Removing filterable reactive phosphorus from highly coloured stormwater using constructed wetlands

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Abstract A constructed wetland design, consisting of 16 repeating cells was proposed for Henley Brook (Perth, Western Australia) to optimise the removal of FRP from urban stormwater. Three replicate experimental ponds (15 m²), were constructed to represent at a 1:1 scale a single cell from this design. Three 5 m zones of each pond were sampled: shallow (0.3 m) vegetated (*Schoenoplectus validus*) inflow and outflow zones and a deeper (1 m), V-shaped central zone. In 1998/99, inflows and outflow waters were intensively sampled and analysed for FRP and Total P. In addition, all major pools of P (plants, sediment) within the ponds, and important P removal processes (benthic flux, uptake by biofilm and S. validus) were quantified.

A removal efficiency of 5% (1998) and 10% (1999) was obtained for FRP. Initial uptake was mainly in plant biomass, although the sediment became an increasingly important sink. Benthic flux experiments showed that anoxia did not cause release of P from sediments, indicating that most of the P was bound as apatite rather than associated with Fe or Mn. The highly coloured waters were believed responsible for the very low biofilm biomass recorded (<1 g.m⁻²). We have demonstrated that constructed wetlands can be effective for removing FRP immediately after construction, although their long-term removal capacity needs further research.

Keywords Amended sediment; biofilm; constructed wetlands; phosphorus; stormwater

Introduction

Around Australia wetlands are being constructed for stormwater pollution control, and a variety of manuals for their design have been produced (e.g. Lawrence and Breen, 1998; DLWC, 1998; WRC, 1998). These typically focus on the engineering aspects of the design rather than on optimising the biological/chemical processes that are responsible for the nutrient removal. The prevailing view appears to be that constructed wetlands are little more than water treatment plants rather than the reality that they are constructed ecosystems. Western Australia has experimented with several constructed wetlands, early designs were essentially retrofitted groundwater recharge basins and more recent examples have been purpose built. The largest and most studied of these newer examples is the Bartram Road Buffer lakes (BRB). The BRB system became operational in 1993 and consists of 5 cells (3.2 ha) designed to reduce P by 30% (Braid, 1995). It has been speculated that constructed wetlands in Perth face greater difficulties in treating stormwater than elsewhere in the world due to the high DOC and FRP levels (WRC, 1997). Perth has a Mediterranean climate and as a result stormwater and drainage flows are largely restricted to between May and November, therefore constructed wetlands (and associated plants) have to cope with prolonged dry periods.

Over 80% of Western Australia’s population live on the Swan Coastal Plain (SCP) with the majority congregated in the city of Perth. The SCP consists of a series of parallel dunal systems of varying ages between the Indian Ocean to the west and the Darling Scarp to the east. As urban expansion pushes the limits of the city, many new developments are taking place on the older Bassendean sand dune system. This area was once considered only suitable for semi-rural development as it is largely situated over large groundwater mounds.
These mounds are used to supplement (up to 50%) Perth’s drinking water supplies and so have been traditionally protected from intensive urban development. In the 1990s the southern mound was opened up for high density urban development and drainage schemes were put in place to reduce the flooding risk. The BRB system was constructed as part of this scheme. Bassendean sands are highly leached and so have very poor nutrient retention capacities. As a result stormwater and groundwater in these areas typically carry high concentrations (up to 80% of Total P) of filterable reactive P (FRP), nitrates/nitrites and ammonium. Initially, as the development commences, most of the baseflow within the drains is actually groundwater. Groundwater in Bassendean sands is often highly coloured by humic and fulvic acids (dissolved organic carbon (DOC)) leached from vegetation. This colour inhibits algal growth either through light limitation or more likely by forming complexes with P and trace elements (Lund and Ryder, 1998).

Braid (1995) highlighted a number of problems with constructed wetlands in Perth that reduced their performance and evaluation. A common feature was that construction often did not match design, resulting in short-circuiting. The criteria against which performance was evaluated were often poorly developed and the methods used for measuring performance of these wetlands were often inadequate.

