Ecological Engineering 79 (2015) 132–142

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Phosphorus removal performance of a large-scale constructed treatment wetland receiving eutrophic lake water

Ed J. Dunne *, Michael F. Coveney, Victoria R. Hoge, Roxanne Conrow, Robert Naleway, Edgar F. Lowe, Lawrence E. Battoe, Yaping Wang

Saint Johns River Water Management District, 4049 Reid Street, Palatka, FL 32177, USA

ARTICLE INFO

Article history:
Received 30 October 2013
Received in revised form 12 February 2015
Accepted 23 February 2015
Available online 21 March 2015

Keywords:
Constructed wetland
Phosphorus
Performance
Economic costs
Benefits

ABSTRACT

Eutrophication continues to impact watersheds and their receiving water bodies. One approach to mitigate this problem is to use constructed treatment wetlands. Our objectives were to determine long-term phosphorus (P) removal by a large-scale constructed treatment wetland (the marsh flow-way at Lake Apopka, Florida, USA) that treats lake water and to quantify the monetary costs for performance. The marsh flow-way treated substantial amounts of lake water (30 m yr^{-1}, which is about 30% of the lake's volume on an annual basis). Associated with this, P was removed at an average rate of 0.85 g m^{-2} yr^{-1} (2.6 metric tons yr^{-1}). The marsh flow-way removed mostly particulate P, while it released dissolved P fractions (mostly during the first few years of operation; thereafter, release was negligible). The long-term first-order removal rate constant (k) for P averaged 27 m yr^{-1}. Phosphorus removal performance varied seasonally, with greater removal during cool periods (September–May) and poor removal during warm periods (June–August). Incurred annual operation and maintenance (O&M) costs averaged $455,000 (2012$), which was equivalent to $1,648 ha yr^{-1} or $177 per kilogram of P removed. We also calculated costs for a 25-year project life cycle, and compared the incurred and the 25-year costs to other systems that illustrated the marsh flow-way was cost competitive. Both P removal and costs were useful metrics in helping us determine operational and management changes. This resulted in a seasonal management strategy that contributed to increased P removal and a reduction in O&M, thereby increasing cost effectiveness. In addition to costs, treatment wetlands provide benefits that include a range of ecosystem services. We challenge ourselves and other treatment wetland managers to adopt both a cost and benefit approach to assessing system performance.

1. Introduction

About 64% of US lakes and reservoirs, along with 44% of rivers and streams are impaired (U.S. EPA, 2009). Factors contributing to water quality degradation include excess loss of the nitrogen (N) and phosphorus (P) from watersheds. Eutrophication of water resources affects ecosystem stability (Smith and Schindler, 2009) and negatively affects the economy. Phosphorus-related water quality problems in the Great Lakes, Florida Everglades, and elsewhere in the US cause over $2.2 billion per year in economic losses (Dodds et al., 2009). In Florida, Stanton and Taylor (2012) estimated that the economic value of clean water ranged between $1.3 and $10.5 billion dollars annually. These estimates include the total use and non-use values related to water-quality improvements.

Controlling and mitigating eutrophication typically involves reducing nutrient inputs to and/or reducing excess nutrients in receiving aquatic ecosystems such as rivers, ponds, lakes, and wetlands. One approach to reducing nutrients in impacted waters and watersheds is to use treatment wetlands. Treatment wetlands, both natural and constructed, provide a range of ecosystem services (Brander et al., 2013) including flood control, water quality improvement, and provision of ecological habitat and biodiversity. Treatment wetlands, which are ecologically-engineered systems, can improve water quality by storing excess nutrients on both a short- and long-term basis (Braskerud et al., 2005; Blankenberg et al., 2006; Kadlec, 2009; Maynard et al., 2009).

With sufficient resources, treatment wetland managers can assess nutrient removal performance by a wetland system. For example, we can measure concentration reduction, mass removal, mass removal rate, percent mass removal, and first-order rate

* Corresponding author. Present address: National Research Council, 500 5th ST NW, Washington, DC 20001, USA. Tel.: +1 202 334 3136.
E-mail address: edunne@nas.edu (E.J. Dunne).

http://dx.doi.org/10.1016/j.ecoleng.2015.02.003
0925-8574/

constants as water passes through the wetland. The cost-effectiveness of a system can also be easily determined using capital, operating and maintenance costs. However, few studies in the peer-reviewed literature report the costs of constructed treatment wetlands to remove nutrients from eutrophic waters. We hope to address this gap.

In addition to determining project costs, valuing ecosystem goods and services (e.g., providing good water quality, biodiversity, and recreational opportunities) are an important part of total economic value (Costanza et al., 1997). There is a growing body of literature on the use of non-market approaches to estimate economic value of wetland services (Brander et al., 2013). Brander et al. (2013) suggest that decision-making by resource managers does not take into account the value of wetland ecosystem services, as there is a lack of understanding and information. Further, regulatory agencies typically do not consider ecosystem services in their permitting process of treatment wetlands and may only mandate nutrient/contaminant reductions. However, quantifying cost effectiveness and valuing the benefits of providing ecosystem services could be important tools for treatment wetland managers. Adopting a cost and benefit approach would contribute to a more sustainable approach to managing water resources.

Our primary objective for this paper is to report the long-term P removal performance by a large-scale constructed treatment wetland (hereafter the “marsh flow-way”) that treats water from Lake Apopka, Florida, USA. The goal of the marsh flow-way project is to maximize P removal from eutrophic lake water and to achieve this we operate at a high hydraulic loading rate (Dunne et al., 2012). This management approach is quite different to many constructed wetlands operated to improve water quality, and we will discuss this later. Our other objective is to report the land, capital and operating costs associated with the marsh flow-way, and to quantify performance costs during the nine years of operation. We also estimate costs for a 25-year project life. This timescale is a fairly standard period for estimating project costs. Furthermore, now that infrastructure is in place to control external P loading to Lake Apopka, we expect water quality to improve and approach the total phosphorus (TP) restoration target of 55 $\mu g\,L^{-1}$ over a similar time frame based on initial responses (Coveney et al., 2005).

2. Materials and methods

2.1. Program and site description

Lake Apopka received decades of nutrient loading from surrounding farms and other sources (Coveney et al., 2005). This caused the lake ecosystem to degrade and eutrophication to persist for many years. The overall restoration program for Lake Apopka implemented by the St. Johns River Water Management District (SJRWMD) focuses on reducing external P load to the eutrophic lake, combined with cost-effective approaches to reduce P already in the lake (Dean and Lowe, 1998; Hoge et al., 2003). The marsh flow-way is one approach that helps SJRWMD achieve this goal, while also providing ecosystem services like recreational space for bird watching, hiking, biking, and horseback riding (SJRWMD, 2011).

The marsh flow-way is a constructed wetland located along the northwestern shore of Lake Apopka, Florida (Fig. 1). A detailed site description is provided in Dunne et al. (2012). Briefly, the marsh flow-way contains four treatment cells. Inflow structures are screwgates, and outflow structures are culverts with riser boards that can be raised or lowered to manipulate water depth and subsequently the hydrologic gradient between inflow and outflow. All treated water collects in a pump basin, where it is discharged into the Apopka-Beauclair Canal. Water returns to the lake or flows downstream (north) through the canal towards Lake Beauclair.

Cells contain similar vegetative communities. These communities include shallow marsh, shrub swamp, and areas of open water. The entire project, which includes cells, levees, and canals, encompasses about 350 hectares in area. The treatment area is 276 hectares with individual wetland cells varying between 49 and 78 ha (Dunne et al., 2012).

