Final

Monitoring of Yellagonga Regional Park Groundwater Quality

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Prepared for,

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

Mine Water and Environment Research Centre

Centre for Ecosystem Management

Report No. 2015-06

1. MINE WATER AND ENVIRONMENT RESEARCH CENTRE

Founded at Edith Cowan University in 2008, the Mine Water and Environment Research (MiWER) Centre is led by Associate Professor Mark Lund. MiWER arose from the Western Australian Government Centre of Excellence in Sustainable Mine Lakes. The research group has a focus on pit lakes formed from mining, and other mine effected waters. Our research covers most aspects of rehabilitation, remediation and the ecology of inland waters. MiWER's aim is to further understanding of freshwater science using creative, cutting-edge technologies and innovative approaches for practically improving resource sustainability and environmental condition.

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

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2. ACKNOWLEDGEMENTS

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

FRONTISPIECE

Figure 1. Photograph taken of South Lake Joondalup on March 2015.

This report should be referenced as follows.

Gonzalez-Pinto, J., and Lund, M. A., (2015). *Monitoring of Yellagonga Regional Park Groundwater Quality: Report 2015.* Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2015-06, Edith Cowan University, Perth, Australia. 45pp. Unpublished report to the Cities of Joondalup and Wanneroo, Western Australia.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. In 2014, two further bores were provided at Neil Hawkins Park and Ariti Avenue by the Cities.
2. Monitoring was conducted monthly and 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. Sampling commenced in July 2013. This report covers monitoring from July 2014 to June 2015.
3. The bores on the western side of increase in conductivity and related parameters in late summer, following 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, Hg, 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 and Hg identified in the wetlands.
5. 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.

6. Key recommendations from the study are to continue monitoring for one more year (due to the addition in 2014/2015 of two new bores) at monthly intervals to allow clarification of seasonal effects and to promote a better understanding of processes. It is also recommended to measure alkalinity as alkalinity:sulphate ratios are considered better indicators of acid sulphate soils than chloride:sulphate ratios (currently used).

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 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, Lund et al. 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 and McComb 1976, Congdon and McComb 1976, Gordon, Finlayson et al. 1981, Congdon 1985, Congdon 1986, Davis, Rosich et al. 1993, Kinnear, Garnett et al. 1997, Kinnear and Garnett 1999, Lund, Brown 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, McCullough et al. 2011, Newport, Lund et al. 2011, Newport and Lund 2012, Newport and Lund 2013, Newport and Lund 2014). An investigation in the southern section of Wallubuenup Swamp identified the presence of ASS (Newport, Lund et al. 2011, Newport and Lund 2013, Newport and Lund 2014).

Newport and Lund (2012) 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 second annual monthly monitoring of these groundwater bores from July 2014 – June 2015.

6. METHODS

6.1 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 monthly 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).

6.2 SAMPLING

This report covers monthly sampling of the groundwater bores between the July 2014 and June 2015. 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°C 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 interference (particularly U and Se) are now more reliable and have lower detection limits. Instrument failure meant that May and June 2015 data for trace metals is not available at the time of writing and this data will be included in the 2015/16 report.

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

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)

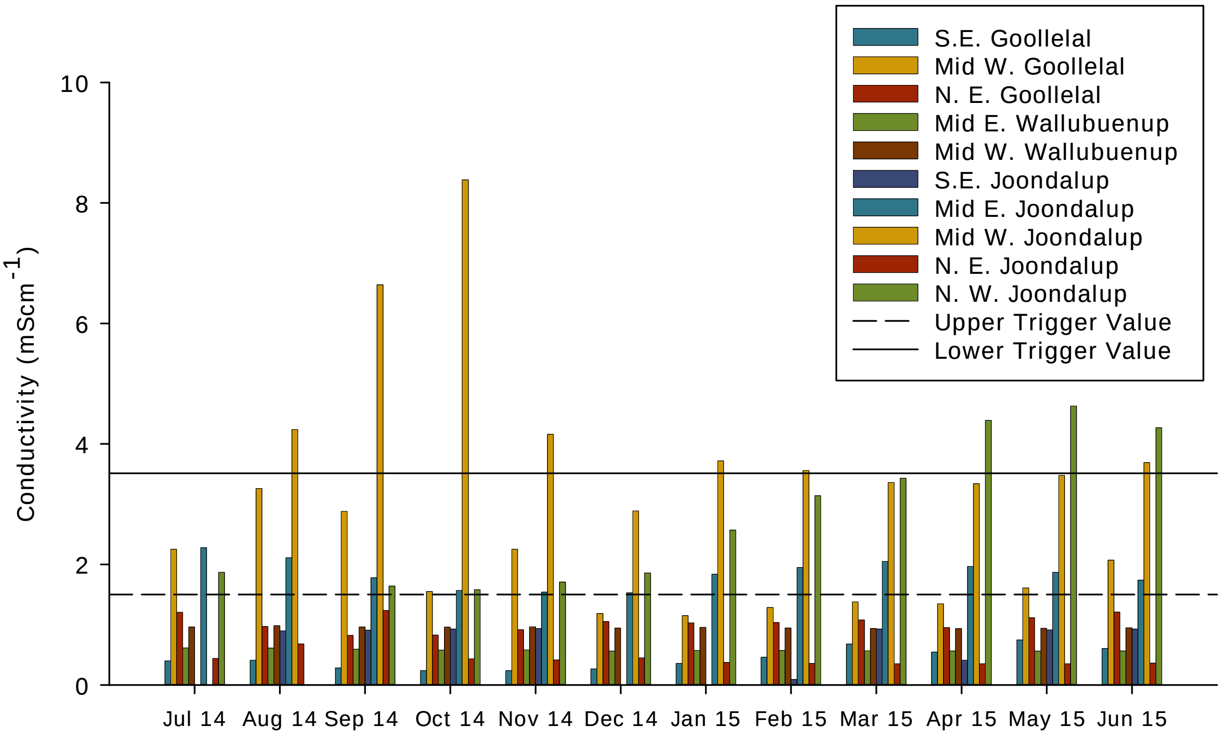
7. RESULTS AND DISCUSSION

The two new groundwater bores (S.E. Joondalup and Mid W. Joondalup) were sampled from August 2014. The S.E. Joondalup bore was inaccessible from December 2013 to January 2014 due to the change on the padlock.

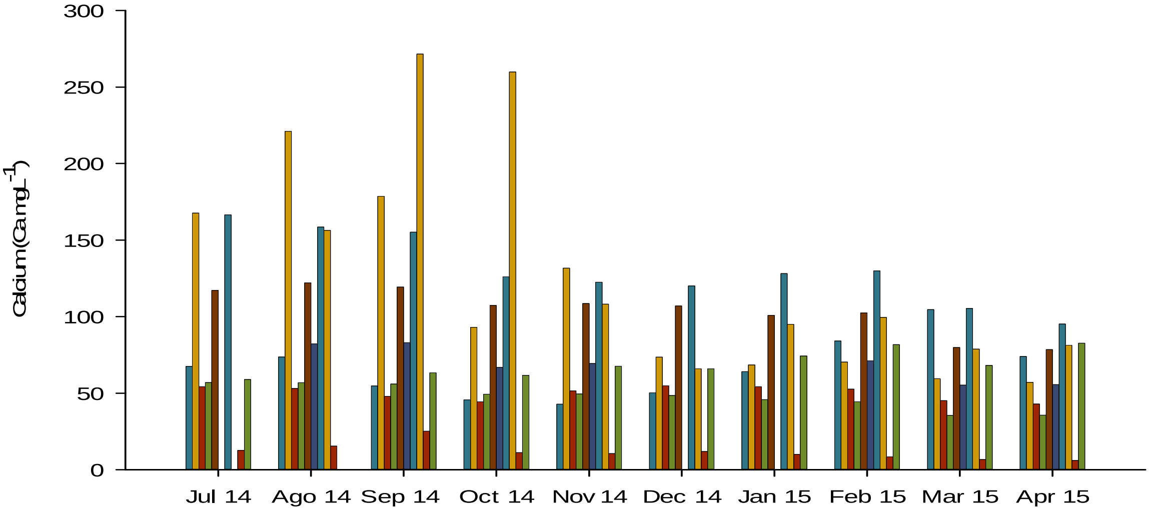
7.1 PHYSICO-CHEMISTRY

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 high EC in Mid W Joondalup in spring, N.W. Joondalup and Mid W. Goollelal in winter. 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. Similar trends can be seen in Ca, K, Mg, Na and Cl across all sites and times reflecting their contribution to EC and evapoconcentration in the lake. Table 1 illustrates the mean and ranges for each of the common ions.

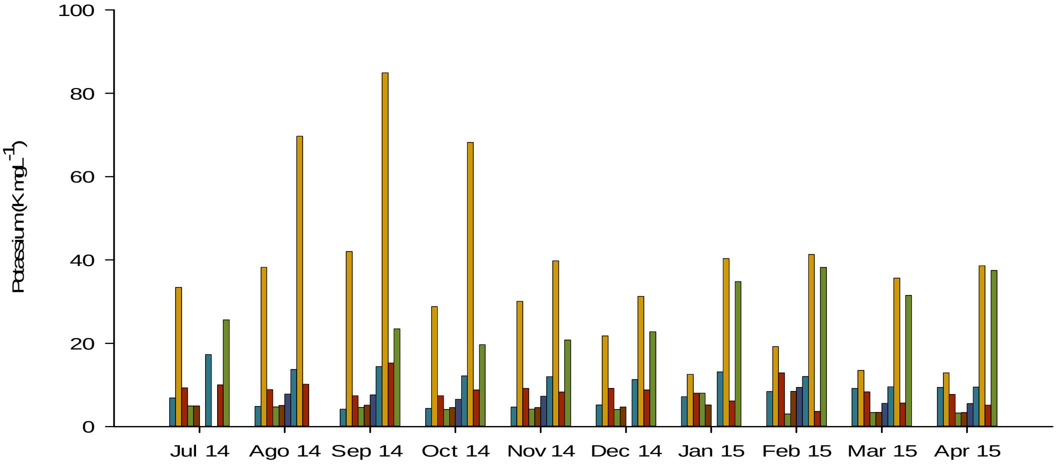
a) Electrical conductivity



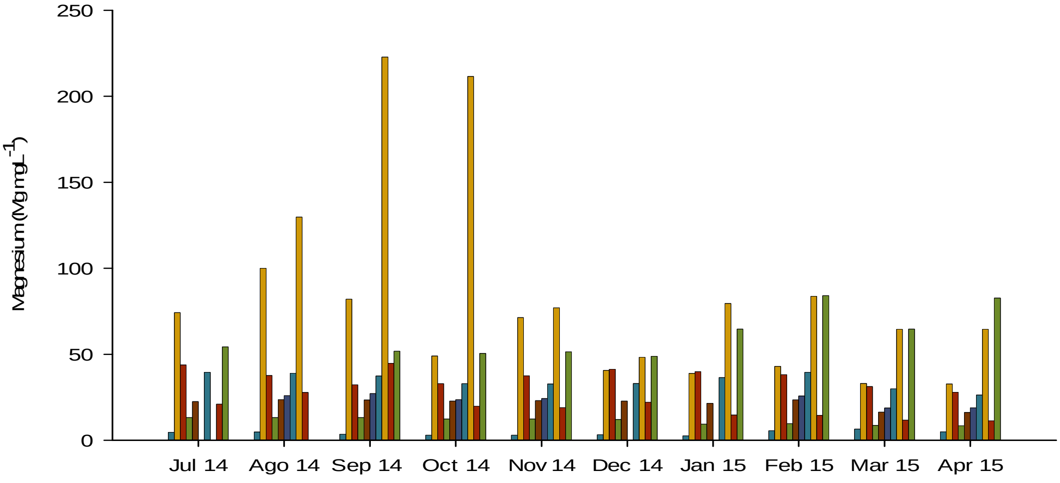
b) Calcium (Ca)



