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Nutrient and metal loads in and out of Beenyup Swamp

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Centre for Ecosystem Management

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ACKNOWLEDGEMENTS

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Figure 1. Beenyup Swamp input site, showing the boarding used to target and control flows for more accurate determination of flow volumes

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CONTENTS

1 EXECUTIVE SUMMARY

1. Beenyup Swamp has been identified in a number of studies as the major source of nutrients entering Lake Joondalup. In particular, it is believed to discharge close to 75% of the phosphorus entering Lake Joondalup annually. The most recent study to support this conclusion was the nutrient and water budget of Cumbers (2004)
2. The Lund (2007) midge audit conducted a one-off study of the southern Yellagonga Regional Park wetlands and concluded there were elevated metal and nutrient concentrations in the water and sediments of Beenyup Swamp and that output concentrations exceeded those of the input.
3. A study by Goldsmith *et al.* (2008) mapped sediment P concentrations across Beenyup Swamp and concluded that sufficient P was bound to sediment to supply the annual export quantity.
4. A study by Gunner *et al.* (2008) examined sediment nutrient release within Beenyup Swamp and concluded that the common forcing conditions (that would normally cause nutrient release) of anoxia, drying and bioturbation did not seem to cause nutrient release.
5. The Lund *et al* (2011) Yellagonga wetland study continued and extended the monitoring program commenced in the Lund (2007) midge audit without further sediment analysis. This study concluded that Beenyup Swamp was exporting more nutrients (P and N) than were entering.
6. This study aimed to quantify whether there was net export of nutrients (N and P) and select metals from Beenyup Swamp. In addition, this study aimed to confirm the previous suggestions regarding the quantity of nutrients entering Lake Joondalup from the southern Yellagonga wetlands. As groundwater springs in Beenyup Swamp may account for much of the nutrient load, groundwater was studied around the Swamp.
7. Stations were constructed at the inlet and outlet to Beenyup Swamp to allow automated and continuous measurement of flows through the system. Automated water samplers were triggered by high flows and at regular intervals to collect

samples for analysis of nutrients (P and N) and select metals and metalloids (Al, As, Ca, Cd, Co, Cr, Fe, Hg, K, Mg, Mn, Na, Ni, Se, U and Zn).

8. Water samples were collected between 11/8/09 and 27/8/10. Over 200 water samples were collected for the inlet and over 350 for the outlet. These were rationalised down to minimise analytical costs but ensure storm events and low flows were adequately sampled. Depths at the outlet were measured at 15 minute intervals for the entire time period and approximately half the period for the inlet due to equipment failure (replaced with manual measurements). Depths were converted to flows by the development of rating curves using measured velocities at a range of depths. As the project commenced during the time of highest flow, outlet structures were not as effective as they appeared (were being undercut) and were rebuilt and re-rated in April 2010. Batteries were changed and samples collected at 3-4 day intervals over the sampling period.

9. Piezometers (short groundwater bores) were installed (to a depth of 2 m) at four locations around the Swamp (3 on the eastern side, 1 on the western side). They were sampled at monthly intervals if they contained water.

10. Groundwater contained low concentrations (most at detection limits) of metals sampled. Although, there were initially high (up to 343 $\mu g\ L^{-1}$) FRP (filterable reactive P) concentrations in the central eastern bore, these by October had decline to <10 which was the typical concentration in the northern and southern eastern bores. High concentrations (407 to 1290 $\mu g\ L^{-1}$) were recorded in western bore; this would suggest that the wetland was exporting phosphorus to groundwater. Concentrations of ammonia (mean 116 $\mu g\ L^{-1}$) and NOx (mean 129 $\mu g\ L^{-1}$; nitrate and nitrite) were generally low in the west, with high levels of ammonia (mean 231 $\mu g\ L^{-1}$) and but similar levels of NOx (mean 124 $\mu g\ L^{-1}$) in the eastern bores. This suggests that the groundwater may be contributing N to the wetland. It should be noted that the piezometers were not deep and probably only intercepted the surficial groundwater, due to the clay layers encountered deeper groundwater could still be problematic to wetland water quality.

11. Over the study there was 1.06 GL of water released from the Swamp, with 1.14 GL entering via the connection to Wallubuenup Swamp. Rainfall contributed 0.013 GL directly to the Swamp. The small area of open water and shading by paperbarks is likely to have limited the significance of evapotranspiration (direct evaporation and plant transpiration) loses from the Swamp. It does not appear that there is a significant net gain or loss to the Swamp from groundwater. The difference between input and output is not considered significant and likely within the estimation errors. The water discharged from the Swamp was five times smaller than previously identified by Cumbers (2004). It is believed this was due to the improved data collection in this study has reduced the errors associated with the monitoring by Cumbers (2004) for this discharge.
12. The Swamp was a net exporter of Total P and all forms of N. The source of the P is most likely sediment release, with FRP being lost in the discharging groundwater as well. Ammonia and NOX are likely the result of sediment release or groundwater inputs. The total quantity of nutrients either exported from Beenyup or passing through for Total P was 415 kg, and Total N it was 1047 kg. These results are substantially smaller than those determined by Cumbers (2004), although errors associated with her flow determinations will translate to load errors. Loads of P and N discharged from Beenyup Swamp are still the most significant nutrient source for Lake Joondalup.
13. Beenyup Swamp was a net exporter of Fe, Mn and Zn with other metals generally not changing across the Swamp. These metals are most likely being liberated from the sediment and/or entering through groundwater. The release of Fe and the small changes seen in FRP are particularly interesting given the high potential for Fe to bind P.
14. Several potential strategies are proposed to reduce the high levels of P from entering Lake Joondalup. These are the potential diversion of flows around Beenyup Swamp (with sufficient water diverted into the Swamp to maintain its ecological values), development of the Southern section of Lake Joondalup (south of Ocean Reef Rd) into a nutrient stripping wetland.

15. It is recommended that an investigation into nutrients in the Southern section of Lake Joondalup be undertaken to determine what impact it is currently having on nutrients entering the main body of Lake Joondalup. This could also determine whether the Fe released from Beenyup Swamp was absorbing and removing the P that was also being discharged. Feasibility studies of flows bypassing Beenyup Swamp are recommended.

2 INTRODUCTION

A number of studies have found that Lake Joondalup is eutrophic (Congdon & McComb, 1976; 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). Nutrient and water budgets prepared by Congdon (1985, 1986) and Cumbers (2004) identified that significant quantities of water and nutrients entered the lake from the southern chain of Yellagonga wetlands. Much of the Yellagonga regional park and catchment was previously used for agricultural activities and it is possible that these activities pose a source of metal and nutrient contamination to the lakes. Furthermore, the main drain from the Wangara industrial area ends in a sump close to the border of the Park with an overflow pathway directly into Wallubuenup Swamp.

Lund (2007), Lund *et al.* (2011) and Kinnear (1997) found that levels of phosphorus leaving Beenyup Swamp were much higher than when they entered from Wallubuenup Swamp. This suggested Beenyup Swamp may have an internal source of phosphorus. Goldsmith et al. (2008) found that the central open water sediments of Beenyup Swamp contained very high concentrations of phosphorus (5.3 mg g^{-1}) and that most of this was probably bound to iron. Goldsmith et al. (2008) suggested that there was sufficient phosphorus in the sediments of Beenyup Swamp to account for the loads believed exported by Cumbers (2004). However, unless the sediments released phosphorus then this load could not be realized. Gunner et al. (2008) tested key factors typically responsible for sediment phosphorus release such as bioturbation, anoxia and drying without achieving significant sustained release. A conclusion from her study was that rather than being a source of nutrients the sediments were probably accumulating nutrients from a groundwater source.

This study aims to determine seasonal changes in nutrient and metal concentrations and loads entering and exiting Beenyup Swamp over a year. This will help confirm the significance of Beenyup Swamp as a source of nutrients to Lake Joondalup, determine the source of any nutrients and provide a baseline for any attempts at remediation or control. Specifically to;

- Quantify the surface water budget of Beenyup Swamp,
- Quantify nutrient loads in and out of the Swamp, which will confirm the significance of the Swamp as a source of nutrients to Lake Joondalup.
- Identify the likely source of any nutrients being exported from the Swamp.
- Quantify loads of select metals in and out of the Swamp.
- Recommend management actions and identify knowledge gaps for any issues identified.

3 METHODS

3.1 STUDY SITE

Yellagonga Regional Park lies on the coastal limestone belt of the Swan Coastal Plain (Kinnear *et al.*, 1997). The park is located in the north-west corridor of Perth and is approximately 20 km north of Perth's central business district. Yellagonga Regional Park covers about 1,400 ha and contains Lake Goollelal, Wallubuenup[1] Swamp (divided into a northern[2] and southern section by Woodvale Drive), Beenyup Swamp, and Lake Joondalup (unevenly divided into a larger northern and smaller southern section by Ocean Reef Rd). All the lakes are interconnected with a natural drainage line[3] (Figure 2), where water flows northwards following the height of the land from Lake Goollelal at 27 m AHD (Australian Height Datum) to Wallubuenup Swamp at 19 m AHD to Beenyup Swamp at 18 m AHD and onto Lake Joondalup at 18 m AHD. The wetlands are nestled in an interdunal depression with a high plateau sloping to the west and generally flat to slightly undulating slopes to the east. (Kinnear *et al.*, 1997). The park is managed by the Cities of Wanneroo and Joondalup, and Department of Environment and Conservation under the Yellagonga Regional Park Management Plan (Dooley *et al.*, 2003).

Urbanisation has increased surface flows into the wetlands through decreased infiltration in the catchment area (Kinnear *et al.*, 1997). This and increased usage of the Gnangara groundwater mound has altered the hydrology of the wetlands. Perth's Mediterranean climate of cool wet winters and hot dry summers, ensure that most of the swamps are normally dry towards the end of summer. Although occasionally dry in the past (Hamann, 1992), since 1999 Lake Joondalup has dried annually to small pools. Lake Goollelal has

[1] Often referred to as Walluburnup Swamp

[2] Whitfords Avenue also cuts off a very small section of the southern end of Wallubuenup Swamp. Between Whitfords Avenue and Hocking Rd is a small section of drain joining Lake Goollelal and Wallubuenup Swamp.

[3] Although water would have naturally flown over land between these wetlands, in some sections a more clearly defined drain has been constructed to facilitate flow.

permanent water. Wallubuenup Swamp dries annually while Beenyup Swamp dries on occasion.

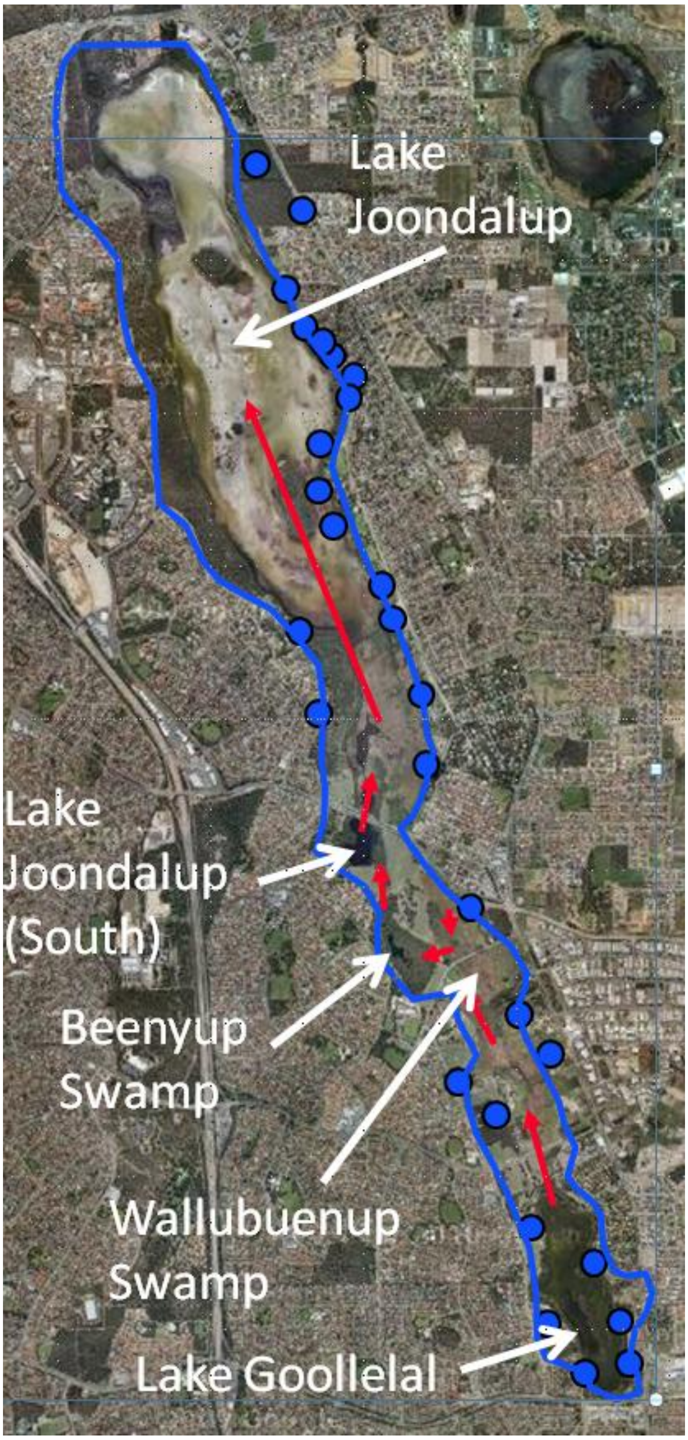


Figure 2. Direction of water flow through the Yellagonga Regional Park wetlands. Blue dots indicate drains entering the system; taken from Ove Arup & Partners (1994) and GoogleMaps (2011).

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

Although the surrounds and parts of Yellagonga Regional Park have been subject to agriculture and more recently urban development, Beenyup Swamp remains highly vegetated. Stands of paperbark (*M. rhaphiophylla*) dominate the landscape, whilst a large portion of the fringing vegetation of Lake Joondalup has been replaced by lawn areas (Upton, 1996). Wallubuenup Swamp has been subject to frequent fires and has no open water with most of the swamp being covered in *Typha orientalis*. Lake Goollelal has properties and public open space bounding to the waters edge but fringing vegetation generally remains in good condition.

