

Appendix 5C-2: Investigation of Stormwater Treatment Area 3/4 Periphyton- based Stormwater Treatment Area Performance, Design, and Operational Factors

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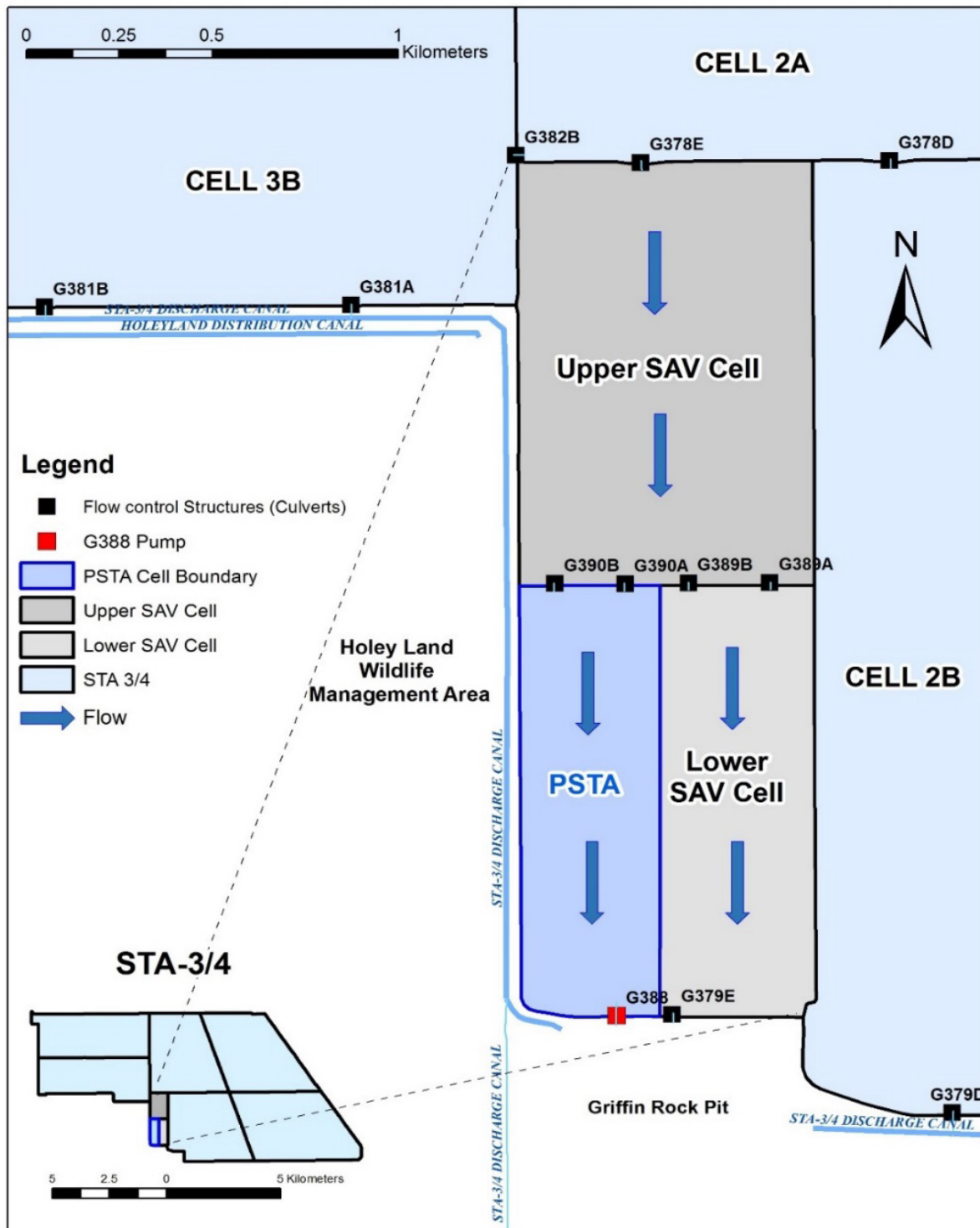
INTRODUCTION

The Everglades Stormwater Treatment Areas (STAs) regularly achieve low outflow total phosphorus (TP) concentrations. However, with the exception of STA-3/4, which achieved 11 micrograms per liter ($\mu\text{g/L}$) in WY2017, these concentrations are regularly above the current water quality based effluent limits for the STAs. As a result, the South Florida Water Management District (SFWMD or District) continues to research ways to further improve phosphorus (P) reduction such as periphyton-based stormwater treatment technology. Periphyton-based stormwater treatment areas (PSTAs) are constructed wetlands primarily dominated by periphyton, submerged aquatic vegetation (SAV), and sparse emergent aquatic vegetation (EAV) capable of attaining outflow TP levels near $10 \mu\text{g/L}$ (Kadlec and Wallace 2009). PSTAs are the final polishing step in the treatment process such that they are not intended to receive the higher P concentrations that enter the upstream EAV and SAV cells.

In 2005, SFWMD constructed a field-scale PSTA to address uncertainties associated with large-scale implementation of the PSTA treatment technology. The PSTA project is located within STA-3/4, on a 161-hectare (ha) site composed of the 81-ha Upper SAV Cell, the 40-ha Lower SAV (LSAV) Cell, and the 40-ha PSTA Cell (**Figure 1**). An important difference between the PSTA Cell and adjacent STA treatment cells is that most of the soil from the PSTA Cell was removed down to the underlying caprock to reduce a potential source of P to the water column and discourage emergent macrophyte growth. As a result, the floor of the PSTA Cell is approximately 0.3 meters (m) lower than the ground elevation of the adjacent treatment cells.

