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Monitoring of Yellagonga Regional Park Groundwater Quality

2014 Report

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Prepared for,

Cities of Joondalup and Wanneroo

Mine Water and
Environment Research
Centre

Centre for Ecosystem Management

Report No. 2014-9

1 MINE WATER AND ENVIRONMENT RESEARCH CENTRE

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

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

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2 ACKNOWLEDGEMENTS

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2.1.1.1 FRONTISPIECE

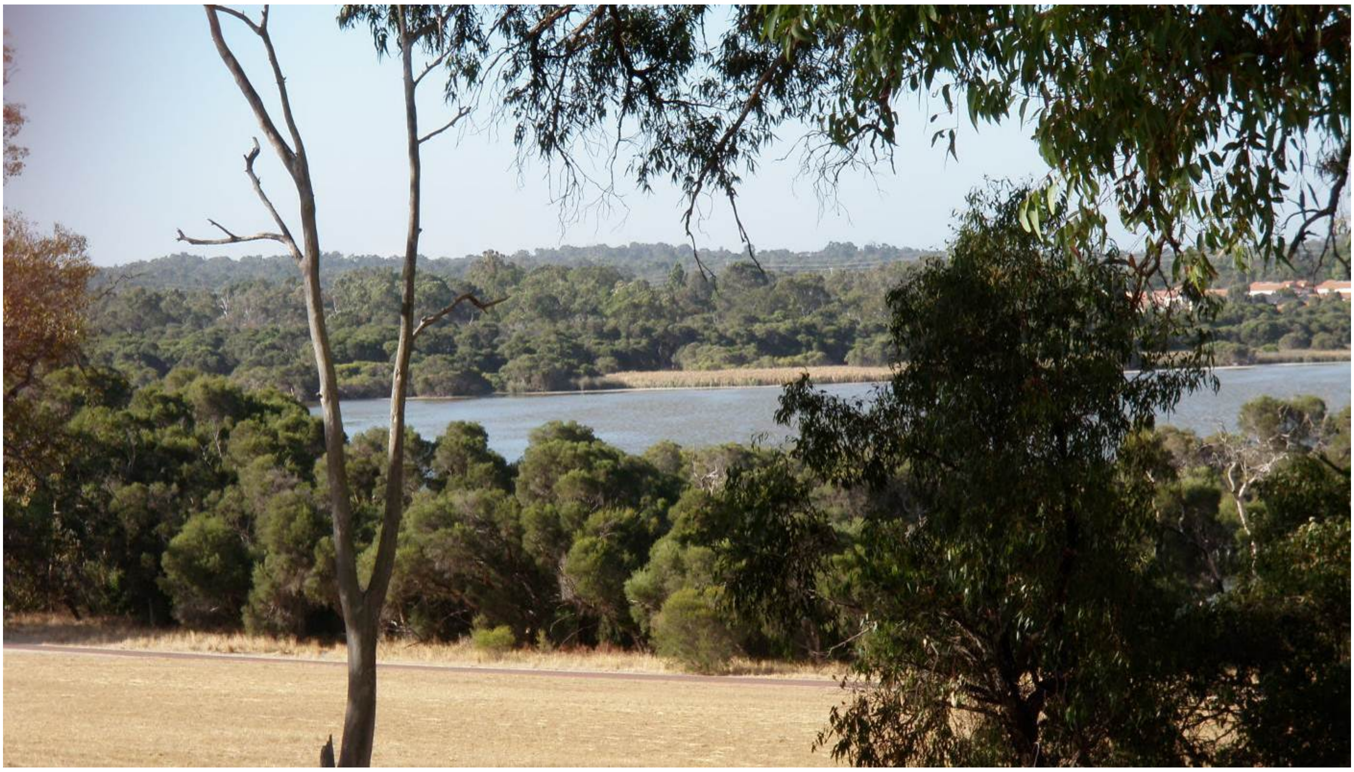

Plate 1. Photograph taken of North Lake Joondalup on the 10th March 2014.

This report should be referenced as follows.

Newport, M., and Lund, M. A., (2014). *Monitoring of Yellagonga Regional Park Groundwater Quality: Report 2014.* Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2014-9, Edith Cowan University, Perth, Australia. 33 pp. Unpublished report to the Cities of Joondalup and Wanneroo, Western Australia.

3 CONTENTS

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. Groundwater flows from the eastern side to the west.
2. Monitoring was conducted monthly and involved measurement of groundwater height, physico-chemical parameters, nutrient concentrations and selected metal/metalloid concentrations. Two bores were located on the eastern side of Lake Joondalup, one 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 eight bores throughout Yellagonga were sampled. Sampling commenced in July 2013 and reported here to June 2014.
3. There was an obvious increase in conductivity and related parameters in late summer, leading to evapo-concentration of solutes in the lakes, particularly noticeable in the western bores.
4. There was evidence of ASS impacts in most bores based on molar ratios of sulphate to chloride. This was not reflected in pH results (which only dropped to just below 6), but in metal concentrations such as Al, Cd, Hg, and Zn which exceeded ANZECC & ARMCANZ (2000) guidelines for the 95% protection of aquatic systems by up to an order of magnitude (10 times) on occasion. These guidelines are not specific to groundwater, but reflect possible issues when the groundwater is exposed as surface water in the wetlands. Concentrations of metals were down on 2012/2013 possibly reflecting increased rainfall this year.
5. High concentrations of P and N were recorded in the bore on the middle of Lake Joondalup, suggesting groundwater is an important source of nutrients into the wetland system. From September 2013 onwards, there appeared to be strong denitrification of NOx driven by low ORP and dissolved oxygen levels. This denitrification would reduce NOx entering the wetlands.
6. The key recommendation from the study was to continue monitoring at monthly intervals until there is at least 3 years’ worth of data for each bore. In addition, as the middle of Lake Joondalup bore appears to be a significant source of contamination to the northern end of the lake, it is recommended that the extent of the contaminated plume be investigated so potential control strategies can be developed.

5 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 & Cook, 2009). The Gnangara Mound covers an area of approximately 2200 km^2 and is the most significant water resource utilised by the population of Perth, providing 85% of its total domestic water requirements (Elmahdi & 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 & 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 & 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 & McComb, 1976a; Congdon & McComb, 1976b; Gordon *et al.*, 1981; Congdon, 1985, 1986; Davis *et al.*, 1993; Kinnear *et al.*, 1997; Kinnear & Garnett, 1999; Lund *et al.*, 2000; Lund, 2003; Cumbers, 2004; Khwanboonbumpen, 2006; Lund, 2007). 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 & Lund, 2012b). An investigation in the southern section of Wallubuenup Swamp identified the presence of acid sulphate soils (Newport *et al.*, 2011b; Newport & Lund, 2013a).

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. In addition, the City of Joondalup installed two new groundwater bores on the eastern side of Lake Goollelal. This report details the results of monthly monitoring of these groundwater bores from July 2013 – June 2014.

6 METHODS

6.1 STUDY SITE

Five bores were located on the eastern side of Yellagonga, on the western side of the regional park, one bore was located in the south western corner, a second situated at the intersection of Wallubuenup Swamp and Beenyup Swamp and a third bore in the north western corner of the park (Figure 1.).The bores sampled on a monthly basis are listed below with their corresponding AWRC reference number or identifying number:

Joondalup NW (JoonNW) – AWRC ref: 61611423

Joondalup NE (JoonNE) – AWRC ref: 61610629

Joondalup Mid E (JoonMidE) – AWRC ref: 61610661

Wallubuenup W (WallW) – AWRC ref: 61610679

Wallubuenup Mid E (WallE) – WN12

Goollelal NE (GoolNE) – CoJ1

Goollelal Mid W (GoolMidW) – AWRC ref: 61611870

Goollelal SE (GoolSE) – CoJ2

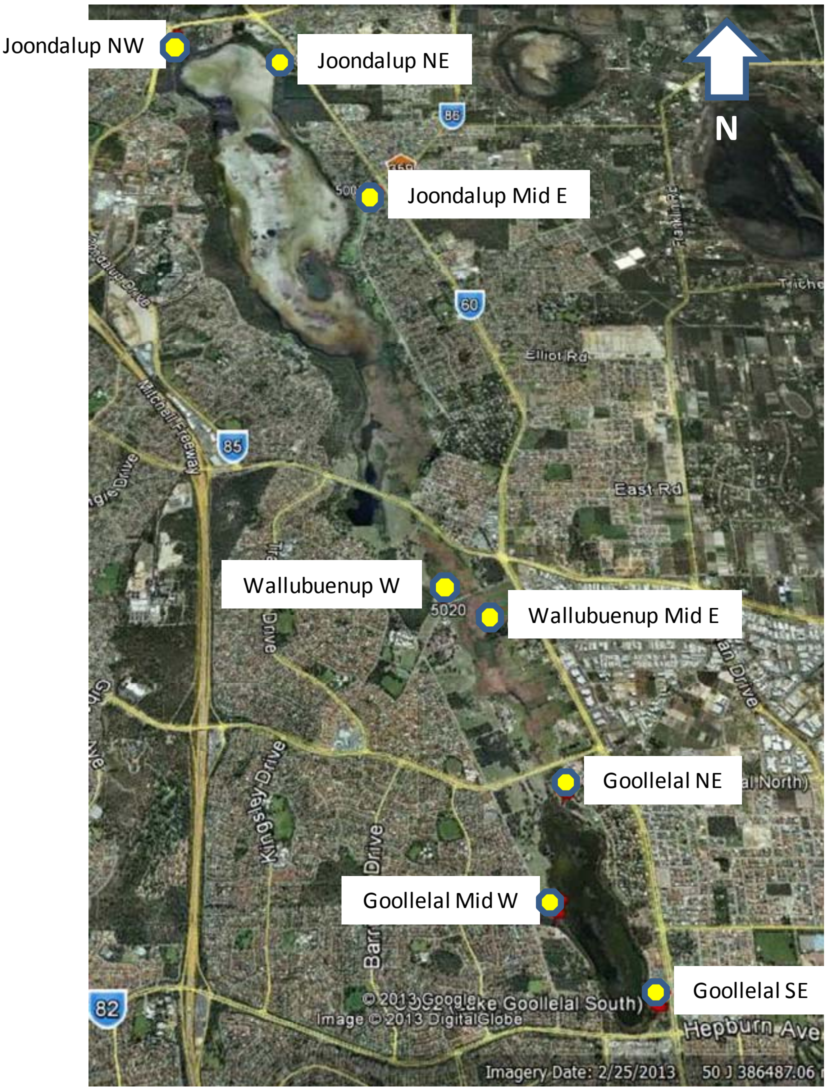

Figure 1. Location of the eight groundwater bores used for monthly monitoring in Yellagonga Regional Park (adapted from Google Earth 2013).

