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Phosphorus Flux in the Taylor Creek Stormwater Treatment Area: Potential Causes and Recommended Control Strategies

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EXECUTIVE SUMMARY

Soils play a critical role in the short-term and long-term performance of stormwater treatment areas (STAs). Since they could be a source of or a sink for phosphorus (P), it is important to understand the soil factors and processes influencing the dynamics of P exchange at the soil/water interface and the resulting water column P concentrations. Phosphorus flux and equilibrium dynamics of soils from the Taylor Creek Stormwater Treatment Area (TC-STA) located in Okeechobee, Florida, were investigated in May 2013. Triplicate intact soil cores were collected from ten sites along a transect from inflow to outflow points of this 2-celled STA, and subjected to a series of floodwater exchanges with increasing TP concentrations over six 10-day hydraulic retention cycles, in the laboratory under aerobic conditions. The rates at which P was released to the water column or retained by the soil varied between cells, locations within each cell and initial floodwater TP concentrations. Overall, soils from Cell 1 locations released less P and/or retained more P at a given floodwater TP concentration compared to Cell 2 soil columns. However, significant differences in flux rates were detected only at initial floodwater TP concentrations (Co) of 0.245 mg L^{-1} ($p = 0.014$) and 0.454 mg L^{-1} ($p = 0.042$) by Wilcoxon Rank Sum Test. At these initial P concentrations, C1 soils functioned as a sink while C2 soils acted as a source of P. The difference in mean P-flux rates between Cells 1 and 2 was attributed to difference in concentrations of labile P forms (organic and inorganic), which were both higher in Cell 2 soils. Phosphorus release rates averaged over all stations ranged from 4.92 mg P m^{-2} d^{-1} at C_o = 0.010 mg P L^{-1} to 1.23 mg P m^{-2} d^{-1} at C_o = 0.245 mg P L^{-1}. The soils removed P from the water column at higher initial floodwater TP concentrations. Mean P retention rates of -1.22 and -6.20 mg P m^{-2} d^{-1} were obtained at C_o = 0.454 mg P L^{-1} and Co = 1.018 mg P L^{-1}, respectively.

Consistent with the P flux results, the estimated equilibrium P concentration (EPC_w) in the water column varied considerably between cells. Mean EPC_w value of 0.165 mg P L^{-1} for Cell 1 soils was significantly lower than EPC_w of 0.595 mg P L^{-1} for Cell 2 soils. This indicates that soils in Cell 1 are likely to act as a sink for P while soils in Cell 2 could be a source of internal P load to the STA depending on the TP concentration of the runoff water entering the STA. EPC_w values were significantly correlated with soil labile P and moderately labile organic P concentrations, indicating that these P forms are likely to exert significant influence on P release and equilibrium dynamics of soils/sediments within the Taylor Creek STA. A number of management actions ranging from vegetation enhancement to chemical treatment and STA operational adjustments have been suggested to effectively control P flux in the Taylor Creek STA and help increase its P treatment efficiency in the long-run.

1. INTRODUCTION/BACKGROUND

The Taylor Creek STA is one of two pilot-scale STAs being implemented by the South Florida Water Management District (District or SFWMD) as part of the Critical Restoration Projects authorized by Congress through Section 528 of the Water Resources Development Act of 1996. Constructed in April 2006, this two-cell STA has an effective treatment area of 118 acres. The TC-STA was designed to remove, on average, approximately two metric tons of total phosphorus (TP) from the Taylor Creek drainage basin per year.

Flow-through operations at the TC-STA commenced on June 26, 2008. By the end of Water Year 2013 (WY2013), the TC-STA had almost 37 months of flow-through operation: eight months in WY2009 (June 26, 2008-February 24, 2009), a little less than eight months in WY2011 (September 8, 2010-April 30, 2011), twelve months in WY2012 (May 1, 2011-April 30, 2012), and nine months in WY2013 (May 1, 2012-January 31, 2013). The STA did not operate year round due to interruptions resulting from construction repairs and drawdown activities. The TC-STA performed effectively during the first 16 months of flow-through operation with TP load reductions of 31 and 64 percent in WY2009 and WY2011, respectively. However, between July 2011 and January 2013, the STA performed below expectations. Of the 5.51 mt of TP the STA received in WY2012, 4.40 mt were discharged back into Taylor Creek, resulting in a net TP load removal of 1.11 mt and a TP load reduction of only 20 percent. This was well below the projected long-term average TP reduction of 38 percent or 2.02 mt P/year. An unprecedented number of reversals in weekly TP concentrations reflected the relatively poor load reduction of the TC-STA during WY2012. Reversals refer to instances when the TP concentration measured at the outflow was higher than the TP concentration measured at the inflow. During WY2012, the TC-STA had fifteen reversals (averaging 0.043 mg P L^{-1}), nine of which were recorded between November 10, 2011 and February 15, 2012, corresponding with the normal dry season in south Florida (**Fig. 1**). This same pattern of reversals was observed in WY2013, which prompted the District to temporarily cease flow-through operation on February 1, 2013, in an effort to curtail release of P from the STA back into Taylor Creek.

The lack of consistency in STA performance during WY2012 and WY2013 led to investigations of the potential causes of P release associated with soil and P conditions in the STA. Transect water quality sampling conducted in September 2010 and December 2012 revealed distinct spatial patterns in TP concentrations across the STA under low (~0.100 mg L^{-1}) and high (> 500 mg L^{-1}) inflow TP concentrations (**Fig. 2**). When water entering the STA had a TP concentration > 500 mg L^{-1}, the STA functioned as a sink for P, as evidenced by a gradient of decreasing TP concentration along the flow-way (**Fig. 2, right**). However, at inflow TP concentrations of about 0.100 mg L^{-1}, surface water TP concentrations increased in both cells, indicating that P was being released from decaying vegetation, the sediments and/or porewater to the water column (**Fig. 2, left**).