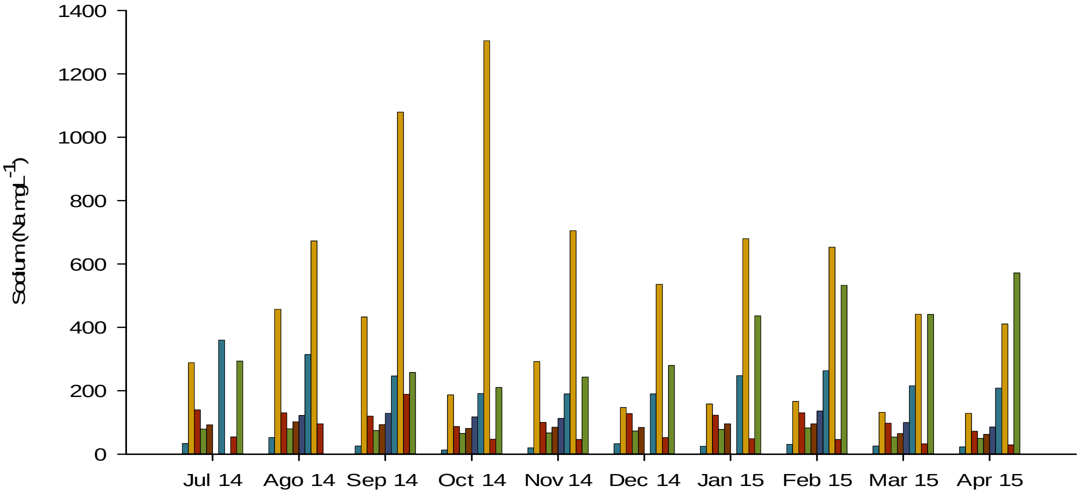
c) Potassium (K)



d) Magnesium (Mg)



e) Sodium (Na)



f) Chloride (Cl$^-$)

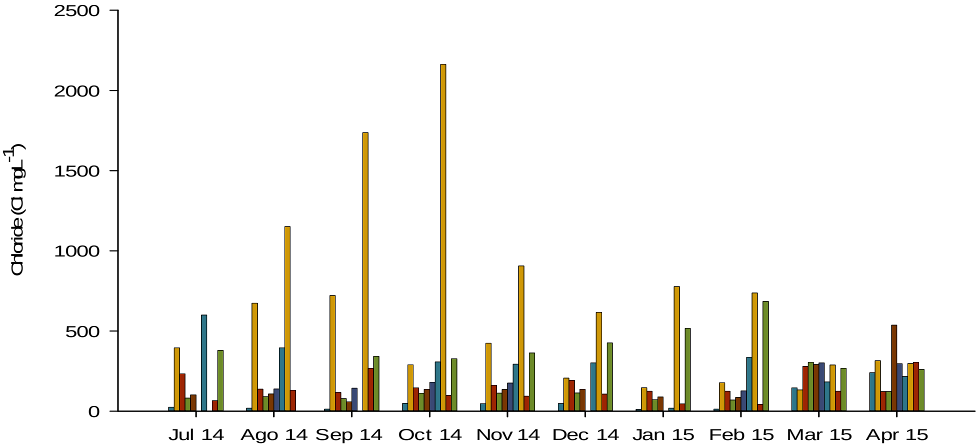


Figure 2. Changes in a) electrical conductivity, b) calcium, c) potassium, d) magnesium, e) sodium and f) chloride over the period of monitoring at each site (July 2014 – June 2015).

Table 1 Mean ± standard error (range) for selected solutes during the monitoring period July 2014 to June 2015

	Ca	**K**	**Mg**	**Na**	**Cl^-**	**SO_4^{2-}**
DL	**< 0.2**	**< 0.2**	**< 0.2**	**< 0.2**	**< 0.5**	**< 0.5**
S.E. Goollelal	71 ± 6 (43-105)	7 ± 1 (4-9)	4 ± 0 (3-7)	27 ± 3 (13-52)	57 ± 20 (11-241)	48 ± 24 (8-300)
Mid W. Goollelal	105 ± 16 (57-221)	24 ± 3 (13-42)	54 ± 6 (33-100)	229 ± 33 (129-457)	335 ± 56 (132-722)	182 ± 42 (53-503)
N.E. Goollelal	49 ± 1 (43-55)	9 ± 0 (7-13)	35 ± 1 (28-44)	110 ± 6 (72-140)	161 ± 14 (118-280)	180 ± 20 (126-380)
Mid E. Wallubuenup	45 ± 3 (34-57)	4 ± 0 (3-8)	11 ± 1 (8-13)	67 ± 4 (49-82)	108 ± 19 (65-306)	25 ± 3 (15-50)
W. Wallubuenup	99 ± 5 (74-122)	5 ± 0 (3-8)	21 ± 1 (16-24)	81 ± 4 (61-102)	155 ± 39 (59-537)	146 ± 13 (17-203)
S.E. Joondalup	66 ± 4 (53-83)	7 ± 0 (5-9)	22 ± 1 (18-27)	106 ± 7 (76-136)	181 ± 23 (118-301)	72 ± 6 (57-106)
Mid E. Joondalup	123 ± 8 (84-166)	12 ± 1 (9-17)	33 ± 2 (22-40)	233 ± 16 (178-359)	290 ± 43 (19-600)	96 ± 11 (36-156)
Mid W. Joondalup	126 ± 22 (66-272)	49 ± 5 (31-85)	102 ± 18 (48-223)	664 ± 88 (403-1304)	919 ± 173 (288-2163)	278 ± 59 (103-736)
N.E. Joondalup	11 ± 2 (6-25)	8 ± 1 (4-15)	19 ± 3 (11-45)	58 ± 13 (29-189)	115 ± 25 (44-305)	69 ± 16 (29-231)
N.W. Joondalup	69 ± 2 (59-83)	30 ± 2 (20-40)	65 ± 4 (49-84)	399 ± 44 (210-593)	502 ± 104 (267-1189)	160 ± 36 (84-460)

Calculated hardness of water samples from the bores are shown in Figure 3. Hardness was generally higher than in 2013/14 and 2012/13 reflecting the low annual rainfall which increased concentrations of key components of the water hardness. The only exception was the very high hardness of Mid E Joondalup in 2013/14, the exact cause of which is unknown. Hardness was highest in western bores, reflecting evapo-concentration of solutes passing through the lake. Eastern bores around Lake Joondalup tend to contain harder water than around Lake Goollelal reflecting differences in the catchments, with more limestone around Lake Joondalup.

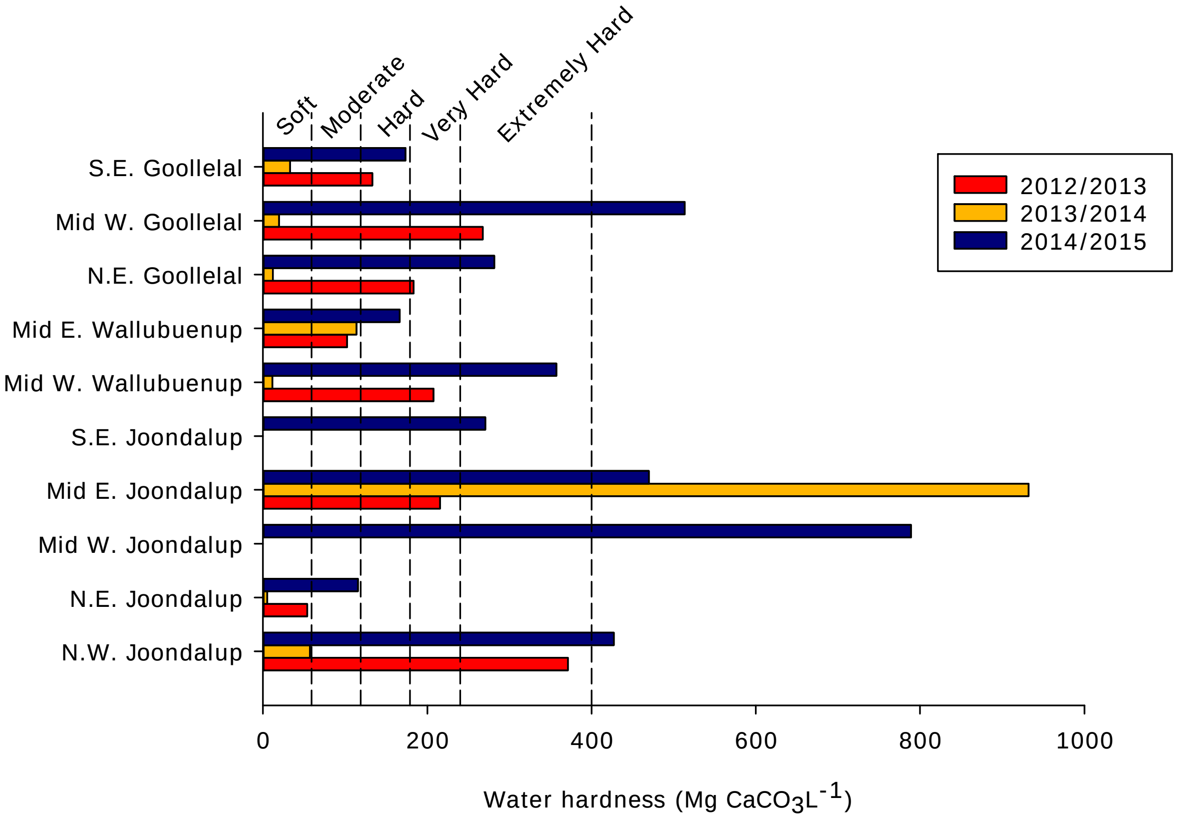
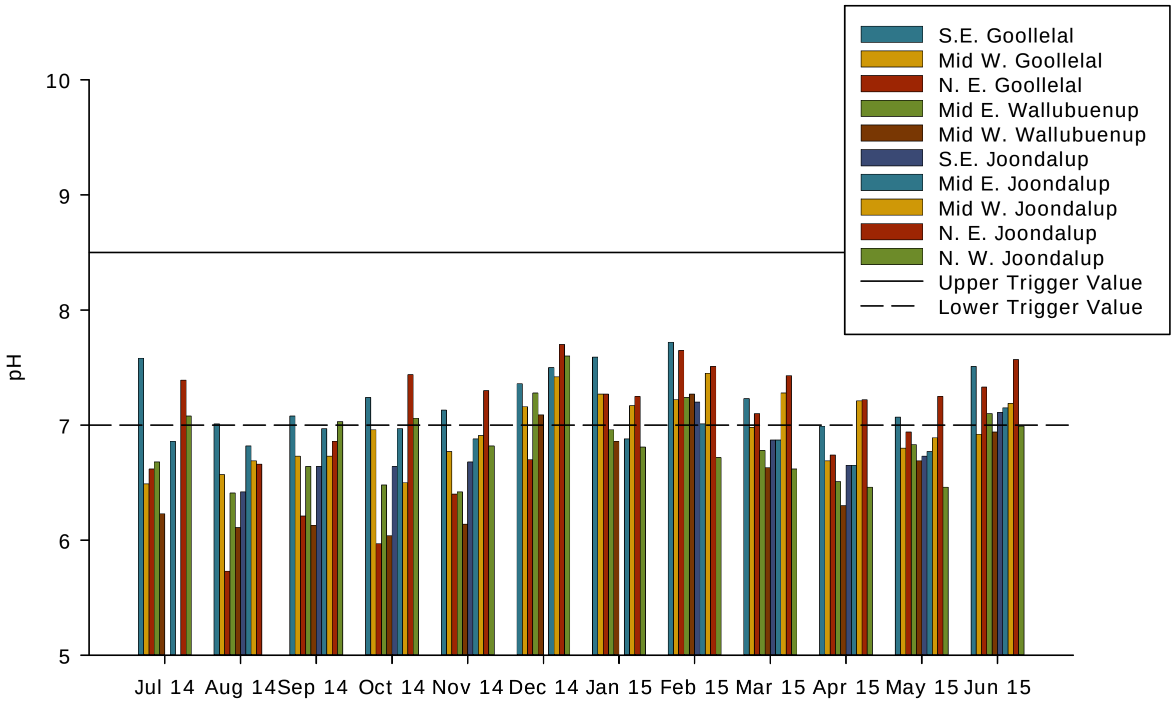