A simple conceptual model for P removal in Australian constructed wetlands was proposed by DLWC (1998). The model (Figure 1) suggests that overall contaminant removal efficiency (percentage of incoming nutrient load retained by the wetland (CRE)) is related to three key processes, sedimentation, short-term uptake (sediments and macrophytes) and long term uptake (biofilm, filtration and litter/peat accumulation). The model does not indicate the magnitude of the processes or the timeline for each. This project aims to validate the model and quantify timelines and magnitudes where possible. This aim will be addressed through measuring the efficacy of a “state of the art” design for FRP removal in highly coloured stormwater through intensive in and outlet monitoring, and quantification of P sinks and the processes responsible for any accumulation.

**Methods**

**Study site**

A conceptual design for Henley Brook was proposed in 1997. This design represented “state of the art” when this project commenced (Jim Davies & Associates, 1997); more...
information on the rationale for the project can be found in Bayliss (1998). The design consisted of a series of repeating cells, designed specifically to facilitate P removal (Figure 2).

This project constructed three experimental ponds (15 m long by 5 m wide) next to the Thomsons Lake Main Drain in Jandakot (Figure 3). This drain supplies the BRB system downstream of the site. Unlike the Henley Brook design (HBD) the ponds were isolated from the groundwater by a concrete shell covered with a PVC liner. The ponds were built (June 1998) to represent a single HBD cell at 1:1 scale. The liner was covered by 0.4 m of Bassendean sands (from the site), covered with a 0.1 m layer of red sand. Bauxite residues neutralised by gypsum have been tested as soil amendment to improve P retention on SCP farmlands with reasonable success (see Summers et al., 1996a and b). The residue is available in two forms, commonly called red mud (<150 µm particle size fraction) and red sand (≥150 µm particle size fraction); red mud has been used in several constructed wetlands as a sediment amendment, although in the BRB system problems were encountered with clumping and resuspension. This study chose to use red sand which has a lower P Retention Index (WRC, 1998) but is less prone to resuspension and redistribution. Each pond was divided along its length into three 5 m wide zones. The inlet and outlet zone was vegetated with the native rush Schoenoplectus validus, these zones slope (1:7.5; 0.2 to 0.5 m water depth) towards the central zone. A 1:5 sloped V-shape occupies the central zone (maximum water depth ~1 m). The slope was determined to minimise sediment slippage and limit plant encroachment of the open water section. The V-shape was used to increase the volume of water in the wetland to increase the hydraulic residence time (HRT).

In addition, during periods of no flow (i.e. summer), the V-shape retained water to support the plants and facilitated the establishment of natural convection circulation patterns that should ensure the bottom of the V remains oxygenated. This was seen as essential to preventing a redox driven release of P following reestablishment of flow conditions. Inlet and outlet structures were designed to facilitate plug flow through the ponds. The HRT was 8 h and 24 h in 1998 and 1999 respectively. Eight hours more accurately reflects the HRT of individual cells of the HBD. Flow rates were constant throughout the experiment. When the Thomsons Lake Main Drain was flowing (June to November), a sump pump was used to lift the water into a small header tank where flow was regulated into each pond, outflow was directed back into the drain downstream of the sump pump. In addition, to extend the flow...
period, drain water could be supplemented with groundwater, which was added upstream of the sump to allow aeration.

**Sampling methods**

In 1998, the ponds were sampled between 1/10/98 and 28/11/98 and in 1999, between 20/7/99 to 23/11/99. Autosamplers (ISCO®) were used to collect samples composited at 6 hour intervals over 2 or 3 days from the inlet and each pond outlet. Water samples were frozen and later analysed for Total P and FRP. In 1998, these samples were also analysed for DOC and in 1999, the samples were also used to determine total suspended solids (TSS), both organic and inorganic components. Loads were calculated from dataloggers that were attached to flow meters installed on the inlet pipes. As the ponds were isolated from groundwater and surface runoff it was assumed that inflow equalled outflow. Estimates of rainfall, transpiration and evaporation suggest that this assumption is reasonable, with these parameters representing less than a day’s flow over the entire sampling period. Water samples were taken in the open water zone and drain at 3–4 day intervals, filtered through glass fibre filterpaper, which was then analysed for chlorophyll \( a \).