2.2. Operation and maintenance (O&M)

The marsh flow-way has operated since November 2003. We report data between November 2003 and November 2012 (nine years of operation). During this time, maintenance of the system occurred for several months during 2007, 2008, and 2009. The B cells underwent maintenance during 2007 and 2008, while C cells maintenance occurred in 2008 and 2009. Maintenance included a range of activities such as water level drawdown, mowing of vegetation, removal of sediments in ditches, plugging hydrologic short-circuits, construction of finger dikes, planting, reflooding, and the use of alum to mitigate short-term releases of dissolved P when cells were reflooded. During maintenance, affected cells did not treat lake water. For this paper, we only analyzed performance data from periods when the marsh flow-way treated Lake Apopka water; however, we tabulate costs for the complete nine-year period.

2.3. Sample collection and laboratory analyses

During normal operating periods, water samples were collected weekly at the inflow and outflow structures of the marsh flow-way system. Water was collected using a Van Dorn sampler placed at mid-water depth; water samples were field filtered if required (0.45 μm filters) and preserved, if needed. Samples were then placed on ice and transported to the laboratory for analysis.

Water samples were analyzed for total P (TP), total dissolved P (TDP), and ortho-phosphate (ortho-P). Total P was measured on a preserved, unfiltered sample (added H_2SO_4 to $<$pH 2) using a Perstorp autoanalyzer according to EPA Method 365.4. Total dissolved P was determined on a preserved, filtered sample also using the Perstorp autoanalyzer according to EPA Method 365.4. Finally, ortho-P was measured on an unpreserved filtered sample using a LabChat Quickchem AE using EPA Method 365.1. We calculated particulate P (PP) as TP minus TDP and dissolved organic P (DOP) as TDP minus ortho-P.

2.4. Performance calculations and analyses

We calculated hydraulic loading rate (HLR), nominal hydraulic residence time (HRT), mass loads into and out of the system, loading rates, removal rates, and percent mass removed for TP, DOP, PP and ortho-P (Dunne et al., 2012). To calculate daily loads into and out of the system, we multiplied daily flows by daily constituent concentrations. Daily concentrations were estimated by linear interpolation between weekly measurements. Mass removal, mass removal rates, percent mass removal and mass areal removal rates were also calculated on a daily basis. We typically represent data as monthly or annual averages. To characterize long-term P removal performance, we used mass removal and cumulative mass removal ($g\,m^{-2}$), areal mass removal rate ($g\,m^{-2}\,yr^{-1}$), percent mass removal (%), along with the first-order removal rate constant k calculated for TP using the “P-k-C^*” removal model of Kadlec and Wallace (2009):

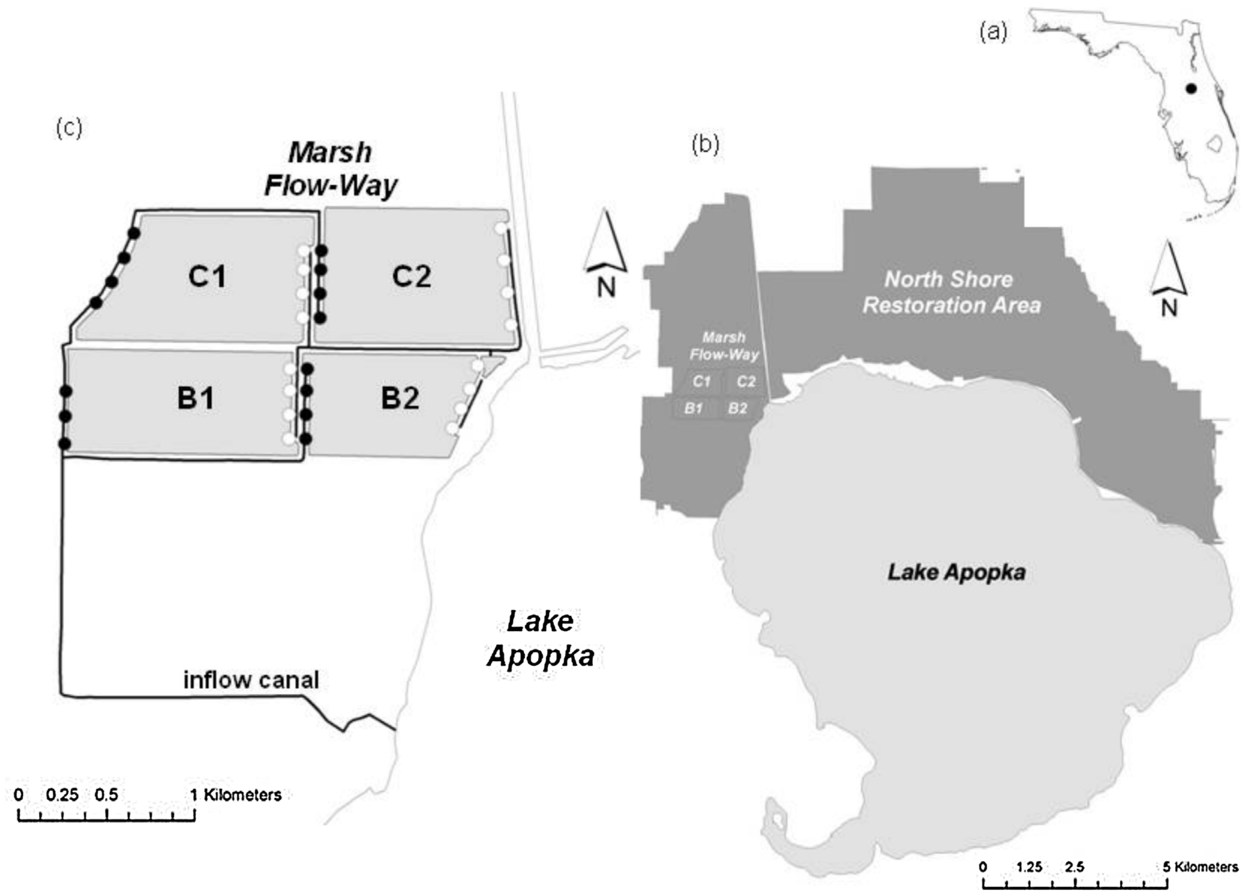

Fig. 1. (a) Location of the marsh flow-way in Florida. (b) Schematic of the marsh flow-way located along the northwest shore of Lake Apopka. The area highlighted in grey is the North Shore Restoration Area. (c) Marsh flow-way cells (B1, B2, C1, and C2) are highlighted in grey. Canals are represented as black lines. Inflow structures are solid circles, while outflow structures are represented as hollow circles.

$$\frac{C_o - C^*}{C_i - C^*} = \frac{1}{(1 + k/Pq)^P}$$

where

C_o = outlet concentration, mg L^{-1}
C_i = inlet concentration, mg L^{-1}
C^* = background concentration, mg L^{-1}
k = first-order areal rate constant, m yr^{-1}
P = apparent number of tanks in series
q = hydraulic loading rate, m yr^{-1}.

Apparent background TP concentration (C^*) was based upon a relationship between monthly TP concentrations within the wetland and water temperature (figure not shown). We fitted the lower bounds of the TP data using an approximation of the Arrhenius equation (see Coveney et al., 2002) and calculated a theoretical temperature-dependent background (C^*) TP concentration ($C^* = 0.04 \times 1.02^{(T-25.0)}$), where T is temperature in Celsius. Using temperature dependent C^* values, we then estimated average annual first-order areal rate constant k values using the Kadlec and Wallace (2009) model described above. The combined model used three tanks in series. Kadlec and Wallace (2009) suggest using three tanks when P is not measured, as in our case.

