Centre for ecosystem management

EDITH COWAN UNIVERSITY
PERTH WESTERN AUSTRALIA

December 2008

Factors Controlling Release of Sediment-Bound Phosphorus from a Seasonal Wetland (Beenyup Swamp)

By, Rebecca Gunner
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2008-18

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Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2008-18

Prepared for,

Cities of Wanneroo and Joondalup and Department of Conservation and Environment

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Frontispiece

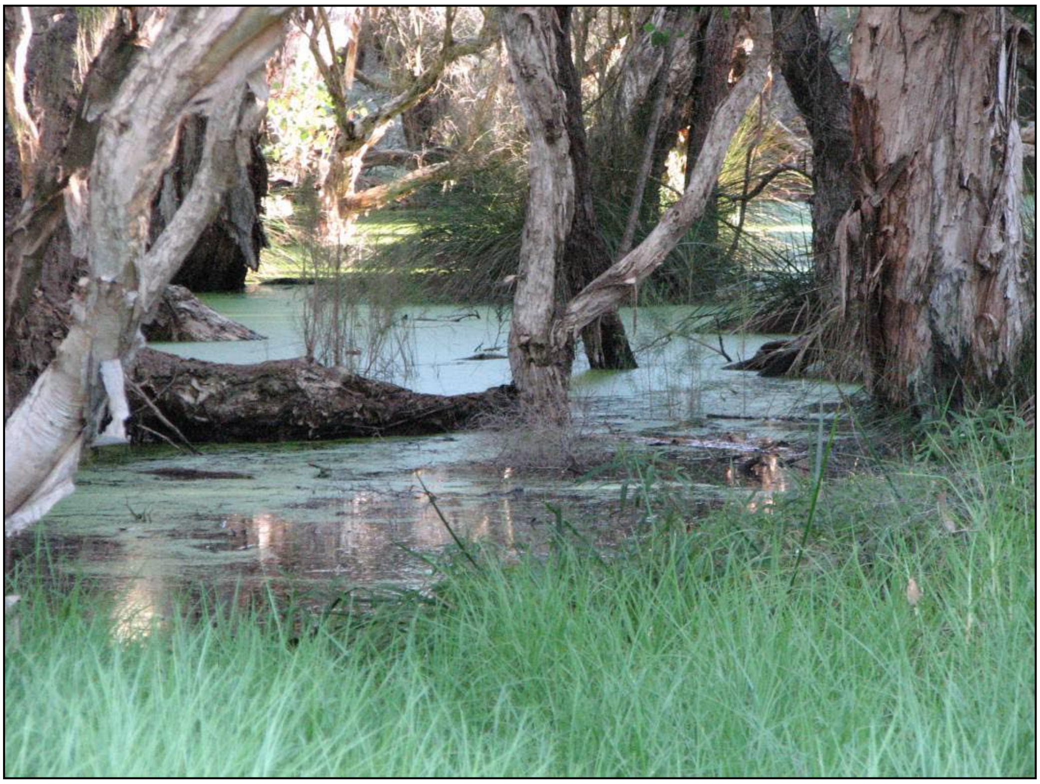

Figure 1. Flooded section of Beenyup Swamp (winter 2008).

This document should be referenced as follows.

Gunner, R.; Lund, M. A. & McCullough, C. D. (2008). *Factors controlling the release of sediment bound phosphorus from a seasonal wetland (Beenyup swamp).* Mine Water and Environment Research/Centre for Ecosystem Management Report No. 2008-18, Edith Cowan University, Perth, Australia. 32pp. Unpublished report to the Midge Steering Committee (Cities of Wanneroo and Joondalup, and DEC).

This report is based on the 3rd Year Project report completed by Rebecca Gunner. It has been edited for this report by Mark Lund and Clint McCullough.

1 Contents

2 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 discharges close to 75% of the phosphorus entering Lake Joondalup annually.
2. 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.
3. Goldsmith *et al.* (2008) recommended that further research be undertaken to examine the mechanisms by which this sediment stored P could be released and contribute to the annual export of P from the Swamp. Goldsmith *et al.* (2008) further recommended that bioturbation, drying and oxidation reduction potential changes were the most likely mechanisms.
4. This study experimentally tested the three mechanisms recommended by Goldsmith *et al.* (2008) to test whether the sediment bound P in Beenyup Swamp was the source of P exported to Lake Joondalup. The mechanisms examined were; the effects of sediment drying, introduction of midge larvae (bioturbation) and release of sediment P under anoxia induced by sediment BOD.
5. Drying of sediments can cause release of P through oxidative breakdown of the sediment and organic matter. Upon rewetting the P can then be released back to the Swamp. Bioturbation is the direct movement of nutrients from the sediments through the action of organisms such as midge larvae. Bioturbation can be significant and can overcome conditions which would typically prevent nutrient release. In Beenyup Swamp it is likely that most of the stored P is bound to iron (Fe) (see Goldsmith *et al.*, 2008). Iron exists in two forms, insoluble Fe^{3+} which binds P and soluble Fe^{2+}, which releases P. When the oxidation reduction potential drops (<100 mV) then Fe^{3+} is reduced to Fe^{2+} and P released. A common way of achieving this in natural wetlands is a reduction in dissolved oxygen concentrations in the overlying water to anoxia (0 mg L^{-1}).

6. These three treatments were compared to an untreated control over four weeks in replicated (3) cores (containing undisturbed sediment and water) taken from Beenyup Swamp.
7. P concentrations remained constant in controls throughout the course of the experiment. In the anoxia experiment, the low amount of biochemical oxygen demand from the sediment failed to reduce oxygen levels to below 20% saturation, although ORP dropped below 0 mV. This was considered sufficient to cause release of Fe^{3+} sediment bound P; however, no P was released from the sediments. This finding agrees with that of Sommer (2006) who observed a similar response for floc-type sediments in Lake Goollelal. Drying the sediment caused an initial release of P upon rewetting but this P was within 8 days rebound to the sediment. Bioturbation was not considered further as it is suspected that all the added midge larvae died within days of addition.
8. The results of this study suggest that, despite containing P in high concentrations, it does not appear that Swamp sediment, is the main source of P exported from the Swamp. Instead, it is suspected that direct groundwater input is the main source.
9. It is recommended that further work be undertaken to verify the previous estimates of P exported from Beenyup Swamp. By close monitoring on inputs and outputs of the Swamp and measuring of groundwater inputs, the source of P into Lake Joondalup is likely to be confirmed. Once the source is determined then remediation strategies may then be developed.

3 Introduction

Eutrophication is a serious, global environmental problem affecting many water bodies (Smith *et al.*, 1999). Under specific conditions such as excessive nitrogen and phosphorus, slow current velocity, and high temperatures most wetlands have the potential to become eutrophic (Prepas & Charette, 2003). Elevated levels of nutrients stimulate the growth of algae, resulting in algal blooms (Schindler, 1975). Other important issues include decreases in water transparency, dissolved oxygen, and reduced biodiversity (Correll, 1998; Sondergaard *et al.*, 2003). Nutrient enriched waterways often provide an ideal habitat for the proliferation of unwanted weeds and pests, such as midges, whilst also drastically lowering the visual amenity of an affected location (Millennium Ecosystems Assessment, 2005).

