



Effectiveness of vegetation on phosphorus removal from reclaimed water by a subsurface flow wetland in a coastal area

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Abstract

This work was conducted to evaluate the effectiveness and influence factors of vegetation on phosphorus (P) removal from reclaimed water in constructed wetlands. Comparisons were conducted between one pilot scale subsurface flow wetland (P-SSFW) and two demonstration subsurface flow wetlands, which were series-wound and named as first subsurface flow wetland (F-SSFW), and second subsurface flow wetland (S-SSFW), respectively. The three wetlands had the same vegetation and substrate, but different pH values, total dissolved solids (TDS) and P loads. Results showed that the P content in the vegetation shoots of the F-SSFW was 2.16 mg/g, while 2.31 mg/g in the S-SSFW and 2.69 mg/g in the P-SSFW. These differences were likely caused by the higher pH and TDS in the reclaimed water. The P content also differed among the tissues of the plant, which were 5.94–6.44 mg/g, 2.20–2.77 mg/g, 1.31–1.46 mg/g and 1.53–1.88 mg/g in the flowers, leaves, stems, and roots, respectively. The greatest discrepancy was observed in the leaves, indicating that the environment of the wetlands had the greatest influence on the leaves. When the total phosphorus (TP) load was lower, the proportion of P removed by vegetation assimilation was 16.17% in the P-SSFW, 12.90% in the F-SSFW and 13.29% in the S-SSFW. However, the relative removal efficiency by vegetation among the three wetlands did not vary greatly from that observed in other studies. Moreover, the influence of pH, TDS and TP load was not as great as the influence of the vegetation species, type of substrate, influent style or climate.

Key words: wetland; reclaimed water; phosphorus; coastal area; *Phragmites communis* Trin

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Introduction

Utilization of reclaimed water is receiving increased attention in many countries, such as the United States, Europe and China (Salgot, 2008). The applications of reclaimed water include industrial reuse, irrigation of agricultural crops, golf courses, landscapes, and groundwater recharge (Kanarek and Michail, 1996; Liberti and Notarnicola, 1999; US EPA, 2004; Wade, 2006). In China, one important application of reclaimed water is supply for rivers and lakes. Although reclaimed water contains low concentrations of pollutants, it may still threaten the environment if supplied directly (Doriot et al., 1998). Phosphorus (P), the limiting nutrient of eutrophication, is an important contaminant in reclaimed water that should be removed.

Constructed wetlands (CWs) can remove P that is otherwise difficult to degrade by secondary treatment, especially in biological treatment systems with plants (Hu et al., 2005). P removal mechanisms in CWs include physical (sedimentation), chemical (adsorption, precipitation and

complexation) and biological processes (vegetation and microbial) (Kadlec and Knight, 1996; Reddy et al., 1999), as well as the emission of phosphine gas (Devai and Delaune, 1995; Han et al., 2010). Vegetation is a necessary part of CWs that plays an important role in pollutant removal. Brix (1997) pointed out the contribution of wetland vegetation to pollutant removal through filtration and sedimentation, stabilization of the wetland surface, light attenuation, and additional surface area for the attachment of microorganisms. In addition, plant uptake and harvests were found to be the only sustainable removal mechanism in CWs (Frasera et al., 1998).

During the last decade, studies of wetland vegetation have been conducted worldwide, including in cold climates (Allen et al., 2002), tropical areas (Sim et al., 2008) and saline areas (Klomjek and Nitorisovt, 2005). The effectiveness for P removal with different plants have also been compared (Frasera et al., 2004; Iamchaturapatr et al., 2007; Barbera et al., 2009). However, most CWs studied to date are used to treat sewage, and very few studies investigated the use of CWs in reclamation.

Due to different P concentrations in solutions, the P

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adsorption capacities of substrates vary greatly (Drizo et al., 2002). In our previous research, the P removal mechanism and performance of substrates were found to differ in the treatment of reclaimed water and sewage (Hu et al., 2009). The role that vegetation in CWs plays in P removal during the treatment of reclaimed water might also differ from that of vegetation in CWs used to treat sewage. In this study, we investigated the vegetation in three subsurface flow wetlands, one in pilot scale and two in demonstration scale. Specifically, we measured the P content in vegetation from different parts of the plant as well as the P removal by the entire wetland to determine the P removal efficiency of the vegetation. Additionally, we attempted to identify the influencing factors involved in P removal by vegetation.