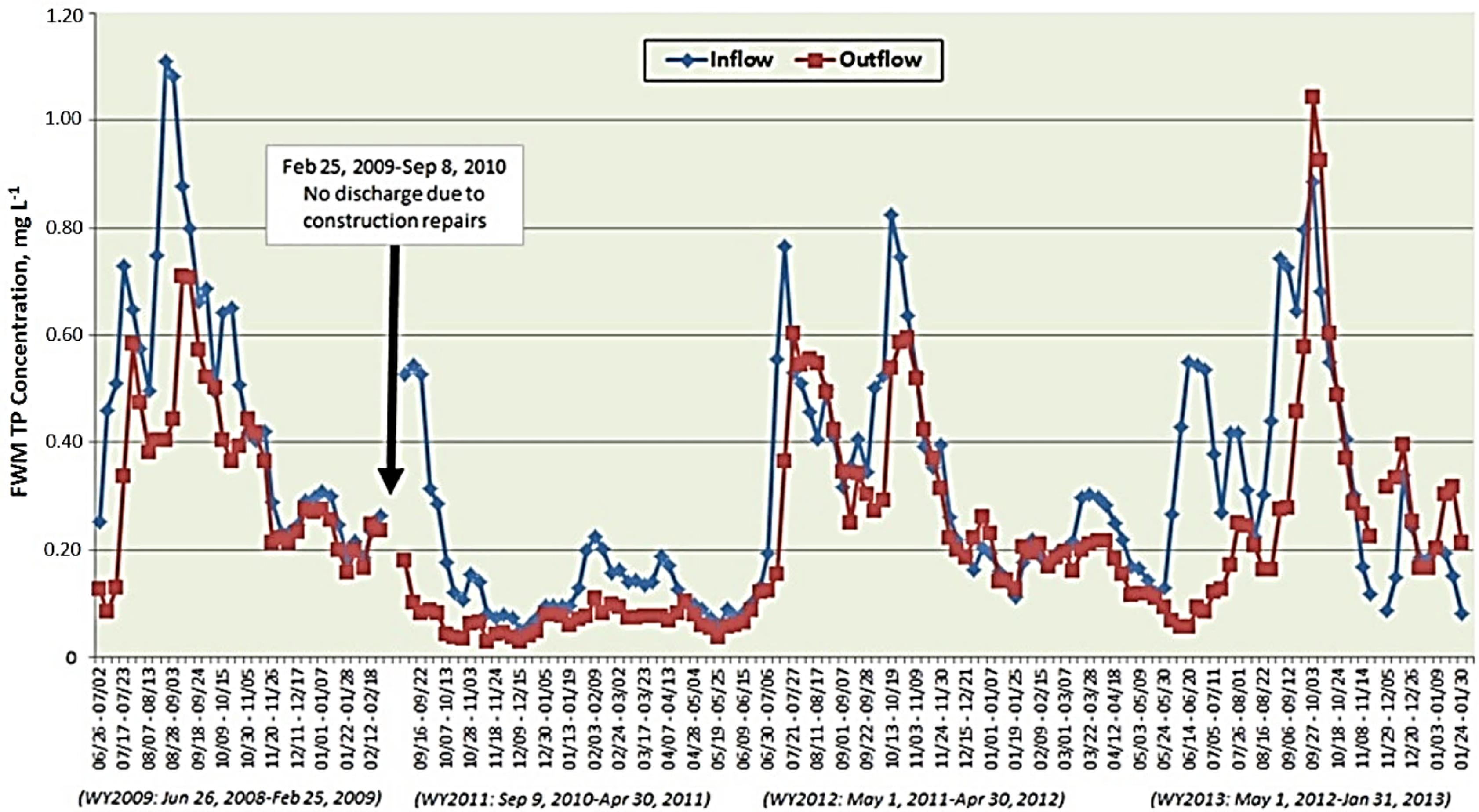

Figure 1. Weekly flow-weighted mean total phosphorus (TP) concentrations at the inflow (S390) and outflow (S392) of the Taylor Creek STA for the entire period of flow-through operation. The STA was offline during the last three months of WY2013.

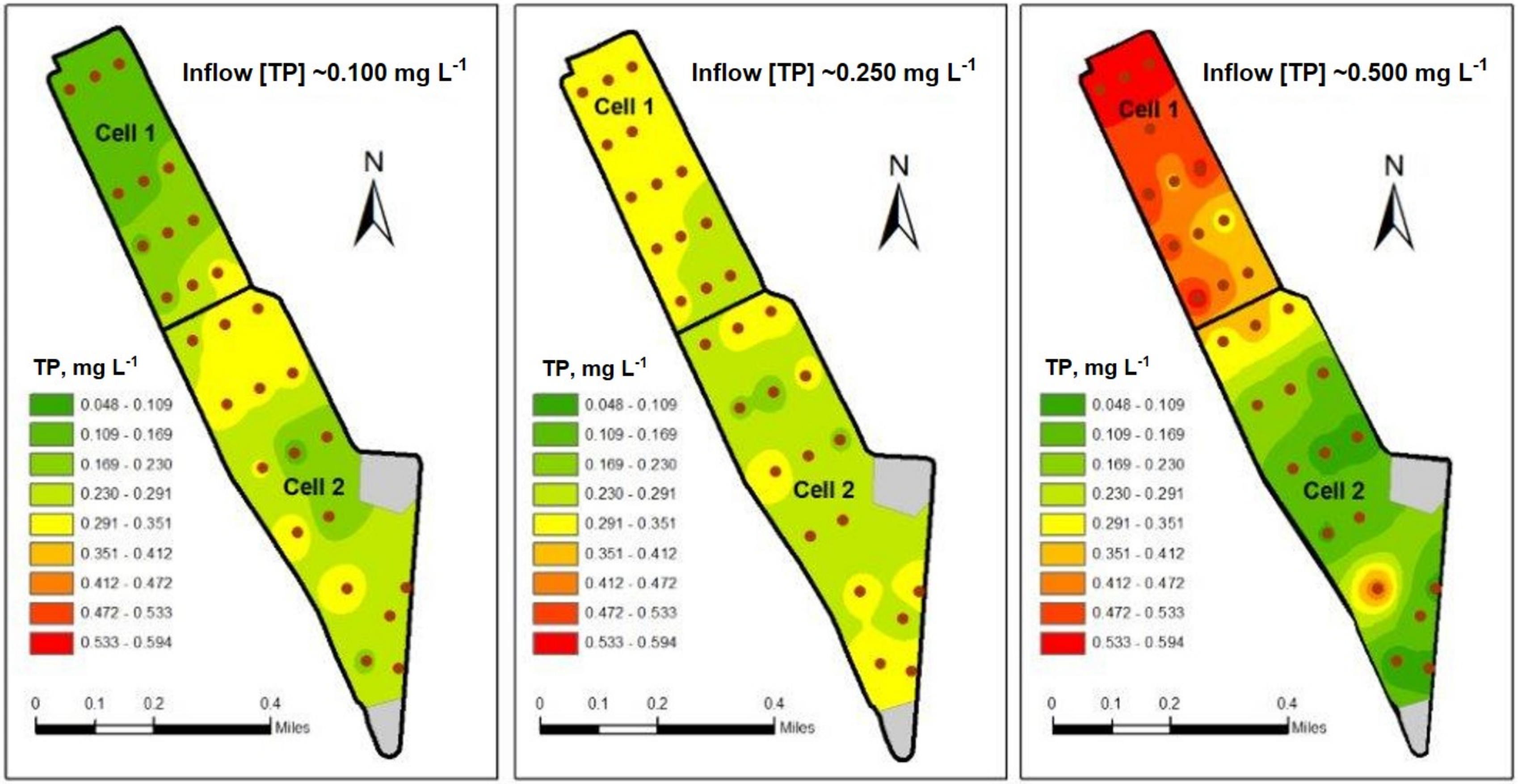

Figure 2. Spatial distribution of total phosphorus (TP) concentrations in the Taylor Creek STA on December 6, 2012, December 20, 2012 and September 17, 2010 at measured inflow TP concentrations of 0.101, 0.242 and 0.561 mg L^{-1}, respectively.

When inflow TP concentration was around 0.250 mg L^{-1}, water column P concentrations were uniform throughout the STA, which is an indication that the STA was in a state of "equilibrium" with respect to P conditions at which there was no measurable net flux of P from the sediment to the water column and vice versa (**Fig. 2, middle**). These observations suggest that there exists an Equilibrium Phosphorus Concentration in the water column (EPC_w) that would dictate whether adsorption or desorption occurs in the sediments. The EPC_w is the concentration of P in the water column at which no net flux, i.e., P release or retention, occurs between sediments and the overlying water column (**Fig. 3**) (Reddy et al., 2007). Thus, when the overlying water column P concentration is greater than the EPC_w, the underlying sediment will remove P (P sink). Conversely, P will flux from the sediment (P source) if the P concentration in the water column is below the EPC_w.

