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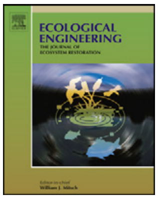

Efficacy of a large-scale constructed wetland to remove phosphorus and suspended solids from Lake Apopka, Florida

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ABSTRACT

Constructed wetlands treat various types of waters. We examined the efficacy of a large-scale constructed wetland (the marsh flow-way), which was designed to treat lake water by maximizing the removal rate of total phosphorus (TP), and total suspended solids (TSS) from Lake Apopka. The flow-way was constructed on former agricultural land and has four independently operated wetland cells (treatment area is ~276 ha). During the operating period (November 2003–March 2007), hydraulic loading rate (HLR) was high, with annual median values between 32 and 49 m yr^{-1}. On average, 87% of the treated water returned to the lake, and the remainder flowed downstream. The wetland released soluble P (mostly soluble reactive P [SRP]), which was probably caused by P release from soils and/or senescing vegetation. This release was high initially and high during summers, but declined overall with time. Despite SRP release, the system removed TP over annual periods, with maximum net TP removal in 2007 (1.8 g m^{-2} yr^{-1}). Most of the incoming and retained P was particulate. Median percent mass removal was 58% for particulate P (PP) and about 30% for TP. Total suspended solids were always removed (median removal rate = 1.4 kg m^{-2} yr^{-1}) and the percent mass removal was high (93%). Median first-order rate constants (P-*k*-C* model) were 43 m yr^{-1} for TP and 228 m yr^{-1} for TSS. Removal rates of TP and PP appeared to increase linearly up to the highest loading (5–6 g m^{-2} yr^{-1}), whereas removal rate of TSS may have approached an asymptote at loading >3 kg m^{-2} yr^{-1}. We found that C* declined from 0.070 in the previous pilot project to 0.045 mg L^{-1} in the current flow-way system. Continued reduction in C* as TP declines in inflow lake water would assist P removal. Otherwise, selective wetland operation during periods of high lakewater TP concentrations may be required in the future to maintain net P removal.

1. Introduction

Wetlands are often constructed within watersheds to provide ecosystem services such as water quality improvement (Day et al., 2004; Koskiaho and Puustinen, 2005), flood control (Brouwer and Bateman, 2005; Jiang et al., 2007); habitat for wildlife (Davis et al., 2008; Johnson et al., 2007); and recreational space (Janssen et al., 2005). Both natural and constructed wetlands treat various types of incoming water, which include river water (Anderson and Mitsch, 2006; Anderson et al., 2005), lake water (Coveney et al., 2002; Domotorfy et al., 2003; Pomogyi, 1993), agricultural and stormwater runoff (Blankenberg et al., 2006; Braskerud, 2002; Fink and Mitsch, 2004), and point-source wastewaters (Day et al., 2004; Dunne et al., 2005; Nurk et al., 2005).

At the watershed and lake scale, some studies report the effectiveness of restoring and/or creating wetlands to help improve watershed and lake water quality. In Florida, examples of this include the large-scale stormwater treatment areas (STAs) in south Florida that treat runoff from the Everglades Agricultural Areas (Chimney and Goforth, 2006; Juston and DeBusk, 2006; Kadlec, 2006). Lowe et al. (1989) proposed that treatment wetlands could be used to improve water quality at the lake scale by removing particulate phosphorus (P) from incoming eutrophic water from Lake Apopka, Florida and returning treated water back to the lake. Later studies (Coveney et al., 2002) reported the performance of a 2.1 km^2 pilot project constructed wetland at Lake Apopka, which was the precursor to the full-scale constructed wetland discussed herein. The pilot project wetland was constructed on former farm fields, which are adjacent to and within the treatment cells of the full-scale wetland. During a 29-month operation period (1990–1994), percent mass removal by the pilot project was between 89 and 99% for total suspended solids (TSS), 30–67% for total P (TP), and 30–52% for total nitrogen (TN). Coveney et al. (2002) argued that

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process improvements could increase P removal rates from 0.5 to 3 g P m^{-2} yr^{-1}.

The overall restoration program for Lake Apopka implemented by the St. Johns River Water Management District focuses on reducing external P load to the lake, combined with a cost-effective program both to remove P and to reduce recycling of P in the lake (Dean and Lowe, 1998; Hoge et al., 2003). Hydrologic changes and agricultural development of floodplain wetlands at Apopka began in the late 1800s, reducing lake water depth and increasing external P loading to the lake. Increased loading contributed to shifting the lake to a plankton dominated aquatic system in the 1940s (Lowe et al., 1989; Schelske et al., 2005). Presently, external P loading to the lake is declining, as agricultural lands are converted back to emergent marsh wetland along the north shore of the lake and by stormwater treatment elsewhere within the watershed. Other methods to improve lake condition include restoring lake habitats and harvesting *Dorosoma cepedianum* (gizzard shad) as a means of removing nutrients from the lake. Water quality of the lake is improving (Coveney et al., 2005).

The large-scale treatment wetland (the marsh flow-way) discussed here was designed to accelerate the lake's response to reduced P loading by removing particle-bound P, algae, and suspended sediments from Lake Apopka (Lowe et al., 1992; Coveney et al., 2002). The marsh flow-way began operating in November 2003, and we report performance through March 2007 when regular operation was interrupted for maintenance.

Typically, constructed wetlands designed to improve water quality treat water in a single pass (Kadlec, 2005; 2006; Nungesser and Chimney, 2006) and have an operational goal to reduce outflow nutrient concentrations to a specific criterion. Because the objective of the flow-way is to remove P from lake water, it has a different operational goal: to maximize the mass removal rate, or power. To achieve this, it has been operated at a high hydraulic loading rate (HLR). Lowe et al. (1989) projected high P removal rates and a long-term removal goal of 30% of inflow P mass, with sedimentation as the dominant biogeochemical removal process. They also suggested that ancillary benefits of adopting a wetland approach in close proximity to the lake included increased habitat for aquatic and wetland plants and wildlife.

Other aspects of the flow-way that differ from many conventional constructed wetland projects are its large scale, inflow rate and nutrient concentration of inflowing water vary with changing lake conditions, and the circumstance that it was built on organic soils which have a legacy of high available P from more than 40 years of agricultural use. The P legacy has implications for marsh flow-way management and we discuss this in later sections.

Our objectives for this manuscript were threefold: (1) determine the efficacy of the marsh flow-way to remove and retain P and suspended solids from incoming lake water, (2) examine the interrelationships between concentrations, flows, mass loadings, removal rates and percent removal, and (3) compare the wetland's performance with the earlier pilot project.

