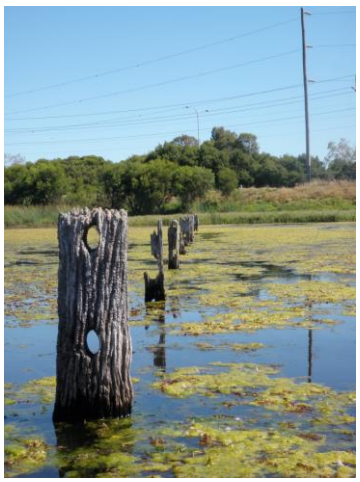

Monitoring of Yellagonga Regional Park Groundwater Quality

2013 Report

By, Michelle Newport and Mark Lund

Prepared for,

Cities of Joondalup and Wanneroo

Mine Water and Environment Research Centre

Centre for Ecosystem Management

Report No. 2013-10

1 MINE WATER AND ENVIRONMENT RESEARCH CENTRE

Founded at Edith Cowan University in 2008, the Mine Water and Environment Research (MiWER) Centre was formed by Dr. Clint McCullough and Assoc. Prof. Mark Lund. The research group has a focus on mine waters; particularly pit lakes formed from open-cut mining. However, the group's research also covers all inland water bodies for rehabilitation, remediation and ecological assessment.

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

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2 ACKNOWLEDGEMENTS

The support of Lara O'Neill at the City of Joondalup and Tristan Bruyn at the City of Wanneroo has been greatly appreciated. Thanks to the Cities of Joondalup and Wanneroo for funding this work. Thanks to Edith Cowan University for the provision of in-kind and infrastructure support for the project. Thanks also to the volunteers and Research Assistants that have helped with various aspects of the project.

2.1.1.1 FRONTISPIECE

Plate 1. Neil Hawkins Park, Mid Lake Joondalup 23rd August 2012

This report should be referenced as follows.

Newport, M., and Lund, M. A., (2013). *Monitoring of Yellagonga Regional Park Groundwater Quality.* Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2013-10, Edith Cowan University, Perth, Australia. 39 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 Unpublished report to the Cities of Joondalup and Wanneroo, Western Australia.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.
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 (new) 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 August 2012 and reported here to June 2013.
3. Although the western side of the park is poorly covered, there was an obvious trend for conductivity and related parameters to increase in late summer, leading to evapo-concentration of solutes in the lakes.
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, but in metal concentrations such as Al, As, Cd, Cr, Hg, Ni, Se, U 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. It appeared that groundwater was a source of Al, As and Hg identified in the wetlands.
5. High concentrations of P and N were recorded in a number of the eastern bores, suggesting groundwater is an important source of nutrients into the wetland system. From February 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. Key recommendations from the study are to continue monitoring for one more year at monthly intervals to allow clarification of seasonal effects and to promote a better understanding of processes. Three additional bores are recommended to improve the spatial resolution of groundwater entering the lakes.

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 of paramount importance 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 a north-westerly direction through the park (Newport, Lund, & McCullough, 2011).

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, 1985, 1986; R. A. Congdon & A. J. McComb, 1976; R. Congdon & A. McComb, 1976; Cumbers, 2004; Davis et al., 1993; Gordon, Finlayson, & McComb, 1981; Khwanboonbumpen, 2006; Kinnear & Garnett, 1999; Kinnear, Garnett, Bekle, & Upton, 1997; M.A Lund, 2003, 2007; M.A Lund, Brown, & Lee, 2000). More recently, a water quality monitoring program has produced results that support previous findings of nutrient enrichment and metal contamination, which exceed ANZECC and ARMCANZ (2000) national water quality guidelines consistently (M.A. Lund, McCullough, Somesan, Edwards, & Reynolds, 2011; Newport, Lund, & McCullough, 2011; Newport & Lund, 2012b). A preliminary investigation in the southern section of Wallubuenup Swamp identified the presence of ASS (Newport, Lund, McCullough, & Patel, 2011).

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 Joonalup 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 August 2012 – June 2013.

6 METHODS

6.1 STUDY SITE

Ground-truthing of groundwater bores identified a total of eight bores suitable for monitoring; this included the two bores established in 2012 by the City of Joondalup. 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

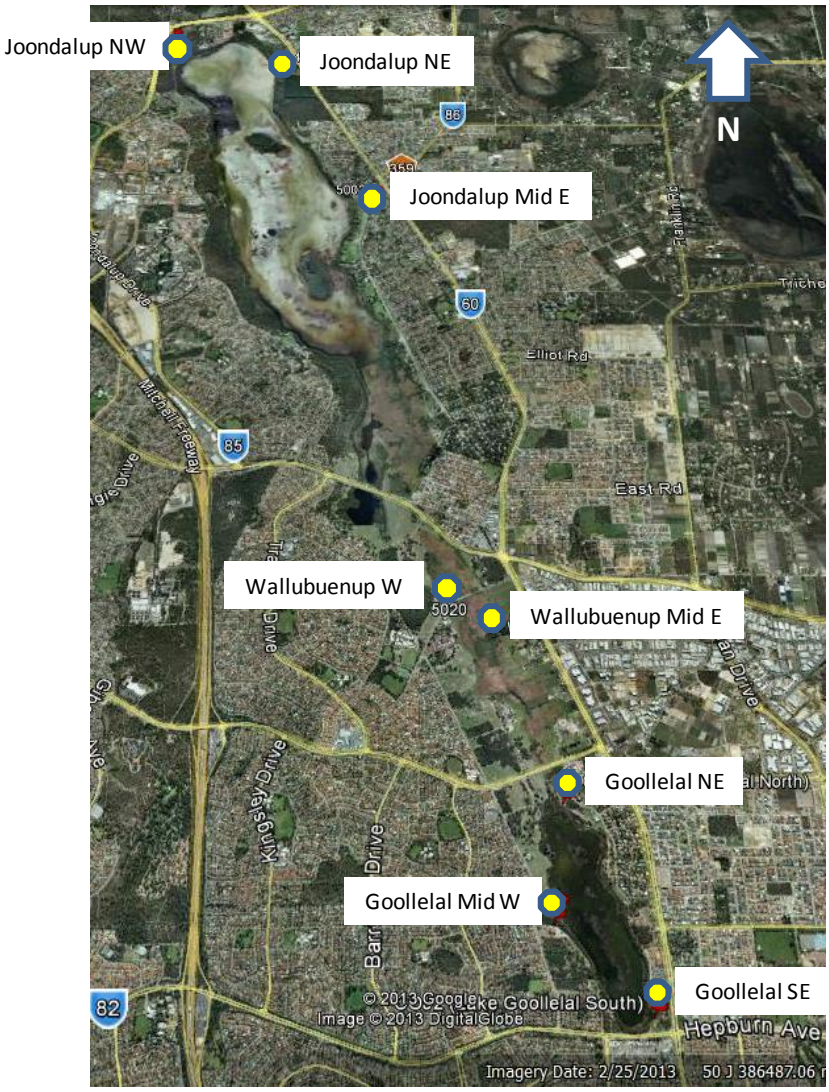


Figure 1. Location of the eight groundwater bores used for monthly monitoring in Yellagonga Regional Park (adapted from Google Earth 2013).

6.2 SAMPLING

The analysis conducted for groundwater monitoring mirrored that of surface water monitoring 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 14th August 2012 and 13th June 2013. 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(1% v/v) and then kept at 4°C for later determination by ICP-AES of a range of metals (Al, As, Ca, Cd, Co, Cr, Fe, Hg, K, Mg, Mn, Na, Ni, Se, U & Zn). All analyses were performed at the Natural Sciences Analytical Laboratory (Edith Cowan University) as per APHA (1998).

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.

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

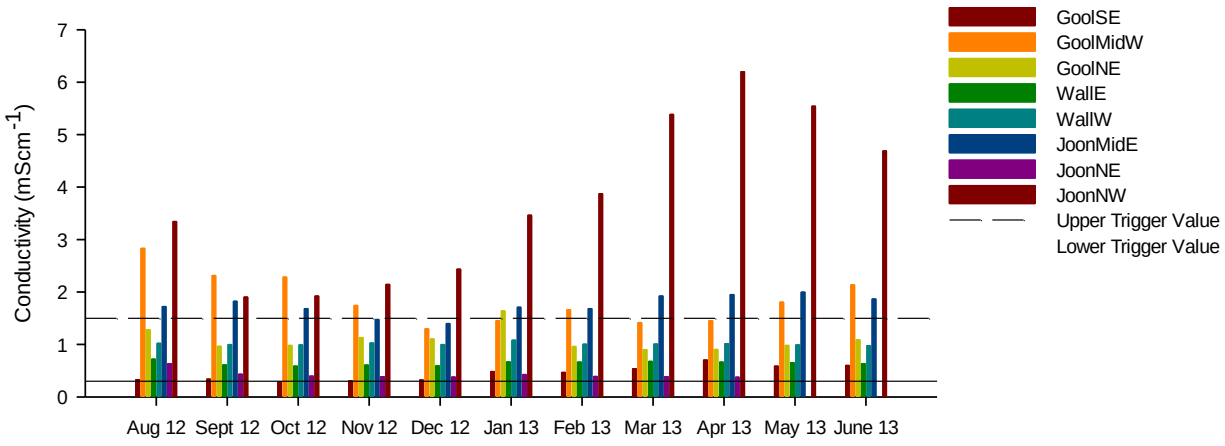
7 RESULTS AND DISCUSSION

The groundwater bore located on the north eastern side of Lake Joondalup, identified as Joondalup NE, was inaccessible for May and June 2013 sampling events due to the Department of Water (DoW) changing the padlock. An access request was lodged and has since been granted by DoW.

