Incorporation of powdered iron into the root bed of experimental constructed wetlands removes phosphorus from treated sewage to levels that easily meet government guidelines for discharge into natural water bodies. Various combinations of powdered iron and sand were used to determine the best arrangement that removes the largest amount of phosphorus. Macrophytes fulfill a beneficial function by delivering oxygen to the root zone and by improving drainage in the wetland. In these wetlands, cattails (Typha latifolia L.) also take up phosphorus during growth and store significant quantities of it in their leaves.

Key words: constructed wetlands, phosphorus removal

Phosphorus is a primary nutrient for aquatic plant growth and is a major cause of eutrophication in rivers and lakes. Small communities are often faced with the expense of major public works to bring phosphorus discharges into compliance with local regulations. In terms of phosphorus removal, a combination of primary and secondary sewage treatment systems can only remove up to 20 to 30% of the input loading (Hocking 1985). When the effluent from the secondary process is not acceptable, tertiary or advanced treatments must be used. Two commonly used methods utilized are shallow lagoons or chemical coagulation.

Shallow lagoons have good sunlight penetration and oxygen exchange to the bed, which allows for continued microbial action as well as photosynthetic waste utilization. It was the photosynthetic removal of phosphates that led to the concept of using shallow lagoons for nutrient removal. In order to maintain phosphorus removal, a system to remove algae must be employed. Shallow lagoons have the advantage of being simple in concept, but the processes require relatively long retention times to be effective and necessitate significant land areas for their use. In addition, complications can arise from imbalances in nutrient ratios, proper pH, and temperature.

The predominant reactions involving iron and aluminum ions with water are hydrolysis reactions to form metal hydroxides. The removal of phosphorus is considered to occur as a co-precipitation, or adsorption onto the hydroxides that form. These coagulants are added at various
stages in the treatment scheme, which is based on the design of the treatment facility. In order to achieve high removal efficiencies, an excess of 90% of the coagulant is required (Viessman and Hammer 1985). This excess contributes to increased sludge formation that is also high in mineral loading. Further treatment of these sludges by anaerobic digestion has the potential of releasing phosphorus back into solution, which is then returned to the influent of the treatment plant. The counterions of the coagulants may also pose a problem in terms of salt loading or elevated pH levels in the effluent.

Even employing these advanced methods, wastewater treatment may not be efficient enough to meet increasingly stringent discharge limits. To make matters worse, the treatment plants themselves are often beyond the capabilities of local authorities to maintain and operate (Alexander and Wood 1987). Failures to meet regulated effluent discharge control levels have prompted a demand for simpler, lower-cost technologies (Lemon et al. 1996).

**Constructed Wetlands**

The concept of using a constructed wetland (CW) for wastewater treatment was pioneered in the 1950s by Seidel (Kruzic and White 1996), and eventually a system based on this research was patented in 1973. Interest in this technology remained low until 1980. Since then, the most rapid growth in the use of wetlands occurred in the U.S. between 1988 and 1995, from approximately 150 sites in 1988 to well over 1000 sites by 1995 (Reed et al. 1985). The advantages that are realized in an artificially created wetland include the freedom to design, build, and control/modify the system to achieve specific goals. Canadian constructed wetlands are found in Leamington, Pelee Island and the Niagara Peninsula, Ontario.

Constructed wetland systems have been employed in a wide variety of wastewater applications that range from large sites treating mine drainage, to small post-septic tank plots. For domestic wastewater applications, CWs require a significantly greater area of land compared with conventional treatment plants, but are less expensive to build, operate, and maintain. Due to the land requirements, CWs are best suited for small communities. Depending on the size of the community, CWs can be implemented as treatment systems in themselves or in combination with conventional methods.

There are two basic types of constructed wetlands, the free water surface wetland (FWS), and the subsurface flow wetland (SF) (Reed and Brown 1992). All early designs were FWS systems, while most of the systems developed since 1988 are SF. The FWS system is similar to a natural marsh with a soil bottom, emergent vegetation, and a water surface exposed to the atmosphere. Wastewaters travel through this system in sheet flows, and most of the removal is by settling. The soil bottom offers sites for complexation of phosphorus and heavy metals. The SF system uses a porous medium (i.e., rock, gravel, soil) in which emergent vegetation is planted, and the water level is designed to remain below
the surface. SF systems can be subdivided into horizontal and vertical flow systems.