Wetlands are typically highly productive ecosystems that may support a high diversity of biota (Millennium Ecosystems Assessment, 2005). However, many anthropogenic practices have accelerated the degradation and eutrophication of many wetlands around the world. Since 1950, human influence has emerged as one of the most significant forces on freshwater ecosystem change (Millennium Ecosystems Assessment, 2005). Wetlands found within the heavily industrialized regions of USA and Europe face serious problems from eutrophication (Bouwman & Vuuren, 1999). Eutrophication of wetlands in parts of South America, large areas of Asia and areas of Western, Eastern and Southern Africa is also increasing (Bouwman & Vuuren, 1999). It is argued that the state of wetlands in response to excessive nutrients has improved, specifically under the protection of Environmental Protection Authorities and the Ramsar Convention. However, nutrients may often be still elevated within the water column, even once external sources have been eliminated. Most efforts have been to control external sources of phosphorus, whilst less attention has focused on controlling internal sources, which can be a significant contributor of phosphorus to the water column. Once an internal source of phosphorus is managed, secondary symptoms associated with eutrophication can be remediated (Millennium Ecosystems Assessment, 2005). As phosphorus is the main limiting factor in freshwater ecosystems, phosphorus is typically the nutrient responsible for eutrophication (Reddy *et al.*, 1999; Prepas & Charette, 2003).

Although it is an essential nutrient, phosphorus is not normally readily available in wetlands (Correll, 1998; Bostic & White, 2007). In excessive quantities, phosphorus through its impact on algal blooms can become detrimental to wetland ecosystem, including impairing system function and reducing biodiversity (Carpenter *et al.*, 1998; Reddy *et al.*, 1999). In order to successfully rehabilitate nutrient enriched wetlands, the management of phosphorus from external and internal sources may be required. Although excess phosphorus is largely contributed to a wetland through external sources (e.g., domestic fertiliser inputs, runoff from agricultural land and erosion of soil), phosphorus mobilisation from prior contaminated wetland sediment itself can play a large role in providing a continuing internal source of nutrients to the water column (Bostic & White, 2007). Internal stores of phosphorus have the potential to be released via a number of forcing mechanisms, which can continue to cause eutrophication (Bostic & White, 2007).

The capacity of sediments to retain phosphorus is influenced by a variety of biological, physical and chemical factors (Holdren & Armstrong, 1980; Reddy *et al.*, 1999). Bioturbation through the physical movements of macroinvertebrates (digging and irrigation) can result in the increase in contact between the interstitial water and overlying water (Sondergaard *et al.*, 2003). In addition to this, respiration, feeding and defecating activities of the macroinvertebrates can alter sediment properties and chemical exchange between the sediment and the water (Sondergaard *et al.*, 2003). If sediment phosphorus retention capacity is high, this may also reduce the quantity of excess nutrients that are then carried to downstream wetlands (Johnston, 1991). Previous studies have identified phosphorus release upon rewetting of dry sediments, the influence of anoxic conditions and the presence of macroinvertebrates as important mechanisms of phosphorus release from sediments (Holdren & Armstrong, 1980). The organic release upon rewetting of dry sediments, which is experienced following summer and/or associated drought, may increase the concentration of phosphorus within the water column (Reddy *et al.*, 1999; Baldwin & Mitchell, 2001). Studies conducted by Qiu and McComb (1994) found that under both aerobic and anaerobic conditions, drying of sediments from eutrophic lakes can result in the release of phosphorus. Phosphorus bound to iron or manganese can be released due to changes in oxidation and reduction (ORP) conditions, often consistent with changes from aerobic to anaerobic conditions (Congdon, 1986; Reddy *et al.*, 1999; Gachter & Muller, 2003). Correll (1998) explored the role of dissolved oxygen and found that low dissolved oxygen levels resulted in the release of phosphorus normally bound to sediments. It is possible that hypoxic (low dissolved oxygen concentrations) water could release phosphorus from the sediment, without fully reaching anoxic (no oxygen) conditions.

Lake Joondalup is a large (440 ha), shallow (0-1.5 m deep), seasonal eutrophic wetland in urban Perth (Western Australia). The Lake is considered to be mildly eutrophic (Davis *et al.*, 1993). The northernmost lake of a chain of interconnected wetlands (Lake Goollelal, Wallubuenup Swamp, Beenyup Swamp and Lake Joondalup) that forms the Yellagonga Regional Park. Lake Joondalup has substantive problems resulting from eutrophication particularly with nuisance midges (Chironomidae) (Lund *et al.*, 2000; Lund & Ogden, 2005; Lund, 2007). Lund (2007) 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 areas 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 release phosphorus then this load cannot be realized.

The aim of this study was to investigate whether the high phosphorus concentrations found in the sediments of Beenyup Swamp by Goldsmith *et al.* (2008) could be the source of the high phosphorus exports from the Swamp that then enter Lake Joondalup. To be the main source, the stored P must be released and this study examined the three most likely environmental forcing conditions that could trigger release: bioturbation, sediment drying and low dissolved oxygen conditions.

4 Methods

4.1 Study Site

Beenyup Swamp forms part of a chain of wetlands on the Swan Coastal Plain that lies within the Yellagonga Regional Park. The park is located in the north-west corridor of Perth and is approximately 20 km north of the central business district (Figure 2). Yellagonga Regional Park covers about 1,400 ha and is situated on the Spearwood Dune System. The area is managed by the Cities of Joondalup and Wanneroo, and Department of Environment and Conservation under the Yellagonga Regional Management Plan (Dooley *et al.*, 2003).

Perth has a Mediterranean climate (cool wet winters and hot dry summers) causing Beenyup Swamp to be a seasonal wetland. Although Lake Joondalup is classed as one of the largest permanent lakes on the Swan Coastal Plain, it does dry during summer in some years, unlike Beenyup Swamp which usually completely dries out (Congdon, 1986; Kinnear & Garnett, 1999). The length of summer drying of this seasonal wetland is potentially enhanced by the increasing demand for groundwater from the Gnangara Mound (Balla & Davis, 1995).

The Yellagonga wetlands are connected and water flows northwards, from Lake Goollelal to Wallubuenup Swamp, to Beenyup Swamp and finally into southern Lake Joondalup (Semeniuk, 1988). The wetland landscape is characterised by steep slopes on the western side and more gentle slopes on the eastern side of the Park (Dooley *et al.*, 2003). The western side of Beenyup Swamp experiences steeper slopes leading down to the north-west side of Lake Joondalup (Dooley *et al.*, 2003). 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). The sediment of Beenyup Swamp is comprised of loose floc, thick consolidated organic matter and Beonaddy sand (Goldsmith *et al.*, 2008).

Although Yellagonga Regional Park has been subjected to extensive urbanisation over the past decade, 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).