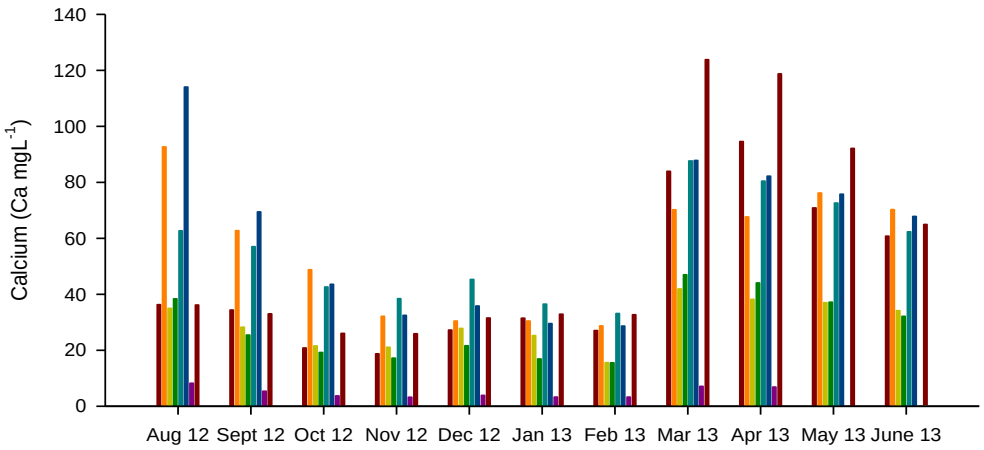
7.1 PHYSICO-CHEMISTRY

The EC followed a trend of typically higher values in autumn and lower values in spring, which reflected the height of groundwater table on the Swan Coastal Plain (Figure 2). The highest values were recorded in JoonNW and GoolMidW, as these were sites of outflow concentrations may reflect evapo-concentration of salts in the lake being transferred into exiting groundwater. Incoming groundwater EC concentrations were also elevated in GoolNE and JoonMidE possibly reflecting localised sources of salts. Similar trends were seen in all major ions (K, Ca, Mg, Na and Cl) which contribute to EC. Table 1 illustrates the mean and ranges for each of the common ions.

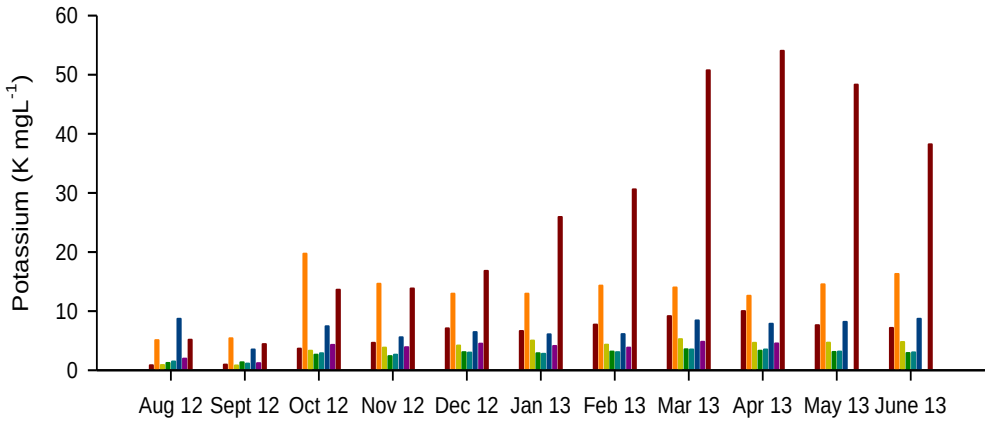
a) Electrical conductivity



b) Calcium (Ca)



c) Potassium (K)



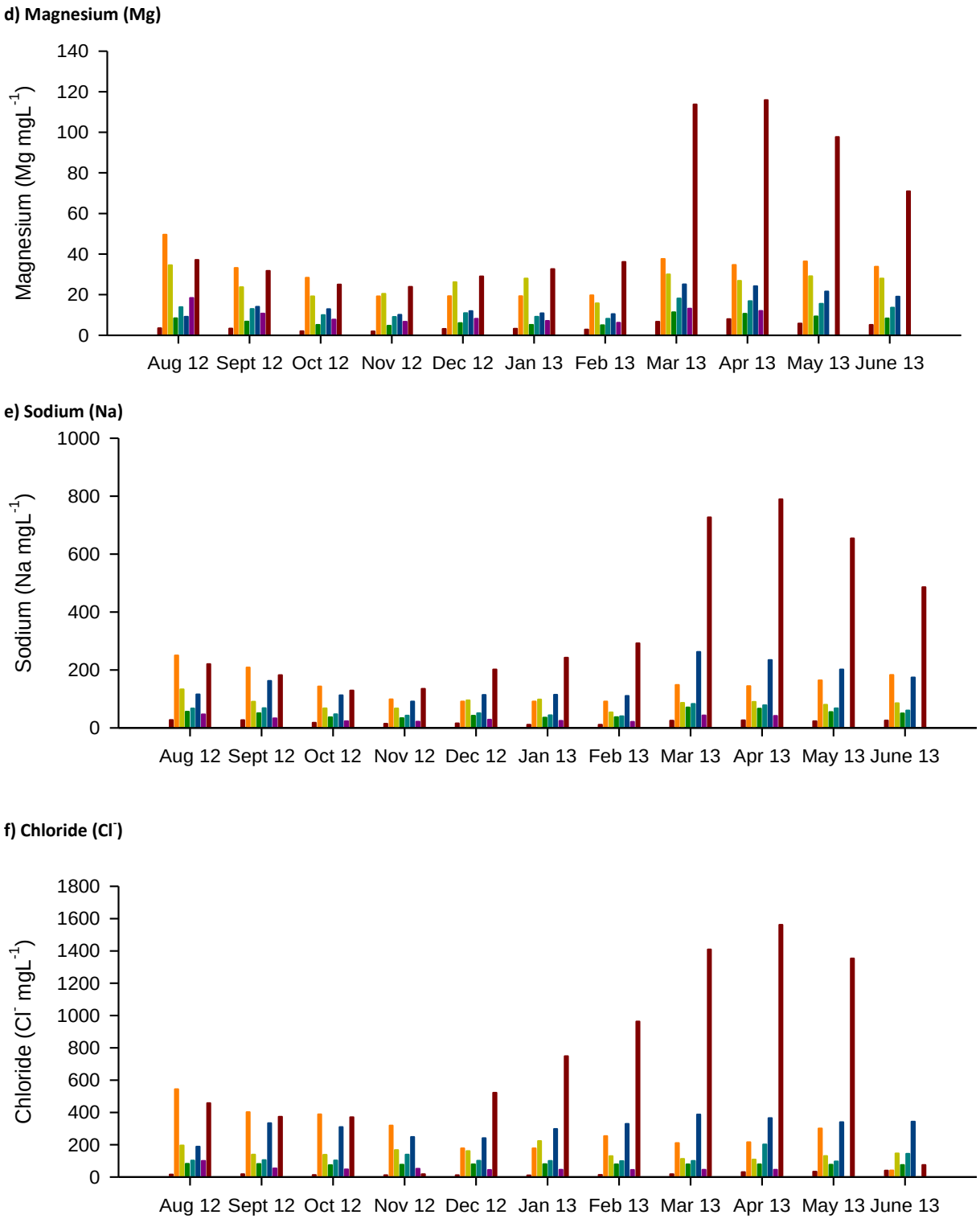


Figure 2. Changes in a) electrical conductivity, b) calcium, c) potassium, d) magnesium, e) sodium and f) chloride over the period of monitoring at each site (August 2012 – June 2013).

Table 1 Mean ± standard error (range) for selected solutes during the monitoring period August 2012 to 2013

Site	Ca	K	Mg	Na	Cl	SO_4
	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}
Detection Limit	**<0.05**	**<0.5**	**<0.1**	**<0.5**	**<0.5**	**<0.5**
GoolSE	45.9 ± 8.68 (18.7-94.6)	5.93 ± 1.02 (0.81-9.98)	4.14 ± 0.67 (1.96-8.01)	20.3 ± 2.57 (10.8-27.3)	19.2 ± 3.38 (10.2-39.9)	18.7 ± 2.93 (11.5-35.3)
GoolMidW	55.4 ± 6.75 (28.7-92.6)	12.9 ± 1.29 (5.08-19.7)	30.08 ± 2.99 (19.2-49.5)	146 ± 15.9 (90.9-250)	275± 41.1 (40.1-543)	185 ± 40.9 (35.6-447)
GoolNE	29.8 ± 2.50 (15.6- 41.9)	3.73 ± 0.47 (0.78-5.23)	25.5 ± 1.63 (15.8-34.5)	85.1 ± 6.22 (53.5-133)	148 ± 10.5 (107-222)	207 ± 11.9 (160-302)
WallE	28.6 ± 3.49 (15.5-38.4)	2.67 ± 0.23 (1.23-3.14)	7.33 ± 0.72 (4.74-8.40)	48.4 ± 3.81 (33.7-55.6)	77.8 ± 0.75 (73.7-81.9)	33.1 ± 2.48 (24.3-38.1)
WallW	56.2 ± 5.61 (33.1-87.6)	2.72 ± 0.23 (1.11-3.51)	12.6 ± 1.02 (8.17-18.1)	58.8 ± 4.49 (39.9-82.7)	99 ± 10.7 (3.8-144)	207.84 ± 4.73 (168-224)
JoonMidE	60.6 ± 8.58 (28.6-114)	6.98 ± 0.49 (3.48-8.68)	15.4 ± 1.80 (9.15-25.1)	154 ± 17.3 (91.04-262)	307 ± 17.9 (188-386)	77.8 ± 4.10 (52.6-99.3)
JoonNE	4.97 ± 0.65 (3.17-8.22)	3.67 ± 0.41 (1.19-4.81)	9.99 ± 1.33 (6.20-18.3)	31.2 ± 3.33 (20.6-46.2)	52.25 ± 5.95 (43.3-99.0)	59.8 ± 2.28 (53.3-74.5)
JoonNW	56.1 ± 11.4 (26.0-124)	27.40 ± 5.50 (4.41-54.0)	55.8 ± 11.1 (25.0-116)	369 ± 75.0 (129-789)	713.3 ± 162 (370-1560)	183 ± 34.8 (162.9-371)

Calculated hardness of water samples from the bores are shown in Figure 3. The western bores tended to have harder water than the eastern side reflecting evapo-concentration in the lake water. Both JoonMidE and GoolNE had higher hardness than the other eastern bores for each of their respective lakes. The source of this additional hardness is not known at this time.