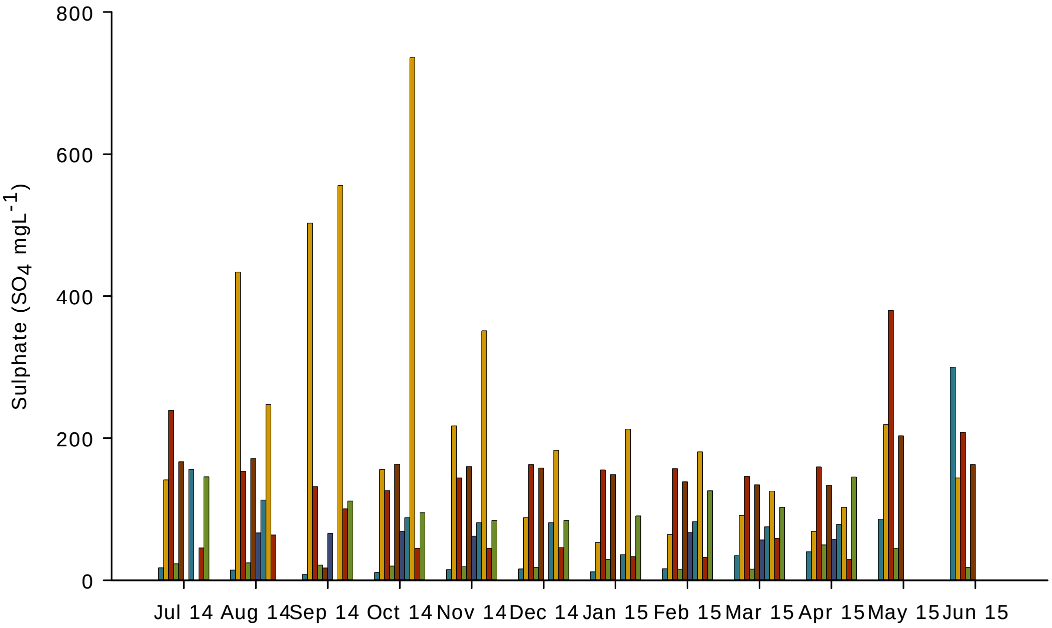
Figure 3. Calculated mean water hardness for the period of monitoring at each bore (June 2014 – July 2015) with ANZECC & ARMCANZ (2000) categories indicated.

Chloride to sulphate molar ratios is commonly used to indicate the presence of acid sulphate soils (ASS). Oxidation of metal sulphides (typically pyrites) into sulphuric acid, increasing sulphate relative to conservative chloride ions, which results in low molar ratios. A molar ratio of four or less is considered a good indicator of ASS contamination (Department of Local Government and Planning 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. pH of the groundwater ranged from circum-neutral to <6 (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 <1 unit. Sulphate concentrations were generally highest in the western sites (Mid W. Joondalup and Mid W. Goollelal). Molar ratios indicated the possible presence of ASS contamination at all sites except Mid W. Joondalup and N.W. Joondalup.

a) pH



b) Sulphate (SO_4)



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

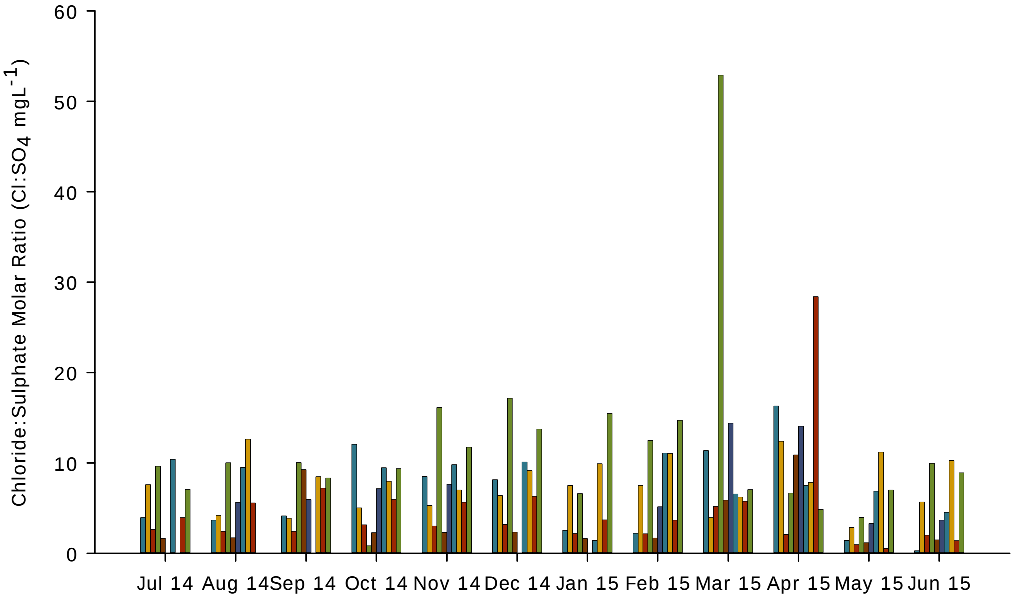
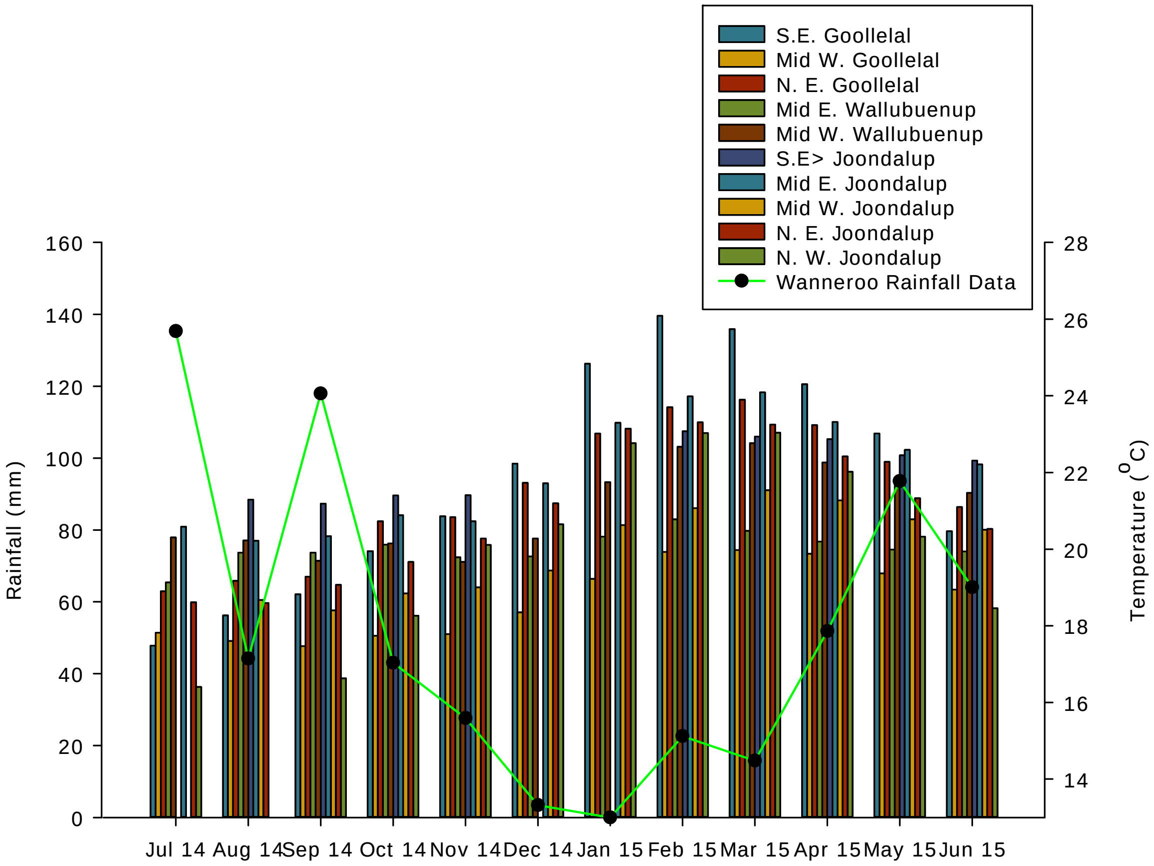


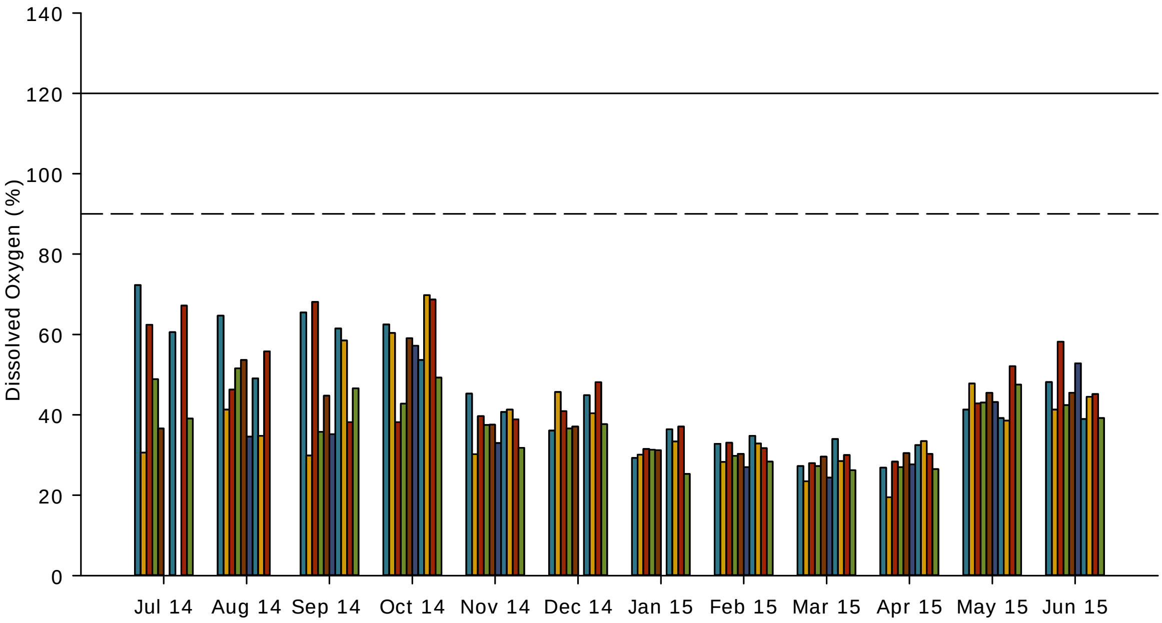
Figure 4. Changes in a) pH, b) sulphate and c) chloride to sulphate molar ratios over the period of monitoring at each bore (July 2014 – June 2015) with ANZECC & ARMCANZ (2000) trigger values for the protection of aquatic ecosystems (95%).

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 >19% saturation. Despite low dissolved oxygen concentrations, ORP was generally >0 mV across the year and for sites Mid W. Goollelal, Mid W. Joondalup, N.W. Joondalup, and on a couple of occasions for S.E. Goollelal and Mid E. Wallubuenup. These low ORP values indicated chemical processes rather than oxygen as the driver for ORP changes. Water levels in the bores illustrated little seasonal variation (<0.5 m), highest in October and lowest in May, with almost no change in Mid W. Wallubuenup.

