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Yellagonga Regional Park wetlands groundwater monitoring 2016/17 report

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

Mine Water and Environment Research Centre

Final Report No. 2017-4

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.

MiWER Centre

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2. ACKNOWLEDGEMENTS

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3. FRONTISPIECE

Plate 1: Lake Goollelal

This report should be referenced as follows.

Gonzalez Pinto, J., Lund, M.A., & Quintero Vasquez, M. (2017). *Yellagonga Regional Park wetlands groundwater monitoring 2016/17 report.* Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2017-4, Edith Cowan University, Perth, Australia. 36pp. Unpublished report to the Cities of Joondalup and Wanneroo.

4. EXECUTIVE SUMMARY

1. In 2012, MiWER completed a review of available groundwater data for the area surrounding the Yellagonga Regional Park. It identified the paucity of information relevant to management of the Park. In response, the City of Joondalup installed two bores on the eastern side of Lake Goollelal. In August 2012, MiWER commenced a groundwater monitoring program utilising the new bores and existing bores that were best located to gain an understanding of groundwater impacts on the Yellagonga wetlands. In 2014, two further bores were provided at Neil Hawkins Park and Ariti Avenue by the Cities.
2. In 2016/17, monitoring of bores was reduced from monthly to bimonthly. Monitoring involved measurement of groundwater height, physico-chemical parameters, nutrient concentrations and selected metal/metalloid concentrations. Three bores were located on the eastern side of Lake Joondalup, two on the western side. Wallubuenup Swamp had one bore sampled on its eastern side and one on the western side. Two bores were sampled on the eastern side of Lake Goollelal and one on the western side. A total of ten bores throughout Yellagonga were sampled. This report covers monitoring from June 2016 to May 2017.
3. 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.
4. Ratios of sulphate to chloride and sulphate to alkalinity indicated the possible presence of ASS contamination at N.E. Goollelal, W. Wallubuenup, S.E. Joondalup and Mid E. Joondalup, although pH was not <5 or aluminium concentrations >1 mg L^{-1}, these sites had some very high iron concentrations. Overall the likelihood of ASS contamination of these bores has increased since 2015/16.
5. Metal concentrations such as Al, As, and Zn exceeded ANZECC & ARMCANZ (2000) guidelines for the 95% protection of aquatic systems by up to an order of magnitude (10 times) on occasion. Concentrations of Al were however not at levels indicative of active ASS, although Fe concentrations were very high on occasion. The groundwater should continue to be monitored to keep a watch out for possible ASS problems which might necessitate management action. It appeared that groundwater was a source of Al and Zn identified in the wetlands.
6. 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. Concentrations of P appear to have increased since 2015/16, although the distribution over time and between sites was very similar. Concentrations of N appear to have

decreased slightly although lower organic N has been replaced with higher concentrations of the more problematic NOx.

7. Key recommendations from the study are to continue monitoring at the current frequency as this appears to be striking a balance between detail and cost. 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 a shallow unconfined aquifer known as 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, 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, 2007, Lund et al. 2000). More recently, a water quality monitoring program has produced results that support previous findings of nutrient enrichment and metal contamination, which exceed ANZECC/ARMCANZ (2000) national water quality guidelines (Lund et al. 2011, Newport et al. 2011a, Newport and Lund 2012b, 2013b, 2014b). An investigation in the southern section of Wallubuenup Swamp identified the presence of ASS (Newport et al. 2011b, Newport and Lund 2013a, 2014a).

Newport and Lund (2012a) undertook a review of groundwater data in the vicinity of Yellagonga Regional Park. They identified 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. This report details the results of third annual monitoring of these groundwater bores from June 2016 – April 2017.

7. METHODS

7.1 STUDY SITE

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

7.2 SAMPLING

This report covers bimonthly sampling of the groundwater bores between the June 2016 and April 2017. 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 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[1]) 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 4ºC for later determination by ICP-AES/MS for a range of metals (Al, As, Ca, Cd, Co, Cr, Fe, Hg, K, Mg, Mn, Na, Ni, Se, U & Zn). All analyses were performed at the Natural Sciences Analytical Laboratory (Edith Cowan University) as per APHA (1999). Alkalinity was measured on an unfiltered aliquot of water, according to the methods of APHA (1999).

The analysis conducted for groundwater monitoring mirrored that of surface water monitoring (see Newport and Lund 2014b) so as to be effective in evaluating inputs/outputs associated with nutrient enrichment and metal contamination in the Yellagonga system.

7.3 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 data was analysed in Primer v6 (E-Primer) following removal of parameters with missing values (Ca) and calculated values (such as Organic P). Data was tested with a draftsman plot to identify any correlations >±0.95 (dissolved oxygen measured as mg L^{-1} and %saturation were highly correlated and so %saturation was removed). All metal and nutrient data was $\log_{10}$ transformed (to improve normality) and then all data were normalised. A Principal Components Analysis (PCA) was used to place samples in a two-dimensional space so that the degree of similarity is reflected in the distance between sites (i.e. similar sites are closer together than less similar sites).

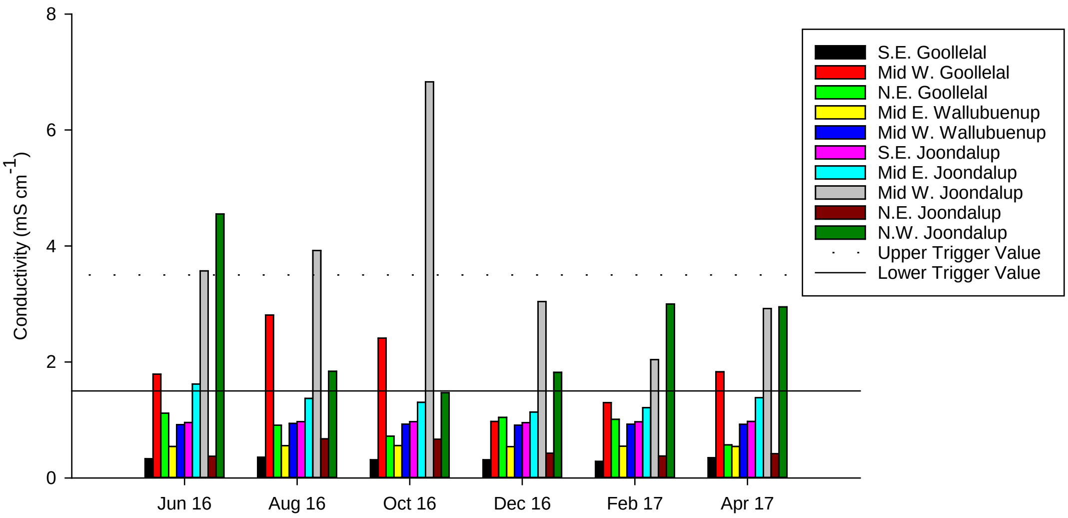
[1] All nutrients are measured as the key elements ie. TN-N, TP-P, NOx-N, FRP-P and NH_4-N (includes NH_3)

8. RESULTS AND DISCUSSION

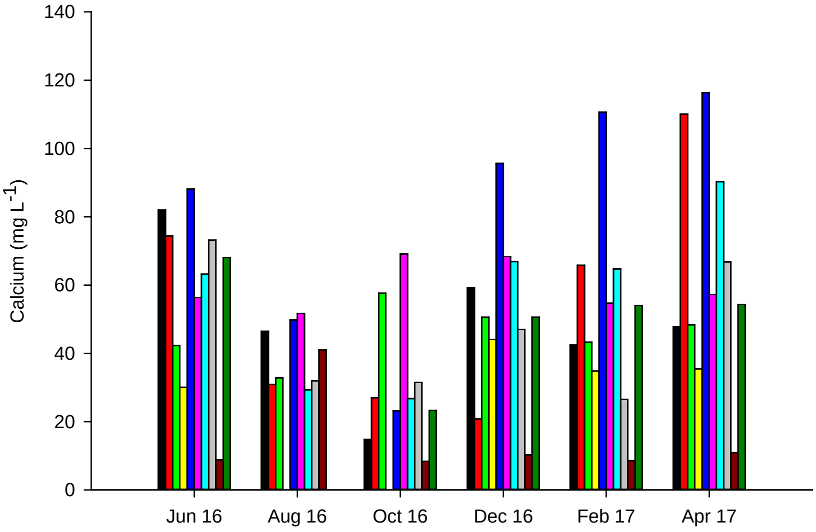
8.1 PHYSICO-CHEMISTRY

The EC followed a trend of typically higher values in western bores compared to eastern ones, the only exception was Mid W Wallubuenup (Figure 2). Evapoconcentration of salts in the lakes is reflected in a cycle throughout the year of high and low EC. In Mid W Joondalup, peak EC occurs in October, with the trough in February. In N.W. Joondalup the peak EC is in June and trough in October, whereas in Mid W. Goollelal EC peaks in August and is lowest in December. The difference in the timing of peak EC between the western bores probably reflects time taken for the lake water to move from the lake through to the bore. The main ion contributing to the high EC in western bores is Cl, which shows very similar peaks and troughs. Calcium concentrations cycled in W. Goollelal and Mid W Wallubuenup, but changed little across time for other sites. Cycles were found for Na, Mg and K in Mid W Joondalup and NW Joondalup, with a couple of high values in August and October for Mid E Wallubuenup.