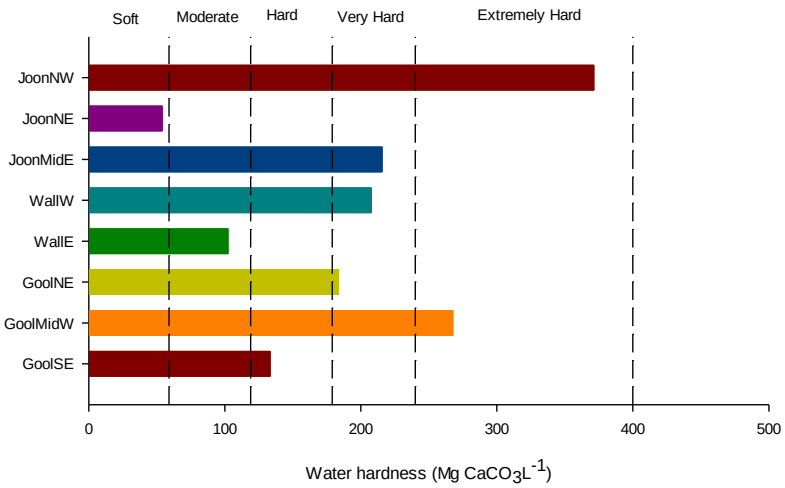
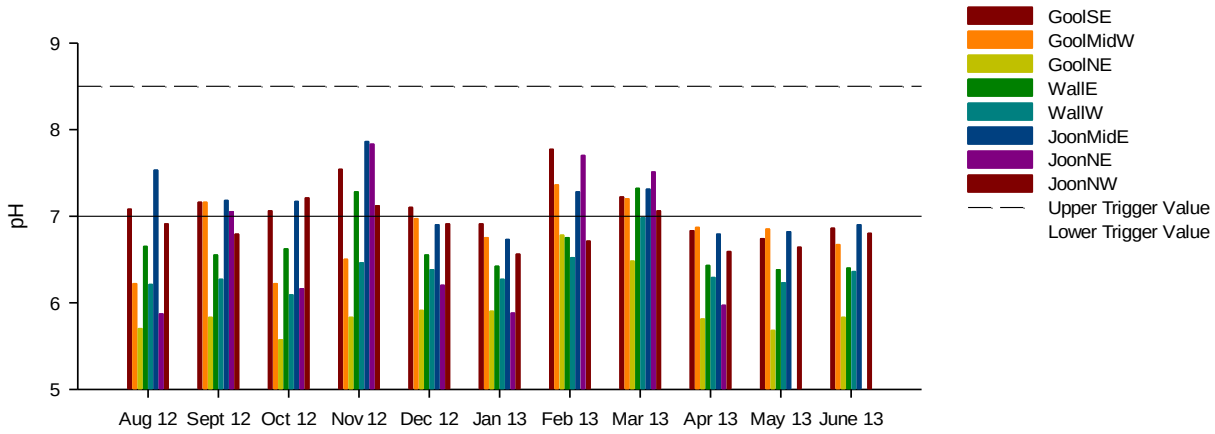


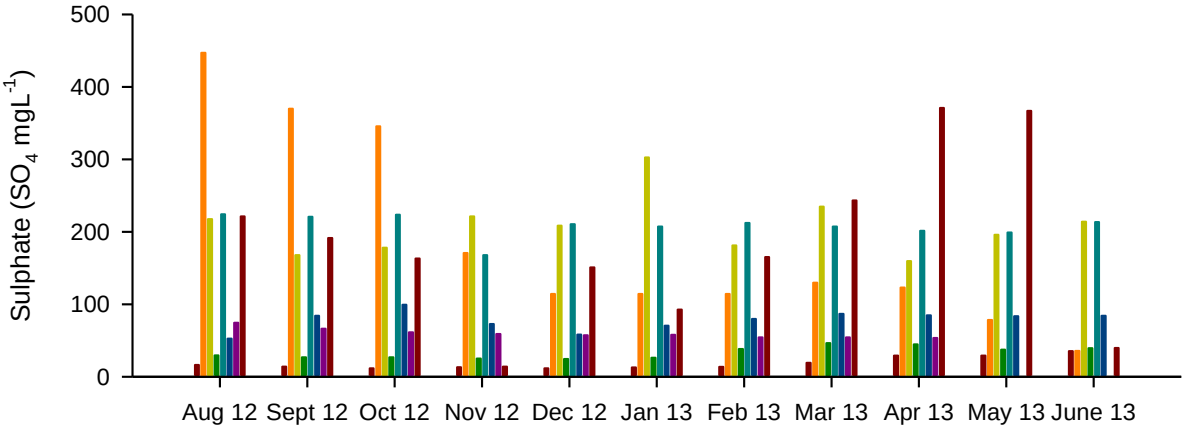
Figure 3. Calculated mean water hardness for the period of monitoring at each bore (August 2012 – June 2013) with ANZECC & ARMCANZ (2000) categories indicated.

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) and was highest in February and March. Overall pH was relatively constant across the year. Sulphate concentrations were generally highest in the western sites. Molar ratios indicated the presence of ASS contamination at all sites except WallE, JoonMidE and JoonNW. The water hardness at most sites would tend to reduce the impact of any ASS contamination.

a) pH



b) Sulphate (SO_4)



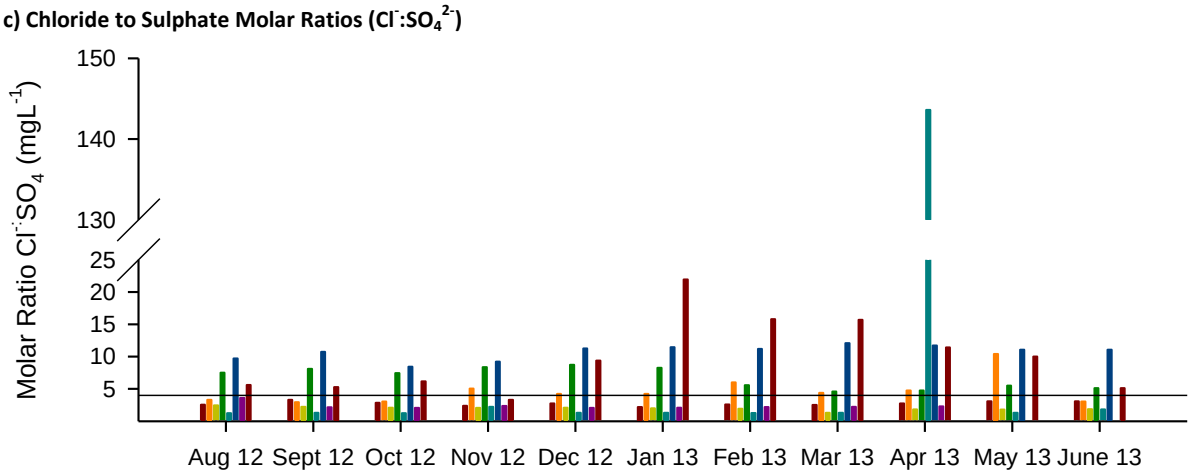
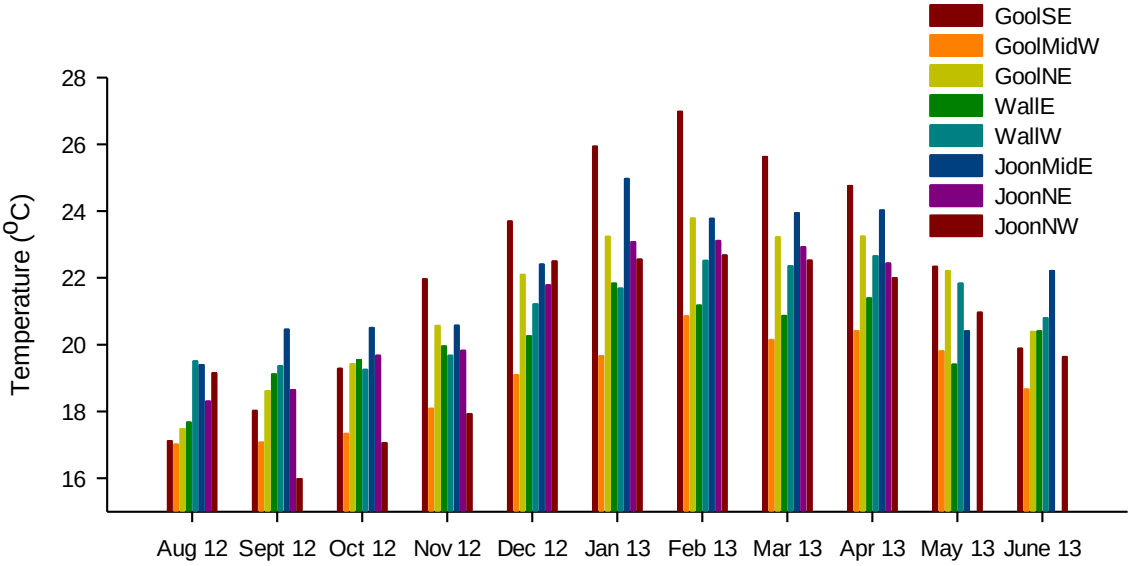


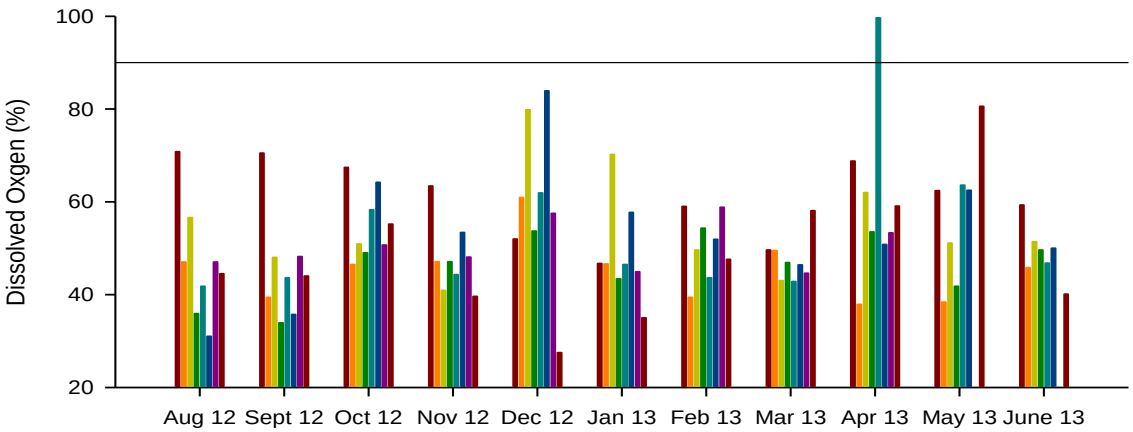
Figure 4. Changes in a) pH, b) sulphate and c) chloride to sulphate molar ratios over the period of monitoring at each bore (August 2012 – June 2013) with ANZECC & ARMCANZ (2000) trigger values for the protection of aquatic ecosystems (95%).