6.2 SAMPLING

The analysis conducted for groundwater monitoring mirrored that of surface water monitoring (see Newport & Lund, 2013b) so as to be effective in evaluating inputs/outputs associated with nutrient enrichment and metal contamination in the Yellagonga system.

This report covers monthly sampling of the groundwater bores between the July 2013 and June 2014. 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 4^oC 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).

In July 2014 the Natural Sciences Analytical Laboratory (Edith Cowan University) was able to upgrade their analytical equipment providing a higher quality of chemical analysis. Consequently, the results of metals and metalloids sensitive to contamination from interference are now more reliable and analysed to a finer resolution. Uranium and Se concentrations in previous reports are now considered to be unreliable and should be ignored.

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.

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[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)

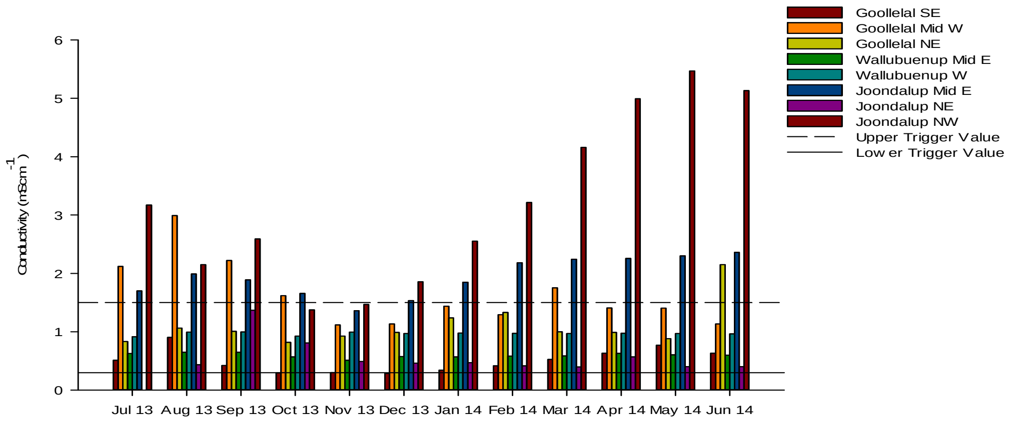
7 RESULTS AND DISCUSSION

The groundwater bore located on the north eastern side of Lake Joondalup, identified as Joondalup NE, was inaccessible for July 2013 sampling event due to the Department of Water (DoW) changing the padlock. An access request from DoW was processed in time for the following sampling event in August.

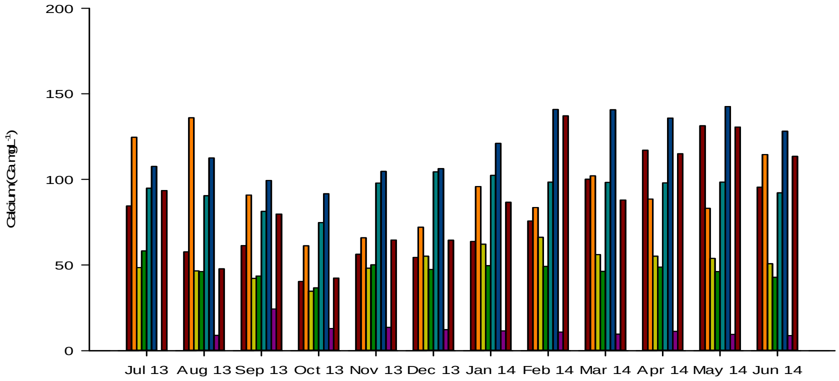
7.1 PHYSICO-CHEMISTRY

Electrical conductivity was higher in the western bores compared to the eastern ones; this shows the impact of evapo-concentration as the groundwater moves through the lakes (Figure 2). The EC of GoolNE and JoonMidE and to lesser extent JoonNE were higher (reaching 2.2 mS cm^{-1}) than the other eastern bores. The EC followed a trend of typically higher values in autumn and lower values in spring in GoolMidW, JoonMidE and most strongly in JoonNW. This cyclic pattern for EC is likely associated with dilution in spring and evapo-concentration in autumn which is easily explainable for western bores, but it is unusual in JoonMidE. Close inspection of JoonMidE suggests that there might simply be a dilution in spring (as groundwater levels peak) rather than an increase in EC in autumn. Similar trends were seen in the major ions (K, Mg, Na and Cl) which contribute to EC. Table 1 illustrates the mean and ranges for each of the common ions.

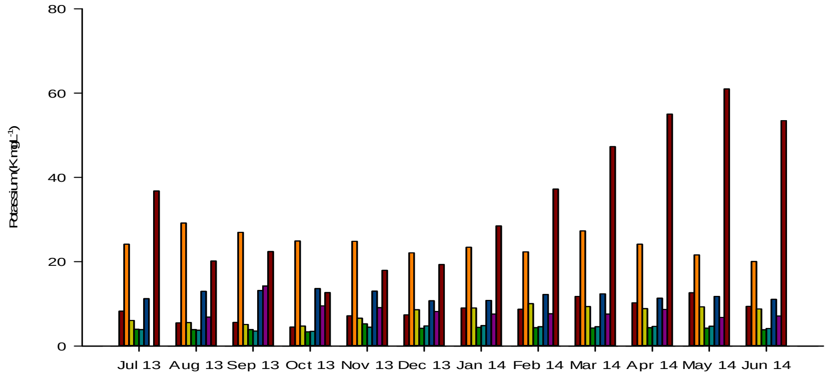
a) Electrical conductivity



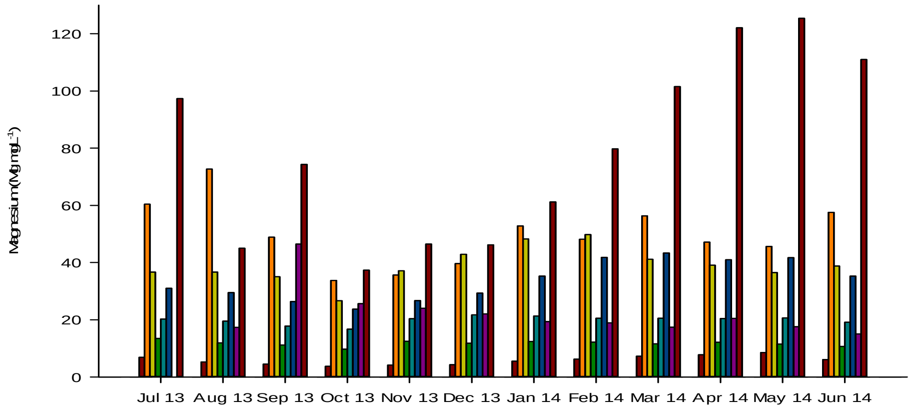
b) Calcium (Ca)



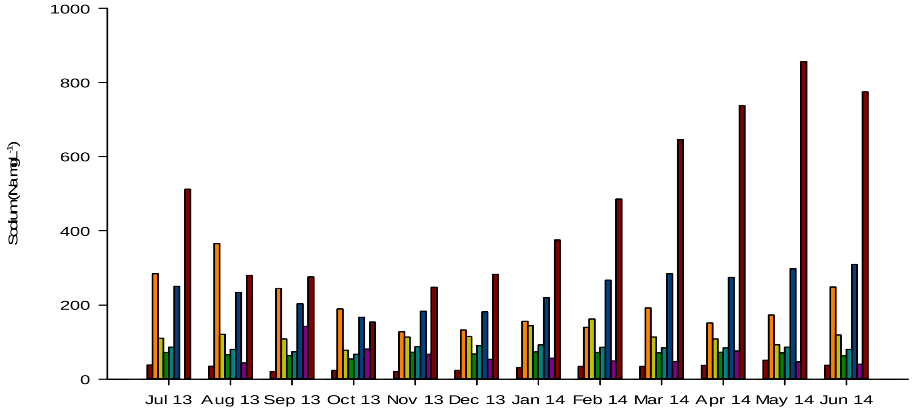
c) Potassium (K)



d) Magnesium (Mg)



e) Sodium (Na)



f) Chloride (Cl^{-})

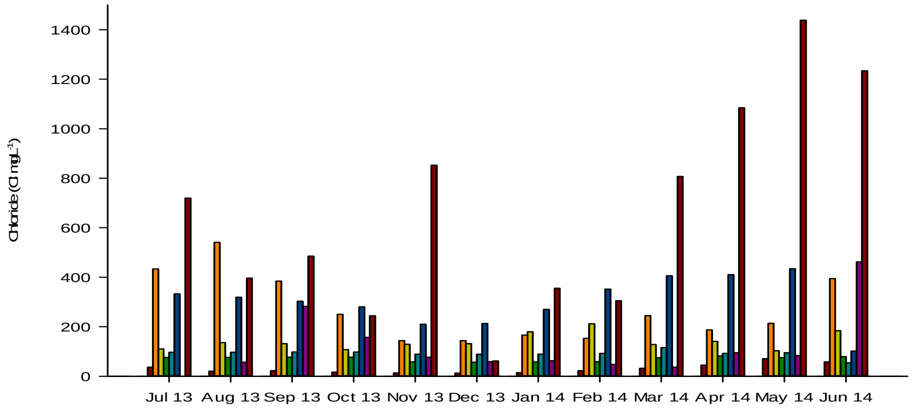


Figure 2. Changes in a) electrical conductivity, b) calcium, c) potassium, d) magnesium, e) sodium and f) chloride over the period of monitoring at each site (July 2013 – June 2014).