The following sites within Yellagonga wetlands were sampled (Figure 3)

In – the inlet to Beenyup Swamp, marked by a wooden raised pathway
Out – this is the outlet to Beenyup Swamp and is marked by the culvert and bridge.

Figure 3.Location of the study sites in Beenyup Swamp (adapted from Google Earth).

These sites were chosen to capture all surface inflows into and outflows from Beenyup Swamp. Photographs of the sites are shown in Figure 4.

a) In (northwards)

b) In (southwards)

c) Instrumentation at Out

d) Weir at Out (east)

Figure 4. Photographs of the sampling sites in Yellagonga Regional Park.

Three piezometers (2 m deep) were installed on the western side of the lake and one on the eastern side (Figure 3). They consisted of 60 mm PVC pipe, slotted in the bottom 0.6 m. A hand auger was used to prepare a slightly larger hole which was backfilled around the pipe with gravel. The top of the pipe was raised 0.2 m off the ground to prevent surface ingress and capped (Figure 5).

Figure 5. Photograph of the north eastern piezometer installed at Beenyup Swamp

3.2 SAMPLING

At both the inlet and outlet sites an automatic sampling station was constructed, consisting of an ISCO Autosampler (6700) and ISCO bubble flow meter. Sampling and depth sensing occurred in stilled water behind weir structures. Weirs were installed in July 2009 when water levels were at maximum, this created significant problems for the outlet, which was rebuilt several times (with a major reorganisation in April 2010) to overcome poor sealing to the sediment and subsequent undercutting of the weirs.

At Beenyup In, there is a raised wooden walkway across the channel between Wallubuenup Swamp and Beenyup Swamp. The profile of the channel is very wide and shallow; therefore to concentrate the flow, sections of the walkway were sealed to the sediment using 16mm plywood (bonded with marine grade glue). There are 14 sections demarcated by the support pillars (2-3 m intervals). Of these 5-11 were left open (counting northwards), however this was reduced to 5-7 and 11 on August 2009, later in April 2010, 7 was blocked. Each section had the depth to sediment profiled across its length at 5 equally spaced points. These data were used to create cross-sectional areas for any measured water depth.

Beenyup Out was constructed at the concrete culvert/bridge. This structure has two flow channels, both sides had weirs made of 16 mm plywood (bonded with marine grade glue) installed. The weir was designed to create a simple rectangular profile across the entire channel. The weirs were initially installed at 50-150 mm above the sediment due to the depth of water at the time of installation. Later it became apparent that the weirs were being undercut which was reducing their accuracy at high flows, despite a number of attempts to rectify, in April 2010, the weirs were lowered to <50 mm above the sediment. Initially the eastern weir was used for monitoring; however it receives lower flows than the western side, so in April 2010 the western side was used for monitoring.

At both sites, YSI (6000XL) probes were installed in the channels to measure at 30 min intervals, pH, oxidation reduction potential (ORP), conductivity, temperature and dissolved oxygen (% saturation and mg L^{-1}). At approximately monthly intervals, the probes were recovered and data downloaded. They were then cleaned and recalibrated before being redeployed.

The depth versus flow relationship was determined for both inlet and outlet sites, using a Marsh McBirney flow meter. This was used to generate a rating curve that was then used to program the autosamplers and determine flows. New rating curves were constructed after April 2010 to reflect the alterations made to the weirs. The autosamplers were programmed to take samples after a predetermined quantity of water had passed the weir. The quantities were varied through the sampling program to ensure that all important phases of the storm hydrograph were sampled. Samples were collected twice per week and if necessary manual samples were collected where no autosampler samples were taken.

For each water sample collected (1 L), an unfiltered aliquot (subsample) was frozen for later determination of total nitrogen (total N[4]) and total phosphorus (total P). A filtered (through 0.5 µm Pal Metrigard filter paper) aliquot was frozen for later determination of

[4] All nutrients are reported as per their respective elements i.e. Total N-N, Total P-P, FRP-P, NOx-N and NH_3-N

nitrate/nitrite (NO_x), filterable reactive phosphorus (FRP) and ammonia (NH_3). Another filtered aliquot was acidified with nitric acid (1%) and then kept at 4^{o}C for later determination by ICP-OES for a range of metals (Al, As, Ca, Cd, Co, Cr, Fe, Hg, K, Mg, Mn, Na, Ni, Se, U & Zn).

The groundwater bores were sampled at monthly intervals, a bailer was used to collect the sample. Where possible, the bailer was used to empty the bore before allowing it to refill, then a sample was taken. The sample was filtered through 0.5 µm Pall Metrigard™ filter papers and then an aliquot was frozen for later determination of NOx, FRP and NH_3. A further aliquot was acidified with nitric acid (1%) and then kept at 4^{o}C for later determination by ICP-OES 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) using standard methods as per APHA (1998).

4 RESULTS

4.1 WATER BUDGET

4.1.1 INLET

Inlet data was taken at 15 minute intervals until April 2010, after which due to equipment issues, the depths were measured manually. The total estimated inflow was 1.14 GL, although the reduced intensity of measurement after April 2010 is likely to have reduced the accuracy of the estimate during this period. The daily flows are shown in Figure 6a, flows were taken as being consistent over the time between measurements and after April 2010, total flows were divided by the number of days between measurements to estimate daily flows (this is reflected in the more stepped pattern seen after April 2010. On occasion between February and March 2010, there was no inflow into the Swamp. The maximum daily flow was recorded on the 21/8/09 at 20,162 m^3 d^{-1}, reflecting the 108.4 mm of rainfall the preceding 11 days (Figure 6b). The only other similarly intense rainfall event was 107.6 mm over 5 days that occurred in July 2010. This resulted in peak flows of 13,582 m^3 d^{-1} over 13-15/7/10, however this flow peak may have been higher but the interval between sampling does not allow it to be estimated. The highest single daily rainfall event (43.2 mm) occurred on 23/3/10 (this was Perth's worst hailstorm on record). There had been no rainfall for the preceding 122 days. On the 9/3/10, a small flow of 563 m^3 d^{-1} was measured after a week of no flows; by 16/3/10 this had increased to 811 m^3 d^{-1}, but jumped to 1805 m^3 d^{-1} on 23-24/3/10 before returning back to baseflow on the 1/4/10. The event generated an estimated increase above baseflow of 4,016 m^3. As this additional flow can only have come from rainfall, it can therefore be used to estimate the size of the catchment at 9.3 Ha. This suggests that runoff alone from the section of Wallubuenup Swamp north of Woodvale Drive would have been sufficient to generate this. Despite relatively low annual rainfall, there was water flowing through the system for most of the year, suggesting that much was groundwater derived.

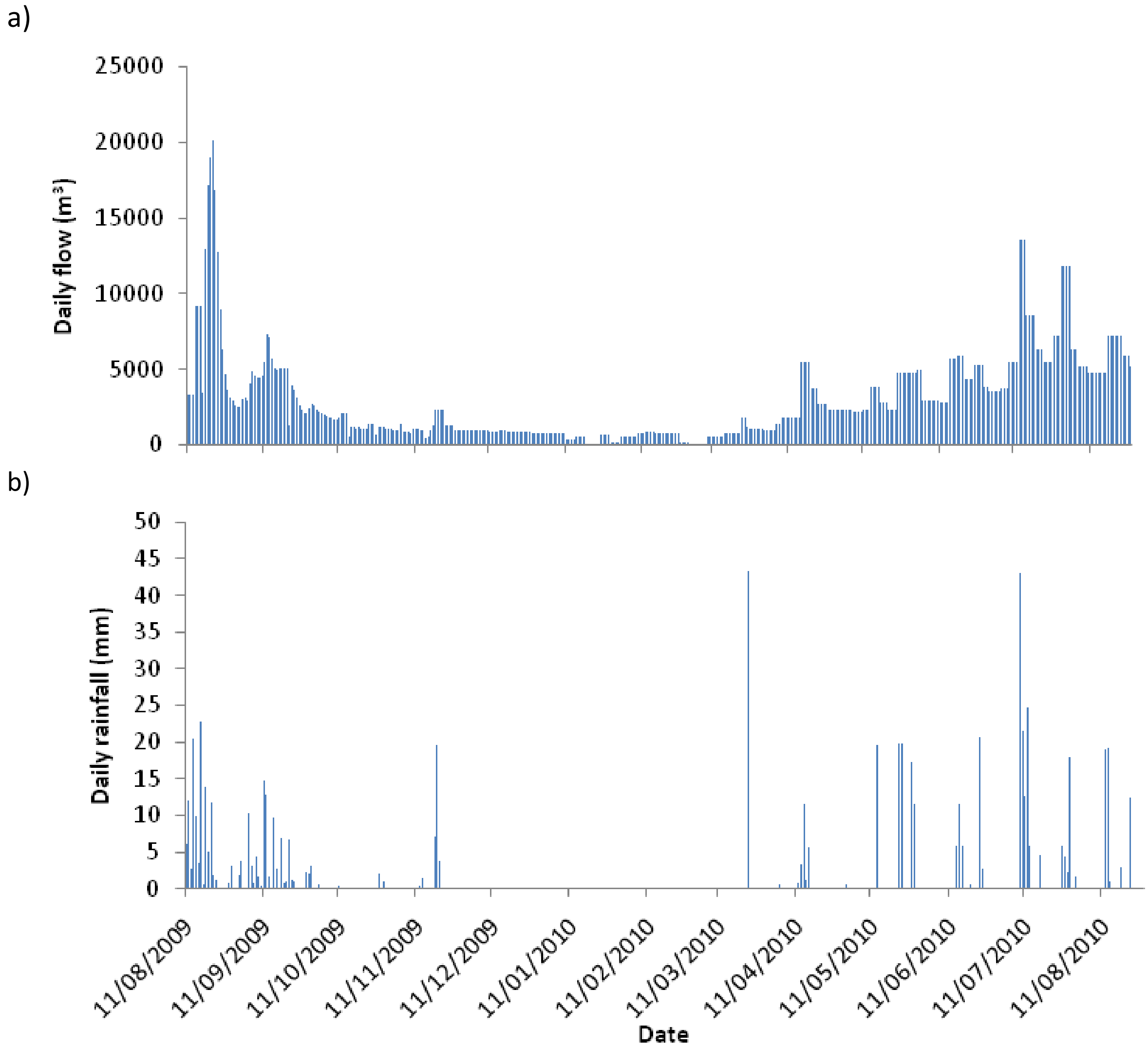


Figure 6. Total daily a) flow and b) rainfall for the inlet to Beenyup Swamp over the study period.

4.1.2 OUTLET

Almost complete records at 15 minute intervals were possible for the outlet from Beenyup Swamp. The daily flows are shown in Figure 7, noticeable is the flatten pattern prior to April 2010. This is believed to be due to undercutting of the weir which meant that peaks seen post April 2010 were absent. Therefore these daily flows are likely underestimates of the true flow. A total of 1.06 GL of water is estimated to have left the Swamp during the study. There was no outflow between 16/1/10 and 29/3/10. The maximum discharge occurred on 18/8/09 at 12,578 m^3 and remained at >11,000 m^3 until 8/9/09. Compared to the inlet, the peak occurred a few days earlier but high flows lasted longer. These results also reinforce the hypothesis that undercutting of the weir was underestimating outflows as it is reasonable to expect a peak in the outlet after the peak in the inlet, which did not occur. Overall, the Swamp appears to be able to absorb peak flows from the inlet and release them more slowly through the outlet. This is believed to be due to the outlet being slightly higher than the inlet. The outlet clearly shows the impact of the 23/3/10 rainfall event which saw flows remain at 0 m^3 discharge until 30/3/10 when the first discharge commenced, peaked on the 2/4/10 at 9,044 m^3 before stopping altogether on the 4/4/10. It took 18,773 m^3 of inflow and 864 m^3 of direct rainfall to fill the Swamp sufficiently to cause discharge. There appears to a 2 day residence time in the Swamp between rainfall and discharge (e.g. 49.6 mm on 22-23/5/10 and peak discharge on 25/5/10).

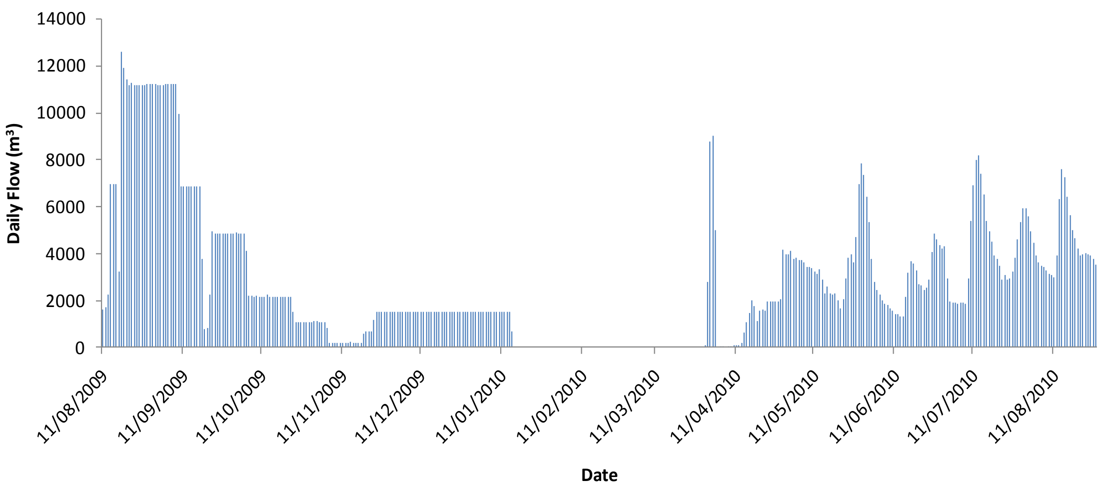


Figure 7. Total daily flows from the outlet of Beenyup Swamp.