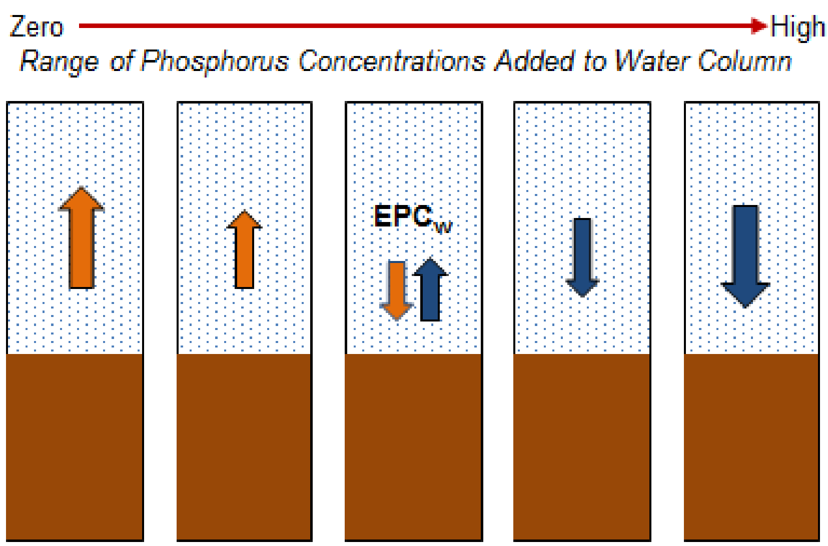

Figure 3. Equilibrium phosphorus (P) concentration in the water column (EPC_w). The upward arrow indicates net P release while the downward arrow signifies net P retention. The size of the arrow corresponds to the magnitude of P flux. The middle graphic shows an equilibrium condition where the rate of P release is balanced by the rate of P retention. (Adapted from Reddy, 2007).

1.1 Objectives

The objectives of this study were to: (1) determine the effect of increasing floodwater TP concentrations on P release/retention by soils; (2) estimate the EPC_w of the soils in the STA based on P-flux study results; (3) identify the soil variables that may exert influence on EPC_w; and (4) recommend potential management strategies to control P flux in the TC-STA.

2. MATERIALS AND METHODS

2.1 Soil/Sediment Sampling and Analysis

Intact sediment cores were collected in triplicate from ten stations along a transect that ran from the inflow to the outflow points of the STA. The transect consisted of four locations in Cell 1 (B2, C2, D2 and E2) and six sites in Cell 2 (A2, B2, C2, D2, E1 Old and F1) (**Fig. 4**). The cores were collected by driving a 10-cm diameter stainless steel corer into the soil to a depth of approximately 30 cm. The sediment cores were retrieved and carefully transferred intact into individual butyrate tubes (60-cm long), capped, and sealed at the bottom for transport to the laboratory (**Fig. 5**). Thirty intact cores (10 stations x 3 replicates) were collected on May 1, 2013.

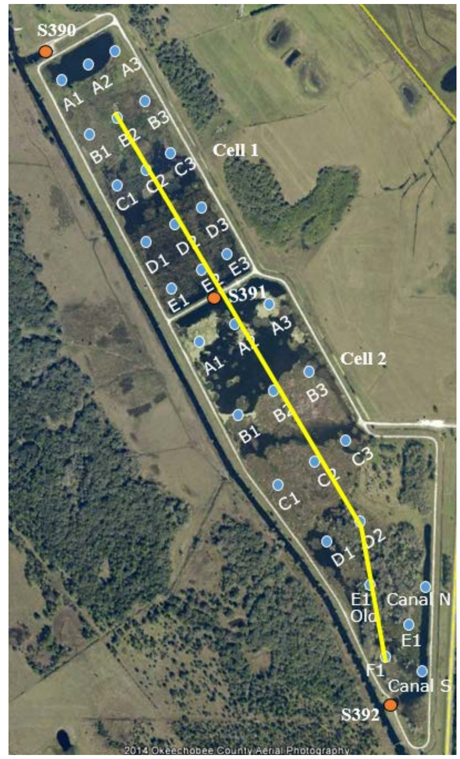

Figure 4. Map showing the sampling locations along the Taylor Creek STA flow path where sediment cores were taken.

Another set of ten sediment cores from the same locations were collected on the same day and divided into 0-10 and 10-30-cm sections, for basic soil characterization and P fractionation. The surficial (0-10 cm) soil samples were analyzed for pH, bulk density, moisture content, organic carbon, TP, nitrogen (N), sulfur (S) and carbon (C), extractable calcium (Ca), magnesium (Mg), iron (Fe) and aluminum (Al). Inorganic P in the same samples was separated into loosely bound P, Fe/Al-bound P and Ca-bound P fractions by sequential extractions with 1 M potassium chloride (KCl), 0.1 M sodium hydroxide (NaOH) and 0.5 M hydrochloric acid (HCl) following Reddy et al. (1998). Moderately labile organic P was estimated as the difference between P in the digested and undigested NaOH extract.

Figure 5. A photo of sediment collection in the field (photo by SFWMD).

The highly resistant P fraction in the soil residue after HCl extraction was estimated by subtracting the sum of all extracted P fractions from the TP content of the soils. All soil chemical and physical analyses were performed by the District's Chemistry Laboratory.

2.2 Laboratory Set-up and Incubations

The P flux study was conducted using the methodology outlined in Das et al. (2012), with minor modifications. Prior to initiation of the study, the STA water above the sediment in the core tubes was siphoned off and the core bottoms re-sealed/taped to ensure there were no leaks. The core tubes were secured in fabricated wooden racks that were mounted on top of black plastic tubs filled with tap water (**Fig. 6**). This helped regulate the temperature inside the cores that were partly submerged in the water-filled tubs. Floodwater exchanges consisting of six water-column P concentration spikes that ranged from 0.010 to 1.000 mg P L^{-1} were performed over six sequential 10-day incubation periods. Actual TP concentrations in the stock waters were 0.010, 0.047, 0.093, 0.245, 0.454 and 1.018 mg P L^{-1}. The different stock water P concentrations were prepared either by dilution of Taylor Creek site water with deionized water or by addition of 1000 mg L^{-1} standard stock solution of monopotassium phosphate (KH_2PO_4). The cores were initially flooded with 20 cm (~1450 mL) of Taylor Creek water diluted to 0.010 mg P L^{-1}. The water column in the cores was kept aerobic by bubbling air using an aquarium pump and tygon tubing inserted down into the water column. The cores were covered with black polyethylene bags to exclude light and prevent algal growth and incubated at an average room temperature of 21°C (**Fig. 7**). Thirty

Figure 6. The Taylor Creek STA sediment cores at the S5A laboratory before a sampling event. (photo by SFWMD).

Figure 7. The sediment cores at the S5A laboratory after a sampling event. (photo by SFWMD).

milliliters of floodwater were collected on days 0, 1, 2, 4, 7, and 10 during each incubation period, filtered and analyzed for soluble reactive phosphorus (SRP). An equal volume of floodwater was also collected on day 10 of each incubation period for TP analysis. The volume of floodwater removed on days 0, 1, 2, 4 and 7 was replenished with the same stock water while water lost through evaporation was replaced with deionized water. At the end of each 10-day incubation period, the remaining water in the cores was removed by applying gentle suction to minimize disturbance to the floc layer and the core tube was refilled with stock water containing the next higher P spike, e.g., the initial 0.010 mg P L^{-1} spike was replaced with the 0.047 mg P L^{-1} spike. These steps were repeated until the last floodwater exchange at the highest P spike of 1.018 mg P L^{-1} was completed. *In situ* measurements of pH, dissolved oxygen (DO), temperature and specific conductivity were made with a YSI field meter on days 1 and 10 of each incubation period.