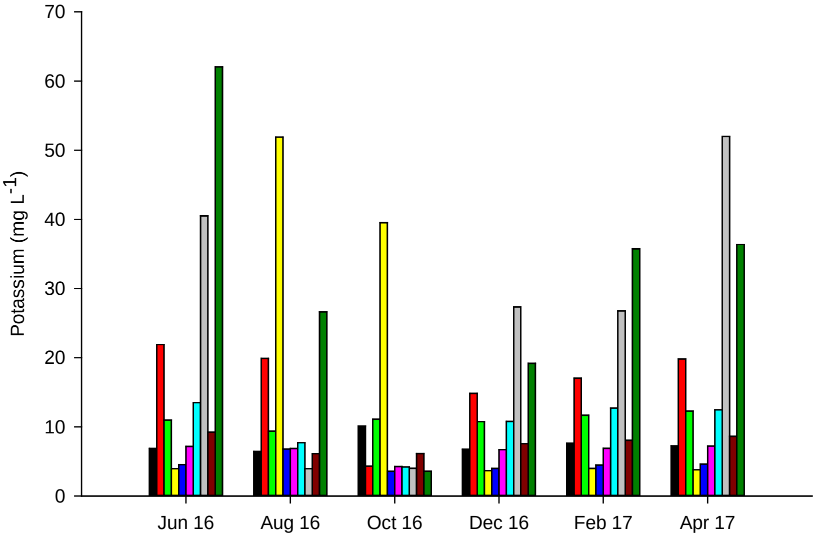
a) Electrical conductivity



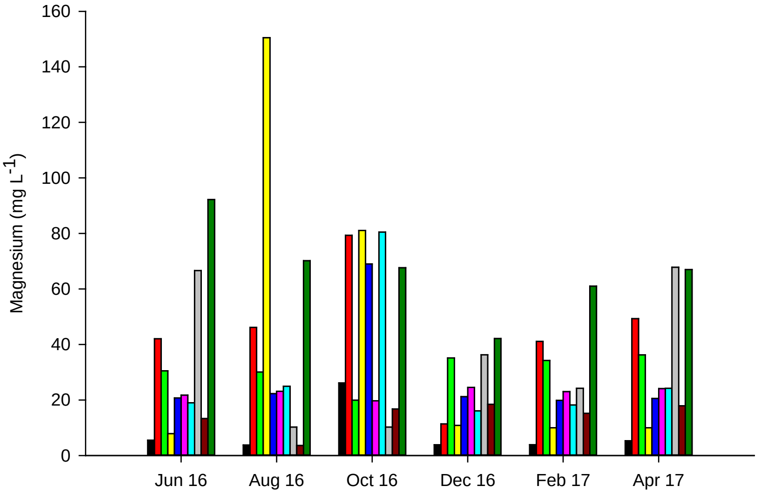
b) Calcium (Ca)



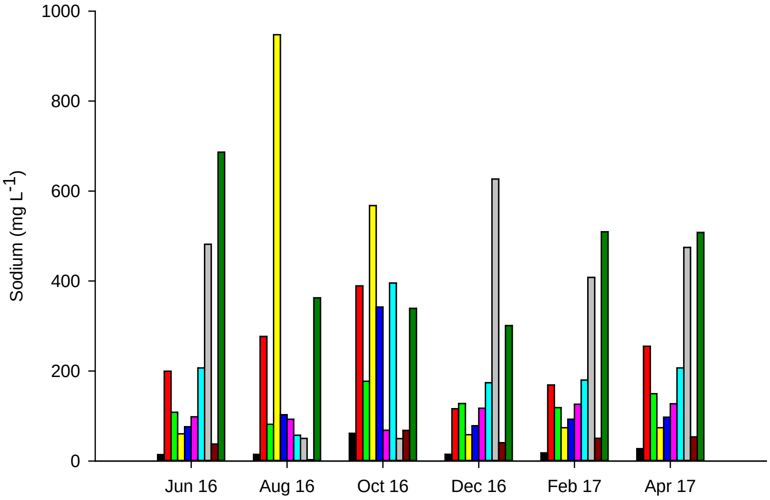
c) Potassium (K)



d) Magnesium (Mg)



e) Sodium (Na)



f) Chloride (Cl^-)

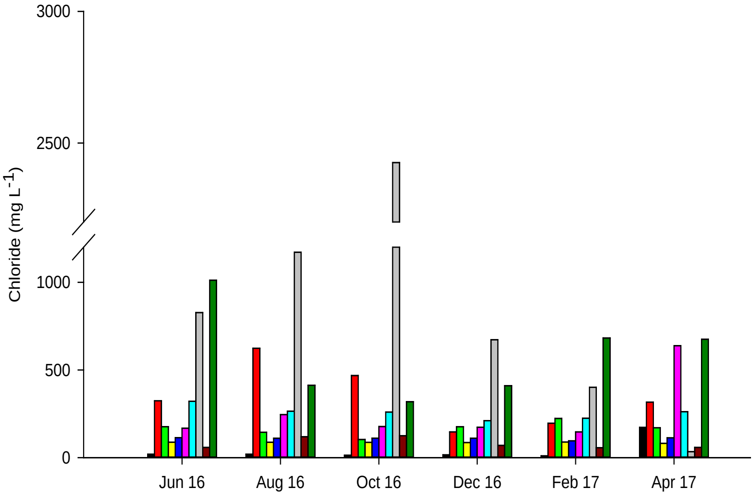


Figure 2. Changes in a) electrical conductivity, b) calcium, c) potassium, d) magnesium, e) sodium and f) chloride over the period of monitoring at each site (June 2016 – April 2017).

Table 1 Mean ± standard error (range) for selected solutes during the monitoring period June 2016 to April 2017 (all in mg L^{-1})

	Ca	K	Mg	Na	Cl^-	SO_4^{2-}
DL	<0.2	<0.2	<0.2	<0.2	<0.5	<0.5
S.E. Goollelal	49 ± 9 (15-82)	8 ± 1 (6-10)	8 ± 4 (4-26)	25 ± 8 (14-61)	42 ± 26 (11-173)	43 ± 32 (3-205)
Mid W. Goollelal	55 ± 14 (21-110)	16 ± 3 (4-22)	45 ± 9 (11-79)	234 ± 39 (116-389)	346 ± 72 (147-624)	203 ± 54 (94-392)
N.E. Goollelal	46 ± 3 (33-58)	11 ± 0 (9-12)	31 ± 2 (20-36)	127 ± 14 (81-177)	166 ± 16 (104-224)	161 ± 21 (77-207)
Mid E. Wallubuenup	36 ± 3 (30-44)	18 ± 9 (4-52)	45 ± 24 (8-151)	297 ± 154 (58-948)	87 ± 1 (81-89)	13 ± 2 (8-17)
W. Wallubuenup	81 ± 15 (23-116)	5 ± 0 (4-7)	29 ± 8 (20-69)	132 ± 42 (76-342)	110 ± 3 (96-115)	170 ± 8 (137-192)
S.E. Joondalup	60 ± 3 (52-69)	7 ± 0 (4-7)	23 ± 1 (20-25)	105 ± 9 (68-127)	259 ± 77 (147-639)	66 ± 6 (42-78)
Mid E. Joondalup	57 ± 10 (27-90)	10 ± 1 (4-14)	30 ± 10 (16-80)	203 ± 45 (57-396)	258 ± 16 (212-321)	72 ± 5 (56-90)
Mid W. Joondalup	46 ± 8 (27-73)	26 ± 8 (4-52)	36 ± 11 (10-68)	348 ± 99 (50-627)	922 ± 339 (35-2426)	187 ± 75 (12-534)
N.E. Joondalup	15 ± 5 (8-41)	8 ± 1 (6-9)	14 ± 2 (4-18)	42 ± 9 (3-68)	82 ± 13 (57-126)	59 ± 6 (44-80)
N.W. Joondalup	50 ± 7 (23-68)	31 ± 8 (4-62)	67 ± 7 (42-92)	451 ± 59 (301-686)	585 ± 105 (319-1012)	167 ± 52 (86-423)

Calculated hardness of water samples from the bores are shown in Figure 3. Hardness was generally slightly lower than in 2015/2016, in the western sites but slightly higher in the eastern sites. Despite the low rainfall in 2015, this does not seem to have had a large effect on hardness. Hardness was highest in western bores, reflecting evapo-concentration of solutes passing through the lake.

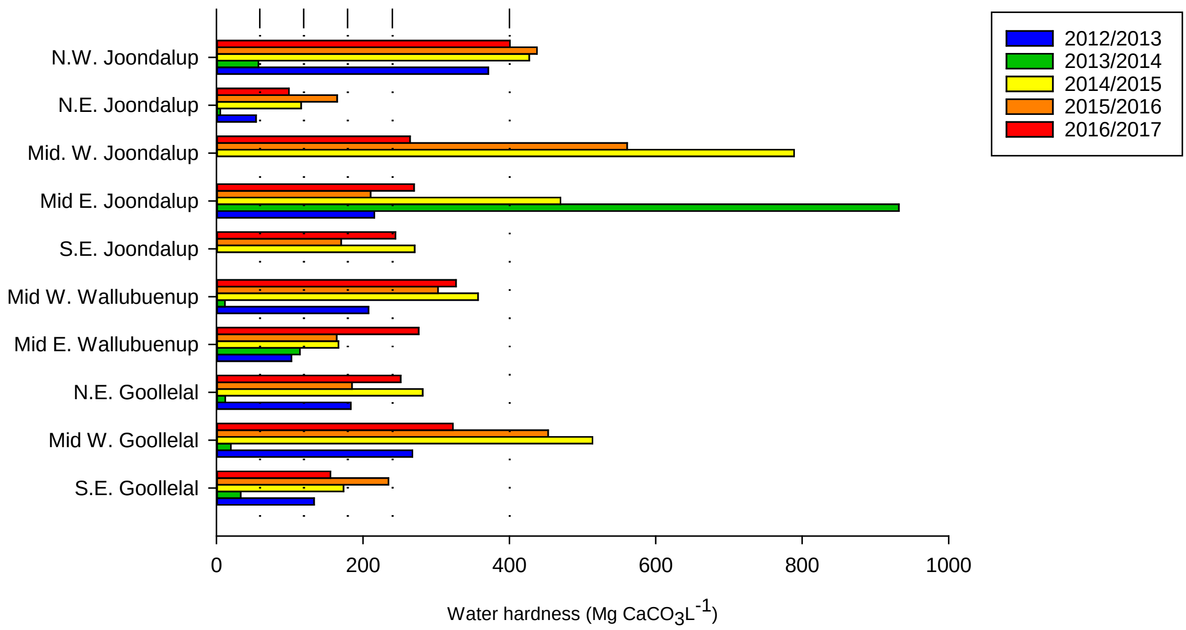
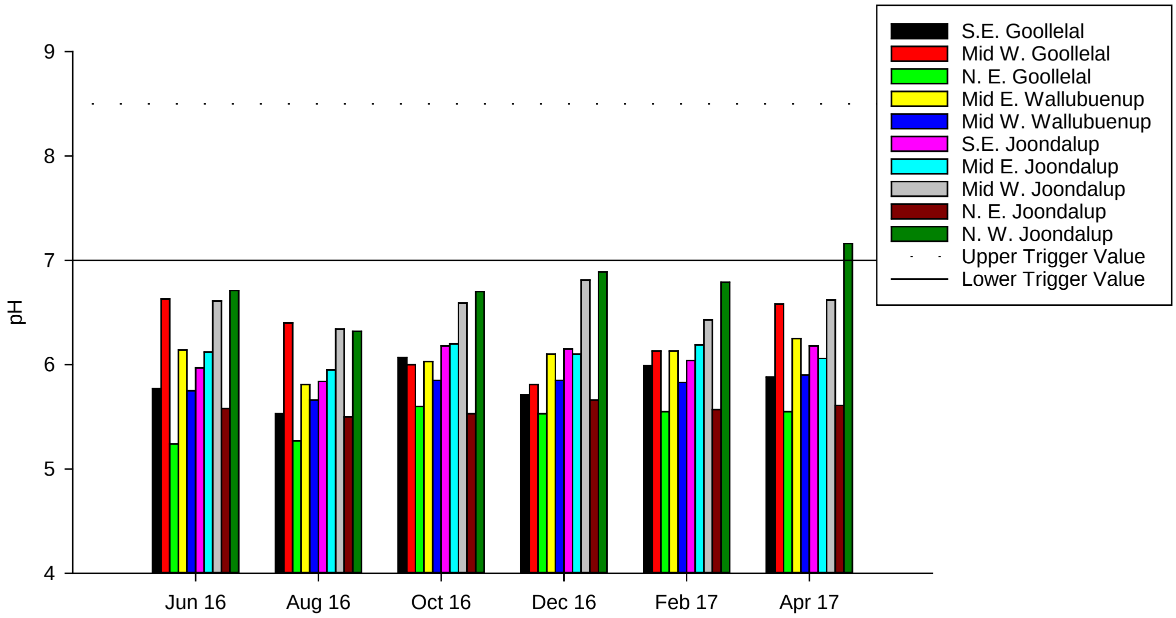