4.1.3 WATER BUDGET

A nutrient and water budget was prepared for December 1979 to December 1980 for Lake Joondalup by Congdon (1985, 1986). In the budget, 3.4 GL (a billion litres) of water entered the lake through precipitation, 0.9 GL through surface inflows (stormwater and water passing under the old Ocean Reef Rd culvert), with 5.0 GL lost to evaporation, leaving a net gain of 0.8 GL from groundwater (difference between inputs and loss). Cumbers (2004) found for the year September 2003 to August 2004, that there was 4.3 GL from precipitation, 5.3 GL from the southern drain (only 1.2 GL estimated to pass under the Ocean Reef Culvert), 0.2 GL from stormwater drains, a 2.4 GL increase in lake volume and 8.1 GL lost to evaporation (+ transpiration) and a further loss of 2 GL in groundwater. Cumbers (2004) increased the amount of evaporation by including the estimated rate of transpiration from the beds of rushes, which Congdon (1985) did not include. Interestingly these findings show that despite the number of low rainfall years recently experienced in Perth that the two water budgets are remarkably similar. Rainfall being very similar at 609.2 mm in 2004 and 646.6 mm in this study; data from Perth Airport (Bureau of Meteorology). Changes to the Ocean Reef Rd culvert and a slight increase in stormwater drains have increased surface runoff into the lake slightly. The differences in groundwater inputs between the two studies are probably related to time periods over which each study was conducted rather than substantial changes in the groundwater in and outflows. In this study of Beenyup Swamp, it appears that Cumbers (2004) might have over-estimated flows from the Swamp by almost 5 fold. In Cumbers (2004) it was assumed that the difference between the water moving under the culvert into Lake Joondalup and that arriving from Beenyup Swamp was due to filling and loss of the south of Ocean Reef Rd portion of Lake Joondalup. However this amounted to 4.1 GL which is not that likely given that this portion of the lake holds between 20 and 30 ML of water. The revised estimate from this study seems much more appropriate at just over 1 GL. Cumbers (2004) collected significantly less data than this study, did not use proper monitoring stations, and this may account for the discrepancy.

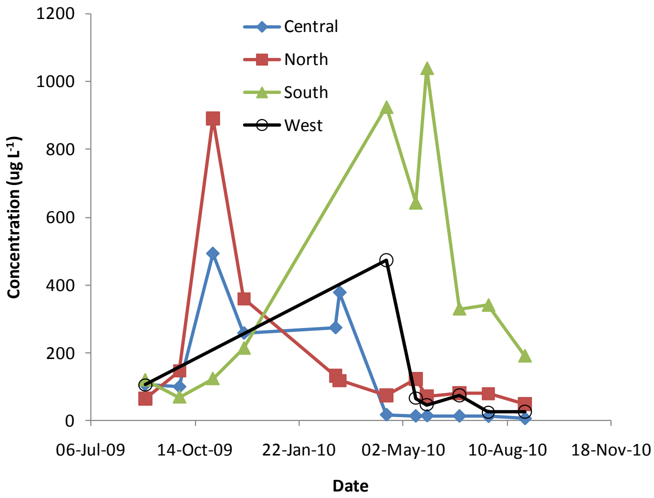
4.2 GROUNDWATER

Although there were initially high (up to 343 µg L^{-1}) FRP (filterable reactive P) concentrations in the central eastern bore, these by October had decline to <10 which was the typical concentration in the northern and southern eastern bores (Figure 8). High concentrations (407 to 1290 µg L^{-1}) were recorded in western bore; which would suggest that the wetland was exporting P to the groundwater. Concentrations of ammonia (mean 116 µg L^{-1}) and NOx (mean 129 µg L^{-1}) were generally low in the west, with high levels of ammonia (mean 231 µg L^{-1}) and but similar levels of NOx (mean 124 µg L^{-1}) in the eastern bores. This suggests that the groundwater may be contributing N to the wetland. It should be noted that the piezometers were not deep and probably only intercepted the surficial groundwater, due to the clay layers encountered deeper groundwater could still be problematic to wetland water quality.

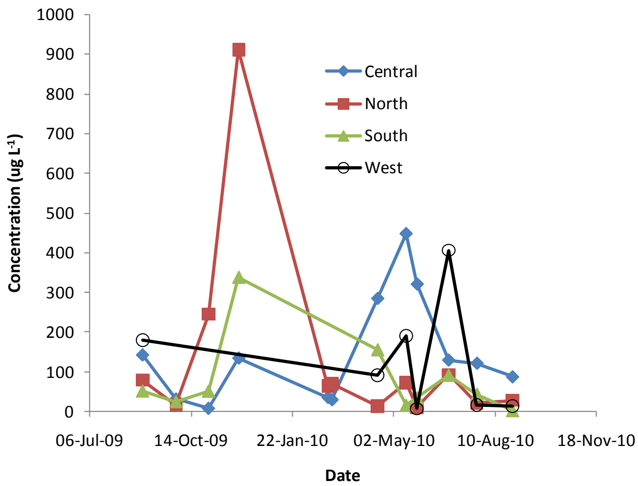
The concentrations of Al (<0.1, with two exceptions of 0.27 and 0.52 mg L^{-1}), As (<0.05, except 0.12 mg L^{-1} on 27/8/09 for the central eastern bore), Cd (<0.01), Co (<0.01), Cr (<0.01 mg L^{-1} except on 14 occasions which ranged between 0.01-0.02 mg L^{-1} only in eastern bores), Hg (<0.1), Se (<0.02) and Ni (<0.02, except on 30/11/09 for central eastern bore at 0.03mg L^{-1}) were all below detection in the groundwater samples (Table 1). Common ions such as Ca, K, Mg, Fe, and Na were all recorded in relatively low concentrations. Uranium and Zn were recorded above detection limits on occasion. Zn concentrations exceeded ANZECC/ARMCANZ (2000) guidelines. There are only interim guidelines for U at 0.5 µg L^{-1}, which were revised by Hogan et al. (2005) to 6 µg L^{-1}. These concentrations were frequently exceeded in the groundwater.

Congdon (1986) suggested that the high calcium carbonate content in the sands surrounding the lake would be effective at binding P leaving the lake in groundwater. However Cumbers (2004) found relatively high concentrations of P in groundwater from a number of bores on the western side of the lake. High P concentrations in the groundwater used to supply artificial lakes such as the ECU Campus Lake and Central Park Lake are responsible for algal blooms that have occurred in these lakes. This suggested that there was a loss of P from the lake into the groundwater. This study also found high P concentrations in the western bore, suggesting export of P from Beenyup Swamp. However, there were decreases in incoming Fe and ammonia from east to west suggesting release into Beenyup Swamp surface waters.

a)



b)



c)

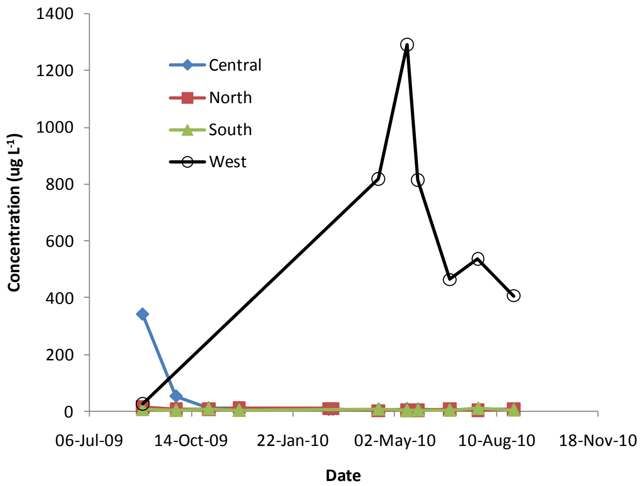


Figure 8. Concentrations of a) ammonia, b) NOx and c) FRP from bores around Beenyup Swamp.

Table 1. Exceedance of ANZECC/ARMCANZ (2000) water quality guidelines for the 95% protection of aquatic ecosystems for metals and metalloids recorded in this study

Metal/ Metalloid (mg L^{-1})	ANZECC/ ARMCANZ (2000) Trigger Value	Detection Limit	Mean ± se (maximum value)		No. exceeding detection limit (No. exceeding trigger value)	
			East	West	East	West
Aluminium (Al)	0.055	<0.1	<0.1-0.27	<0.1-0.52	1 (1)**	1 (1)
Arsenic (As)	0.013 - 0.024*	<0.05	<0.05-0.12	<0.05	1 (1)**	
Calcium (Ca)	—	<0.05	63.9±4.8 (179)	64.4±7.9 (88)	34	7
Cadmium (Cd)	0.0009^{H}	<0.01	<0.01	<0.01**		
Cobalt (Co)	ID	<0.01	<0.01	<0.01		
Chromium (Cr)	ID - 0.004*	<0.01	<0.01-0.02	<0.01	14 (14)**	
Iron (Fe)	ID	<0.05	2.1±0.7 (17)	0.4±0.1 (0.8)	30	6
Mercury (Hg)	0.0006 - ID*	<0.1	<0.1	<0.1**		
Potassium (K)	—	<0.5	4.6±0.3 (9.7)	10.3±1.2 (14.9)	34	7
Magnesium (Mg)	—	<0.1	14.2±1.9 (56.6)	14.3±0.8 (31.79)	34	7
Manganese (Mn)	1.9	<0.01	0.036±0.005 (0.12)	0.024±0.003 (0.04)	29	7
Sodium (Na)	—	<0.5		64.7±3.5 (150.7)	78	
Nickel (Ni)	0.047^{H}	<0.02	<0.02	<0.02)		
Selenium (Se)	0.011*	<0.05	<0.05	<0.05**		
Uranium	ID	<0.05	<0.05-0.08	<0.05-0.12	17	3
Zinc (Zn)	0.034^{H}	<0.05	<0.05-0.33	<0.05-0.17	24 (24)**	3 (3)

^{H} Value corrected for hardness (increases trigger) as per ANZECC/ARMCANZ (2000), hardness calculated from mean values of collected data for Ca, Mg, Sr, 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)

4.3 WATER QUALITY

4.3.1 PHYSICO-CHEMICAL PARAMETERS

At each monitoring station multiparameter probes were installed which recorded pH, temperature, ORP, dissolved oxygen and conductivity at 30 minute intervals between 27/8/09 and 21/7/10. The data is not continuous as there are needs to maintain probes (back in the laboratory), and times when the areas where probes were located dried out. Water temperature varied on a both daily and seasonal basis, no differences were seen between inlet and outlet (Figure 9). Conductivity varied between 0.9 and 1.2 mS cm^{-1} at both sites, with the highest conductivities recorded in summer, due to evapoconcentration (Figure 10). pH was circum-neutral throughout the entire year but smaller increases were seen in February when the water was not flowing allowing for algal growth (Figure 11). Algae can increase pH as CO_2 is removed from the water by photosynthesis. At the outlet site, the dissolved oxygen indicates the water had very low oxygen concentrations (<3 mg L^{-1}) and low ORP (typically negative), this could be due to the probe sitting too close to the sediment or could reflect oxygen consumption in the water behind the weir (flow is limited by the sewage pipe prior to the weir). At the inlet during periods of high flow the dissolved oxygen concentration ranged between 6 and 7 mg L^{-1}, at low flows this dropped to >3 mg L^{-1}. ORP at the inlet declined during low flows but always remained positive.

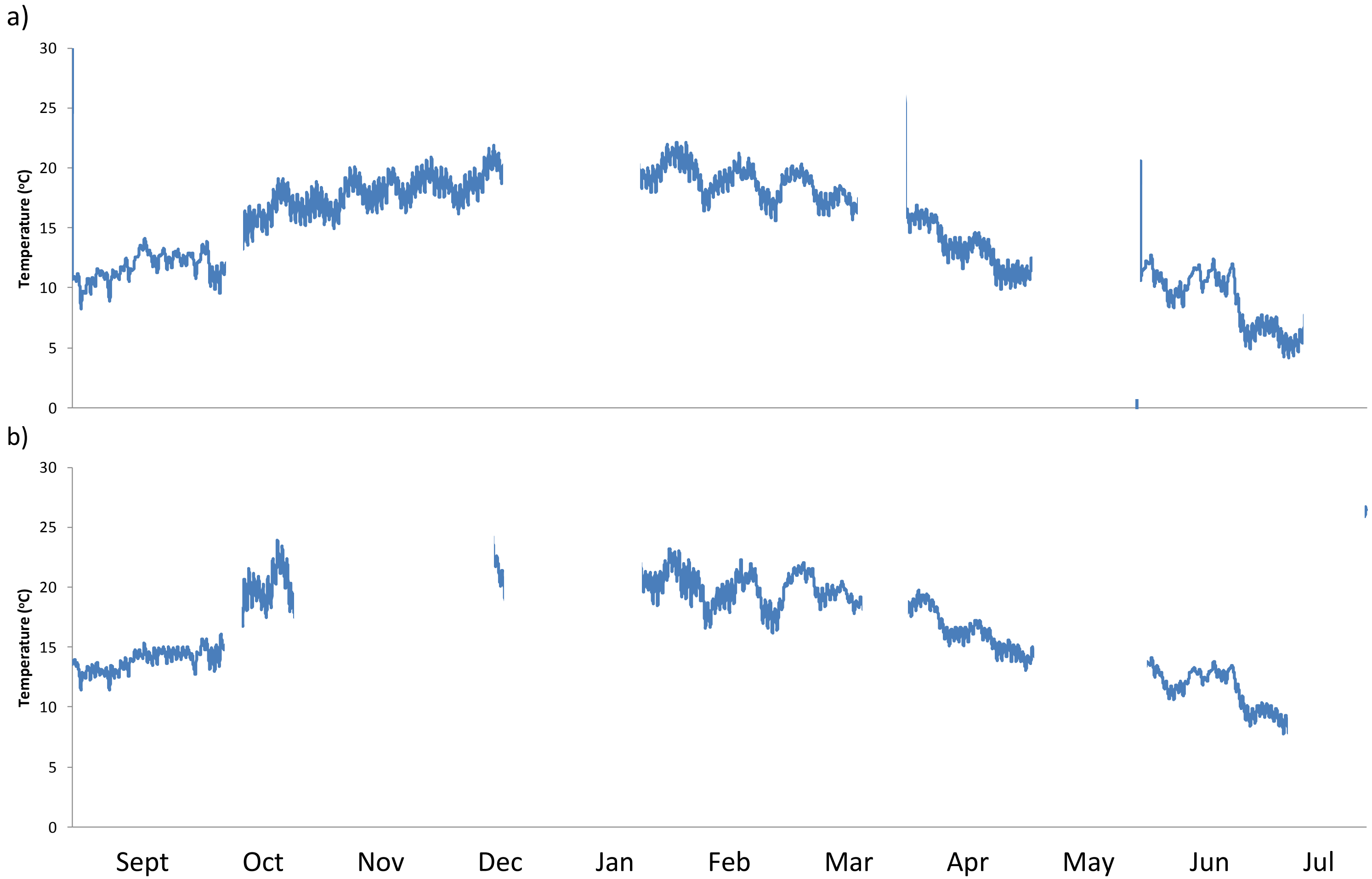
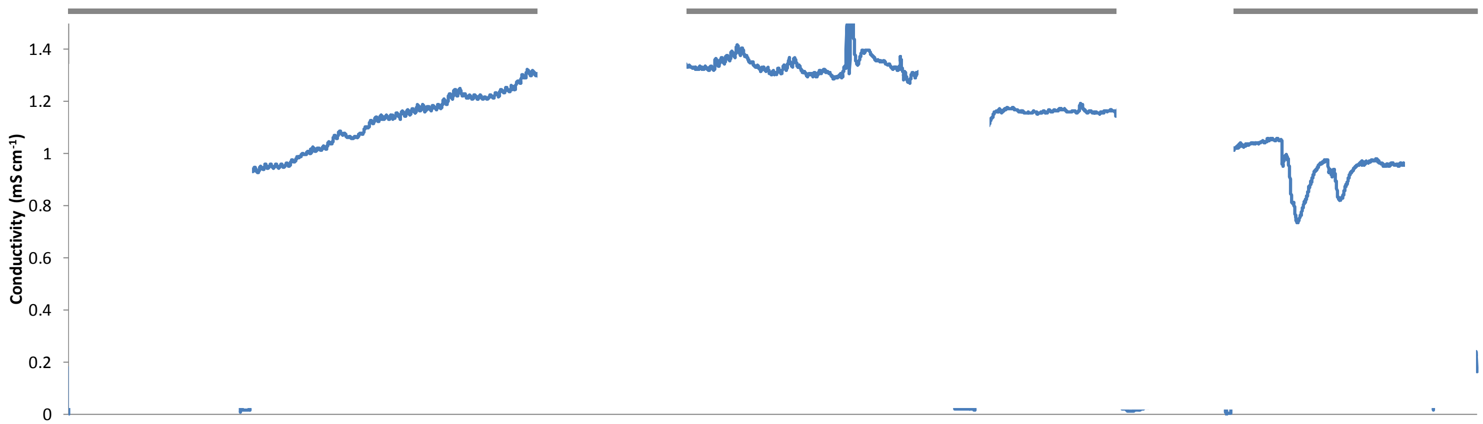