2. Materials and methods

2.1. Site description

Water flows by gravity from Lake Apopka through the marsh flow-way (Fig. 1). It enters at the southeast corner, flows west and then north through a main canal, then enters each of the four independently operated cells (B1, B2, C1 and C2) via gated culverts. There are four to five inflow and outflow culverts for each cell. Cells vary in size from about 50 to 76 ha (Table 1). Within each cell, there are lateral (1.5 m wide × 1.5 m deep) ditches every 80 m that run perpendicular to inflowing water. Water flow within all cells is from west to east, and daily outflows are quantified in each cell using measured water stage and weir flow equations. Inflows are estimated using daily outflow, rainfall and evapotranspiration. Total flow into and out of the system is the sum of flow into and out of the four individual wetland cells. As water leaves the wetland cells, it collects in a basin and the treated water is pumped back into Lake Apopka. During this study, the majority of treated

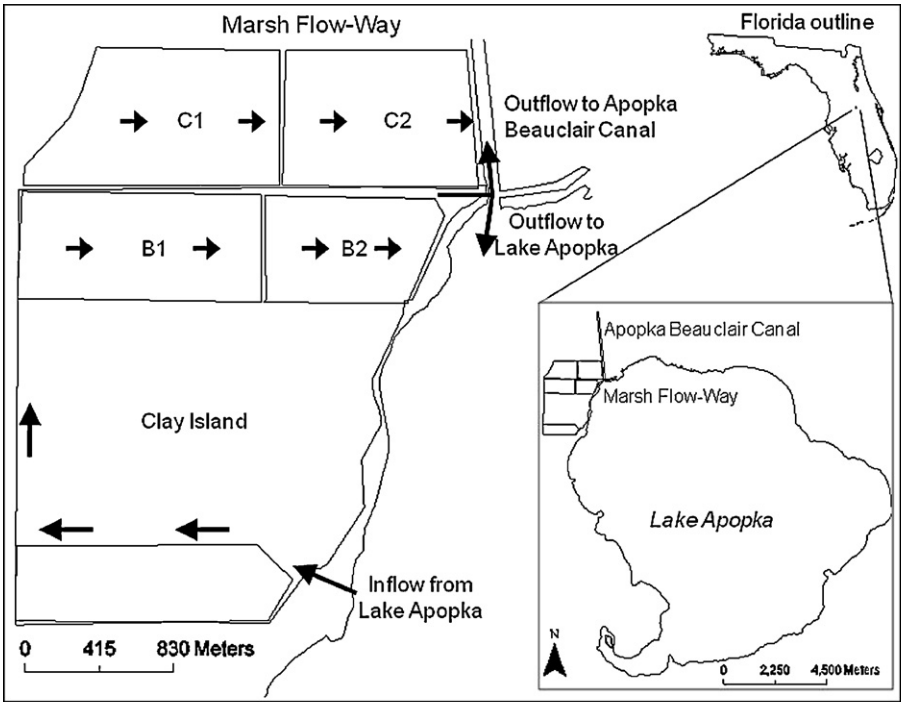

Fig. 1. Location of the marsh flow-way and Lake Apopka in central Florida and diagram of the water flow path through the system. Water exits the flow-way and both returns to Lake Apopka (south) and flows downstream (north, Apopka-Beauclair Canal).

Table 1
Marsh flow-way cell and system area, aspect ratio, inflow rate, hydraulic loading rate and hydraulic residence time at Lake Apopka, FL. The monitoring period was from November 25, 2003 until March 27, 007. Inflow rate, loading rate and residence time are median values for the monitoring period.

Cell	Area (ha)	Aspect (length/width) ratio	Inflow rate ($m^3\,d^{-1}$)	Hydraulic loading rate ($m\,yr^{-1}$)	Hydraulic residence time (Days)
B1	73.1	2.2	9.3	46.5	3.5
B2	49.2	1.5	7.2	53.3	3.0
C1	77.9	1.4	10.3	48.5	2.5
C2	76.2	1.4	10.4	49.9	3.1
Sum of cells	276		37.2		
System[a]	308				

[a] Sum of B and C cells plus the area of canals in the marsh flow-way system.

Table 2
Methods for total suspended solids and phosphorus analyses, including preservative if used and storage temperature, laboratory instrument, nominal detection limit, and the standard method. Values reported below detection limits were used without censoring.

Analyte	Abbrev.	Preservative	Instrumentation	Detection limit ($mg\,L^{-1}$)	Method
Total suspended solids	TSS	Cool, 4 °C		1.0	EPA 160.2
Total phosphorus	TP	Cool, 4 °C, H_2SO_4 to pH <2	Perstorp autoanalyzer	0.01	EPA 365.4
Total dissolved phosphorus	TDP	Filtered immediately, cool 4 °C	Perstorp autoanalyzer	0.01	EPA 365.4
Soluble reactive phosphorus	SRP	Filter immediately, cool 4 °C	LabChat Quickchem AE	0.012	EPA 365.1

water (87% ± 12%; mean ± one standard error, calculated from daily flows) was returned to Lake Apopka, while the remainder flowed downstream towards Lake Beauclair (Fig. 1).

Soils in both the B and C cells are Histosols and classified as Everglades muck, depressional Euic, hyperthermic Typic Haplohemists. These soils are nearly level and are very poorly drained (Furman et al., 1975). Prior to flow-way operation, six soil samples were collected in May 2000 to a depth of 30 cm. Soils were acidic, at about 5.5 pH units. Soil TP was high in all cells. Total P concentrations averaged 559 ± 126 mg kg^{-1} dry wt. in B cells and 969 ± 251 mg kg^{-1} dry wt. in C cell soils.

During the initial stages of the earlier pilot project, which included the B cells, TP storage in soils was 25.9 g m^{-2} (soils were sampled to a depth of 40 cm), while inorganic and organic P fractions were 32% and 68% of soil total P, respectively (Reddy et al., 1995). Reddy et al. (1995) also found quite high equilibrium P concentrations (EPC_o) of soils with water (EPC_o ranged between about 0.6 and 0.9 mg L^{-1}). Equilibrium P concentrations increased when soils were incubated under anaerobic conditions relative to aerobic conditions.

In 2003, prior to marsh flow-way operation, soils were amended with an alum-based water treatment residual. This treatment was done to mitigate the anticipated release of legacy soluble reactive P (SRP) from soils, which were historically enriched with P through fertilization and oxidation of organic matter. Soils were amended at a rate of 22.4 wet metric tons of alum residual per hectare (560 dry g m^{-2}).

Since operation started, vegetation developed similarly in all wetland cells. Using georectified aerial photography, we estimated that shallow marsh covered about 65% of the total treatment area, and shrub swamp covered about 18% in 2006. Shallow marsh was dominated by *Typha* spp. *Pontederia cordata* L., *Sagittaria* spp., *Panicum hemitomon* Schult. and other broad-leaved herbs and grasses. Shrub swamp communities were dominated by *Ludwigia peruviana* (L.) Hara and some *Salix* spp. Open water areas were common in all cells and averaged 17% of the total treatment area.

2.2. Sample collection and analyses

We report marsh flow-way operation data from November 25, 2003 until March 27, 2007. Operation of the marsh flow-way was interrupted at the end of March 2007 for maintenance of B cells. During the operation period reported here, water was sampled weekly from the main inflow to the system, the inflow and outflow culverts of the individual wetland cells, and from the pump basin (main outflow of the system). A Van Dorn horizontal water sampler (Wildco, Yulee, FL) was lowered to mid-water depth in front of culverts to collect water and samples were preserved, as required, and stored at 4 °C prior to analyses (Table 2). Samples were filtered in the field through a Gelman Supor 450 (0.45 μm pore size) filter for later analyses of dissolved P forms. Water samples were analyzed for TP, total dissolved phosphorus (TDP), SRP, TSS, (Table 2) and other constituents not reported here, using standard methods. Total suspended solids were measured gravimetrically on a Whatman GF/C filter. Water quality constituents derived from measured values included particulate phosphorus (PP) (TP minus TDP) and dissolved organic phosphorus (DOP) (TDP minus SRP).