2.3 P Flux Calculations

Phosphorus flux measurements were based on the changes in water column SRP concentrations over each 10-day incubation period, which is representative of the Taylor Creek STA's nominal hydraulic retention time. The amount of P retained by the soil or released to the water column at a given P spike concentration was calculated by taking the difference between water column P concentrations at time *t* and the preceding sampling event *t -1* and multiplying it by the volume of the overlying water column (V) divided by the inner cross-sectional area of the sediment core (A) (Pant and Reddy, 2003; Dunn et al., 2010):

$$P_r = \frac{(C_t - C_{t-1}) * V}{A}$$

where:

- P_r = net change in P mass per unit surface area of the sediment core, mg P m^{-2}
- C_t = water column P concentration at time t, mg L^{-1}
- C_{t-1} = water column P concentration at preceding sampling event, mg L^{-1}
- V = volume of overlying water column in the core, L
- A = cross-sectional area of the sediment core, m^2

To estimate the rate at which P was released into the water column or retained by the soil, the mass of P in the water column (expressed as mg P m^{-2} of core surface area) at a given P spike concentration was regressed against *t* (sampling day). The slope of the resulting line gives the P release or retention rate expressed as the linear change in P mass per unit surface area per unit time (i.e., mg P m^{-2} d^{-1}).

2.4 EPC_w Estimations

Using the results from the P-flux study, the EPC_w of the soils from the transect locations along the

STA's flow path was estimated by plotting cumulative mass of SRP released/retained from the six 10-day incubation periods (net P change between days 0 and 10) against initial floodwater TP concentration (Malecki et al., 2004). Graphically, the EPC_w is the point at which the regression line crosses the x-axis (**Fig. 8**). Computationally, the EPC_w values were estimated using a linear equation of the form: $y = mx + b$, where m is the slope of the straight line and b is the y-intercept. The equation was equated to zero and solved for the value of x, which is the EPC_w (Das et al., 2012; Reddy et al., 1999).

2.5 Experimental Conditions During Incubations

Water column temperatures across treatments during the six 10-day incubation periods averaged 20.7±0.5°C. The specific conductance of the overlying water column throughout the study was low with a mean of 197±33 μmhos cm^{-1}. Incubated cores from Cells 1 and 2 maintained mean water-column pH of 6.91 and 6.92, respectively. Mean pH was calculated from the negative logarithm of hydronium ion concentration. Similarly, average DO concentrations in Cells 1 and 2 water column were almost identical at 8.58 and 8.57 mg L^{-1}, respectively. Water columns were aerated to mimic aerobic conditions in the overlying water of a flowing STA.

3. STATISTICAL ANALYSIS

Data were analyzed statistically using JMP (v 11.2; SAS Institute Inc., Cary, NC). Initially, the raw data were tested for normality using the Shapiro-Wilk test. As virtually all data sets deviated significantly from normality, differences in measured soil parameters between treatment cells (Cell 1 vs Cell 2) were evaluated using the Wilcoxon/Kruskal-Wallis Rank Sum test, the non-parametric counterpart of one-way analysis of variance (ANOVA). Simple linear regressions were used to estimate P flux rates and EPC_w as described above. Correlative relationships between soil physicochemical properties and EPC_w values were explored using Spearman's rank correlation coefficient rho (ρ), a non-parametric measure of the strength of association between two variables. The significance of all statistics was evaluated at an alpha level (α) of 0.05.

4. RESULTS AND DISCUSSION

Phosphorus Flux Estimates

The estimated P retention (-) or release (+) rates as a function of increasing floodwater TP concentrations for the ten stations selected for this study are summarized in **Table 1**. Phosphorus flux varied widely between cells, between locations within each cell, and with initial floodwater TP concentrations. In general, P release was highest at the lowest initial TP concentration and gradually decreased with increasing floodwater TP concentrations. Overall, soils from Cell 1 locations released less P and/or retained more P at a given initial floodwater TP concentration. In contrast, soils from Cell 2 locations showed greater potential to release P at $C_o \leq 0.454$ mg L^{-1} and lower affinity for added P at $C_o \geq 0.454$ mg L^{-1}. The majority of Cell 2 soils did not start removing P from the water column until C_o was increased to 1.018 mg P L^{-1}. One location in particular, Cell 2-D2, released far more P than any other locations at the lowest floodwater TP concentration. Statistically, the P-flux rates between the two cells were significantly different only at initial floodwater TP concentrations of 0.245 and 0.454 mg P L^{-1} (**Table 1**). Phosphorus release rates averaged over all stations decreased from 4.92 mg m^{-2} d^{-1} at C_o = 0.010 mg P m^{-2} d^{-1} to 1.23 mg P m^{-2} d^{-1} at C_o = 0.245 mg P L^{-1}. At higher initial TP concentrations of 0.454 and 1.018 mg L^{-1}, the soils removed added P from the water column at overall mean rates of -1.22 and -6.20 mg P m^{-2} d^{-1}, respectively (**Table 1**). There was a highly significant negative correlation between P release/retention and initial floodwater TP concentrations based on Spearman's correlation coefficient (ρ = -1.000, $p<0.0001$). Correlation was performed using average values for each site.

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Table 1. Effect of increasing initial floodwater phosphorus concentrations (C_0) on P release (+)/retention (-) rates of soils from the Taylor Creek STA. Values are the arithmetic average of three replicates.

Station	P Release/Retention Rate, mg P m^{-2} d^{-1}					
	C_0=0.010 mg P L^{-1}	*C_0=0.047 mg P L^{-1}*	*C_0=0.093 mg P L^{-1}*	*C_0=0.245 mg P L^{-1}*	*C_0=0.454 mg P L^{-1}*	*C_0=1.018 mg P L^{-1}*
Cell 1, B2	5.19	6.05	1.06	-2.98	-5.71	-7.75
Cell 1, C2	0.60	1.03	0.30	-2.04	-5.70	-12.61
Cell 1, D2	3.52	5.42	-0.14	-2.74	-5.37	-8.60
Cell 1, E2	4.06	0.28	1.49	-1.25	-2.73	-6.83
Cell 2, A2	6.09	4.00	0.91	0.29	-5.50	-11.38
Cell 2, B2	2.29	3.29	3.33	5.97	4.44	0.09
Cell 2, C2	1.52	3.23	5.42	2.62	1.57	-0.02
Cell 2, D2	17.93	6.02	4.62	2.35	2.04	-2.27
Cell 2, E1 Old	3.76	6.76	1.12	3.03	-1.25	-7.26
Cell 2, F1	4.22	6.14	5.18	7.04	6.05	-5.39
Mean, Cell 1	3.34	3.19	0.68	-2.25	-4.88	-8.95
Mean, Cell 2	5.97	4.91	3.43	3.55	1.22	-4.37
Overall Mean	4.92	4.22	2.33	1.23	-1.22	-6.20
p- value[a]	0.594	0.337	0.070	*0.014*	*0.042*	0.109

[a] Probability level computed using Wilcoxon Rank Sum Test at 5% level of significance. When p-value is < 0.05, there is a significant difference in P-flux rates between treatment cells.