All statistics were calculated using Minitab® Statistical Software Version 16. We determined statistical significance at the $p < 0.05$, 0.01, and 0.001 levels. A suite of summary statistics was calculated and we also undertook some analyses that included t-tests and regression analyses. Of particular interest were the relationships between concentrations into and out of the marsh flow-way, along with relationships with loading and removal rates. Throughout the manuscript, we typically report values as mean ± one standard deviation.

2.5. Economic cost analysis

Land acquired for the project was purchased in 1990 (C cells) and 1988 (B cells). We estimated a total land acquisition cost for the project footprint (cells, levees, and canals). We also report the initial capital and construction costs, capital costs incurred during marsh flow-way operation, and O&M costs during the nine years of operation. Initial capital costs were incurred in the years 1998 and 2000, prior to initiating marsh flow-way operation in November 2003. All costs and dollar amounts were converted to 2012 US dollars using the USA Bureau of Labor Statistics Consumer Price Index.

We used power usage for the electric pumps at the marsh flow-way pump basin to quantify pumping costs. These reports included monthly and daily power usage (kWh), unit cost per kWh ($), and cost per day. We estimated personnel costs using both budget planning tools and by polling SJRWMD staff on how much time they were spending on marsh flow-way activities. The amount of time ranged between 5 and 20% of their total working time. We then multiplied the percentage for a given position by salary and benefits. Alum costs were recorded and tabulated. Alum was used intermittently, typically post-maintenance during re-flood periods. We tabulated costs associated with contracted work using contract records and purchases using purchasing records.

To determine cost effectiveness of the marsh flow-way to treat water and remove TP, we used land acquisition costs, capital and

O&M costs, along with various performance components that included wetland size, volume of water treated, and the TP mass removed from Lake Apopka water. We did this for past performance and for a 25-year project life (nine years of past performance +16 years of forecasted performance, which was equal to the mean of the last three years (2010–2012) of actual performance). The forecasted volume of treated water was 22 m yr^{-1} or 182,000 m^3 d^{-1} and the associated TP removal rate was 2300 kg yr^{-1}. For forecasted costs, we used our best professional judgment of anticipated capital costs. We anticipate spending about $1 million dollars on a new intake structure from the lake (capital cost) and used an annual O&M cost equal to the mean of the last three years of operation ($355,000). The last three years of operation include both maintenance and non-maintenance periods. We applied a three percent annual inflation rate to O&M costs for the 16-year period.

3. Results and discussion

3.1. Hydrology

Hydraulic loading rates to the marsh flow-way varied between 12 and 44 m yr^{-1} (Table 1). Earlier years (2004 and 2006) had greater HLRs than latter years. During the period of record (POR) the average long-term HLR to the flow-way was 30 ± 11 m yr^{-1}. The volume of water treated during the nine years of operation equated to three times the lake volume or about 30% of the lake's volume annually. Lake water hydraulic inflows were many times greater than either rainfall or evapotranspiration (ET) (Dunne et al., 2012). For example, during the POR, rainfall averaged 1 ± 0.13 m yr^{-1}, while ET was 1 ± 0.15 m yr^{-1}.

Compared to other large-scale constructed wetlands in Florida, these HLRs are high. Pietro (2012) reports maximum HLRs up to about 27 m yr^{-1} in large constructed wetlands built for Everglades restoration (the stormwater treatment areas [STAs]). We operate high HLRs through the marsh flow-way, as our main treatment goal is to maximize P removal from incoming Lake Apopka water. This approach is very different from the conventional approach adopted in many constructed treatment wetlands that are operated to achieve a specific outflow P concentration.

Average annual water depth within the marsh flow-way was about 50 cm, while HRT typically ranged between 3 and 5 days (Table 1). Water depth is an important component of a wetland's water regime (Kadlec and Wallace, 2009). It affects vegetative growth and community spatial patterns. The hydrologic tolerance for most of the common wetland species that occur in the marsh flow-way (*Typha* spp., *Pontederia cordata* L., *Sagittaria* spp., *Panicum hemitomon* Schult. *Ludwigia peruviana* (L.) Hara, and *Salix* spp.) ranges up to a water depth of approximately 50 cm (Kadlec and Knight, 1996).

Table 1
Hydrologic budget components of the marsh flow-way constructed wetland at Lake Apopka, FL. HLR = the hydraulic loading rate, and HRT = hydraulic residence time. Annual averages were calculated from monthly averages. Values in brackets are one standard deviation of the annual average. November and December 2003 are partial months. The period of maintenance during 2007 was not included.

Year	Number of months	HLR (m yr^{-1})		Water depth (m)		HRT (d)	
2003	2	12	(5)	0.45	(0.0)	11	(3.0)
2004	12	37	(8)	0.52	(0.0)	4	(0.7)
2005	12	33	(6)	0.54	(0.1)	5	(1.0)
2006	12	44	(6)	0.52	(0.1)	3	(0.9)
2007	9	32	(13)	0.41	(0.3)	3	(0.3)
2008	12	27	(6)	0.38	(0.2)	4	(0.7)
2009	12	19	(6)	0.52	(0.0)	5	(0.7)
2010	12	33	(2)	0.56	(0.0)	4	(0.3)
2011	12	25	(9)	0.52	(0.1)	4	(1.2)
2012	12	20	(4)	0.48	(0.1)	4	(1.3)

3.2. Phosphorus concentrations

Inflow TP and PP concentrations increased dramatically during 2008 (Fig. 2) when lake stage decreased greatly due to a prolonged drought. After 2008, lake inflow TP and PP concentrations decreased coincident with recovery in lake stage but began to increase again during a drought in 2012.

The pattern of change through time was similar for both inflow and outflow TP and PP concentrations, with outflow concentrations typically being lower than inflow concentrations. This indicates the wetland retained P. Also, outflow concentrations tended to track inflow concentrations closely, indicating a relatively constant efficiency of P removal. Removal of P probably was dominated by sedimentation, rather than processes like sorption, precipitation, and vegetation uptake, since most of the incoming P is in a particulate form (Fig. 2). During the POR, concentration differences between inflow and outflow PP (mean concentration difference = 0.05 mg L^{-1}) were greater than the difference between inflow and outflow TP concentrations (mean concentration difference = 0.03 mg L^{-1}) (*t*-test; $p < 0.001$; $n = 104$). The average concentration reduction for inflow TP was 16%, while the average concentration reduction for inflow PP was 44%.

Ortho-phosphate and DOP concentrations had similar temporal patterns (Fig. 2). Outflow concentrations of both dissolved fractions between 2004 and 2007 were greater than inflow concentrations (net release), with the magnitude of difference between inflow and outflow concentrations being greatest for ortho-P. We hypothesize that the dissolved P release during the initial years of operation was a legacy of P stored in soil, along with P release from senescing non-wetland vegetation. After 2007, inflow and outflow concentrations were similar; however, some dissolved P was released during summer warm periods and post cell maintenance. During these periods, dissolved P release to the water column may have been a result of P loss from decaying plant biomass and subsequent P mineralization (Pant and Reddy, 2001).

Generally, inflow and subsequently outflow concentrations of all P fractions increased during spring and early summer. This was related to seasonal changes in lake water P concentrations, which we discuss in a later section.

3.3. Relationships between inflow and outflow phosphorus concentrations

Both TP and PP inflow concentrations were linearly related to outflow concentrations ($R^2 > 0.60$; $p < 0.001$; Fig. 3). Most inflow and outflow concentrations of both fractions ranged between 0.05 and 0.28 mg L^{-1} with annual POR averages being 0.112 and 0.088 mg L^{-1}, respectively.