Water temperatures varied by 10 ^{o}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. Despite ORP >0 mV between February and June and for sites GoolMidW and JoonNW ORP was typically <0 mV. This indicated chemical processes rather than oxygen as the driver for ORP changes. Water levels in the bores illustrated little seasonal variation (<0.5 m), except in JoonNE and JoonNW. In JoonNW water levels rose by nearly 2 m between August and September before slowly declining by 1 m to June 2013. JoonNE dropped by about 1 m between November and December before recovering back to November levels. These short term variations are difficult to explain and may be an artefact of the depth measuring technique used.

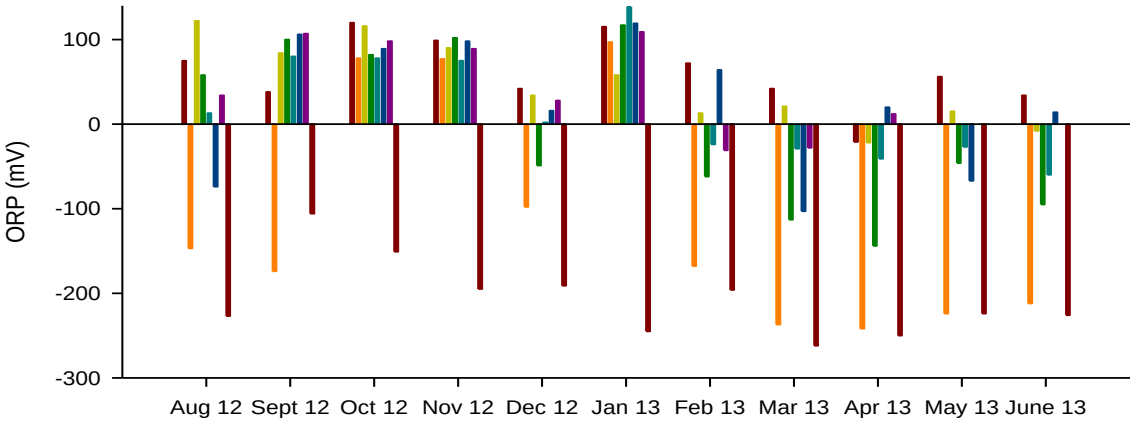
a) Temperature



b) Dissolved Oxygen



c) ORP



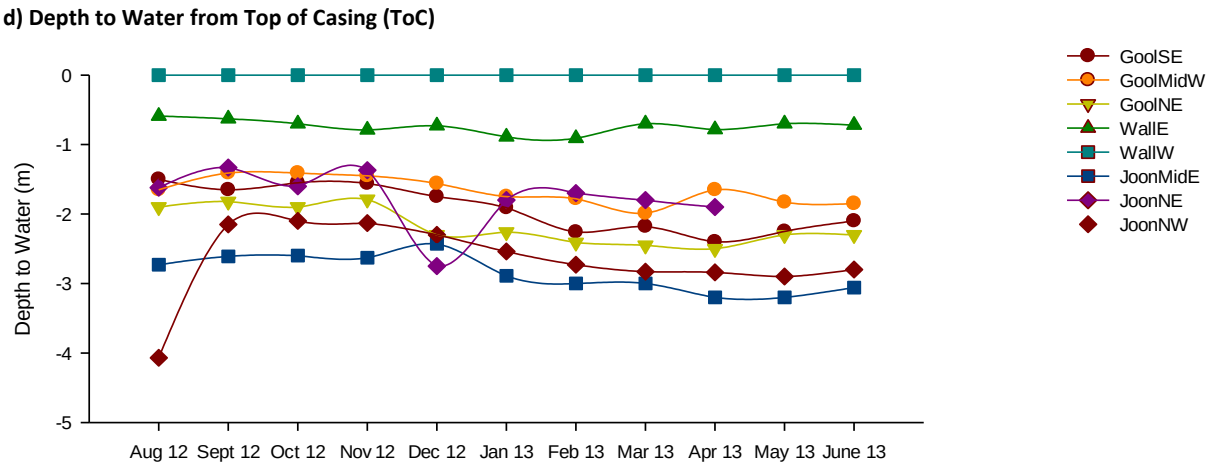


Figure 5. Variation throughout groundwater monitoring period for a) temperature, b) dissolved oxygen, c) ORP and d) depth to water between August 2012 and June 2013 at each bore.

Table 2 Mean ± standard error (range) for physicochemical variables over the monitoring period (August 2012- June 2013)

Site	Depth to Water (m)	Dissolved Oxygen		ORP	Electrical Conductivity	pH	Temperature
		%	mg L^{-1}	mV	mS cm^{-1}		°C
GoolSE		60.80 ± 6.41 (46.70-70.80)	5.30 ± 0.60 (3.77-6.85)	59.89 ± 14.06 (-21-120)	0.45 ± 0.06 (0.28-0.7)	7.10 ± 0.69 (6.74-7.77)	22.63 ± 2.39 (17.11- 26.97)
GoolMidW		45.27 ± 2.22 (37.9-60.9)	4.19 ± 0.21 (3.39-5.59)	-103.8 ± 43.24 (-242-97)	1.82 ± 0.16 (1.29-2.83)	6.81 ± 0.12 (6.22-7.36)	18.94 ± 0.46 (17.01- 20.85)
GoolNE		55.21 ± 3.87 (40.9-79.8)	4.86 ± 0.32 (3.67-6.9)	53.1 ± 15.33 (-22-122)	1.08 ± 0.07 (0.9-1.64)	5.95 ± 0.12 (5.57-6.78)	21.38 ± 0.70 (17.47- 23.78)
WallE		45.95 ± 2.28 (33.90-54.30)	4.15 ± 0.19 (3.13-4.82)	7.50 ± 29.39 (-114-117)	0.64 ± 0.01 (0.58-0.72)	6.70 ± 0.11 (6.38-7.32)	20.12 ± 0.40 (17.67- 21.83)
WallW		54.78 ± 6.51 (41.8-101.4)	4.81 ± 0.55 (3.70-8.69)	48.5 ± 38.49 (-29-331)	1.01 ± 0.01 (0.99-1.08)	6.37 ± 0.09 (6.09-6.98)	21.00 ± 0.50 (19.25- 22.65)
JoonMidE		53.75 ± 4.74 (31-83.9)	4.59 ± 0.41 (2.71-7.21)	26.8 ± 26.05 (-103-119)	1.73 ± 0.06 (1.39-1.99)	7.16 ± 0.11 (6.73-7.86)	22.04 ± 0.63 (19.39- 24.96)
JoonNE		50.34 ± 1.73 (44.6-58.8)	4.47 ± 0.14 (3.82-5.01)	46.44 ± 18.73 (-31-109)	0.42 ± 0.03 (0.37-0.63)	6.69 ± 0.28 (5.87- 7.83)	21.08 ± 0.66 (18.30- 23.11)
JoonNW		49.03 ± 4.74 (27.5-80.6)	4.41 ± 0.42 (2.35-7.10)	-201.1 ± 15.05 (-262--106)	3.50 ± 0.53 (1.90-6.20)	6.81 ± 0.08 (6.53- 7.21)	20.05 ± 0.90 (15.98- 22.67)

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, Cr, Hg, Ni, Se, U 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. Detection limits for some of the metals/metalloids measured were higher than guideline values meaning that it was not possible to be certain of the exact number of exceedances. 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 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 August 2012 and June 2013

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	<0.02	0.12 ± 0.017 (1.33)	82 (73)
Arsenic (As)	0.013 - 0.024*	<0.01	0.01 ± 0.0015 (0.09)	16 (13)
Calcium (Ca)	—	<0.05	43.06 ± 3.015 (123.8)	86
Cadmium (Cd)	0.0003 – 0.0019[H]	<0.002	0.004 ± 0.0005 (0.024)	34 (86)**
Cobalt (Co)	ID	<0.005	0.012 ± 0.0013 (0.039)	41
Chromium (Cr)	ID - 0.004*	<0.005	0.007 ± 0.0009 (0.034)	23 (86)**
Iron (Fe)	ID	<0.05	0.74 ± 0.12 (4.95)	57
Mercury (Hg)	0.0006 - ID*	<0.05	0.025 ± 0.00037 (0.057)	1 (86)**
Potassium (K)	—	<0.5	8.37 ± 1.12 (54.01)	86
Magnesium (Mg)	—	<0.1	20.35 ± 2.26 (115.90)	86
Manganese (Mn)	1.9	<0.01	0.01 ± 0.0009 (0.046)	31 (0)
Sodium (Na)	—	<0.5	116.17 ± 15.16 (789.2)	86
Nickel (Ni)	0.0181 – 0.0933[H]	<0.02	0.023 ± 0.0025 (0.118)	25 (86)**
Selenium (Se)	0.011	<0.04	0.041 ± 0.0046 (0.22)	22 (86)**
Uranium (U)	0.005+	<0.01	0.149 ± 0.01145 (0.51)	78 (86)**
Zinc (Zn)	0.0132 – 0.0679[H]	<0.05	0.048 ± 0.006 (0.227)	41 (86)**

[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)

Aluminium concentrations were highest on average in Lake Goollelal bores, declining northwards. Aluminium was also exported into westerly bores (Table 4). Arsenic tended to be higher in the western bores, with the exception of Lake Joondalup. Cadmium, Cr and Co concentrations show no particular trends spatially. Iron concentrations were highest in the northern sections of Lake Goollelal, then declined northwards, with a high concentration in the western Lake Joondalup bore. This pattern matched our previous findings of an iron gradient throughout the park from high in the south declining northwards.