Table 1 Mean ± standard error (range) for selected solutes during the monitoring period July 2013 to June 2014

	Ca **mg L^{-1}**	**K** **mg L^{-1}**	**Mg** **mg L^{-1}**	**Na** **mg L^{-1}**	**Cl^-** **mg L^{-1}**	**SO_4^{2-}** **mg L^{-1}**
Detection Limit					**<3**	**<3**
Goollelal SE	61 ± 9.1 (40.4-84.5)	6 ± 0.8 (4.5-8.3)	5.1 ± 0.7 (3.7-6.9)	29.3 ± 4.3 (20.3-38.5)	27.9 ± 5.3 (12.6-70.8)	20.5 ± 4.9 (7.7-61.6)
Goollelal Mid W	103.2 ± 16.9 (61.3-136)	26.3 ± 1.1 (24.2-29.2)	53.9 ± 8.3 (33.8-72.7)	270.8 ± 37 (189.2-65.3)	299.4 ± 40.4 (143.6-540.6)	145.5 ± 36.5 (36.5-414.3)
Goollelal NE	43 ± 3.1 (34.7-48.5)	5.4 ± 0.3 (4.7-6)	33.8 ± 2.4 (26.6-36.7)	104.5 ± 9.2 (78-120.9)	137.2 ± 9.7 (103.1-211.4)	204.9 ± 17.2 (154.7-352.5)
Wallubuenup Mid E	46.2 ± 4.5 (36.6-58.3)	3.8 ± 0.1 (3.4-3.9)	11.6 ± 0.8 (9.7-13.5)	64.1 ± 3.6 (54.7-71.9)	70 ± 2.9 (56.8-81.6)	24.3 ± 2.1 (15.9-33.3)
Wallubuenup W	85.4 ± 4.5 (74.7-94.9)	3.7 ± 0.1 (3.5-3.9)	18.6 ± 0.8 (16.7-20.2)	76.9 ± 4.1 (67.5-86.5)	95.5 ± 2.3 (88.5-116.2)	178.6 ± 3.7 (161.4-197.1)
Joondalup Mid E	102.8 ± 4.6 (91.6-112.6)	12.8 ± 0.5 (11.2-13.6)	27.7 ± 1.6 (23.7-31)	213.4 ± 18.3 (167-250.6)	321 ± 22.9 (209.7-434.4)	115.9 ± 6.9 (82.1-149.7)
Joondalup NE	15.4 ± 4.6 (8.9-24.3)	10.2 ± 2.2 (6.8-14.2)	29.8 ± 8.7 (17.3-46.5)	89.1 ± 28.7 (43.7-142.3)	95.7 ± 24.6 (36.9-282.7)	55.6 ± 8.1 (41.1-118.9)
Joondalup NW	65.9 ± 12.4 (42.4-93.6)	23 ± 5 (12.7-36.7)	63.5 ± 13.8 (37.3-97.3)	305.3 ± 74.8 (154-512.1)	613.5 ± 123.3 (61.7-1438)	170.6 ± 27.7 (98.8-373.6)

Calculated hardness of water samples from the bores are shown in Figure 3. As seen in the surface waters (2013/14) the groundwater was harder than in 2012/13. Although the reason for the increase is not known, it does show how significant groundwater is for the surface waters. The western bores tended to have harder water than the eastern side reflecting evapo-concentration in the lake. JoonMidE had higher hardness than the other eastern bores. The source of this additional hardness is not known at this time.

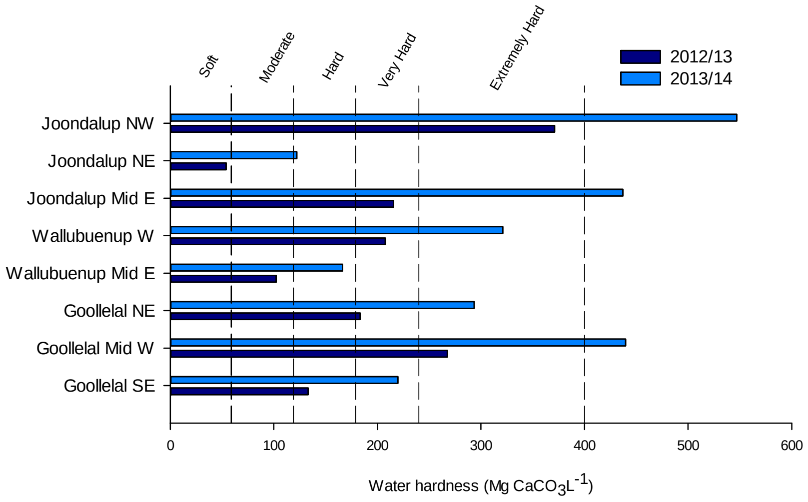
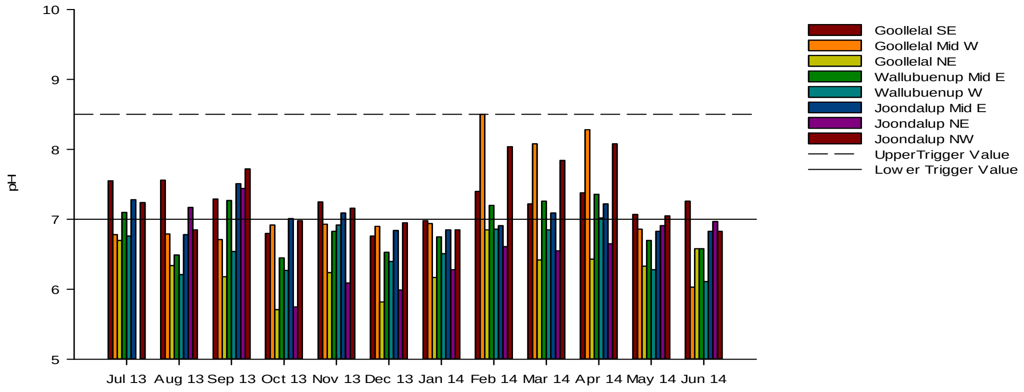


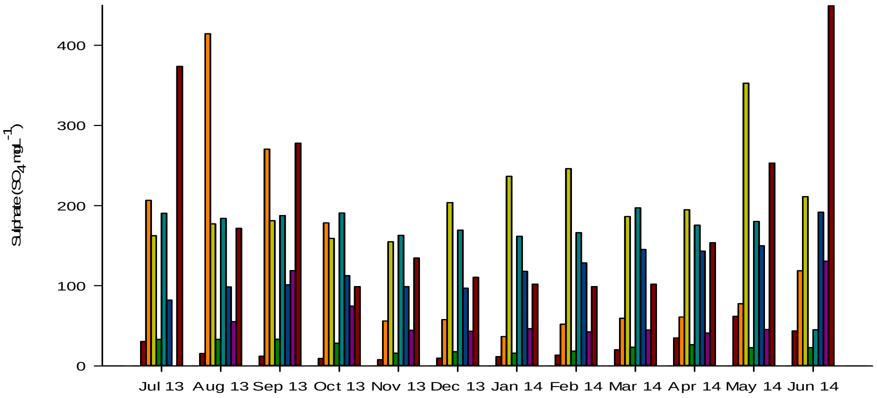
Figure 3. Calculated mean water hardness for the period of monitoring at each bore (August 2012 – June 2013) with ANZECC & ARMCANZ (2000) categories indicated.

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, increases sulphate relative to conservative chloride ions and results in low molar ratios. A molar ratio of four or less is considered a good indicator of ASS contamination (Department of Local Government and Planning & Department of Natural Resources and Mines, 2002). pH of the groundwater ranged from circum-neutral to <6 (GoolNE, JoonNE) and was highest between February and April. Sulphate concentrations were generally highest in the western sites. Molar ratios indicated the presence of ASS contamination at all sites except WallMidE, JoonMidE and JoonNW, as seen in 2012/13. The molar ratios were also lowest during the winter months. The water hardness at most sites would tend to reduce the impact of any ASS contamination by neutralising the acidity.

a) pH



b) Sulphate (SO_4)



c) Chloride to Sulphate Molar Ratios (Cl^{-}:SO_4^{2-})

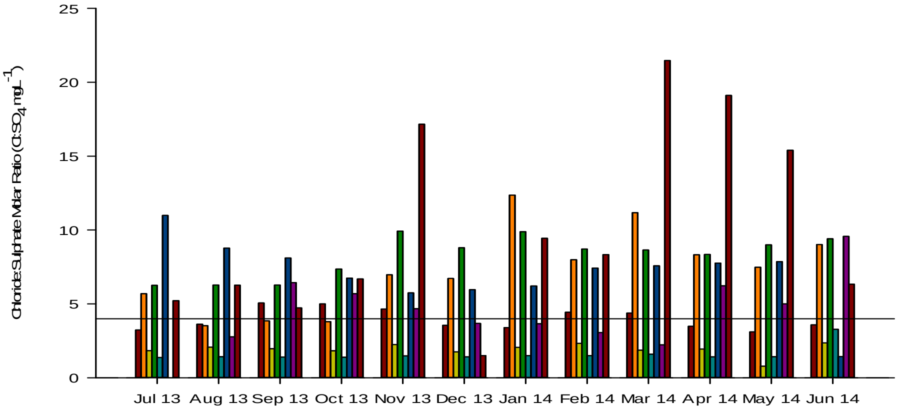
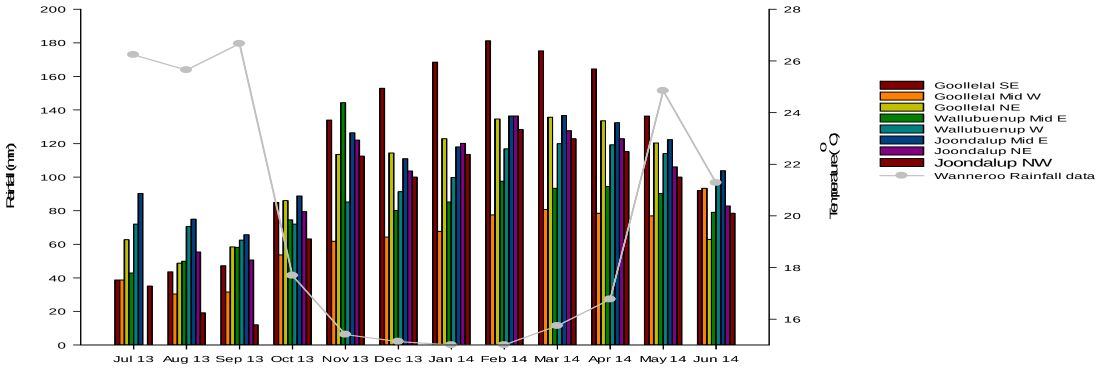


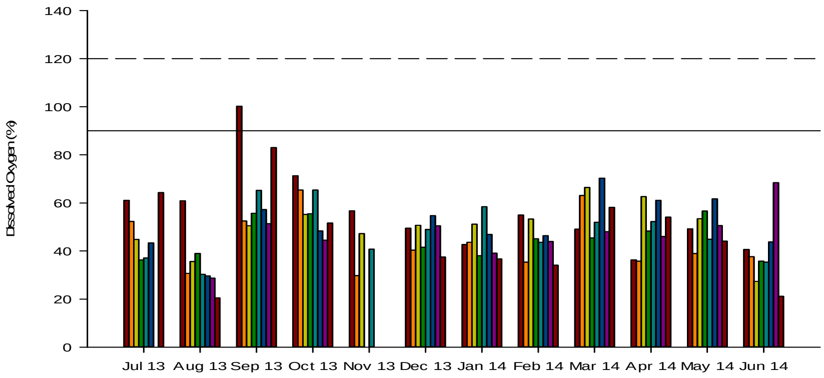
Figure 4. Changes in a) pH, b) sulphate and c) chloride to sulphate molar ratios over the period of monitoring at each bore (July 2013 – June 2014) with ANZECC & ARMCANZ (2000) trigger values for the protection of aquatic ecosystems (95%).