We did not observe a statistically significant relationship between DOP inflow and DOP outflow concentrations (Fig. 3). Inflow and outflow concentrations of both ortho-P and DOP were less than 0.025 mg L^{-1}. The ortho-phosphate mean monthly outflow concentrations were more variable coefficient of variation (CV) = 195%) than DOP outflow concentrations (CV = 57%) suggesting different controlling biogeochemical processes. Contributing factors could include within-wetland nutrient cycling and P release via mineralization (Pant and Reddy, 2003; Noe, 2011).

3.4. Background phosphorus concentrations

We calculated a temperature-dependent (based on a modified Arrhenius relationship; not shown) background (C^*) TP concentration. At the highest water temperature (30.8 °C; in August 2005) C^*

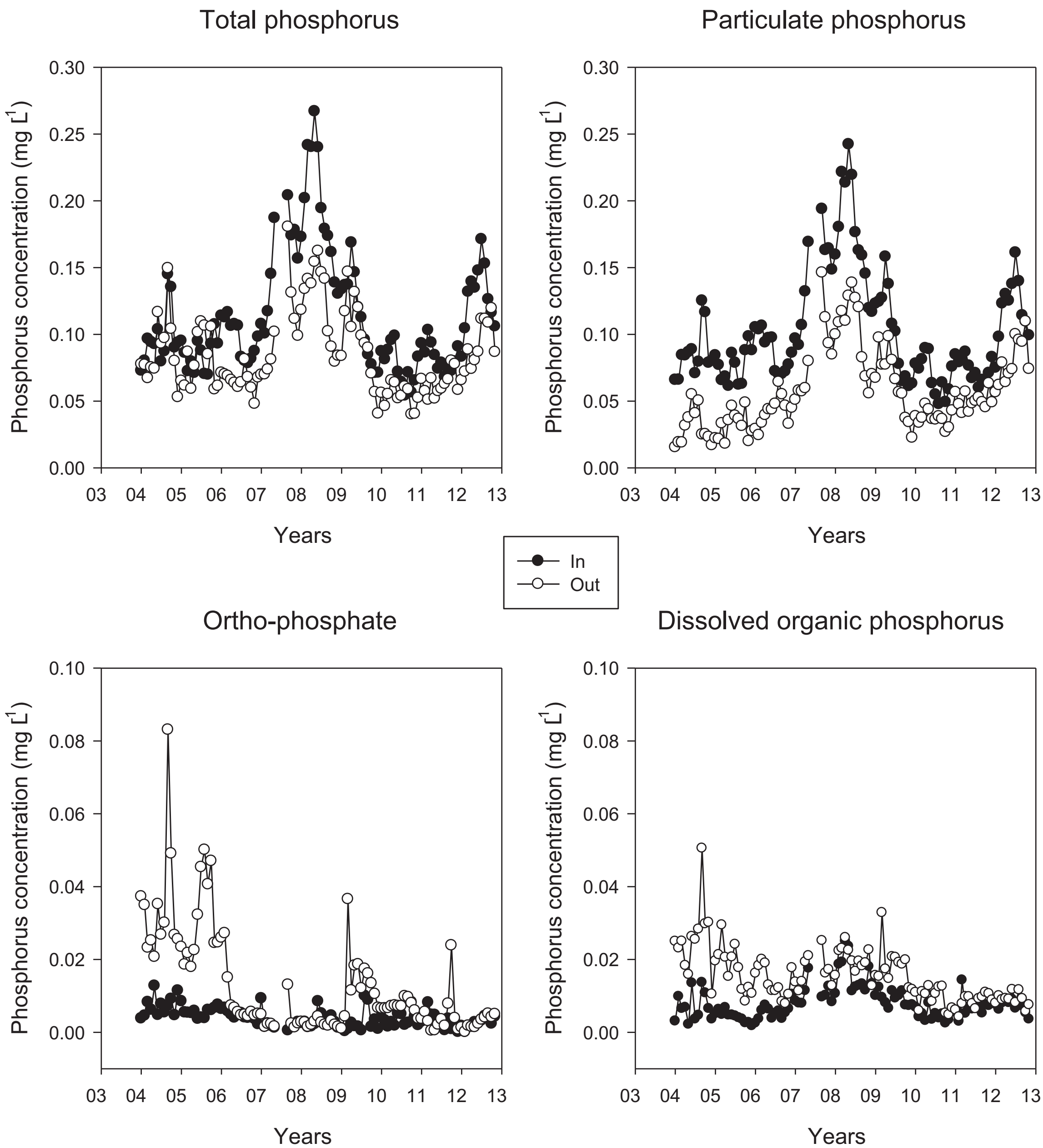

Fig. 2. Time series (November 2003 through November 2012) of average monthly inflow and outflow concentrations of total phosphorus (TP), particulate phosphorus (PP), ortho-phosphate, and dissolved organic phosphorus (DOP). Inflow concentrations to the marsh flow-way are black circles and outflow concentrations are white circles.

was 0.044 mg L^{-1}, while at the lowest temperature (10.9 °C; in December 2010) C^* was lower, 0.030 mg L^{-1}.

3.5. Phosphorus removal performance

We found weak, but statistically significant relationships between inlet TP and PP loading rates and outflow concentrations (Fig. 4). The maximum inlet loading rate for both TP and PP was 8 g m^{-2} yr^{-1}. During the POR, average inlet TP loading rate was 3.24 ± 1.4 g m^{-2} yr^{-1} with inlet loading rates varying considerably. Loading rates varied with changes in HLR and incoming lake TP concentrations. Average monthly outflow concentrations were also variable; concentrations ranged between 0.04 and 0.17 mg L^{-1}. The weak relationships between outflow concentrations and inlet P loads for the marsh flow-way (Fig. 4) differ from the linear log-log relationships that have been constructed for other data sets (e.g., Kadlec and Wallace, 2009). However, Kadlec and Wallace (2009) discuss the fact that, while aggregated project data sets spanning orders of magnitude of inflow P concentrations show generally linear log–log relationships between outflow P concentration and inlet P load, data sets with narrower concentration ranges (e.g., the marsh flow-way) do not. The weaker relationships for the marsh flow-way reflect the fact that the wetland tended to remove a constant fraction of inflow P despite changes in P load, as shown by good linear relationships between outflow and inflow concentrations (Fig. 3). One potential cause of a constant percent removal of P in a wetland is a positive relationship between k and HLR, as discussed by Kadlec (2000).

There were significant linear relationships between TP and PP inlet loading rates and their respective removal rates (Fig. 4). During the POR, TP mass removal rate averaged 0.85 ± 0.9 g m^{-2} yr^{-1}, while average PP removal rate was 1.37 ± 0.8 g m^{-2} yr^{-1}. The