Figure 9. Water temperature measured at 30 minute intervals for a) inlet and b) outlet for Beenyup Swamp 27/8/09 to 21/7/10

a)



b)

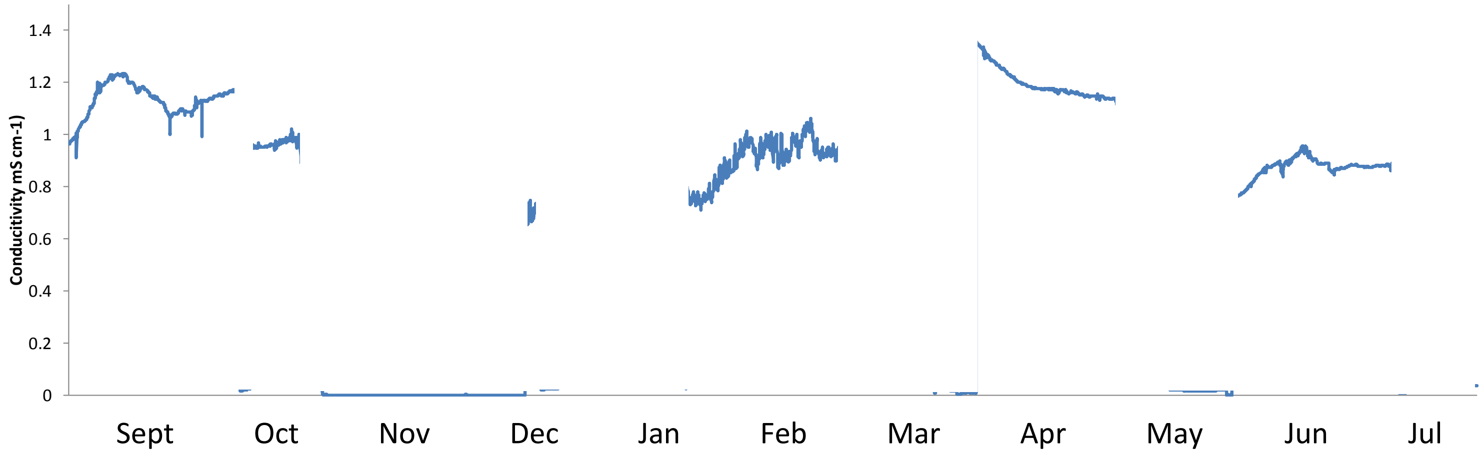


Figure 10. Conductivity measured at 30 minute intervals for a) inlet and b) outlet for Beenyup Swamp 27/8/09 to 21/7/10

a)

Figure 11. pH measured at 30 minute intervals for a) inlet and b) outlet for Beenyup Swamp 27/8/09 to 21/7/10

4.3.2 NUTRIENTS

Beenyup Swamp was a net exporter of Total P (36% increase, 109 kg), but not of FRP, which although showing a slight increase of 10% this was probably within the margin of error in the estimations (Table 2). The Swamp was a net exporter of nitrogen ranging from 366 kg (54%) of additional Total N, to 72 kg of NOx (107%) and 42 kg of NH_3 (138%). The total quantity of nutrients leaving Beenyup for Total P was 415 kg, and Total N was 1047 kg. Cumbers (2004) estimated that there were 24 kg of P and 471 kg of N entering the lake through rainfall, 1215 kg of P and 979 kg of N entering through the Ocean Reef culvert, 40 kg of P and 239 kg of N from stormwater. Congdon (1986) found in 1979/80 that 269 kg P and 838 kg of N entered through the Ocean Reef culvert with 3 kg of P and 39 kg of N entering through stormwater. His study estimated that 97 kg of P and 1953 kg of N entered through rainfall. The City of Wanneroo has or is in the process of upgrading the drains on the eastern side of the lake. This should help reduce nutrient inputs from stormwater. Khwanboonbumpen (2006) found that for stormwater drains entering Lake Joondalup, overspray of fertilizers and groundwater (reticulation) onto the roads and car emissions can account for majority of nutrients in the stormwater.

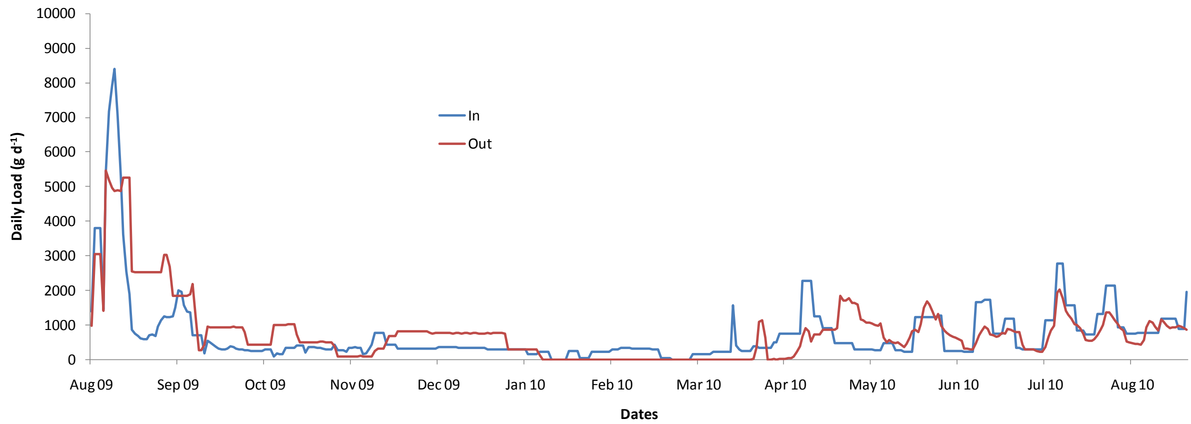
Table 2. Estimated total loads of nutrients between 13/8/09 and 27/8/10 in and out of Beenyup Swamp, with the percentage difference shown.

Mass in kg	In	Out	% difference
NH_4	30	72	138
NO_x	67	139	107
Total N	681	1047	54
FRP	273	300	10
Total P	306	415	36

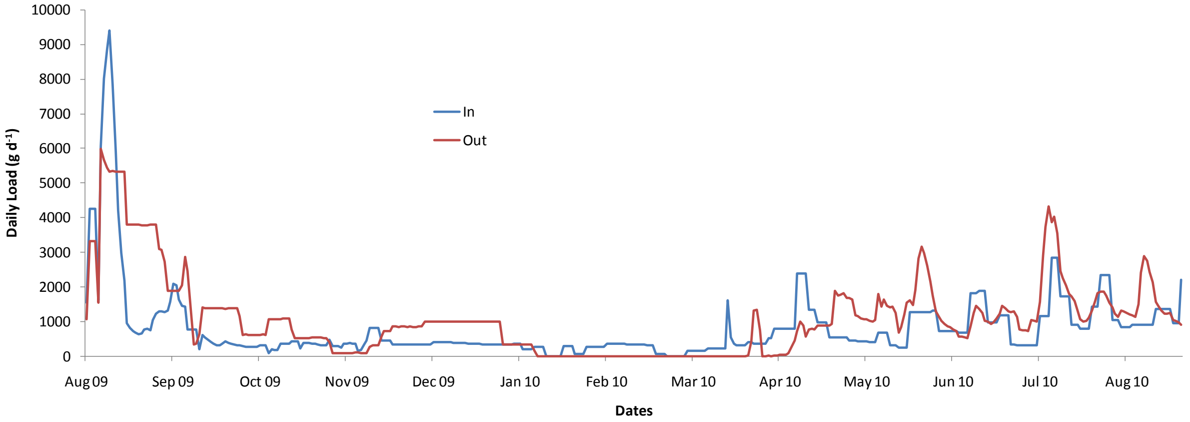
These figures are substantially lower than determined by Cumbers (2004) who estimate Total P exported from Beenyup Swamp to be 5369 kg and Total N to be 4325 kg. Given the fivefold higher estimates of water discharged from the Swamp in the Cumbers (2004) report, this may explain some of differences seen. Congdon (1986) estimated that Beenyup Swamp discharged 269 kg of Total P and 838 kg of Total N into southern Lake Joondalup.

This was based on a calculated discharge of 0.79 GL, which is less than in this study, interestingly adjusting the discharge and loads to match 2009/2010 suggests that Total P loads have increased by approximately 80 kg per year while Total N has not changed. As both Congdon and Cumbers found the loads from Beenyup Swamp substantially exceed all other sources into Lake Joondalup. Cumbers (2004) identified loads of 40 kg Total P and 239 kg Total N from stormwater and even the 366 kg of Total P estimated from water bird droppings. Her loads from stormwater correspond well with those found by Khwanboonbumpen (2006) for the Ariti Avenue (Lake Joondalup) stormwater drain of 1.51 kg of Total P per year. Cumbers (2004) reported that she observed virtually no difference in nutrient concentrations between Beenyup Swamp and those passing through the Ocean Reef Culvert which suggested that the southern part of Lake Joondalup (below Ocean Reef Road) has little impact on water quality. Using the data from Cumbers (2004) only approximately 66% of the water discharged from Beenyup Swamp entered the northern part of Lake Joondalup via the Ocean Reef Culvert (21/6/04-30/8/04). As some of the discharge from Beenyup Swamp is required to fill the southern part of Lake Joondalup prior to it discharging then this estimate is probably a little high.