Seasonal sampling (January, May, July, October) was undertaken to estimate P pools in sediments and plants. All sampling was conducted from a platform above the water surface to minimise sediment/plant disturbance. Three random sediment cores (44 mm dia. Perspex corer) were collected from each zone in each pond. Cores were divided into 0–10 mm and 10–50 mm sections, then dried and analysed for Total P. Plant biomass (divided into rhizome, stem base, stem and roots) was measured for each zone, above ground biomass was estimated using length-weight regressions and below ground biomass was estimated by taking sediment cores. All plant material was washed, dried and analysed for Total P. Biofilm was measured using glass slides (0.0375 m\(^2\)), two slides were scraped,
dried and analysed for Total P, one slide was scraped for Chlorophyll \( a \) determination and one slide was used to measure organic and inorganic biomass.

The benthic flux for FRP was measured in July and October using intact cores taken from 3 sites in each zone (as per Lavery et al., in press). Phosphorus isotherms for the sediment were measured seasonally from 3 sites in each zone by the Government Chemistry Laboratory (Perth).

Total P, FRP and chlorophyll \( a \) were analysed according to Standard Methods for the Examination of Water and Wastewater (1998) at the Marine and Freshwater Research Analytical Laboratory (Murdoch University) or at a nutrient analysis laboratory (Edith Cowan University).

**Results and discussion**

The HBD had a wetland area of 5.1 ha, an average HRT of 11.9 days (minimum 4 days), an annual load of 68 kg of P, and was predicted to reduce P by 40–60% per year (Jim Davies & Associates, 1997). In the two years of operation (July 1998 to January 2000) the experimental ponds each received loads of 4.8 to 5.4 kg of P, of which 3.2 to 3.7 kg were in the form of FRP. In this study and for the HBD the ratio of FRP:TP was very high (~70%), although in the HBD, the bulk of the FRP was from groundwater inputs, which suggests that baseflow in the Thomsons Lake Drain has a large groundwater input. In the ponds, concentrations of Total P appeared substantially lower in 1998 (347 ± 57 µg l\(^{-1}\)) than 1999 (648 ± 87 µg l\(^{-1}\)), although FRP concentrations were very similar (1998, 273 ± 28 µg l\(^{-1}\); 1999, 265 ± 20 µg l\(^{-1}\)). It was suspected that sampling technique may have been responsible for underestimating the Total P in 1998, however a comparison of different methodologies failed to indicate a problem. In 1998, the CRE for FRP ranged between 1.5–4.5%, increasing to 11.4–12.1% in 1999. These figures suggest that the ponds are performing extremely well, certainly in the predicted range for HBD when scaled to an operational size. The loading rates in the ponds were substantially higher than that predicted for HBD (HBD: 13 kg P/ha/yr; Ponds: 320–360 kg P/ha/yr). The CRE for Total P in the ponds was substantially poorer at –1.8 to 2.4% in 1998 and 4.2 to 7.5% in 1999. It should be noted that in both years the net amount of FRP removed frequently exceeded the net amount of Total P removed due to increases in particulate/organic P at the outlet. The ponds were not designed to promote sedimentation, as this is a reasonably well understood process and is typically incorporated into constructed wetlands prior to the macrophyte cells.

In 1999, only 16% of the suspended solid (SS) load into the ponds was inorganic, which reflects the sandy nature of the catchment. The ponds generated suspended solids with organic loads increasing from 5.8–5.9 kg to 7.5–9.5 kg and inorganic loads from 1.1 kg to 1.5–2.6 kg. Interestingly, the highest inorganic loads are associated with the lowest CRE for Total P. Resuspension of sediment is the most likely source of the increased inorganic SS load. We found evidence of slumping of the red sand fraction and sampling of plants and sediments also appeared to cause small amounts of resuspension.