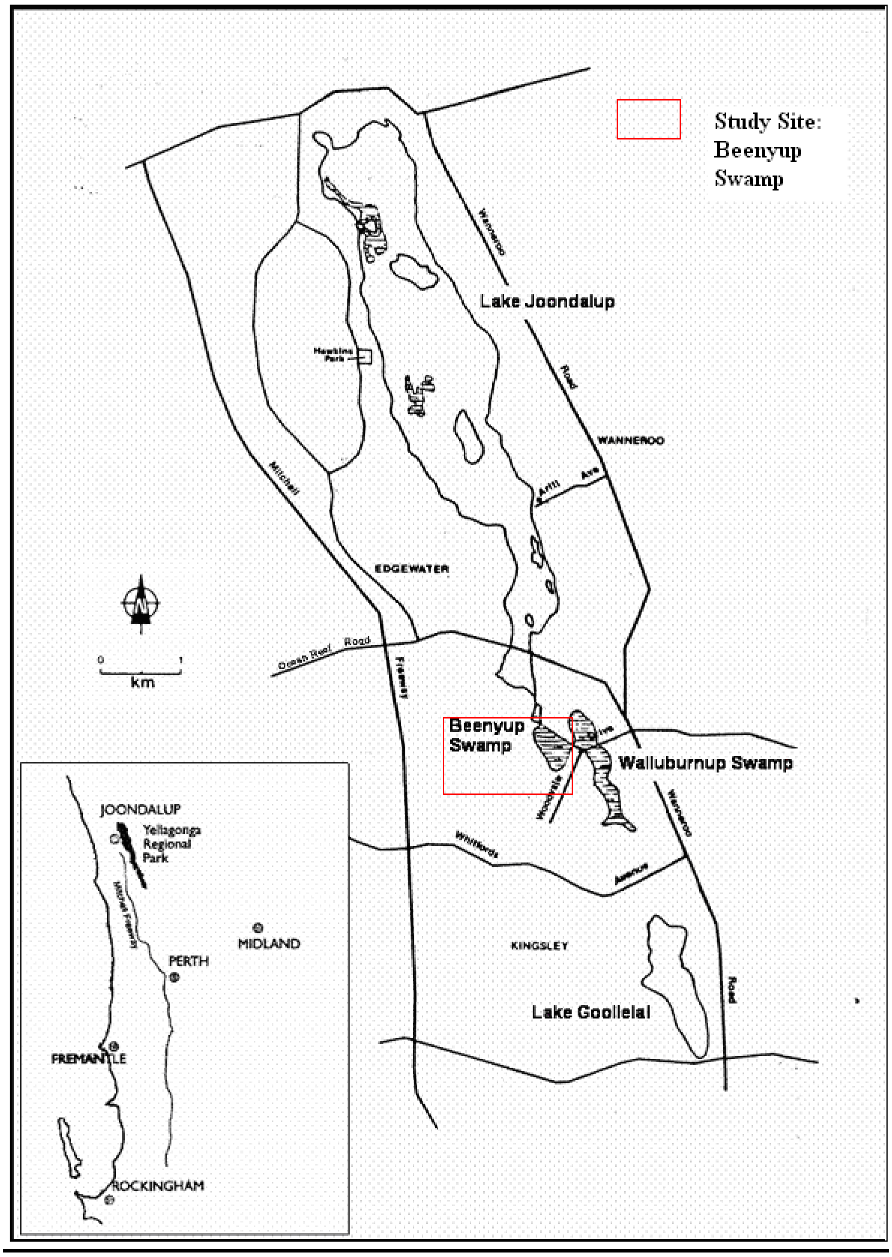

Figure 2. Yellagonga Regional Park, including Beenyup Swamp (after Cumbers, 2004).

4.2 Sampling methods

Sediment collection was conducted on the 30th of August 2008. Collection occurred in an open water area identified in Goldsmith *et al.* (2008) as containing sediment high in phosphorus (Figure 3). Twelve cores (120 mm diameter and 600 mm long) were pushed into the littoral sediments to a depth of 150 mm, the top was sealed with a rubber bung and the core extracted. The bottom was then tightly sealed with rubber bung. Sampling occurred randomly within a 10 m^2 area. In addition, a water sample and three additional cores were collected for sediment analysis (Total P). The water sample was split into an unfiltered sample (Total P and N) and a filtered sample (0.5 µm Pal Metrigard glass fibre filter paper) for filterable reactive P (FRP), nitrate/nitrite (NOx) and ammonia (NH_3). Water and sediments samples were frozen at -20^{o}C prior to analysis at the Natural Sciences Analytical Laboratories at Edith Cowan University. Physico-chemical parameters (oxidation reduction potential (ORP), pH, electrical conductivity, dissolved oxygen, temperature) of the water were measured *in situ* at 0.1 and 1m depths using a Hydrolab Quanta (Austin USA) multiprobe. An extra 40 L of surface water was collected to top up the microcosms back at the laboratory. Remaining wetland water was stored at 4^{o}C for use in rewetting the treatment 2 microcosms. A sweep with a dip net (500 µm mesh) was carried out within the area to collect midge larvae for a bioturbation treatment.

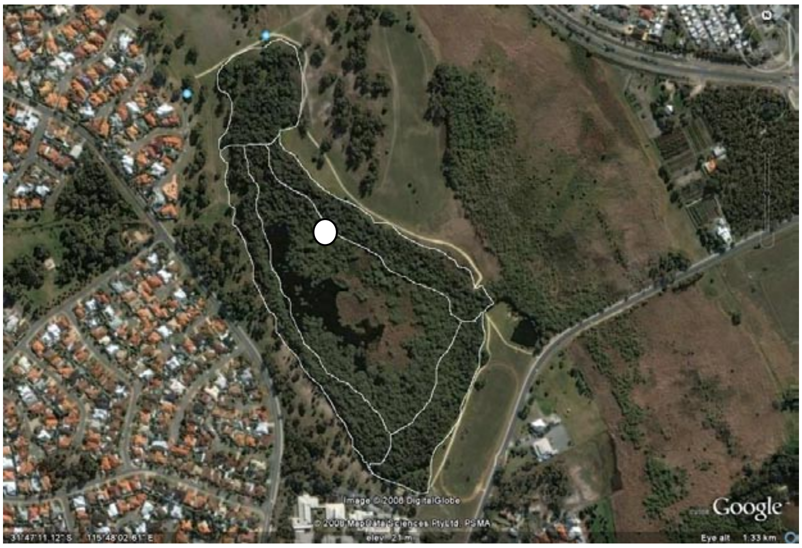

Figure 3. The white circle indicates the location of the sediment collection site at Beenyup Swamp, which was identified as having a high internal store of phosphorus (after Goldsmith *et al.*, 2008).

4.3 Experimental design (microcosms)

Sediment cores (microcosms) were arranged in a 50 L tub at the MiWER laboratories at Edith Cowan University and the tub filled with water to evenly distribute the temperature. The microcosms were topped up to within 50 mm of the top, using extra water collected from the site and the laboratory was maintained at 25ºC. The microcosm experiment consisted of the following four treatments that were randomly assigned to three replicate microcosms per treatment:

- **Controls** were not treated in any way.
- **Treatment 1** tested the hypothesis that anaerobic conditions cause phosphorus to be released from sediment by exposing microcosms to anaerobic conditions. Tightly fitting caps were used to seal the microcosms (limiting oxygen ingress) and then the sediment biochemical oxygen demand (BOD) was relied upon to consume existing oxygen in the water.
- **Treatment 2** tested the effects of sediment drying as a P-release forcing mechanism. The microcosms were carefully drained from the top using pipettes to remove the last traces of surface water and then were then placed in a fume hood with an air stone placed close to the sediment to enhance the drying process through air circulation. After three weeks, the microcosms sediments were dry to touch and resembled seasonally dried sediments. The sediments were now rewet using the stored Swamp water with care taken to minimize disturbance of the sediment.
- **Treatment 3** tested the hypothesis that bioturbation releases phosphorus from the sediment. The microcosms were found to naturally contain no midge larvae, therefore 50 midge larvae were removed from 1 m^2 sweep samples from Joondalup Lake and added to each Treatment 3 microcosm.

Control, treatment 2 and 3 microcosms were gently aerated with air stones. Physico-chemical variables (pH, ORP, conductivity, temperature and dissolved oxygen) were measured weekly (day 0, 7, 14, 21 and 28) in each microcosm using a calibrated YSI 600XLM (Yellow Springs, USA) multiprobe. In Treatment 2, the same physico-chemical parameters were measured at day 0, 1, 3 and 8 after rewetting. At the same times, the amount of phosphorus released in the water was also sampled from each microcosm. This was done by taking a 30 ml water sample, which was filtered (0.5 µm Pall Metrigard filter paper) for FRP and an unfiltered 50 ml sample for total P. Water samples were frozen at -20ºC and were transported to the Natural Sciences Analytical Laboratories for analysis.