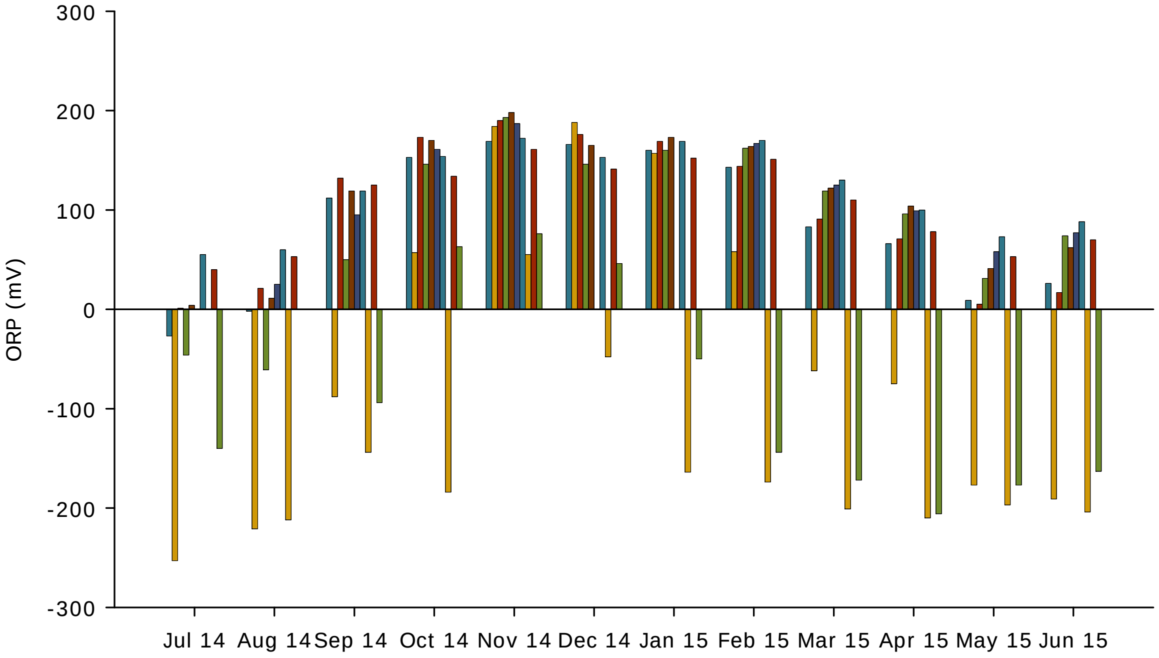
a) Temperature and Rainfall



b) Dissolved Oxygen



c) ORP



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

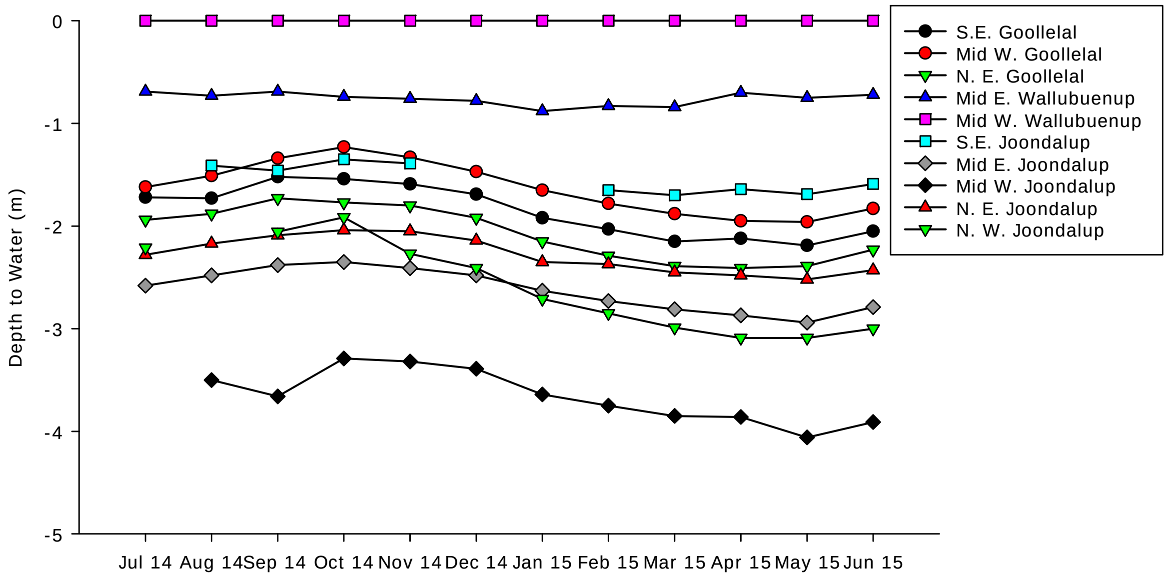


Figure 4. Variation throughout groundwater monitoring period for a) temperature, b) dissolved oxygen, c) ORP and d) depth to water between July 2014 and June 2015 at each bore.

Table 2. Mean ± standard error (range) for physicochemical variables over the monitoring period (July 2014- June 2015)

	Temperature (°C)	**Conductivity (mS cm^{-1})**	**Dissolved Oxygen (mg L^{-1})**	**Dissolved Oxygen (%)**	**pH**	**ORP (mV)**
S.E.	21.8 ± 0.9	0.44 ± 0.05	4.1 ± 0.5	46 ± 4.8	7.29 ± 0.07	88 ± 21
Goollelal	(17.5-26.1)	(0.24-0.75)	(2.2-7)	(26.9-72.3)	(6.99-7.72)	(-27-169)
Mid W.	18.7 ± 0.3	1.85 ± 0.2	3.3 ± 0.3	35.7 ± 3.4	6.88 ± 0.07	-35 ± 46
Goollelal	(17.5-20)	(1.15-3.26)	(1.8-5.7)	(19.5-60.4)	(6.49-7.27)	(-253-188)
N.E.	21.5 ± 0.6	1.02 ± 0.06	3.8 ± 0.4	43.1 ± 4.3	6.72 ± 0.18	99 ± 22
Goollelal	(18.9-23.9)	(0.82-1.21)	(2.4-6.3)	(28-68.1)	(5.73-7.65)	(1-190)
Mid E.	20 ± 0.1	0.58 ± 0.01	3.5 ± 0.2	37.8 ± 2.3	6.78 ± 0.09	89 ± 24
Wallubuenup	(19.1-20.8)	(0.56-0.61)	(2.4-4.7)	(27-51.6)	(6.41-7.28)	(-61-193)
W.	21.1 ± 0.3	0.95 ± 0	3.6 ± 0.3	40.1 ± 2.8	6.54 ± 0.12	111 ± 19
Wallubuenup	(19.7-22.8)	(0.94-0.98)	(2.5-5.4)	(29.6-59.1)	(6.04-7.27)	(4-198)
S.E.	22.1 ± 0.3	0.77 ± 0.1	3.3 ± 0.3	37.2 ± 3.8	6.77 ± 0.08	110 ± 18
Joondalup	(21.2-23.1)	(0.09-0.94)	(2.3-5)	(24.4-57.2)	(6.42-7.2)	(25-187)
Mid E.	22 ± 0.4	1.85 ± 0.07	3.9 ± 0.3	43.9 ± 2.9	6.94 ± 0.06	120 ± 13
Joondalup	(20.2-24.1)	(1.53-2.28)	(2.7-5.7)	(32.5-61.5)	(6.65-7.5)	(55-172)
Mid W.	20 ± 0.3	4.31 ± 0.5	3.7 ± 0.3	41.5 ± 3.7	7.04 ± 0.09	-153 ± 25
Joondalup	(18.4-21.5)	(2.89-8.38)	(2.5-6.3)	(28.5-69.8)	(6.5-7.45)	(-212-55)
N.E.	21 ± 0.5	0.48 ± 0.07	4.1 ± 0.4	45.3 ± 3.9	7.3 ± 0.08	106 ± 13
Joondalup	(18.6-23.3)	(0.35-1.24)	(2.6-6.4)	(30-68.7)	(6.66-7.7)	(40-161)
N.W.	20.2 ± 0.7	2.83 ± 0.36	3.3 ± 0.3	36.1 ± 2.7	6.88 ± 0.1	-87 ± 32
Joondalup	(16.4-23)	(1.58-4.63)	(2.1-4.6)	(25.3-49.3)	(6.46-7.6)	(-206-76)

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, Hg, 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. Fewer metals were problematic than in 2013/14. 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 July 2014 and April 2015

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	0.07 ± 0.014 (0.89)	95 (22)
Arsenic (As)	0.013 - 0.024*	<0.00001	0.0058 ± 0.0008 (0.0518)	95 (4)
Calcium (Ca)	—	<0.2	76.39 ± 4.37 (271.55)	115 (0)
Cadmium (Cd)	0.0011 – 0.0016^{H}	<0.00001	0.0001 ± 0.00001 (0.00062)	69 (0)
Cobalt (Co)	ID	<0.00002	0.0004 ± 0.0001 (0.0025)	85 (0)
Chromium (Cr)	ID - 0.006^{H}	<0.00005	0.0016 ± 0.0001 (0.0064)	92 (0)
Iron (Fe)	ID	<0.0005	0.99 ± 0.17 (7.45)	95 (0)
Mercury (Hg)	0.0006 - ID*	<0.00002	0.0009 ± 0.0001 (0.0046)	85 (42)
Potassium (K)	—	<0.2	15.12 ± 1.42 (84.93)	115 (0)
Magnesium (Mg)	—	<0.2	36.11 ± 3.2 (222.82)	115 (0)
Manganese (Mn)	1.9	<0.00005	0.01 ± 0 (0.03)	95 (0)
Sodium (Na)	—	<0.2	194.03 ± 20 (1304)	115 (0)
Nickel (Ni)	0.0480 – 0.0687^{H}	<0.00005	0.0017 ± 0.0002 (0.0181)	95 (0)
Selenium (Se)	0.011	<0.00005	0.0033 ± 0.0007 (0.02)	51 (0)
Uranium (U)	0.005+	<0.00002	0.00008 ± 0.00001 (0.00088)	93 (12)
Zinc (Zn)	0.0350 – 0.05^{H}	<0.00025	0.065 ± 0.004 (0.232)	95 (49)

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 in 2013/14. In 2014/15, Al concentrations were high in S.E. Goollelal, but reached up to 890 µg L^{-1} in Mid W. Joondalup and S.E. Joondalup. Aluminium was also exported into westerly bores (Table 4). Arsenic tended to be higher in the western bores, except around Wallubuenup where the eastern bore had the highest recorded concentration of 51.8 µg L^{-1}. Cadmium, Cr and Co concentrations show no particular trends spatially. Iron concentrations were high in the northern sections of Lake Goollelal and Mid W. Joondalup, but were highest at 7446 µg L-1 in W. Wallubuenup. This pattern was quite different to 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 July 2014 to April 2015 monitoring period with ANZECC & ARMCANZ (2000) water quality trigger values for 95% protection of aquatic ecosystems for metals and metalloids for reference.