Table 4 Mean ± standard error (range) for selected metals over the 11 month monitoring period (August 2012 – June 2013). Metal concentrations recorded as BDL were below the detection limit.

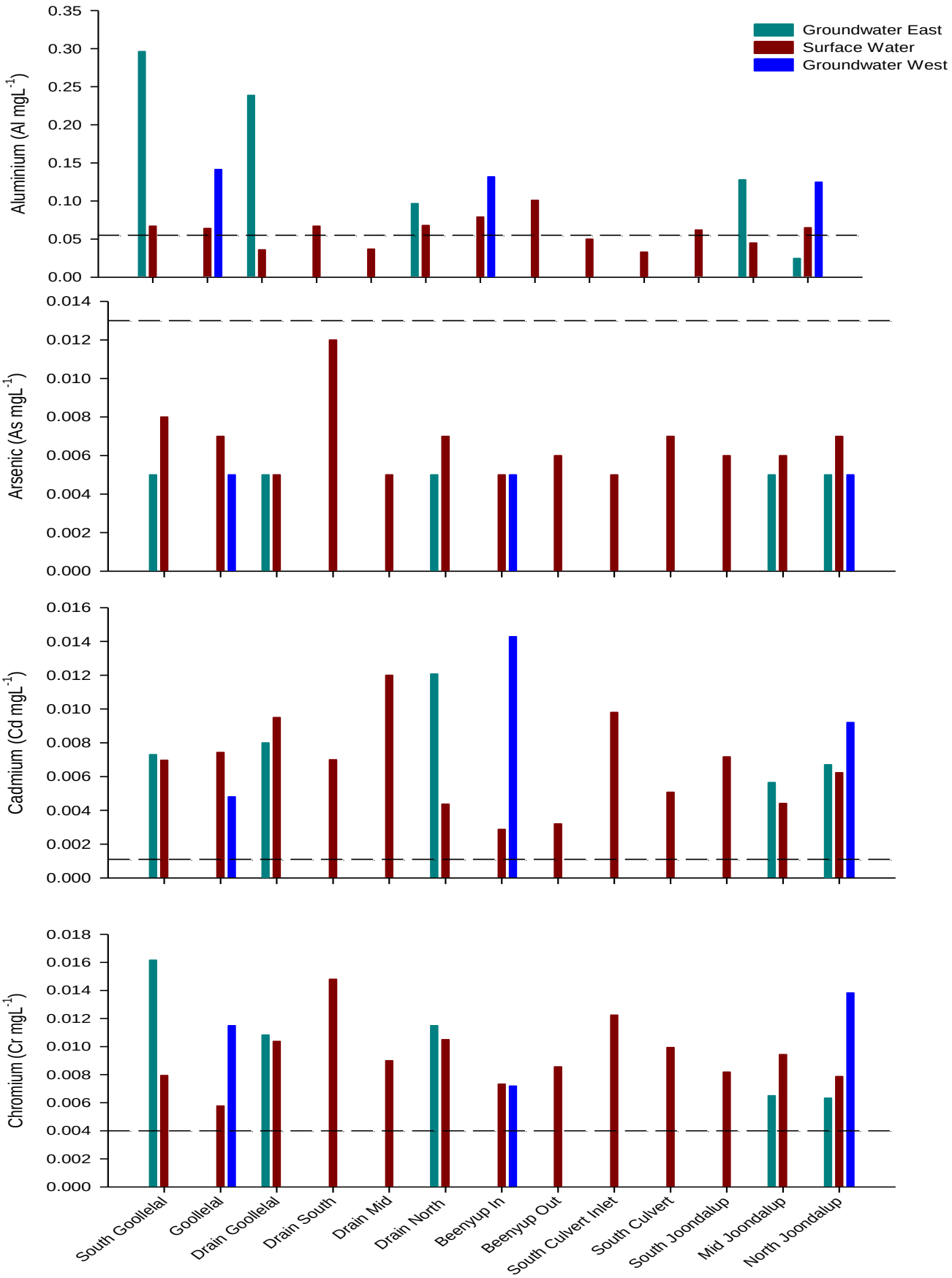
Site	Al	As	Cd	Co	Cr	Fe
	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}
Detection Limit	**<0.02**	**<0.01**	**<0.002**	**<0.005**	**<0.005**	**<0.05**
GoolSE	0.22 ± 0.11 (0.073- 1.33)	0.008 ± 0.003 (BDL-0.04)	0.004 ± 0.001 (BDL-0.013)	0.012 ± 0.003 (BDL -0.032)	0.009 ± 0.02 (BDL -0.034)	0.036 ± 0.012 (BDL -0.153)
GoolMidW	0.12 ± 0.012 (0.06- 0.19)	0.016 ± 0.006 (BDL -0.052)	0.002 ± 0.0006 (BDL -0.074)	0.016 ± 0.005 (BDL -0.037)	0.008 ± 0.003 (BDL -0.025)	2.52 ± 0.46 (0.553-4.952)
GoolNE	0.17 ± 0.058 (0.04- 0.7)	0.006 ± 0.0009 (BDL -0.014)	0.004 ± 0.001 (BDL -0.016)	0.015 ± 0.004 (BDL -0.039)	0.008 ± 0.003 (BDL -0.034)	1.593 ± 0.33 (0.134-3.714)
WallE	0.08 ± 0.009 (0.05- 0.15)	0.008 ± 0.003 (BDL -0.04)	0.004 ± 0.002 (BDL -0.018)	0.011 ± 0.003 (BDL -0.032)	0.006 ± 0.002 (BDL -0.024)	0.058 ± 0.029 (0.012-0.348)
WallW	0.11 ± 0.009 (0.06- 0.16)	0.015 ± 0.008 (BDL -0.09)	0.006 ± 0.002 (BDL -0.024)	0.012 ± 0.003 (BDL -0.031)	0.004 ± 0.001 (BDL -0.017)	1.22 ± 0.187 (0.685-2.765)
JoonMidE	0.11 ± 0.01 (0.06- 0.15)	0.012 ± 0.004 (BDL -0.04)	0.002 ± 0.0008 (BDL -0.009)	0.014 ± 0.004 (BDL -0.035)	0.006 ± 0.003 (BDL -0.03)	0.038 ± 0.007 (BDL -0.96)
JoonNE	0.02 ± 0.005 (BDL - 0.05)	0.009 ± 0.003 (BDL -0.0104)	0.003 ± 0.001 (BDL -0.01)	0.007 ± 0.003 (BDL -0.015)	0.006 ± 0.002 (BDL -0.018)	0.074 ± 0.022 (BDL -0.214)
JoonNW	0.12 ± 0.009 (0.09- 0.18)	0.005 ± 0.0005 (BDL -0.0102)	0.004 ± 0.002 (0.003-0.018)	0.012 ± 0.004 (BDL -0.038)	0.008 ± 0.003 (BDL -0.033)	0.279 ± 0.073 (0.178-0.985)

The only bore where Hg concentrations were found to be above detection limits and substantially above guideline levels was GoolNE (Table 5). This was a one off event in August 2012, the source of which is currently unknown, but coincidently similar concentrations to the July 2012 Hg spike through Yellagonga surface waters. Concentrations of Mn, Ni, Se, U and Zn were relatively similar across all the bores, although high one off values was common.

Table 5 Mean ± standard error (range) for selected metals over the 11 month monitoring period (August 2012 – June 2013), concentrations recorded as BDL were below the detection limit.

Site	Hg	Mn	Ni	Se	U	Zn
	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mgL^{-1}	mg L^{-1}
Detection Limit	**<0.05**	**<0.01**	**<0.02**	**<0.04**	**<0.01**	**<0.05**
GoolSE	BDL	BDL	0.02 ± 0.006 (BDL -0.07)	0.034 ± 0.008 (BDL -0.1)	0.162 ± 0.003 (BDL -0.277)	0.043 ± 0.017 (BDL -0.165)
GoolMidW	BDL	0.015 ± 0.003 (BDL -0.033)	0.022 ± 0.006 (BDL -0.063)	0.056 ± 0.019 (BDL -0.175)	0.197 ± 0.03 (BDL -0.372)	0.031 ± 0.015 (BDL -0.174)
GoolNE	0.028 ± 0.003 (BDL -0.056)	0.008 ± 0.001 (BDL -0.015)	0.027 ± 0.085 (BDL -0.1)	0.038 ± 0.006 (BDL -0.079)	0.097 ± 0.013 (0.047-0.161)	0.059 ± 0.019 (BDL -0.195)
WallE	BDL	0.006 ± 0.0008 (BDL -0.014)	0.022 ± 0.006 (BDL -0.056)	0.024 ± 0.004 (BDL -0.064)	0.11 ± 0.017 (0.052-0.205)	0.062 ± 0.023 (BDL -0.227)
WallW	BDL	0.017 ± 0.002 (BDL -0.028)	0.022 ± 0.008 (BDL -0.084)	0.042 ± 0.012 (BDL -0.12)	0.2 ± 0.028 (0.072-0.32)	0.044 ± 0.014 (BDL -0.134)
JoonMidE	BDL	0.016 ± 0.004 (BDL -0.046)	0.02 ± 0.006 (BDL -0.076)	0.045 ± 0.019 (BDL -0.219)	0.21 ± 0.04 (BDL -0.51)	0.048 ± 0.015 (BDL -0.15)
JoonNE	BDL	BDL	0.017 ± 0.005 (BDL -0.053)	0.055 ± 0.018 (BDL -0.149)	0.019 ± 0.007 (BDL -0.046)	0.04 ± 0.015 (BDL -0.121)
JoonNW	BDL	0.006 ± 0.0007 (BDL -0.011)	0.03 ± 0.011 (BDL -0.118)	0.035 ± 0.01 (BDL -0.114)	0.173 ± 0.03 (0.1-0.357)	0.062 ± 0.018 (0.074-0.16)

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 concentrations were generally higher in the groundwater than surface water samples, suggesting that it might be a source of contamination. Arsenic and Hg concentrations were lower than surface waters suggesting that there were other sources of these metals/metalloids in the Yellagonga system, possibly ASS. For Cd, Cr, Se and U eastern bores generally had similar concentrations to surface waters, although with occasional higher values in the bores. The western bores for Cd, Cr and U tended to have higher concentrations showing potential export of the metals from the system.