2.3. Calculations

Hydraulic loading rate (HLR) was calculated as the flow volume (m^3) divided by the system treatment area (m^2) for a given period, while nominal hydraulic residence time (days) was estimated as the cell volume (m^3) divided by inflow rate ($m^3\,d^{-1}$). Cell water volume was calculated using the average soil elevation for each cell, average daily water elevation, and cell area.

Daily measured and estimated flow ($m^3\,d^{-1}$) values were multiplied by daily P and TSS concentrations ($g\,m^{-3}$) determined by linear interpolation between weekly measurements to calculate daily loads ($kg\,d^{-1}$) into and out of the individual wetland cells. To determine mass removal rates, outflow mass loads ($kg\,d^{-1}$) were subtracted from inflow mass loads ($kg\,d^{-1}$). Percent mass removal was determined as: (mass removed ($kg\,d^{-1}$))/(inflow mass load ($kg\,d^{-1}$) × 100). Mass in, mass out and mass removed also were determined on a mass areal rate basis ($g\,m^{-2}\,yr^{-1}$).

To characterize long-term TP and TSS performance for the marsh flow-way system, we calculated the rate constant (k) using the tanks-in-series model "P-k-C*" (Kadlec and Wallace, 2008) (we used three tanks in series, see discussion below). Because of the elevated TP concentrations in soils due to past agricultural use, we needed to estimate the background concentration (C*) for this site rather than use a generic literature C* taken from unimpacted wetlands. Our approach was to estimate C* from the lowest observed outflow TP concentration. When water temperatures were below 22 °C, we used a constant C* of 0.045 mg TP L^{-1} (see Section 3 for further details). However, when water temperatures were greater than 22 °C, we estimated C* with a modified Arrhenius equation fitted to the lower bounds of the relationship between monthly flow-weighted TP concentrations in outflow water and monthly median outflow water temperature (Coveney et al., 2002).

We used a constant C* of 0.5 mg L^{-1} for TSS, since outflow TSS concentrations were unrelated to temperature (data not shown). This value was slightly less than the lowest monthly median outflow concentration. We did not run dye tracer tests in the wetland; therefore, we assumed three tanks in series based on the mean value (3.4) found by Kadlec and Wallace (2008) for 79 measured wetlands.

We estimated site evapotranspiration using meteorological conditions and a Penman method as cited in Coveney et al. (2002). We estimated rainfall volumes on the site using Nexrad data. Nexrad is a network of high-resolution doppler weather radars operated by the National Weather Service.

3. Results and discussion

3.1. Hydraulic variables and hydraulic loading rate

Lake Apopka hydraulic inflows were 29–160 times greater than rainfall and outflow volumes exceeded evapotranspiration by factors of 27–66 (Table 3). Water depths within the system were similar among years of operation, with annual median water depths ranging between 47 and 57 cm.

The HLR was lowest (median ~12 m yr^{-1}) during the first few months of operation in 2003 and highest during 2006 (median = 47 m yr^{-1}) and 2007 (median = 49 m yr^{-1}) (Fig. 2). In south Florida, the Everglades Nutrient Removal Project, which was a large-scale (1500 ha) wetland, received agricultural runoff at a much lower rate (11 m yr^{-1}) (Gu et al., 2006), while other systems in South Florida report HLRs even lower, ranging between 1 and 11 m yr^{-1} (Gu and Dreschel, 2008; Nungesser and Chimney, 2006). Dierberg and DeBusk (2008) reported that HLRs to stormwater treatment areas STA-1W and STA-2 ranged between 12 and 35 m yr^{-1}. Relative to these systems, the marsh flow-way at Lake Apopka, which treats and returns water back to the lake, was operated at a high HLR (median value for overall operating period = 45 m yr^{-1}). Previous results from the Lake Apopka pilot project had a lower HLR (median = 30 m yr^{-1}) (Coveney et al., 2002), while a median HLR of 10 m yr^{-1} was reported for the North American Treatment Wetland database, which comprises data from over 250 systems (Finney, 2000).

3.2. Dissolved phosphorus

Soluble reactive P was a minor constituent of TP in inflowing lake water (Fig. 3). Inflow TP concentrations ranged between 0.07 and 0.17 mg L^{-1}, whereas inflow SRP concentrations ranged between 0.002 and 0.02 mg L^{-1}. During the start-up period (November 2003–February 2004), flow-weighted concentrations of SRP in outflows were much greater than flow-weighted inflow concentrations, indicating a release of SRP from within the flow-way, possibly via sediments and/or from transformation of particulate P to SRP. The SRP release rate declined sharply with time (Fig. 3; Table 4), although release increased seasonally during late summer and early fall in subsequent years. By early 2006, SRP concentrations in both inflows and outflows were low, indicating that the system approached an operational equilibrium with negligible net release or retention of SRP. Prior to early 2006, SRP averaged 36% of outflow TP concentrations, whereas after that point, SRP averaged 7% of outflow TP concentration.

Coveney et al. (2002) found a similar high, but declining release rate of SRP during the first six months of the pilot project at Lake Apopka. They suggested that release was due to SRP flux from historically fertilized organic soils since the pilot project was also located on lands previously used for intensive row crop agriculture. Water level fluctuations can alter the stability of P, which can cause a release of P from soil to water via mineralization (Pant and Reddy, 2001). In both the pilot and full-scale marsh flow-way systems, the steep decline in release of SRP through time indicates that the source was legacy stores of P in soils, rather than recently accumulated particulate matter. During the pilot project, EPC_0 values for these organic soils were high, up to 0.9 mg L^{-1} (Reddy et al., 1995). These observations were consistent with the flux of SRP from soil to water observed in both the pilot and the full-scale project. Another contributing potential source of SRP is the release of P from decomposing terrestrial vegetation upon initial flooding, and this source was not distinguishable from soil sources in our work.

Similar to the pattern we observed in SRP, DOP release rates decreased through time. In contrast, the previous pilot project released variable amounts of DOP through time (Coveney et al., 2002).

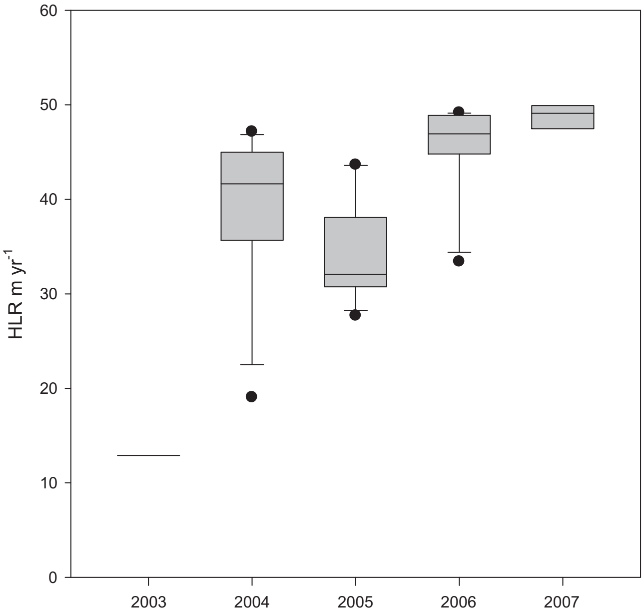

Fig. 2. Annual hydraulic loading rates (HLRs) (m yr^{-1}) for the marsh flow-way between 2003 and 2007. Period of operation was November 25, 2003 until March 27, 2007. Box plots show data distributions and monthly median values. There were too few monthly values in 2003 (two) and 2007 (three) for calculating all box plot summary statistics. Centerlines of each box are yearly medians. The box boundary closest to zero and furthest from zero represent the 25th and 75th percentiles, while the error bars above and below the box are the 90th and 10th percentile, respectively. Outliers are represented by asterisks.