It was stated early in the development of CW systems, that many researchers simply treated the wetland as a black box into which influent, and from which effluents, were measured (Kruzic and White 1996). This approach, combined with design philosophies that have been described as “seat of the pants”, has continued to prevail in the field (Reed and Brown 1992). A direct result of this approach is the generally poor performance of CW systems for phosphorus removal (30–60%) (Reed and Brown 1995). In order to fully realize the treatment potential of these systems, it is important to understand the components of a wetland and how they interact.

Phosphorus Removal Processes

Phosphorus removal can be accomplished through four main processes. These are filtration (settling), macrophyte uptake, microbial action and substratum adsorption.

Filtration

Filtration removes phosphorus that is associated with suspended solid matter, such as insoluble metal complexes and microbial flocs. However, as the microbial floc decomposes, the phosphorus can be released back into the waste stream. Using an approach that parallels traditional wastewater treatment, the addition of iron or calcium salts increased filtration efficiencies by complexing with phosphorus. A system which used quick lime obtained removal efficiencies in the range of 87 to 90% (Willadsen et al. 1990). If this approach is taken, however, consideration must be given to the production of counter ions, increased costs, and the possible plugging of the substratum.

Macrophyte uptake

Phosphorus is absorbed through plant root systems mainly as charged primary and secondary ortho-phosphate ions. Plants can only be considered a temporary storage medium, as nutrients are released back into the wastewater during dieback periods (Gehrels and Mulamoottil 1989). Uptake occurs during periods of active growth in warm seasons, when eutrophication is most pronounced. Harvesting of plants is not considered a suitable method of sustainable phosphorus removal, due to problems of access and the high labour costs involved (Reed et al. 1985).

In terms of the overall constructed wetland performance, however, plants are an essential component. They act as an oxygen pump transporting atmospheric oxygen to the root zone, providing an aerobic environment. The subsurface plant parts (stems, roots, rhizomes) provide a support for microbial communities and numerous contact sites with their wastewater substrate (Wood and McAtamney 1996). The stems and leaves above the water level provide a filter for sunlight, which limits algal growth in FWS systems. When dieback occurs, this canopy acts as an insulator, preventing heat loss during cold periods.
**Microbial action**

Microbes also require phosphorus as a nutrient. On a dry weight basis their ratio of C:N:P has been determined to be 100:5:1 (Rochfort et al. 1997). Microbial organisms provide macrophytes with soluble phosphorus ions by breaking down insoluble metal complexes and mineralizing organo-phosphates (Atlas and Wood 1987).

**Substratum adsorption**

The fixation of phosphorus by adsorption onto the substrate is widely considered to be the most important mechanism in a CW (Reed et al. 1985; Gehrels and Mulamoottil 1989; Wood and McAtamney 1996; Kadlee and Hammer 1982; Golterman 1995; Jennsen et al. 1996). The fixation is attributed mainly to the presence of iron, aluminum, and calcium species present on the surface of the substrate material. The factors which control the fixation are hydrologic conditions, anaerobic and aerobic sites, pH, and ionic strength (Mann and Bavor 1993). FWS systems using soil bottoms usually show good phosphorus removal characteristics during the start of operations but the performance drops off as the limited binding sites are used up. Soils rich in Fe, Al, or Ca have been tried in SF designs but have failed due to hydraulic flow problems. A system using fine gravel coated with iron oxides has demonstrated excellent phosphorus removal efficiencies (Reed and Brown 1995), and the use of chemically modified substrates that are coated with Fe and Al oxides is recommended (Reed et al. 1985; Mann and Bavor 1993; Wood and McAtamney 1996).