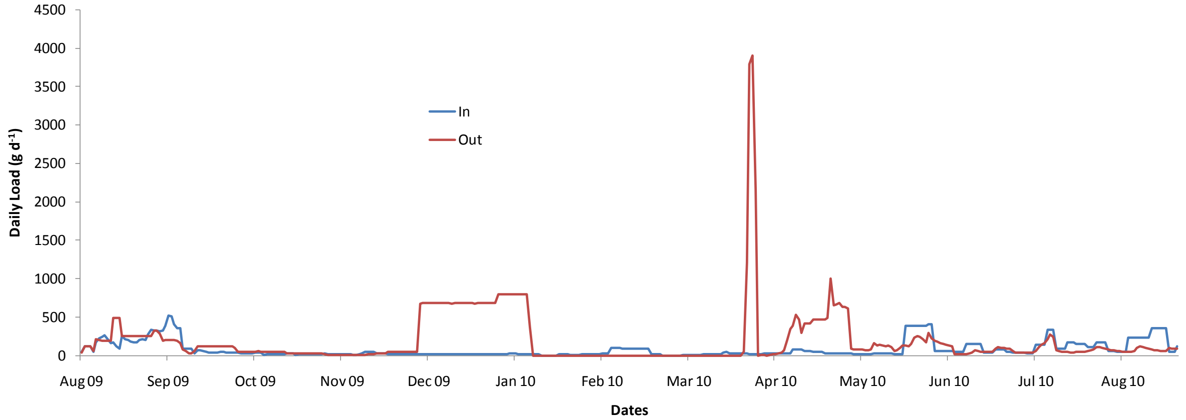
a) FRP



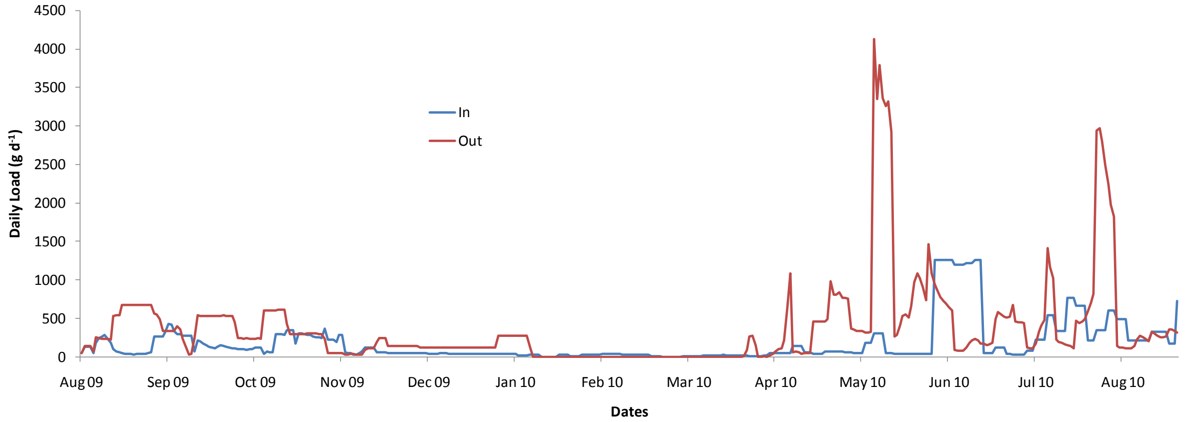
b) Total P



c) Ammonia



d) NOx



e) Total N

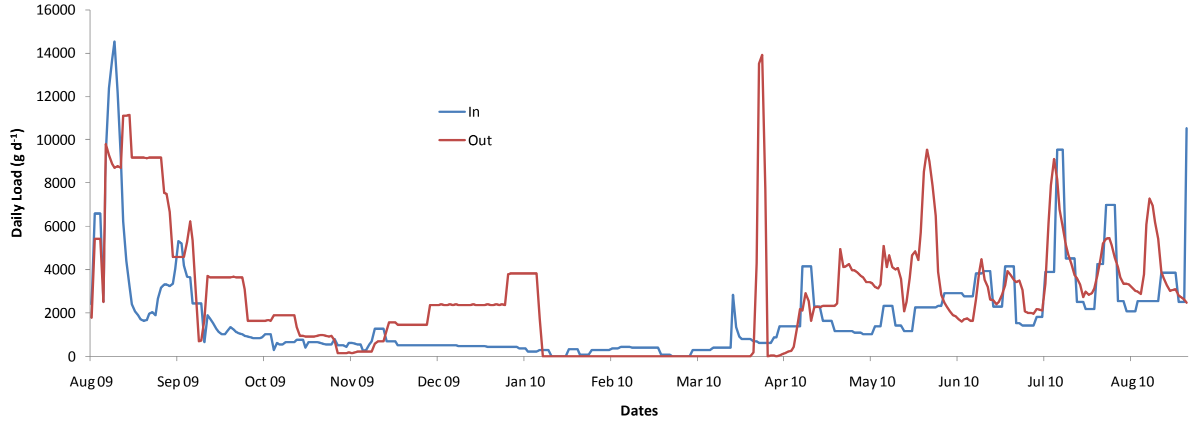
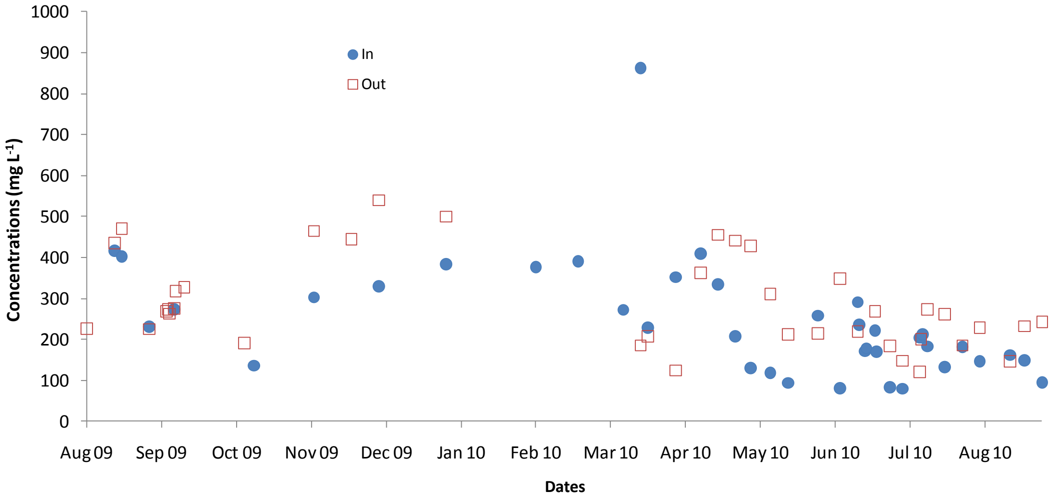


Figure 12. Daily loads of a) FRP, b) Total P, c) NH_4, d) NOx, and e) Total N estimated for Beenyup Swamp inlet and outlet. Loads across dates with no flow data were evenly spread across those dates.

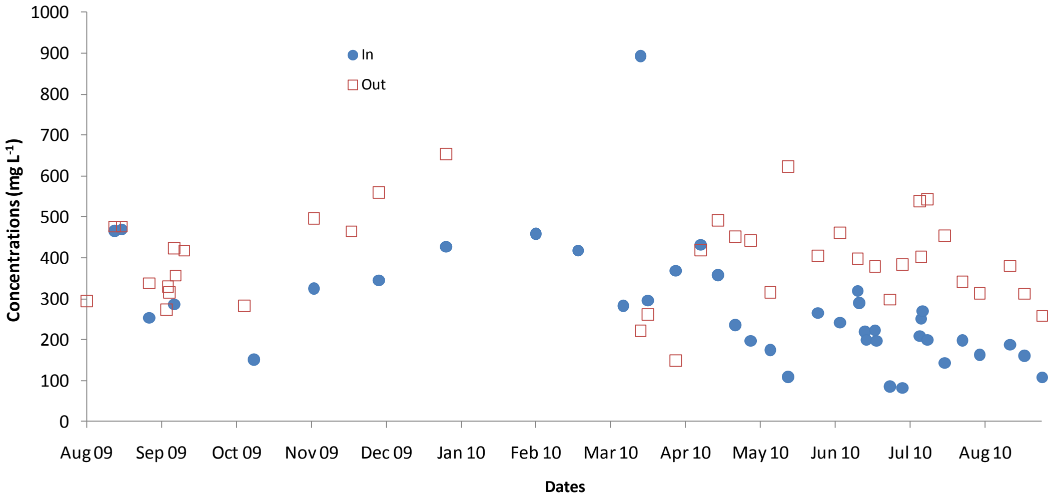
Daily loads for P show a very similar pattern between inlet and outlet (Figure 12). Ammonia loads in the outlet were highest relative to the inlet during December and January when flows were very low, and following the March 2010 major rainfall event. This was different to NOx loads which were highest in May to August 2010 in the outlet compared to the inlet. Ammonia is normally converted to NOx, and only tends to accumulate after sediment drying (where drying and subsequent oxidation of the sediment breaks down organic matter liberating ammonia) and rewetting or during periods of anoxia (where nitrification cannot occur). In Figure 13 the very high concentrations of ammonia in the outlet water are not matched by the inflow concentrations further supporting that the source is release from the Swamp sediment. The peaks in ammonia coincide with low to no discharges from Beenyup Swamp. This would allow water in the Swamp to become anoxia and sections of the Swamp to dry out providing a source of ammonia. Nitrogen concentrations are very high in sediments of the Swamp (Goldsmith *et al.*, 2008). These conditions should also suit liberation of P from the sediment (particularly from Fe and Mn bound P) however this did not appear to be the case or the P was rapidly rebound to the sediment. This fits with the findings of Gunner et al (2008) who was unable to get anoxia to release P in Beenyup Swamp. Drying did release P, but there was very rapid uptake by the rewet sediments. Examining the concentrations shows significantly higher concentrations of FRP and Total P during the March storm, however this is entering the inlet, this suggests that the intense rain had washed in a source of P that normally was not available – possibly water out of the Wangara drain. Throughout the rest of the year, concentrations of P were highest at times of low flow and lower in the winter months presumable due to dilution. The concentrations of NOx were very variable but peaked soon after peak ammonia concentrations started to decrease, suggesting nitrification of ammonia to NOx was occurring. Total P concentrations followed those of FRP very closely as in the inlet it accounted for a remarkably high median of 90% of the Total P. In the outlet, FRP only accounted for a median of 76% of Total P. This is suggestive of some algal growth in the open water of Beenyup Swamp in the warmer months taking up FRP and converting it to organic P. As FRP is a good approximation of available P, these represent very high concentrations and the risk of algal blooms is therefore extremely high. This risk is most likely to occur in the Southern section of Lake Joondalup provided residence time is sufficient for the algae to grow.

The groundwater concentrations of NOx and NH_3 are higher on the eastern side of the Swamp than on the western side suggesting that there was a release of these nutrients into the Swamp water.

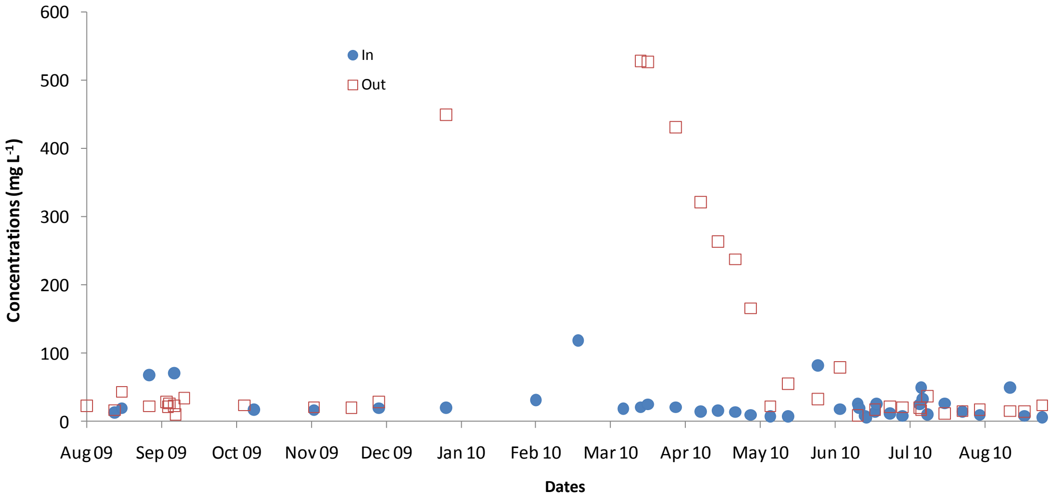
a) FRP



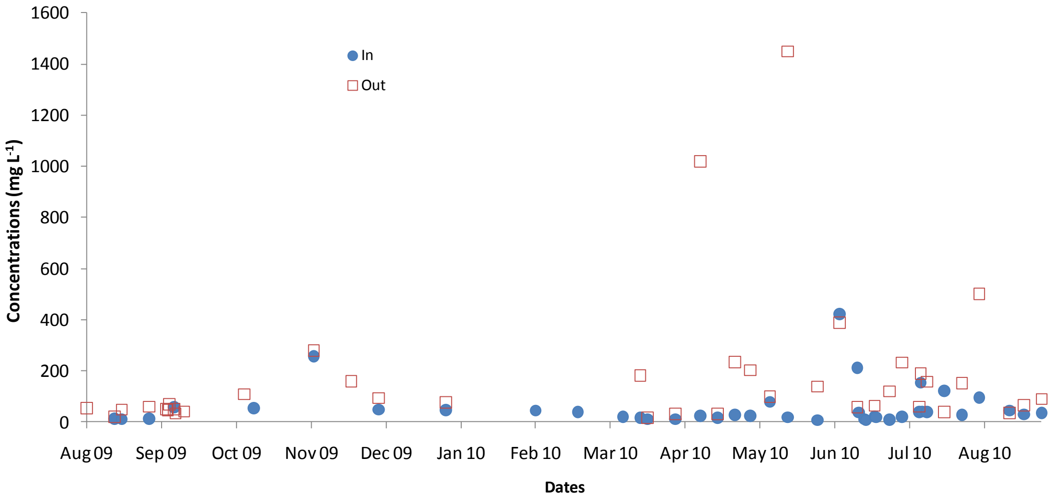
b) Total P



c) Ammonia



d) NOx



e) Total N

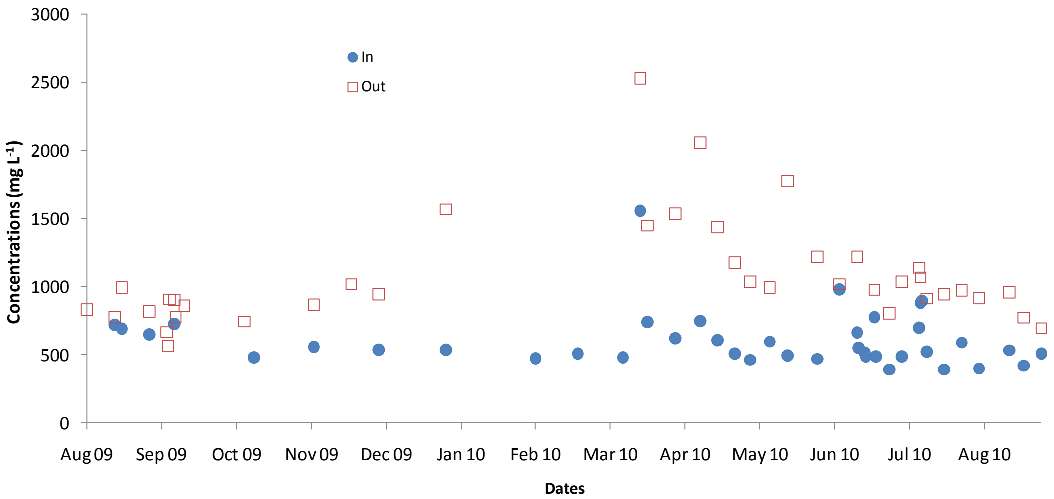


Figure 13. Concentrations of a) FRP, b) Total P, c) ammonia, d) NOx and e) Total N in the inlet and discharge waters from Beenyup Swamp between August 2009 and 2010

4.3.3 METALS

The metals, As (<0.05 mg L^{-1}), Cd, Cr, Co (<0.01 mg L^{-1}), Hg (<0.1 mg L^{-1}), Ni (<0.05 mg L^{-1}) and Se (<0.2 mg L^{-1}) were mainly below detection, with Hg and Se having no values above detection. The loads of these metals therefore follow water flow and are therefore not shown.

