Phosphorus removal in a vertical upflow constructed wetland system

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Abstract
Mechanisms for P removal in a vertical upflow macrophyte system were studied in controlled laboratory columns filled with sand and planted with Phragmites australis. Substrate P removal was shown to increase with flow rate, a parameter which can be enhanced through effluent recirculation. An alternative substrate (leca, light expanded clay aggregate) provided improved equilibrium adsorption characteristics, but uncrushed and within the kinetic constraints of a macrophyte system gave no improvement for P adsorption over sand. Intermittent loading of the sand based macrophyte system permitted control of the P concentration, with lower effluent peak concentrations for increased resting interval (no P inflow). Where P loading was targeted, continuous flow provided the optimum mass removal conditions.

Keywords Effluent recirculation; intermittent loading; phosphorus adsorption; plant uptake; vertical flow; wetland system

Introduction
Constructed wetland technology is a low energy, low cost alternative for the removal of nutrients from industrial and municipal wastewater and agricultural runoff (Kadlec and Knight, 1996). If nutrients can be retained in the wetland then recycling for agricultural or other purposes becomes a real possibility (Farahbakhshazad and Morrison, 2000). This potential is hindered by a lack of understanding of nutrient removal mechanisms under different hydraulic conditions. Oxygen demanding substances and suspended solids are less affected by hydraulic conditions and are generally well removed, although a wide range of performances for nutrient removal has been reported (Kadlec and Knight, 1996).

A common problem in constructed wetlands with horizontal flow is that the main water body avoids the dense root-zone and passes through the deeper gravel bed untreated and the plant uptake was considered a minor process (Breen and Chick, 1995). Clogging and surface runoff are common problems in wetlands containing clay, the clay being added for improved P removal, and consequently large surface areas (>20 m² per person equivalent) have been suggested to improve the removal capacity of horizontal wetlands (Schierup and Brix, 1990).

Water-root contact can be optimised in vertical systems through an upward flow (Breen and Chick, 1995; Farahbakhshazad and Morrison, 1997). An even root system distribution has been observed in upflow systems, which promotes plant uptake and indeed, nitrogen species have been satisfactorily removed (Farahbakhshazad and Morrison, 1997, 2000).

A vertical macrophyte system, which captures nutrients through rhizome storage, has the potential to remove nutrients from agricultural runoff, although the luxury root uptake/rhizome storage of P. australis provides a high N/P ratio in the roots (Farahbakhshazad and Morrison, 2000).

Phosphorus removal can be explained through a complex of physical, chemical and microbiological processes, although adsorption to the substrate has usually been
considered to be the main removal process (Kadlec and Knight, 1996). However, due to the limited P adsorption capacity of preferred substrates (i.e. sand or gravel) the adsorption process is reversible (Lantzke et al., 1999).

Variable P removal efficiencies have been reported for vertical flow wetlands (Lantzke et al., 1999; Rogers et al., 1990; Farahbakhshazad and Morrison, 2000). Plant uptake has been reported as the main removal process and represents a long term irreversible removal mechanism in batch loaded bucket systems (Rogers et al., 1990). It has been claimed that in vertical upflow systems a mixing hydraulic format is responsible for the decreasing water detention time in the system (Rogers et al., 1990). However, it was later reported that mixing the rhizosphere liquid and forced convection provided accelerated orthophosphate removal in bucket systems (Lantzke et al., 1999).

A difference between planted and unplanted systems was observed for P removal in horizontal gravel beds receiving agricultural waste. It was proposed that plant litter, providing additional organic material and thereby new sites for P adsorption, was responsible for a better mass removal performance of the planted systems (Tanner et al., 1999). Meanwhile, it was claimed that the large differences between planted and unplanted P removal in bucket systems results from gravel rejuvenation due to the irreversible plant P uptake which is not as rapid as substrate adsorption (Lantzke et al., 1999).

There is some uncertainty concerning the role of microbial uptake in P removal, although it has been claimed that biotic processes have a considerable effect on phosphorus removal, which is influenced by the bioavailable carbon source in the sediment (Khoshmanesh et al., 1999).

In the present study the mechanisms for P removal were investigated at a laboratory-scale in vertical upflow systems planted with Phragmites australis.