1 Materials and methods

1.1 Pilot scale wetland

A pilot subsurface flow wetland (P-SSFW) made of wood was placed in a greenhouse. The pilot wetland system was 2.4 m long, 0.4 m wide and 0.65 m high. The system had a 0.1-m layer of sand at the bottom overlaid by a 0.35-m gravel (16–30 mm diameter) layer that was covered with a 0.2-m layer of soil in which *Phragmites communis* Trin were planted (Fig. 1). Reclaimed water entered the wetland from the top of the inlet zone through an influent pipe and flowed out through an effluent pipe in the bottom of the outlet zone. During the experiment, the water level in the wetland was fixed at 40 cm, and the hydraulic loading rates (HLRs) of the wetland were set at 20 or 10 cm/day.

The mineralogical compositions of the gravel were studied using X-ray photo electron spectroscopy (XPS) before being put into the wetlands. XPS studies were conducted on an ESCALAB MK II spectrometer using Al $K\alpha$ ($h\nu = 1486.6$ eV) as the excitation source. The binding energies of all elements were standardized for specimen charging using C 1s as the reference at 284.8 eV. The results showed that the gravel included 46.64% O, 8.78% Ca, 14.44%

Si, 5.71% Al, 2.60% Fe and 0.88% Mg. These findings indicated that O was the most important element, which suggests that the other elements were all predominantly present as oxides/oxyhydroxides.

Reclaimed water in China is usually the secondary effluent from treatment, with P content of around 1 mg/L and nearly no particulate in water. To simulate actual reclaimed water, synthetic reclaimed water was prepared using the following fertilizers (purity > 98%): $C_6H_{12}O_6$, KH_2PO_4 , K_2HPO_4 , NH_4NO_3 , $(NH_2)_2CO$, $CaCl_2$, $MgSO_4$, $FeSO_4$, $ZnSO_4$, $CuSO_4$, $(NH_4)_6Mo_7O_{24}$, H_3BO_3 and Al_2O_3 , which were added to provide (mg/L) 1.1 P, 7 NH_4 -N, 8 NO_3 -N, 60 COD and 18 K. The P levels were analyzed every week throughout the study period.

1.2 Demonstration wetlands

Demonstration wetlands were operated from April to October of 2008 at T City to purify the remnant P in the reclaimed water before it drained into the river. The entire demonstration wetland was about 2500 m² and consisted of subsurface flow wetlands, surface flow wetlands and ponds (Fig. 2). To make comparisons to pilot scale wetland, only the subsurface flow wetlands were investigated in this study, which were named as first-SSFW (F-SSFW) and secondary-SSFW (S-SSFW) according to their positions in the entire demonstration wetland.

The configurations of the F-SSFW and S-SSFW were the same as that of the P-SSFW. In addition, *P. communis* and gravel used in the demonstration SSFW were the same as those used in the pilot SSFW.

The influent of the demonstration wetland was the effluent of a membrane bio-reactor from a reclaimed water plant in T City. The reclaimed water entered the F-SSFW and first-SFW through pip-age and an inlet pipe, after which it passed through the ponds and then into the S-SSFW. The water then flowed out of the demonstration wetland into another pond.

The water level in the wetlands was both controlled at 40 cm by overflow weirs. The influent quantity was set at three levels during the research time, as 100, 150 and 200 ton/day. Because of the different areas, the HLRs of