The STA-3/4 PSTA Cell has shown promising treatment performance by consistently discharging water with very low TP concentrations. During the past ten water years of operation, which were Water Year 2008 (WY2008; (May 1, 2007, to April 30, 2008) to WY2017, the PSTA Cell's outflow flow-weighted mean (FWM) TP concentrations ranged from 8 to $13 \mu\text{g/L}$, making it one of the best performing treatment cells in the STAs.

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In 2013, SFWMD identified several key studies to be included in the Restoration Strategies *Science Plan for the Everglades Stormwater Treatment Areas* (Science Plan; SFWMD 2013). One of these studies was the Investigation of STA-3/4 PSTA Performance Design and Operational Factors (PSTA Study). The purpose of the PSTA Study was to assess the chemical and biological characteristics as well as the design and operational factors of the PSTA Cell in STA-3/4 that contribute to the superior treatment performance of this technology (Chimney 2015). The operational ranges under which the PSTA Cell achieved ultra-low outflow TP levels and the management practices required to sustain this superior performance were evaluated. Current and historical performance of the PSTA Cell is summarized below. In addition, several PSTA Study tasks and findings are described and presented.

ANNUAL PERFORMANCE

Hongying Zhao

To assess the PSTA Cell's treatment performance, data from WY2008 to WY2017 were used to calculate the cell's annual hydraulic loading rate (HLR), P loading rate (PLR), hydraulic residence time (HRT), and TP settling rate (k) (**Table 1**). As in previous annual reports, these calculations accounted for the duration of the PSTA Cell's operational period. The operational period was defined as the span of time over which one or both PSTA Cell's inflow structures (G-390A and G-390B) were open. Days when both gates were closed due to protective measures for nesting birds, structure maintenance, or to preserve water during droughts were excluded from the operational period.

Table 1. Summary of annual hydraulic and treatment performance parameters in the STA-3/4 PSTA Cell during each operational period from WY2008 to WY2017. ^a

Water Year	HLR (cm/d)	HRT (d)	Q _{in} ^b (ha-m)	Q _{out} ^c (ha-m)	FWM TP _{in} (µg/L)	FWM TP _{out} (µg/L)	PLR (g/m ² /yr)	k (m/yr)	Operational Periods	Operational Period (d)
WY2008	5.5	5.8	360	642	27	12	0.24	14.2	July 5, 2007–December 12, 2007	161
WY2009	6	5.9	408	753	14	8	0.14	13.8	July 9, 2008–December 23, 2008	168
WY2010	6.2	6.2	866	1,243	20	10	0.42	27.4	May 25, 2009–April 30, 2010	341
WY2011	6.1	6.7	394	485	18	11	0.17	7.3	May 1, 2010–December 7, 2010	159
WY2012	8.6	4.4	919	1,185	17	12	0.39	12.5	July 19, 2011–April 5, 2012	262
WY2013	7.7	5.1	1,150	1,377	16	11	0.45	17.8	May 1, 2012–April 30, 2013	365
WY2014	3.3	16.7	497	468	24	13	0.29	10	May 1, 2013–April 30, 2014	365
WY2015	5.8	9.4	862	911	15	11	0.33	11.9	May 1, 2014–April 30, 2015	365
WY2016	6.9	7.3	1,023	1,285	11	9	0.27	11.6	May 1, 2015–April 30, 2016	366
WY2017	5.6	12.9	827	659	10	8	0.2	6.7	May 1, 2016–April 30, 2017	365

a. Key to units: µg/L – micrograms per liter; cm/d – centimeters per day; d – days; g/m²/yr – grams per square meter per year; ha-m – hectare-meters; and m/yr – meters per year.

b. Q_{in} – average daily surface water inflow rate during the operational period.

c. Q_{out} – average daily surface water outflow rate during the operational period.

WY2017's performance summary accounted for differences in the operational period when calculating HLR, PLR, HRT, and k for the PSTA Cell. The equations used for these calculations are as follows:

$$HLR = \frac{Q_{in}}{A} \times 100 \text{ centimeters per meter } \left[\frac{\text{cm}}{\text{m}} \right] \quad (1)$$

$$PLR = \frac{\left[\left(C_{in} \times \frac{10^3 \text{ l}}{\text{m}^3} \times \frac{\text{g}}{10^6 \text{ ug}} \right) \times (V_{load}) \right]}{A} \quad (2)$$

$$HRT = \frac{V}{(Q_{in} + Q_{out})/2} \quad (3)$$

$$k = \frac{\frac{(V_{in} + V_{out}) \times N}{2}}{A} \times \left(\left(\frac{C_{in} - C^*}{C_{out} - C^*} \right)^{\frac{1}{N}} - 1 \right) \quad (4)$$

where

HLR = the surface water hydraulic loading rate (centimeters per day [cm/d])

PLR = the TP loading rate (grams per square meter per year [g/m²/yr])

HRT = the nominal hydraulic residence time (day)

k = the TP settling rate (i.e., removal coefficient) (meters per year [m/yr])

V = the PSTA Cell's average storage volume during the operational period (cubic meters [m³])

V_{in} = the total surface water inflow volume (cubic meter per year [m³/yr])

V_{out} = the total surface water outflow volume (m³/yr)

V_{load} = the total surface water inflow water volume during operational period in a water year (m³/yr)

Q_{in} = the average daily surface water inflow rate during the operational period (cubic meters per day [m³/d])

Q_{out} = the average daily surface water outflow rate during the operational period (m³/d)

A = the PSTA Cell effective treatment area (square meter [m²])

N = the number of continuously stirred tanks-in-series (= 6)

C^* = the background TP concentration (= 4 µg/L) (background concentration in STA design)

C_{in} = the surface water inflow FWM TP concentration during the operational period (µg/L)

C_{out} = the surface water outflow FWM TP concentration during the operational period (µg/L)

In summary, for WY2017, the PSTA Cell produced an annual outflow FWM TP concentration of 8 µg/L with an inflow TP FWM concentration of 10 µg/L. Both concentrations were the lowest for the 10-year operational period from WY2008 to WY2017. For WY2017, the HLR and PLR of 5.6 cm/d and 0.20 g/m²/yr were within the same range as previous water years. Due to the low HLR and inflow FWM TP concentration, the settling rate k was the lowest in the 10-year operational period.