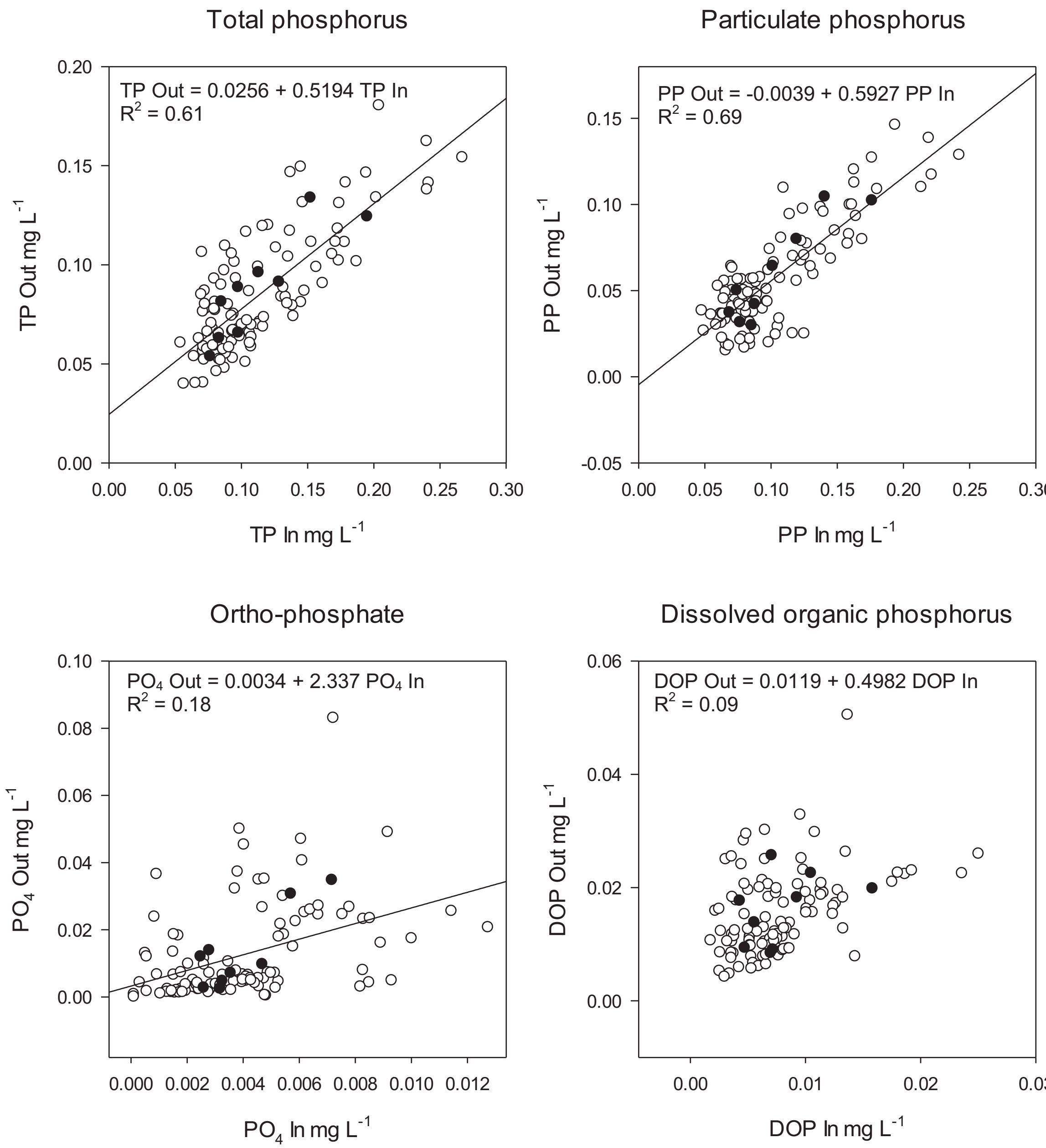

Fig. 3. Marsh flow-way inflow concentrations versus outflow concentrations. Total phosphorus (TP), particulate phosphorus (PP), ortho-phosphate, and dissolved organic phosphorus (DOP) concentrations are represented as average monthly values (white circles) and average annual values (black circles). We determined linear regression using monthly data. All relationships were significant at the $p < 0.05$ level. Period is from January 2004 through November 2012.

TP mass removal rate was greatest during periods when HLR and TP loading rate – due to a combined effect of high HLR and high inflow TP concentration – were also the greatest. This occurred during 2006, 2007, and 2008. Operating at a HLR greater than 35 m yr^{-1} and an incoming TP concentration greater than 0.1 mg TP L^{-1} increased the likelihood for P removal (Dunne et al., 2012). Similarly, in our present study, we found that when HLR was 34 m yr^{-1}, coupled with an annual inlet TP concentration of 0.15 mg L^{-1}, we got some of the highest annual TP removal rates of 1.7 g m^{-2} yr^{-1}. This is well above our long-term target of 30% removal from incoming TP mass. Wetland Solutions Inc. (2009) estimated a P mass removal rate between 1.5 and 2 g m^{-2} yr^{-1} for large-scale wetlands in South Florida. This removal rate was a function of aspect ratio and HLR, with HLR varying between 22 and 44 m yr^{-1}. Other large-scale treatment wetlands that are operated for concentration reduction (the Everglades STAs) removed P at a rate of 0.5 g m^{-2} yr^{-1}, which was equivalent to a 73% mass removal (Pietro, 2012).

Phosphorus removal and release rates by the marsh flow-way were variable from month to month. Total P and PP removal rate was lowest during the warm summer periods (June through August; Fig. 5). This reduction in TP and PP removal rates during summer months was due primarily to large declines in percent removal efficiency for both constituents (Dunne et al., 2012). These declines in removal efficiency did not reflect a simple break-through of particulate matter from inflows, since removal efficiency for TSS showed no similar seasonal pattern (Dunne et al., 2012). Instead, we hypothesize that relatively P-rich particles were released from the wetland during summers. After August/September, P removal rates began to increase and were greatest during cool periods (September through May). Lake Apopka TP concentrations tend to increase in the fall/winter months and