The three most recent applications of a substratum that have been specifically chosen to maximize the phosphorus removal have either used the locally available minerals laterite (Wood and McAtamney 1996) and wollastonite (Goehring et al. 1995), which are rich in iron and/or aluminum oxides, or a manufactured light expanded clay aggregate (LECA) (Jennsen et al. 1996) that is coated in calcium oxide. The CW experiment using laterite achieved an average of 93% removal efficiency over a 28-day test period. Results for wollastonite have only been for column studies, whereby adjustments to column length and retention times, removal efficiencies of 90% have been reported. While each of these materials may have merit, their long-term effectiveness has yet to be demonstrated, and the local availability may limit their usefulness. As LECA is a product that is intentionally manufactured for use in CWs, local availability should not be a problem. Norwegian CW systems using LECA have achieved removal efficiencies ranging from 34 to 97% over periods of 3 years. However, the long-term usefulness of LECA remains unknown. One aspect of LECA that may seriously limit its use is the effect that it can have on the pH of the wastewater. Once the calcium oxide coating is exposed to water, it will quickly react to produce calcium hydroxide. Systems employing LECA have initially produced waste-waters with pH values of 11 to 12, however the pH levels did decrease with time to values of 8 to 9.
SWAMP Project

The SWAMP Project was initiated in 1991 as a joint project between the Friends of Fort George and the Niagara Region. The goals of the Project were to examine the use of CWs as a tertiary treatment alternative for the polishing of Niagara-on-the-Lake’s secondary sewage lagoon wastewater. The success of the CW systems was based upon meeting a set of site-specific requirements, presented in Table 1, set by the Ontario Ministry of Environment and Energy (Lemon et al. 1996).

The pilot project consisted of sets of pulse-flooded, vertical-flow SF cells operated in series using various media in the beds. The study found that the objective levels could be met most or all of the time for all parameters except total phosphorus. The challenge in meeting the objective level for phosphorus led to this study which was performed in cooperation with the SWAMP Project. The goals of this Project were to study the processes at work in the substratum and to examine the performance of substratum enrichment by readily available materials chosen to maximize the phosphorus removal capability.

Experimental

Sample Preparation

Plant material

Initial work concentrated on the development of methods to determine the phosphorus content of wetland samples. Various plant samples were collected for analysis from wetlands close to Brock University. All rhizomes used in this study were taken from a one-metre square within the wetland. It was decided that the sample preparation technique would be a wet acid digestion rather than thermal ashing. Small samples (0.1–1.0 g) of plant material can be converted into aqueous samples by heating the sample in various strong acids, or strong acid and oxidizer combinations. This type of sample preparation is not as time consuming, nor does it require the same amount of handling as dry thermal ashing. In addition, there is less chance of analyte loss due to volatilization, or mechanical transport, and a reduced possibility of sample contamination.

<table>
<thead>
<tr>
<th></th>
<th>Objective</th>
<th>Non-compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>15 mg/L</td>
<td>25 mg/L</td>
</tr>
<tr>
<td>Total suspended solids</td>
<td>15 mg/L</td>
<td>25 mg/L</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>0.5 mg/L</td>
<td>1 mg/L</td>
</tr>
<tr>
<td>Total ammonia</td>
<td>5 mg/L summer</td>
<td>10 mg/L summer</td>
</tr>
<tr>
<td></td>
<td>12 mg/L winter</td>
<td>20 mg/L winter</td>
</tr>
</tbody>
</table>
The method developed for the digestion used nitric acid in combination with hydrogen peroxide. The samples were first cut into small squares and then dried at 105°C for a period of 24 hours. Small samples (0.1–0.5 g) of the dry plant material were then weighed into 100 mL beakers. Nitric acid (10 mL conc.) was added and the beakers were covered with watch glasses and slowly heated until a mild reflux was attained. The heat was gradually increased as the evolution of the dense brown oxides of nitrogen started to decrease. Each sample was then boiled down to ~5 mL and removed from the hot plate to cool for a few minutes. Hydrogen peroxide (5 mL, 17.5%) was then added, and the beakers were slowly heated to a fast reflux. Each sample gradually became clear and colourless; some samples retained a slight yellow tint. The samples were boiled until just enough solution remained to cover the bottom of the beaker, then they were removed from the hot plate. After cooling for a couple of minutes, only a few drops of solution and a damp residue remained. Three successive washings of ~20 mL of 5% nitric acid and 10.0 mL of potassium chloride solution (19.2%, required as an ionization buffer), were transferred to 100-mL volumetric flasks and diluted to the mark with 5% nitric acid. The entire process was complete in under 4 hours, and yielded samples that ranged in appearance from clear and colourless to a clear, pale yellow colour.