WATER AND TP BUDGET ANALYSES

Hongying Zhao, Tracey Piccone, and Manuel F. Zamorano

INTRODUCTION

The objective of this task was to evaluate the PSTA Cell's performance through water and TP budget analyses (Zhao et al. 2015). This effort incorporated improvements to structure flow estimates, seepage water quality and quantity estimates, updated annual water budgets and TP mass balances, and estimated annual and long-term average annual TP settling rates (TP removal), as well as sensitivity analyses.

METHODS

The water and TP budgets were developed for the period of May 1, 2007, to April 30, 2014. Flow, stage, rainfall, evapotranspiration (ET), and seepage estimates were used to conduct the water budget analyses. The District's Water Budget Tool and Nutrient Load Program were used for this analysis.

RESULTS AND DISCUSSION

From WY2008 to WY2014, the total inflow volume to the PSTA Cell was 6,522 hectare-meters (ha-m). Of this total, 4,605 ha-m (71%) was through inflow structures G-390A and G-390B; 377 ha-m (6%) was rainfall; and 1,681 ha-m (24%) was seepage inflow. The total outflow volume from the PSTA Cell was 6,642 ha-m. Of this total, 6,197 ha-m (92%) was through the outflow structure G-388; 445 ha-m (1%) was seepage outflow; and 391 ha-m (6.0%) was ET. The mass balance error percentage was 2.7%. This relatively small error percentage suggests that the overall mass balance result was satisfactory. The PSTA Cell had a seven-year annual average FWM outflow TP concentration of 11 µg/L, and FWM outflow TP for all years was at or below 13 µg/L.

The seepage coefficient estimated by Sangoyomi et al. (2011) for the STA-3/4 northern levees averaged 0.10 (cubic meter per second per meter of head difference per kilometer of levee length (m³/s/m/km) and was used for the west and south levees of the PSTA Cell. The seepage coefficient for the PSTA Cell east and north levees was estimated for the period from April 6 to July 3, 2012, when the PSTA Cell inflow structures were closed. This period was selected because the uncertainty from inflow structures was excluded. The seepage coefficient was 0.35 m³/s/m/km for these east and north levees; this value was used in the water and TP budget analyses for this task.

Compared to the total annual inflow to the PSTA Cell, the percentage of net seepage to the PSTA Cell ranged from 5 to 37% depending on the hydrological conditions. During the years with a large percentage of estimated seepage into the PSTA Cell, the stage differences between the PSTA Cell and the surrounding water bodies were higher than the years with less percentage of seepage. The smallest net estimated seepage occurred in WY2014, with an estimate of 26.3 ha-m. This small seepage volume compared to other years can be explained by the 0.15-m increase in the operational stage that was fully implemented in WY2014. As a result of this change, the head difference between the PSTA Cell and the surrounding water bodies was reduced. In addition, greatly reduced inflows to the STA-3/4 Central Flow-way in WY2014 due to vegetation enhancements also contributed to the very low inflow volumes to the PSTA Cell.

Overall, the amounts of rainfall and ET were small compared to the other water budget components and were approximately equivalent in volume, thereby cancelling out in the annual water balance. This is consistent with observations from other water bodies in South Florida (Abtew 2005, Abtew et al. 2007). For the seepage water quality component, large variance in the PSTA Cell well sample concentrations resulted in high uncertainties. Due to uncertainties with the seepage data, a range of seepage TP concentrations was used to develop a range of PSTA Cell performance values. Based on the monitoring

well median TP concentration of 10 µg/L, the PSTA Cell had an annual average TP load reduction of 34%, annual average FWM TP concentration reduction of 31%, and annual average settling rate of 17.5 m/yr² during the seven-year study period. The TP concentration value applied to the seepage water had a major influence on the calculations for TP load, FWM concentration reduction, and settling rate estimates.

ESTIMATING SEEPAGE USING PRINCIPAL COMPONENT ANALYSIS

Ceyda Polatel and Manuel Zamorano

INTRODUCTION

Difficulties in estimating the amount and quality of groundwater seepage to or from the wetlands complicate interpretation of observed performance and hinder conclusive demonstration of effects of other influencing parameters. In this task, hydrologic data from a monitoring network were used to characterize the hydraulic connectivity of adjacent water bodies to the PSTA Cell (Polatel and Zamorano 2016). For each nearby water body, daily stage differences with respect to the PSTA Cell were identified. Principal component analysis (PCA) was used to reduce the dimensionality of the variables. The adjacent water bodies accounting for most of the variability were identified. A linear model was developed and calibrated to selected head difference variables.

METHODS

PCA is one of the many multivariate analysis methods available to analyze large data sets. It helps determine which factors are the most important in explaining the performance of a system, and provides a visual tool in grouping variables to identify “index stages”. Multivariate analysis methods were used to estimate the sources, volumes, and direction of the seepage flow for the PSTA Cell. To estimate the seepage from flow and stage data, several steps were followed: (1) time series stage data were gathered for all water bodies in the vicinity of the PSTA Cell; (2) a matrix of stage differences as the driving force for seepage flow was developed; (3) the dimensionality of the stage difference matrix to estimate index stages was reduced using PCA and correlation analysis; (4) two calibration periods were determined to estimate seepage from water budget residuals; (5) seepage coefficients were estimated by multiple linear regression; and (6) seepage coefficients were applied to the rest of the period of record to determine seepage flow rates.