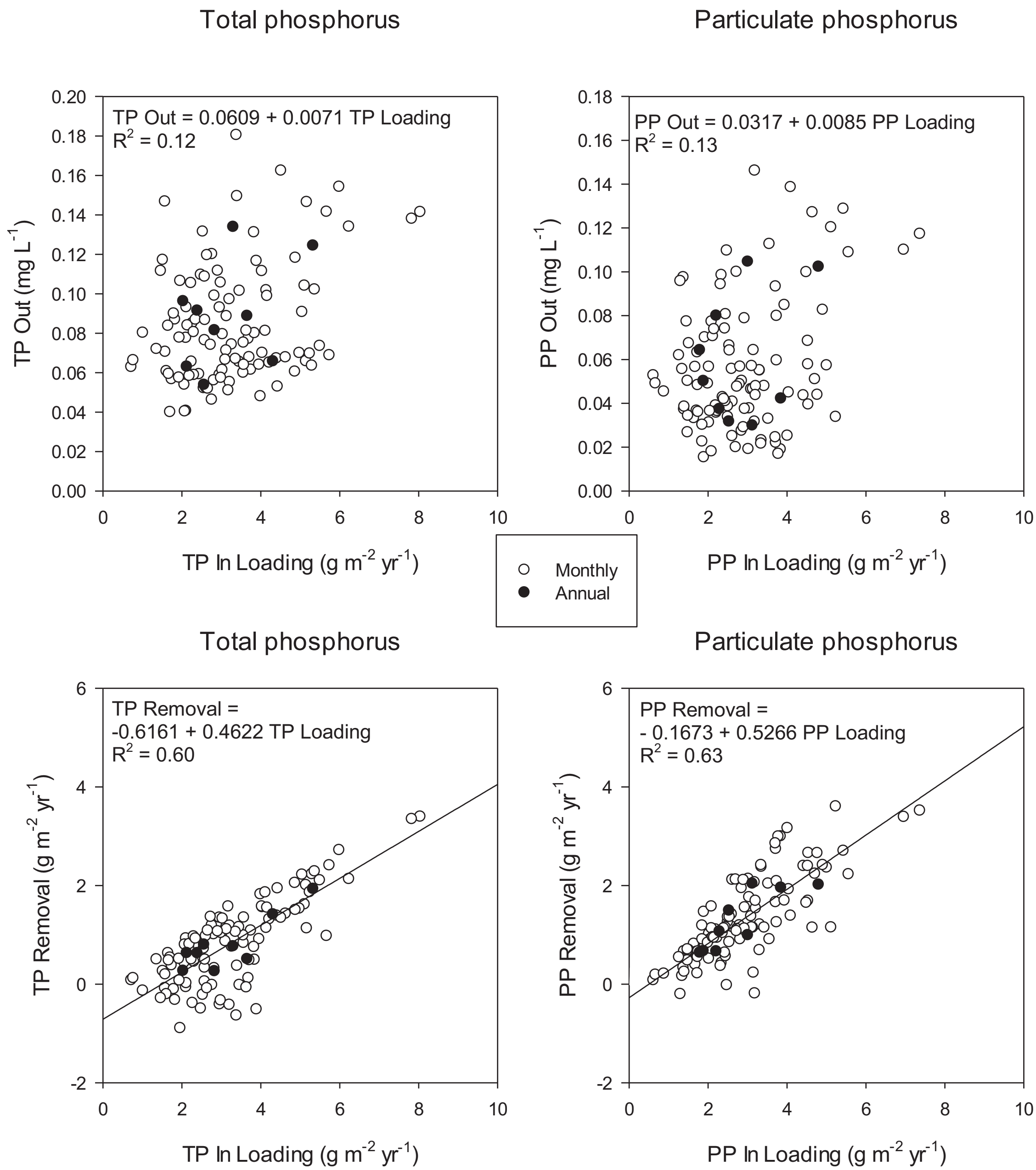

Fig. 4. Marsh flow-way *PP* loading rate (g m^{-2} yr^{-1}) versus outflow concentration (mg L^{-1}) for total phosphorus (TP), and particulate phosphorus (PP) (top panels). The lower two panels show the relationships between loading rate (g m^{-2} yr^{-1}) and removal rate (g m^{-2} yr^{-1}) for TP and PP, respectively. Values in all four plots are average monthly values (white circles) and average annual values (black circles). We used monthly data (January 2004 through November 2012) for regression analyses. All relationships were significant at the $p < 0.05$ level.

reach greatest concentrations during spring. For example, between 1987 and 2012, average spring TP concentrations (0.19 mg TP L^{-1}) were 19% greater than summer concentrations (0.16 mg TP L^{-1}; $p < 0.001$; $n = 78$; calculated using monthly average lake concentrations; data not shown). Possible mechanisms that may contribute to lake TP concentration increases include reduced in-lake sedimentation associated with increased wind velocities (Coveney et al., 2005).

Compared to TP and PP removal rates, the marsh flow-way tended to release both DOP and ortho-P (Fig. 5). However, after the latter part of 2007, the magnitude of release decreased and continued to decrease through time until 2012. This suggests a steady state or equilibrium between inflow and outflow dissolved P concentrations. This maybe explained, in part, by a decrease in dissolved P diffusion from underlying soil to overlying water column (Reddy et al., 1999).

During the nine years of operating the marsh flow-way, removal of TP was mostly due to PP removal, while the flow-way released dissolved P fractions, most of which occurred in the first few years (Fig. 6). The increase in P removal was incremental from year to year; however, between 2006 and 2008, P removal increased (especially in 2008), relative to other years. This is a result of increased P loading due to increases in Lake Apopka water column TP concentrations. During 2008, the lake had extreme low water levels, and TP concentrations have been shown to increase during low water events in this system (Coveney et al., 2005). Since 2008, cumulative P removal by the marsh flow-way was steady and did not reach an asymptote. This implies the system has not reached a

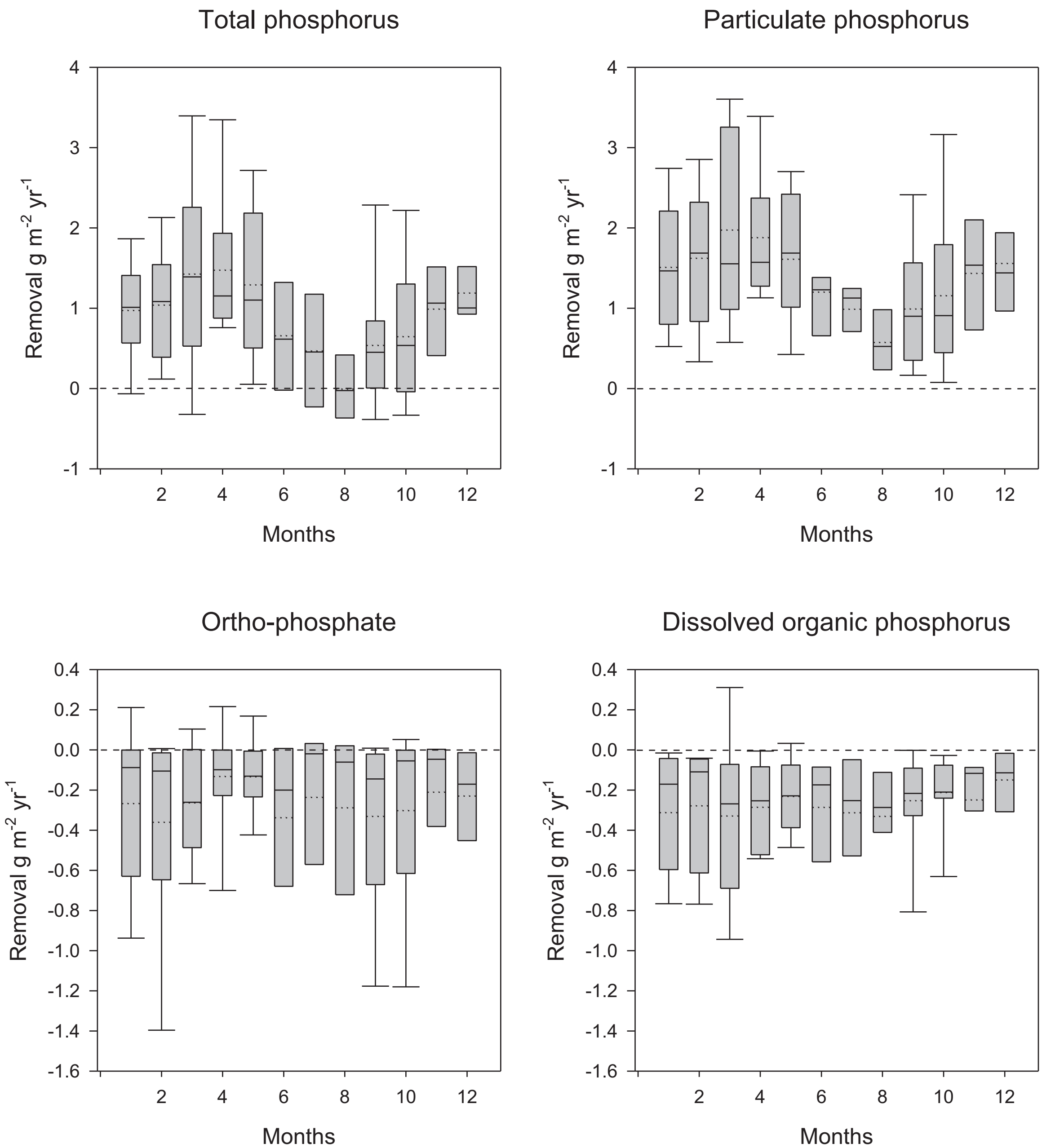

Fig. 5. Box plots of phosphorus removal rates for calendar months January through December (1 through 12). Period is from January 2004 through November 2012. The solid line within the box is the median, while the dotted line is the mean. The upper and lower boundaries of the box are the 75th and 25th percentiles, respectively. Whiskers (error bars) above and below the box are the 90th and 10th percentiles.

maximum P storage capacity. This is an important finding, as our main management goal is to maximize P removal from Lake Apopka water. Further, it is not a surprising finding, as long-term P storage is governed by mechanisms like accretion, which can continue indefinitely given the appropriate environmental conditions.