**Aqueous samples**

Aqueous samples analyzed ranged from laboratory-prepared solutions of ortho-phosphate to primary lagoon effluent from the sewage treatment plant of the town of Niagara-on-the-Lake. Sample aliquots of 5.0 mL were transferred into small disposable culture tubes. Next, 1.0 mL of a stock solution containing nitric acid and KCl buffer was added to each tube, which was then covered with parafilm and inverted several times.

**Analysis of Samples**

The most common analytical technique used to analyze aqueous samples for phosphorus is a spectrophotometric analysis of a phosphomolybdate-blue complex (Clescesi et al. 1989). The work of Dore and Kahn (1997) demonstrated that this technique is matrix-sensitive, and is not ideally suited for this type of sample.

Plasma emission spectroscopy traditionally has not been the method of choice for the analysis of phosphorus. A strong factor in this is that the most sensitive emission lines at 213.618 and 214.914 nm fall very close to strong copper emission lines at 213.598 and 214.897 nm. The next most sensitive line at 253.565 nm is overlapped by a very strong iron line at 253.560 nm. Adequate resolution is not provided by most common spectrometers to allow the use of these lines. The only useful interference-free emission lines fall into the vacuum U.V. at 178.287 and 177.499 nm which require either purged or vacuum optic systems. Various instrumental and procedural approaches have been developed in order to determine phosphorus, however they usually involve a compromise in areas such as
detection limits or speed of measurement (Fried and Dean 1955; McLeod et al. 1985; Epstein et al. 1987).

**Direct Current Plasma — Atomic Emission Spectrometry**

The determination of phosphorus and iron was performed using a Spectraspan V Direct Current Plasma — Atomic Emission Spectrometer. The equipment was modified from its original specifications and delivered, for phosphorus, values below the reported instrument detection limits (IDL) (approx. 70 ng/mL MDL vs. 100 ng/mL reported IDL).

**Iron Particle Analysis**

**Scanning electron microscopy (SEM)**

Samples of the powdered iron that was used as column packing were sent to the Ministry of Environment and Energy for analysis by scanning electron microscopy.

**Iron and Iron/Sand Columns**

A glass column (19 mm i.d.), which had a plug of glass wool inserted in the end, was packed with powdered iron (100 g iron shot, 5–70 mesh). A glass tube with a fritted end was fixed inside the column with the frit just above the surface of the iron and the open end connected to a compressed air source. The column was washed with two 250-mL portions of aerated, distilled water and left to sit overnight. Aerated orthophosphate solutions (10 ppm as P), at a pH of ~6.5, were run through the column. Initially, 70 mL of column eluent was collected in 5-mL fractions. The total daily amount of eluent collected was increased from 70 to 80 mL, then 100 mL, collected in 10 mL fractions. Finally, the total volume of eluent collected daily was increased to 200 mL, collected in 50 mL fractions.

To evaluate the performance of an iron/sand mixture, a column was packed with 10 g quartz sand and 20 g powdered iron. The procedure outlined in the previous paragraph was followed with a daily total eluent volume of 70 mL, collected in 5 mL fractions.

**Performance of Substratum Media Modifications in a Constructed Wetland**

**Lab-scale wetland using powdered iron: indoor trial**

Laboratory-scale wetlands were constructed to evaluate the performance of an iron/sand mixture in the removal of phosphorus. Indoor lighting was supplied using a 400 W high-pressure sodium light source. Four cells were set up; two with external iron/sand beds, one with an iron/sand layer built into the planted cell, and the fourth was simply a planted quartz sand bed for comparison and control purposes. Wastewater obtained from the Niagara-on-the-Lake primary sewage lagoon was brought to the lab in food-grade, 205-L plastic drums weekly. A variable-speed, single-piston pump was used to deliver the wastewater to the test cells through a manifold system using equal length latex. Small
propipet tips were affixed into the ends of the tubing, and then clamped onto retort stands at the front end of each cell. The back pressure provided by the tips resulted in spray rates that were within ±0.5 mL/min for each cell. The pulsations from the pump created elliptical spray patterns that covered approximately three quarters of the length and a third of the width of each cell. A timer was used to automate five daily spray periods of one hour in duration.

