICP-MS analysis commenced in 2013.
2. Acid sulphate soils remain an ongoing threat to the Yellagonga Lake System, with obvious ongoing reductions in water pH and it is recommended that initially a mapping of possible sources be undertaken within the park and Wanneroo catchment – to reveal the extent of the problem and opportunities for control.
3. As drying is the main threat to the Yellagonga Lake System, it is recommended to develop reliable water budgets for at least Lakes Joondalup and Goollelal would allow permit opportunities for increasing inflows and reducing losses to be explored. The Smart Cities project (if successful) by the two Cities, ECU, and technology partners would address this recommendation.
4. Although nutrient concentrations are relatively low in Lake Goollelal, there are occasionally high concentrations that might encourage algal blooms and indirectly midge problems. It is recommended that a nutrient budget for Lake Goollelal would help identify the major sources (potentially septic systems on the eastern side) and provide a basis for improved management actions to maintain water quality within the lake. Detailed work could also determine the significance of septic tank leachate to nutrients entering the lake.
5. High levels of particularly P occur in the drain area (site 4-6), it would be useful to understand the sources of this P to determine how significant it is to total loadings within the park and whether it is a cause for concern.
6. The two current bores on the eastern side of Lake Goollelal are located at the extremes of the lake (top and bottom), understanding of the importance of groundwater into the lake would be substantially enhanced by a bore located between the two.

13. REFERENCES

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

Appleyard S, Cook T (2009) Reassessing the management of groundwater use from sandy aquifers: acidification and base cation depletion exacerbated by drought and groundwater withdrawal on the Gnangara Mound, Western Australia Hydrogeology Journal 17:579-588 doi:10.1007/s10040-008-0410-2

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 Soil Research 42:579-585 doi:http://dx.doi.org/10.1071/SR03074

Boardman L (2000) Metaphyton in Lake Joondalup. Bachelor of Engineering (Environmental), University of Western Australia, Perth, Australia

Bryant T (2000) The release of phosphorus from wetland sediment: A study of Lake Joondalup. Edith Cowan University, Perth

Congdon R, McComb A (1976a) 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

Congdon RA (1985) The water balance of Lake Joondalup. Western Australian Department of Conservation and Environment,

Congdon RA (1986) Nutrient loading and phytoplankton blooms in Lake Joondalup, Wanneroo, Western Australia. Department of Conservation and Environment, Western Australia,

Congdon RA, McComb AJ (1976b) 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, Edith Cowan University

Davis JA, Rosich RS, Bradley JS, Growns JE, Schmidt LG, Cheal F (1993) Wetland classification on the basis of water quality and invertebrate community data vol 6. Wetlands of the Swan Coastal Plain. Water Authority of Western Australia and the Western Australian Department of Environmental Protection, Perth

Department of Environmental Regulation (2015) Identification and investigation of acid sulfate soils and acidic landscapes. Government of Western Australia, Perth, Western Australia

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

Elmahdi A, McFarlane D (2009) A decision support system for a groundwater system Case Study: Gnangara Sustainability Strategy Western Australia. In: Brebbia CA, Popov V (eds) Water Resources Management V. Wessex Institute of Technology, UK, pp 327-339

Goldsmith K, Lund MA, McCullough CD (2008) Nutrient Loading in Sediment of Beenyup Swamp (Yellagonga Regional Park) vol 2008-20. MiWER/Centre for Ecosystem Management, Perth

Gonzalez-Pinto J, Lund MA (2015) Yellagonga Regional Park wetlands water quality monitoring 2015 report. Edith Cowan University, Perth

Gonzalez-Pinto J, Lund MA (2016) Yellagonga Regional Park wetlands water quality monitoring 2015/16 report. Edith Cowan University, Perth

Gonzalez-Pinto J, Lund MA, Quintero Vasquez M (2017) Yellagonga Regional Park wetlands water quality monitoring 2016/17 report. Edith Cowan University, Perth

Gordon DM, Finlayson CM, McComb AJ (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

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

Judd S, Horwitz P (2017) Annual Report for the Gnangara Mound Environmental Monitoring Programme - Macroinvertebrate and Water Quality Wetland Monitoring for Spring 2016. Final Report to the Western Australian Department of Water. March 2017. Centre for Ecosystem Management, Edith Cowan University, Perth

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

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

Lund M, McCullough C, Newport M (2011a) Nutrient and metal loads in and out of Beenyup Swamp. Mine Water and Environment Research Centre/Centre for Ecosystem Management, Perth

Lund MA (2003) Midge Monitoring Program of the Cities of Joondalup and Wanneroo: A Review. Centre for Ecosystem Management, Edith Cowan University, Perth

Lund MA (2007) Midge Desktop Audit 2007. Centre for Ecosystem Management, Perth

Lund MA, Brown S, Lee G (2000) Controlling midges at Lake Joondalup and Lake Goolelall. Centre for Ecosystem Management, Edith Cowan University, Perth

Lund MA, McCullough CD, Somesan N, Edwards L, Reynolds B (2011b) Yellagonga wetlands nutrient and metal study. City of Wanneroo, City of Joondalup and Department of Environment and Conservation, Perth, Western Australia

McArthur WM, Bartle GA (1980) landforms and soils as an aid to urban planning in the Perth metropolitan north west corridor, Western Australia vol 5. CSIRO, Melbourne

Newport M, Lund M, McCullough CD (2011a) Yellagonga Regional Park wetlands water quality monitoring 2011 report. Edith Cowan University, Perth

Newport M, Lund M, McCullough CD, Patel S (2011b) Acid Sulphate Soil Investigation of Southern Yellagonga Regional Park. Edith Cowan University, Perth

Newport M, Lund MA (2012a) Review of Yellagonga Regional Park wetlands groundwater data. Mine Water and Environment Research Centre/Centre for Ecosystem Management, Perth, Australia

Newport M, Lund MA (2012b) Yellagonga Regional Park wetlands water quality monitoring 2012 report. Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia

Newport M, Lund MA (2013a) Acid Sulphate Soil Investigation of Southern Yellagonga Regional Park Report: Stage 2. Mine Water and Environment Research Centre/Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia

Newport M, Lund MA (2013b) Yellagonga Regional Park wetlands water quality monitoring 2013 report. Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia

Newport M, Lund MA (2014a) Acid Sulphate Soil Investigation of Southern Yellagonga Regional Park Report: Stage 3. Mine Water and Environment Research Centre/Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia

Newport M, Lund MA (2014b) Yellagonga Regional Park wetlands water quality monitoring 2013-2014 report. Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia

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

Rose TW (1979) Periphyton and metaphyton in Lake Joondalup. University of Western Australia

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

Upton K (1996) Temporal and Spatial Patterns in Water Chemistry, Phytoplankton Biomass and Microcrustacea in Lake Joondalup and Beenyup Swamp, Western Australia. Honours, Edith Cowan University

Wilson BA, Valentine LEE (2009) Biodiversity values and threatening processes of the Gnangara Groundwater System. Department of Environment and Conservation, Perth, Western Australia