During the POR, the marsh flow-way removed about 26% of the incoming TP mass, which equates to 2.6 metric tons per year of TP removed from Lake Apopka. To give context, in recent years, the average TP mass in Lake Apopka's water column was 30 metric tons. The long-term percent mass removal we cite is similar to the long-term goal of 30% removal of incoming P mass originally projected by Lowe et al. (1989). During years (2006–2008) with greater TP loading, we achieved higher (~35%; annual average) percent mass removals, while during other years, we achieved much lower percent removals. The percent TP removals we cite are much lower than those cited for the STAs by Pietro (2012). The goal of STAs is to remove excess P from surface runoff before waters reach the Everglades; therefore, reducing concentrations down to very low levels is an important operational goal. This operational goal is very different to the operational goal of the marsh flow-way. We operate the marsh flow-way to maximize P removal from an already impacted lake; therefore, focusing on greater rates of mass removal rather than operating for high efficiency and trying to meet an outflow P concentration criteria. Further, relative to the STAs, the flow-way is operated at much shorter HRTs, has very different inflow water characteristics, and removes mostly PP.

The average annual k value was $27 \pm 14\,\mathrm{m\,yr^{-1}}$. Greatest annual values ($49\,\mathrm{m\,yr^{-1}}$) occurred in 2006 and 2010, while smallest values (17 and $13\,\mathrm{m\,yr^{-1}}$) occurred in 2004 and 2012, respectively.

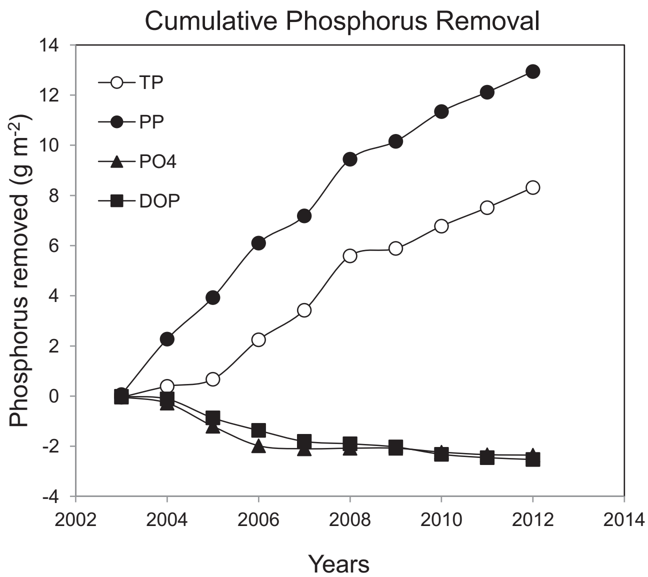

Fig. 6. Cumulative phosphorus removal and release ($g\,m^{-2}$) by the marsh flow-way at Lake Apopka from the start of operation (November 2003) through November 2012. We express cumulative removal on a mass per unit area basis ($g\,m^{-2}$) for total phosphorus (TP), particulate phosphorus (PP), ortho-phosphate (PO_4), and dissolved organic phosphorus (DOP). Positive numbers indicate retention, while negative numbers represent release.

Table 2
Table of land acquisition costs, capital costs, and operation and maintenance (O&M) costs for the marsh flow-way at Lake Apopka, FL. All costs were those incurred up through the 2012 fiscal year. Land acquisitions costs were an estimate of the project footprint that included treatment area, levees, and canals. Capital costs include initial costs and those costs incurred during operation. The O&M costs were grouped into broad categories and totals tabulated for the nine years of operation. Miscellaneous expenditures include contracts, purchase orders and costs associated with water quality analyses. All values are in 2012 dollars.

Description	Incurred cost
Land acquisition costs	$4,028,558
Capital costs	
Construction	$3,646,554
Design and engineering	$502,360
Pumps	$621,894
Soil amendment	$134,070
Alum injection system	$29,862
Earthwork	$175,459
Total capital costs	$5,110,199
Operation and maintenance costs	
Pumping	$1,132,268
Alum	$505,724
Personnel	$1,908,703
Miscellaneous expenditures	$546,459
Total O&M costs	$4,093,154
Annualized O&M cost ($/yr)	$454,795
Capital + O&M	$9,203,353
Land acquisition + capital + O&M	$13,231,911

In addition, we found a strong seasonal pattern. During the cool period (October through May), when P removal was greatest, median *k* values were twice ($32\,m\,yr^{-1}$) what they were during warm periods (June through September) ($15\,m\,yr^{-1}$), and percent removal efficiency was low during summer periods. During warm periods, P removal rate was least (Fig. 5). Kadlec and Wallace (2009) report temperature dependent *k* values for both cold and warm climate constructed wetland systems. These systems were mostly from North America; however, systems from Sweden, Australia and India were also included. There were few differences between cold and warm climate systems, with a median *k* value of $18\,m\,yr^{-1}$. In earlier work, Kadlec (2006) suggested that at semi-tropical latitudes, variation in performance may occur.

3.6. Economic costs for a wetland approach

We estimate that land acquisition costs for the marsh flow-way project footprint were about $4 million. Total capital was $5.1 million, while the incurred O&M costs were $4.1 million (Table 2). Initial design and engineering of the system, along with pump purchases ranged between 10 and 12% of the total capital cost. Construction accounted for the greatest portion of project costs, at 71%. The remaining capital costs, which include earthwork, alum injection, and soil amendment, were all less than four percent of the total capital costs. Some of these costs were incurred during maintenance periods. One way to illustrate capital costs and economy of scale is to express capital costs as a function of flow rate (Kadlec and Wallace, 2009). With increasing flows, one should expect increasing capital costs. Our capital cost for treating eutrophic lake water was $\$20\,m^{-3}\,d^{-1}$ and on average, the project reduced lake water TP concentrations down to $90\,\mu g\,P\,L^{-1}$, while removing P at an average rate of $0.85\,g\,m^{-2}\,yr^{-1}$.

Incurred O&M costs (past nine years of operation) were 31% of the total costs (land acquisition + capital costs + O&M costs; Table 2). The annualized cost for O&M was about $455,000. Major components of O&M included personnel (47%), electric costs associated with pumping water through the system (28%), alum (12%), along with some contracts, purchases, and miscellaneous expenditures (13%). Our estimate of personnel time on the marsh flow-way project is probably an overestimate for routine O&M. Especially in the first several years, personnel often undertook additional water quality sampling, site investigations, data reporting, and data analyses for research purposes, rather than routine duties to maintain operation of a treatment system. In recent years, personnel costs have decreased due to staff reductions, decreased maintenance activities, and operational changes. During 2011–2012, personnel costs were $83,000 per year. In previous years, costs were much greater ($249,000 per year, between 2004 and 2010). Annual average pumping costs were $\$126{,}000 \pm \$32{,}000$ with year-to-year variability being a result of lake water levels, weather patterns, performance, and on-site O&M activities. In 2006, pumping costs were $183,000 (HLR was $40\,m\,yr^{-1}$), while in 2012; pumping costs were $78,000 (HLR was $19\,m\,yr^{-1}$). There is a direct relationship between pumping costs and HLR to the marsh flow-way. We previously mentioned that cell maintenance was undertaken in years 2007, 2008, and 2009. The incurred cost for B cell maintenance ($265,000) was less than the cost associated with C cell maintenance ($353,000). The difference was mostly due to the construction of finger dikes in C2 cell. We include all maintenance costs in Table 2.