Water temperatures varied by 10 °C over the year, highest in summer and lowest in winter (Figure 5, Table 2). Dissolved oxygen was measured in all bores at >30% saturation. ORP was <0 mV for sites GoolMidW and JoonNW over the year, with central sites (GoolNE, WallMidE, WallW) having <0 mV on many occasions especially during the summer months. ORP was typically <0 mV. As dissolved oxygen was present albeit at low levels, this indicates chemical processes rather than oxygen as the driver for ORP changes. Water levels in the bores showed generally little seasonal variation (<1 m), except in JoonMidE and JoonNW. In JoonNW water levels rose by nearly 2 m between August and September before slowly declining by 1 m to June 2013. JoonMidE increased by over 1.5 m between July and October 2013 before returning to July 2013 levels in May 2014. These short term variations are difficult to explain but may represent some unique local condition.

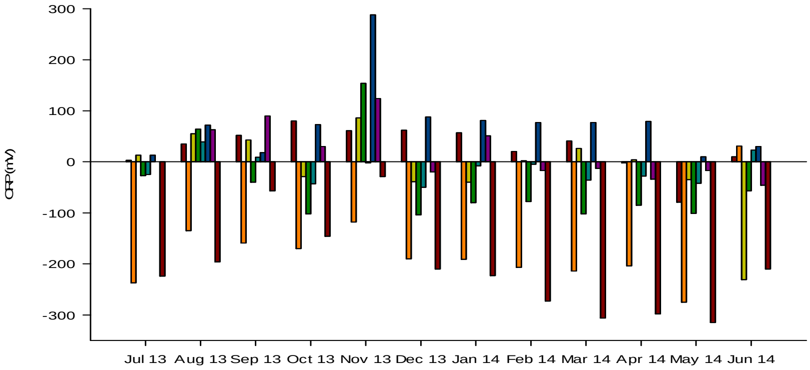
a) Temperature and Rainfall



b) Dissolved Oxygen



c) ORP



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

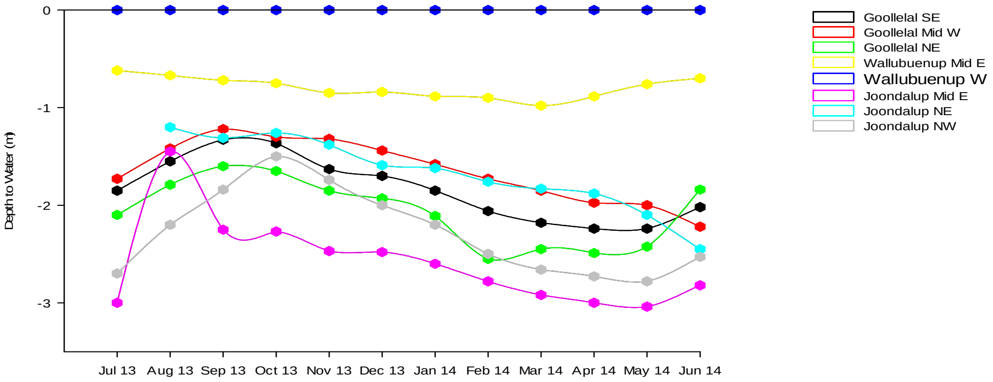


Figure 5. Variation throughout groundwater monitoring period for a) temperature, b) dissolved oxygen, c) ORP and d) depth to water between June 2013 and June 2014 at each bore.

Table 2 Mean ± standard error (range) for physicochemical variables over the monitoring period (July 2013- June 2014)

	Temperature (°C)	**Electrical Conductivity (mS cm^{-1})**	**DO (mgL^{-1})**	**DO (%)**	**pH**	**ORP (mV)**
Goollelal SE	22.5 ± 1.04 (17.5-26.8)	0.5 ± 0.1 (0.3-0.9)	5.1 ± 0.5 (3.5-9.4)	56.3 ± 4.7 (36.3-100.2)	7.2 ± 0.1 (6.8-7.6)	28.8 ± 12.2 (-79-80)
Goollelal Mid W	19.1 ± 0.4 (17-21.1)	1.6 ± 0.2 (1.1-3)	4.1 ± 0.3 (2.7-6.1)	43.8 ± 3.4 (29.8-65.4)	7.1 ± 0.2 (6-8.5)	-172.4 ± 22.2 (-275-31)
Goollelal NE	21.2 ± 0.6 (18.1-23.8)	1.1 ± 0.1 (0.8-2.2)	4.2 ± 0.2 (2.5-5.6)	48.4 ± 3.1 (27.4-66.4)	6.3 ± 0.1 (5.7-6.8)	-15.6 ± 23 (-231-86)
Wallubuenup Mid E	20.4 ± 0.5 (17.8-24.4)	0.6 ± 0.01 (0.5-0.6)	4.1 ± 0.2 (3.2-5.1)	45.2 ± 2.4 (35.8-56.6)	6.9 ± 0.1 (6.4-7.4)	-46.5 ± 22.9 (-104-154)
Wallubuenup W	21.1 ± 0.4 (19.1-22.8)	1 ± 0.01 (0.9-1)	4.1 ± 0.3 (2.8-6)	47.9 ± 3.3 (30.3-65.4)	6.6 ± 0.1 (6.1-7)	-14 ± 8.1 (-50-39)
Joondalup Mid E	22.1 ± 0.4 (19.3-23.9)	1.9 ± 0.1 (1.4-2.4)	4.4 ± 0.3 (2.7-5.9)	51.2 ± 3.4 (29.6-70.3)	7 ± 0.1 (6.8-7.5)	75.5 ± 21.1 (10-288)
Joondalup NE	21.5 ± 0.6 (18.3-23.9)	0.6 ± 0.1 (0.4-1.4)	4.2 ± 0.3 (2.7-6.2)	47.1 ± 3.2 (28.7-68.4)	6.6 ± 0.2 (5.8-7.4)	19.2 ± 16.9 (-46-124)
Joondalup NW	20.4 ± 0.8 (15.8-23.4)	3.2 ± 0.4 (1.4-5.5)	4.2 ± 0.6 (1.9-8.1)	45.9 ± 5.7 (20.5-83)	7.3 ± 0.1 (6.8-8.1)	-207.2 ± 26.5 (-315)-(-29)

7.2 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 this groundwater discharges into the lake it provides an indicator of potential issues. Aluminium, As, Cd, Hg and particularly Zn all had concentrations that on occasion were higher than guideline levels (often by an order of magnitude) indicating potential problems for the lakes. Fewer metals were problematic in 2013/14 compared to 2012/13, which also matches the trend seen for surface waters.

Table 3 Exceedances of ANZECC & ARMCANZ (2000) water quality trigger values for 95% protection of aquatic ecosystems for metals and metalloids recorded in this study between July 2013 and June 2014

Metal/Metalloid (mg L^{-1})	ANZECC/ ARMCANZ (2000) Trigger Value	Detection Limit	Mean ± se (maximum value)	No. exceeding trigger value
Aluminium (Al)	0.055	<0.002	0.03 ± 0.002 (0.12)	9
Arsenic (As)	0.013 - 0.024*	<0.001	0.004 ± 0.0005 (0.02)	0
Calcium (Ca)	—	<0.005	67.0 ± 5.8 (136)	
Cadmium (Cd)	0.0003 – 0.00165^{H}	<0.00002	0.0002 ± 0.00002 (0.01)	1
Cobalt (Co)	ID	<0.00002	0.0002 ± 0.00001 (0.0006)	
Chromium (Cr)	ID - 0.004*	<0.00002	0.0014 ± 0.00007 (0.0032)	0
Iron (Fe)	ID	<0.05	0.65 ± 0.097 (3.94)	
Mercury (Hg)	0.0006 - ID*	<0.00002	0.00007 ± 0.00002 (0.002)	2
Potassium (K)	—	<0.5	11.41 ± 1.65 (36.74)	
Magnesium (Mg)	—	<0.1	30.51 ± 4 (97.32)	
Manganese (Mn)	1.9	<0.001	0.009 ± 0.0007 (0.023)	0
Sodium (Na)	—	<0.5	146 ± 20.6 (512.1)	
Nickel (Ni)	0.0181 – 0.0824^{H}	<0.0002	0.001 ± 0.0001 (0.004)	0
Selenium (Se)	0.011	<0.00002	0.0003 ± 0.00002 (0.0008)	0
Uranium (U)	0.005+	<0.00002	0.0001 ± 0.00002 (0.0008)	0
Zinc (Zn)	0.0132 – 0.06^{H}	<0.005	0.06 ± 0.0026 (0.12)	50

^{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)

Aluminium concentrations were highest on average in Lake Goollelal bores, declining northwards (Table 4). Arsenic tended to be higher in the western bores, with the exception of Wallubuenup swamp. Cadmium, Cr and Co concentrations show no particular trends spatially. Iron concentrations were highest in the northern sections of Lake Goollelal, then

Table 4 Mean ± standard error (range) for selected metals over the July 2013 to June 2014 monitoring period with ANZECC & ARMCANZ (2000) water quality trigger values for 95% protection of aquatic ecosystems for metals and metalloids for reference.