Figure 3. Calculated mean water hardness for the period of monitoring at each bore (June 2016 – April 2017) with ANZECC & ARMCANZ (2000) categories indicated.

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. 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. pH levels were slightly lower than in 2015/16. 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)

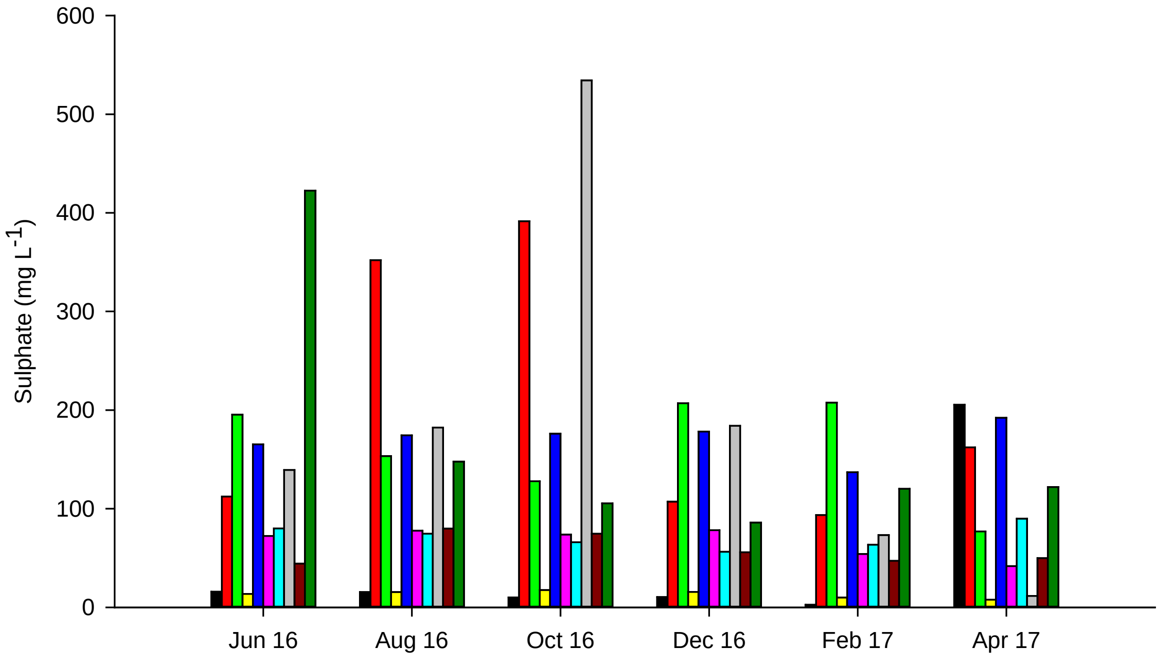


Figure 4. Changes in a) pH and b) sulphate over the period of monitoring at each bore (June 2016 – April 2017) with ANZECC & ARMCANZ (2000) trigger values for the protection of aquatic ecosystems (95%).

Chloride to sulphate molar ratios is commonly used to indicate the presence of acid sulphate soils (ASS). Oxidation of metal sulphides (typically pyrites) in soils and sediments leads to the production of sulphuric acid. The oxidation increases concentrations of sulphate relative to the 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 bores and therefore must be treated with caution. To improve the ability to detect potential ASS, this year we also measured alkalinity (Table 2) as an alkalinity to sulphate ratio of <5 is considered to be a better predictor in freshwater systems (Department of Environmental Regulation 2015).

Ratios indicated the possible presence of ASS contamination at N.E. Goollelal, W. Wallubuenup, S.E. Joondalup and Mid E. Joondalup, 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. Although fewer sites show likelihood of ASS compared to 2015/16, the lower pH and high Fe suggest that at these site acidification may be increasing.

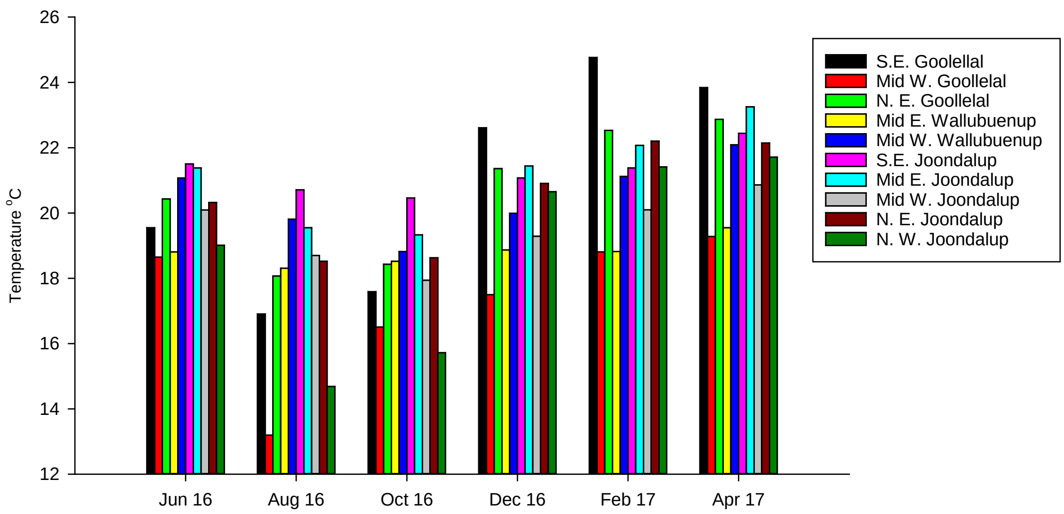
Table 2 Mean ± standard error (range) for chloride to sulphate ratios, alkalinity and alkalinity to sulphate ratios during the monitoring period June 2016 to April 2017

DL	$Cl^-:SO_4$ molar ratio	Alkalinity	Alkalinity:Sulphate
S.E. Goollelal	5 ± 1 (2-11)	102 ± 6 (77-117)	12.8 ± 5.9 (0.4-41.4)
Mid W. Goollelal	5 ± 1 (3-8)	193 ± 26 (120-300)	1.3 ± 0.3 (0.4-2.1)
N.E. Goollelal	3 ± 1 (2-6)	31 ± 8 (13-57)	0.2 ± 0.1 (0.1-0.3)
Mid E. Wallubuenup	19 ± 2 (14-29)	85 ± 12 (33-107)	7.2 ± 1.6 (2.1-13.1)
W. Wallubuenup	2 ± 0 (2-2)	69 ± 2 (63-77)	0.4 ± 0 (0.3-0.5)
S.E. Joondalup	13 ± 6 (6-41)	103 ± 2 (93-110)	1.7 ± 0.2 (1.2-2.6)
Mid E. Joondalup	10 ± 0 (8-11)	138 ± 6 (123-163)	2 ± 0.2 (1.4-2.6)
Mid W. Joondalup	13 ± 1 (8-17)	254 ± 18 (200-303)	5.7 ± 4.1 (0.4-26.1)
N.E. Joondalup	4 ± 0 (3-5)	25 ± 4 (17-47)	0.4 ± 0 (0.2-0.6)
N.W. Joondalup	11 ± 2 (6-15)	164 ± 24 (70-223)	1.3 ± 0.3 (0.5-1.8)

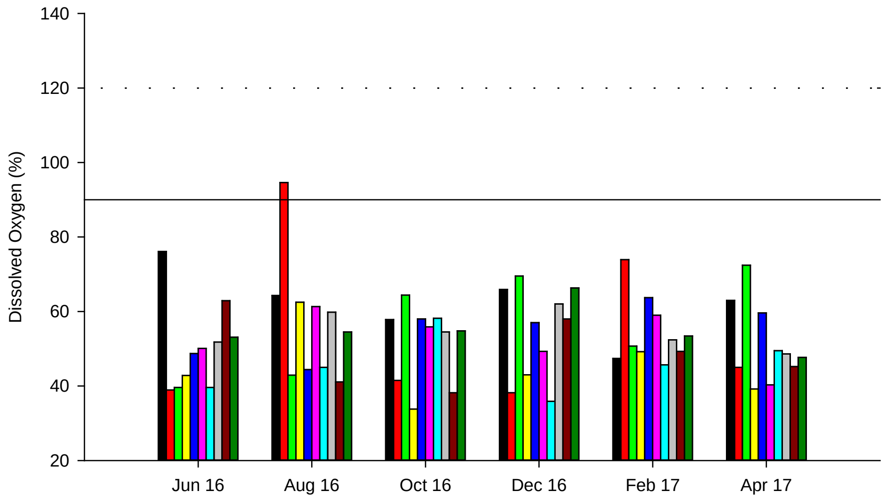
Water temperatures varied by approximately 6 °C at each site over the year, highest in summer and lowest in winter (Figure 5, Table 3). Dissolved oxygen was measured in all bores at >25%

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. This is a similar trend in ORP to that seen in 2015/16. Water levels in the bores illustrated little seasonal variation (<0.5 m), highest in October and lowest in April, with almost no change in Mid W. Wallubuenup.