Methods
Tests were carried out in Plexiglas columns (0.06 m diameter, 0.5 m depth) with an upflow hydraulic regime (Figure 1a). Holes were bored and porous frits on hollow glass rods were tightly inserted in the Plexiglas column and sealed with epoxy glue. Each frit was positioned in the centre of the column and each glass rod extended out of the column to allow polyethylene tubing attachments. The column was filled with sand (median grain diameter, d_50 of 1 mm and a calculated porosity of 40%). Sieve analysis showed a narrow size range (d_10, 0.8 mm; d_90, 1.2 mm). The elemental composition of the sand was determined by plasma emission spectrometry (ICP-AES) as SiO_2 73.3%, Al_2O_3 14.0%, Fe_2O_3 2.0%, CaO 1.7%, MgO 0.7%. Individual shoots of P. australis with approximately 150 mm long rhizomes were planted and established in the columns. Experiments were made with standard solutions in the range of 0.5–8.0 mg l^{-1} phosphate-P. In the experiments with water recirculation (Figure 1b), the phosphorus solutions were introduced to the planted and unplanted systems; outflow from the sampling port at 0.45 m was pumped back to the columns to provide the required number of recirculations, with varied flow rate and for a total detention time of 2 hours (1 × 2 h, 2 × 1 h, 3 × 40 min, 4 × 30 min, 6 × 20 min, 12 × 10 min) to provide flow rates in the range of 0.3–3.6 l h^{-1}.

Adsorption isotherm experiments were carried out in glass beakers (500 ml), stirred with a paddle, in the laboratory. Sand was washed, accurately weighed (30, 50, 100, 150, 200, 250, 300 g) and transferred to each beaker containing a phosphate concentration of 1 mg P l^{-1}. Leca (light expanded clay aggregate) (0–4 mm) was ground (0.125–0.5 mm), washed and weighed (0.1, 0.5, 1, 5, 10, 20, 30 g) and transferred to each beaker containing a phosphate concentration of 1 mg l^{-1}. Samples were taken from each experimental beaker after equilibrium was reached (48 h), filtered through GF/C glass fibre filters and analysed for phosphate-P concentration.
Plant uptake experiments were run with an inflow phosphate-P concentration of 1 mg l\(^{-1}\) and with different periods of rest. The columns were rested through feeding with ultrapure water. A range of rest periods were tested (20, 60, 120 and 180 min) and P was introduced for a 20 min duration. The water detention time in the column was 20 min and effluent samples were collected at 20 min intervals. The columns were tested for continuous P flow without resting and the results were compared.

To study the effect of leca adsorption on P removal, an upflow column system with \textit{P. australis} was filled with leca up to 0.25 m and sand in the final 0.25 m. Concentrations of 0.5–10 mg l\(^{-1}\) phosphate-P were introduced. The results were compared to a planted sand column.

The effect of biomass removal was studied by adding glucose (100 mg C l\(^{-1}\)) to the three columns filled with clean sand, sand from a planted and sand from an unplanted pilot-scale wetland system, respectively. The efficiency of these columns was compared for a range of initial phosphate-P concentrations (0.5–5.0 mg l\(^{-1}\)P) with and without effluent recirculation, at flow rates of 0.3–3.6 l h\(^{-1}\).

The effect of iron precipitation of phosphate was studied by adding 0.5 and 1.0 mg Fe l\(^{-1}\) (as FeCl\(_3\)) to the inflow solution (1 mg P l\(^{-1}\)) with and without effluent recirculation at flow rates of 0.3–3.6 l h\(^{-1}\).

During the experimental period the columns were maintained in a well-lit pump house, with extra artificial lighting, where the temperature varied between 17–25°C. pH values were routinely monitored in the columns during the experiments and were in a range of 5.8–7.8, except for the experiment with iron addition where lower pH values (minimum 4) were observed. Phosphate-P in the samples was determined by standard HACH methods on a HACH 2000 photometer. The relative standard deviation of phosphate-P concentration through this procedure was ±1% based on measurements on standard solutions.