The difference in mean P-flux rates between Cells 1 and 2 can be explained in terms of the total and labile P concentrations in the top 10 cm of the soils from these locations (**Table 2**). Total P concentrations at the four locations in Cell 1 averaged 605 mg kg^{-1} compared to almost 1,300 mg kg^{-1} for the six locations in Cell 2. Similarly, mean labile P concentration in Cell 2 was two-fold higher than labile P concentration in Cell 1 at 11.10 mg kg^{-1}. Cell 2-D2, the site where P release was highest at the lowest initial P concentration, had total and labile P concentrations of 2,180 and 27.6 mg kg^{-1}, respectively, the highest for all locations within both cells of the STA (**Table 2**). Historically, soil P concentrations were higher in Cell 2 than in Cell 1 of the STA. The 2005 baseline soil study indicated that the highest TP concentrations in the top 10 cm of the soil were in the southern portion of the STA, although 80 percent of TP was in stable and relatively unavailable forms (**Fig. 6, top)** (Reddy et al., 2007). Soil TP concentrations obtained in 2013 showed similar spatial distribution across the STA, except that concentrations were much higher, especially in locations near or within the cypress dome (**Fig. 6, bottom**). Because STAs provide an abundant habitat for birds and other wildlife, it is possible that these animals could be an important biotic source of nutrient enrichment in the STA. Cattle egrets and other bird species that use cabbage palm trees and some smaller understory vegetation in the cypress dome as roosting and nesting sites seasonally or year round can have localized effects on P concentrations in water and sediments, particularly if droppings are deposited on these trees and later flushed into the system during rainfall events (**Fig. 7**). Andersen et al. (2003) investigated the effects of bird use on nutrient removal in a 9.9 ha constructed wastewater-treatment wetland in southern California. The estimate of maximum daily P input by birds was 12.4 mg P m^{-2} d^{-1}, which represented only 7.0 percent of the mean daily P load in inflow water from the wastewater treatment plant. While the authors concluded that bird use did not contribute to significant reductions in the performance of the treatment wetland, it is important to determine whether this holds true for Taylor Creek STA, given its small size and the close proximity of the cypress dome to the outfall structure. Nesting season also coincides with the dry season when initial floodwater P concentrations would typically be at their lowest.

Table 2. Summary statistics and cell comparisons of the forms of phosphorus and other physicochemical parameters in the surface soil layer (0-10 cm) collected at transect locations in Cells 1 and 2 of the Taylor Creek STA.

Station	pH	Bulk Den g cm^{-3}	Tot-C %	Org C %	Tot-N %	Tot-S %	Ext-Mg mg kg^{-1}	Ext-Ca mg kg^{-1}	Ext-Fe mg kg^{-1}	Ext-Al mg kg^{-1}	Total P mg kg^{-1}	Labile P mg kg^{-1}	Fe/Al P mg kg^{-1}	Ca/Mg P mg kg^{-1}	Org P mg kg^{-1}	Res P mg kg^{-1}
C1-B2	6.85	0.34	9.03	8.93	0.82	0.50	1029	5770	3488	6446	515	9.75	104.5	24.9	226	149.9
C1-C2	6.88	0.12	27.10	27.00	1.99	1.08	1699	13972	4431	6936	1020	8.15	84.7	59.4	305.1	562.7
C1-D2	6.94	0.26	8.05	7.77	0.74	0.51	872	5667	2710	5000	526	3.36	65.5	20	160	277.1
C1-E2	6.95	0.40	6.96	6.88	0.66	0.40	863	6457	2662	5752	360	2.23	38.5	14.4	119.2	185.7
C2-A2	7.33	1.12	2.57	2.09	0.29	0.20	669	3035	2369	5196	127	0.12	19.4	6.6	37.9	62.9
C2-B2	7.08	0.03	30.10	29.40	2.79	1.39	2305	19306	8578	12445	2068	13.7	86.7	335.6	568.9	1063.1
C2-C2	6.84	0.53	9.21	8.90	0.70	0.37	1053	7879	2753	7382	851	11.46	140.3	107.9	339.1	252.2
C2-D2	6.55	0.07	42.30	42.00	3.72	1.79	2556	19681	5169	5670	2180	27.63	87.5	176.4	615.4	1273.1
C2-E1 Old	6.90	0.04	32.00	31.20	2.81	1.43	2507	17498	6049	9680	1720	10.30	76.6	193.3	565.6	874.2
C2-F1	6.81	0.30	16.00	16.20	1.09	0.49	1505	11511	3581	14378	853	3.37	98.9	25.7	346.7	378.3
C1, Mean	6.90	0.28	12.78	12.64	1.05	0.62	1116	7967	3323	6034	605	5.87	73.3	29.7	202.6	293.8
C1, Std Dev	0.05	0.12	9.58	9.61	0.63	0.31	396	4019	830	843	287	3.64	28.1	20.3	81.3	187.1
C2, Mean	6.92	0.35	22.03	21.63	1.90	0.95	1766	13152	4750	9125	1300	11.10	84.9	140.9	412.3	650.6
C2, Std Dev	0.26	0.42	15.19	15.10	1.39	0.67	805	6815	2347	3724	815	9.60	39.1	121.9	218.7	487.0
p-value[a]	0.749	0.749	0.241	0.337	0.455	0.915	0.241	0.241	0.337	0.241	0.241	0.241	0.594	0.166	0.110	0.337

[a]Probability level computed using the Wilcoxon Rank Sum Test at 5% level of significance. When p-value is < 0.05, parameter concentrations between treatment cells are significantly different.