4.4 Statistical Analysis

Physico-chemical and nutrient data from the microcosms was analysed using the Primer (v6) multivariate analysis package (PRIMER-E Ltd, 2006). Data pre-treatment involved ln(x+1) transformation, followed by normalisation. A correlation matrix (draftsman plot) then identified variables with correlations [>0.95], from the suite of which only a single variable was then retained for analysis (this simplified data interpretation without loss of information). A Principal Component Analysis (PCA) was then used to show any relationship between microcosm chemistry, treatments and time, where the distance between sites on the plot is equivalent to their degree of similarity (i.e., similar sites are grouped closely together).

5 Results

5.1 Microcosms

On the day of sampling, physico-chemical parameters measured at the Swamp's surface and 1 m depth were very similar (Table 1). The pH, conductivity and the temperature of the water remained largely unchanged at 6.8–6.8, 0.825–0.834 mS cm^{-1} and 12.4–12.3°C respectively surface and 1m. There was a slight decrease in dissolved oxygen from 49% to 38% (5.4–4.1 mg L^{-1}) and this was reflected in the decrease in ORP from -2 mV at the surface to -45 mV at 1 m. Nevertheless, ORP was well within the range (<120 mV), where Fe^{3+} can be reduced to soluble Fe^{2+} (Boulton & Brock, 1999).

Table 1: Mean (±standard error) of physico-chemical parameters measured at the surface and 1 m depths at Beenyup Swamp on the day of microcosm collection and in the control microcosms on Day 0.

	Temperature (◦C)	pH	Conductivity ($mScm^{-1}$)	Dissolved Oxygen (%)	Dissolved Oxygen (mgL^{-1})	ORP (mV)
Beenyup Swamp (surface)	12.4	6.80	0.825	49.4	5.4	-2
Beenyup Swamp (1m)	12.3	6.82	0.834	37.9	4.1	-45
Control (Day 0)	25.27±0.13	8.08±0.07	0.803±0.003	136.5±5.0	11.2±0.4	91±5

Laboratory microcosms at day 0 showed a higher temperature, pH, dissolved oxygen and ORP compared to the Swamp on collection day. The aeration of the microcosms would have increased the dissolved oxygen and ORP. The higher pH is unusual but might be due to increased algal production under the laboratory lighting.

Beenyup Swamp water on the day of sampling had a total P concentration of 400 µg L^{-1} and FRP of 98 µg L^{-1}, with total N of 890 µg L^{-1}, ammonia of 114 µg L^{-1} and NOx of 114 µg L^{-1}. By comparison, once the experiment was established (Day 0), the FRP in the control was 31±11 µg L^{-1}, 96±95 µg L^{-1} in treatment 1 and 64±60 µg L^{-1} in treatment 3, while Total P concentrations were 240±170 µg L^{-1}, 205±170 µg L^{-1} and 235±67 µg L^{-1} for control, treatment 1 and treatment 3 respectively. Settling of particulates and sediment uptake are probably responsible for the slight declines see in Total P and FRP in the microcosms on Day 0 compared to the Swamp on the day of collection. The increase in ORP, while not high enough to ensure all sediment iron was as Fe^{3+}, would have encouraged more P uptake than concentrations seen in the Swamp.

The site sampled was located between Sites 5, 16 and 17 of Goldsmith *et al.* (2008). Goldsmith *et al.* recorded sediment P concentrations of 0.9, 6.2 and 2.7 mg g^{-1} respectively at this site. At the site sampled sediment P concentrations were 0.3±0.06 mg g^{-1}. Although this site had lower P concentrations than nearby areas in Beenyup Swamp, this concentration was still larger than recorded by Davis *et al.* (1993) for Lake Joondalup and nearly 50% of the other wetlands which they sampled. This is not surprising as sediment nutrient concentrations can be extremely heterogeneous as found by Lund *et al.* (2000) for Lake Joondalup.

5.2 Treatments

Anaerobic treatment 1 showed a strong difference in the PCA compared to the other treatments (Figure 4). There is clear movement of this treatment from left to right of the ordination from Day 0 to Day 7, with Days 14, 21 and 28 clustered together. This movement occurred in the opposite direction to vectors for ORP, dissolved oxygen and pH, and therefore appears to describe the onset of anoxia, eventually stabilizing at Day 14. Replicates of Treatment 1 were the most variable and this may reflect the reliance on microcosm sediment to create anoxic conditions with small variations in the sediment chemistry making a large difference to BOD. The main source of this variability appears to be in water P levels, although these P values were consistent within each microcosm over time.

The PCA (Figure 1) also shows that there was virtually no change in control or treatment 3 over time and that treatment 3 strongly overlapped with control. This suggests that either bioturbation had no influence on sediment P release rates or that the midge larvae did not become established in the microcosm. Alternatively, no midge larvae were found in the microcosms at the end of the experiment suggesting they did not survive after transfer.

The effects of drying in treatment 2 were to cause an initial release of P with the replicates cluster near the top of the graph, however over time P concentration treatment 2 decreases and the replicates move back across the ordination toward the control. It therefore appears that while drying does cause release of P upon rewetting that within 1–2 days the sediment has re-absorbed all the released P.