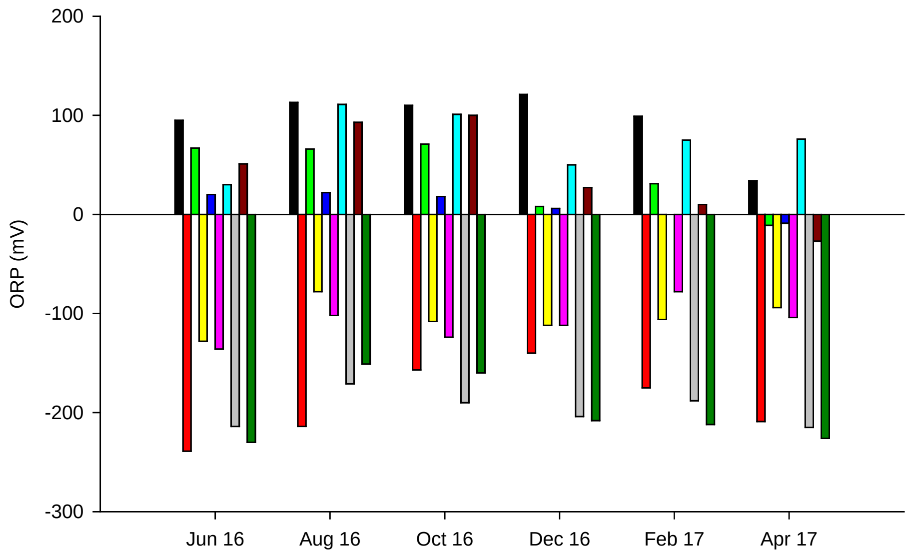
a) Temperature



b) Dissolved Oxygen



c) ORP



d) Depth to Water from Top of Casing (ToC)

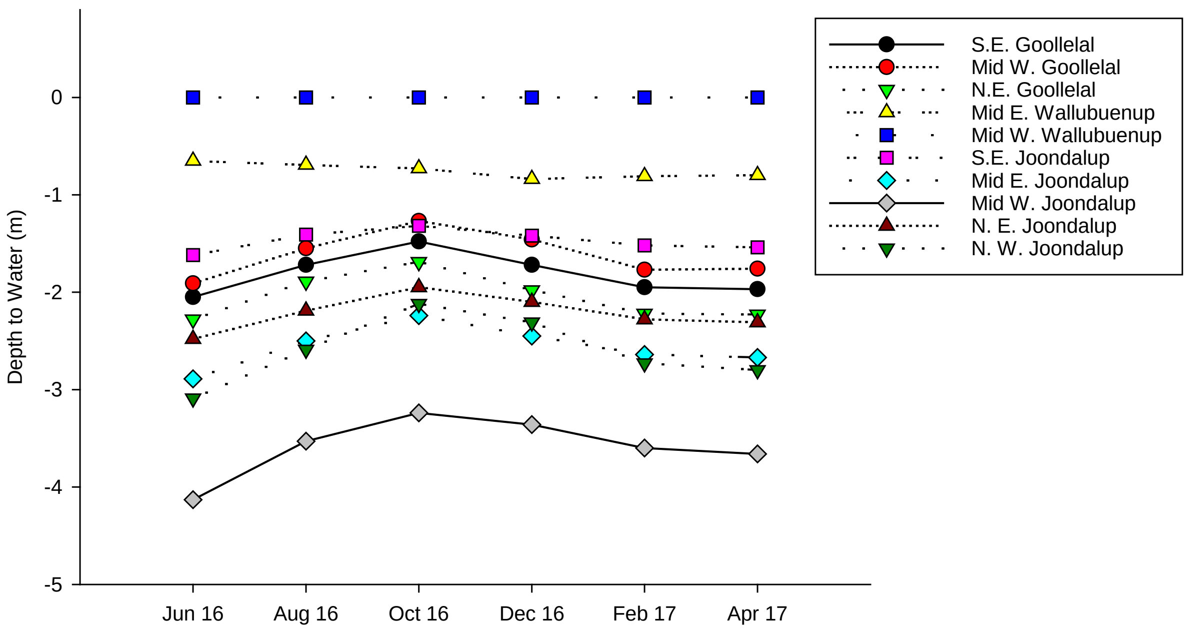


Figure 5. Variation throughout groundwater monitoring period for a) temperature, b) dissolved oxygen, c) ORP and d) depth to water between June 2016 and April 2017 at each bore.

Table 3. Mean ± standard error (range) for physico-chemical variables over the monitoring period (June 2016- April 2017)

	Temperature (°C)	Conductivity (mS cm^{-1})	Dissolved Oxygen (mg L^{-1})	Dissolved Oxygen (%)	pH	ORP (mV)
Goollelal SE	22.0 ± 0.9 (17.5-26.1)	0.44 ± 0.04 (0.26-0.75)	4.8 ± 0.5 (2.6-9.0)	53.9 ± 5 (32.1-99.4)	6.72 ± 0.12 (5.94-7.51)	69 ± 10 (8-132)
Goollelal Mid W	18.7 ± 0.3 (16.9-20.2)	1.8 ± 0.17 (1.23-2.96)	4.3 ± 0.3 (2.6-6.7)	46.8 ± 3.4 (28.3-73.9)	6.68 ± 0.10 (5.49-6.97)	-201 ± 13 (-280--104)
Goollelal NE	21.4 ± 0.5 (18.4-23.6)	1.13 ± 0.07 (0.79-1.80)	4.2 ± 0.2 (2.2-5.4)	47.6 ± 2.7 (26.5-59.5)	6.01 ± 0.16 (5.39-7.33)	16 ± 12 (-57-94)
Wallubuenup Mid E	19.5 ± 0.2 (18.7-20.4)	0.55 ± 0.00 (0.53-0.58)	4.2 ± 0.2 (2.9-5.2)	45.5 ± 2 (32.5-56.9)	6.5 ± 0.10 (5.67-7.10)	-64 ± 22 (-145-78)
Wallubuenup W	21.7 ± 0.4 (19.5-22.6)	1.02 ± 0.06 (0.88-0.97)	4.6 ± 0.3 (2.4-5.6)	52.2 ± 3.1 (28.2-65.2)	6.47 ± 0.11 (5.5-6.94)	39 ± 15 (-70-98)
Joondalup SE	22 ± 0.2 (20.9-23.3)	0.94 ± 0.00 (0.91-0.96)	4.5 ± 0.3 (2.8-6.7)	51.4 ± 3.5 (32.6-78.3)	6.52 ± 0.11 (5.86-7.11)	-72 ± 25 (-167-77)
Joondalup Mid E	22.2 ± 0.3 (20.1-24.6)	1.47 ± 0.01 (1.16-1.87)	4.3 ± 0.2 (2.4-5.6)	50 ± 2.7 (29.7-63.9)	6.67 ± 0.10 (5.91-7.15)	60 ± 11 (-83-117)
Joondalup Mid W	20.0 ± 0.3 (18.4-21.4)	4.21 ± 0.40 (1.89-7.05)	4.9 ± 0.4 (3.4-7.5)	54.4 ± 4.1 (38.6-85.6)	6.86 ± 0.08 (6.54-7.61)	-206 ± 10 (-251--128)
Joondalup NE	20.9 ± 0.5 (18.5-23.1)	0.38 ± 0.01 (0.35-0.41)	4.9 ± 0.3 (3.4-7.6)	54.9 ± 3.5 (40.3-87.7)	6.09 ± 0.21 (5.04-7.57)	25 ± 12 (-31-123)
Joondalup NW	19.5 ± 0.7 (15.0-22.5)	3.92 ± 0.49 (2.07-7.33)	5.0 ± 0.5 (2.4-9.4)	55.7 ± 5.5 (28.7-111.3)	7.08 ± 0.11 (6.46-8.14)	-227 ± 13 (-348--163)

8.2 METALS AND METALLOIDS

Table 3 shows the number of samples from all the bores that exceeded ANZECC & ARMCANZ (2000) guidelines for the protection of aquatic ecosystems. It should be noted that these guidelines were not designed for groundwater, but assuming that as this groundwater discharges into the lake 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. Aluminium, and Zn concentrations were particularly problematic affecting 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 4. 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 2016 and April 2017

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	0.096 ± 0.05 (3.391)	60 (19)
Arsenic (As)	0.013 - 0.024*	<0.00001	0.0047 ± 0.0008 (0.0292)	60 (1)
Calcium (Ca)	—	<0.2	43.68 ± 6.57 (357.53)	57 (0)
Cadmium (Cd)	0.0011 – 0.0016^{H}	<0.00001	0.00006 ± 0.00002 (0.0006)	28 (0)
Cobalt (Co)	ID	<0.00002	0.0028 ± 0.0016 (0.1075)	60 (0)
Chromium (Cr)	ID - 0.006^{H}	<0.00005	0.0014 ± 0.0002 (0.0058)	60 (0)
Iron (Fe)	ID	<0.0005	0.99 ± 0.5 (29.02)	60 (0)
Mercury (Hg)	0.0006 - ID*	<0.00002	0 ± 0 (0.0004)	30 (0)
Potassium (K)	—	<0.2	12.19 ± 1.75 (66.24)	60 (0)
Magnesium (Mg)	—	<0.2	28.93 ± 4.16 (186.07)	60 (0)
Manganese (Mn)	1.9	<0.00005	0.02 ± 0.01 (0.39)	60 (0)
Sodium (Na)	—	<0.2	173.4 ± 24.95 (947.71)	60 (0)
Nickel (Ni)	0.0480 – 0.0687^{H}	<0.00005	0.0039 ± 0.0012 (0.069)	60 (0)
Selenium (Se)	0.011	<0.00005	0.0061 ± 0.0016 (0.0607)	57 (20)
Uranium (U)	0.005+	<0.00002	0.00006 ± 0.00001 (0.00036)	59 (0)
Zinc (Zn)	0.0350 – 0.05^{H}	<0.00025	0.104 ± 0.022 (1.342)	60 (48)

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)

Metal concentrations are shown in Table 5. Aluminium concentrations in N.E. Joondalup reached over 3.3 $mg\ L^{-1}$ which are very high, supporting presence of ASS.