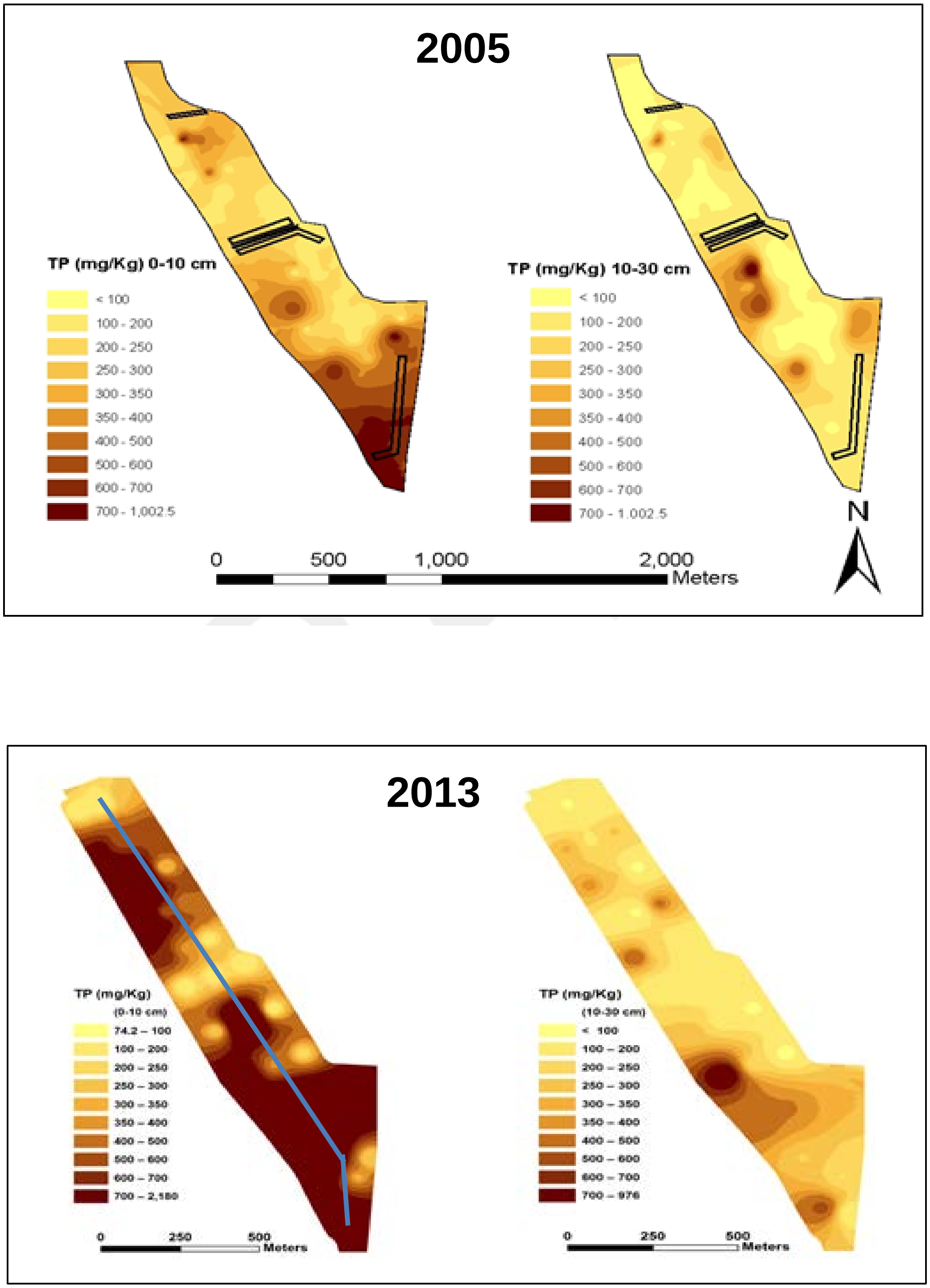

Figure 8. Spatial distribution of total phosphorus (TP) concentrations in the 0-10 and 10-30 cm soil layers within the Taylor Creek STA in 2005 (top) and 2013 (bottom). The blue line shows the approximate transect location used in the P-flux study.

Figure 9. Cattle egrets roosting on cabbage palm trees and other understory plants in the cypress dome located at the southern portion of the Taylor Creek STA, July 2013 (photo by SFWMD).

Estimated Equilibrium P Concentration in the Water Column (EPC_w)

The EPC_w values varied considerably between cells and among different locations within each cell, more so in Cell 2 than in Cell 1. Overall, EPC_w was significantly higher in Cell 2 than in Cell 1 (Wilcoxon Rank Sum Test, $p = 0.037$). Estimated EPC_w values for Cell 1 stations ranged from 0.069 to 0.251 mg P L^{-1} (**Fig. 8a**). By comparison, EPC_w values for Cell 2 stations were higher, ranging from 0.245 to 0.924 mg P L^{-1} with a mean value of 0.595 mg P L^{-1} for five of the six stations in Cell 2 (**Fig. 8b**). EPC_w for station Cell 2-B2 was not calculated due to an uninterpretable linear fit to the data. Consistent with the P-flux results, station Cell 2-D2 had the highest EPC_w at 0.924 mg P L^{-1}. As alluded to earlier, TP and labile P concentrations were highest at this station, which could be an important source of internal P loading to the water column (**Table 2**). The higher EPC_w values for Cell 2 stations were supported by high concentrations of labile P. Richardson and

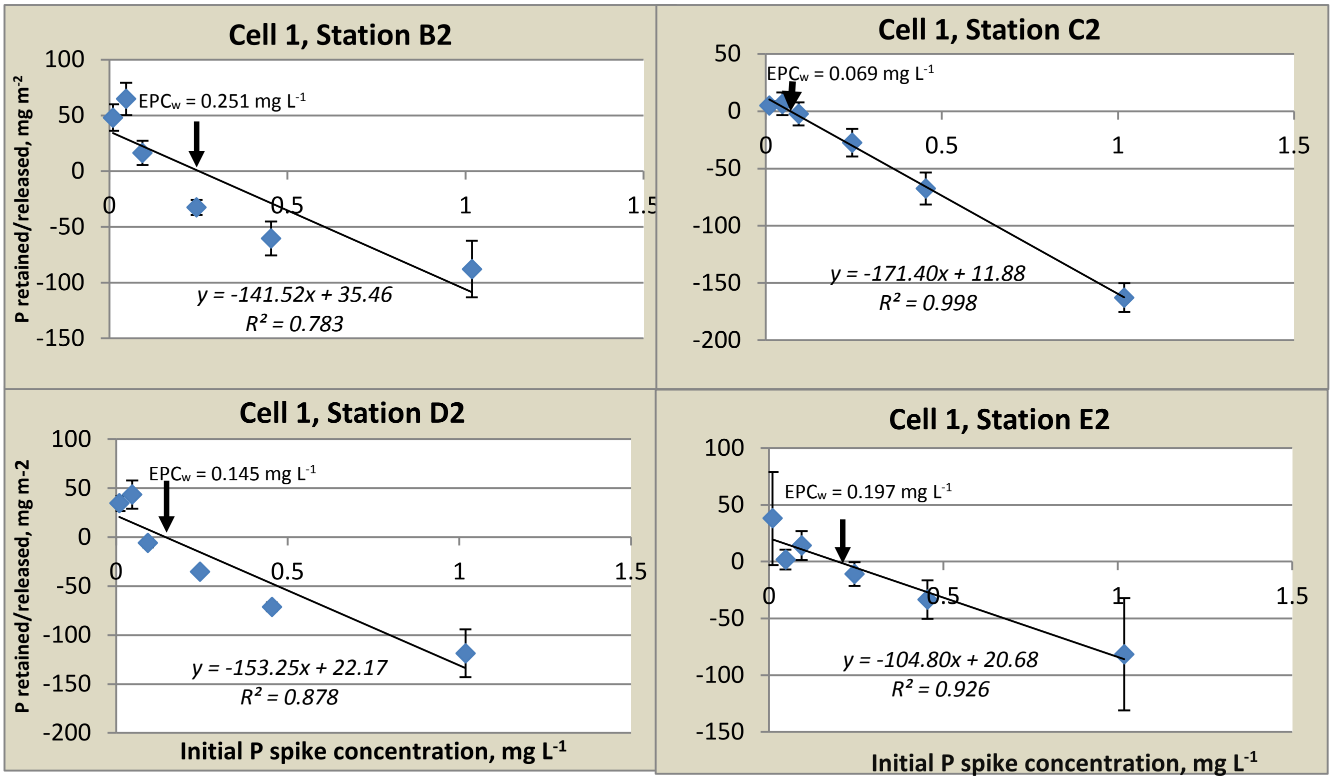

Figure 10a. Equilibrium phosphorus concentrations (EPC_w) estimated for Taylor Creek STA Cell 1 transect locations. Values are the average of three replicates. Error bars are one standard error of the mean. Black arrows identify EPC_w values.