Groundwater East
Surface Water
Groundwater West
Aluminium (Al mgL -1)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Arsenic (As mgL -1)
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Cadmium (Cd mgL -1)
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Chromium (Cr mgL -1)
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
South Goollelal
Goollelal
Drain Goollelal
Drain South
Drain Mid
Drain North
Beenyup In
Beenyup Out
South Culvert Inlet
South Culvert
South Joondalup
Mid Joondalup
North Joondalup

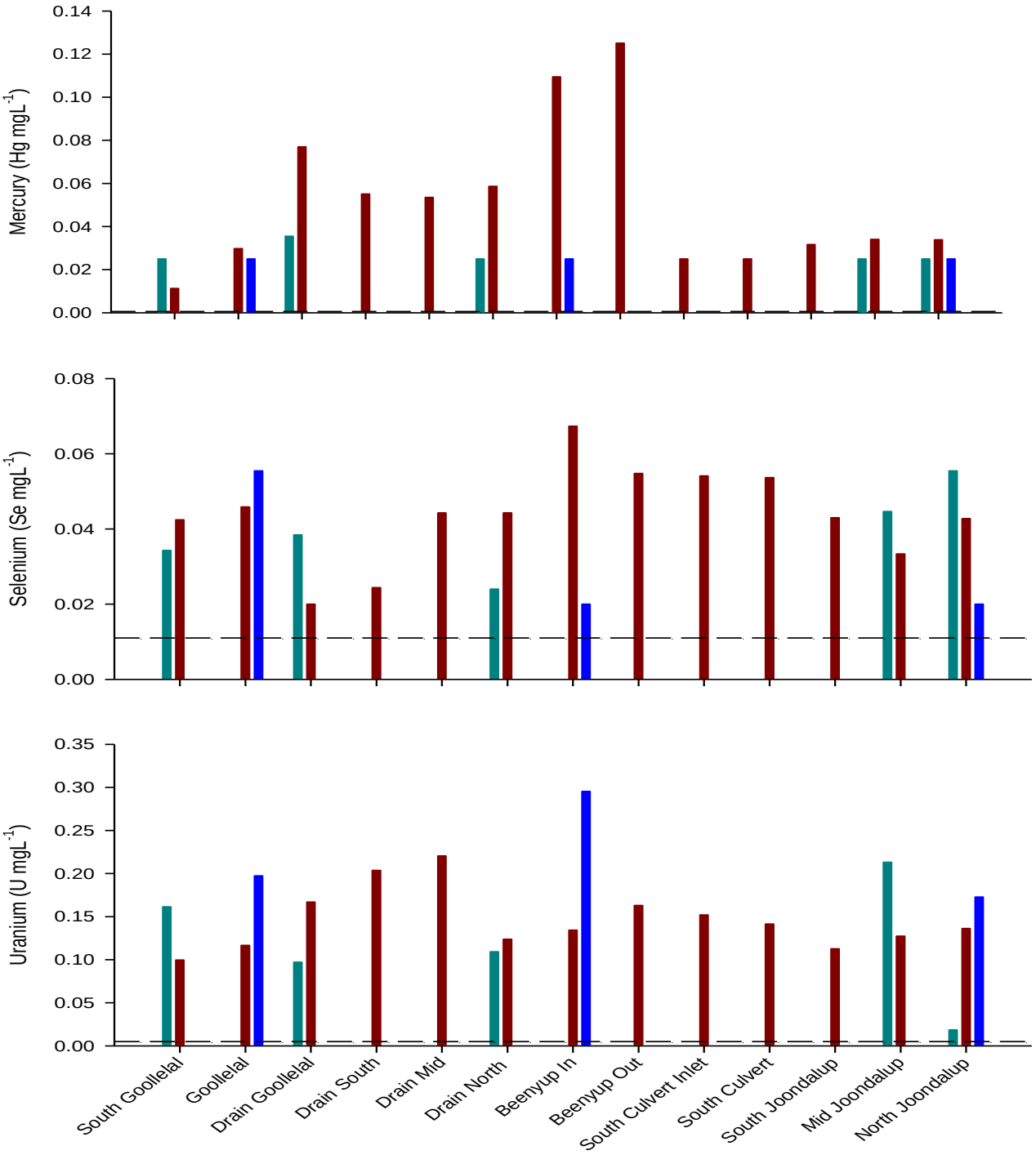


Figure 6. Mean (August 2012 to June 2013) metal/metalloids concentrations for groundwater and surface water. Dotted lines indicate the ANZECC & ARMCANZ (2000) trigger values for the protection of aquatic ecosystems (95%).

7.3 NUTRIENTS

The highest DOC concentrations were found in water leaving Lake Joondalup at JoonNW and Lake Goollelal at GoolMidW (Figure 7). The JoonNW concentrations were highest in Feb to June while for GoolMidW it was August to October. This pattern is almost identical to that seen for EC (Figure 2), and therefore probably an evapo-concentration effect.

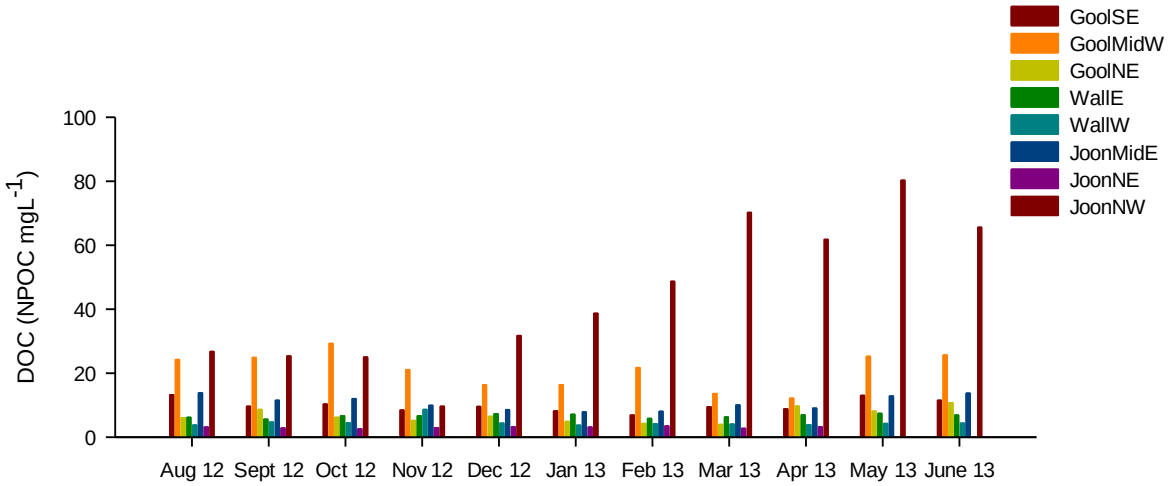
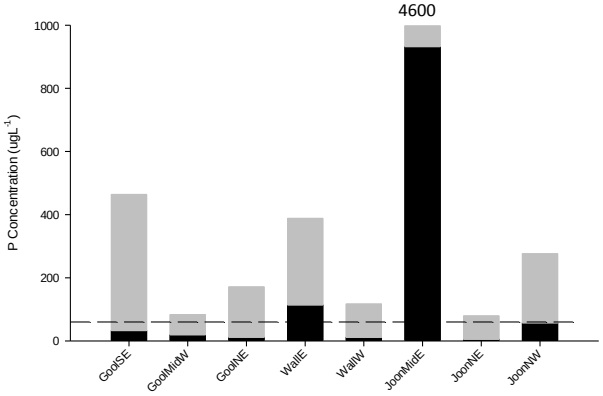


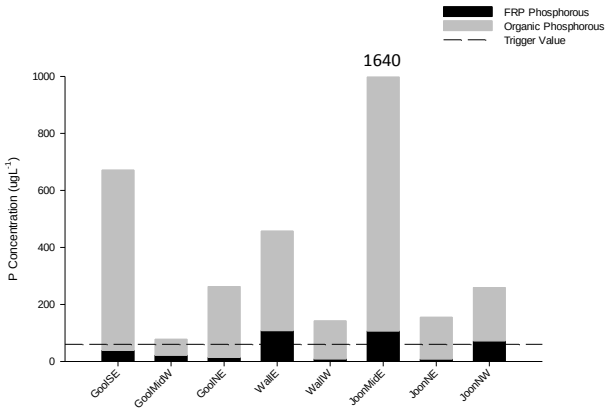
Figure 7. Dissolved organic C concentrations recorded in groundwater bores from August 2012 to June 2013.

JoonMidE had the highest concentrations of FRP in August 2012 and June 2013 at >800 µg L^{-1}, although this dropped for the rest of the year to <150 µg L^{-1}. All sites were dominated by organic P (probably inorganic particulates, as the analysis does not discriminate between organic and inorganic forms). GoollelalSE, WallE and JoonMidE were consistently high demonstrating these areas to be sources of P in wetland system. The JoonNW bore was usually higher in P than JoonNE and was the only western site that showed significant P levels. Phosphorus concentrations were similar to those recorded in the surface water study suggesting that groundwater is an important source of P.