	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	63 ± 29 (8-314)	1.62 ± 0.14 (0.96-2.37)	0.1 ± 0.04 (<0.01-0.4)	0.12 ± 0.02 (<0.02-0.25)	0.82 ± 0.13 (0.35-1.47)	57 ± 6 (32-95)
Mid W. Goollelal	40 ± 18 (8-195)	6.02 ± 0.76 (3.67-10.32)	0.12 ± 0.05 (<0.01-0.43)	0.56 ± 0.32 (<0.02-2.5)	1.03 ± 0.14 (0.17-1.71)	378 ± 111 (83-1284)
N.E. Goollelal	41 ± 8 (15-94)	0.76 ± 0.06 (0.48-1.15)	0.09 ± 0.03 (<0.01-0.24)	0.38 ± 0.24 (<0.02-2.5)	0.64 ± 0.08 (0.34-1.15)	3700 ± 534 (407-6009)
Mid E. Wallubuenup	35 ± 13 (9-151)	12.05 ± 4.5 (3.83-51.84)	0.05 ± 0.02 (<0.01-0.24)	0.37 ± 0.25 (<0.02-2.5)	2.84 ± 0.35 (<0.05-3.85)	72 ± 18 (27-222)
W. Wallubuenup	15 ± 7 (1-77)	1.49 ± 0.11 (0.95-1.97)	0.12 ± 0.04 (<0.01-0.28)	0.29 ± 0.25 (<0.02-2.5)	2.06 ± 0.13 (1.24-2.47)	4208 ± 438 (3049-7446)
S.E. Joondalup	222 ± 109 (33-818)	6.93 ± 0.65 (4.44-9.54)	0.02 ± 0.01 (<0.01-0.05)	0.46 ± 0.34 (<0.02-2.5)	1.66 ± 0.73 (<0.05-5.61)	25 ± 6 (11-47)
Mid E. Joondalup	17 ± 3 (7-34)	1.56 ± 0.05 (1.33-1.79)	0.23 ± 0.05 (<0.01-0.62)	0.36 ± 0.04 (0.21-0.64)	0.69 ± 0.09 (<0.05-1.06)	73 ± 29 (10-330)
Mid W. Joondalup	248 ± 93 (33-890)	22.47 ± 2.72 (14.26-38.3)	0.02 ± 0.01 (<0.01-0.07)	0.16 ± 0.03 (0.03-0.28)	3.63 ± 0.71 (0.8-6.36)	425 ± 136 (98-1193)
N.E. Joondalup	26 ± 11 (9-123)	1.19 ± 0.1 (0.71-1.75)	0.19 ± 0.06 (<0.01-0.57)	0.55 ± 0.33 (<0.02-2.5)	0.94 ± 0.09 (0.43-1.28)	328 ± 55 (100-621)
N.W. Joondalup	54 ± 15 (12-153)	5.52 ± 0.93 (2.08-11.29)	0.05 ± 0.01 (<0.01-0.12)	0.34 ± 0.27 (0.03-2.5)	1.61 ± 0.2 (0.26-2.41)	225 ± 30 (92-354)

Table 44. 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	1.12 ± 0.45 (<0.02-3.9)	1.93 ± 0.42 (0.18-3.94)	1.2 ± 0.07 (0.93-1.58)	0.2 ± 0.03 (0.09-0.34)	0.2 ± 0.08 (<0.02-0.88)	46.58 ± 12.99 (8.25-136.28)
Mid W. Goollelal	0.75 ± 0.28 (<0.02-2.5)	5.75 ± 0.71 (3.77-9.26)	1.69 ± 0.65 (0.74-7.5)	5.12 ± 2.5 (0.06-20)	0.01 ± 0 (<0.02-0.02)	44.54 ± 4.36 (26.55-69.08)
N.E. Goollelal	1.22 ± 0.46 (<0.02-3.8)	10.26 ± 0.88 (6-15.1)	0.98 ± 0.11 (0.57-1.52)	8.63 ± 3.11 (<0.05-20)	0.02 ± 0 (<0.02-0.04)	73.16 ± 17.06 (9.72-166.06)
Mid E. Wallubuenup	0.71 ± 0.34 (<0.02-3.2)	7.72 ± 0.4 (5.63-9.46)	0.9 ± 0.08 (0.53-1.37)	0.61 ± 0.14 (0.11-1.48)	0.11 ± 0.02 (0.04-0.2)	61.89 ± 9.98 (22.8-105.35)
W. Wallubuenup	0.53 ± 0.25 (<0.02-2.3)	20.71 ± 0.92 (17.36-25.01)	0.92 ± 0.08 (0.56-1.31)	6.71 ± 2.91 (<0.05-20)	0.03 ± 0.01 (<0.02-0.07)	82.19 ± 6.96 (36.18-111.17)
S.E. Joondalup	1.67 ± 0.74 (<0.02-4.6)	7.6 ± 1.06 (4.46-13.15)	1.25 ± 0.13 (0.68-1.68)	0.36 ± 0.11 (<0.05-0.73)	0.08 ± 0.02 (<0.02-0.16)	31.92 ± 9.75 (11.36-87.63)
Mid E. Joondalup	0.69 ± 0.3 (<0.02-2.9)	7 ± 1.25 (3.36-16.09)	2.03 ± 0.17 (1.38-2.79)	0.74 ± 0.24 (0.17-2.12)	0.01 ± 0 (<0.02-0.04)	89.07 ± 17.5 (38.09-231.57)
Mid W. Joondalup	1.14 ± 0.46 (0.03-3.88)	4.18 ± 0.58 (1.61-6.89)	5.96 ± 1.92 (1.63-18.11)	1.98 ± 1.14 (0.09-8.85)	0.05 ± 0.02 (<0.02-0.12)	105.22 ± 21.64 (38.16-224)
N.E. Joondalup	0.75 ± 0.31 (<0.02-3)	2.79 ± 0.23 (1.95-4.49)	1.06 ± 0.4 (0.21-4.57)	4.82 ± 2.55 (0.07-20)	<0.02 ± 0.18 (0.32-0.03)	43.28 ± 5.08 (24.2-72.71)
N.W. Joondalup	0.75 ± 0.25 (<0.02-2)	4.92 ± 0.39 (3.5-6.39)	1.17 ± 0.11 (0.6-1.66)	2.72 ± 2.17 (0.08-20)	0.09 ± 0.05 (0.01-0.5)	68.64 ± 5.72 (43.1-93.95)

[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.

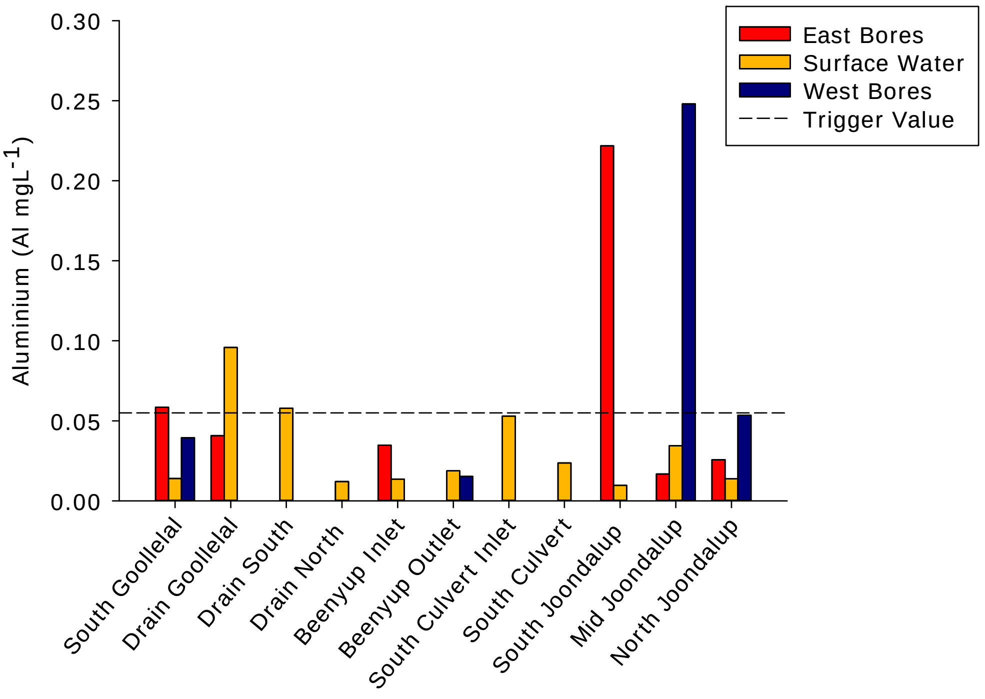
ID Insufficient data to derive a reliable trigger value.

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

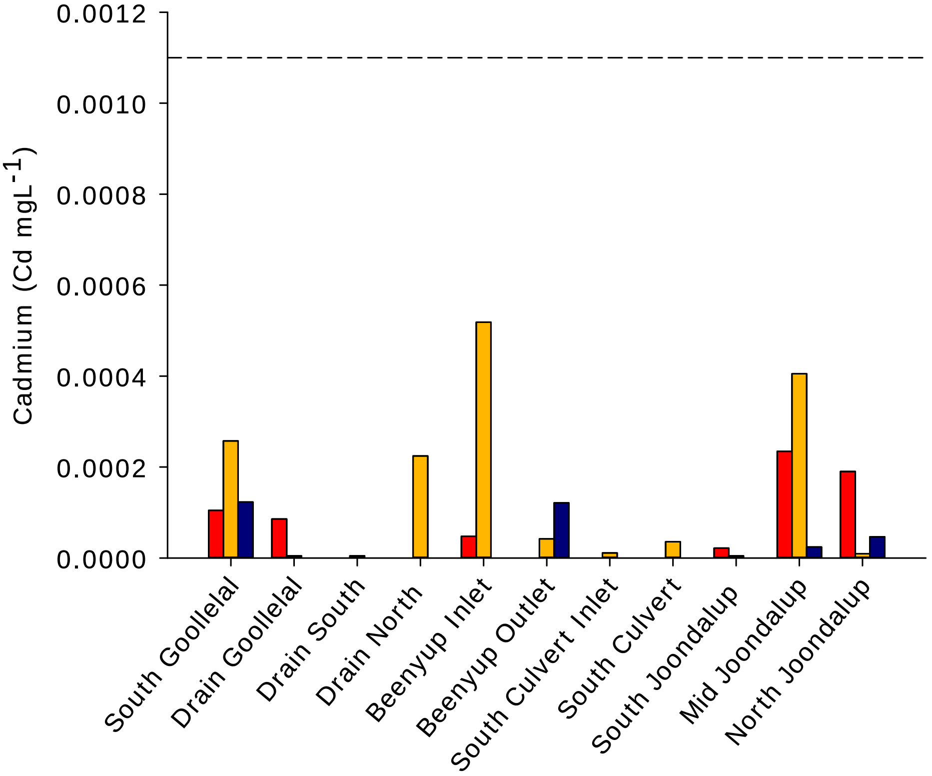
In 2014/15 Hg concentrations were substantially higher than in previous years, exceeding guideline levels at all bores. High Hg concentrations were recorded in the surface waters during 2014/15 and it would appear that the groundwater is the main source. Concentrations of Mn, Ni, Se, U and Zn were relatively similar across all the bores, although high one-off values were common.

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 in 2013/14, but this year this trend was less pronounced. Mercury concentrations were higher in surface waters suggesting that there were other sources of this metal in the system alongside groundwater. For Cd concentrations were generally higher in the surface waters, in contrast to 2013/14. Zinc concentrations were similar between eastern and western bores but significantly higher than found in the surface waters.