	Al µg L^{-1}	**As µg L^{-1}**	**Cd µg L^{-1}**	**Co µg L^{-1}**	**Cr µg L^{-1}**	**Fe mg L^{-1}**
Detection Limit	**<2**	**<1**	**<0.02**	**<0.02**	**<0.02**	**<0.05**
Trigger Value	**55 ugL^{-1}**	**13-24 ugL^{-1}**	**0.3-1.7^{H} ugL^{-1}**	**ID**	**ID-4* ugL^{-1}**	**ID**
Goollelal SE	50 ± 10 (8.3-122.1)	1.3 ± 0.1 (0.8-1.8)	0.08 ± 0.014 (0.042-0.212)	0.128 ± 0.009 (0.094-0.179)	0.8 ± 0.043 (0.577-1.064)	0.05 ± 0.01 (0.03-0.11)
Goollelal Mid W	28.2 ± 4.1 (11-64.6)	6.5 ± 0.7 (3.2-12.3)	0.074 ± 0.017 (0.01-0.231)	0.139 ± 0.025 (0.065-0.334)	1.425 ± 0.073 (0.964-1.918)	0.83 ± 0.19 (0.15-2.29)
Goollelal NE	37.5 ± 7.4 (7.8-98.2)	0.6 ± 0.04 (0.4-0.85)	0.135 ± 0.027 (0.053-0.371)	0.249 ± 0.035 (0.151-0.562)	0.722 ± 0.026 (0.589-0.888)	1.82 ± 0.33 (0.35-3.94)
Wallubuenup Mid E	17.9 ± 2.3 (10.6-37.8)	8.0 ± 0.4 (5.5-10.04)	0.054 ± 0.008 (0.01-0.127)	0.113 ± 0.008 (0.079-0.155)	2.715 ± 0.093 (2.238-3.19)	0.04 ± 0 (0.03-0.06)
Wallubuenup W	7.6 ± 1.2 (3.5-18.5)	1 ± 0.06 (0.8-1.4)	0.204 ± 0.023 (0.1-0.34)	0.086 ± 0.029 (0.045-0.37)	1.676 ± 0.051 (1.478-2.016)	1.91 ± 0.21 (0.84-3.27)
Joondalup Mid E	14 ± 1.9 (5.8-26.4)	1.5 ± 0 (1.4-1.7)	0.42 ± 0.095 (0.114-1.107)	0.303 ± 0.015 (0.241-0.39)	0.763 ± 0.019 (0.684-0.866)	0.04 ± 0 (0.02-0.07)
Joondalup NE	14.6 ± 1.8 (8.5-23.3)	1 ± 0 (0.7-1.2)	0.329 ± 0.09 (0.078-0.899)	0.102 ± 0.021 (0.053-0.266)	1.122 ± 0.071 (0.917-1.493)	0.21 ± 0.05 (0.07-0.58)
Joondalup NW	30.3 ± 4.6 (17.9-71.2)	10 ± 2 (4.9-23.6)	0.076 ± 0.016 (0.001-0.204)	0.131 ± 0.017 (0.049-0.235)	1.841 ± 0.095 (1.445-2.357)	0.22 ± 0.04 (0.09-0.42)

Table 4. cont.

Detection Limit	**Hg** **μg L^{-1}** **<0.02**	**Mn** **mg L^{-1}** **<0.001**	**Ni** **μg L^{-1}** **<0.02**	**Se** **μg L^{-1}** **<0.05**	**U** **μg L^{-1}** **<0.02**	**Zn** **μg L^{-1}** **<0.05**
Trigger Value	**0.6 ugL^{-1}-ID***	**1.9 mgL^{-1}**	**18.1-82.4^{H} ugL^{-1}**	**11 ugL^{-1}**	**5^{+} ugL^{-1}**	**13.2-60^{H} ugL^{-1}**
Goollelal SE	0.123 ± 0.08	0.001 ± 0.0001	1.328 ± 0.11	0.346 ± 0.024	0.347 ± 0.071	39.6 ± 4.7
	(0.002-0.886)	(0.0009-0.0025)	(0.856-1.9)	(0.196-0.425)	(0.097-0.799)	(21.5-66.7)
Goollelal Mid W	0.052 ± 0.023	0.01 ± 0.002	1.3 ± 0.096	0.309 ± 0.022	0.044 ± 0.003	52.3 ± 3.5
	(0.01-0.257)	(0.005-0.021)	(0.701-1.682)	(0.221-0.474)	(0.01-0.041)	(21.4-61.1)
Goollelal NE	0.242 ± 0.151	0.01 ± 0.001	1.41 ± 0.114	0.154 ± 0.022	0.017 ± 0.003	41.2 ± 6.7
	(0.003-1.469)	(0.007-0.021)	(0.928-2.219)	(0.042-0.276)	(0.01-0.036)	(18.7-91.8)
Wallubuenup Mid E	0.0261 ± 0.014	0.009 ± 0.0002	1.259 ± 0.198	0.606 ± 0.03	0.254 ± 0.035	85.4 ± 5.6
	(0-0.169)	(0.008-0.01)	(0.778-3.086)	(0.47-0.755)	(0.131-0.554)	(56.1-111.1)
Wallubuenup W	0.023 ± 0.011	0.02 ± 0.0002	1.124 ± 0.133	0.159 ± 0.026	0.059 ± 0.005	80.6 ± 3.5
	(0.003-0.143)	(0.019-0.022)	(0.7-2.057)	(0.045-0.262)	(0.033-0.087)	(66.9-96.7)
Joondalup Mid E	0.028 ± 0.005	0.008 ± 0.002	2.043 ± 0.237	0.455 ± 0.023	0.187 ± 0.018	74.8 ± 6.8
	(0.003-0.17)	(0.003-0.023)	(1.266-3.706)	(0.307-0.55)	(0.091-0.261)	(49.4-115.7)
Joondalup NE	0.024 ± 0.015	0.004 ± 0.0004	0.956 ± 0.101	0.184 ± 0.022	0.019 ± 0.003	48.8 ± 4.8
	(0.002-0.167)	(0.003-0.006)	(0.671-1.687)	(0.102-0.286)	(0.01-0.038)	(30.6-71.3)
Joondalup NW	0.035 ± 0.013	0.007 ± 0.0006	1.571 ± 0.21	0.415 ± 0.026	0.063 ± 0.004	61.4 ± 3.9
	(0.009-0.134)	(0.004-0.011)	(0.725-2.73)	(0.318-0.544)	(0.046-0.079)	(37.6-80.2)

^{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.

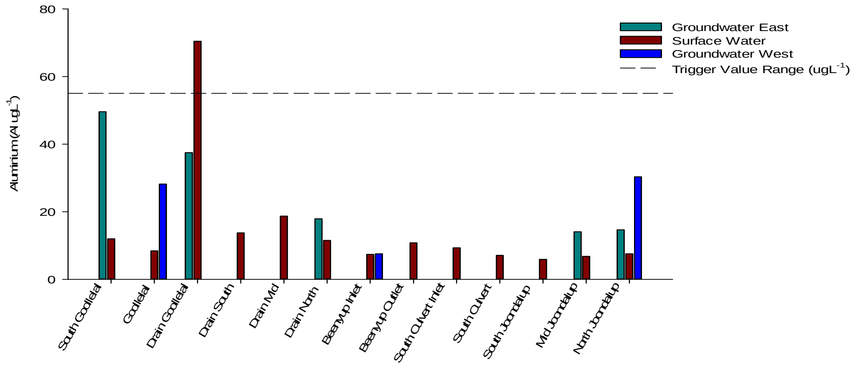
* Range for As III and V, Cr III and VI, and Hg inorganic and methyl.

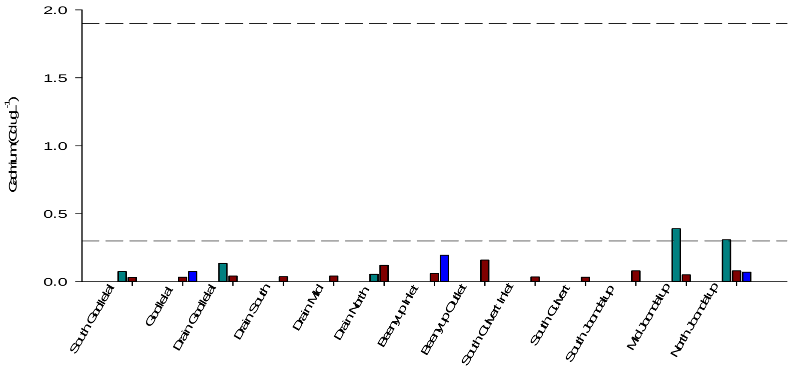
ID Insufficient data to derive a reliable trigger value.

\+ Low reliability, interim working level as prescribed in ANZECC/ARMCANZ (2000) declined northwards,. This pattern matched our previous findings of an iron gradient throughout the park from high in the south declining northwards.

The only bores where Hg concentrations were found to be above guideline levels were around east Lake Goollelal (Table 5). This were peaks in Hg in July 2013 and June 2014, the source of which is currently unknown, but coincides with similar peaks seen in the surface waters at these times. Concentrations of Mn, Ni, Se, and U were relatively similar across all the bores, and did not exceed trigger values. Zinc concentrations frequently exceeded the trigger values across all sites, although were lowest around Lake Goollelal. In the surface waters of Yellagonga park, Zn concentrations are often high, showing the most likely source is groundwater.

Figure 6 shows average concentrations of metals/metalloids that were above detection limits in the eastern and western bores compared to surface water, from the annual Yellagonga surface water monitoring program. Aluminium, Cd, Hg and Zn concentrations were generally higher in the groundwater than surface water samples, suggesting that it was the source of contamination. Both Al and Zn also appeared in high concentrations in the western bores indicating that the metals were also being lost from the system.





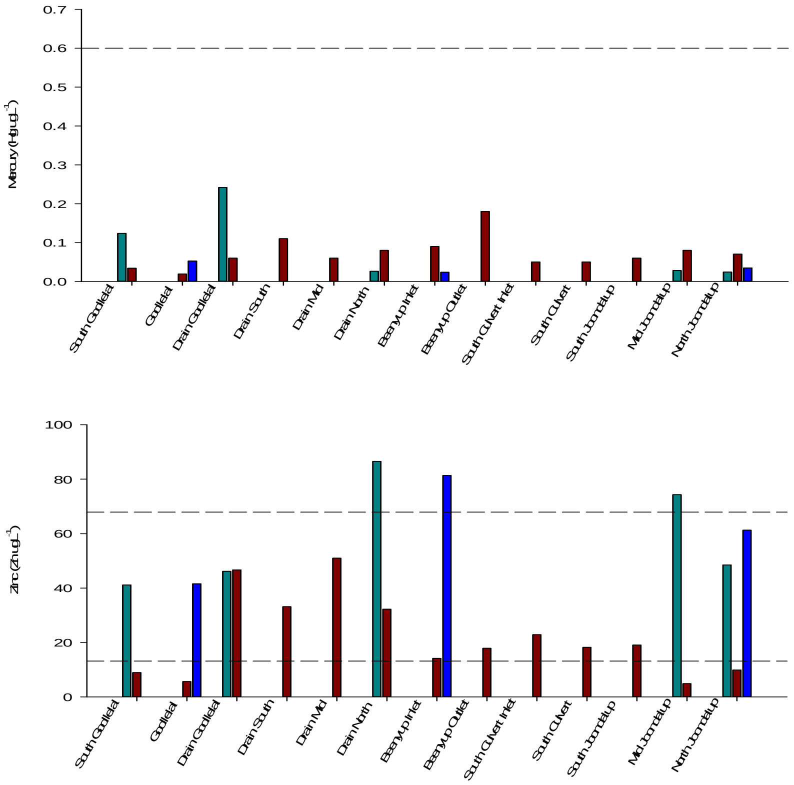


Figure 6. Mean (July 2013 to June 2014) metal/metalloids concentrations for groundwater and surface water. Dotted lines indicate the ANZECC & ARMCANZ (2000) trigger value ranges for the protection of aquatic ecosystems (95%).