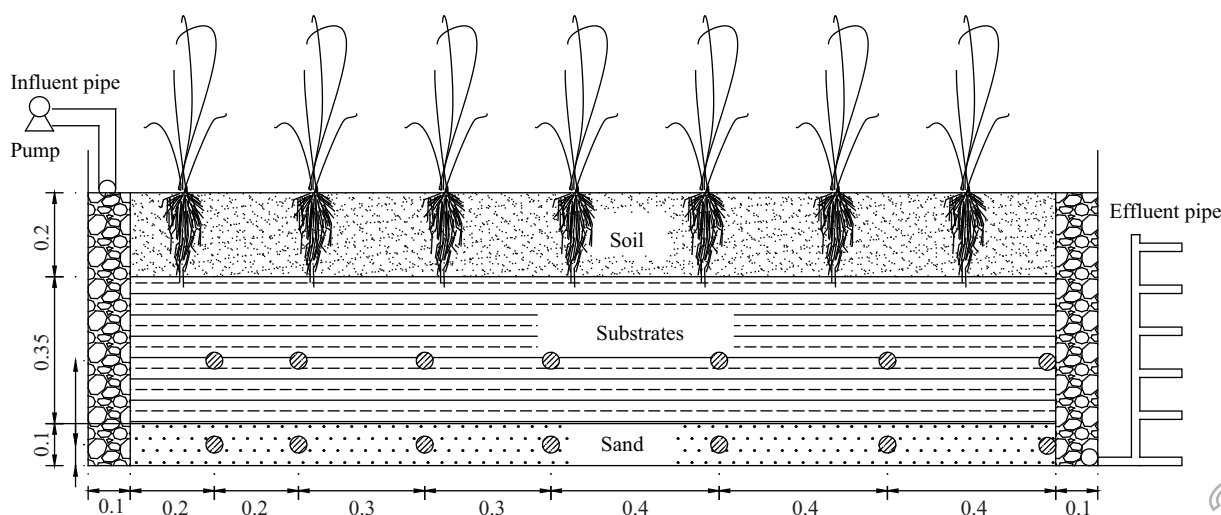


Fig. 1 Configuration of the experimental wetland system (unit: m)

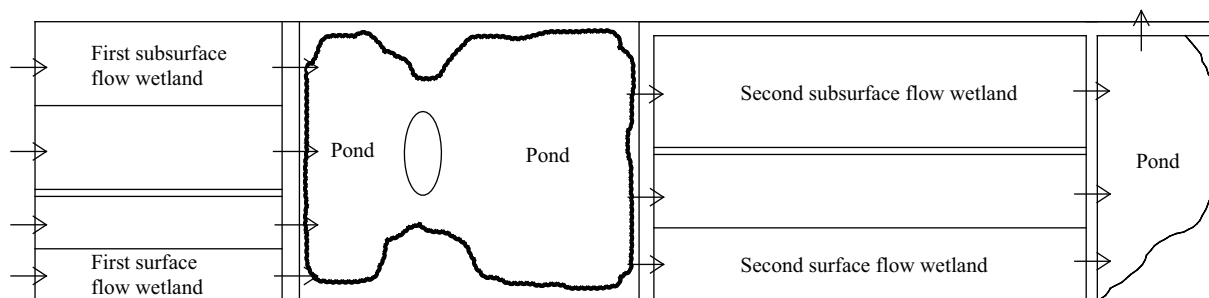


Fig. 2 Diagram of the demonstration wetland (arrows present the flow path of water).

F-SSFW were 20.8, 31.3 and 41.7 cm/day respectively, while the HLRs of S-SSFW were 15.9, 23.8 and 31.7 cm/day respectively.

1.3 Experiments on plants

The P-SSFW was planted on 23 April 2007. On 25 June, after the plants had grown vigorously, the shoots (including the leaves and stems) were cut 5 cm above the soil. On 9 October, all of the new shoots of *P. communis* were harvested at 5 cm above the soil.

The F-SSFW and S-SSFW were planted on April 2009, and the shoots were cut at 5 cm above the soil on 29 June. The new shoots were harvested at 5 cm above the soil on 16 October. The shoots were then harvested again on 16 October, 2010.

A portion of the shoots from each SSFW were mixed together and evaluated as one sample for P content. Conversely, the individual parts of the remainder of the shoots were divided into flowers, stems and leaves and analyzed for P content separately.

Roots of plants were also sampled for P content analyzing. After the shoots were harvested, five random sample points were selected in wetland and each point was 10 cm × 10 cm square area. Plant roots in the square area were dug for 30 cm depth while the 5 cm stems above soil were cut and threw away. Roots from five points were washed clear and mixed for analyzing.

After recording the fresh weight, every sample was oven dried at 60°C for 48 hr and the dry weight was recorded. The dry samples were then ground into a fine powder using a grinder. Three replicates of each sample were evaluated to determine the P content in the tissues. To accomplish this, 75 mg of sample were digested using 1 mL perchloric, 5 mL nitric and 0.5 mL sulfuric acid. After dilution, the phosphorus concentrations were analyzed colorimetrically using the ascorbic acid method (Greenway, 1997).