Recirculation studies for three planted columns resulted in a relative standard deviation of 23% for the inflow P concentration of 0.5 mg l\(^{-1}\) and a relative standard deviation of 21% for the inflow P concentration of 5.0 mg l\(^{-1}\) at 12 recirculations (12 × 10 min). The performance of three unplanted columns gave a relative standard deviation of 9% for the initial concentration of 0.5 mg l\(^{-1}\) phosphate-P and 10% for the initial concentration of 5.0 mg P l\(^{-1}\) at

![Figure 1](https://iwaponline.com/wst/article-pdf/48/5/43/423491/43.pdf)

\textbf{Figure 1} a) Experimental column system, b) Column system with effluent recirculation
12 recirculations. Experiments with 2 h resting intervals were repeated for 3 planted columns. The relative standard deviation was calculated as 27%.

**Results and discussion**

**Effect of flow characteristics on P removal**

It has been claimed that the diffusion controlled substrate adsorption was the major site for initial P removal (Lantzke *et al*., 1999). Forced convection increases the turbulence, which decreases diffusion time/distance, stimulating P adsorption to the substrate (Lantzke *et al*., 1999). This hypothesis was tested in planted and unplanted column systems through water recirculation at different flow rates. The results show that an increase in flow rate improves the performance of both planted and unplanted systems for P removal (Figure 2). Higher flow would be expected to decrease the diffusion distance. Figure 2 shows that the removal of P for low concentrations (0.5–2.0 mg l\(^{-1}\)) increased from 40% for one recirculation (flow, 0.3 l h\(^{-1}\)) to approximately 75% for 12 recirculations (flow, 3.6 l h\(^{-1}\)). For P removal, recirculation has the advantage of allowing a high hydraulic loading to the system.

The results show that the removal efficiency for phosphate was concentration dependent in both planted and unplanted systems for the range of inflow concentrations considered here.

**Effect of substrate adsorption on P removal**

The Freundlich isotherm describes adsorption to heterogeneous surfaces and is used here to study the adsorption capacity of the 1 mm sand used as substrate in the columns and 0–4 mm leca. The Freundlich isotherm is usually expressed as Eq. (1).

\[
q = K_f C^n
\]  

(1)

Where \(q\) is the adsorbed amount to the solid phase of the adsorbate per mass of the adsorbent and \(C\) is the equilibrium concentration of the adsorbate in the solution. \(K_f\) and \(n\) are constants determined by plotting \(\log q\) versus \(\log C\). The adsorption constant \(K_f\) (mg g\(^{-1}\)(l mg\(^{-1}\))\(^{1/n}\)) is equal to the adsorbed concentration \(q\) when \(C = 1\). The exponent \(n\) is related to the surface heterogeneity (Clark, 1996).

Previous studies have reported high P removal on leca substrate (Zhu *et al*., 1997),

![Figure 2](https://iwaponline.com/wst/article-pdf/48/5/43/423491/43.pdf)

**Figure 2** Variation of phosphate removal efficiency with number of recirculations and influent concentration in vertical flow planted and unplanted systems. \(C_o\) = Initial concentration, \(C =\) Final concentration. Experimental time, 2 hours. Range of flow rates, 0.3–3.6 l h\(^{-1}\)
although these studies were not carried out at equilibrium. Freundlich adsorption isotherms are only relevant where equilibrium can be achieved and it is necessary to crush the leca to present the macropore and micropore surface area for adsorption. Because previous studies (Zhu et al., 1997) were on uncrushed leca and with different initial P concentrations, they are not considered comparable with the present study. In this study leca ($K_f = 100; n = 0.8$) provided similar site adsorption characteristics (from the heterogeneity exponent, $n$), but improved equilibrium capacity (as reflected by $K_f$, the Freundlich adsorption constant) compared to sand ($K_f = 5, n = 1.1$). At increasing concentrations an increased competition between phosphorus ions for the relatively scarce adsorption sites of the sand particles becomes apparent. This effect could be prevented by the use of materials with more adsorptive sites. Results for three initial concentrations (0.5, 5.0 and 10 mg l$^{-1}$) in leca/sand and sand columns are reported in Figure 3.

According to these experiments phosphate is removed satisfactorily in both leca/sand and sand columns for a low concentration of 0.5 mg P l$^{-1}$. The sand column shows a better removal efficiency for higher P concentrations than leca. These results show that adsorption to leca does not improve the performance of the system. As Freundlich adsorption isotherms do not account for the kinetics of adsorption in column systems, it is perhaps not surprising that leca and sand are similar as substrates for P removal in these systems.