7.3 NUTRIENTS

The highest dissolved organic carbon (DOC) concentrations were found in water leaving Lake Joondalup at JoonNW and Lake Goollelal at GoolMidW (Figure 7). The DOC in the western bores was lowest in November to February. This pattern is almost identical to that seen for EC (Figure 2), and therefore probably an evapo-concentration effect.

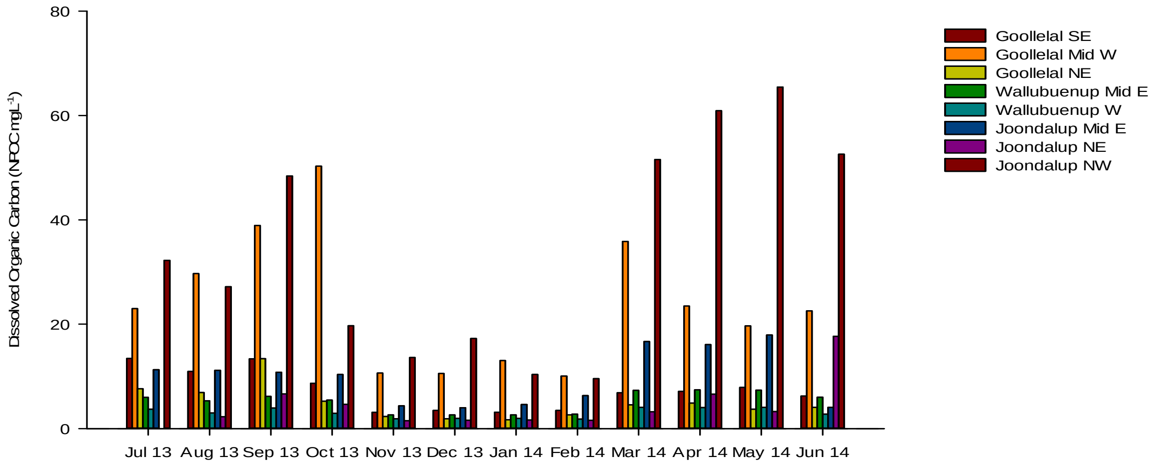
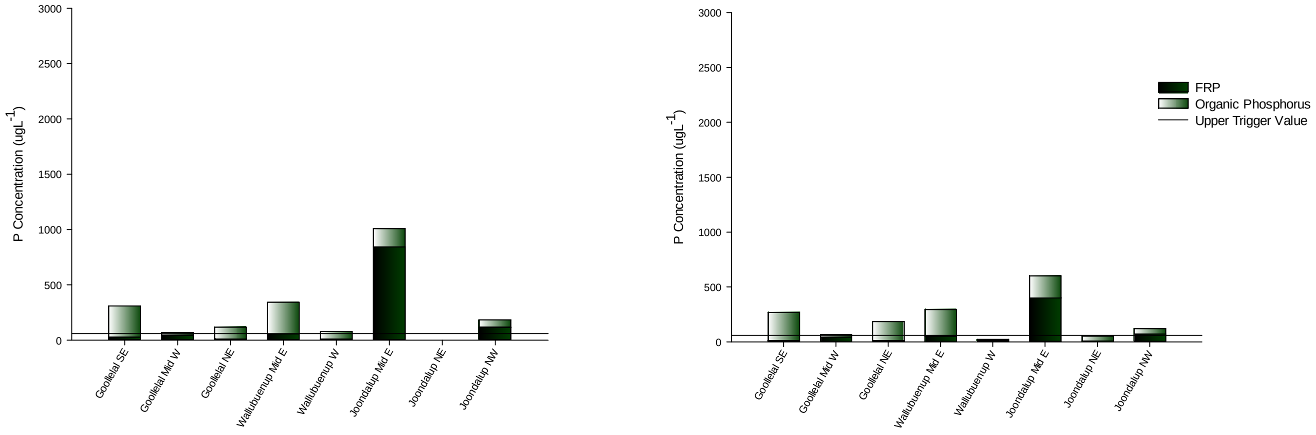


Figure 7. Dissolved organic C concentrations recorded in groundwater bores from July 2013 to June 2014.

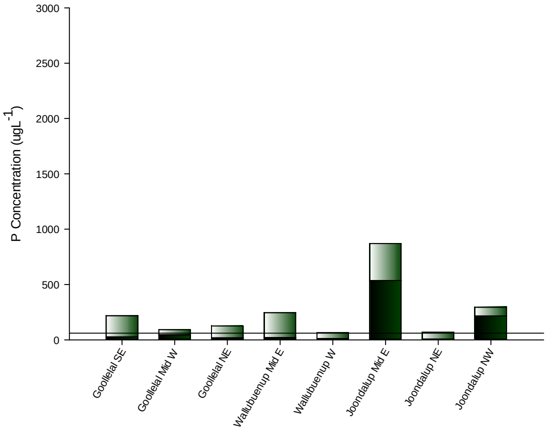
JoonMidE had the highest concentrations of filterable reactive P (FRP) over 2013/14, similar to 2012/13 with an average of 389 ± 69 µg L^{-1} (Figure 8 & Table 6). JoonNW also had high FRP concentrations of 126 ± 16 µg L^{-1} supporting Cumbers (2004) finding of significant export of P in outgoing groundwater. All other bores had relatively low FRP concentrations explaining the generally low surface water concentrations of P seen in both lakes. Total P the sum of FRP and organic P (most likely inorganic forms) and represents all the P present in the water. In bores around Lake Goollelal organic P was substantially higher than FRP, whereas in the north around Lake Joondalup this is not always the case. In the northern bores, on occasion, very high total P values were measured up to 2920 µg L^{-1} (WallW in February 2014).