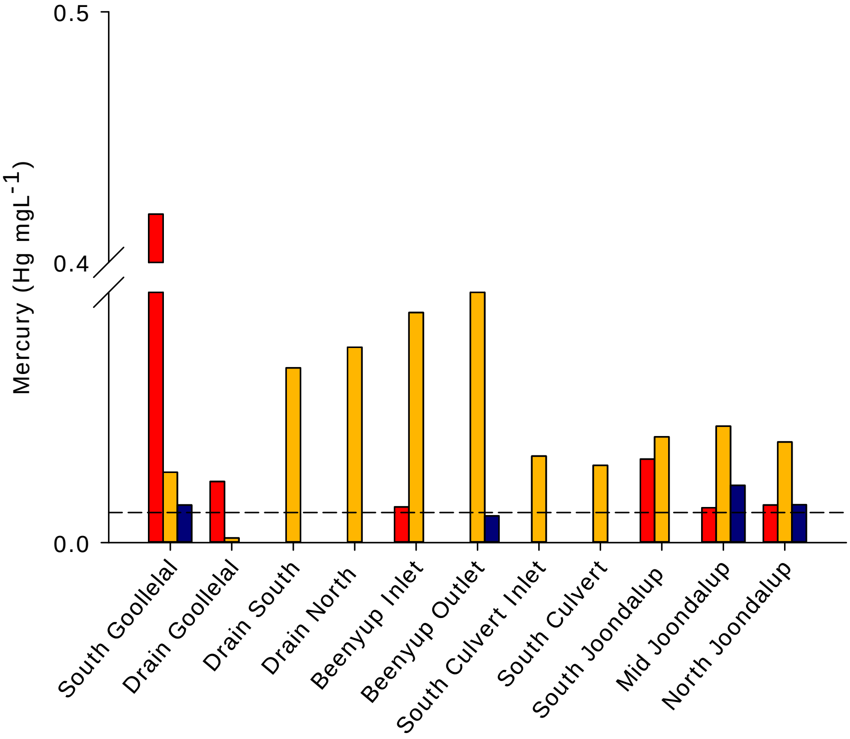
a) Aluminium



b) Cadmium



c) Mercury



d) Zinc

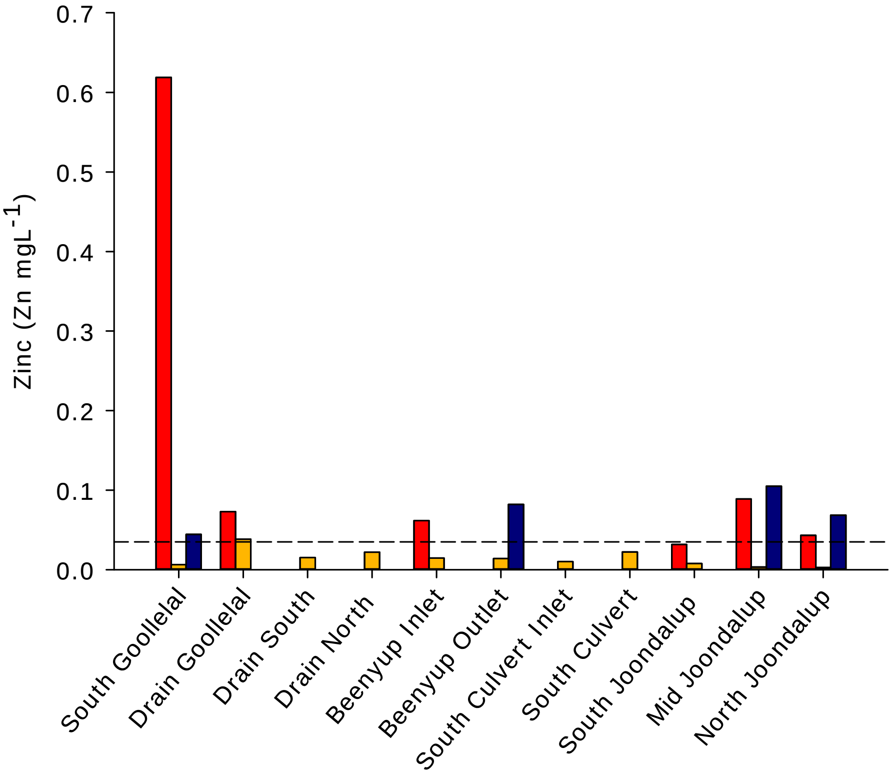


Figure 6. Mean (July 2014 to June (April for groundwater) 2015) metal concentrations for groundwater and surface water. Dotted lines indicate the ANZECC & ARMCANZ (2000) trigger value ranges for the protection of aquatic ecosystems (95%).

7.3 NUTRIENTS

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

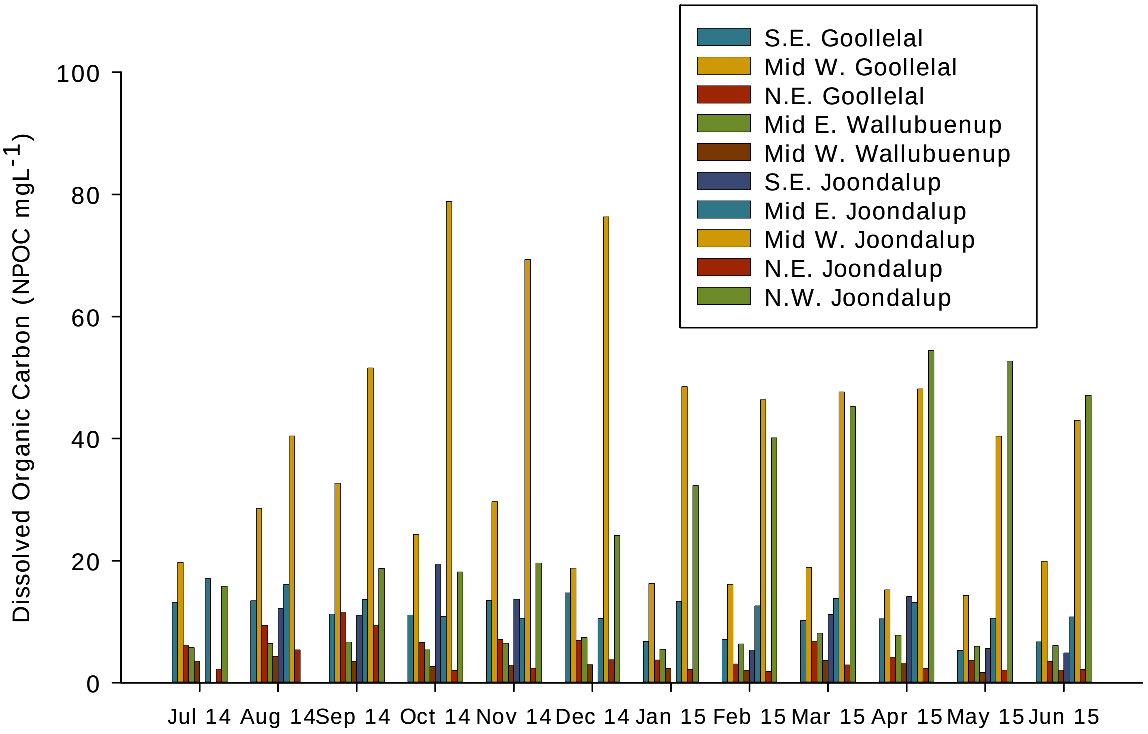
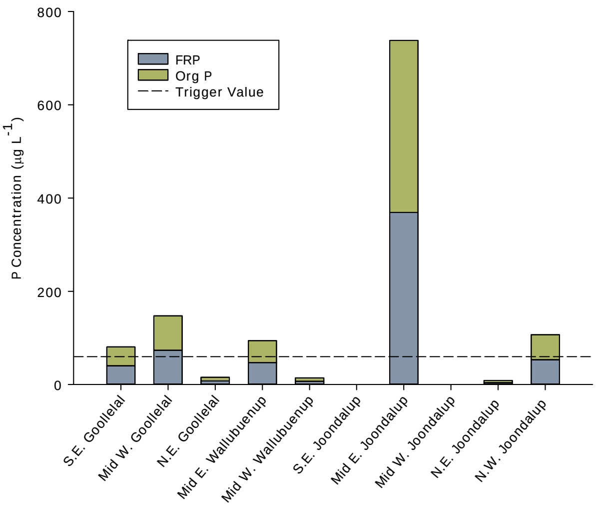


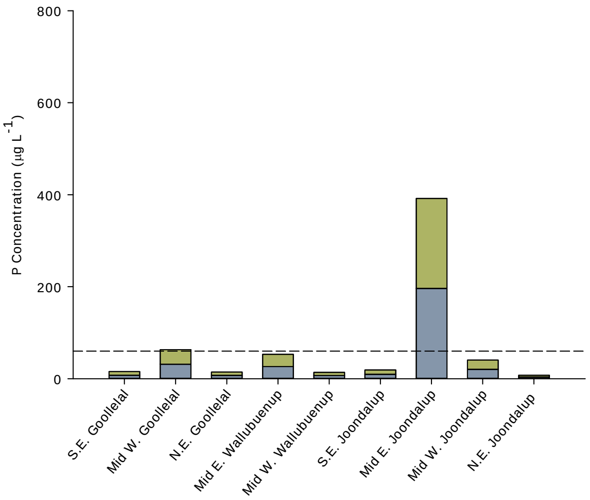
Figure 7. Dissolved organic C concentrations recorded in groundwater bores from July 2014 to June 2015.

Mid E Joondalup had the highest concentrations of FRP in April 2015 at 369 µg L^{-1}, although this was almost half that recorded in 2013/14. 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. The N.W. Joondalup bore was usually higher in P than N.E. Joondalup 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.