RESULTS AND DISCUSSION

The “index stages” (e.g. stage differences between PSTA and the given nearby locations) resulted in nine potential measures to include in this analysis. The loading plot of principal components for the Calibration Period 1 show that the nine index stages cluster into four groupings (**Figure 2**). The closer to 1, the stronger the correlation between the index and corresponding principal component. The four index stages retained for further seepage analysis in Calibration Period 1 were Lower SAV, Outfall Canal, S7 Headwater, and Holey-Land. For Calibration Period 2, the four index stages retained were Lower SAV, Outfall Canal, S7 Headwater, and S7 Tailwater (analysis not shown). Multiple regression analyses, using the four indices, revealed that the Lower SAV and Holey Land estimates explained a significant amount of

² Settling rate “k” values for PSTA are generally lower than those for EAV and SAV because PSTA areas are intended to receive very low inflow TP concentrations (i.e., 22 µg/L and below).

the residual inflow for Calibration Period 1 and the Lower SAV explained a significant amount of the residual inflow for Calibration Period 2 (**Table 2**).

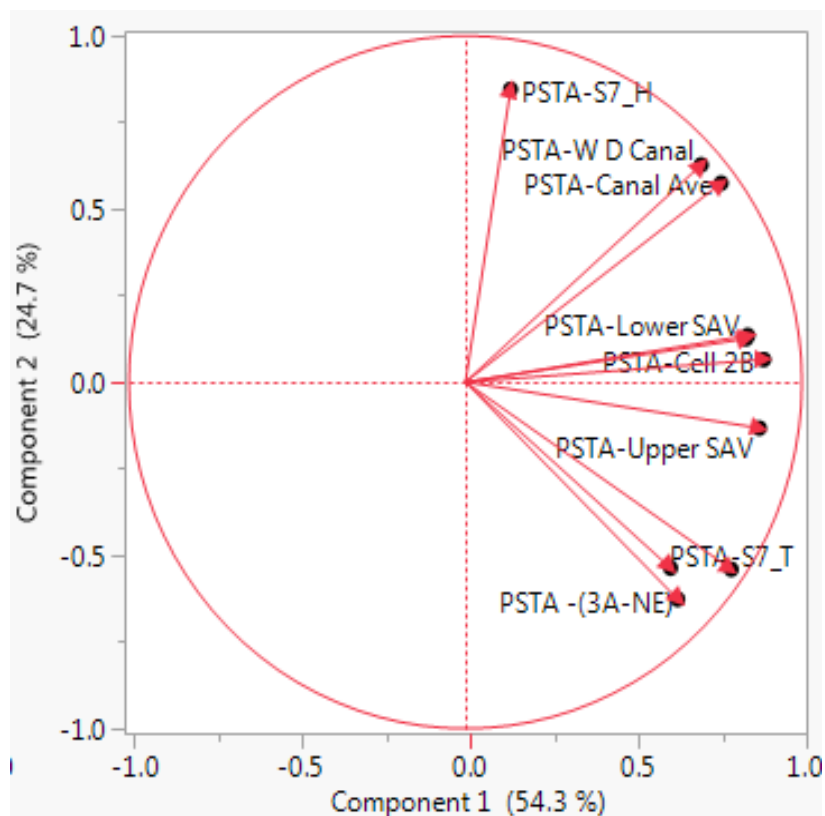


Figure 2. Scatter plot of principal component analysis of differences between the PSTA cell stage and surrounding cells. Component 1 is positively related to the Lower SAV, Upper SAV, and Cell 2B stage differences while Component 2 is positively related to S7 Headwater stage difference.

Table 2. Estimated parameter values, tau statistic, and p-values for the two calibration periods.

Seepage Coefficients for Calibration Period 1:

	Estimate	Standard Error	t-Statistic	P-Value
1. Lower SAV	-1.20555	0.249886	-4.82441	1.82947×10^{-6}
2. Outfall Canal	-7.41604×10^{-8}	0.326725	-2.26981×10^{-7}	1
3. S7 Headwater	-9.99268×10^{-10}	0.249336	-4.00772×10^{-9}	1
4. Holey-Land	-0.27911	0.105972	-2.63382	0.00868525

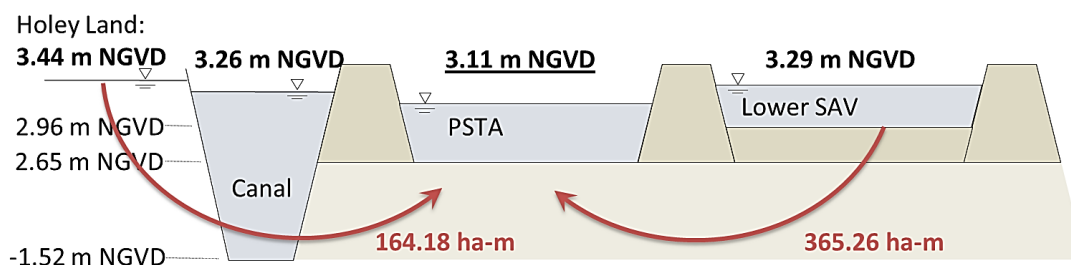
Seepage Coefficients for Calibration Period 2:

	Estimate	Standard Error	t-Statistic	P-Value
1. Lower SAV	-1.20555	0.174751	-6.89867	1.13119×10^{-11}
2. Outfall Canal	-0.255692	0.166751	-1.53337	0.125614
3. S7 Headwater	-1.10665×10^{-6}	0.181018	-6.1135×10^{-6}	0.999995
4. S7 Tailwater	-3.13849×10^{-9}	0.0475418	-6.60153×10^{-8}	1.