Table 3
Annual hydrologic variables (water depth, hydraulic residence time, rainfall, inflow, evapotranspiration (ET), and outflow) for the marsh flow-way at Lake Apopka, FL. All values are yearly medians calculated from daily values. Both 2003 and 2007 are partial years. The year 2003 includes November 25 through December 31, and 2007 includes January 1 through March 26.

Parameter	Years				
	2003[a]	2004	2005	2006	2007[a]
Water Depth, m	0.47	0.52	0.56	0.57	0.53
Hydraulic residence time, d	8	3	4	3	3
Inputs					
Rainfall, m	0.01	1.2	1.26	1.02	0.11
Inflow, m	1.6	41.5	36.7	49.4	13.3
Outputs					
ET, m	0.06	1.11	1.11	1.11	0.2
Outflow, m	1.6	41.6	40.1	49.3	13.2

[a] Partial years.

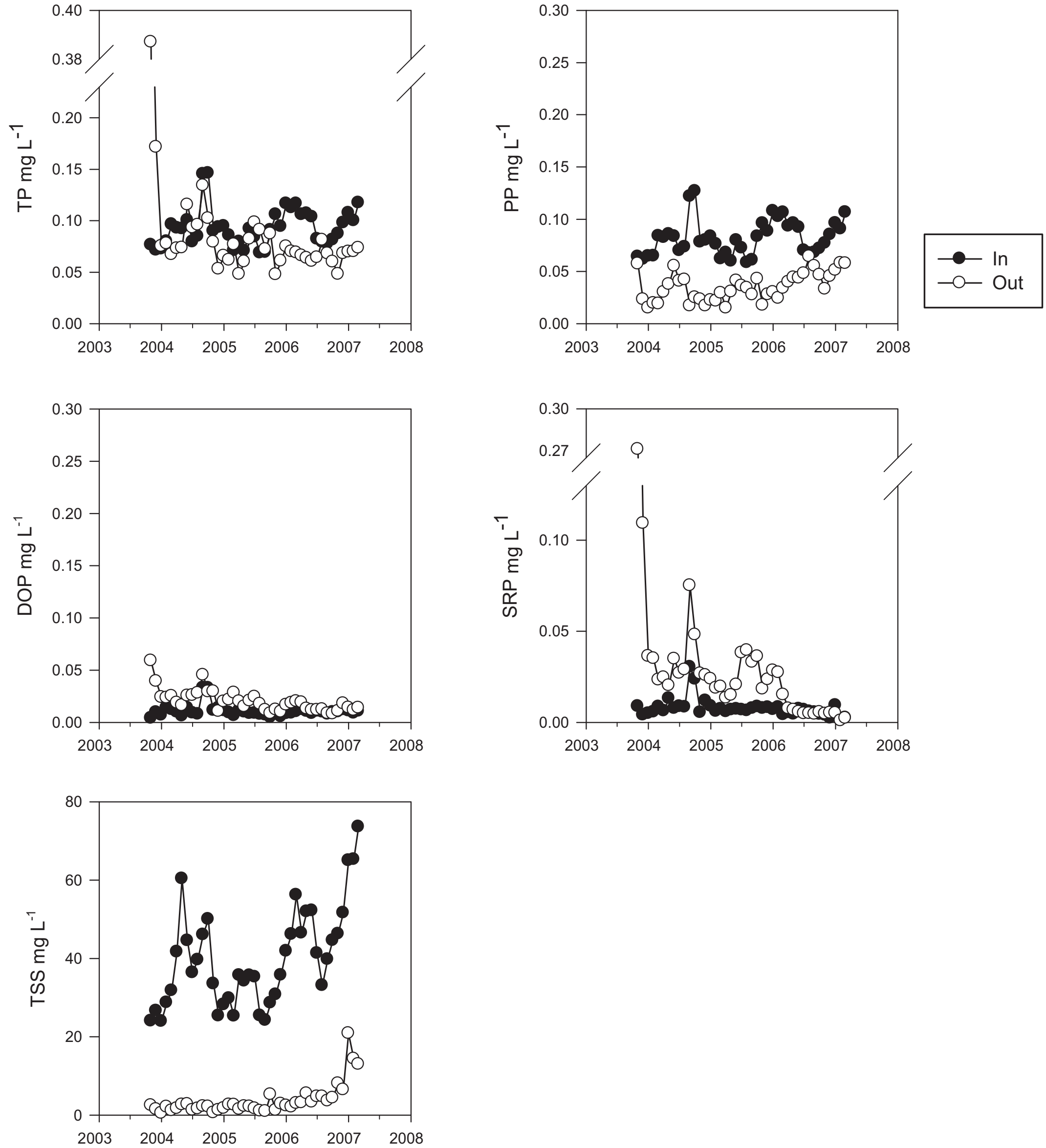

Fig. 3. Flow-weighted monthly inflow and outflow concentrations (mg L^{-1}) of total phosphorus (TP), particulate phosphorus (PP), dissolved organic phosphorus (DOP), soluble reactive P (SRP), and total suspended solids (TSS) in the marsh flow-way system. Values are monthly medians from November 2003 through March 2007.

3.3. *Total and particulate phosphorus*

The main pathway for TP removal in the flow-way was sedimentation of incoming PP (Table 4). Sedimentation is often the dominant TP removal mechanism in wetlands (Braskerud, 2002). In general, organic matter accumulation and subsequent accretion is also an important biogeochemical process for long-term P storage (Craft and Richardson, 1993; Reddy et al., 1999). Total P was released from the marsh flow-way during the start-up period between November 2003 and February 2004 (Fig. 3;

Table 4
Mass areal removal rates (g m^{-2} yr^{-1}) of total suspended solids and phosphorus for the marsh flow-way at Lake Apopka, FL between November 25, 2003 and March 27, 2007. Statistics per parameter represent the 1st quartile, **median** and the 3rd quartile of daily values for a given year. Summary statistics for partial years 2003 and 2007 were annualized for comparative purposes. Positive values are removal rates and negative values are release rates.

Parameter	2003			2004			2005			2006			2007		
	g m^{-2} yr^{-1}														
TSS	169	**257**	579	1038	**1396**	1747	748	**926**	1232	1486	**1859**	2349	2232	**2537**	2947
TP	−2.3	**−1.9**	−0.2	−0.2	**0.5**	1.2	−0.1	**0.4**	1.1	0.7	**1.6**	2.0	1.5	**1.8**	2.2
PP	0.1	**0.4**	1.0	1.4	**2.0**	2.6	1.0	**1.3**	2.1	1.0	**2.0**	2.7	1.6	**2.1**	2.5
SRP	−2.2	**−1.7**	−0.9	−1.0	**−0.8**	−0.5	−0.8	**−0.5**	−0.3	−0.2	**−0.1**	0.0	0.0	**0.0**	0.0
DOP	−0.7	**−0.4**	−0.3	−0.8	**−0.7**	−0.6	−0.5	**−0.6**	−0.5	−0.4	**−0.3**	−0.2	−0.3	**−0.2**	−0.2

TSS = Total suspended solids; TP = Total phosphorus; PP = Particulate phosphorus; SRP = Soluble reactive phosphorus; and DOP = Dissolved organic phosphorus.