Table 5. Mean ± standard error (range) for selected metals over the June 2016 to April 2017 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	31 ± 7 (16-56)	1.75 ± 0.14 (1.19-2.24)	0.05 ± 0.02 (<0.01-0.12)	0.18 ± 0.05 (0.04-0.42)	0.83 ± 0.09 (0.53-1.1)	84 ± 32 (30-240)
Mid W. Goollelal	37 ± 10 (19-82)	5.74 ± 1.76 (0.14-13.24)	0.03 ± 0.01 (0.01-0.08)	3.16 ± 2.64 (0.04-16.22)	0.93 ± 0.21 (0.3-1.85)	390 ± 138 (75-977)
N.E. Goollelal	68 ± 11 (25-112)	0.89 ± 0.23 (0.27-1.81)	0.1 ± 0.06 (0.01-0.31)	0.27 ± 0.09 (0.05-0.62)	0.81 ± 0.09 (0.47-1.13)	4836 ± 1117 (75-7813)
Mid E. Wallubuenup	27 ± 8 (9-66)	14.62 ± 3.09 (9.09-29.24)	0.03 ± 0.02 (<0.01-0.1)	0.94 ± 0.49 (0.09-2.5)	3.52 ± 0.25 (2.72-4.42)	132 ± 50 (31-326)
W. Wallubuenup	28 ± 13 (4-88)	1.62 ± 0.41 (0.15-2.78)	0.06 ± 0.04 (<0.01-0.25)	2.05 ± 1.13 (0.04-7.14)	1.68 ± 0.39 (0.34-2.66)	3528 ± 1106 (40-6476)
S.E. Joondalup	27 ± 5 (7-43)	1.37 ± 0.26 (0.76-2.23)	0.03 ± 0.02 (<0.01-0.15)	0.91 ± 0.5 (0.04-2.5)	0.96 ± 0.33 (0.52-2.6)	997 ± 962 (29-5807)
Mid E. Joondalup	108 ± 41 (29-307)	1.47 ± 0.38 (0.13-2.43)	0.14 ± 0.1 (<0.01-0.6)	2.96 ± 2.73 (0.12-16.6)	0.9 ± 0.21 (0.29-1.78)	742 ± 632 (65-3902)
Mid W. Joondalup	135 ± 45 (16-242)	17.41 ± 1.72 (10.78-22.83)	0.03 ± 0.02 (<0.01-0.11)	0.49 ± 0.4 (0.05-2.5)	3.71 ± 0.52 (2.3-5.66)	149 ± 45 (57-362)
N.E. Joondalup	581 ± 562 (9-3391)	1.2 ± 0.22 (0.48-2)	0.18 ± 0.07 (<0.01-0.45)	18.8 ± 17.75 (0.08-107.53)	0.83 ± 0.12 (0.33-1.16)	145 ± 67 (58-480)
N.W. Joondalup	40 ± 12 (20-97)	7.45 ± 1.71 (0.16-13.27)	0.03 ± 0.02 (<0.01-0.1)	2.11 ± 1.14 (0.06-7.27)	1.37 ± 0.29 (0.39-2.46)	184 ± 27 (123-299)

Table 5. 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	0.04 ± 0.02 (<0.02-0.14)	12.84 ± 8.05 (1.21-52.58)	2.52 ± 1.5 (0.48-10)	1.37 ± 0.51 (<0.02-2.5)	0.09 ± 0.02 (0.05-0.16)	101.63 ± 9.38 (81.25-141.43)
Mid W. Goollelal	0.05 ± 0.02 (<0.02-0.12)	24.35 ± 19.05 (2.34-119.56)	5.77 ± 3.52 (0.44-21.66)	1.32 ± 0.53 (0.1-2.5)	0.04 ± 0.01 (<0.02-0.05)	72.93 ± 15.59 (42.91-144.42)
N.E. Goollelal	0.06 ± 0.03 (<0.02-0.16)	27.44 ± 9.47 (10.19-71)	2.55 ± 1.49 (0.56-10)	1.35 ± 0.52 (0.17-2.5)	0.04 ± 0 (0.03-0.05)	223.66 ± 23.86 (175.16-319.71)
Mid E. Wallubuenup	0.04 ± 0.02 (<0.02-0.11)	7.67 ± 1.52 (2.16-11.94)	3.49 ± 1.47 (0.96-10)	0.27 ± 0.09 (0.07-0.63)	0.1 ± 0.03 (0.05-0.18)	94.88 ± 18.11 (19.63-141.85)
W. Wallubuenup	0.04 ± 0.01 (<0.02-0.09)	32.93 ± 7.19 (19.44-66.6)	4.51 ± 2.41 (0.36-13.87)	1.32 ± 0.53 (0.05-2.5)	0.05 ± 0 (0.04-0.07)	107.95 ± 9.75 (81.36-144.54)
S.E. Joondalup	0.07 ± 0.03 (<0.02-0.17)	20.4 ± 2.59 (13.79-31.47)	2.76 ± 1.56 (0.46-10)	1.37 ± 0.51 (0.05-2.5)	0.06 ± 0.01 (0.05-0.1)	125.3 ± 8.36 (98-148.64)
Mid E. Joondalup	0.05 ± 0.02 (<0.02-0.11)	41.14 ± 18.51 (8.4-123.58)	4.51 ± 3.36 (0.58-21.26)	0.73 ± 0.36 (0.23-2.5)	0.04 ± 0 (0.03-0.05)	150.11 ± 23.06 (90.8-254.01)
Mid W. Joondalup	0.06 ± 0.03 (<0.02-0.14)	5.61 ± 1.73 (1.31-11.2)	0.91 ± 0.17 (0.49-1.62)	0.65 ± 0.37 (0.1-2.5)	0.05 ± 0.01 (0.04-0.08)	90.85 ± 21.76 (40.04-169.33)
N.E. Joondalup	0.04 ± 0.02 (<0.02-0.11)	68.17 ± 65.17 (1.57-393.99)	13.82 ± 11.13 (0.69-68.95)	1.21 ± 0.48 (0-2.5)	0.03 ± 0.09 (0.17-0.02)	153.29 ± 77.17 (38.47-533.58)
N.W. Joondalup	0.04 ± 0.01 (<0.02-0.09)	16.06 ± 9.67 (4.7-64.32)	2.86 ± 2.27 (0.09-14.17)	1.38 ± 0.73 (0.14-4.53)	0.05 ± 0 (0.05-0.06)	52.93 ± 12.3 (14.24-101.16)

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.

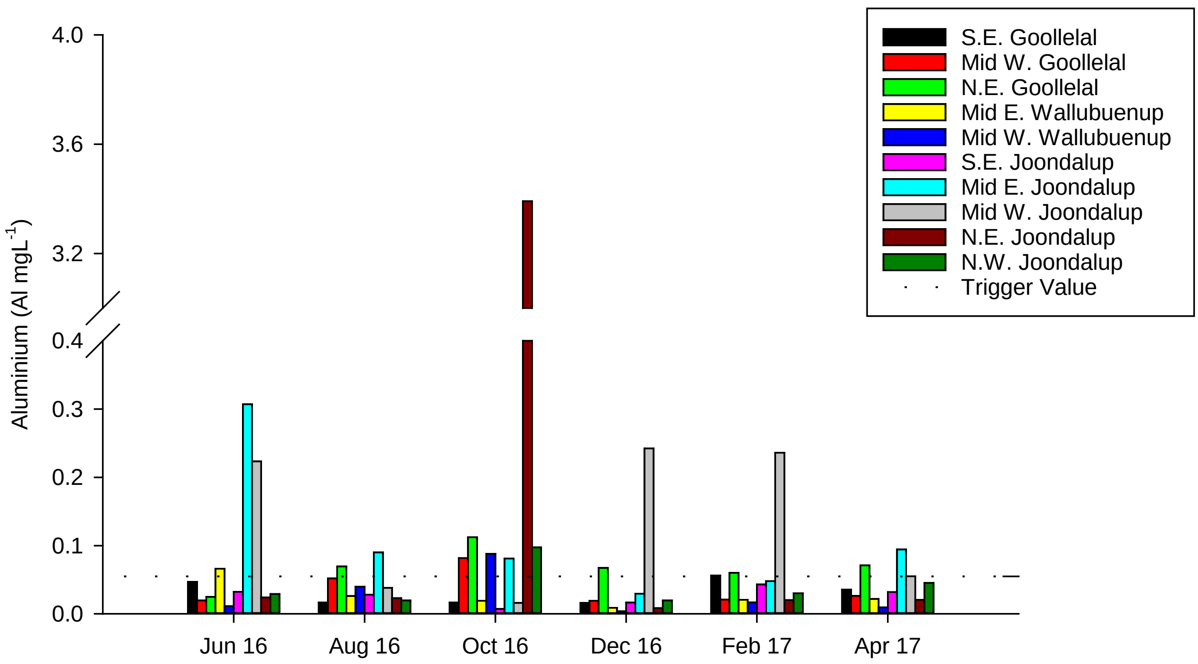
* Range for As III and V, Cr III and VI, and Hg inorganic and methyl.