Occasionally, wastewater shortages occurred due to delivery problems, spillage, frozen drums etc. As a temporary measure, potassium hydrogen phosphate and ammonium chloride were added to tap water to make a solution that was ~5 ppm phosphorus and ~25 ppm ammonium, which was then mixed with any remaining wastewater. Samples were collected from each cell and between stages for the 2-stage cells. These samples were analyzed for the total phosphorus and iron content.

Lab-Scale Wetland Design (Fig. 1)

Laboratory experiments were conducted on laboratory-scale wetland cells, which were constructed as follows:

**Cells 1, 2, and 4**
Into Rubbermaid tubs (45 × 35 × 25 cm) which had drain spouts sealed into the bottom of the front face, a 2-cm layer of “Hadite” (hydroponic growth medium) was placed and covered with landscaping cloth. This cloth was then covered with a 14-cm layer of quartz sand. Three 8 to 10 cm lengths of cattail rhizome were then planted at equal spacing in the sand layer.

**Cell 3**
Into a similar tub, the 14-cm sand layer was replaced by a 2-cm quartz sand layer, followed by a 10-cm layer of 1:1 iron/sand (v/v) which was then covered by a second 2-cm quartz sand layer. Three 8 to 10 cm lengths of cattail rhizome were then planted at equal spacing in the top of the iron/sand layer.

**External iron/sand bed**
Into similar tubs, which only had the Hadite layer at the front third, a layer of 1:1 iron/sand (the same amount as Cell 3) was placed.

**Cell Description (Fig. 2)**

The arrangement of the cells, shown in Fig. 2, was used initially during indoor experiments and subsequently they were transferred outside, as described below:

Cell 1: Control — consisted of a planted sand layer, over which influent waste from the sewage lagoon at Niagara-on-the-Lake was sprayed. The effluent from the cell was collected into a sample bottle placed in a 20-L pail.
Cell 2: Iron/sand post filter — consisted of a planted sand layer, over which influent waste from the sewage lagoon at Niagara-on-the-Lake was sprayed. The effluent from the cell was then trickled onto the surface of an iron/sand bed post filter. The effluent from the post filter was collected as in Cell 1.

Cell 3: Internal iron/sand layer — consisted of a planted sand-iron/sand-sand layers over which influent waste from the sewage lagoon at Niagara-on-the-Lake was sprayed. The effluent from the cell was collected as in Cell 1.

Fig. 1. Cell components.
Cell 4: Iron/sand pre-filter — consisted of an iron/sand bed pre-filter over which influent waste from the sewage lagoon at Niagara-on-the-Lake was sprayed. The effluent from the filter was then trickled onto the surface of a planted sand layer. The effluent was collected as in Cell 1.
Lab-Scale Wetland Using Powdered Iron: Outdoor Trial

The cells used for the duration of the indoor trial were set up outside and are shown in Fig. 3. New plants were added to Cells 2, 3, and 4, while Cell 1 was left as an unplanted control. Primary lagoon effluent was introduced in the same manner as the indoor trial.
Results and Discussions

Powdered Iron

Initially, the examination of powdered iron was due to its availability. A 20-L pail of powdered iron, face-centred and cubic, was donated to the SWAMP Project by D.B. Services Inc. (Campbellville, Ontario). Powdered iron has been used in conventional wastewater treatment for the removal of phosphorus (Yoshida and Mihaghi 1989; Ida et al. 1986). These processes require oxidizing conditions to promote the corrosion of the iron to ferric hydroxide. Settling or filtration is then employed to remove the phosphorus that is adsorbed or coprecipitated by the ferric hydroxide. Prior to this project, powdered iron was not used as a substrate in a CW application.

In the column tests, phosphorus was not detected when the daily application rate was from 70 to 80 mL. It was decided to increase the application rate to push the performance of the column. The first detectable quantity of phosphorus in the effluent occurred at 760 mL, during applications of 100 mL of solution. No further quantities could be detected until 920 mL, when 200 mL portions were applied. From this point on, the column was observed to allow increasing amounts of phosphorus to pass with each subsequent fraction of a trial. The column regenerated overnight between trials, as the first fraction of each day had a greater removal efficiency than the final fraction of the previous day.