1.4 Water quality monitoring

Influent and effluent samples from the P-SSFW, F-SSFW, and S-SSFW were collected during the study period and analyzed immediately in the laboratory for pH, total phosphorus (TP) and total dissolved solids (TDS) according to the standard methods (Greenberg, 1985). Samples for TDS were passed through filter paper, after which 100 mL aliquots were added to an evaporating dish and dried at 105°C for 48 hr. The samples were then cooled and weighed as A. And then the samples were drying at (180 ± 2°C) for 1 hr and then weighed as B. The B

was then subtracted from A and divided by the volume of sample water to give the TDS. To measure the TP, the water samples were digested in pressure cooker in 120°C with 1 mL H₂SO₄ and 5 mL HNO₃. Then the samples were cooled, after which approximately 20 mL of distilled water were added, followed by 0.05 mL phenol-phthalein indicator and as much 1 mol/L NaOH solution to produce a faint tinge. The sample volume was then adjusted to 100 mL with distilled water, after which the concentration of TP was then measured by the vanadomolybdophosphoric acid colorimetric method.

2 Results and discussion

2.1 Water qualities of influent and effluent

The influent and effluent qualities of the P-SSFW, F-SSFW, and S-SSFW are shown in Table 1.

The pH value of the influent was greatest in the F-SSFW and lowest in the P-SSFW. After the reclaimed water flowed through the wetlands, the pH in the water was affected by the release of ions from the substrates. The pH of the effluent of all the three wetlands decreased to nearly the same level because of the gravel. pH plays an important role in the removal of P from wetlands, which can influence the absorption of P by substrates (Arias et al., 2001), P mineralization (Pant et al., 2002) and P uptake by vegetation (Schachtman et al., 1998; Oguz, 2004).

The demonstration wetlands in T City were located in a coastal area; therefore, the reclaimed water had a high TDS. Specifically, the TDS was 1744–1857 mg/L in the F-SSFW and 1521–1670 mg/L in the S-SSFW, which was much higher than in the P-SSFW (172–207 mg/L). The wetlands reduced the TDS which indicated the total salt concentration of water. Many researchers had found salt has influence on the vegetation and biotic functions (Megan and Rowe, 2003; El-Keblawy and Al-Rawai,

Table 1 Water quality of influent and effluent

	P-SSFW	F-SSFW	S-SSFW
Influent pH	7.90 ± 0.16	8.42 ± 0.21	8.02 ± 0.29
Effluent pH	7.71 ± 0.07	8.06 ± 0.37	7.79 ± 0.35
Influent TDS (mg/L)	207 ± 55	1857 ± 572	1670 ± 306
Effluent TDS (mg/L)	172 ± 33	1744 ± 434	1521 ± 339
Influent TP (mg/L)	1.12 ± 0.07	1.65 ± 0.18	1.02 ± 0.18
Effluent TP (mg/L)	0.29 ± 0.14	1.17 ± 0.23	0.36 ± 0.11

P-SSFW: pilot scale subsurface flow wetland; F-SSFW: first subsurface flow wetland; S-SSFW: second subsurface flow wetland. Data are presented as mean ± SD (n = 18).

2005), and the salt is sure to influence the vegetation in the treatment wetlands.

The TP of reclaimed water in T City was 1.65 mg/L, and this value decreased to 1.02 mg/L before the water flowed into the S-SSFW. A lower TP indicates less nutrition in the environment for vegetation assimilation.

2.2 Phosphorus content in the vegetation of wetlands

Phosphorus content in the vegetation of wetlands varied with pH, TDS or P concentration. The P content in the vegetation of the P-SSFW, F-SSFW and S-SSFW was 2.69, 2.16 and 2.31 mg/g, respectively.

The pH and TP in the P-SSFW were similar to those in the S-SSFW; therefore, the difference in the P content of the vegetation was likely due to the changes in TDS. The influence of TDS on vegetation might have occurred for two reasons. The first possibility is that the dissolved concentrations were much higher than those in the cells of vegetation due to the saline conditions of water in T City. In such an environment, the water in the vegetation cells would be lost through osmosis, resulting in plasmolysis in the vegetation. Thus, the growth and nutrition assimilation of vegetation would be influenced. The second possibility is that the high TDS results in more cations and anions being present in the water. P assimilation by vegetation must occur through the uptake of ions, including PO_4^{3-} , HPO_4^{2-} or H_2PO_4^- , therefore, the presence of more ions in water would lead to less P being assimilated by vegetation.