ID Insufficient data to derive a reliable trigger value.

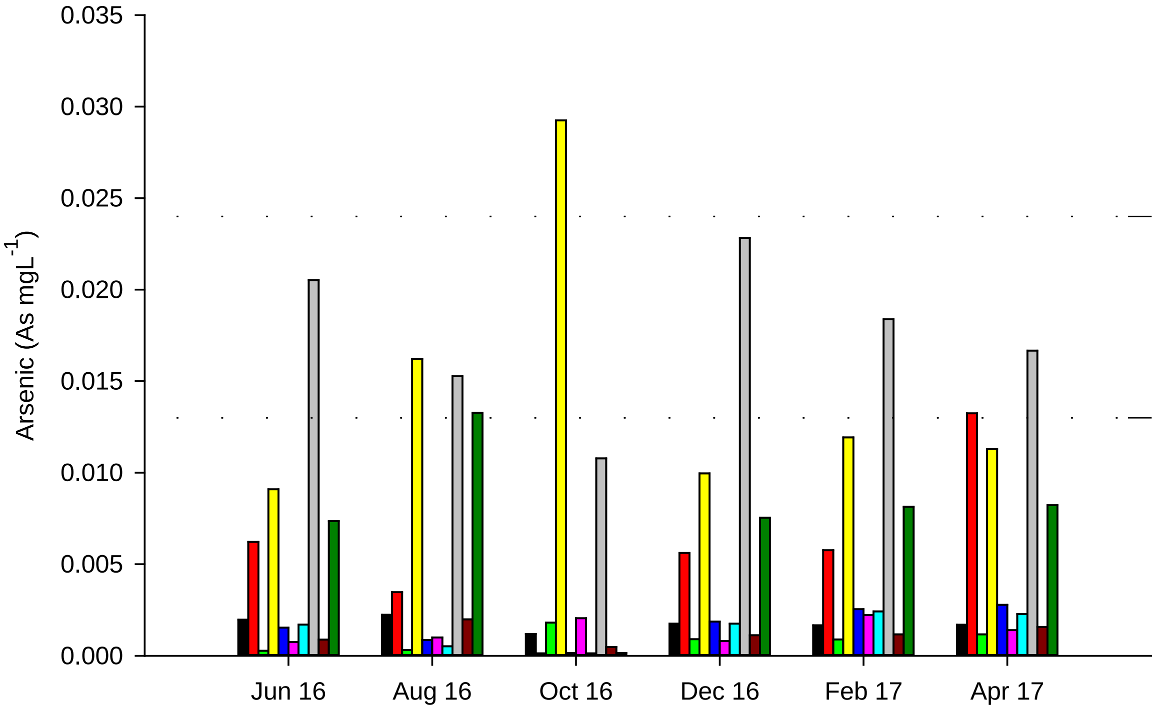
\+ Low reliability, interim working level as prescribed in ANZECC/ARMCANZ (2000)

Figure 6 shows metal concentrations where the metal exceeded ANZECC/ARMCANZ guidelines for protection of freshwater ecosystems. Figure 6a shows high Al concentrations associated with bores likely contaminated by ASS. Arsenic only exceeded the upper guideline once at Mid E Wallubuenup, but exceeded the lower guideline a number of times at Mid E Wallubuenup and Mid W. Joondalup. 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 6b). Zinc concentrations were similar or higher than in 2015/16, the source of the Zn is unknown but potentially toxic levels are found in all bores (Figure 6c). The slow increase in Zn was noted last year, in comparison to 2014/15.

a) Aluminium



b) Arsenic



c) Zinc

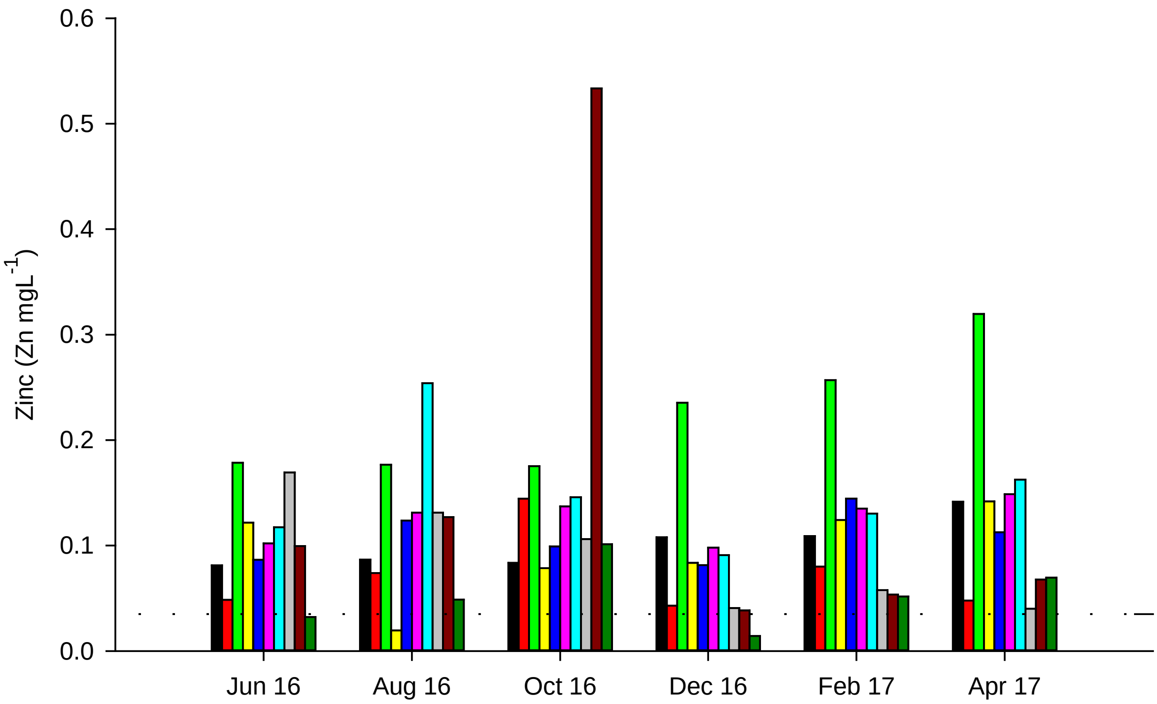
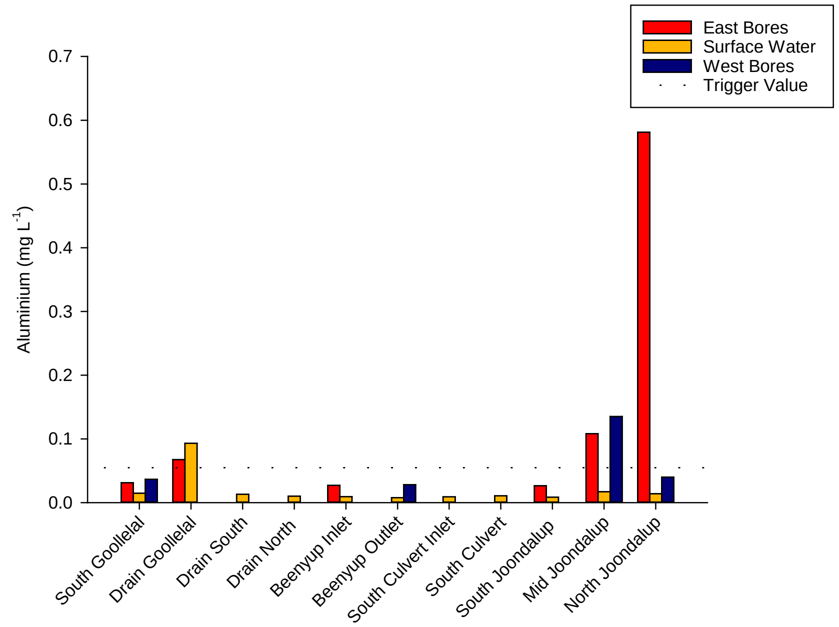


Figure 6. Metal concentrations for groundwater samples taken between June 2016 and April 2017 for all sites sampled. Dotted lines indicate the ANZECC & ARMCANZ (2000) trigger value ranges for the protection of aquatic ecosystems (95%).

Aluminium and Zn that had individual values that exceeded guideline levels in eastern and western bores were compared to the nearest surface water, from the annual Yellagonga surface water monitoring program in Figure 7. Aluminium concentrations were generally higher in the groundwater around the lakes than in the lake. Zinc concentrations were similar between eastern and western bores but higher than found in the surface waters.

a) Aluminium



b) Zinc

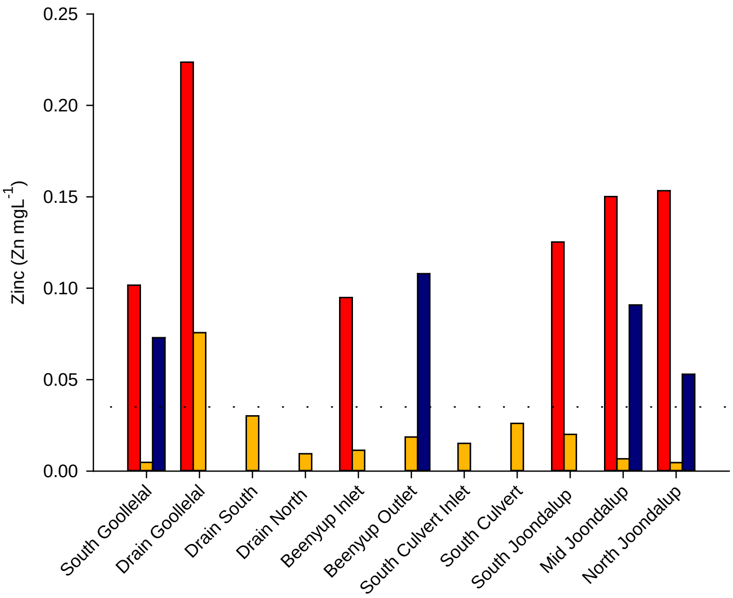


Figure 7. Mean (June 2016 to May 2017) metal concentrations for groundwater and surface water. Dotted lines indicate the ANZECC & ARMCANZ (2000) trigger value ranges for the protection of aquatic ecosystems (95%).