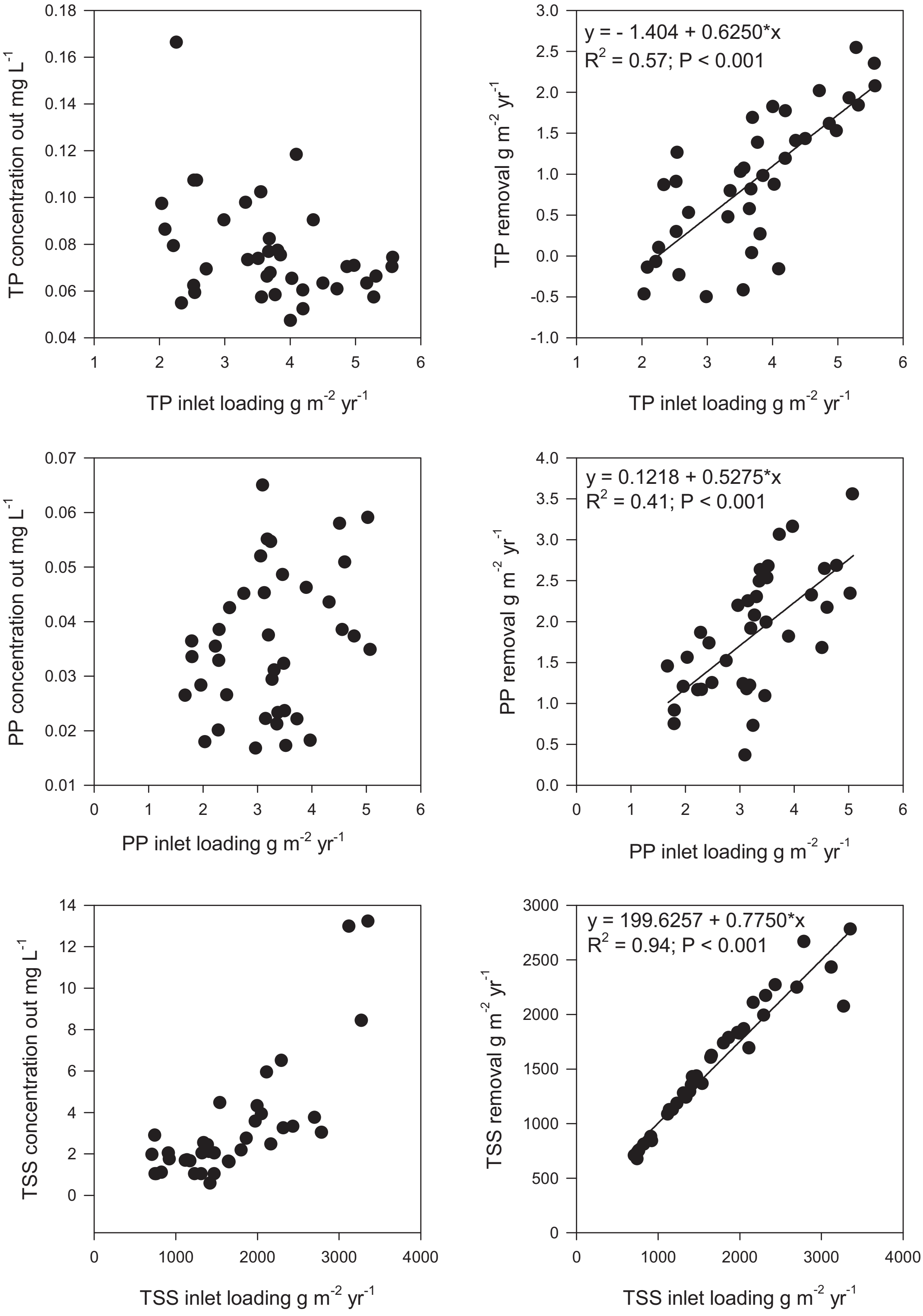

Fig. 4. Relationships between outflow concentrations (mg L^{-1}) and mass areal removal rates (g m^{-2} yr^{-1}), and inlet mass areal loading rates (g m^{-2} yr^{-1}) for total phosphorus (TP), total suspended solids (TSS) and particulate phosphorus (PP) in the marsh flow-way. Values are monthly medians from February 2004 through March 2007.

Table 4). This net release suggests that release of dissolved P within the wetland exceeded the sedimentation rate of PP from incoming lake water. As explained above, the high initial release of P was probably a combination of upward flux from historically P-loaded soils and the decomposition of terrestrial vegetation upon initial flooding. After this start-up period, TP retention increased with greatest areal mass removal rates occurring during 2006 and 2007 (medians ~2 g P m^{-2} yr^{-1}; Table 4). These highest areal mass removal rates were about three times the average TP removal rate measured in the pilot project (Coveney et al., 2002). High removal rates during 2006–2007 were associated with increased HLRs and greater inflowing TP concentrations from Lake Apopka

(Figs. 2 and 3). This is congruent with earlier suggestions that P removal by wetlands increase with increasing P loading (Reddy et al., 1999). Inflow TP concentrations in lake water ranged between 0.07 and 0.17 mg TP L^{-1} with high concentrations concomitant with a hurricane in 2004 and a decrease in lake stage and volume due to a drought in 2006 and 2007.

In contrast to TP removal rates, removal rates for PP were positive during the start-up period and did not show a less variable year-to-year trend (Table 4). Removal of PP by sedimentation was the primary mechanism of P removal and, consequently, net removal depended upon the downward flux of PP exceeding the upward flux of soluble P. Removal rates of PP by the marsh flow-way were similar to those for the pilot project at Lake Apopka (PP removal rate 1.9 g m^{-2} yr^{-1}). During the period of operation, PP was the dominant P fraction (86% of TP; based on monthly mass medians) in incoming lake water. Settling of incoming particulate matter is an important biogeochemical process for P storage (Kadlec and Wallace, 2008). Treatment wetlands in Florida often retain most of their incoming P, as PP (Farve et al., 2004). Dierberg and DeBusk (2008) suggest that as water passes through a wetland, PP can also increase in structural stability, thereby reducing the likelihood of PP conversion to forms that are more bioavailable.

Outflow TP and outflow PP concentrations in the marsh flow-way were not related to inlet loading (Fig. 4). Outflow TP concentrations (~0.05–0.11 mg L^{-1}; Fig. 4) were similar to values compiled by Kadlec and Wallace (2008) from 240 free water surface wetlands with equivalent inlet TP loading (2–6 g m^{-2} yr^{-1}) and inflow TP concentration (~0.1 mg L^{-1}). In contrast to outflow concentrations, removal rates for TP and PP increased linearly with increasing loading rates and did not reach an asymptote of maximum removal rate. When considering wetland design, Kadlec and Wallace (2008) point out limitations in regressing mass areal removal rate against mass areal loading rate because hydraulic loading appears in both axes. They suggest that the most useful feature of the graph is the regression slope, which, if the regression line is driven through the origin, represents percent reduction. However, at the operational level, we have found it useful to know mass areal removal rate at a given areal mass loading rate. The linear relationships suggest that the maximum removal rate was not achieved under our operating conditions at the marsh flow-way.