Different types of vegetation have different potentials for growth under saline conditions. *P. communis* grows almost worldwide, and can grow well in coastal areas. However, based on the results of the present study, saline conditions still have an effect on its P assimilation ability.

When compared with the S-SSFW, the F-SSFW had an equivalent TDS and higher TP, which should result in a high P content in vegetation. However, our results showed that the P content in the vegetation of the F-SSFW was lower than that of the S-SSFW. These differences might have been due to differences in the pH. The form in which P exists in solution changes according to pH. Below pH 7.2, most P will be present as H_2PO_4^- , while HPO_4^{2-} and PO_4^{3-} will be present in only minor proportions. At higher pH, P will mainly be present as HPO_4^{2-} and PO_4^{3-} (Schachtman et al., 1998; Oguz, 2004). Several studies have found that plants tend to take up P as the monovalent form (Furihata et al., 1992, Schachtman et al., 1998). In the present study, the pH in the F-SSFW was higher than that in the S-SSFW, which led to lower P assimilation in the vegetation. Based on these results, pH has a bigger impact on P assimilation than the TP concentration.

2.3 Phosphorus content in different tissues of vegetation

Phosphorus content of the flowers, leaves, stems and roots differed widely, being 6.44, 2.77, 1.46 and 1.88 mg/g in the P-SSFW, 5.94, 2.20, 1.34 and 1.61 mg/g in the F-SSFW, and 6.29, 2.35, 1.31 and 1.53 mg/g in the S-SSFW, respectively (Fig. 3).

Among the four tissues evaluated, the flowers had the

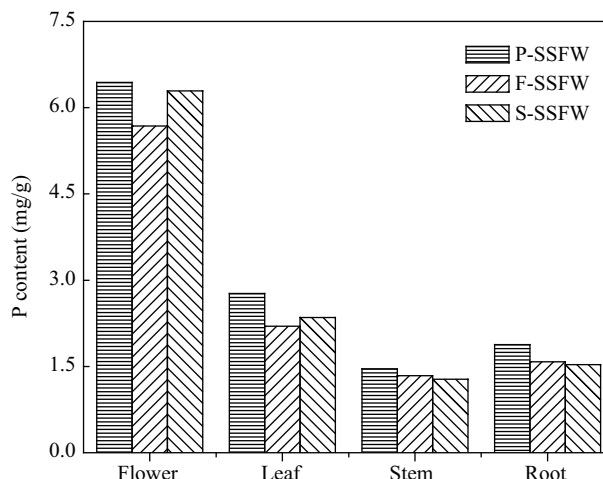


Fig. 3 Phosphorus content in different tissues. Data are the means of triplicate analysis of samples.

highest P content. This was likely because of the greater amount of nutrition required for propagation. Conversely, the stems, which were primarily composed of fascicule, had a lower nutrition demand.

Considering the influence of pH and TDS, the growth environment for vegetation was poorest in the F-SSFW, while it was best in the P-SSFW. The different environments obviously influenced the P content in each tissue differently. Specifically, the respective P contents in the flowers, leaves, stems and roots in the P-SSFW were 1.08, 1.26, 1.09 and 1.23 times greater than those in the F-SSFW. In addition, the P content in the flowers did not differ greatly between the P-SSFW and S-SSFW, even though the pH and TDS were different. These results indicate that the environment had a greater influence on leaves and roots than on flowers and stems.

In one growth period of *P. communis*, leaves and stems developed from spring until autumn, while roots developed between each year, and flowers only grew in autumn. Accordingly, the environment would have less of an influence on the flowers. The reduced influence on the stems might result from its fasciculi configuration.

Figure 4 shows the change in the P content of tissues between the first year and second year. Drizo et al. (2008) found that the P content of vegetation was greatest during

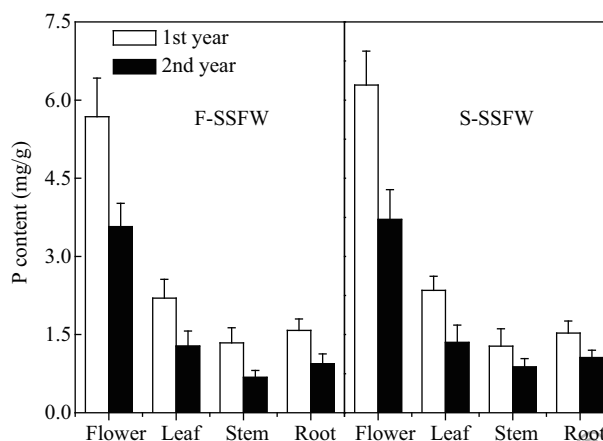


Fig. 4 Phosphorus content in vegetation tissues during the first and second year. Data are the means of triplicate analysis of samples.