As with most physical phenomena, seepage to or from a wetland can be explained if adequate data are available for analysis. Observed stage and flow data can be used for water budgets as well as in explaining treatment performance and developing seepage estimates for constructed wetlands. The results of this study indicate that the major seepage exchange for the PSTA Cell occurs with the adjacent Lower SAV Cell (**Figure 3** and **Table 1**). Depending on the target control elevation of the cell, other water bodies in the vicinity contribute to the seepage flow.

Calibration Period 1:

	Seepage Coeff.	Ave PSTA Diff (m)	Seepage (ha-m)	Percent Seepage	Direction
Lower SAV	-1.206	-0.164	363.26	+69%	To PSTA
Holey Land	-0.279	-0.321	164.18	+31%	To PSTA



Calibration Period 2:

	Seepage Coeff.	Ave PSTA Diff (m)	Seepage (ha-m)	Percent Seepage	Direction
Lower SAV	-1.206	-0.053	160.85	+133%	To PSTA
Outfall Canal	-0.256	0.063	-40.09	-33%	From PSTA

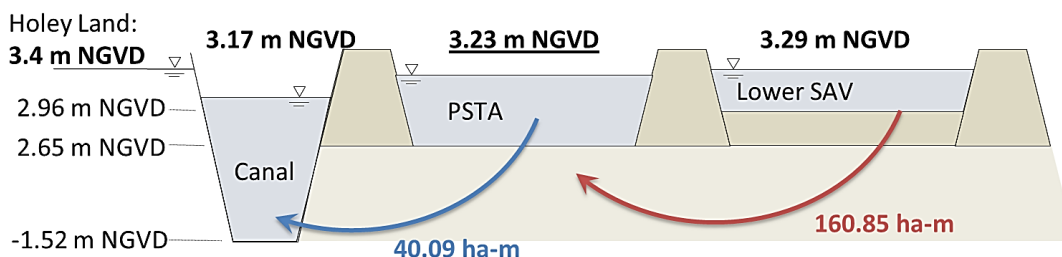


Figure 3. Average stages in the PSTA Cell and nearby water bodies, and the estimated seepage volumes and direction for two calibration periods: Calibration period 1 – October 24, 2011–April 19, 2013 and Calibration period 2 – April 30, 2013–April 30, 2015. (Note: Coeff. – Coefficient; Diff – Difference; and NGVD – National Geodetic Vertical Datum of 1929.)

INFLUENCE OF SEEPAGE ON TREATMENT PERFORMANCE

Manuel F. Zamorano

INTRODUCTION

To characterize the influence of seepage on the treatment performance of the STA-3/4 PSTA Cell, this task analyzed water surface elevation (i.e., stage) and water quality data collected from January 2012 to September 2015 (Zamorano 2017). The data included water level and water quality measurements from wells situated in the PSTA Cell's east and west perimeter levees, water surface elevation and water quality measurements in the PSTA Cell and adjacent water bodies, and chemical characterization of surface water and groundwater in the vicinity of the PSTA Cell.

METHODS

Daily stages in the PSTA Cell, LSAV Cell, and the STA-3/4 Discharge Canal from January 2012 to October 2015 were evaluated. Daily groundwater and surface water stages in the nearby Holey Land Water Management Area were included in this evaluation. In addition, water level and water quality measurements were collected from four shallow wells (2.4 m), two intermediate wells (6.1 m), and four deep wells (11 m) situated in the PSTA Cell's east and west perimeter levees. Well water and surface water samples were analyzed for calcium, magnesium, sodium, potassium, chloride, sulfate (SO_4^{2-}), alkalinity, TP, total dissolved P (TDP), and soluble reactive P (SRP). Particulate P (PP) was determined by subtracting TDP from TP, and dissolved organic P (DOP) was calculated as the difference between TDP and SRP. Ion concentrations were expressed as milliequivalents per liter (meq/L) to calculate the ionic balance. Results were evaluated and interpreted in the context of the local hydrogeology. Water level data were used to determine the source, direction, and periods in which seepage was entering or leaving the PSTA Cell. Major ionic compositions of well water and surface water in and around the PSTA Cell were used to identify the geochemical characteristics and interactions of groundwater and surface water, and to determine the possible sources of waters sampled within the PSTA region by using a previous classification of South Florida waters (Parker et al. 1955, Frazee 1982, Harvey and McCormick 2009).

RESULTS AND DISCUSSION

Water levels in the shallow perimeter wells surrounding the PSTA Cell responded more rapidly than the deep perimeter wells to changes in stages in the LSAV and PSTA cells, an indication of greater lateral seepage contribution (versus groundwater upwelling) to the PSTA Cell. Evaluation of continuous water level data in the PSTA wells obtained from August to October 2015 supports that the primary source of lateral seepage into the PSTA Cell was the LSAV Cell consistent with the results of the PCA (Polatel and Zamorano 2016). Seepage from the LSAV Cell into the PSTA Cell was greater during periods when the LSAV Cell stage was higher than 3.4 m National Geodetic Vertical Datum of 1929 (NGVD29). On the other hand, water generally seeped out of the PSTA Cell into the STA-3/4 Discharge Canal with a few exceptions in which seepage appeared to enter the PSTA Cell during periods in which the discharge canal stage also was greater than 3.4 m NGVD29 (Zamorano 2015). Furthermore, consistent head differences in the east and west levee wells with respect to the PSTA Cell inflow stage suggest that greater seepage occurred along the levees near the G-388 outflow pump station.