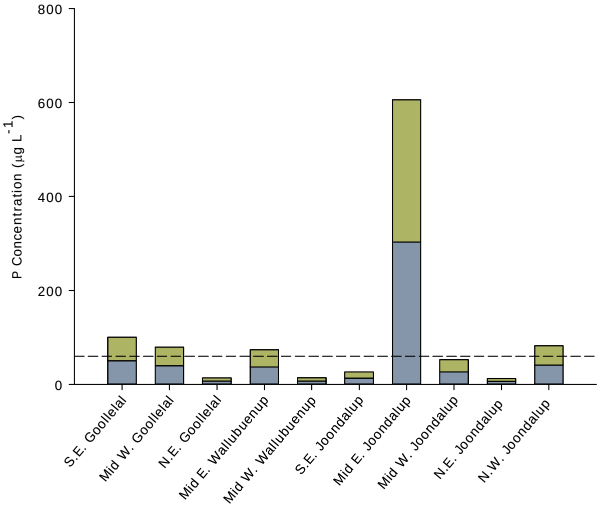
July 2014



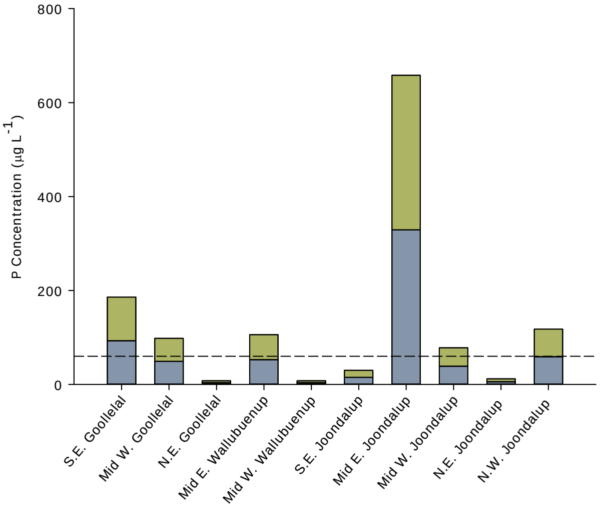
August 2014



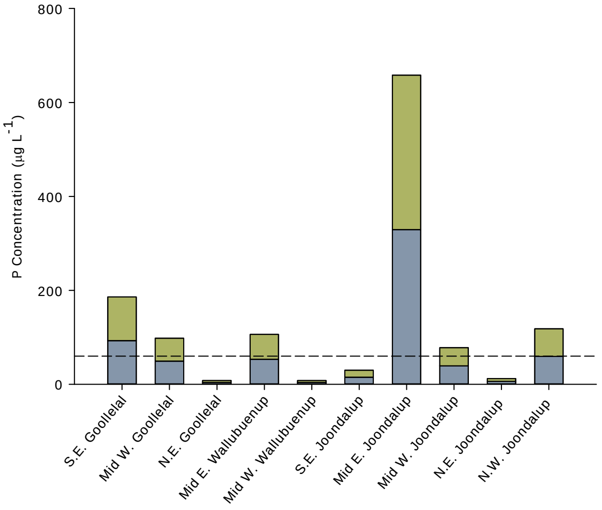
September 2014



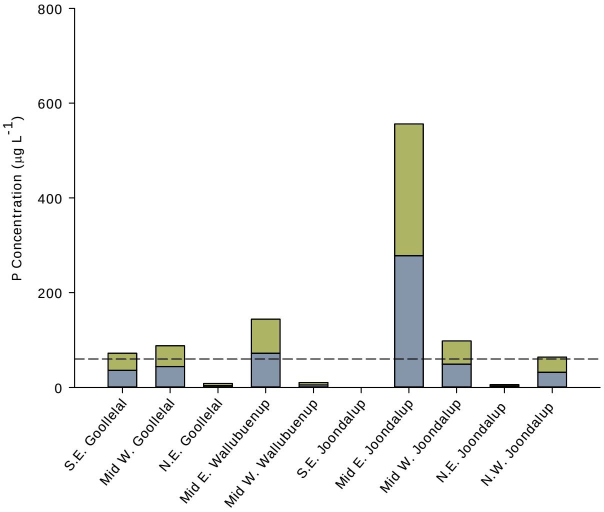
October 2014



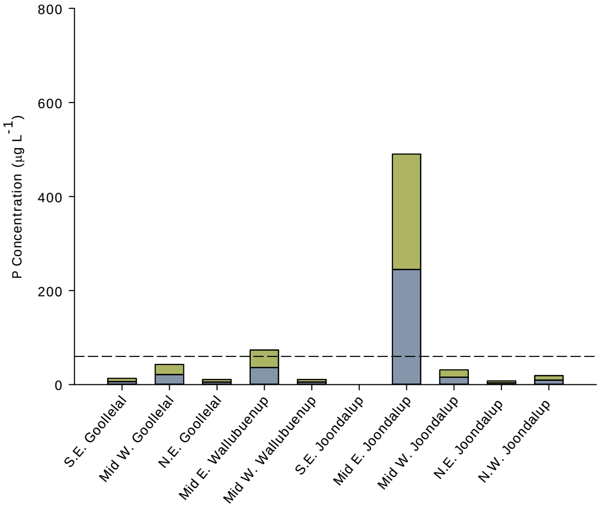
November 2014



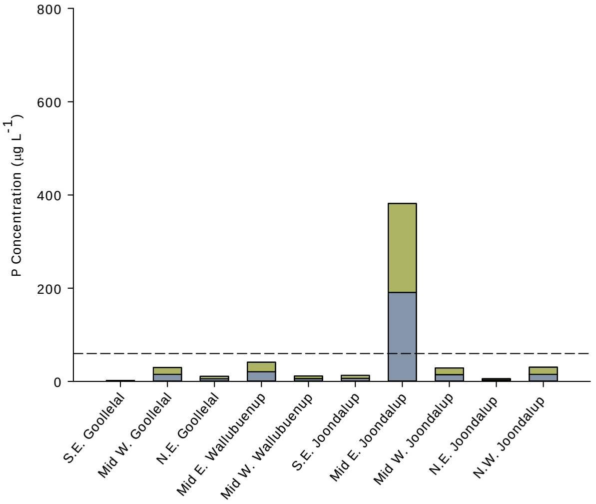
December 2014



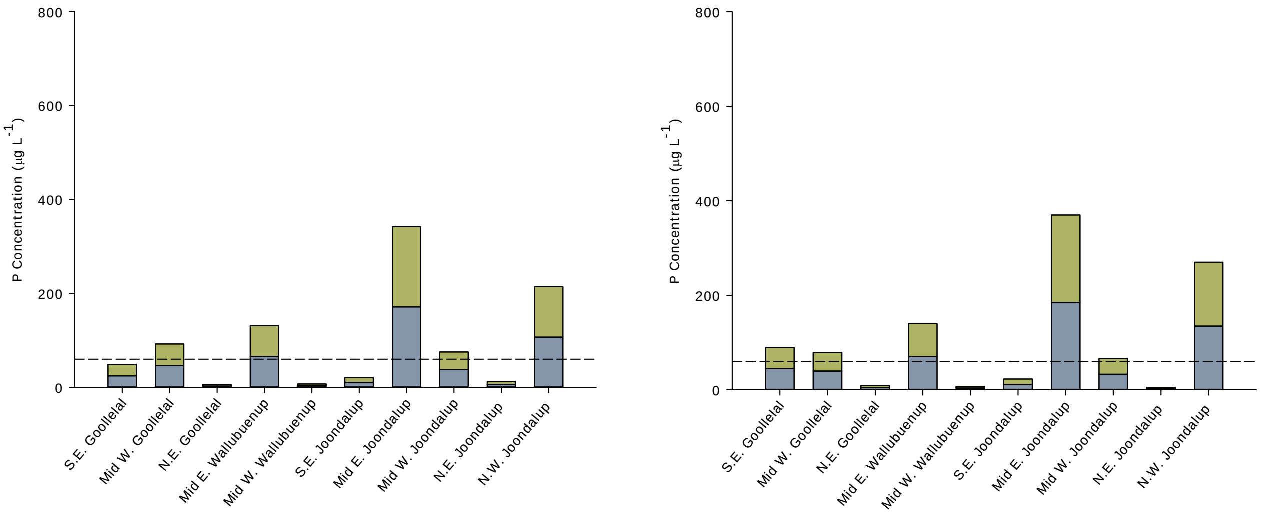
January 2015



February 2015



March 2015 **April 2015**



May 2014 **June 2014**

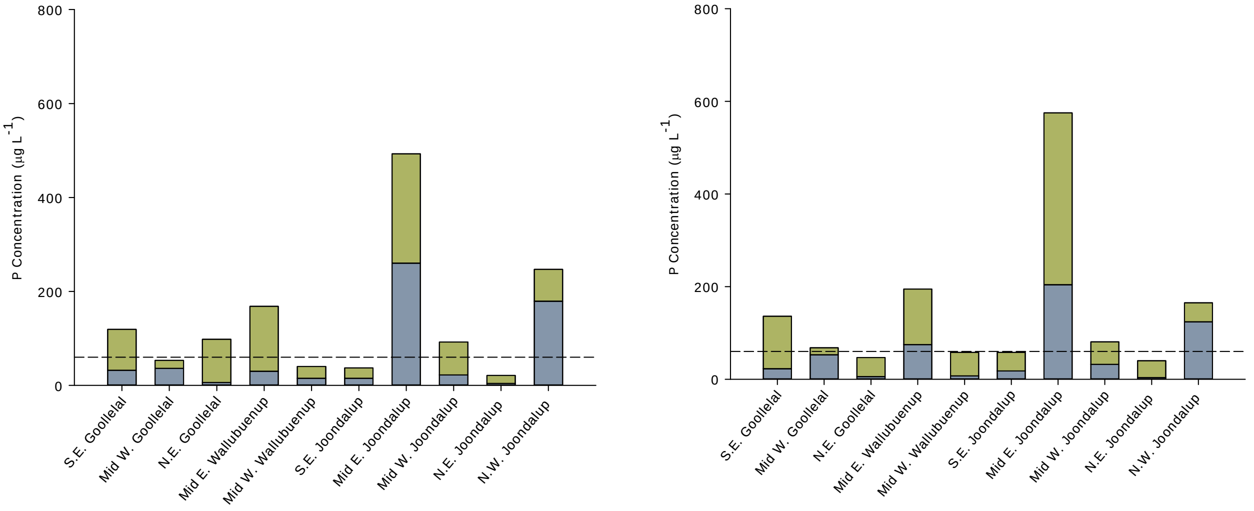
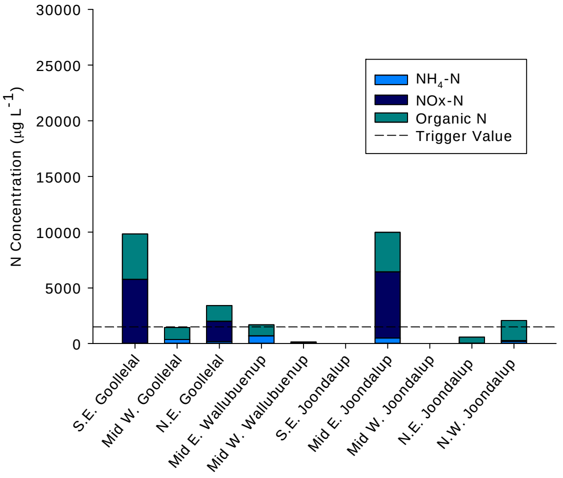


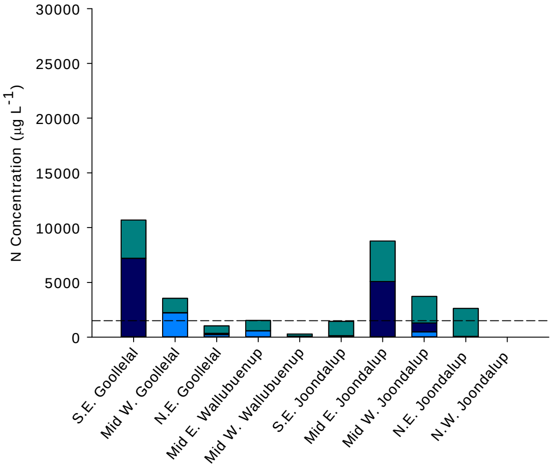
Figure 5. Breakdown of total phosphorus into chemical fractions (organic P and FRP) recorded in groundwater at each bore between July 2014 and June 2015 with the ANZECC & ARMANZ (2000) trigger value for total phosphorus shown.

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. 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. Mid E. Joondalup and S.E. Goollelal consistently had 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. Occasional spikes of NH_4 are seen in western bores. The source of this NH_4 for Mid W Joondalup is most likely the nearby South Lake Joondalup which had very high concentrations of NH_4 during May 2015. 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).