Monthly median values for percent mass removal of TP varied from negative (release) to 48% removal (Fig. 5). The median TP percent mass removal for the overall operating period was 30%, which was identical to the projected long-term goal for the marsh flow-way (Lowe et al., 1992). Percent TP removal was about one-half that reported for the Kis-Balaton wetland in Hungary, which is another single-pass treatment wetland used to reduce lake loading (Pomogyi, 1993). A subset of large-scale STAs in Florida, which include areas of submerged aquatic vegetation and continuously flooded emergent marsh, retained greater than 85% of incoming TP loads (TP loading rate ~2 g m^{-2} yr^{-1}) (Juston and DeBusk, 2006).

Particulate P percent mass removal ranged between 10 and 85% for any given month, with a median value of 58% for the overall operating period. There was a distinct seasonal decline in the percent mass removal of PP during summers (Fig. 5). This decline in net PP removal, together with increased SRP release during summer in early years (Fig. 3), resulted in a strong seasonal pattern of low TP removal during summer periods (Fig. 5).

3.4. Total suspended solids

The marsh flow-way removed TSS from incoming Lake Apopka water from the start of operation, with yearly median areal mass removal rates ranging between 257 and 2537 g m^{-2} yr^{-1} (Table 4). The TSS removal rate by the earlier pilot project was about 2000 g m^{-2} yr^{-1} (Coveney et al., 2002). During the pilot project, inflow concentrations of TSS were much greater (35–190 mg TSS L^{-1}; Coveney et al., 2002) than inflow concentrations during the marsh flow-way operating period (20–70 mg TSS L^{-1}; Fig. 3). Low water velocities, in addition to plant litter and emergent vegetation, contribute to intercepting and settling incoming particulates. Much of the marsh flow-way area was dominated by emergent vegetation (~83%), with remaining areas being mostly open water. Areas dominated by vegetation

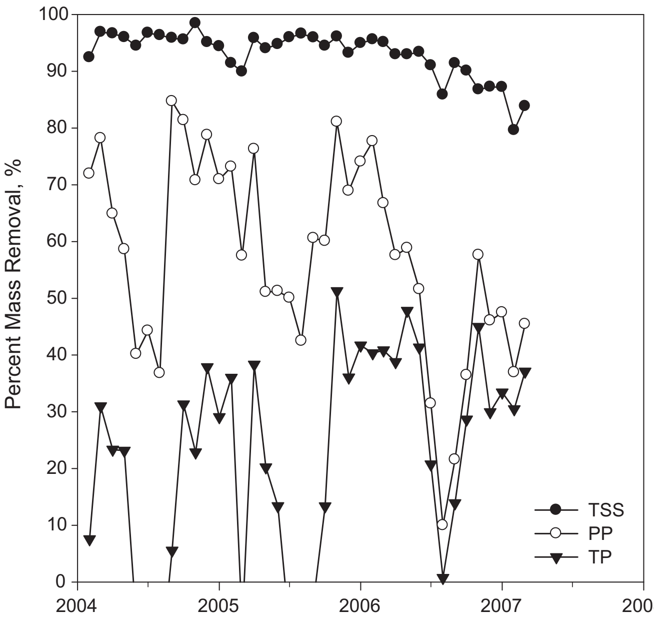

Fig. 5. Percent mass removal of total phosphorus (TP), particulate phosphorus (PP) and total suspended solids (TSS) between February 2004 and March 2007. Values are monthly medians.

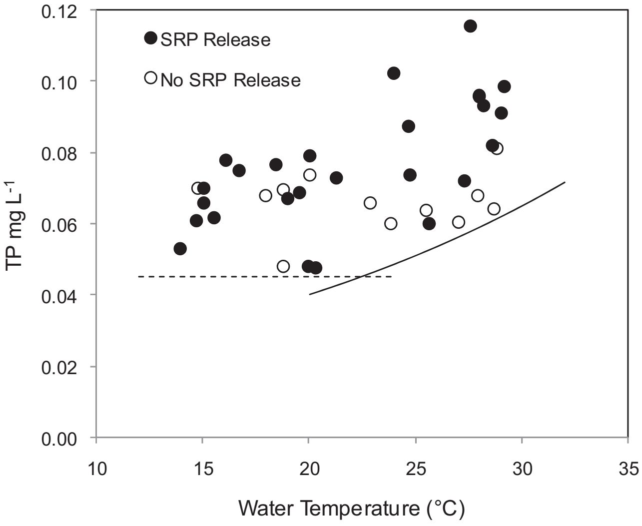

Fig. 6. Relationships between flow-weighted concentrations (mg L^{-1}) of outflow total phosphorus (TP) and outflow water temperatures (°C) used to predict C* for TP. Flow-weighted concentrations were calculated as monthly outflow TP mass divided by monthly flow volume. Temperatures were monthly medians. Observations were divided into two periods: SRP Release (February 2004–March 2006) and No SRP Release (April 2006–March 2007). Dashed line shows C* estimated from the lower bounds of outflow TP as a constant 0.045 mg L^{-1} below 22 °C. Solid line shows a modified Arrhenius equation used to estimate C* from the lower bounds of outflow TP above 22 °C.

contribute to P sedimentation via plant detritus and mitigate the resuspension of accumulated solids (Braskerud, 2001), while open water areas contribute mostly to sedimentation of suspended material (Harter and Mitsch, 2003).

Outflow TSS concentrations from the marsh flow-way generally were lower than values from 136 wetlands reported by Kadlec and Wallace (2008). We compared values using their regression of outflow TSS concentration on TSS loading. For example, at TSS loadings of 1000 and 3000 g m^{-2} yr^{-1}, the lower (2.5%) bounds for their regression were 3.0 and 7.4 mg L^{-1}, respectively. Virtually all outflow concentrations from the marsh flow-way were below these lower bounds (Fig. 4). Higher outflow concentrations in the marsh flow-way coincided with the highest TSS loading rates (Fig. 4). However, high loading may not have caused high outflow concentrations, since all the elevated outflow values occurred in 2007 after a period with decreasing percent removal of both TSS and PP (Fig. 5).

Total suspended solids removal rate increased almost linearly with inlet loading rate (Fig. 4), which reflected the near-constant percent mass removal of TSS for most of the operating period (Fig. 5). The percent mass removal of TSS was always greater than 80%, but showed a slight decreasing trend in later periods (Fig. 5). Lower TSS removal in 2007 was caused by declining removal in B cells. Although not reported here, unpublished data indicate that B cell performance was restored following cell drawdown, ditch and vegetation maintenance during the spring of 2007.

3.5. Background concentrations and rate constants

To characterize long-term TP removal for the marsh flow-way system, we calculated the rate constant (k) using the tanks-in-series model "P-k-C*" (Kadlec and Wallace, 2008). We used three tanks in series. Characterization of background (C*) TP concentrations for this calculation was made difficult by the substantial initial release of SRP from soils and/or vegetation in the wetland that declined through time. In addition, an increase in SRP release occurred during warm (summer) periods (Fig. 3). Biogeochemical processes that release P to the wetland are important to consider in estimating C* (Kadlec and Wallace, 2008), and our approach was to estimate C* empirically as the lower bound of observed outflow TP concentrations.