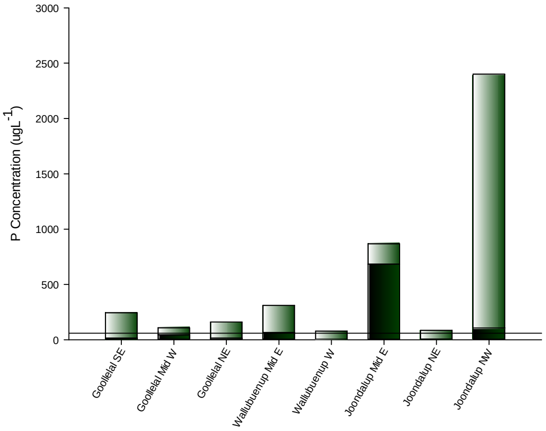
July 2013

August 2013

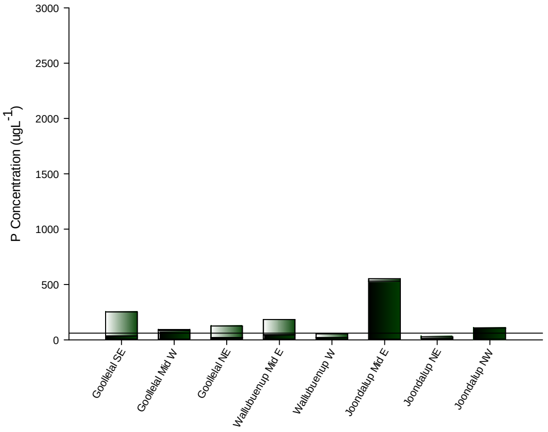
September 2013



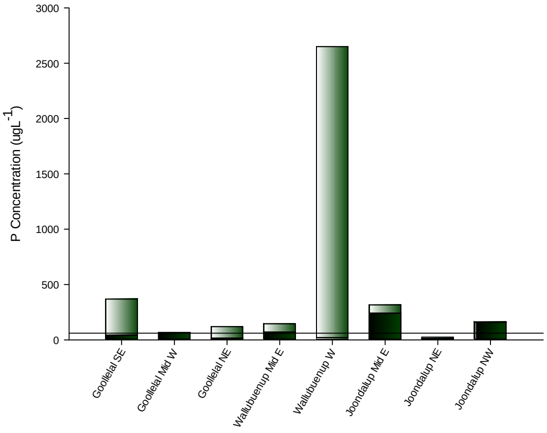
October 2013



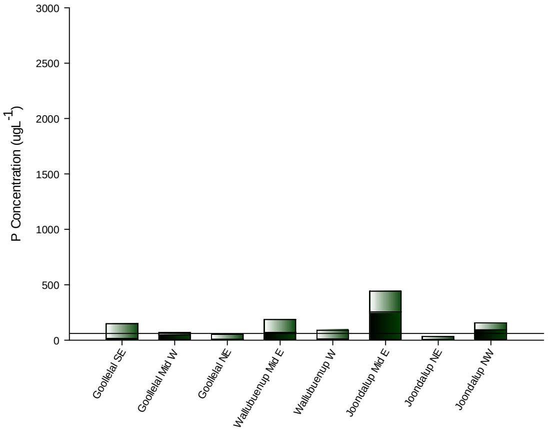
November 2013



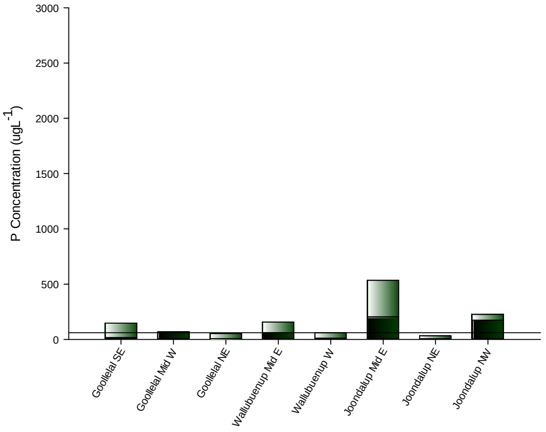
December 2013



January 2014



February 2014



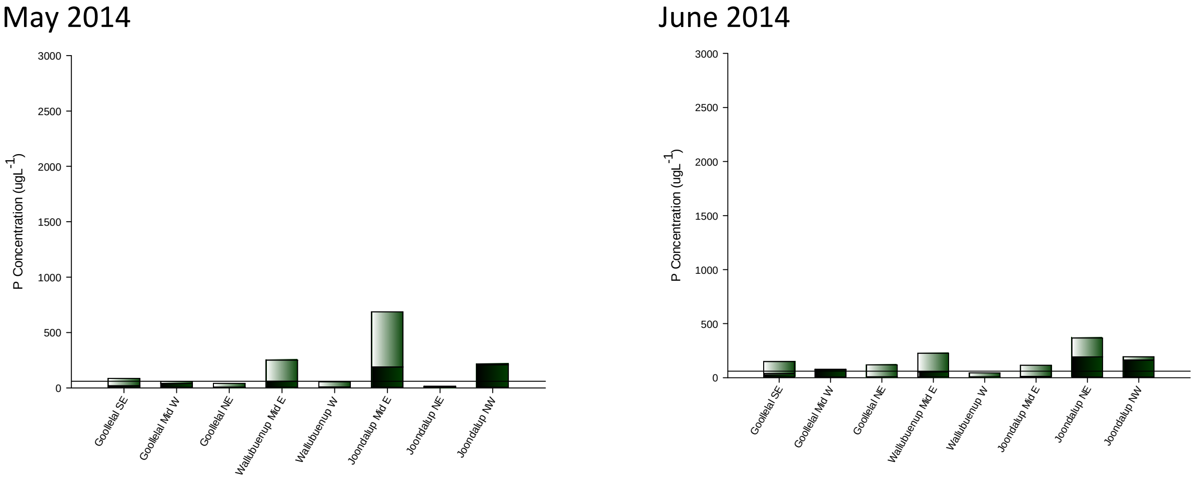
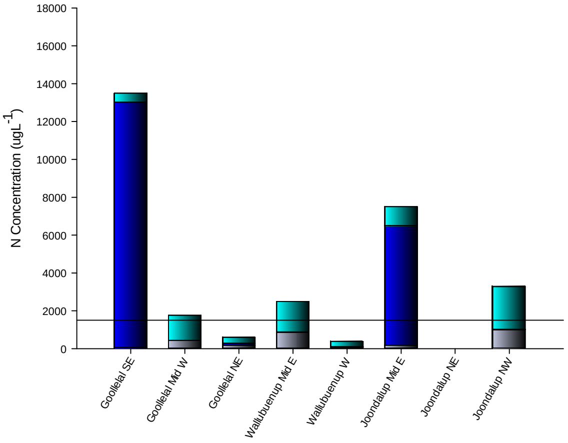


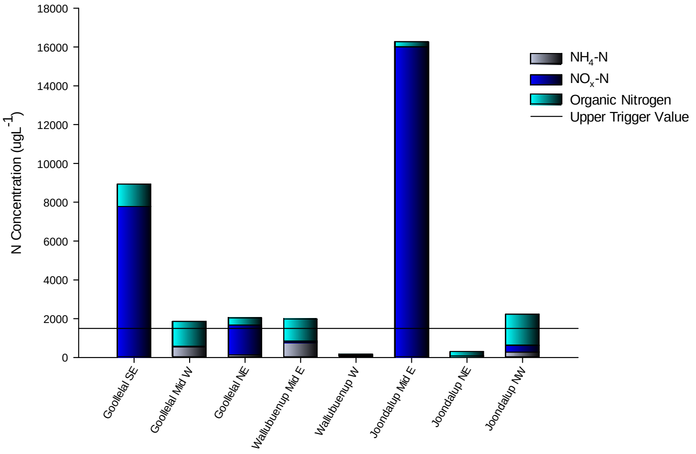
Figure 8. Breakdown of total phosphorus into chemical fractions (organic P and FRP) recorded in groundwater at each bore between July 2013 and June 2014 with the ANZECC & ARMANZ (2000) trigger value for total phosphorus shown.

Nitrogen concentrations in the groundwater were mainly dominated by organic N (the analysis used does not discriminate between organic and inorganic forms), most probably N associated with colloidal particles (Figure 9 & Table 6). This domination lasted the entire year, as opposed to 2012/13 where it only occurred for part of the year (August 2012 to February 2013). Unlike in the previous year nitrate/nitrite (NOx) concentrations were very high and often the dominant form of N present. JoonMidE had consistently very high NOx concentrations; these may be from the former landfill areas on the eastern side or as a result of fertiliser use on lawns. In 2012/13, after March 2013, NOx concentrations dropped substantially and there is an increase in ammonia/ammonium (NH_4). This coincides with the drop below 0 mV in ORP in the majority of bores. This year it appears that this occurred from September. The drop in NOx suggest that at low ORP, NOx is being reduced and lost from the system through denitrification (conversion back to N gas). Ammonia is accumulating in the low ORP environment as it cannot be nitrified to NOx. The mechanisms creating these low ORP conditions are interesting in that they present an opportunity to reduce N contamination of the lake. Generally very little NOx is exported from the lakes, presumably being used by plants in the lakes. However when water levels are very low in the lakes we see significant export of ammonia into the groundwater. Ammonia is probably being produced in the lakes in the shallow water as organic matter is broken down (ammonification).

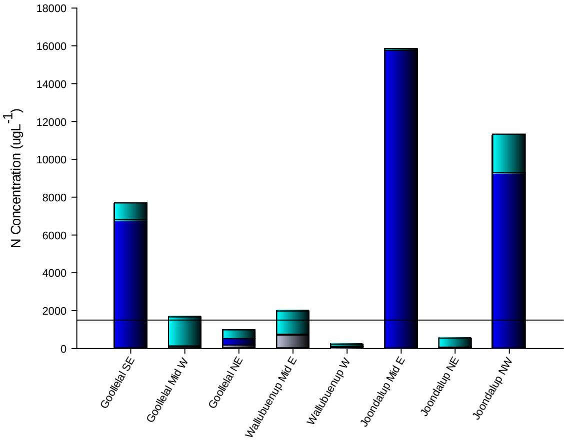
July 2013



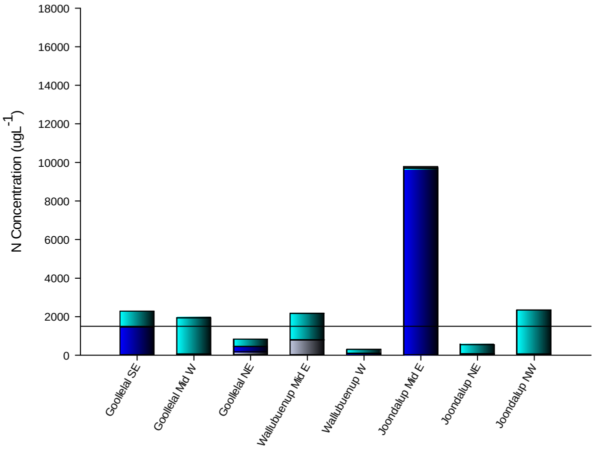
August 2013



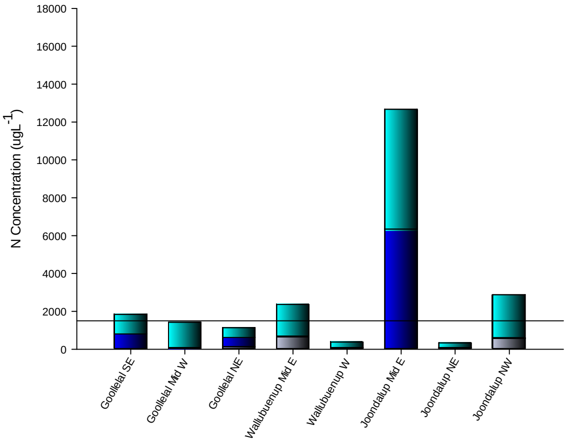
September 2013



October 2013



November 2013



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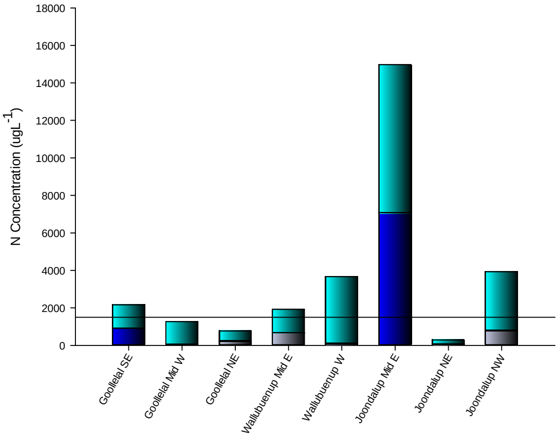
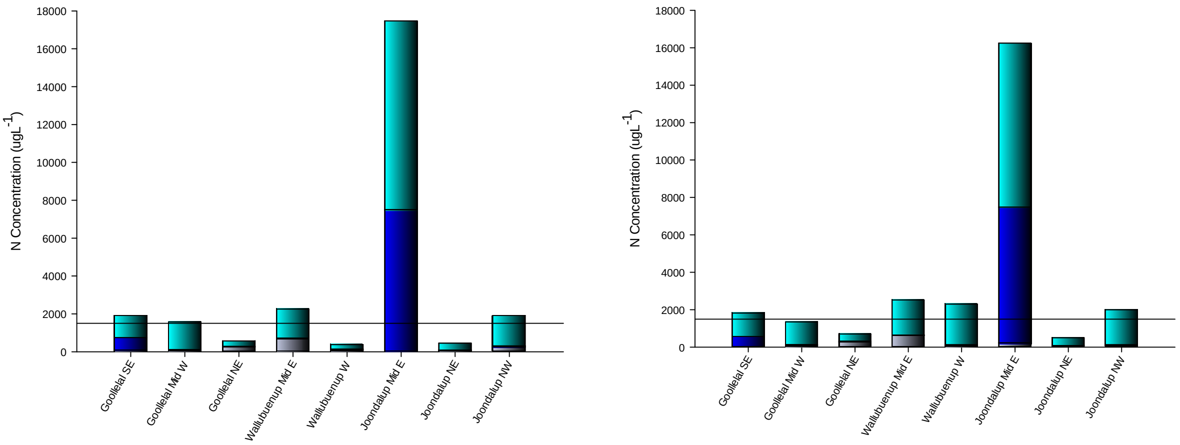