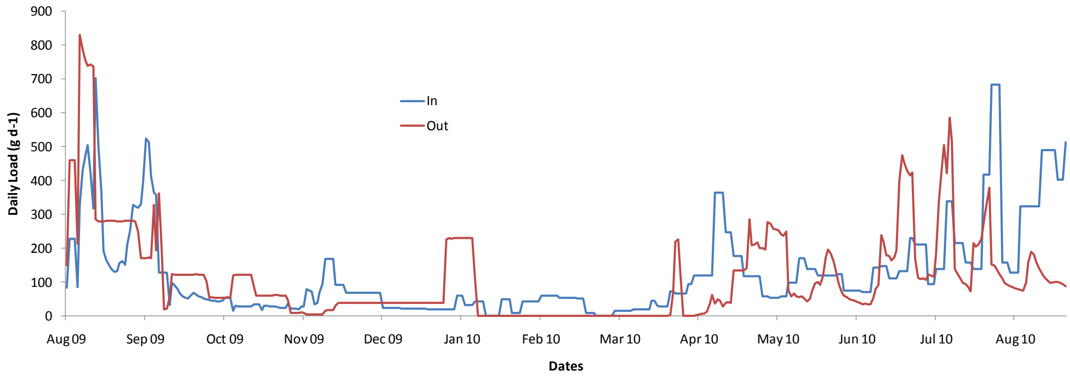
Beenyup Swamp was a net exporter of Fe (151% increase), Mn (210%) and Zn (33%), whereas it accumulated and retained Ca (-21%), all other metals had differences between inlet and outlet of 15% or less which is within the margin of error for the calculations. (Table 3).

Table 3. Estimated total loads of metals between 13/8/09 and 27/8/10 in and out of Beenyup Swamp, with the percentage difference shown.

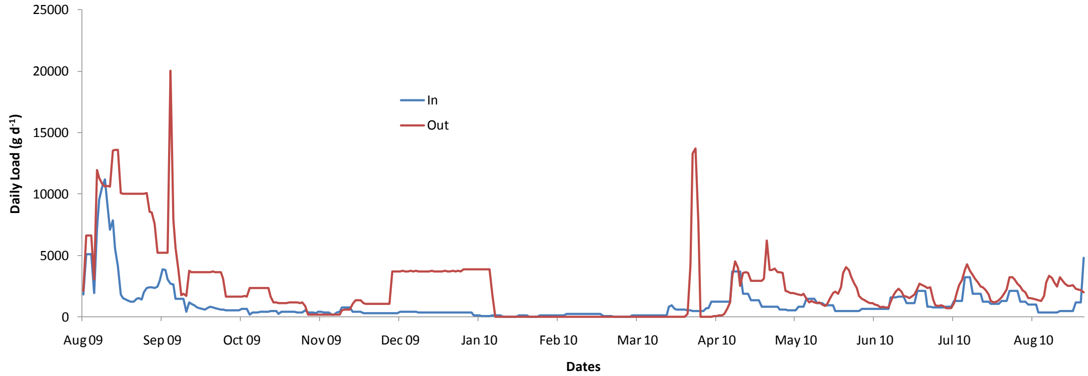
Mass in kg	In	Out	% difference
Al	47	43	-9
Ca	70536	55464	-21
Fe	374	940	151
K	9500	8615.	-9
Mg	42156	36083	-14
Mn	13	40	210
Na	90808	77956	-14
U	134	114	-15
Zn	58	76	33

Loads of Al, Fe, Mn and U all show peak daily loads around the March 2010 storm event. This was associated with high concentrations in the outflow but not in the inflow suggesting they were the results of release from the sediments. Iron, Mn and Zn were in high concentration just prior to the ceasing of outlet discharge, it is likely that possible anoxia at this time saw these elements become oxidised and released. Interestingly, as P binds strongly to Fe and Mn, release of these metals would be expected to be accompanied by P release, which did not occur. In fact P concentrations following the March 2010 storm which resulted in discharges from Beenyup Swamp were lower than typical. A possible explanation is that the sediment has a high capacity to bind P and that while P may have been released it was quickly taken up when stormwater started to flow in. Groundwater on the eastern side also contains high concentrations of Fe, while the western side did not. Groundwater inputs may be responsible for the constant production of Fe by the Swamp.

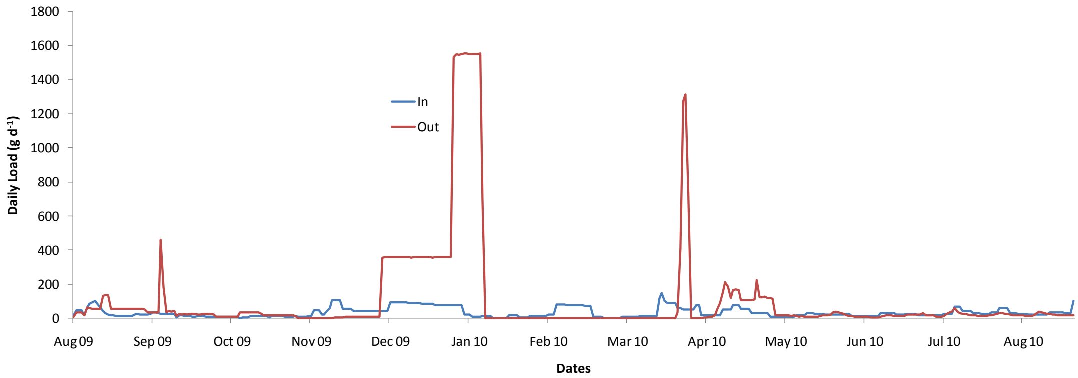
a) Al



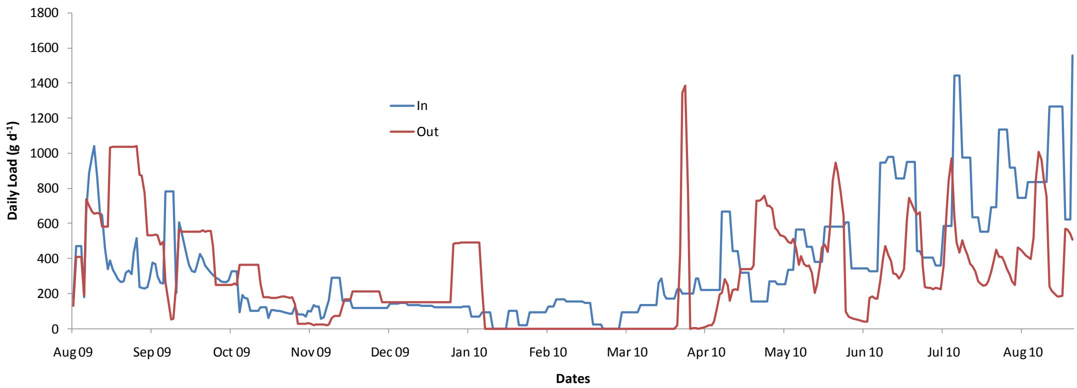
f) Fe



h) Mn



k) U



l) Zn

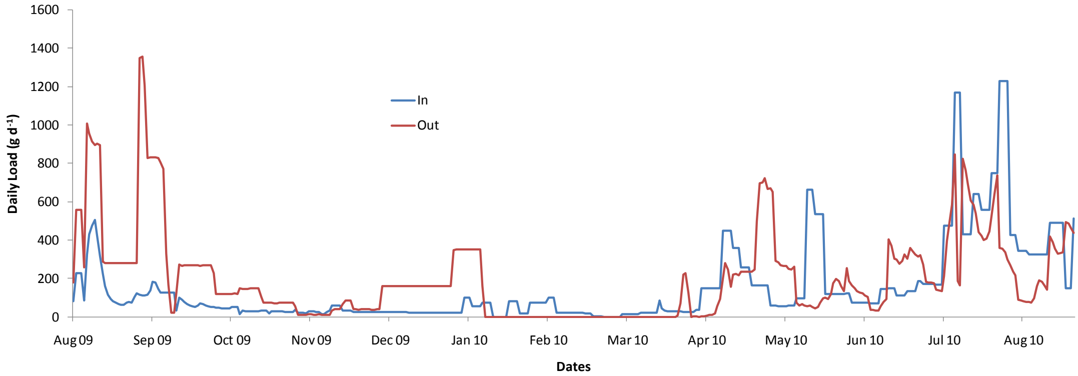
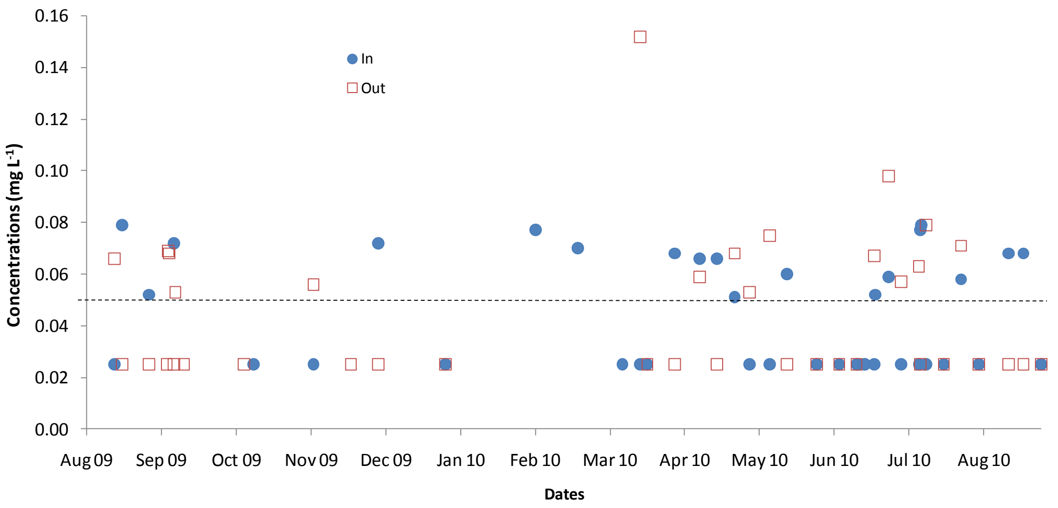


Figure 14. Daily loads of a) Al, b) Fe, c) Mn, d) U and e) Zn estimated for Beenyup Swamp inlet and outlet. Loads across dates with no flow data were evenly spread across those dates.

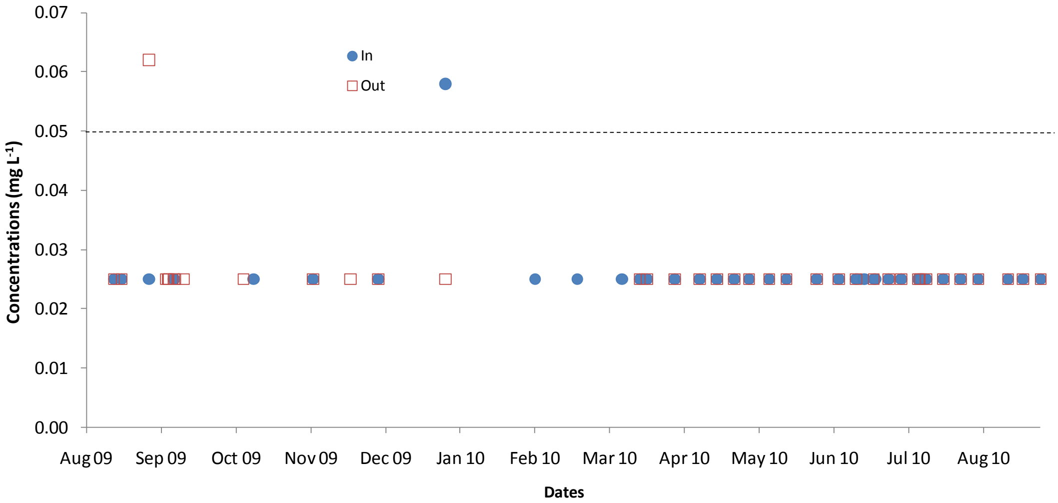
The concentrations of Al, As, Cd, Cr, Ni and Zn in the outlet and inlet at times exceeded ANZECC/ARMCANZ (2000) guidelines for the protection of aquatic systems (95% protection). High metal levels in the waters of Yellagonga Regional Park wetlands have been described in Lund et al. (2011).