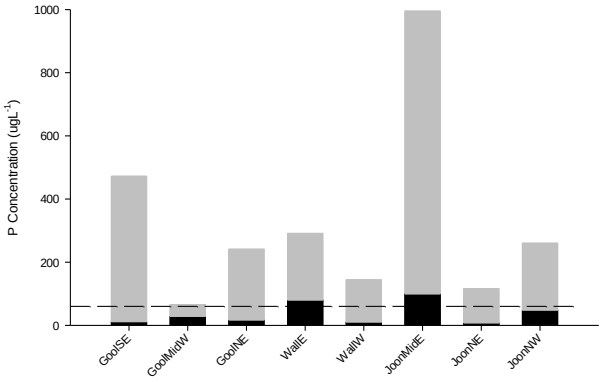
August 2012



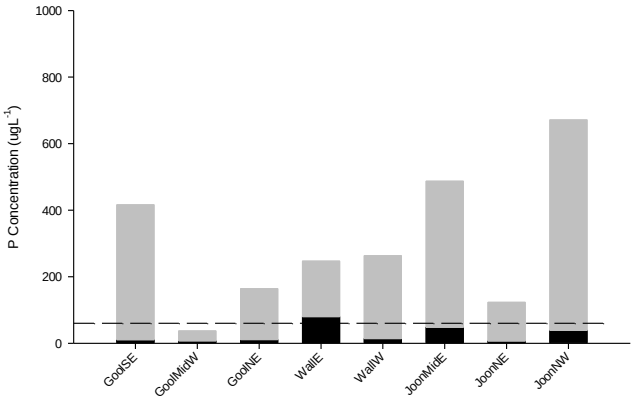
September 2012



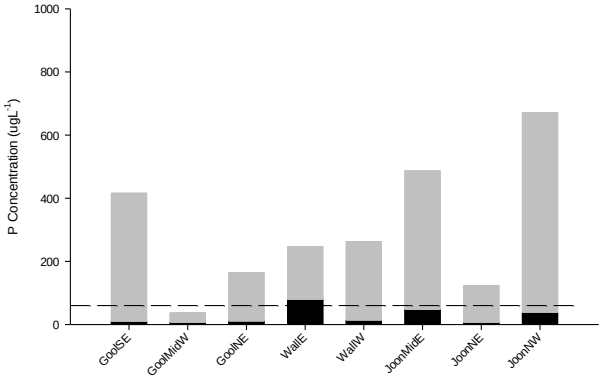
October 2012



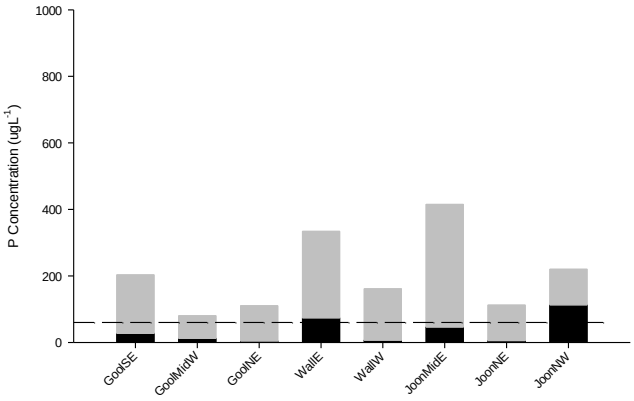
November 2012



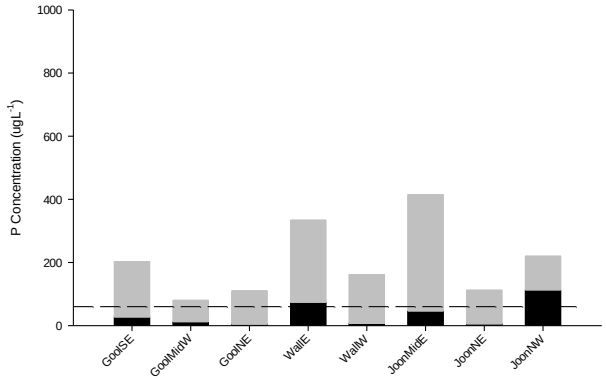
December 2012



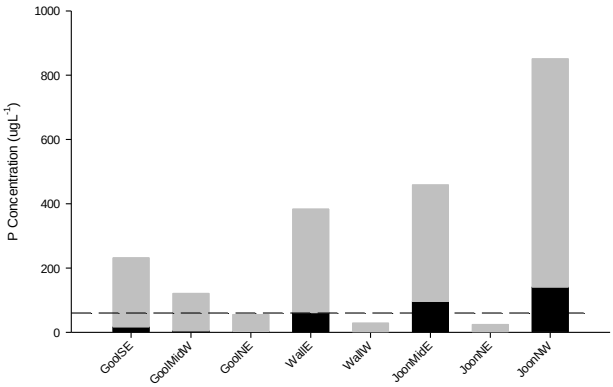
January 2013



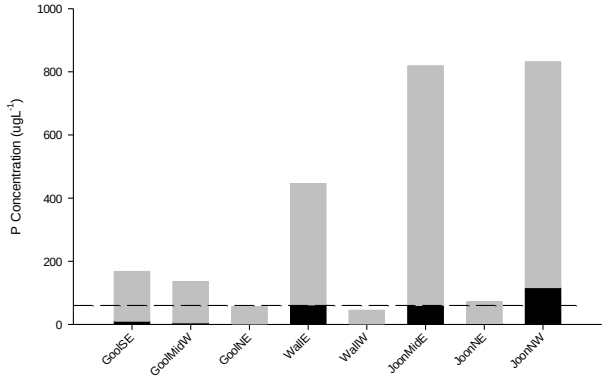
February 2013



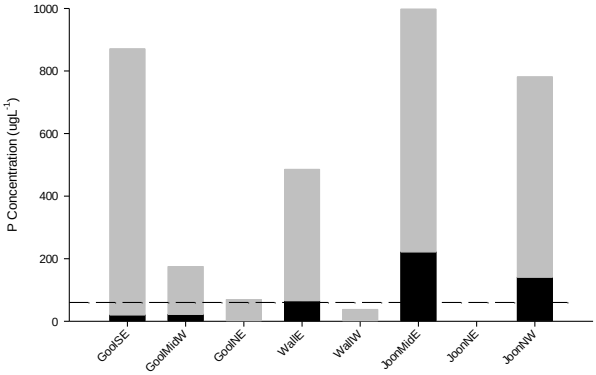
March 2013



April 2013



May 2013



June 2013

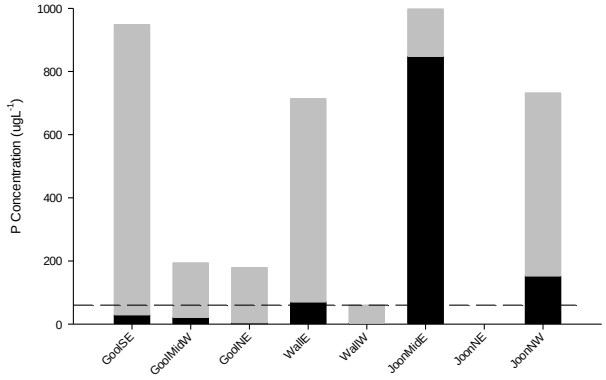
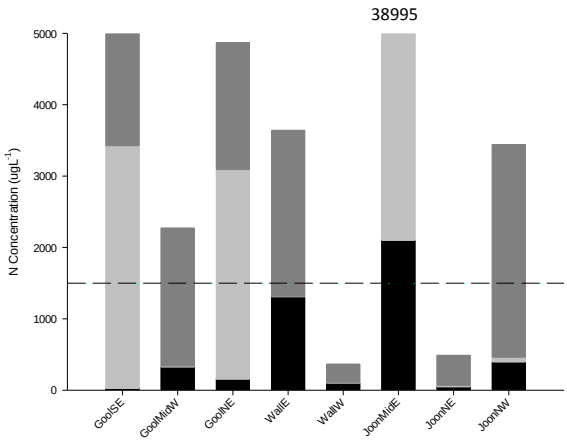


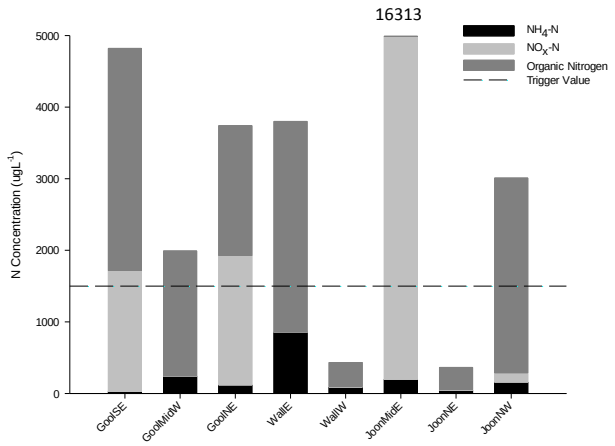
Figure 8. Breakdown of total phosphorus into chemical fractions (organic P and FRP) recorded in groundwater at each bore between August 2012 and June 2013 with the ANZECC & ARMANZ (2000) trigger value for total phosphorus shown.

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. This domination lasted from August 2012 to February 2013, after which this form of N was almost absent. This loss of organic N is unusual and a further years monitoring is required to determine if this is a seasonal effect or an artefact. 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. GoolSE was also a major source of NOx whereas GoolNE was occasionally a major source. The monthly variability in N levels is also surprising and difficult to explain. In March 2013, NOx concentrations dropped substantially and there is an increase in NH4. This coincides with the drop below 0 mV in ORP in the majority of bores, those bores (GoolSE and JoonMidE) that had a >0 mV ORP retained the high NOx concentrations. This suggested 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).