Vaithayanathan (1995) reported a linear increase in EPC values from un-enriched to enriched sites in WCA-2A. EPC values for the enriched soils were an order of magnitude higher than for un-enriched soils. The EPC_w values obtained from this study are within the range of EPC_w values reported for stream sediments in Lower Kissimmee River Basin (EPC_w = 0.13 mg P L^{-1}) and for the nutrient impacted wetland soils in Fisheating Creek and Lake Istokpoga Basins (1.95 and 3.90 mg P L^{-1}, respectively) (Reddy et al., 1995). These values indicate that when overlying floodwater TP concentrations are above EPC_w, underlying soils and sediments can act as a sink for P. Conversely, soils will release P when floodwater TP concentrations are lower than the EPC_w.

While EPC_w values provide useful information regarding the potential ability of the soils/sediments in the STA to either retain or release P as a function of floodwater TP concentrations, they should be regarded as experimental, for they were derived from abiotic laboratory experiments, in which plants were absent. These estimates only take into consideration diffusive flux across the sediment-water interface and no other factors such as biotic uptake and release, bioturbation and resuspension. Therefore, caution must be exercised when extrapolating laboratory results to full-scale field conditions.

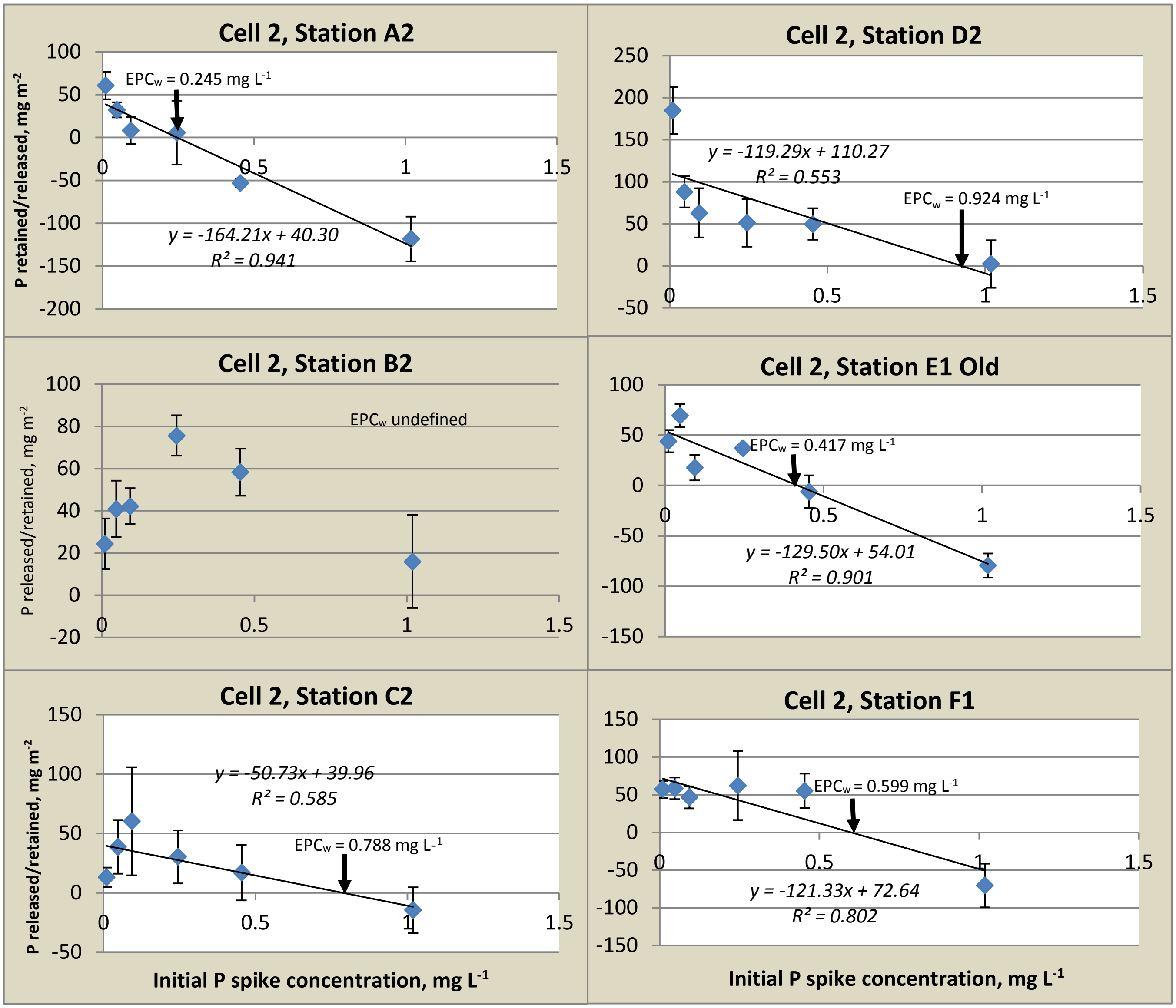

Figure 10b. Equilibrium phosphorus concentrations (EPC_w) estimated for Taylor Creek STA Cell 2 transect locations. Values are the average of three replicates. Error bars are one standard error of the mean. Black arrows identify EPC_w values.

Correlation of EPC_w with Soil Physicochemical Parameters and P Forms

Phosphorus flux from soils to the overlying water column depends on various factors including physicochemical properties and concentration of P in the overlying water column (Pant and Reddy, 2003). The top 10 cm of the soil from both cells exhibited high variability with respect to selected physicochemical properties and different P pools as evidenced by large standard deviations (**Table 2**). Soils from both cells are highly flocculent and organic, with a mean bulk density of 0.32 g cm^{-3}. The soils were circumneutral, with mean pH values of 6.90 and 6.92 for Cells 1 and 2, respectively. Concentrations of total C, total N, total S and total P were generally higher in Cell 2 than in Cell 1. The same trend was observed for acid extractable Ca, Mg, Fe and Al. The relative sizes of the different P pools in the cells reflected the total P content of the soils. Cell 2 had a mean TP of 1300 mg kg^{-1} compared to 605 mg kg^{-1} for Cell 1 (**Table 2**). Hence, the amounts of the different soil P fractions were greater in Cell 2 than in Cell 1. Residual P, which consists of highly resistant organic P forms that are biologically unavailable, was the dominant P fraction in both cells, followed by moderately labile organic P. Labile P, the pool of inorganic P that is important in controlling P concentration in the water column accounted for less than 1 percent of TP in both soils. Although the differences in parameter concentrations between two cells appear substantial, no statistically significant differences were detected, likely the result of having a small number of observations (**Table 2**).

To identify the soil variables that exert influence on the estimated EPC_w values of the soils in the Taylor Creek STA, a non-parametric measure of statistical significance between two variables called Spearman's rank correlation coefficient, *rho (ρ)* was used. EPC_w was negatively correlated with soil pH (ρ = -0.717, $p < 0.05$) and positively correlated with labile P (ρ = 0.683, $p < 0.05$) and moderately labile organic P (ρ = 0.700, $p < 0.05$) (**Table 3**). The significant correlation with labile P confirms an earlier claim that high labile inorganic P concentration in the Taylor Creek STA soils supported the higher EPC_w values. The positive correlation with moderately labile organic P suggests that this P pool could provide a steady source of labile P in the soil that could help maintain high EPC_w in the water column. Organic P is known to be an important source of potentially available P (Ahlgren et al., 2007). The degradation and mineralization of organic P could regulate primary production and affect the availability of dissolved P in aquatic systems (Fisher and Reddy, 2010). It should be noted that this correlation and regression analysis was based on a relatively small sample size hence; caution must be exercised when interpreting the results.