**Effect of biofilm on removal efficiency**

Bacterial P uptake is an important removal mechanism, which is stimulated by the introduction of a bioavailable carbon source (Khoshmanesh et al., 1999). This hypothesis was tested. No effect was found in the efficiency of the columns (with clean sand, sand from planted and unplanted pilot-scale wetlands) either with or without C addition. Bacterial uptake however, is a slow kinetic process and the effect of the added glucose was first observed after 50 h on the removal of P ($C_o = 1$ mg l$^{-1}$ phosphate-P) in wetland soils in laboratory-scale experiments (Khoshmanesh et al., 1999). The role of biofilm removal is therefore of limited importance for the range of detention times and concentrations in the present study.

**Effect of chemical precipitation on P removal**

The role of chemical precipitation for P removal has been discussed in earlier studies with vertical flow bucket systems. This process is claimed to have a minor effect on P removal in constructed vertical flow wetlands, decreases with time and is slower than adsorption reactions (Lantzke et al., 1999). The most common metal salts used in P removal from

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**Figure 3** Phosphate-P removal performance in the vertical planted sand and leca columns
wastewater are iron and aluminium salts. The results of adding 0.5 and 1 mg l⁻¹ Fe (as FeCl₃) to inflow water (1 mg l⁻¹ phosphate-P) indicated the absence of any effect of Fe addition on P removal for the range of detention times and concentrations used here.

**Effect of plant uptake on P removal**

First studies with vertical batch loaded bucket systems indicated that plant uptake has a major role in P removal and mass balance studies showed approximately 45% of the influent P in the above ground, roots and rhizomes of *P. australis* (Mitchell *et al.*, 1990). In unplanted buckets more than 50% of the influent mass accumulated in the substrate, with substrate alone being responsible for P adsorption when plants were not present. Other studies with bucket systems showed that the major site for initial P uptake had to be gravel (until the sites become saturated), as adsorption was the only removal process with a sufficient rate (Lantzke *et al.*, 1999).

In the present study (*Tₕ* = 2 h, 1 × 2 h –12 × 10 min) a removal efficiency of 98% was found in the planted system (for 12 recirculations, 12 × 10 min) when the plants were starved of nutrients for one week, while the unplanted system showed 40% removal under the same experimental conditions (Figure 4).

The difference between planted and unplanted systems was clear from the first recirculation. These results indicate the role of plants in P uptake, following prolonged rest/starvation.

Experiments with a range of starvation periods (20–180 min intervals, running ultrapure water through the columns) were carried out. P was introduced in pulses of 20 minutes (*C₀* = 1 mg l⁻¹) and the hydraulic detention time of the columns was 20 minutes (*Q* = 30 ml min⁻¹). The result is reported for rest intervals of two hours with four pulses of phosphorus (Figure 5). The peak concentration in the effluent was observed 20 minutes after each P addition, which is consistent with the theoretical detention time. The results for 120 min washing interval for an unplanted system indicate the role of the plant uptake in smoothing the outflow peaks (Figure 5).

P mass removal was calculated for the experiments with and without resting intervals (Figure 6a). A high degree of removal is reached for prolonged rest periods (Figure 6b). Therefore the system could be batch loaded with suitable rest periods to reach a target concentration removal. However, the mass loading rate correlates with the mass removal rate. For full-scale systems the inflow mass loading could be adjusted to meet mass removal efficiency.

![Figure 4](https://iwaponline.com/wst/article-pdf/48/5/43/423491/43.pdf)  
**Figure 4** Performance of the planted and unplanted columns after nutrient starvation and with effluent recirculation. *C₀* = 0.5 mg l⁻¹ phosphate-P
Conclusions

The vertical planted and unplanted systems presented here removed phosphorus through a combination of removal mechanisms. The adsorption mechanism was affected by the flow characteristics by modifying the turbulence and thus the diffusion distance. A recirculation system with high flow rate is therefore preferable for P removal. Sand has a limited removal capacity and adsorbed phosphate might later return to the wastewater. Plant uptake is an irreversible process, which has been claimed not to be as rapid as sand adsorption. Batch loading of the system with resting periods of no P in inflow and short intervals of nutrient input promotes plant uptake.

References