Water levels in all the deep perimeter wells suggested that groundwater upwelling to the PSTA Cell is more likely to occur during the wet season. However, groundwater upwelling may not be a significant contributor because the total estimated seepage into the PSTA Cell was only about 10% of the PSTA Cell's overall water budget (**Figure 4**) and most of the seepage to the PSTA Cell is confirmed to occur from the

LSAV Cell. Therefore, data indicate that the effect of groundwater upwelling on the PSTA Cell's performance was negligible.

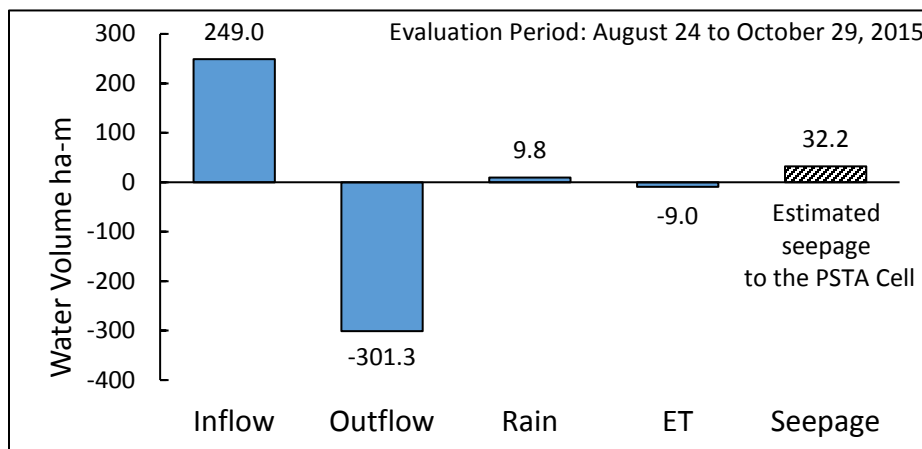


Figure 4. Total PSTA Cell inflow, outflow, rain, ET, and seepage in ha-m, from August 24 to October 29, 2015. Derived from SFWMD's web-based Water Budget Tool.

Chemical characterization of major ions, and stage and water level data in the PSTA Cell's surface water, surrounding surface water, and groundwater in wells adjacent to the PSTA Cell indicated possible interactions between the surface water in the PSTA Cell and groundwater. Surface water and groundwater within the vicinity of the PSTA Cell primarily are characterized by calcium bicarbonate, $\text{Ca}(\text{HCO}_3)_2$, which is within the Everglades Agricultural Area classification. Higher concentrations of carbonates in the groundwater suggest there is higher dissolution of calcium carbonate, CaCO_3 , which is the primary mineral in limestone. Furthermore, geochemical characteristics in the surface water within the LSAV Cell and PSTA Cell indicated that the two water bodies intersect in the shallow and deep wells in the levee between the LSAV Cell and PSTA Cell, resulting in a transitional or mixed water type. Surface water in the STA-3/4 Discharge Canal also appeared in the form of transitional water (**Figure 5**).

The highest TP concentrations were observed in the shallow wells (2.4 m) located in the levee between the PSTA Cell and the STA-3/4 Discharge Canal. However, these wells are, on average, 0.55 m higher than the wells located in the east levee, and the bottoms of the wells consistently were above the stage in the PSTA Cell and STA-3/4 Discharge Canal. Therefore, water levels in the wells could not reflect interactions between the PSTA Cell and STA-3/4 Discharge Canal, and the TP concentrations measured in the wells should not be used in PSTA Cell P budgets. TP concentrations generally were higher in the LSAV Cell surface water and the shallow wells in the levee between the LSAV Cell and PSTA Cell compared to generally lower TP concentrations in the PSTA Cell and deep wells (11 m, **Figure 6**). This suggests that the PSTA Cell's performance could be constrained through TP enrichment from seepage water from the LSAV Cell. In contrast, TP concentrations in the STA-3/4 Discharge Canal surface water and the deep wells in the levee between the PSTA Cell and the STA-3/4 Discharge Canal were comparable to TP concentrations in the PSTA Cell, suggesting no impact on the PSTA Cell from seepage from the STA-3/4 Discharge Canal.