The short HRT of the ponds would have prevented the development of detectable phytoplankton loads, and the highest chlorophyll \( a \) concentration recorded in the ponds was 9.9 µg l\(^{-1}\), although the majority were ≤1 µg l\(^{-1}\). It is assumed that the phytoplankton within the ponds was washed in from the drain, although there does appear on average to be a slightly higher concentration of chlorophyll leaving the ponds than entering them (Drain 0.7 ± 0.1 µg l\(^{-1}\); Ponds 1.3 ± 0.1 µg l\(^{-1}\)), a slight increase is also seen in Phaeophytin (Drain 0.4 ± 0.1 µg l\(^{-1}\); Ponds 1.1 ± 0.1 µg l\(^{-1}\)). A possible source for this increase may be turnover of biofilm. Biofilm was estimated to have a standing crop per pond (assuming a 485 m\(^2\) surface area in the vegetated zone and 30 m\(^2\) in the open water) in 1999 (Sept to Nov) of 28–216 g inorganic and 67–233 g organic components. These estimates suggest...
that if there was a rapid turnover of the biofilm that it could be a major source of the SS load, 
but not of particulate P, as the pool of P in the biofilm was estimated to be only 8.3–31 mg at 
any one time in each pond. Lawrence and Breen (1998) and DLWC (1998) suggest that a 
key component for the long term removal of P from constructed wetlands is through biofilm 
accumulating FRP and during turnover adding that P to the sediment. Although there is a 
paucity of data on biofilm biomass, results from Cronk and Mitsch (1994) suggest that 
Fig 4 biofilm biomass in the ponds is an order of magnitude below that recorded in their con-
structed wetlands. The inflow water was highly coloured with a mean DOC concentration 
of 50.8 ± 1.6 mg C l⁻¹ and this is probably responsible for the low biomass recorded. The 
reasons are twofold with rapid attenuation of PAR, such that below 0.4 m there is effective-
ly no light available for photosynthesis and chelation of essential elements (Lund and 
Ryder, 1998).

Another potential source of organic SS is from the decomposition of macrophyte tissue. 
The growth of S. validus was substantial and by January 2000 biomass had reached 1.6–5.1 
kg DW m⁻² above ground and 1.2–2.2 kg DW m⁻² below ground depending on the area. 
This was aided by bird netting to prevent birds uprooting the tube stock. As the two years 
of the study represent the establishment phase of the stand, the stem turnover rates are 
therefore likely to be low. This indicates that macrophytes were unlikely to be making a 
substantial contribution to the organic SS. The V-slope proved very successful in prevent-
ing S. validus encroaching into the open water area, which would simplify maintenance.

In 1999, the amount of P retained for FRP was extremely consistent between ponds, with 
a similar result for Total P. In 1998, CRE was highly variable for both FRP and Total P, this 
may reflect the maturation of the ponds or reduced HRT in 1999. Lantzke et al. (1999) sug-
gest that there is not a linear relationship between CRE and HRT, and this was also apparent

Figure 4  Pools (net change) and loadings of P (in grams) in 1998 and 1999 over the monitoring period for 
each experimental pond (negative values indicate a decline in the pool; NM = not measured)
here. The P isotherms indicate that by January 2000, that the sediments still had a reasonable capacity for P adsorption. The sediments accumulate little P during the monitoring period (Figure 4). One unexpected result was the apparent migration of P deep (50 mm) into the sediment; the mechanism responsible for this is currently unknown but suggests that all of the top 50 mm of sediment is available for P uptake. Benthic flux experiments suggest that P is primarily bound to Ca in the sediment, as under anaerobic conditions P was still being taken up. The remainder of the uptake can be accounted for by uptake into plant biomass. The pools of P in S. validus were highly variable, with a large proportion found in the above ground biomass. It is suspected that now the stand has matured, uptake by plants will become less important for the CRE than in the first two years. Lantzke et al. (1999) suggested that the major pathways for removal (in the order of months) were macrophyte > sediments >> biofilm, and this appears to have been the case here.

It is suggested that the short term removal curve (Figure 1) should be divided into plants and sediments, with a similar shape. It appears that at 2 years, the uptake by macrophytes may have peaked in the systems. It is unlikely that sediment uptake has yet peaked. It currently appears that high DOC concentrations will limit the development of long term removal pathways through biofilm. This suggests that the long term efficiency of constructed wetlands receiving highly coloured waters may be lower than indicated during the macrophyte establishment phase. Substantial improvements in the efficiency of the HBD appear possible by reducing resuspension of sediment and/or enhancing sedimentation processes.

Conclusions
The experimental ponds proved extremely effective at removing FRP from incoming water in their second year of operation. The sediment accounted for little of the P removal, with P incorporation into plant biomass responsible for the majority of removal. As the plant stand has now become established it is anticipated that plant uptake will become less significant in subsequent years. Biofilm development appears limited due to the highly coloured waters, this suggests that biofilm may not be able to make a substantial contribution to long term P removal. This in turn suggests that the long term removal capacity of constructed wetlands receiving coloured waters needs further investigation.

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References


*Lund et al.*