We accounted for the apparent seasonal temperature dependence of C* using the relationship between monthly outflow TP concentrations and monthly water temperature (Fig. 6). Because the initially high release of SRP from soils declined with time (Fig. 3), we divided the operational period into two phases. In the first phase, February 2004–March 2006, SRP was released from the flow-way at a rate of 0.65 ± 0.26 g m^{-2} yr^{-1} (average ± one standard deviation). In the second phase, after March 2006, SRP release was negligible (0.04 ± 0.07 g m^{-2} yr^{-1}). The ideal situation for accurate empirical estimation of C* would be for outflow TP values from both operational phases to show the same relationship with temperature (Fig. 6). However, analysis of covariance showed that outflow TP values from the first and second phases were significantly different ($p = 0.012$) after the effects of temperature were removed. Our use of a single relationship between outflow TP and temperature to provide an empirical estimate of C* likely underestimated C* slightly at water temperatures above 25 °C during the first operational phase, which had appreciable SRP release (Fig. 6).

Median annual k values for TP generally increased through time (Fig. 7). This is somewhat dissimilar to other treatment wetlands such as Houghton Lake where k values were greatest during initial periods, relative to the long-term average (26-year mean average of 19 ± 6 m yr^{-1}) (Kadlec, 2009). We hypothesize that k values of the marsh flow-way increased between years 2004 and 2006, in part because of decreases in dissolved P (SRP and DOP) release. Furthermore, any underestimation of C* during warmer months in 2004 and 2005 would have resulted in underestimation of k as well.

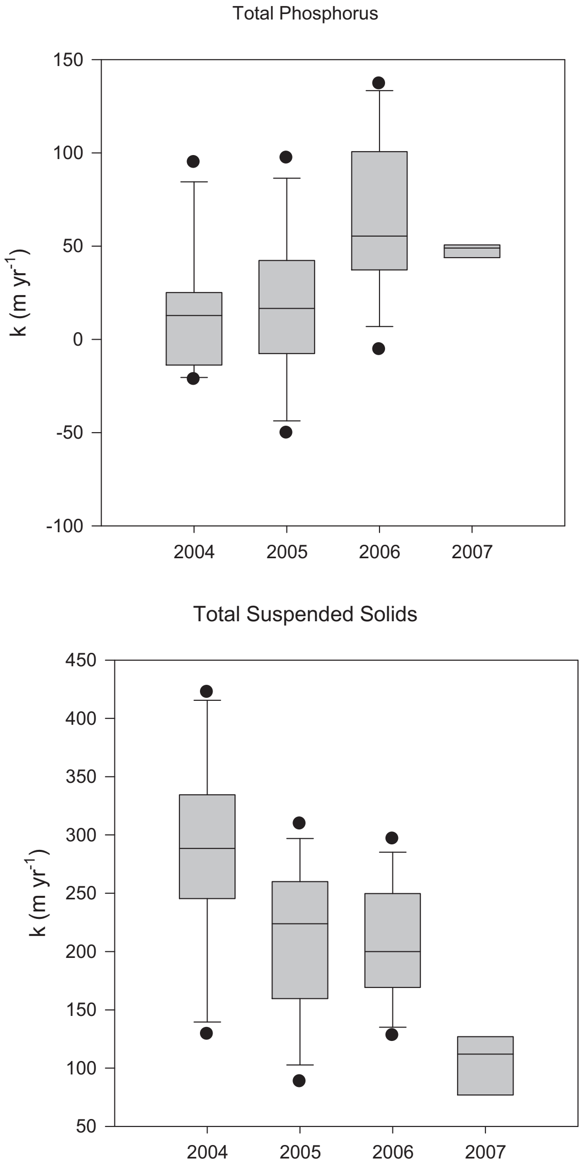

Fig. 7. Box plots of total phosphorus (TP) and total suspended solids (TSS) rate constants (k) for each year of operation. Period of record is from February 2004 through March 2007. Box plots show distributions of monthly values. Centerlines of each box are yearly medians. The box boundary closest to zero and furthest from zero represent the 25th and 75th percentiles, while the error bars above and below the box are the 90th and 10th percentile, respectively. Outliers are represented by asterisks. An extreme outlier (1130 m yr^{-1}; November 2004) was not included in the TSS plot.

The median TP k value for the operating period (February 2004 through March 2007) was 43 m yr^{-1} compared to 63 m yr^{-1} for the pilot project reported by Coveney et al. (2002). However, rate constants for the marsh flow-way during 2006 and 2007 were similar to the pilot project. Rate constants were also similar to those reported for a large submerged aquatic vegetation dominated STA (40 m yr^{-1}) (Knight et al., 2003) and much greater than the median k value (10 m yr^{-1}) reported for over 280 systems within North America (Kadlec and Wallace, 2008).

We also calculated k values for TSS using the tanks-in-series model and we sued three tanks in series. We observed no temperature dependence of lower-bound TSS monthly median outflow concentrations. Therefore, we used a constant C* of 0.5 mg L^{-1}, which was slightly less than the minimum monthly median outflow concentration. Total suspended solids *k* values typically decreased through time (Fig. 7), whereas TP *k* values increased through time. Declining rate constants for TSS removal were consistent with the decrease in percent mass removal of TSS (Fig. 5). During 2006–2007, we also noticed increasing open water areas within B cells with the possibility for large-scale hydraulic short-circuits. Using these multiple lines of evidence, we decided to draw down the B cells for maintenance after March 2007.

3.6. *Implications for management*

The performance of the marsh flow-way demonstrates that a treatment wetland can effectively remove TP and TSS from eutrophic lake water. Net removal of TP over annual periods was achieved, despite the initial and seasonal release of SRP from soils enriched in soluble P by previous agricultural activities. The marsh flow-way removed about 8×10^6 g TP (2.6 g m^{-2}), and 15×10^9 g TSS (4900 g m^{-2}) from Lake Apopka water between November 2003 and March 2007. For net removal of P to occur, the downward flux of PP via sedimentation had to exceed the upward flux of soluble P from soils (Table 4). Because the rate of sedimentation increased with increasing HLR and inflow TP concentration and the rate of soluble P release did not, net removal was positively correlated with HLR and with inflow TP concentration. We found that operating individual cells in the marsh flow-way at a HLR greater than about 35 m yr^{-1} and an incoming TP concentration greater than about 0.1 mg TP L^{-1} increased the likelihood for P removal (Fig. 8). The multiple linear regression of P removal rate on HLR and inflow TP concentration was significant ($p < 0.0001$) and explained about 50% of the variance (Fig. 8). In this data set, both variables contributed equally to determining P mass removal rate (standardized regression coefficients were approximately equal).

The primary goal of the marsh flow-way was to maximize the mass P removal rate from incoming Lake Apopka water rather than percent removal based on mass (Lowe et al., 1992). Total P loading ranged between 1 and 5.5 g m^{-2} yr^{-1} (Fig. 4), which is similar to other studies in Florida (Coveney et al., 2001; Moustafa et al., 1996) and other wetlands elsewhere that were enhanced to help improve lake water quality (Pomogyi, 1993). As nutrient loading rate increases, nutrient removal rate also increases (Reddy et al., 1999; Qian and Richardson, 1997). Coveney et al. (2001) suggested that TP loading from Lake Apopka between 10 and 15 g P m^{-2} yr^{-1} (which was equivalent to a hydraulic load rate of 60–90 m yr^{-1}) should maximize P removal rates at around 4 g P m^{-2} yr^{-1}. However, HLR in the marsh flow-way was limited to about 50 m yr^{-1} because of pumping constraints.