Table 2 Phosphorus storage in plants of both CWs

Wetland	P-SSFW	F-SSFW	S-SSFW
Biomass ^a (g/m ²)	502	735	776
P storage in vegetation ^b (g/m ²)	1.35	1.59	1.79
P removal by wetlands (g/m ²)	8.35	12.33	13.47
P removal by vegetation assimilation	16.17%	12.90%	13.29%
TP load (g/(m ² -day))	0.13	0.48	0.23

^a The weight of reed shoots re-grown over three months in each wetland.

^b P storage = biomass × the mean P content.

the first year, but that it decreased by an average of 3-fold in the second year, and then increased in the third year. This phenomenon was also observed in the present study. However, further investigations are needed to determine the cause of this phenomenon.

2.4 Role of vegetation in P removal by wetlands

The biomass of *P. communis* in the P-SSFW was no more than 70% of that in the F-SSFW or the S-SSFW (Table 2). This might be due to the limited area of the pilot wetland, which limited the growth and spread of vegetation. Because of the larger biomass, the P storage in the vegetation of the S-SSFW and the S-SSFW was higher than that of vegetation from the P-SSFW, despite the lower P content in the vegetation.

Even though the P storage in the vegetation was higher, the proportion of P removed by vegetation assimilation was still lower in the F-SSFW and S-SSFW. The only explanation for this difference is the higher TP load. Our results confirm the suggestion of former studies, which found that the relative removal efficiency of vegetation might be higher when the nutrient load decreases (Shaver and Mellio, 1984; Greenway, 2005).

The proportion of P removed by vegetation assimilation in wetlands varies greatly between studies, which are likely due to the wide range of P loading, ages and geographic locations of wetlands, as well as the types of plants, substrates and the influent used in such studies. In the study conducted by Naylor et al. (2003), only 8.9% of the P was incorporated into the plant shoots in a wetland constructed of slag, limestone and granite. Comparatively, Tanner et al. (1995) reported that 11%–29% and Greenway and Woolley (2001) found that 21%–26% of P was incorporated into the shoots under a TP load of 0.20–0.33 g/(m²-day).

In the present study, the three wetlands had the same vegetation and substrate, as well as the same climate. The difference in TP load, pH and TDS was not found to have a great influence on the P removal by vegetation assimilation when compared with the proportion observed in other studies. These findings indicate that the wetlands environment and TP load influenced the relative removal efficiency by vegetation, but this influence was not as great as the influence of the vegetation species, substrate, influent type and climate.

Phosphorus assimilation by vegetation via growth metabolism is visible and measurable, and has long been recognized as an important method of P removal in wetlands (Hammer, 1992; Kadle and Knight, 1996; Brix, 1997). In addition, vegetation can create appropriate con-

ditions for microbial activity by increasing the substrate surface area in the water, oxygenation of the environment around roots, and facilitation of filtration and sedimentation via encouragement of quiescent conditions (Klompjek and Niisoravut, 2005). Thus, the role of vegetation in P removal by wetlands is greater than just the proportion physically removed by the plants.

3 Conclusions

The role of vegetation in P removal by wetlands is known to be influenced by many factors. In this study, the influence of pH, TDS and TP load was studied. The pH and TDS of the reclaimed water of T City induced a lower P content in the vegetation of the F-SSFW and S-SSFW than that of the P-SSFW. The influence of TDS on vegetation occurred via two mechanisms. First, the high TDS led to plasmolysis in vegetation, which was caused by the loss of water through osmosis. Second, more cations and anions in the water would disturb P assimilation by vegetation. The influence of pH and TDS also presented differently in the different vegetation tissues, and had a greater influence on leaves than on flowers and stems.

With a lower TP load, the P removal by vegetation assimilation in the P-SSFW was 16.17%, while it was only 12.90% in the F-SSFW and 13.29% in the S-SSFW. However, when compared with other studies, the relative removal efficiency by vegetation among wetlands did not differ greatly. The influence of the pH, TDS and TP load was not as great as the influence of the vegetation species, substrate type, influent style and climate.

Acknowledgments

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