Table 3. Correlation of EPC_w with selected soil parameters at transect locations in Cells 1 and 2 the STA (n=9).

Soil Variable	Spearman's rho	PROB>[p]
pH	-0.7167*	0.0298
Bulk density	-0.0667	0.8647
Total P	0.4333	0.2400
Total N	0.3333	0.3807
Total C	0.4833	0.1875
Total S	0.0833	0.8312
Organic Carbon	0.4333	0.2440
Extractable Ca	0.4667	0.2054
Extractable Mg	0.4833	0.1875
Extractable Fe	0.3833	0.3085
Extractable Al	0.3667	0.3317
Labile P	0.6833*	0.0424
Fe/Al-P	0.5833	0.0992
Ca/Mg-P	0.5667	0.1116
Organic P	0.7000*	0.0358
Residual P	0.3000	0.4328

* Significant at $p<0.05$.

5. SUMMARY AND CONCLUSIONS

The rates at which P was retained by the soils or released to the water column varied widely between cells, locations within each cell and floodwater TP concentrations. Overall, soils from Cell 1 locations released less P and/or retained more P at a given floodwater TP concentration. In contrast, soils from Cell 2 locations showed greater potential to release P and lower retention of added P in the water column. Mean P flux rates for Cell 1 soils ranged from 3.34 mg P $m^{-2}d^{-1}$ at C_o = 0.010 mg P L^{-1} to -8.95 mg P m^{-2} d^{-1} at C_o = 1.018 mg P L^{-1}. In comparison, P flux rates for Cell 2 soils ranged from 5.97 to -4.37 mg P m^{-2} d^{-1}. The difference in mean P flux rates between Cells 1 and 2 was attributed to difference in concentrations of moderately labile organic P and labile inorganic P, which were both higher in Cell 2 soils.

Consistent with the P flux results, the estimated EPC_w varied considerably between cells. The mean EPC_w value for Cell 1 soils was 0.165 mg P L^{-1} compared to 0.595 mg P L^{-1} for Cell 2 soils. This indicates that soils in Cell 1 are likely to act as a sink for P while soils in Cell 2 could be a source of internal P load to the STA depending on the TP concentration of the runoff water entering the STA. EPC_w values were significantly linearly related to both labile inorganic P and moderately labile organic P concentrations, indicating that these P forms are likely to exert significant influence on P release and equilibrium dynamics of soils/sediments within the Taylor Creek STA.

6. RECOMMENDATIONS

The strong positive correlation between EPC_w and labile P indicates the importance of this P pool in controlling the release of P from the soils/sediments to the overlying water column. The soil in Cell 2, which is more P-enriched than the soil in Cell 1 has less capacity to act as a sink for P. Therefore, the key to regulating soluble P concentrations in the STA, particularly in Cell 2 and prevent release of P to the downstream waters would be to effect a change in the equilibrium P concentration between P in the water column and soil porewater (EPC_w) and/or between P in the solid and soil solution phases (EPC_o). Following is a list of management actions that the District could potentially implement to effectively control P flux in the STA and help increase its P treatment efficiency in the long-run.

- **Add chemical amendments to sequester soluble P in the water column and suppress further release of P from the sediment into the water column**. The most common soil amendments that have been tested include various salts of aluminum, iron and calcium. Alum application improved water quality in a municipal wastewater treatment wetland in Orlando, Florida. Alum was most effective at binding SRP, with 40 percent more removal compared to the controls (Malecki-Brown et al., 2009) but had negative impacts on the rate of microbial activity and structure of the microbial community in a municipal wastewater treatment wetland (Malecki et al., 2007). St. John's River Water Management District has successfully demonstrated the effectiveness of surface applied alum residuals in controlling P flux in a short-term pilot study within the Lake Apopka restoration area. However, calcium-based amendments such as gypsum and lime were not quite as effective as alum residuals (Hoge et al., 2003). The District has also tested several P-binding products (e.g., Phoslock®) under the New Alternative Technology Assessment (NATA) program with varying levels of success (Chimney et al., 2013).

- **Modify existing vegetation coverage.** Currently, emergent vegetation in the TC-STA covers about 80 percent of Cell 1 and only 55 percent of Cell 2. Additional plantings of macrophytes, such as cattail and alligator flag in Cell 2 especially, should help to establish a reliable and sustainable treatment system with maximum phosphorus uptake capability.

- **Mechanically remove the newly accreted sediment layer, the major storage of P in the STA**. The removal of the accrued sediment layer in the Everglades Stormwater Treatment Area STA-1W Cell 1B reduced sediment TP concentration from 1,300 to < 400 mg kg^{-1} (SFWMD, 2007). The physical removal of the accreted organic soil in combination with alum treatments significantly reduced P flux from organic soils in a municipal wastewater treatment wetland in Orlando, Florida (Lindstrom and White, 2011).

- **Flip over the accrued sediment layer to reduce flux from enriched sediments to the overlying water column.** Soil inversion on a 40-acre parcel southwest of Indian Prairie

Canal in the northwest littoral zone of Lake Okeechobee, using two established tilling techniques (Baker and moldboard plows), was shown to be effective at burying surficial P-enriched sediments and reducing internal P loading (Water and Soil Solutions, LLC, 2009). Laboratory incubations of undisturbed and tilled soils showed P release from the plowed/inverted soils to be several orders of magnitude lower than P release from undisturbed soils. While small-scale demonstration of soil inversion has shown potential for reducing internal P loading, this management technique requires the STA or individual STA cells to be taken offline for varying periods. Once such a system has been serviced, the question is how much additional time would be needed to restore pre-maintenance conditions and achieve stable effluent quality.

- **<u>Clear out the palms and understory vegetation to eliminate a lot of the roosting in the STA, thus, eliminating a potential source of P for the STA.</u>** The flocks of birds that use cabbage palm trees and other understory plants, in the cypress dome at the southern portion of the STA, as roosting or nesting sites, could be adding P to the soil and water column. Although large flocks of birds may influence the ability of treatment wetlands to achieve ultra-low concentrations, they would not likely affect treatment at the secondary or primary level (Kadlec and Wallace, 2009). The District is currently collecting data to estimate population sizes of foraging wading birds and waterfowl in the STAs (although not specifically for roosting or nesting birds). Once good population estimates are obtained, the published data on excretion rates, P content of excreta, etc. can be used to estimate their effects on P-cycling (Mark Cook, personal communication, January 20, 2016).

- **<u>Increase the hydraulic retention time within the STA by reducing hydraulic loading.</u>** Performance data over the last two water years have shown net reductions in both TP concentrations and loads during periods of high flows. However, during low flow conditions that usually commence in mid-October, TC-STA has demonstrated inconsistent performance that lasted through the end of the dry season. As reversals in TP concentrations have become a common occurrence during periods of decreasing flow and TP concentrations, as an initial response, the District can increase the hydraulic retention time by reducing hydraulic loading to give various biotic and abiotic P removal mechanisms within the STA sufficient time to operate.

- **<u>Suspend flow-through operation if reversals persist for weeks, until Taylor Creek flows and P concentrations increase following wetter conditions and increased basin runoff.</u>**

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