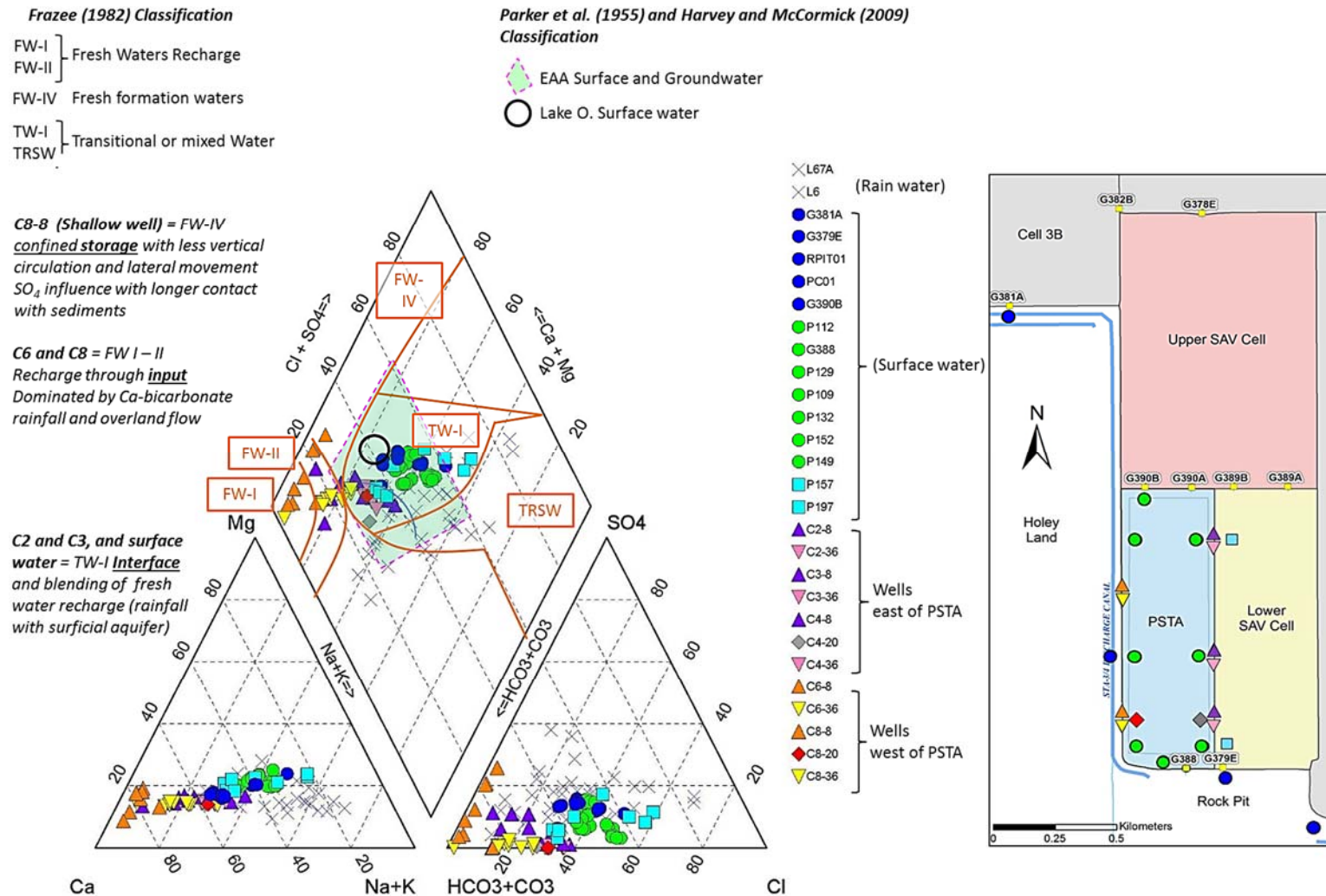


Figure 5. Piper diagram showing the chemical composition of surface water, rainwater, and well water collected from specific locations in the vicinity of the PSTA Cell, indicating the areas of freshwater recharge (FW-I and FW-II), interface water recharge (TW-I), and freshwater confinement (FW-IV). (Note: Ca – calcium; Cl – chloride; CO₃ – carbon trioxide; HCO₃– bicarbonate; Lake O – Lake Okeechobee; K – potassium; Mg – magnesium; NA – sodium, SO₄ – sulfate.)

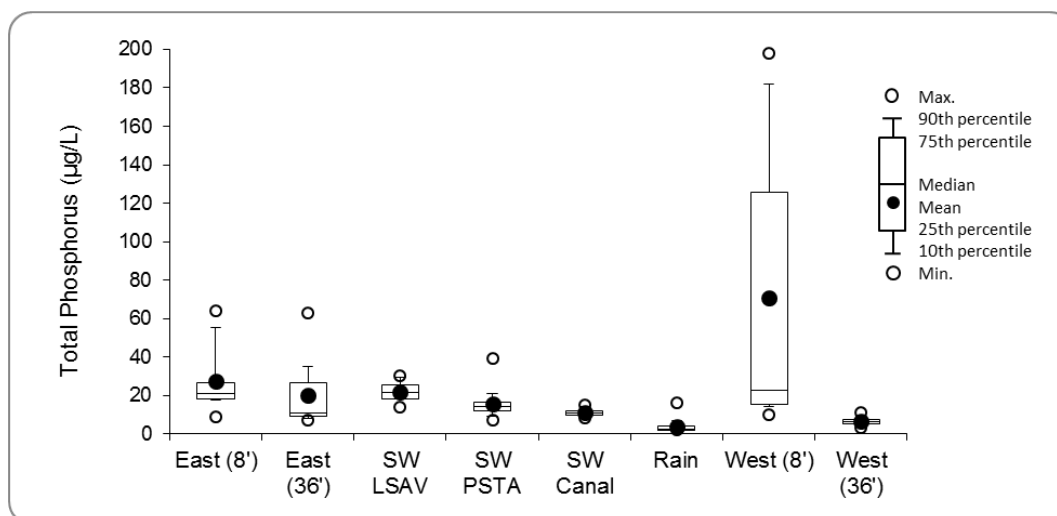


Figure 6. Comparison of TP concentrations in samples collected from rainwater, surface water (SW) in the LSAV Cell and PSTA Cell, and shallow (2.4 m) and deep (11 m) wells in the PSTA Cell's east and west levees. (Note: Max. – maximum and Min. – minimum.)

EFFECTS OF PULSE FLOW EVENTS ON TREATMENT PERFORMANCE

Manuel F. Zamorano

INTRODUCTION

Historic (WY2008–WY2012) annual HLRs for the PSTA Cell generally were within the range of rates observed for STA-3/4 Cell 2B (the adjacent full-scale treatment cell); however, the peak 3-day HLR in the PSTA Cell was lower than that observed in Cell 2B. Therefore, there was a concern that the flows delivered to the PSTA Cell over its initial period of operation did not adequately represent hydraulic conditions that occurred in full-scale STA treatment cells. It was hypothesized that low outflow TP concentrations had resulted from the moderation of hydraulic and P loading to the PSTA Cell and that higher P loads would result in higher outflow TP concentrations. The purpose of this task was to study the effects of hydraulic pulses on the PSTA Cell's performance (Zamorano 2015).