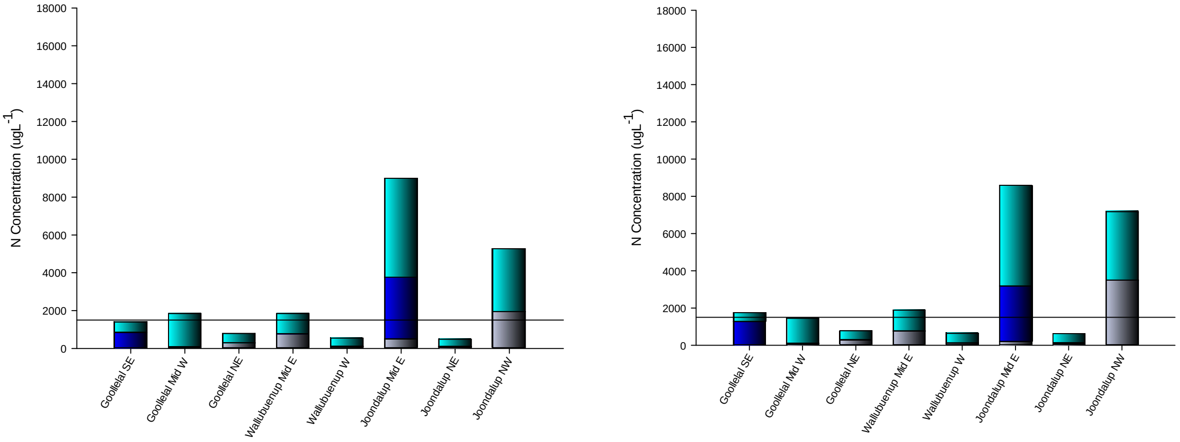
January 2014

February 2014



March 2014

April 2014



May 2014

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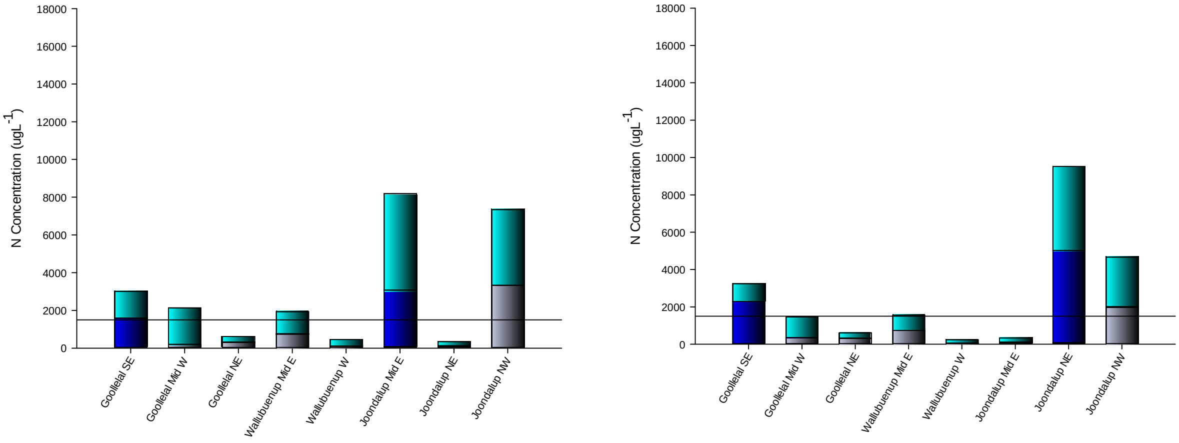

Figure 9. Breakdown of total nitrogen into chemical fractions (organic nitrogen, nitrate/nitrite (NO_X) and ammonium (NH_4)) recorded in groundwater at each bore between July 2013 and June 2014 with the ANZECC & ARMANZ (2000) trigger value for total nitrogen.

Table 6 Mean ± s.e. (range) for nutrients in water recorded at each bore over the course of the monitoring period (July 2013-June 2014), concentrations recorded as < were below the detection limit.

	NH_4	**NO_x**	**TN**	**FRP**	**TP**	**DOC**
	µg L^{-1}	**µg L^{-1}**	**µg L^{-1}**	**µg L^{-1}**	**µg L^{-1}**	**mg L^{-1}**
Detection Limit	**<3**	**<0.05**	**<0.5**	**<0.5**	**<0.5**	**<2**
ANZECC & ARMCANZ (2000) Trigger Value	**40 ugL^{-1}**	**100 ugL^{-1}**	**1500 ugL^{-1}**	**30 ugL^{-1}**	**60 ugL^{-1}**	**-**
Goollelal SE	14 ± 8 (1.5-79)	3232 ± 1241 (554-12984)	5008 ± 1582 (1810-13500)	21 ± 3 (8-42)	228 ± 24 (84-366)	7.4 ± 1.2 (3.1-13.4)
Goollelal Mid W	139 ± 53 (5-529)	202 ± 5 (5-55)	1594 ± 87 (1250-1930)	63 ± 4 (39-81)	122 ± 5 (56-107)	24 ± 3.7 (10.1-50.3)
Goollelal NE	208 ± 18 (123-291)	266 ± 135 (22-1530)	944 ± 169 (561-2030)	11 ± 2 (5-18)	95 ± 16 (23-183)	5 ± 1 (1.7-13.4)
Wallubuenup Mid E	717 ± 22 (612-851)	29 ± 6 (6-72)	2199 ± 83 (1910-2510)	57 ± 5 (18-79)	223 ± 20 (144-340)	5.1 ± 0.6 (2.6-7.4)
Wallubuenup W	82 ± 2 (71-94)	19 ± 4 (1-48)	963 ± 458 (159-3660)	11 ± 2 (3-19)	554 ± 333 (21-2920)	3 ± 0.3 (1.8-4.1)
Joondalup Mid E	109 ± 46 (2-490)	7737 ± 1370 (2980-16007)	13847 ± 1256 (7500-17475)	389 ± 69 (167-841)	592 ± 73 (264-1007)	9.8 ± 1.5 (4-17.9)
Joondalup NE	38 ± 9 (13-85)	44 ± 4 (15-58)	414 ± 43 (275-539)	7 ± 1 (3-11)	41 ± 7 (14-84)	4.6 ± 1.5 (1.5-17.7)
Joondalup NW	1062 ± 388 (13-3490)	893 ± 837 (1-9260)	3729 ± 1112 (1900-11325)	126 ± 16 (71-215)	372 ± 204 (84-2400)	34.1 ± 5.95 (9.6-65.4)

8 CONCLUSIONS

Eight bores (3 western, 5 eastern) were sampled for a broad range of physico-chemical parameters, nutrient and metal/metalloid concentrations between July 2013 and June 2014. As water levels fall in the lakes over summer, there is evapo-concentration of conductivity and related solutes. The high conductivity and solutes concentrations are reflected very rapidly in similar increases in all the western bores.. In September 2013 onwards, low ORP and dissolved oxygen appeared to encourage denitrification in the eastern bores, which would ultimately reduce N entering the lakes. There was evidence that certain bores such as JoonMidE tended to be highly contaminated with metals/metalloids (particularly Cd, Co and Ni) and nutrients (particularly P and NOx). High contaminant concentrations in the groundwater are limited to very localised areas of the groundwater catchment such as around JoonMidE. This suggests that local sources of contamination within the vicinity (or upstream of the bore) are responsible. The source of the contamination around JoondMidE is not known. All the Lake Goollelal bores show evidence of ASS contamination although do not show low pH. Neutralisation of the acidity within the catchment, due to naturally occurring limestone (calcium carbonate) keeps the pH at near neutral and reduces some metal contamination (as many metals are less soluble at neutral pH). However, some metal contamination remains. If neutralisation capacity in the catchment becomes exhausted then low pH and higher levels of contaminants would be likely. The likelihood of exhaustion of neutralising capacity is unknown as is the location of the ASS within the catchment. Groundwater contributes approximately 25% of the water found Lake Joondalup (unknown for Lake Goollelal). All contaminants measured in the groundwater in the eastern bores will end up in the lakes.

9 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 (monthly) continue until each bore has been monitored monthly for at least 3 years, after which we will have a good understanding of interannual and seasonal variability. After the three years, quarterly or every two months will be sufficient frequency.

2. The bore at JoonMidE was the most contaminated with nutrients and to a lesser extent metals. This bore is located away from the lake's edge and so it is unclear how much of this contamination reaches the lake. It is recommended that this source of likely contamination into northern Lake Joondalup be investigated further to determine the extent of the contaminated plume and to determine how significant as a contamination source it is.

10 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. 1,220pp.

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.

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

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

Congdon, R. A. & McComb, A. J. (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 thesis, Edith Cowan University, Perth.

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

Department of 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.

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

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

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

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

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

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

Lund, M. A. (2007). Midge Desktop Audit 2007. Report 2007-08. Centre for Ecosystem Management, Perth.

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

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

Newport, M.; Lund, M. & McCullough, C. D. (2011a). Yellagonga Regional Park wetlands water quality monitoring 2011 report. Unpublished 2011-08 Report to the City of Joondalup. Edith Cowan University, Perth. 51pp.

Newport, M.; Lund, M.; McCullough, C. D. & Patel, S. (2011b). Acid Sulphate Soil Investigation of Southern Yellagonga Regional Park. Unpublished 2011-12 Report to the City of Joondalup. Edith Cowan University, Perth. 21pp.

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

Newport, M. & Lund, M. A. (2012b). Yellagonga Regional Park wetlands water quality monitoring 2012 report. Mine Water and Environment Research Centre/Centre for Ecosystem Management Report 2012-10. Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia. 47pp.

Newport, M. & Lund, M. A. (2013a). Acid Sulphate Soil Investigation of Southern Yellagonga Regional Park Report: Stage 2. Report 2013-9. Mine Water and Environment Research Centre/Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia. 28pp.

Newport, M. & Lund, M. A. (2013b). Yellagonga Regional Park wetlands water quality monitoring 2013 report. Mine Water and Environment Research Centre/Centre for Ecosystem Management Report 2013-11. Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia. 51pp.

Wilson, B. A. & Valentine, L. E. E. (2009). Biodiversity values and threatening processes of the Gnangara Groundwater System. Department of Environment and Conservation, Perth, Western Australia. 626pp.