a) Al



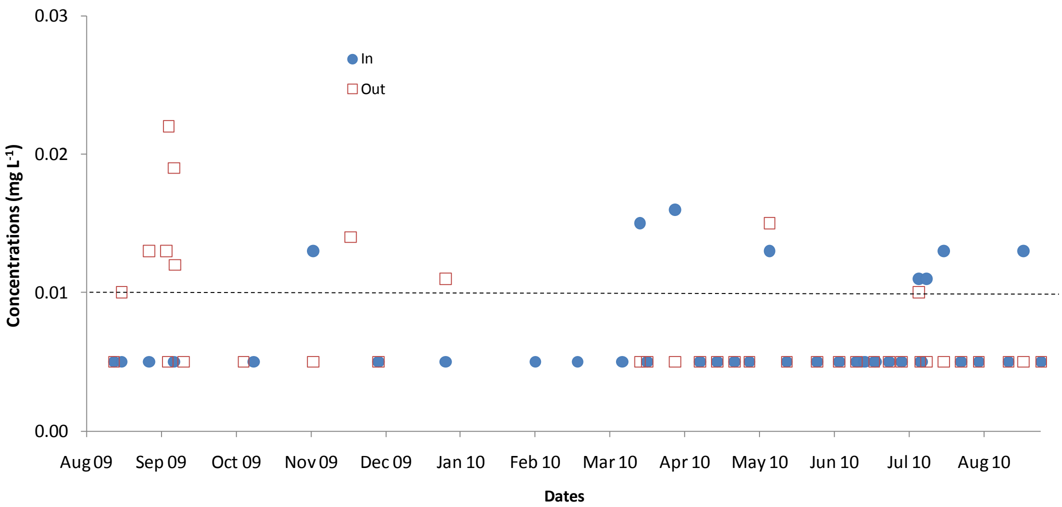
In
Out
Concentrations (mg L-1)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

b) As



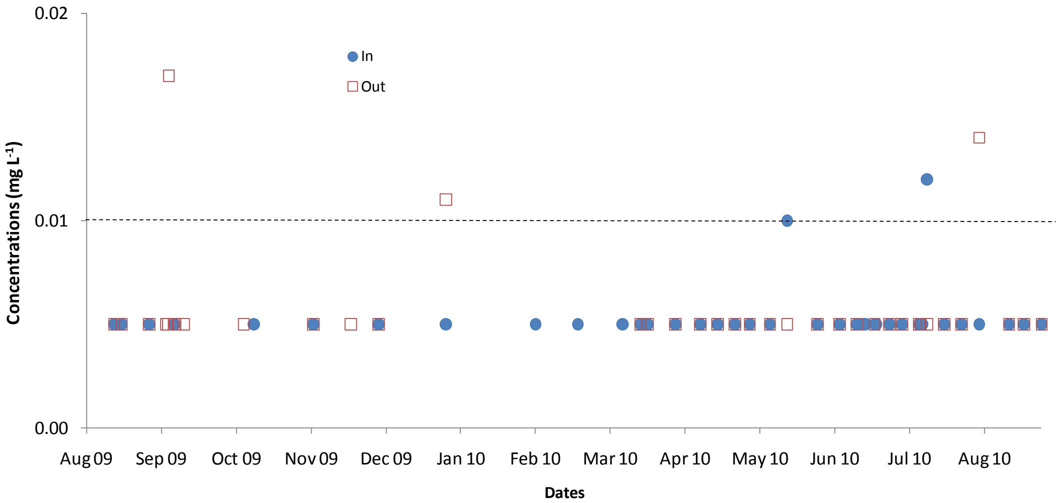
In
Out
Concentrations (mg L-1)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

c) Cd

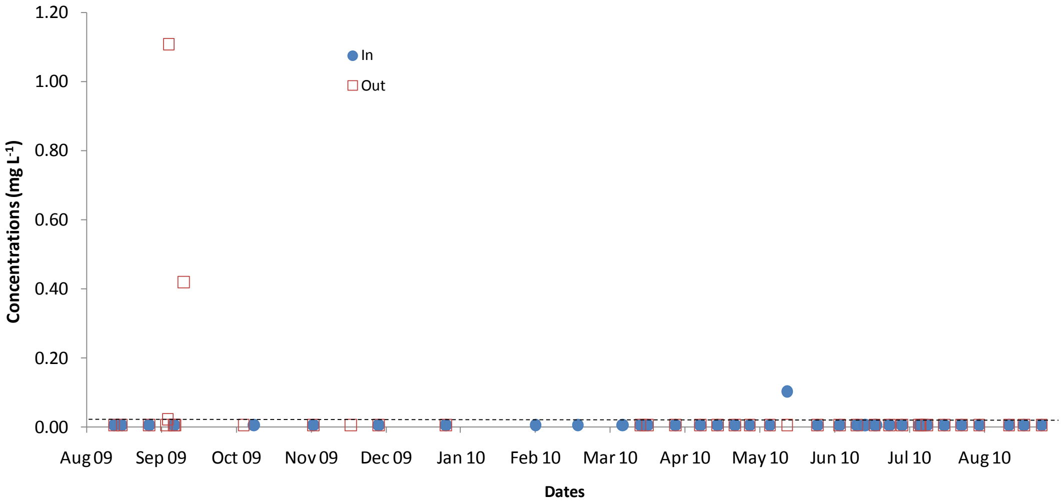


In
Out
Concentrations (mg L-1)
0.00
0.01
0.02
0.03
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

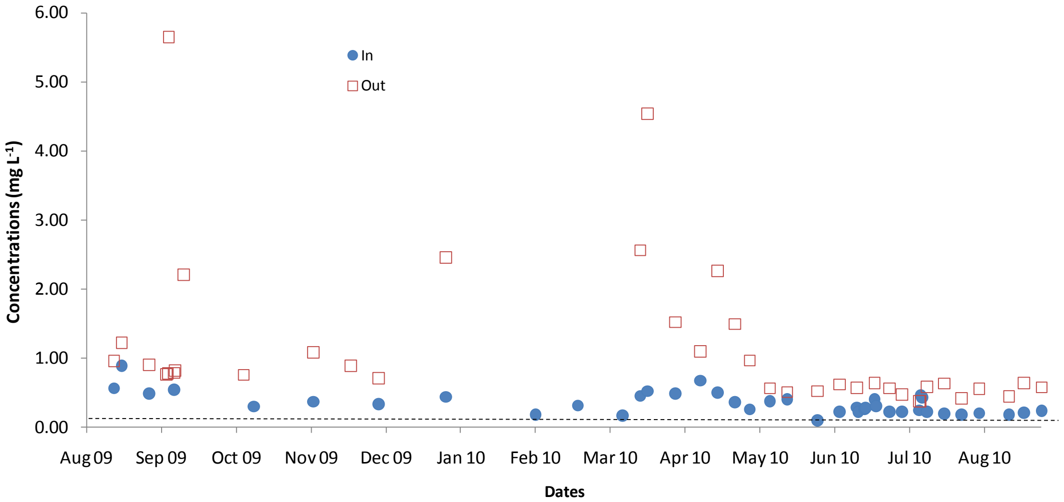
d) Co


0.02
0.01
0.00
In
Out
Concentrations (mg L-1)
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

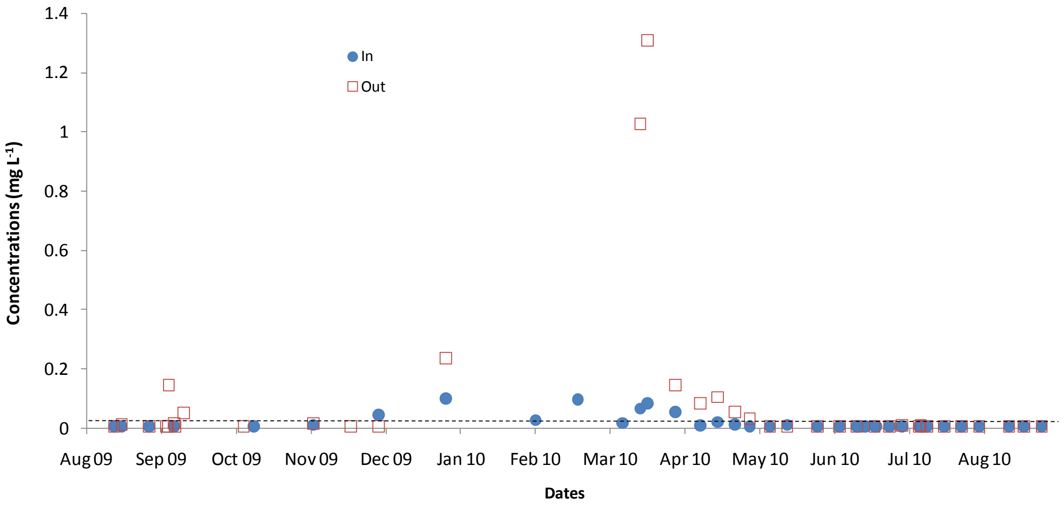
e) Cr


1.20
1.00
0.80
0.60
0.40
0.20
0.00
In
Out
Concentrations (mg L-1)
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

f) Fe

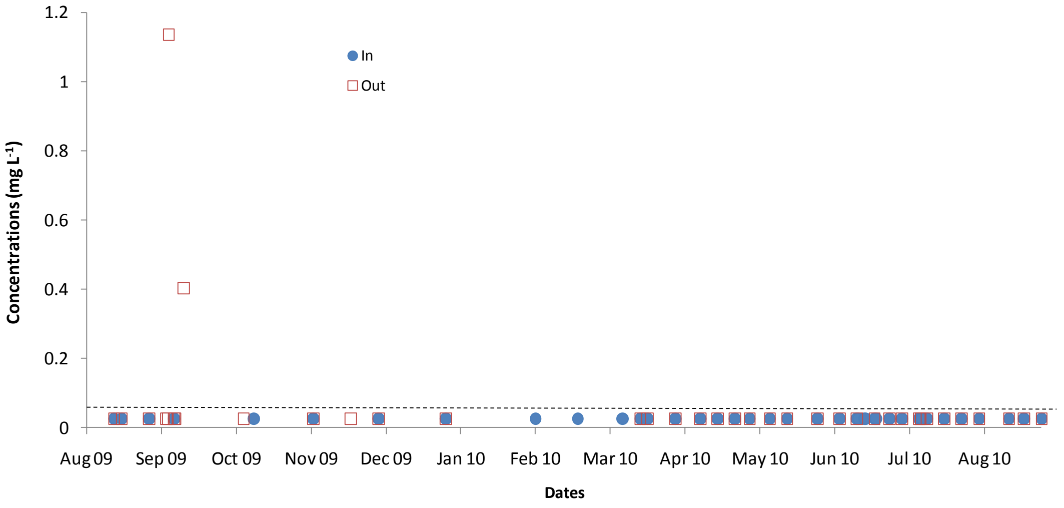

6.00
5.00
4.00
3.00
2.00
1.00
0.00
In
Out
Concentrations (mg L-1)
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

g) Mn



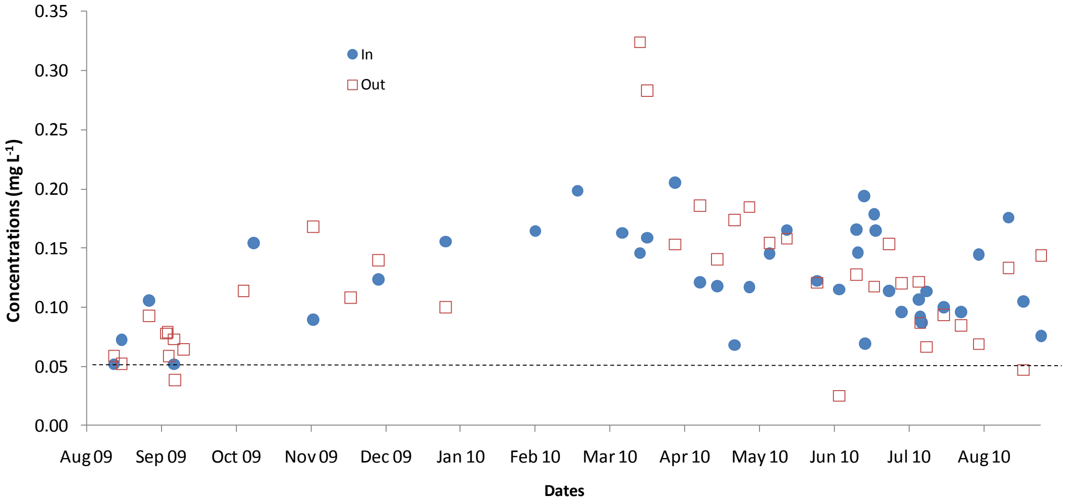
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Concentrations (mg L-1)
In
Out
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

h) Ni



1.2
1
0.8
0.6
0.4
0.2
0
Concentrations (mg L-1)
In
Out
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

i) U



0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Concentrations (mg L-1)
In
Out
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