A scanning electron microscope (SEM) analysis was performed on iron particles selected from the top 2 cm of the column. The analysis revealed relatively high levels of phosphorus in the oxide coating of the particles, while only trace amounts were found on the iron particles free of oxide. These results suggest that the generation of the corrosion product, ferric hydroxide, is responsible for the fixation of the phosphate from solution.

Ferric hydroxide has a higher phosphate-binding capacity, compared to the mineral oxide forms of iron (Parfitt et al. 1975; Hsu 1964) due, most likely, to its large surface area. The regenerative effect of the column indicated that ferric hydroxide was continuously formed. A potential effect of this is the encapsulation of previously adsorbed phosphate through agglomeration. Encapsulation could provide a greater adsorption capacity, and increased protection against desorption of phosphate that can occur in presence of sulfides or under reducing conditions.

As the column aged, a hard crust formed on the top, which eventually caused the flow of liquid to decrease to the point where it was no longer usable. The reduction in hydraulic capacity with time illustrates the need to consider factors such as the hydraulic characteristics of the matrix to be enriched, and the relative amount of powdered iron to be added. Quartz sand that is used as a substratum at the SWAMP site was chosen as a matrix to enrich on the basis that it performed poorly in phosphorus removal, but had good hydraulic flow characteristics. When the iron powder was mixed with the quartz sand and packed into a column, the flow rate increased significantly. In order to obtain 5-mL fractions, the flow rate had to be reduced. This was accomplished by fitting a piece of rubber tubing, restricted with a pinch screw, to the end of the column. The
increased flow rate and the use of considerably less powdered iron (20 vs. 100 g) resulted in a lower overall removal efficiency, from 98 to 88%.

**Lab-Scale Wetland**

**Indoor trial**

The phosphorus removal performance of the indoor trials is shown in Fig. 4. All cells which used iron/sand in the matrix exhibited greater removal efficiencies than the planted control. Cell 2 had the highest overall removal efficiency of 94 ± 5%, while Cells 2 and 3 were close, averaging 91 ± 9% and 91 ± 5%, respectively. This compares to an average removal efficiency of the planted control of 39 ± 21%.

Some problems were encountered using the iron/sand post filters. The concentration of iron present in the effluent of the cells is shown in Fig. 5. This figure indicated that Cell 2, which used the iron/sand as a post filter, occasionally had elevated levels of iron of up to 6 ppm in the effluent. This effect was revealed by the presence of reddish-brown staining on the sample bottle for that cell.

![Fig. 4. Indoor trial: phosphorus concentration for influent waste and cell effluent.](image-url)
Cell 4, which used the iron/sand as a pre-filter, was susceptible to drainage problems due to the formation of a green slime on the surface of the filter. The plugging of the surface resulted in standing pools of the influent waste over the surface. The effect of this is shown between the weeks of 2/28/96 and 3/20/96, where slightly elevated levels of P were detected in the effluent. The drop in performance illustrates the importance of having oxidizing conditions present to promote the corrosion of the iron. Scraping the surface of the filter corrected the problem, and the performance of the cell increased to a level comparable to the other cells.

Intermediate samples were obtained between the external iron/sand filters and the planted sand beds of Cells 2 and 4. Figures 6 and 7 show

Fig. 5. Indoor trial: iron concentration for influent waste and cell effluent.
the concentration of phosphorus in the intermediate sample and final effluent for Cell 2 and 4 respectively. In Cell 2, the planted sand bed removed 32% of the total input phosphorus. The iron/sand filter removed 93% of the phosphorus from the planted bed, which accounted for 63% of the total. The pre-filter used for Cell 4 removed 70% of the total influent phosphorus, while the planted sand bed removed 42% of the phosphorus.

Plant samples obtained at the end of the trial were analyzed for the phosphorus content in the centre portion of the lamina, halfway between the tip and the rhizome. The plants in Cell 2, which had a direct application of influent waste, had an average of 0.764 ± 0.009%, while the plants in Cell 3, which were planted in the sand/iron matrix, had an average of 0.64 ± 0.05%, and the plants of Cell 4 had the lowest value of 0.507 ± 0.008% (% P by dry weight).