The highest DOC concentrations were found in water leaving Lake Joondalup at N.W. Joondalup, Mid W. Joondalup and Mid W. Goollelal (Figure 8). The western Joondalup concentrations were highest in Feb to June, while for Mid W. Goollelal it was August to October, same pattern as seen in 2015/16. This pattern is almost identical to that seen for EC (Figure 2), and therefore probably an evapo-concentration effect. The concentrations of DOC were similar to 2014/15 and 2015/16.

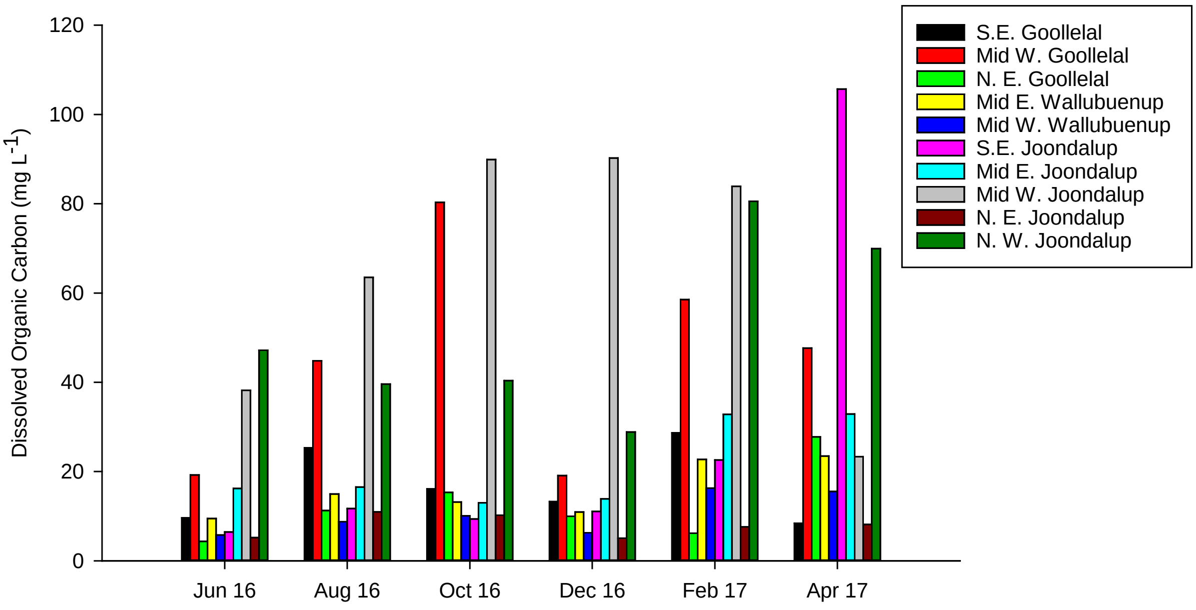
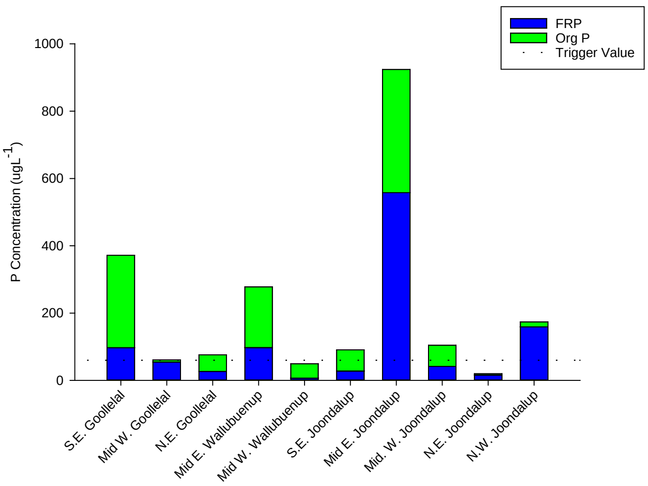


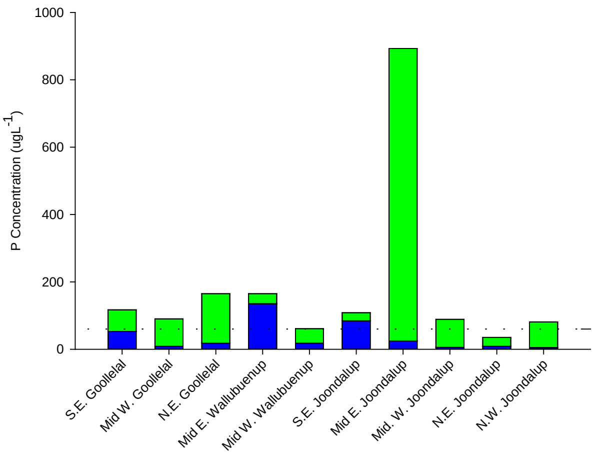
Figure 8. Dissolved organic C concentrations recorded in groundwater bores from June 2016 to April 2017.

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 all months. 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 2013/14 and 2014/15. 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.

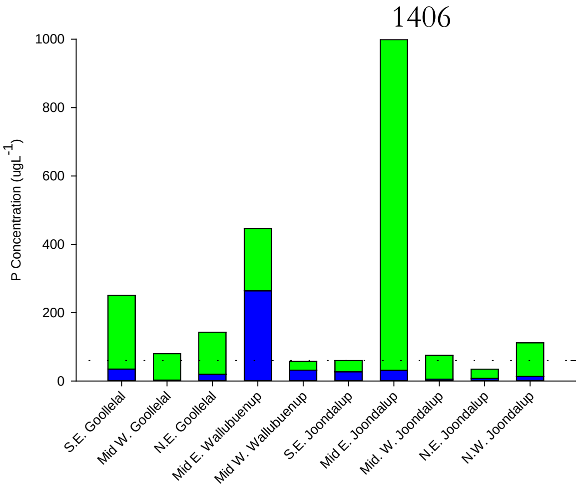
June 2016 **August 2016**



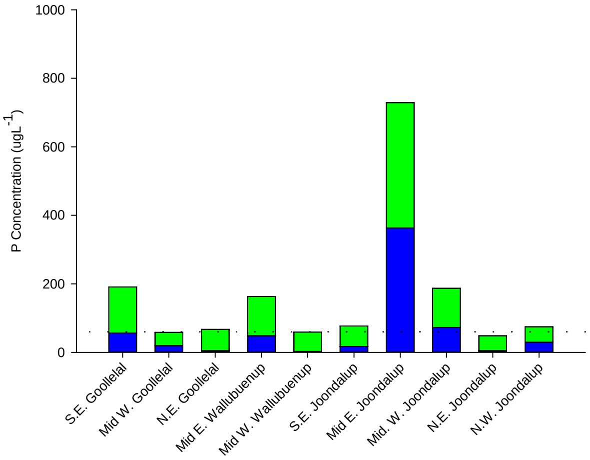
October 2016



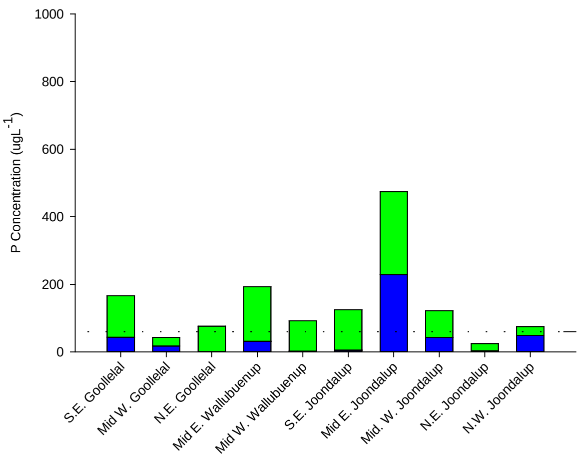
December 2016



February 2017



April 2017



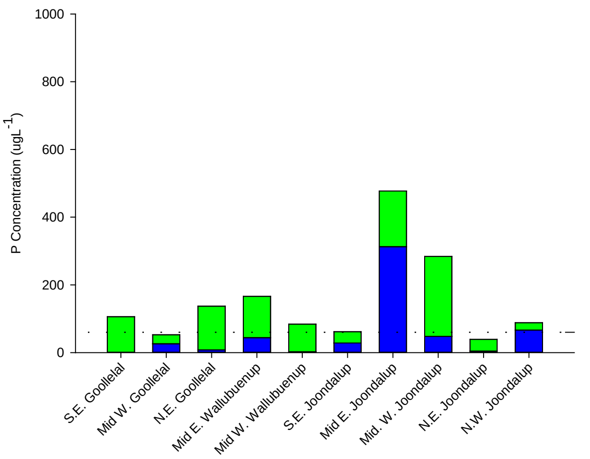


Figure 9. Breakdown of total phosphorus into chemical fractions (organic P and FRP) recorded in groundwater at each bore between June 2016 and May 2017 with the ANZECC & ARMANZ (2000) trigger value for total phosphorus shown.

In 2015/16 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. In 2013/14 this domination of organic N lasted from August 2012 to February 2013, after which this form of N was almost absent. This loss of organic N was unusual and was not repeated in 2014/15 or in 2015/16. In 2016/17 organic N was the dominant form only in August and October, with NOx dominating at other times. 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 2016/15, 2015/16 and 2014/15.