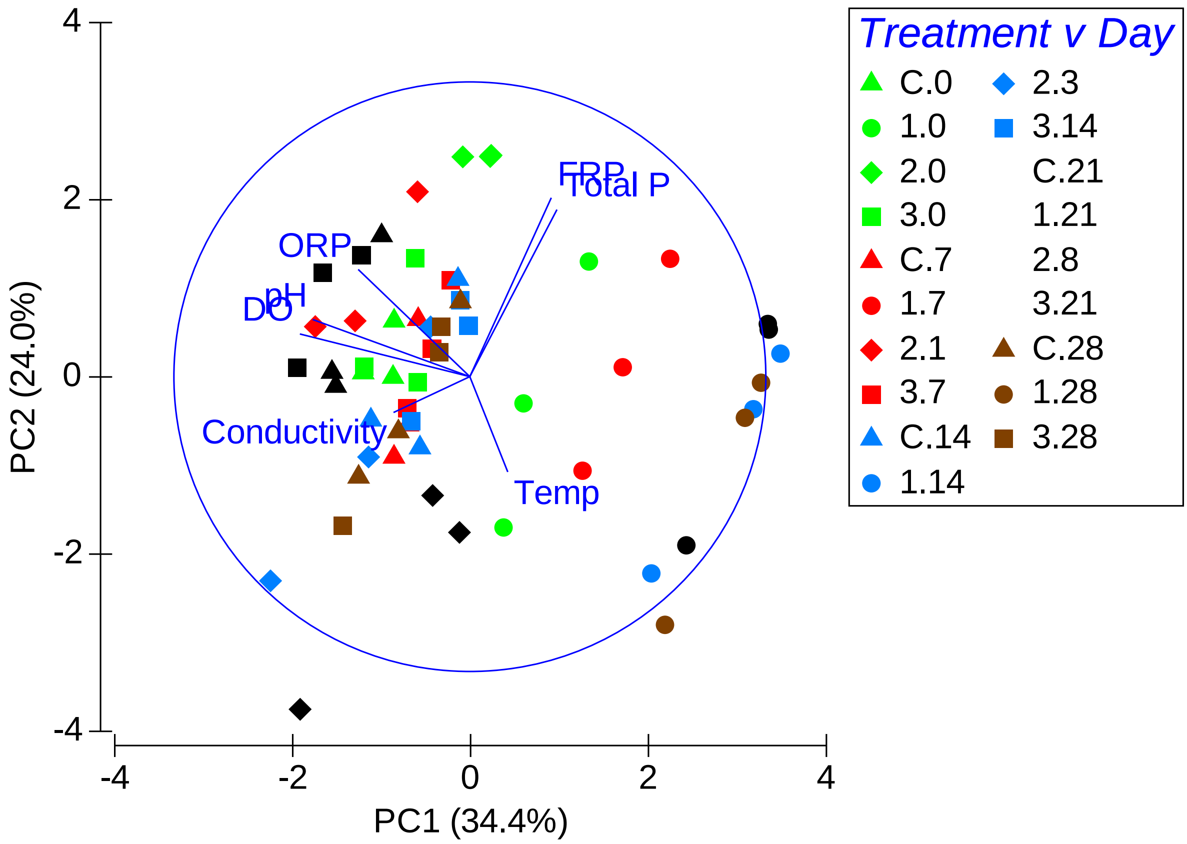

Figure 4. Principal Components Analysis of the microcosm water quality showing the correlations with parameters as positive vectors (times are colour coded, treatments are shape coded, first letter of number indicates treatment, following the "." is the day of experiment).

Temperature varied by <3°C across the microcosms across the study period (Figure 5). pH of control and treatment 3 also remained relatively constant over the duration of the experiment at around pH 8. However, pH of treatment 1 was consistently a pH unit lower at pH 7 for the course of the experiment, closer to that seen in the Swamp. Conductivity varied little over time and between treatments except after Day 21 in Treatment 1 where it appear to decline by 0.1 mS cm^{-1}. This decline was not likely to be biologically significant but was unexpected if anoxia was causing the release of nutrients and metals into the water column, which would then increase conductivity.

After an initial drop from 137% saturation, the dissolved oxygen stabilized at 100% in the control and treatment 3. Treatment 1 decreased over the experiment, reaching 40% saturation (hypoxia) in weeks 3 to 4. The control and treatment 3 had ORP that was always >60 mV, but in treatment 1 it had dropped to <0 mV by Day 14.

Treatment 2 temperature varied by <3oC while pH was similar to the control at approximately 8 (Figure 6). Conductivity of treatment 2 was noticeably higher than the control or other treatments ranging from 1-1.4 mS cm^{-1}. Dissolved oxygen remained above 70% saturation for the entire experiment. However despite the high dissolved oxygen, the ORP declined from around 100 mV to -50 mV by Day 8.

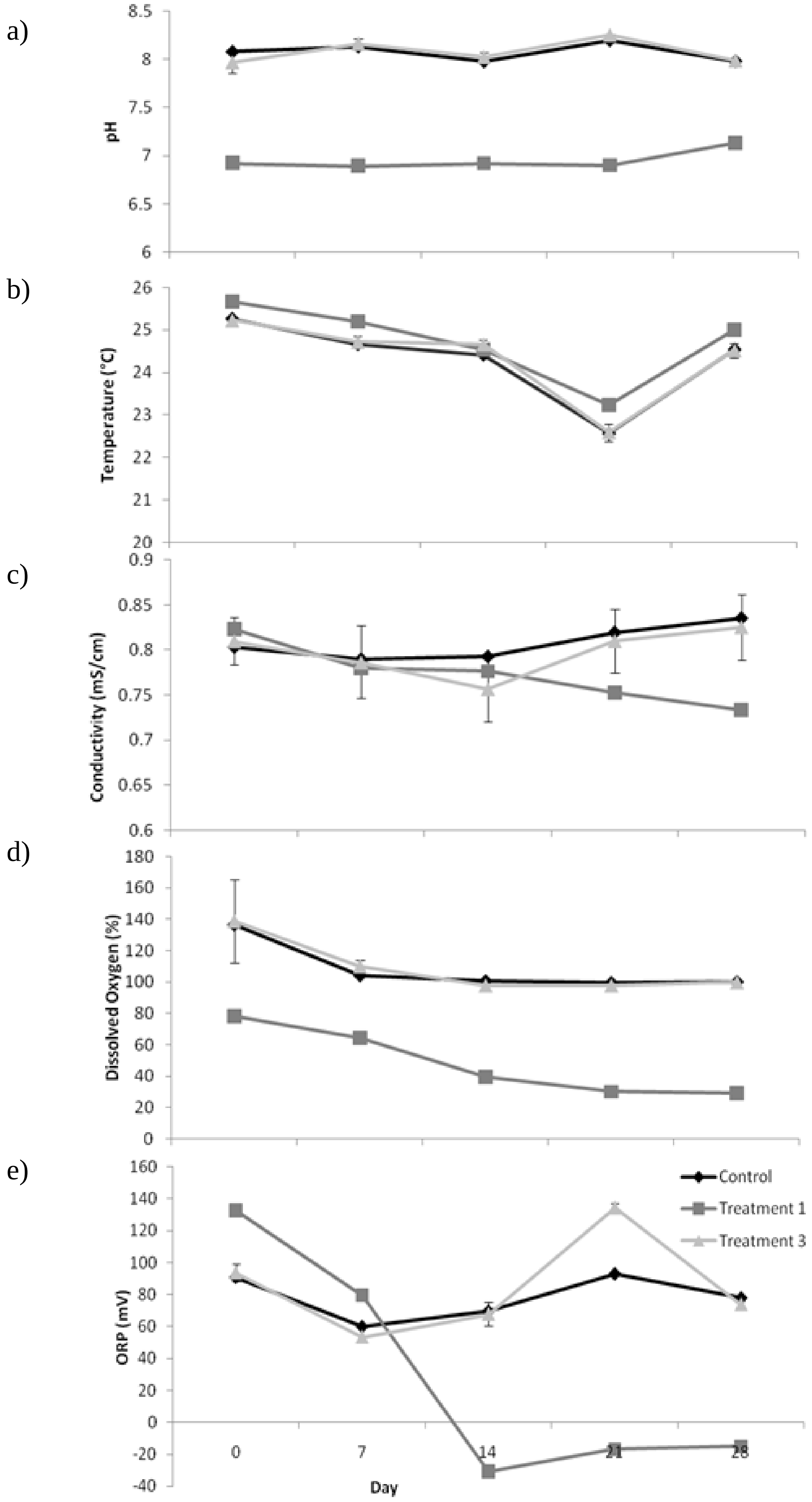

Figure 5. Physico-chemical parameters means (±standard errors) of replicates for control, treatment 1 and treatment 3 for a) temperature, b) pH, c) conductivity, d) dissolved oxygen and e) ORP of microcosms over 28 days.