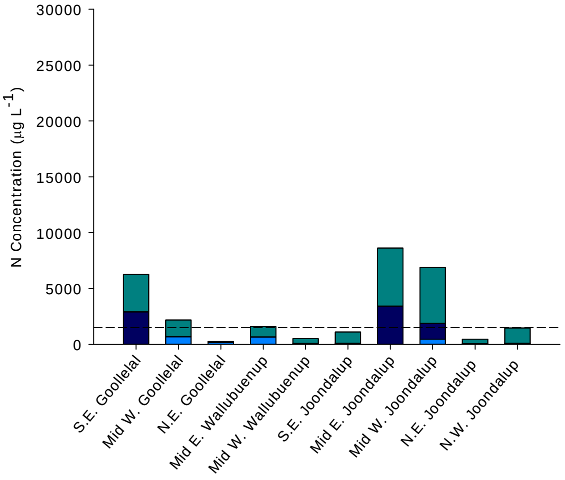
July 2014



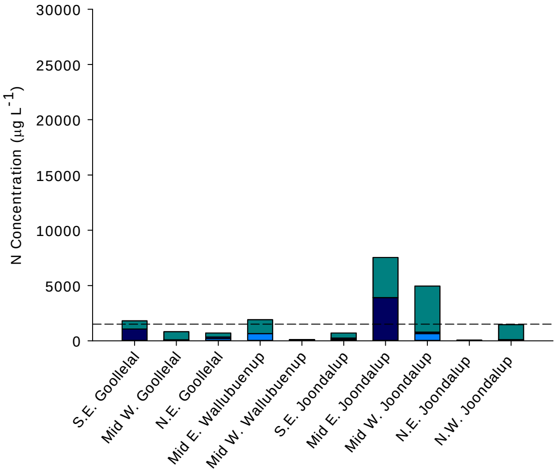
August 2014



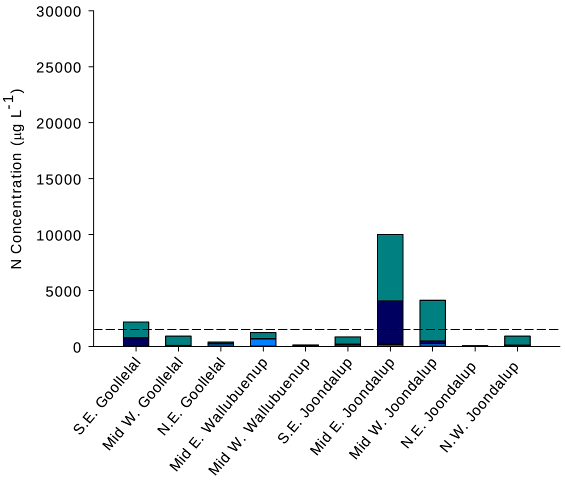
September 2014



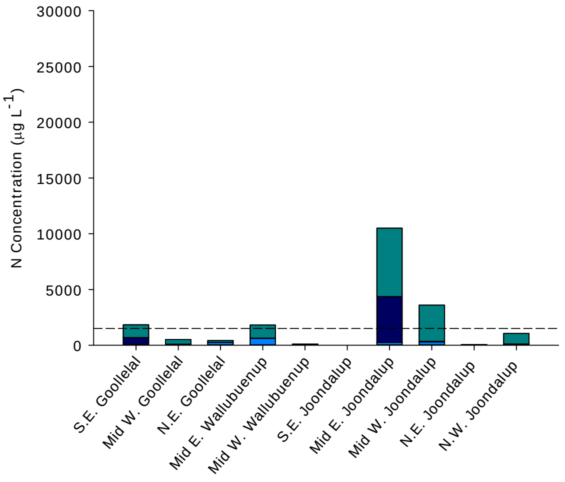
October 2014



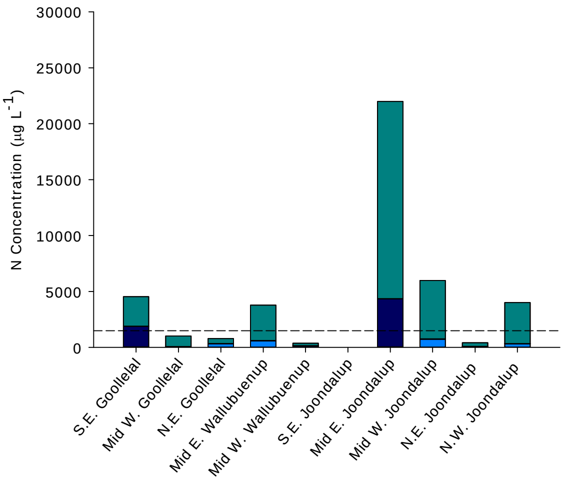
November 2014



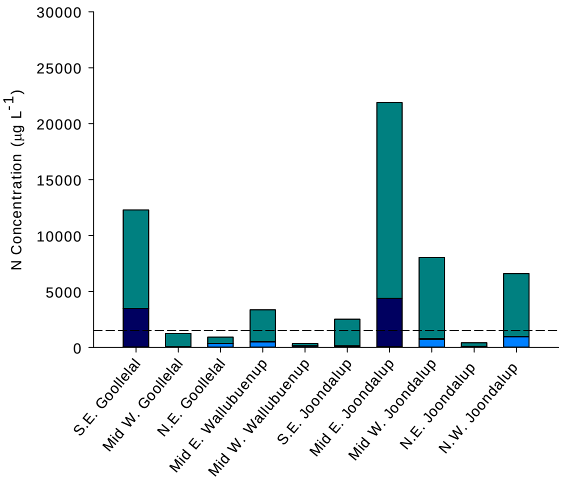
December 2014



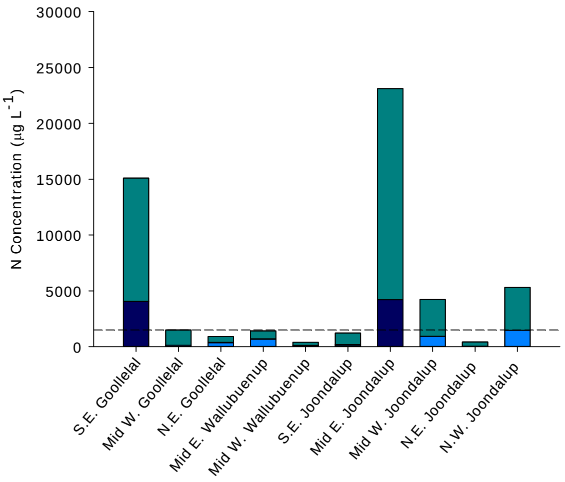
January 2015



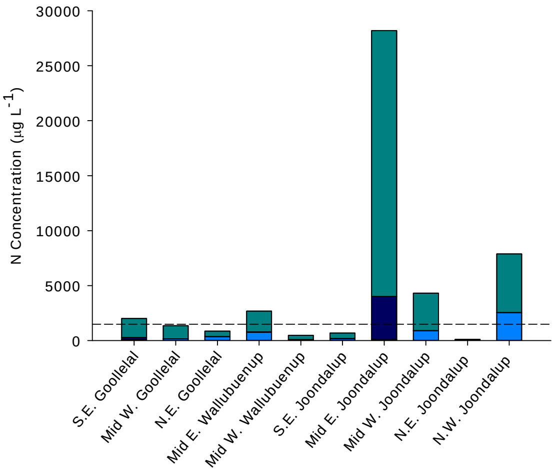
February 2015



March 2015



April 2015



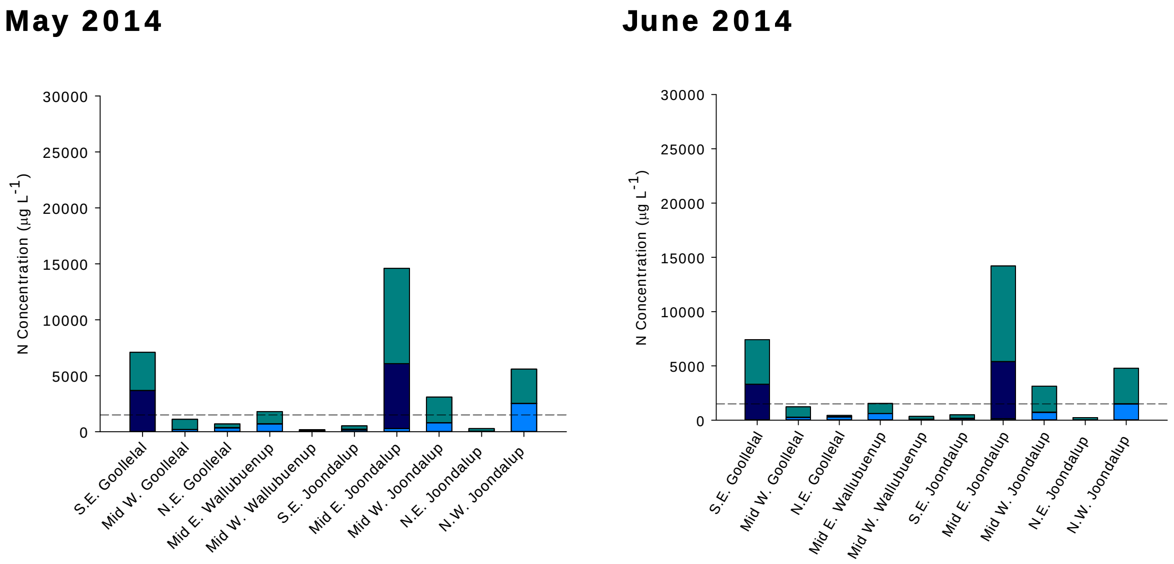


Figure 6. Breakdown of total nitrogen into chemical fractions (organic nitrogen, nitrate/nitrite (NO_x) and ammonium (NH_4)) recorded in groundwater at each bore between July 2014 and June 2015 with the ANZECC & ARMANZ (2000) trigger value for total nitrogen.

Table 5. Mean ± s.e. (range) for nutrients in water recorded at each bore over the course of the monitoring period (July 2014-June 2015), concentrations recorded as < were below the detection limit.

Detection Limit	**NH_4** **µg L^{-1}** **<3**	**NO_x** **µg L^{-1}** **<0.05**	**TN** **µg L^{-1}** **<0.5**	**FRP** **µg L^{-1}** **<0.5**	**TP** **µg L^{-1}** **<0.5**	**DOC** **mg L^{-1}** **<2**
ANZECC & ARMCANZ (2000) Trigger Value	**40 ugL^{-1}**	**100 ugL^{-1}**	**1500 ugL^{-1}**	**30 ugL^{-1}**	**60 ugL^{-1}**	**-**
SE Goollelal	324 ± 909 (11-2910)	3118 ± 2588 (206-7180)	6368 ± 5084 (1810-15100)	61 ± 71 (1-230)	263 ± 144 (49-510)	10.08 ± 4.34 (0.36-14.73)
Mid W Goollelal	393 ± 665 (57-2200)	9 ± 8 (1-29)	1461 ± 863 (523-3550)	39 ± 16 (15-74)	58 ± 26 (10-86)	22.04 ± 6.33 (15.22-32.69)
NE Goollelal	264 ± 82 (157-366)	231 ± 564 (5-1830)	693 ± 261 (256-1030)	5 ± 2 (3-8)	115 ± 104 (10-318)	6.53 ± 2.56 (3.09-11.47)
Mid E Wallubuenup	647 ± 80 (488-785)	12 ± 13 (1-41)	2105 ± 872 (1230-3780)	49 ± 18 (21-72)	192 ± 49 (88-260)	6.6 ± 0.94 (5.42-8.14)
Mid W Wallubuenup	104 ± 21 (82-143)	8 ± 4 (1-13)	293 ± 158 (108-518)	5 ± 1 (4-7)	69 ± 45 (6-130)	3.12 ± 0.7 (2-4.37)
SE Joondalup	123 ± 43 (51-167)	54 ± 37 (14-121)	1221 ± 636 (693-2520)	12 ± 4 (7-18)	155 ± 72 (70-301)	12.43 ± 4.19 (5.38-19.34)
Mid E mid Joondalup	126 ± 150 (23-494)	4304 ± 716 (3420-5950)	15063 ± 7759 (7540-28200)	256 ± 69 (171-369)	462 ± 167 (265-727)	13.17 ± 2.22 (10.52-17.06)
Mid W Joondalup	606 ± 242 (252-925)	304 ± 490 (8-1420)	5094 ± 1548 (3600-8040)	31 ± 12 (15-49)	191 ± 85 (113-379)	56.35 ± 14.38 (40.44-78.84)
NE Joondalup	49 ± 16 (24-73)	15 ± 7 (7-26)	526 ± 766 (53-2630)	4 ± 1 (3-6)	39 ± 32 (10-113)	3.46 ± 2.33 (1.88-9.34)
NW Joondalup	654 ± 863 (67-2550)	21 ± 26 (1-73)	3424 ± 2631 (918-7900)	55 ± 41 (10-135)	141 ± 98 (20-295)	29.85 ± 13.91 (15.81-54.46)

8. CONCLUSIONS

Ten bores (4 western, 6 eastern) were sampled for a broad range of physico-chemical parameters, nutrient and metal/metalloid concentrations between July 2014 and June 2015. 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 tended to be highly contaminated with metals/metalloids and nutrients. It appears likely that landfill around the edge of Lake Joondalup is responsible for the contamination of Mid E. Joondalup. The high level of contamination seen in Mid E. Joondalup bore, is reflected in north 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.

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 due to the recent addition of 2 new bores to the monitoring program. As the groundwater monitoring data set now extends over several years, it is revealing a detailed picture of how the groundwater is contributing to the contamination of the wetlands but also is responsible for the loss of contaminants leaving the wetlands. Improving the understanding of how groundwater interacts with the wetland chain is vital to better manage these groundwater dependent systems.

2. It is recommended that alkalinity be monitored in future as the alkalinity:sulphate ratio is a better indicator of acid sulphate soils (Department of Environmental Regulation 2015) than chloride:sulphate ratios.

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