We operated at high flows to counteract anticipated SRP release from legacy P. Flowing water at high rates should minimize soil–water contact time, while maximizing through-flow of lake water. This strategy is in keeping with our overall goal of maximizing mass removal rate to reduce TP in Lake Apopka. We achieved greatest removal rates for TP during 2006 and 2007 due primarily to high HLR (Fig. 2), high lakewater TP, and low release of soluble P from wetland soils (Table 4). However, the increased water depths and flows during this time probably contributed to the increase in open water areas and hydraulic short-circuiting, which were concomitant with declining percent removal for both TSS and PP (Fig. 5). Furthermore, the subsequent drawdown for maintenance revealed that the lateral ditches constructed in the wetland cells to intercept and redistribute flow largely had filled with sediments, which also may have contributed to declining percent removal of solids.

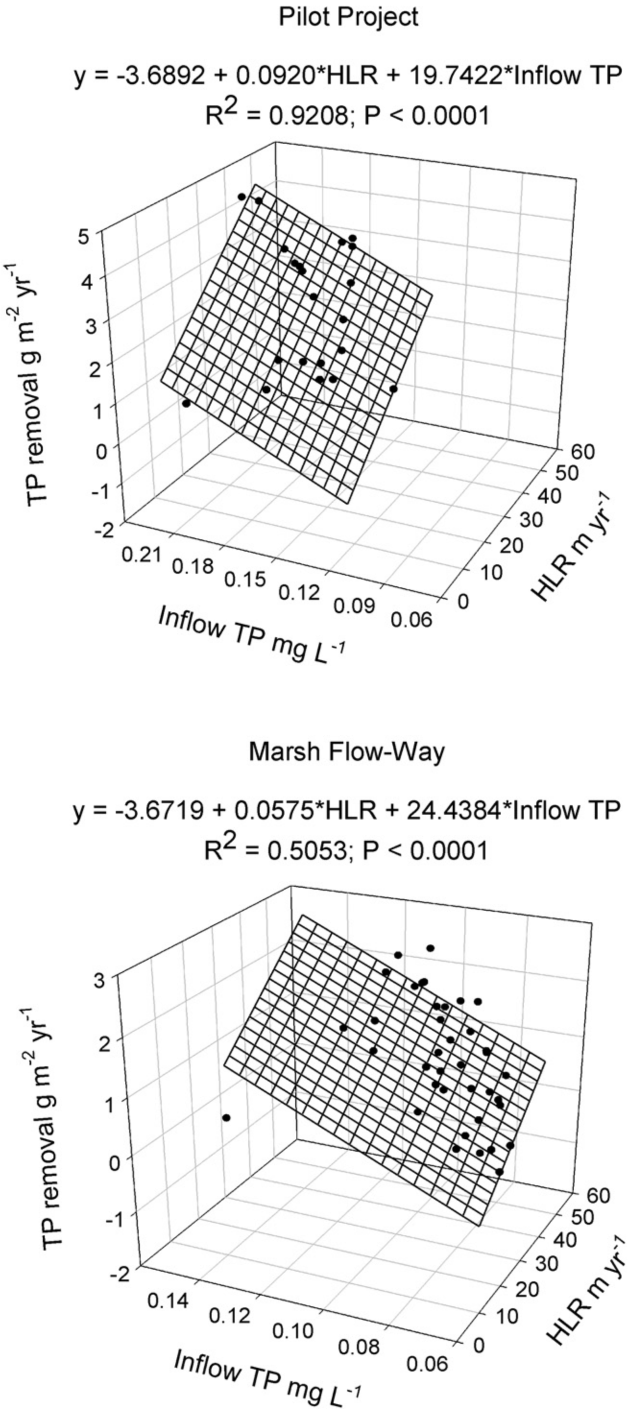

Fig. 8. Relationship between hydraulic loading rate (HLR) (*x*-axis), total phosphorus (TP) concentration (*y*-axis), and TP mass areal removal rate (*z*-axis) for both the pilot project and the marsh flow-way at Lake Apopka. The pilot project includes data for 15-d periods between December 1991 and October 1992. The marsh flow-way data are monthly periods from February 2004 through March 2007. Equations are multiple linear regressions for three-dimensional planes.

High HLR seemed to increase the occurrence of uprooted floating mats of emergent vegetation, suggesting that the system was in a destabilizing state. Creating and maintaining appropriate flow and water depths are critical for successful management of treatment wetlands (Kadlec and Wallace, 2008). During the monitoring period, median water depths in the marsh flow-way cells ranged between about 46 and 57 cm. Stenberg and Clark, 1998 reported that species richness of rooted emergent vegetation in the pilot project at Lake Apopka was greatest at water depths between 15 and 35 cm. Water depths in the flow-way may have been too deep to sustain species diversity and system stability.

In practice, maximum removal rate by the flow-way is probably determined by the monetary constraints of pumping water through the system and the effects on wetland vegetation due to high hydraulic loading and water depths. During the monitoring period, the operating costs of removing TP and TSS based on pumping costs alone were \$42 kg^{-1} of TP and \$0.03 kg^{-1} of TSS, respectively. To increase HLR, additional pump infrastructure would be required.

As Lake Apopka water quality continues to improve through time, inflow TP concentrations in water entering the marsh flow-way will decrease. Therefore, it may be more difficult for the system to remove P unless TP C* also declines. Comparison of the pilot project and the current marsh flow-way provides evidence that C* will decline, as P levels in inflow water, and presumably in the flow-way surface sediments, decline. Median inflow TP and median C* in the pilot project were 0.17 and 0.07 mg TP L^{-1}, respectively (Coveney et al., 2002). In contrast, median inflow TP and C* for the flow-way, built partially in the same area, were 0.09 and 0.045 mg L^{-1}, respectively.

In the long-term, reduced P concentrations in Lake Apopka may require changes to how we manage the marsh flow-way. Examples of changes to management under consideration include varying inflow to the marsh flow-way in proportion to lakewater TP concentration to increase likelihood of P removal, use of alum injection in wetland cells to mitigate seasonal release of SRP, and operating better performing cells, while resting others. One change already implemented is to stop flow through some of the cells during summer months, when percent mass removal of PP tends to decline (Fig. 6), and the risk for SRP release is elevated (Fig. 3).

At some point, the marsh flow-way may no longer be cost-effective for nutrient removal because of successful lake restoration and enhancement. At that time, the former marsh flow-way area could be managed to provide other functions and ecosystem services.

4. Conclusions

The marsh flow-way, a lake-scale treatment wetland, removed substantial amounts of TP, PP, and TSS from incoming eutrophic lake water. The system removed TP over annual periods, despite the initial and seasonal release of SRP, and annual SRP releases declined through time. After about 2.5 years of operation, releases of dissolved fractions were negligible. The marsh flow-way was operated at very high HLRs relative to other constructed wetlands in order to maximize sedimentation of PP, and this contributed to relatively high removal rates. Incoming HLR and TP concentration were equally important in determining TP mass areal removal rates.

Removal rates for PP and TP increased linearly with loading and did not appear to approach asymptotes for loading rates up to about 5.5 g m^{-2} yr^{-1}. In contrast, removal rates for TSS appeared to show less than a linear response at the highest TSS loading rates (>3 kg m^{-2} yr^{-1}), although more data at high loading are needed to define this relationship.

We anticipate improved water quality in Lake Apopka and lower future inlet mass loading rates to the wetland system. Declining P loading may require changes to how we operate and manage the system to maintain cost-effective removal of P and TSS. To date, our evidence suggests that ecologically engineered solutions like the marsh flow-way provide important functions within restoration programs that help improve eutrophic lake conditions.

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