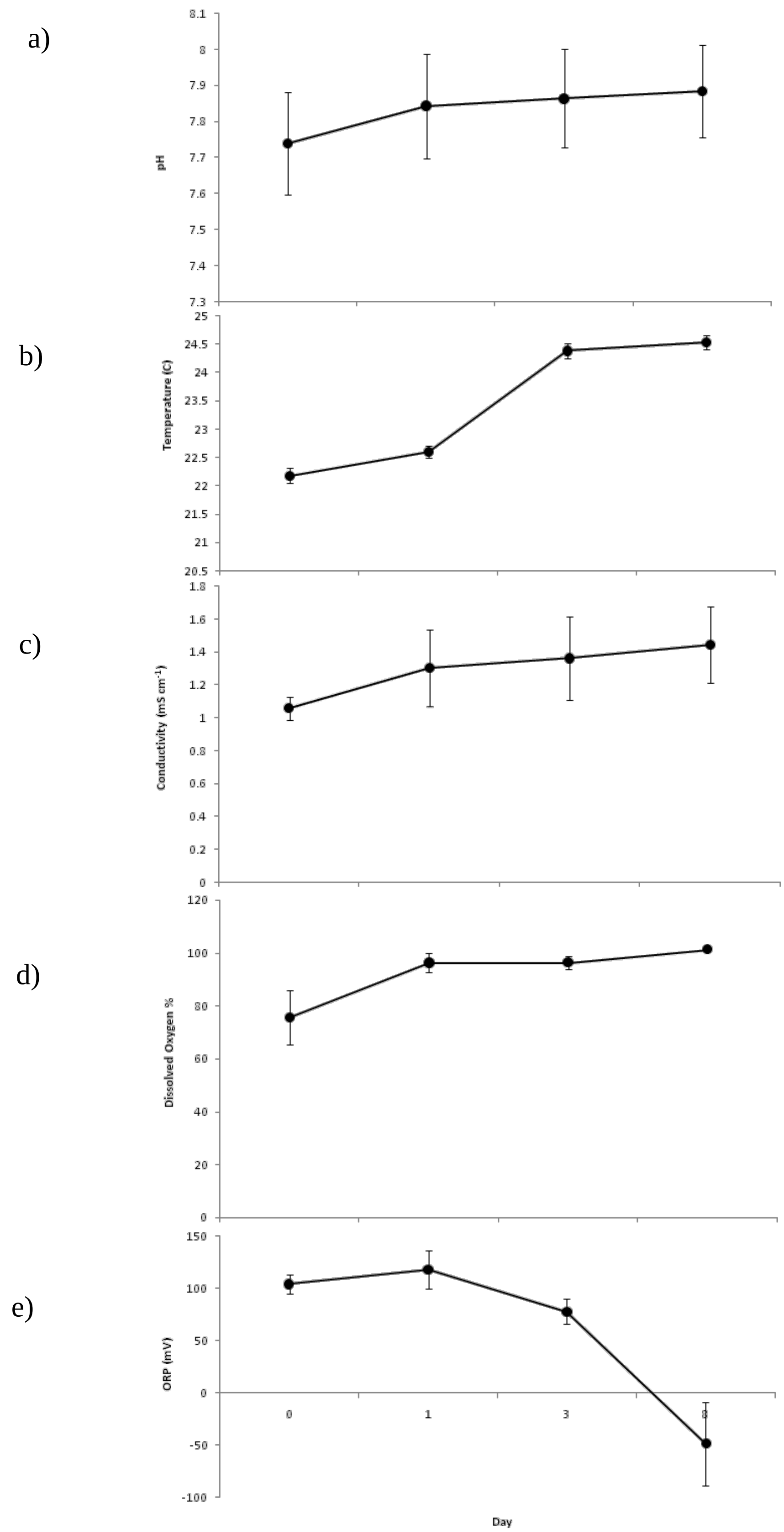

Figure 6. Physico-chemical means (±standard errors) of replicates for treatment 2 a) pH, b) temperature, c) conductivity, d) dissolved oxygen and e) ORP of microcosms over 8 days after rewetting.

5.3 Phosphorus in the Microcosms

Total P and FRP did not appear to be influenced by the treatments 1 or 3 compared to the control (Figure 7). Levels of both total P and FRP appeared relatively constant across the experiment, although there was high degree of variability between replicates. The release of P (both total P and FRP) that occurred following rewetting is evident in Figure 7, with total P initially reaching nearly 400 µg L^{-1} before declining back to levels seen in all the other treatments and control by Day 8.

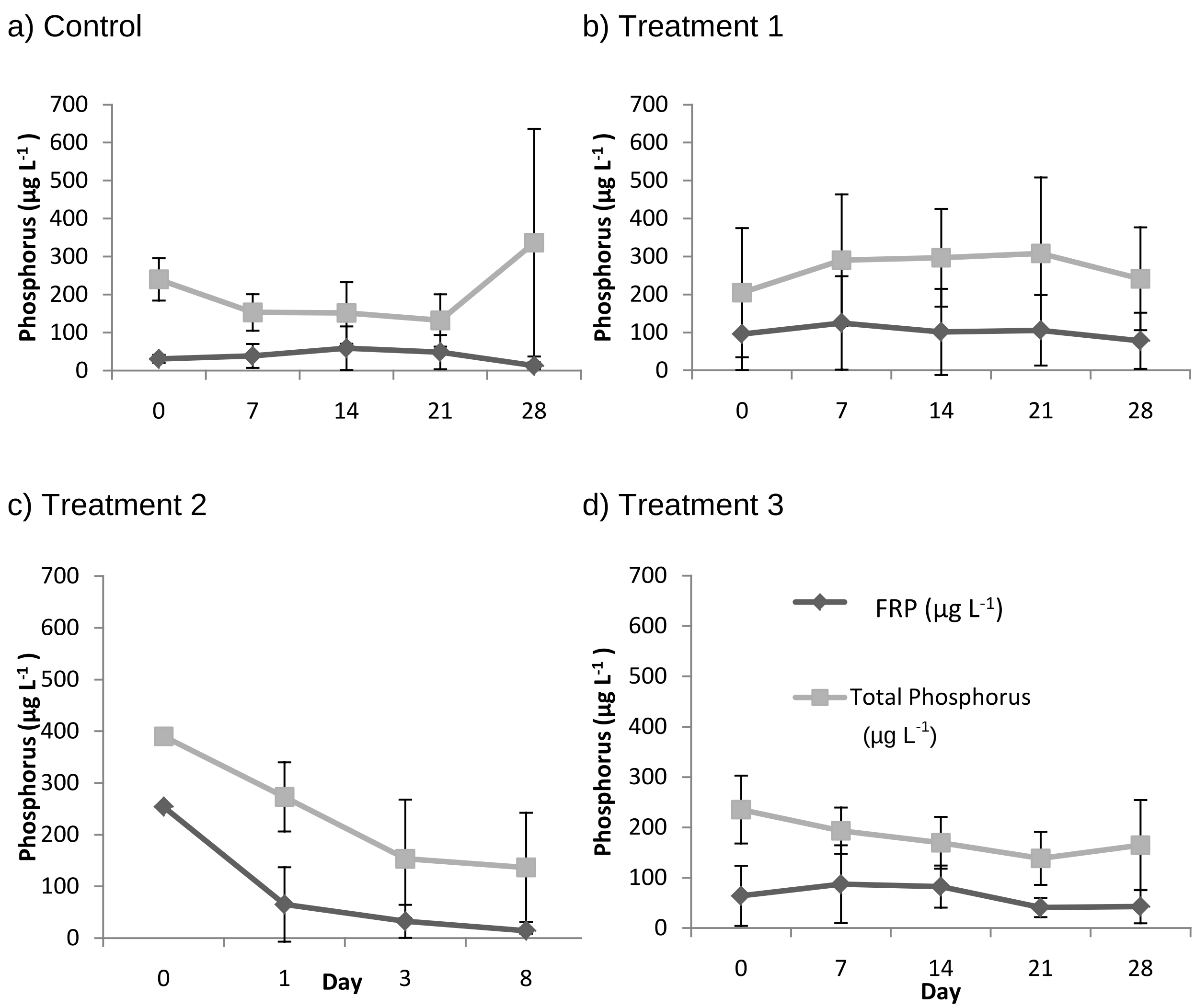

Figure 7. Total Phosphorus and Filterable Reactive Phosphorus means (±standard errors) of replicates for a) Control, b) Treatment 1, c) Treatment 2 and d) treatment 3 of microcosms over the experiment.