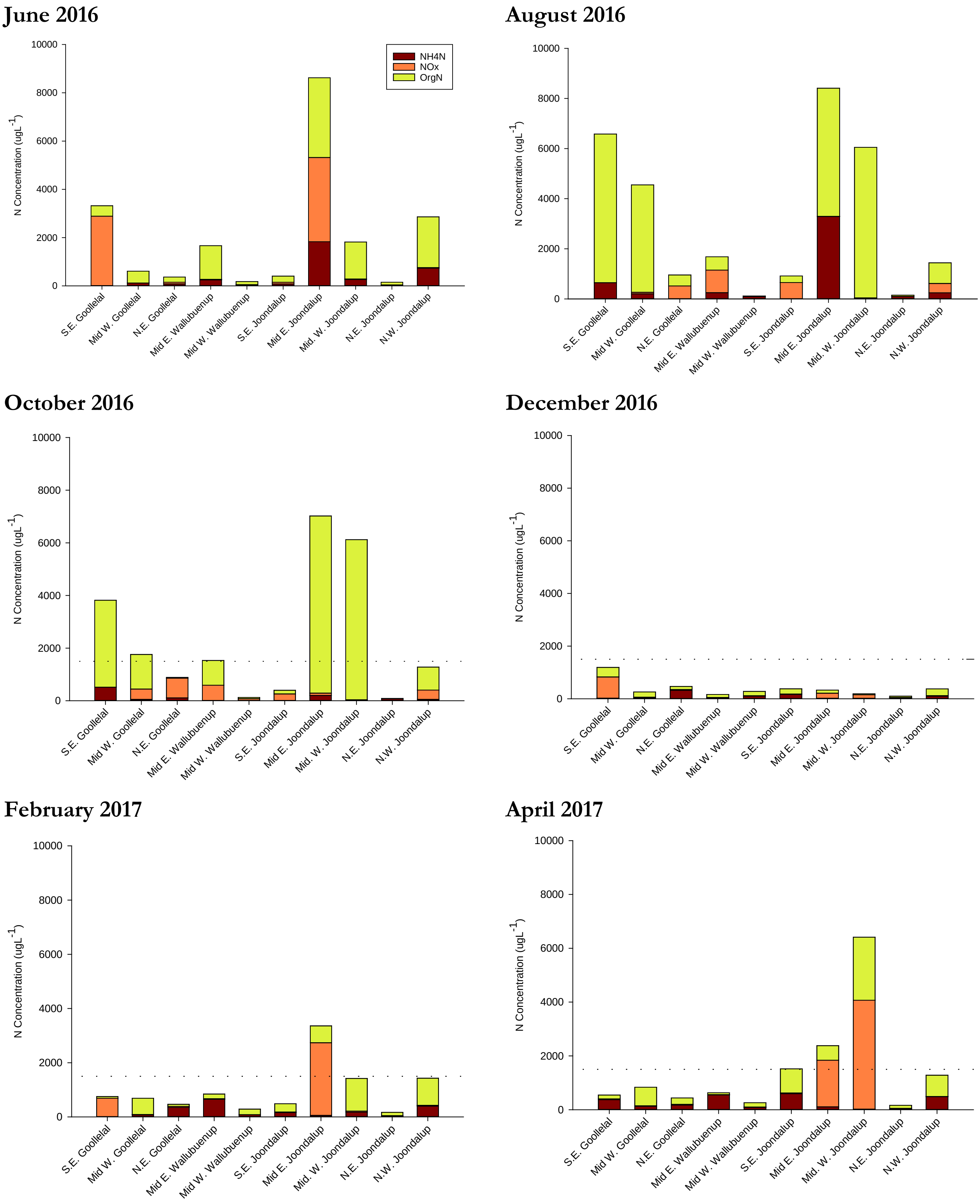


Figure 10. Breakdown of total nitrogen into chemical fractions (organic nitrogen, nitrate/nitrite (NO_x) and ammonium (NH_4)) recorded in groundwater at each bore between June 2016 and April 2017 with the ANZECC & ARMANZ (2000) trigger value for total nitrogen.

Ordination of the water quality data (Figure 11) shows that western bores are separated (to the right) from most of the eastern bores. The W. Wallubuenup bore which is situated close to centre of the wetland system and therefore might not be representative of the western side is more similar to eastern bores. Key features of the western bores are increased EC and associated parameters (SO4, Mg, Cl, Na) and alkalinity. Eastern bores have higher ORP and lower EC and associated parameters than the western bores.

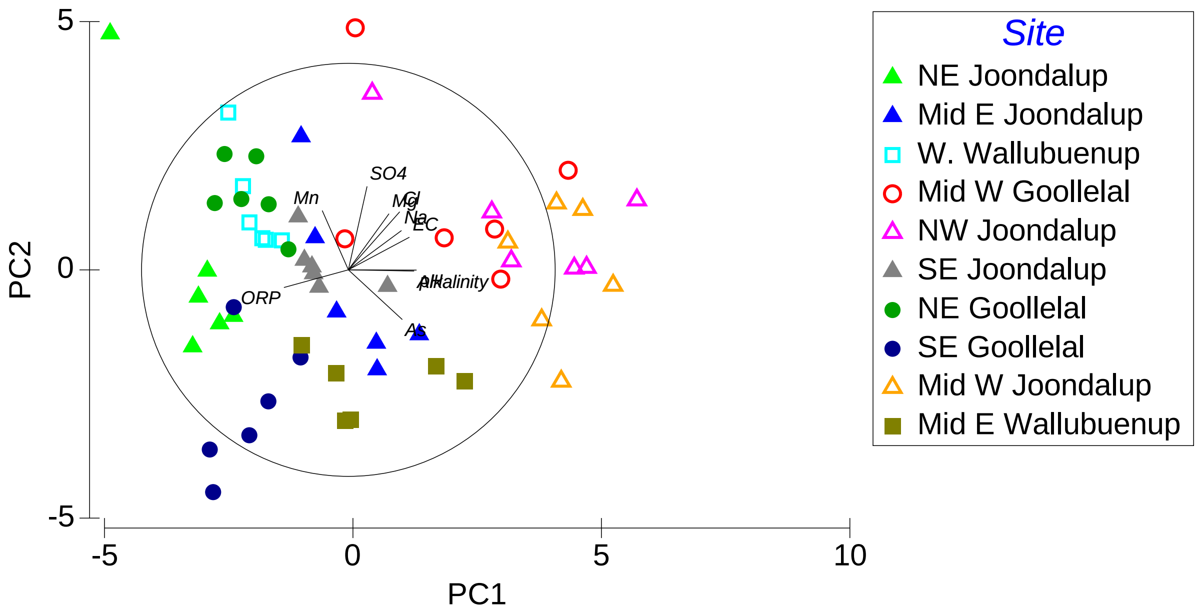


Figure 11. A PCA of physico-chemical, nutrients and metal/metalloid concentrations for all sites and times (overlay plot shows correlations (r>±0.3) with the ordination space (PC1 represents 23.6% of the data and PC2 12.9%).

Table 6. Mean ± s.e. (range) for nutrients in water recorded at each bore over the course of the monitoring period (June 2016-April 2017), 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	263 ± 117 (10-647)	2702 ± 956 (546-6580)	2702 ± 956 (546-6580)	48 ± 13 (<2-97)	201 ± 40 (106-372)	16.9 ± 3.4 (8.4-28.7)
Mid W. Goollelal	104 ± 25 (38-204)	1451 ± 653 (258-4550)	1451 ± 653 (258-4550)	22 ± 7 (3-55)	64 ± 7 (43-90)	44.9 ± 9.6 (19.1-80.3)
N.E. Goollelal	175 ± 56 (<3-350)	597 ± 104 (368-955)	597 ± 104 (368-955)	13 ± 4 (<2-27)	111 ± 17 (67-165)	12.5 ± 3.4 (4.4-27.8)
Mid E. Wallubuenup	289 ± 108 (<3-650)	1086 ± 259 (163-1680)	1086 ± 259 (163-1680)	103 ± 36 (32-264)	235 ± 46 (163-446)	15.8 ± 2.4 (9.5-23.5)
W. Wallubuenup	71 ± 16 (<3-104)	209 ± 32 (115-289)	209 ± 32 (115-289)	11 ± 5 (2-32)	67 ± 7 (50-92)	10.4 ± 1.8 (5.8-16.3)
S.E. Joondalup	169 ± 91 (<3-601)	684 ± 187 (377-1520)	684 ± 187 (377-1520)	32 ± 11 (5-84)	87 ± 11 (60-125)	27.8 ± 15.7 (6.4-105.7)
Mid E. Joondalup	919 ± 553 (20-3290)	5020 ± 1416 (329-8620)	5020 ± 1416 (329-8620)	253 ± 84 (24-558)	815 ± 140 (474-1390)	20.9 ± 3.8 (13-32.9)
Mid W. Joondalup	93 ± 43 (19-270)	3668 ± 1152 (187-6410)	3668 ± 1152 (187-6410)	36 ± 11 (6-73)	144 ± 32 (75-284)	64.9 ± 11.6 (23.3-90.2)
N.E. Joondalup	46 ± 15 (16-102)	138 ± 14 (88-171)	138 ± 14 (88-171)	8 ± 2 (3-16)	34 ± 4 (20-48)	7.9 ± 1 (5.1-11)
N.W. Joondalup	336 ± 104 (54-733)	1445 ± 327 (375-2860)	1445 ± 327 (375-2860)	54 ± 23 (5-159)	101 ± 16 (75-174)	51.1 ± 8.1 (28.9-80.6)

9. CONCLUSIONS

Ten bores (4 western, 6 eastern) were sampled for a broad range of physico-chemical parameters, nutrient and metal/metalloid concentrations between June 2016 and May 2017. 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 metals/metalloids. 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. The contamination by ASS has not yet reached a level that requires intervention.

10. RECOMMENDATIONS

1. It is recommended that groundwater monitoring continue in conjunction with surface water monitoring throughout Yellagonga Regional Park. It is suggested that the frequency of sampling (bimonthly) is working well and should not be further altered.

2. The current bores at Lake Goollelal are located at the extreme northern and southern ends on the eastern side. A new bore located in the middle of the eastern side, opposite to the western bore at Lake in Goollelal would be very helpful in understanding potential nutrient loads entering the lake, possibly from leaking septic systems – it is recommended that a new eastern bore on Lake Goollelal be established.

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