j) Zn

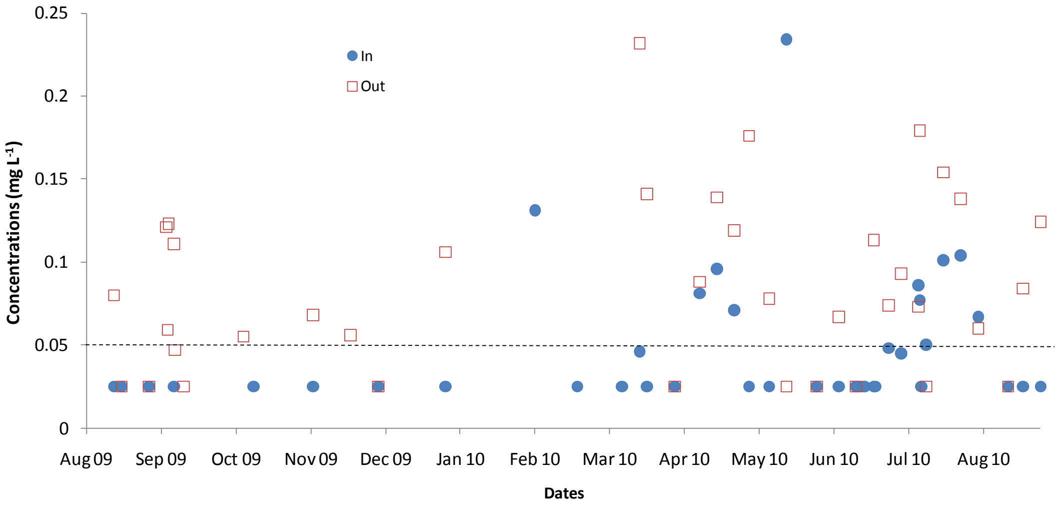
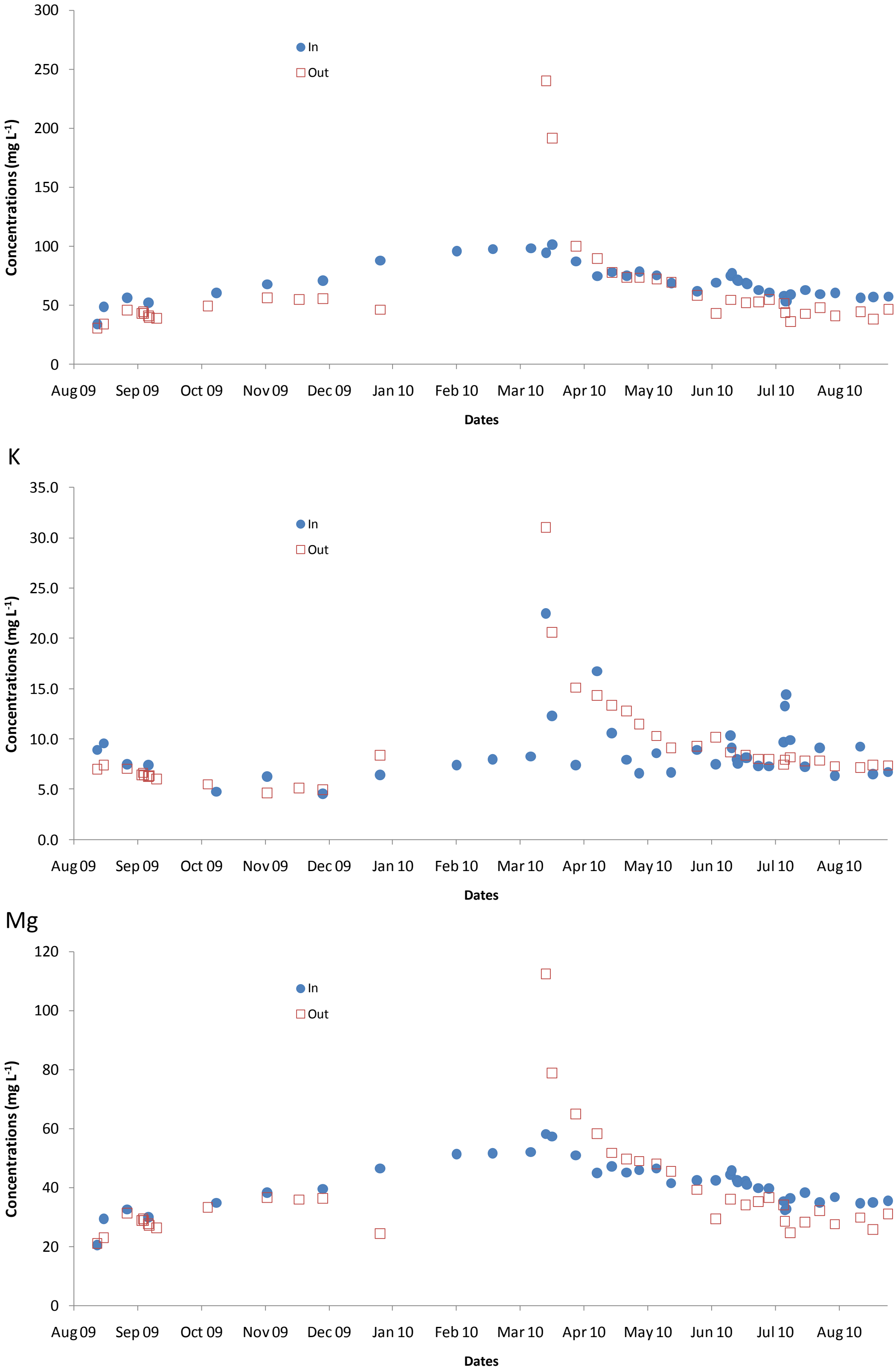


Figure 15. Concentrations of a) Al, b) As, c) Cd, d) Co, e) Cr, f) Fe, g) Mn, h) Ni, i) U and j) Zn in the inlet and discharge waters from Beenyup Swamp between August 2009 and 2010 (dotted line shows detection limits, values below the detection limit are shown at the values used in load calculations, values on the line were at the detection limit).

Concentrations and loads of the alkaline earth metals (Ca, K, Mg and Na) are relatively high compared to the other parameters measured (Figures 16 & 17) as is normal is Swan Coastal Plain wetlands. Concentrations vary little across the year, with a slight increase in summer due to evapo-concentration. Interestingly, high concentrations of all these metals occurred in the outlet discharge following the March 2010 storm event. This might be due to evapo-concentration in the Swamp while it was not discharging prior to this event.

a) Ca


300
250
200
150
100
50
0
Concentrations (mg L-1)
In
Out
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

b) K

35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Concentrations (mg L-1)
In
Out
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

c) Mg

120
100
80
60
40
20
0
Concentrations (mg L-1)
In
Out
Aug 09
Sep 09
Oct 09
Nov 09
Dec 09
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Dates

d) Na

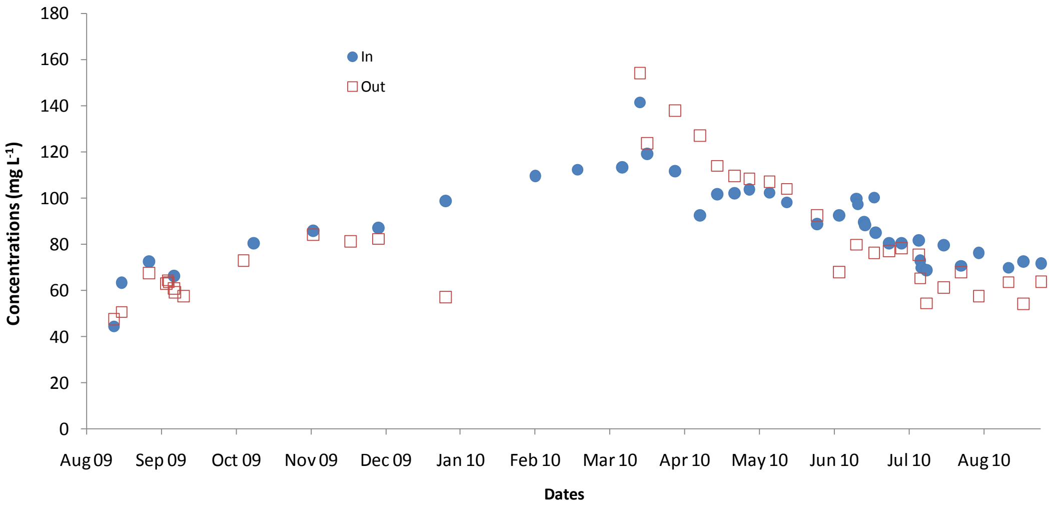
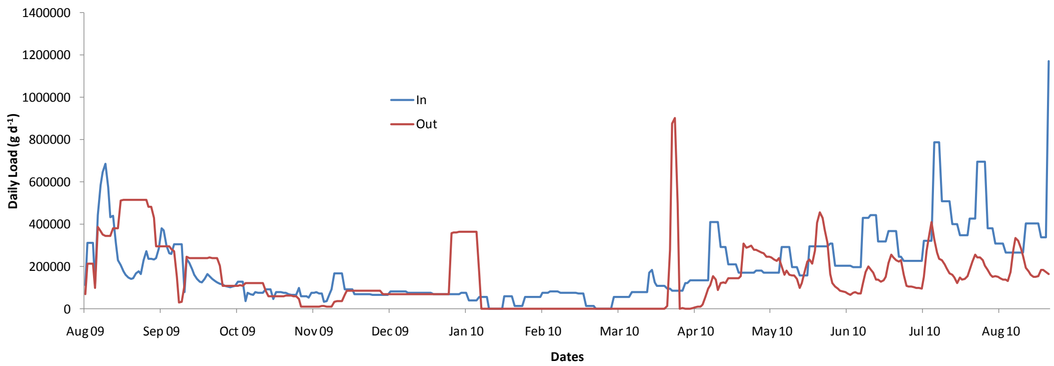
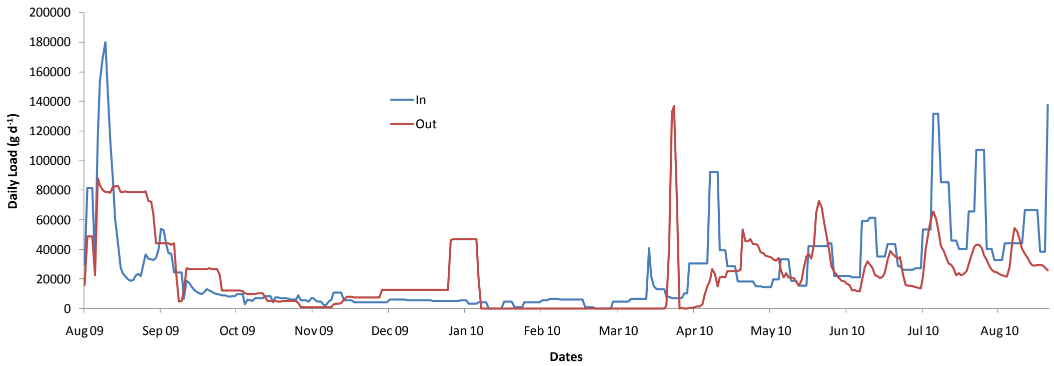


Figure 16. Concentrations of a) Ca, b) K, c) Mg, and d) Na in the inlet and discharge waters from Beenyup Swamp between August 2009 and 2010.

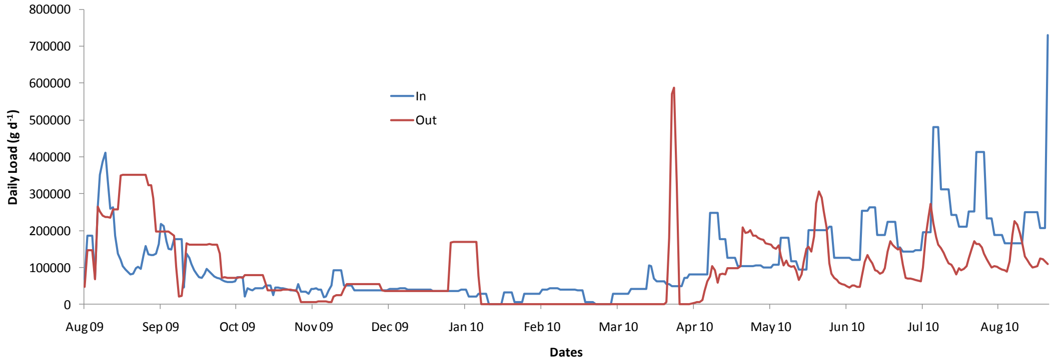
a) Ca



b) K



c) Mg



d) Na

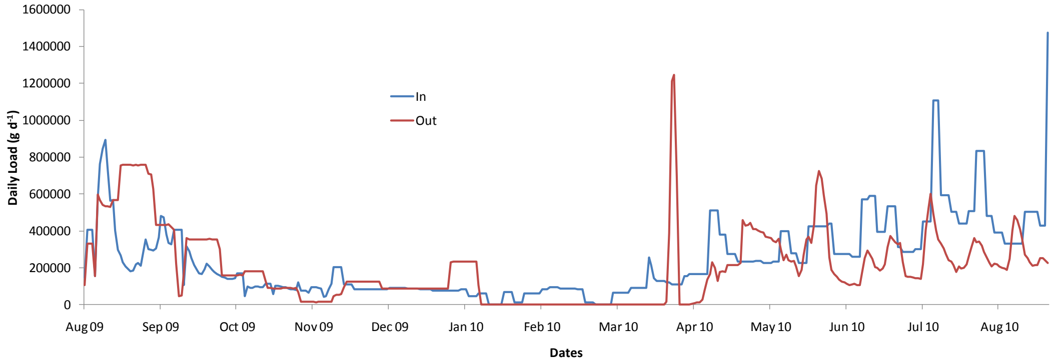


Figure 17. Daily loads of a) Ca, b) K, c) Mg, and d) Na estimated for Beenyup Swamp inlet and outlet. Loads across dates with no flow data were evenly spread across those dates.

5 CONCLUSIONS

This study has provided much more realistic nutrient loads from Beenyup Swamp than Cumbers (2004). The loads were remarkable for their high proportion of dissolved nutrients (FRP, ammonia and NOx). These nutrients are particularly problematic for causing eutrophication. The sources appeared to be sediment release and groundwater. The annual loads of particularly P were still significant to Lake Joondalup compared to other sources such as groundwater and stormwater drains. Therefore the priority of tackling nutrients from the southern wetlands should remain. While Beenyup Swamp is a significant contributor to the load of nutrients (particularly of N), Wallubuenup Swamp also contributes undesirably high concentrations and loads.

One option to reduce nutrients entering into Lake Joondalup would be to bypass Beenyup Swamp taking water directly from Wallubuenup Swamp to the Southern section of Lake Joondalup, using a control structure that provided sufficient water to maintain the Swamp but prevent it from being flow-through. This would provide an approximate 36% reduction in P and a 54% reduction in N. Another option that could be used in combination with the first option is to undertake works at the Southern section of Lake Joondalup that would increase hydraulic residence time and provide opportunity for nutrients to be stripped from the water, in effect turning this part of the lake into a nutrient stripping wetland. A nutrient stripping wetland could substantially reduce N concentrations, but would probably be less effective for P.

In option 1, care is also needed to prevent excessive drying of the sediment of Beenyup Swamp. The sediment is covered by a floc which appears important in preventing nutrient release. Flocs can be destroyed by intense drying. Strategies such as trying to control the sediment release in Beenyup Swamp are not recommended as the floc sediment would make them difficult to implement and it would still not deal with significant loads from Wallubuenup Swamp. Furthermore, the ecological values of Beenyup Swamp are still very high despite its contamination, especially compared to the Southern section of Lake Joondalup.

Additionally, a survey of the Southern section of the Lake Joondalup to ascertain current flow pathways and nutrient status would be required before a plan for a nutrient stripping wetland could be developed. The substantial release of Fe from Beenyup Swamp without any apparent binding to P warrants further investigation as this potentially could remove substantial loads of P relatively easily.

6 RECOMMENDATIONS

- It is recommended that the Southern section of Lake Joondalup (south of Ocean Reef Rd) be redeveloped as a nutrient stripping wetland. To assist, an initial study to investigate sediment nutrient loads in this wetland would be useful.
- It is recommended that the feasibility of diverting the majority of flows past Beenyup Swamp be investigated. Sufficient water should be allowed into the Swamp to maintain its ecological value, whilst preventing discharge. Given the high loads of nutrients in the sediments there is potential for poor water quality leading to algal blooms in a non-flow through Swamp that would need to be adequately investigated.
- It is recommended that a study of water flows and sediment loads be conducted at the Southern section of Lake Joondalup to understand what impact this area has on water entering the Northern section. This study would not need to complete a full water or nutrient budget.
- It is recommended that the relationship between dissolved Fe and P be examined, due to the potential for using this to control P entering Lake Joondalup.

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