5.4 Phosphorus in the replicates

Due to stochastic effects such as heterogeneity, microcosms can be highly variable, particularly for nutrients. Examining individual replicates shows that the most of variability seen in FRP concentrations was due to replicate 1 in all treatments. FRP concentrations remain constant in the control, except in replicate 1 which shows an increase from under 50 µg L^{-1} to over 100 µg L^{-1} followed by a decline back to similar levels to the other replicates by week 4 (Figure 8). Treatment 3 showed a very similar response to P to that of the control. Treatment 2 shows the three replicates for FRP showing a similar trend but at different starting levels (~20 µg L^{-1} in microcosm 3 and ~200 µg L^{-1} in microcosm 1). This trend is similar for Total P, although microcosm 2 showed a slow increase and then decrease in concentration.

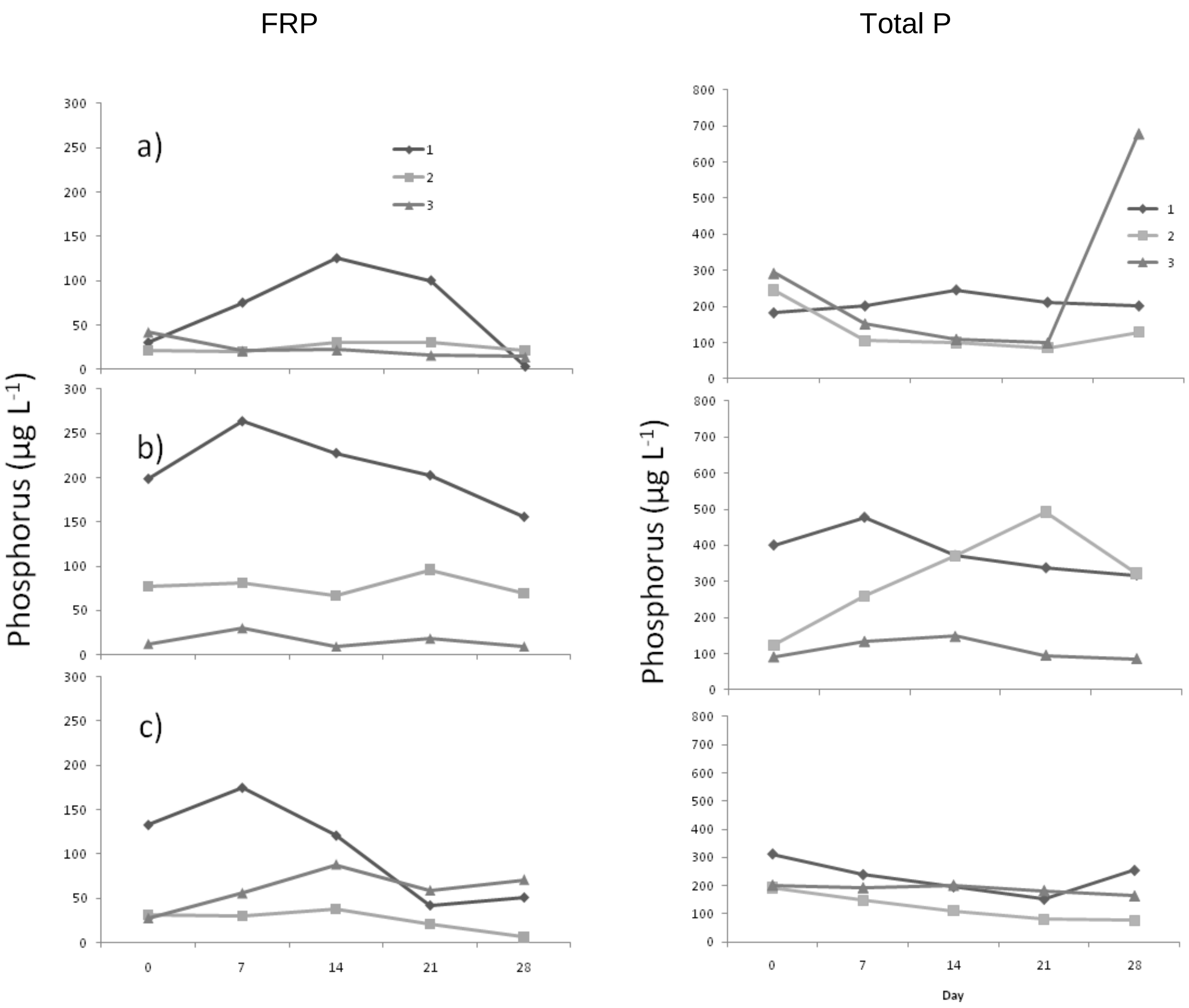

Figure 8. FRP and Total P for individual replicates of a) Control, b) Treatment 1 and c) treatment 3 measured over 28 days.

Total P showed a similar trend to FRP, with little change in the controls over time (an increase in replicate 3 is more likely to be an error than a real result) (Figure 9). In treatment 2 there was no significant change over time for FRP. Treatment 3 showed no change over time, although there is the suggestion of a slight decline in P concentration.

Treatment 2 replicates showed a consistent response to rewetting with a high initial total P and FRP followed by steady reductions to control levels over 8 days, with FRP in two replicates returning to control levels after 1 day (Figure 9).

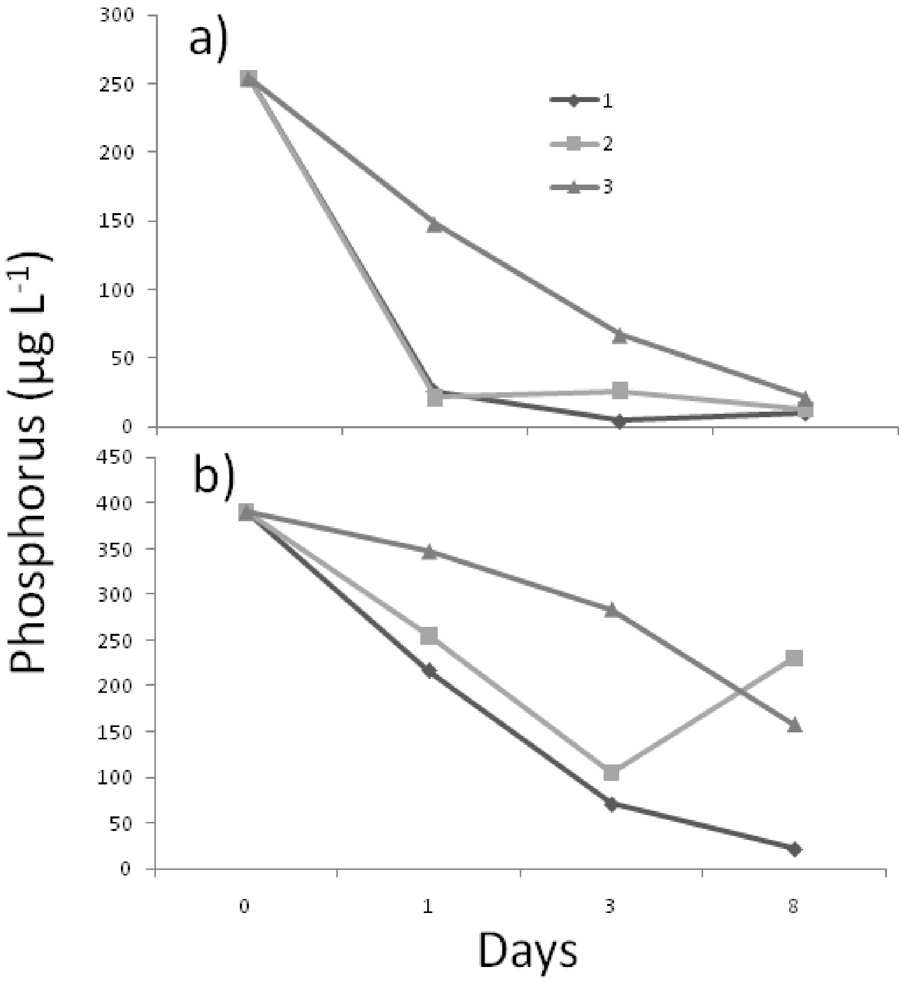

Figure 9. Changes in a) FRP and b) total P concentrations in individual replicates for treatment 2.