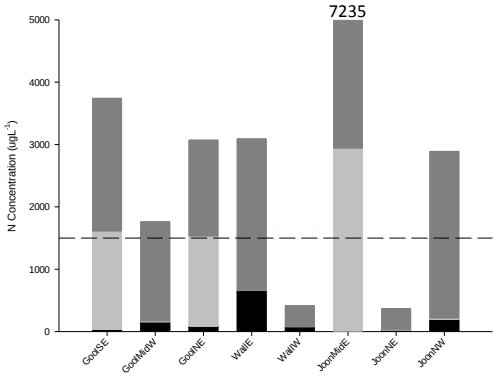
August 2012



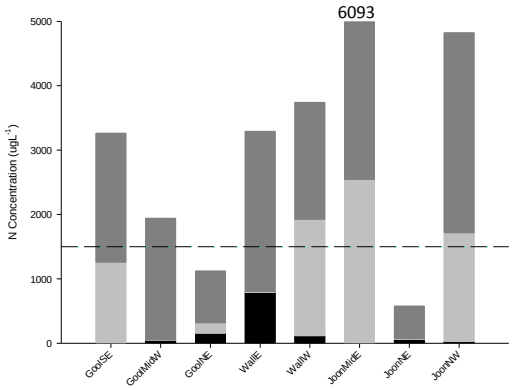
September 2012



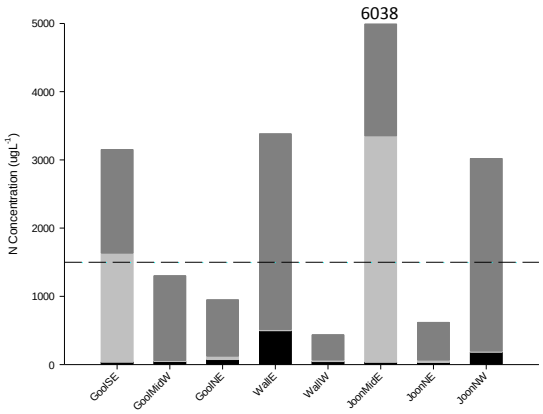
October 2012



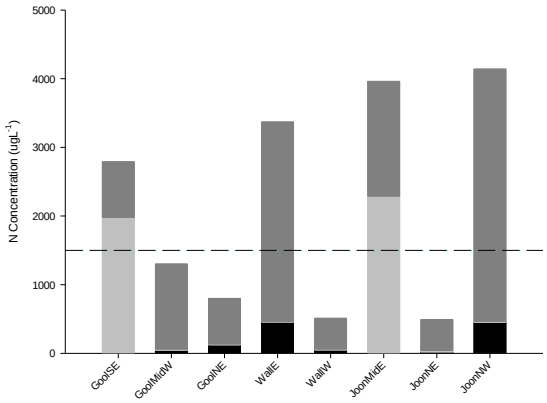
November 2012



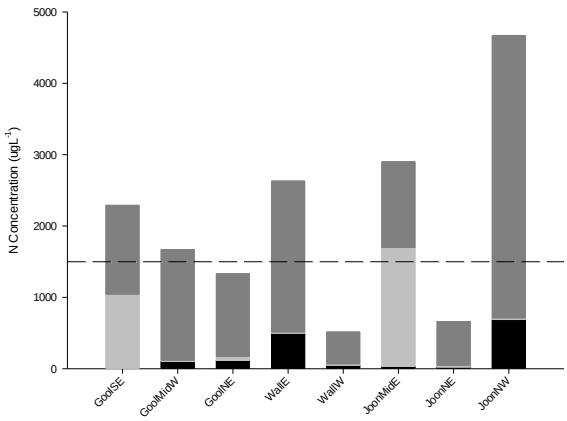
December 2012



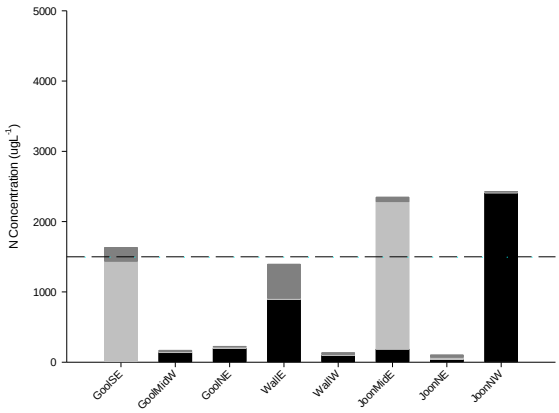
January 2013



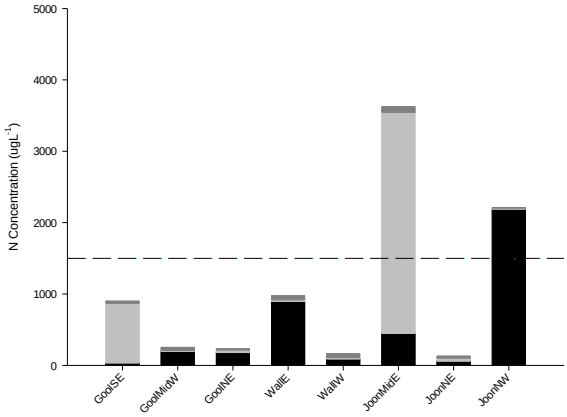
February 2013



March 2013



April 2013



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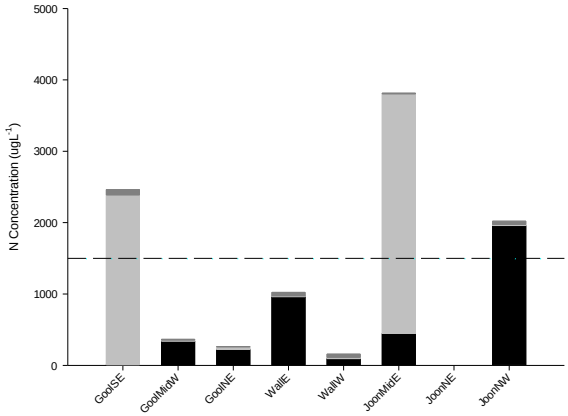

June 2013

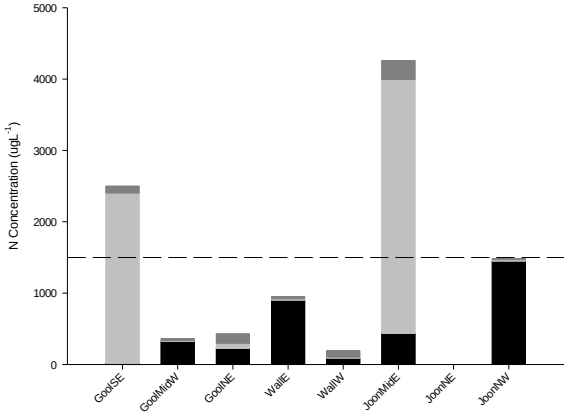

Figure 9. Breakdown of total nitrogen into chemical fractions (organic nitrogen, nitrate/nitrite (NO_x) and ammonium (NH_4)) recorded in groundwater at each bore between August 2012 and June 2013 with the ANZECC & ARMANZ (2000) trigger value for total nitrogen.

Table 6 Mean ± s.e. (range) for nutrients in water recorded at each bore over the course of the monitoring period (August 2012-June 2013), concentrations recorded as BDL were below the detection limit.

Site	Total P	FRP	Total N	NOx	NH_4
	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}
Detection Limit	**<20**	**<2**	**<50**	**<2**	**<3**
GoolSE	468 ± 86 (158-922)	25 ± 4 (11-45)	3100 ± 520 (899.6-6560)	1781 ± 261 (838-3400)	19 ± 4 (BDL-37)
GoolMidW	97 ± 13 (37-174)	16 ± 2 (5-29)	1216 ± 238 (168-2270)	14 ± 1 (5-18)	179 ± 35 (46-341)
GoolNE	152 ± 23 (53-263)	7 ± 2 (BDL-17)	1608 ± 483 (224-4870)	660 ± 302 (15-2940)	158 ± 16 (75-227)
WallE	377 ± 35 (235-650)	78 ± 6 (55-114)	2504 ± 352 (950-3800)	15 ± 2 (6-23)	792 ± 76 (455-1310)
WallW	116 ± 20 (28-263)	46 ± 39 (BDL-434)	642 ± 313 (133-3740)	180 ± 163 (9-1810)	82 ± 7 (44-118)
JoonMidE	1113 ± 366 (288-4580)	239 ± 98 (46-932)	8563 ± 3125 (2346-37600)	3482 ± 574 (1670-8630)	354 ± 183 (BDL-2100)
JoonNE	98 ± 13 (23-155)	6 ± 0.8 (BDL- 9)	422 ± 67 (100-661)	25 ± 4 (11-35)	39 ± 5 (21-58)
JoonNW	431 ± 71 (259-726)	92 ± 13 (49-153)	3103 ± 326 (2890-4820)	186 ± 151 (25-1690)	919 ± 27281 (158-2410)

8 CONCLUSIONS

Eight bores (3 western, 5 eastern) were sampled for a broad range of physico-chemical parameters, nutrient and metal/metalloid concentrations between August 2012 and June 2013. All the bores showed a strong evapo-concentration effect for conductivity and related solutes. This was more pronounced in the western bores as reflected the lake's water quality. In February 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 and nutrients. The groundwater in these areas is almost certainly impacting on the water quality of the wetlands.

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 for the next year, after which it could be reduced to bimonthly or quarterly. Clear trends are visible for some parameters measured in 2012/2013 however continued monthly sampling would be useful to improve understanding of processes.

2. There remains to be areas of the Yellagonga Regional Park where there is an insufficient coverage of bores. In particular, we recommend an additional bore on the eastern side of southern Lake Joondalup and a bore on the mid-western side of Lake Joondalup (possibly near Neil Hawkins Park). The bore at Wallubuenup Swamp west is also poorly located (next to Beenyup Swamp) and would be useful if replaced by another bore located outside the flow path between Wallubuenup and Beenyup. Suggested locations are shown in Figure 10.

Figure 10. Suggested locations of recommended new bores.

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