Outdoor Trial

For the outdoor trials, the same cells were replanted, except for Cell 1, with cattails and set up on a large balcony at Brock University. The materials from the beds were retained from the indoor trial in order to test the longevity of the iron/sand mixtures. Cell 1 was used as an unplanted control, and the intermediate sample from Cell 2 was used as a planted

![Graph](image)

**Fig. 6.** Indoor trial: Cell 2 — phosphorus content in effluent from planted sand bed and the iron/sand post filter.
control. The results of this trial are shown in Fig. 8. The results show an even greater efficiency of removal for all of the cells using iron/sand in the matrix. An average efficiency of at least 97% was achieved for each of these cells. The planted control had an average of 65% reduction, while, with the unplanted control, 105% of the applied phosphorus was recovered in the effluent.

Once the filter was placed outdoors, the slime layer that had accumulated on the pre-filter during the indoor trial quickly shriveled up and peeled back, and no flow problems were observed. The post filter continued to have occasional discharges of iron in the effluent in concentrations up to 6 ppm.

Fig. 7. Indoor trial: Cell 2 — phosphorus content in effluent of iron/sand filter and planted sand bed.
The results of the intermediate and final effluent samples of Cells 2 and 4 are shown in Fig. 9 and 10 respectively. For Cell 2, the efficiency of the planted bed was much higher than in the indoor trials, especially during the months of August and September. This can be attributed to the significantly denser growth of cattails that developed in the outdoor environment (Fig. 1 vs. Fig. 4). The iron/sand filters were also more efficient during the outdoor trials, which may be due to an increased amount of iron oxide present in the filter beds as they aged. This was most pronounced for the iron pre-filter of Cell 4 which increased from 70 to 93%. With the significantly greater growth of the outdoor trial, it was observed that the cattails grown in Cell 4, were noticeably shorter than those grown in the other cells. This trend correlates with the lower phosphorus content found in the plants of this cell during the indoor trials.

**Potential Benefits of Planted Iron/Sand Matrix**

The use of powdered iron in the planted bed matrix could take advantage of the properties of the wetland plants. High concentrations of iron are naturally found in wetland areas. Under reduced conditions, the iron will exist in the ferrous form, which in high concentrations is toxic to many plant species. Some wetland species are known to be tolerant to the toxic effects of iron under these conditions (Wheeler 1985; Taylor 1983). The existence of observable iron "plaques" that are found on the root
structures of the tolerant species led to the assumption that the plants were oxidizing the ferrous iron to insoluble ferric forms by leaking oxygen to the root zone (St-Cyr and Crowder 1989). This effect has been found in many plant species and is complicated by the fact that plants

![Graph](image-url)

**Fig. 9.** Outdoor: Cell 2 — phosphorus content in the effluent of the planted sand bed and the iron/sand post filter.

![Graph](image-url)

**Fig. 10.** Outdoor: Cell 4 — phosphorus content in the effluent of the iron/sand pre-filter and the planted sand bed.
need iron, which they take up in reduced form (Conlin and Crowder 1989). The penetration of roots and rhizomes into the iron/sand layer also maintains good hydraulic conductivity.

**Conclusions**

The use of powdered iron/sand mixtures for the enrichment of the substratum of a constructed wetland dramatically improved the removal of phosphorus from wastewater compared to the planted control. The powdered iron matrix can be used as a pre- or post-external filter, or in the planted bed itself, with no appreciable difference in phosphate removal efficiency.

Using the iron/sand matrix externally from the wetland requires more space and equipment, but has the advantage that existing CWs can be easily fitted with this type of system, and when all of the iron has been used up, it can be easily replaced without disturbing the planted beds. The post-filter application appeared to have healthier plant growth, and did not suffer any surface plugging problems as did the pre-filter. In terms of overall wetland performance the post-filter would probably be preferred to the pre-filter design.

By using the iron/sand mixture in the planted bed of the wetland, valuable space, equipment, and maintenance requirements can be saved, but the long-term performance of the matrix has yet to be established. It is possible that the presence of the planted roots may provide additional benefits with this arrangement.

The application of post-filters at the SWAMP site demonstrated the need to size the filter to the required hydraulic loading.

**Acknowledgments**

We thank the Friends of Fort George and Environment Canada for providing operating funds and a graduate student assistantship (R.L. McLaughlin). D.B. Services of Campbellville, Ontario, generously provided the powdered iron. We would also like to thank Edgar Lemon, Lloyd Rozema and Paul Ragogna for their help in countless ways.

**References**