6 Discussion

The aim of this study was to examine the effects common forcing conditions for nutrient release might have on Beenyup Swamp sediments. Phosphorus concentrations at the sample site were lower by an order of magnitude compared to similar sites sampled by Goldsmith *et al.* (2008) a few months earlier in 2008. It is unlikely that sediment concentrations changed substantially over a few months; rather, it is more likely that sediment P concentration heterogeneity was responsible. This study examined a single site within Beenyup Swamp and therefore caution must be used in extrapolating the results to the entire Swamp. However, the sampled site had sufficient P and similarities to other sediments in Beenyup Swamp as to provide a strong indication of general sediment nutrient dynamics occurring across the Swamp.

Water quality had also improved from Goldsmith *et al.* (2008) study, where total P had dropped from 525-4,900 µg L^{-1} to 400 µg L^{-1} and FRP from 175-1,155 µg L^{-1} to 98 µg L^{-1} of FRP. This suggests that towards the end of winter that there was dilution of P concentrations with higher flows or that less P was being released into the system.

A variety of environmental conditions have the ability to influence the release of phosphorus from the sediment including temperature, pH, redox, biological activity and natural mixing. Higher water temperatures can increase rates of P release from the sediment due to an acceleration of the diffusion rate as a result of increased Brownian movement (Kleeberg & Kozerski, 1997). Temperature increases can also indirectly increase P release through enhanced bacterial activity (Kleeberg & Kozerski, 1997). Laboratory temperatures were substantially higher than field temperatures which would be expected to increase P release from the sediments, but this effect was not seen. Christophoridis and Fytianos (2006) found that ORP and pH greatly influenced release of phosphorus from sediments. Their results showed that the release rates of phosphorus increased under reductive conditions and at high pH values. This study had generally neutral to alkaline pH in all treatments and in treatment 2, after two weeks, a strongly reducing environment and a mildly reducing environment in the remaining treatments. Despite anoxia not being achieved, conditions should have been suitable in treatment 2, and to a lesser extent in the other treatments, to encourage release of

Fe bound P. However, there was no evidence of ORP-mediated P release in the experiments, which is opposed to other findings (i.e. Davis *et al.*, 1993; Sondergaard *et al.*, 2003; Christophoridis & Fytianos, 2006). Similarly, despite containing high concentrations of P, Sommer (2006) found that floc in Lake Goollelal did not release P under anoxic conditions. Sommer suggested that the unique structure of the floc may be responsible for this phenomenon. As Beenyup Swamp sediments in the open water sampled from area appear to be a floc, this distinct sediment-type might account for the results. The results of this current study and those of Sommer (2006) suggest that Beenyup Swamp, and Lakes Goollelal and Joondalup may therefore be less prone to sediment release of P and consequent eutrophication as a result of the presence of floc in wetland sediments.

Correll (1998) found that low dissolved oxygen levels resulted in the release of phosphorus that is normally bound to the sediments and Upton (1996) suggested that the chemical oxidation of organic matter can cause the depletion of dissolved oxygen in water bodies. As Beenyup Swamp is a highly vegetated seasonal wetland and contains a considerable quantity of organic matter, decomposition of this organic matter is expected to consume oxygen. Dissolved oxygen levels in the Beenyup Swamp water were below 100% saturation. Treatment 1 microcosms were sealed from oxygen ingress and it was expected that Swamp sediment would have been sufficient to quickly result in anoxia. However, oxygen levels failed to drop below 20% saturation (hypoxia) suggesting that the sediment had a low BOD and that much of the organic matter was possibly too refractory (resilient) to decomposition. ORP did eventually became negative which was sufficient to cause release of iron-bound P. it is therefore clear that ORP determines the state of Fe and hence P-release rather than dissolved oxygen concentration *per se* (Crosby *et al.*, 1984; Wauchope & McDowell, 1984).

Macroinvertebrate activity within sediments has been shown to influence their nutrient binding and release capacity. For example, previous studies by Congdon and McComb (1976) suggest that P could potentially be released from the sediments via microbial activity. Correll (1998) found that biological activity will gradually mineralize organic phosphorus, releasing it to the surrounding water overlying the sediments. In addition to bacterial action, macroinvertebrates can release P from the sediment via physical interaction through digging. A study by Ignatyeva *et al.* (2005) found that chironomids and amphipods greatly enhanced P release from the sediment, however oligochaetes were not important in this process. Jiang *et al.* (2007) found that chironomids, have the ability to stimulate P release from sediment through the vibrations in their movements, whilst their metabolism can alter the surrounding physico-chemical conditions. This study was unable to examine the role played by bioturbation in P release from the sediments of Beenyup Swamp, as added chironomids from Lake Joondalup were not present at the conclusion of the experiment. It is suspected that they died within a few days of commencing the experiment, possibly due to temperature shock as the cores were warmer than Lake Joondalup (~12^{o}C compared with ~25^{o}C). In the presumed absence of chironomids all the treatment 3 cores were very similar to those of the control.

Drying appeared to trigger a substantial release of P upon rewetting as treatment 2 experienced a high initial increase of P than found in the waters of the control. After 1-4 days the concentration of P then returned to levels similar to the control indicating that a release of P was achieved upon the initial rewetting of the sediment. This response closely resembles the findings of Bryant (2000) in a similar experiment at Lake Joondalup. Given that Beenyup Swamp may take a few days from filling to overflowing into Lake Joondalup, the rapid reabsorbtion of P would ensure that little of the released P entered Lake Joondalup. Qiu and McComb (1994) also found a rapid release of phosphorus from the sediment into the water column occurred when air-dried sediment was exposed to reflooding with aeration. In the study by Bryant (2000), the maintained-wet controls released significantly less concentrations of phosphorus than the air-dried cores, which correlates with the results of this current study.

Beenyup Swamp contains significant stores of P within its sediments however despite small increases in P concentrations in the water noted by Goldsmith *et al.* (2008) this study was unable to determine a mechanism for release of the sediment P. Aside from a short-lived increase following drying and rewetting, the sediments appeared unresponsive to water P, neither taking it up or releasing it. Although there was an initial drop in FRP and total P on establishing the experiment which may have been due to sediment uptake. The absence of obvious chironomids in any of the cores and especially following the addition (treatment 3) prevents the study from determining the role of bioturbation in sediment P release but also suggests that in the absence of chironomids it might not be too important. It remains unclear as to the source of the exported P from the Swamp.

7 Recommendations

It is recommended that;

- a detailed study be undertaken to valid the exported quantities from the lake,
- potential groundwater contamination of the Swamp be examined to see whether it is source,
- floc sediments of the Yellagonga lakes suite are examined in more detail, as it appears to useful in accumulating P and preventing its release under normal forcing conditions.

8 Acknowledgements

Thank you to Assoc. Prof. Mark Lund and Dr. Clint McCullough for their assistance and support in completing this project, Mark Bannister for assistance with chemical analysis, and friends and family for their support. The support of the Midge Steering Committee (Cities of Wanneroo and Joondalup and DEC) is gratefully acknowledged.

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