In addition to tabulating land acquisition, capital, and O&M costs before and during the nine years of operation, we also estimated costs for a 25-year project life (nine years of operation + 16 future years). We estimated that the 25-year project capital cost was $6.1 million and O&M was $11.5 million. The annualized O&M cost for this 25-year project life was $459,000. We compared our study costs with several other P-removal treatment wetlands. We found that the realized marsh flow-way O&M cost was $\$1{,}648\,ha^{-1}\,yr^{-1}$ (25-year cost was $\$1{,}662\,ha^{-1}\,yr^{-1}$), and this cost was similar to the median cost ($\$1{,}856\,ha^{-1}\,yr^{-1}$) for a number or wetlands ($n = 29$) throughout North America (NADB, 1998; Sano et al., 2005; Kadlec and Wallace, 2009; Hazen and Sawyer, 2011). Generally, from reviewing these systems, we found that as wetland size increased, the annualized cost of O&M per unit area decreased.

One can also characterize treatment costs on a dollar per kg of P removed. The realized costs (O&M costs only) for P removal by the marsh flow-way was $177/kg. For the 25-year project life, we estimate a slightly greater cost at $191/kg P removed. SJRWMD did a comprehensive analysis of return on investment for the marsh flow-way that included the cost of the entire land parcel purchased for the project (not just the project footprint) as well as the cost of construction and operation of an earlier pilot project (Coveney et al., 2002) on the same site. For a 19-yr project life (9 realized plus 10 projected), that analysis totaled $477/kg P removed (SJRWMD 2014 unpublished). We reviewed several large-scale treatment wetland systems (either planned or constructed) in Florida (Sano et al., 2005; Wetland Solutions Inc. 2009; Hazen and Sawyer, 2011) and found the median cost (based on O&M only) for P removal was 277 $/kg. Many of these other large-scale systems have different inflow water characteristics (quality and quantity), different site conditions, and different operational and management goals, which contribute to variable cost estimates. For example, P removal costs for the cited systems was 40 to 1000 $/kg P removed. The cost of P removal ($/kg) is one metric for evaluating treatment performance. We recommend using multiple lines of evidence such as those described and discussed above, rather than relying on one metric to assess performance.

3.7. Benefits of using a wetland approach

Constructed wetlands can provide a range of ecosystem services (benefits). Many of these services provide beneficial functions that can have monetary value; however, quantifying this monetary value can be difficult (Costanza et al., 1997; Dodds et al., 2009). Disciplines like ecological economics have estimated dollar values for ecosystem services like water treatment, nutrient cycling, carbon sequestration, and recreational space (Farber et al., 2002; Gascoigne et al., 2011; Brander et al., 2013). Cited values ranged between $400 and $16,000 $ha^{-1}\,yr^{-1}$ depending on the specific ecosystem service (Costanza et al., 1997; Pate and Loomis, 1997; Hein et al., 2006; Dodds et al., 2009; Barbier et al., 2011). For example, Costanza et al. (1997) estimated the economic value of using wetlands to treat waste and for pollution control at $6,471 $ha^{-1}\,yr^{-1}$. If we apply this value to the marsh flow-way treatment area (276 ha), we estimate the system is providing a value of $1.79 million yr^{-1}. This annual value is many times greater than the annual O&M costs; however, rather than focusing on the absolute dollar value, we hope this crude example gives some context of the beneficial values of a wetland approach.

Constructed wetlands, like the marsh flow-way can also offer an economic opportunity for resource recovery and reuse options. Other economic opportunities could include increased public access to aid developing ecotourism opportunities. For example, the marsh flow-way, as part of the larger Lake Apopka Restoration Area is a renowned birding location within the U.S.

4. Challenges and opportunities

During the past several years, we experienced many challenges to operating and managing the marsh flow-way. These include:

- Legacy of past land management practices and internal nutrient cycling.
- Hydrologic short-circuits.
- Variable seasonal performance.

For the first few years of operation, the marsh flow-way released dissolved P; however, this release decreased through time. Probable causes include P release from historically fertilized organic soils that were previously used for intensive row crop agriculture, along with decomposition of upland vegetation as the site transitioned to wetland (Coveney et al., 2002; Dunne et al., 2012). These combined factors contributed to a reduction in TP removal performance during initial years.

During the nine years of operation, several hydraulic short-circuits developed within marsh flow-way cells, and these short-circuits decreased P removal performance. Short-circuits were a legacy of past land uses and/or initial wetland construction. For example, historical agricultural ditches existed within cells that were parallel to flow. Prior to operation, these ditches were filled with organic soil; however, during operation, many of these filled ditches scoured and became short-circuits. In addition, to build some of the external levees during construction, soil was scooped out of the wetland. This created areas of lower elevation within the wetland that were parallel to flow and contributed to short-circuit development. Our management of the marsh flow-way also may have contributed to increased short-circuits. For example, the HLR to the system averaged 30 $m\,yr^{-1}$. This is high compared to other constructed wetland systems. Operating the wetland at high HLRs between 2006 and 2008 (Table 1) provided good P removal during those years (Fig. 6); however, we hypothesize the high HLR contributed to short-circuit development that compromised P removal performance in ensuing years. To mitigate short-circuits, we constructed finger dikes within short-circuit paths to grade elevation. These dikes were perpendicular to flow and helped to divert flow internally to the cell. The dike construction costs were included in Table 2 costs.

Other challenges in managing the marsh flow-way were recognizing and then planning for seasonal changes in performance. We were aware that seasonal variation in performance was likely; however, it took several years for this pattern to emerge. One thing we did not anticipate was the magnitude of performance differences between seasons. Performance decreased during warm months (June through September) and increased during cooler months (October through May; Fig. 5). Average TP removal during cool periods was much greater (1.04 $g\,m^{-2}\,yr^{-1}$) than during warm periods (0.42 $g\,m^{-2}\,yr^{-1}$). Thus, during warm periods, we decided to stop flow through poor performing cells, while continuing to operate better performing cells. This change saved pumping costs during the warm periods, while minimally affecting annual P removal. Therefore, tracking both P removal performance and costs helped us make informed decisions to improve management. Stopping flow through cells also provided an opportunity to draw down water levels in cells to help increase recruitment of herbaceous wetland vegetation. During cool periods, when performance was better, we increased flow through cells to increase nutrient removal. The latter portion of the cool period (March, April, and May) corresponded with a seasonal increase in lake TP concentrations. An increase in hydraulic loading, along with a concomitant increase in incoming TP concentration, presented an opportunity for increased TP removal by the marsh flow-way.

5. Conclusions

One approach to remove nutrients from eutrophic lake water is the use of constructed wetlands. The marsh flow-way treated substantial amounts of eutrophic lake water (~three times Lake Apopka's volume) during nine years of operation. It removed 2.6 metric tons of phosphorus per year, and this equated to 26% removal from incoming P mass loads. Phosphorus removal rates averaged 0.85 $g\,m^{-2}\,yr^{-1}$, while k values averaged 27 $m\,yr^{-1}$. Most of the P removed by the marsh flow-way from Lake Apopka water was in a particulate form. We found that P removal performance increased during cool periods and decreased during warm periods while operating costs remained constant. Using information on both P removal and costs, we adopted a seasonal operating regime with low warm-season flows to increase cost-effectiveness. Our annual O&M costs incurred during the nine years of operation were $455,000. Quantifying both costs and performance using multiple lines of evidence was a very useful approach to give context as to how we were managing the marsh flow-way. We concluded that the marsh flow-way was very cost-competitive to many constructed wetland systems. In addition to the costs, we also challenge ourselves and other wetland managers to consider the broad ecological benefits of a wetland approach to provide effective water resource solutions.

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