METHODS

Three managed flow pulses were conducted in the PSTA Cell: Pulse 1 (August 1–3, 2012), Pulse 2 (October 24–26, 2012), and Pulse 3 (June 24–26, 2014). The target stage for the PSTA Cell was 3.05 m NGVD29 during Pulses 1 and 2, and 3.2 m NGVD29 for Pulse 3. The maximum 3-day average HLRs (ranging from 24.7 to 31.5 cm/d) observed in STA-3/4 Cell 2B during WY2009–WY2012 were used to develop the target flow rates for the PSTA Cell flow pulses. Surface water flows and stages were routinely monitored by SFWMD at the PSTA Cell's inflow (G-390A and G-390B) and outflow (G-388) structures. Remote P analyzer (RPA) units deployed at G-390B and G-388, and were programmed to collect and analyze water samples for TP every 3 hours. The HLR, PLR, and HRT for each managed pulse event were compared. Daily average TP concentration data collected at G-390B were used to compute PLRs. For each

pulse event, the data were partitioned into the following periods for analysis: 28-day pre-pulse, 7-day pre-pulse, 3-day pre-pulse, 3-day pulse, 3-day post-pulse, 7-day post-pulse, and 28-day post-pulse. Daily average outflow TP was lagged by 4 days from the inflow TP data collection to account for HRT. Linear regression was used to assess the relationship between inflow and outflow TP concentrations during each pulse event. One-way analysis of covariance (ANCOVA) was used to evaluate temporal differences between pre-pulse and post-pulse TP concentrations at G-388, where inflow TP concentration was a covariate. Statistical significance level of all analyses was evaluated at $\alpha = 0.05$. All statistical analyses were performed using JMP® statistical software (version 11.2.0; SAS Institute Inc. 2013).

RESULTS AND DISCUSSION

Daily average depths in the PSTA Cell during Pulses 1 and 2 increased by approximately 0.2 m compared to the daily average depths at the 3.05-m NGVD29 target stage. Daily average depths during Pulse 3 increased by 0.1 m compared to the daily average depths at the 3.2-m NGVD29 target stage. Water depths in the PSTA Cell returned to pre-pulse depths one to three days after the pulses were completed (Figure 7).

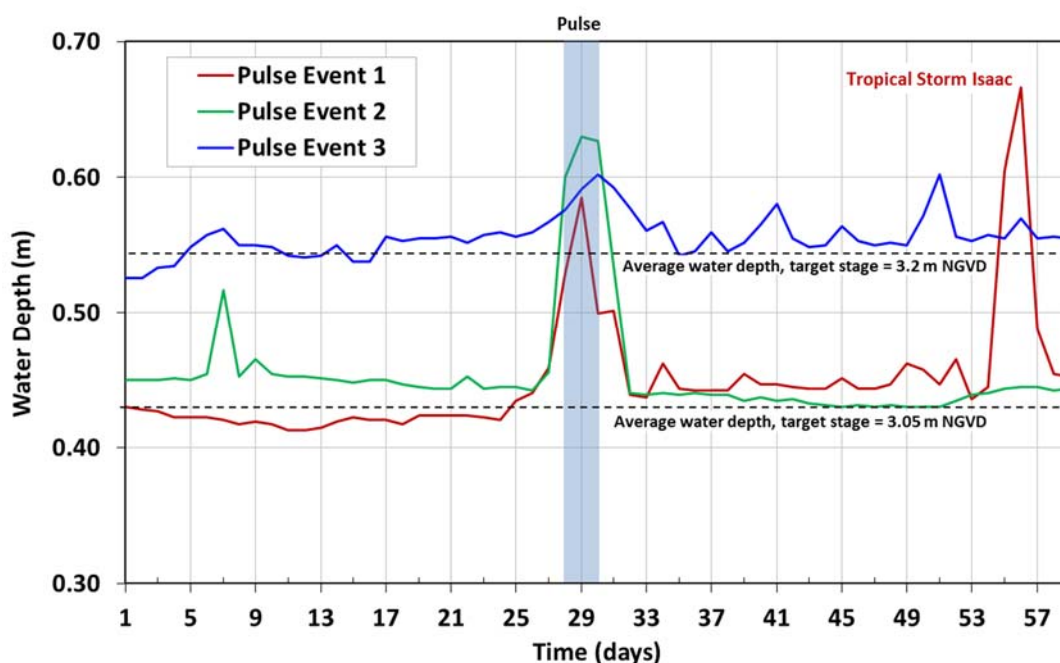


Figure 7. Daily average water depth in the PSTA Cell 28 days before, during, and 28 days after the three pulse flow events under two different target stage regimes. Note that Pulse 3 was conducted after the target stage was increased to 3.2 m NGVD29.

Average flow rates during the pulses (1.5 cubic meters per second [m^3/s] for Pulse 1, 1.6 m^3/s for Pulse 2, and 2.1 m^3/s for Pulse 3) were three to four times higher than average historic flow rates (0.5 m^3/s) in the PSTA Cell, which resulted in HLRs (28.5–43.4 cm/d) approximately three times higher than under typical operations. Pulses 1 and 2 produced 3-day maximum HLRs (28.5 and 32.1 cm/d) that were comparable to STA-3/4 Cell 2B historic 3-day maximum HLRs (24.7 to 31.5 cm/d), while Pulse 3 resulted in a 3-day maximum HLR (43.4 cm/d) that was approximately 1.5 times greater than the 3-day maximum HLRs experienced historically by STA-3/4 Cell 2B (Figure 8).

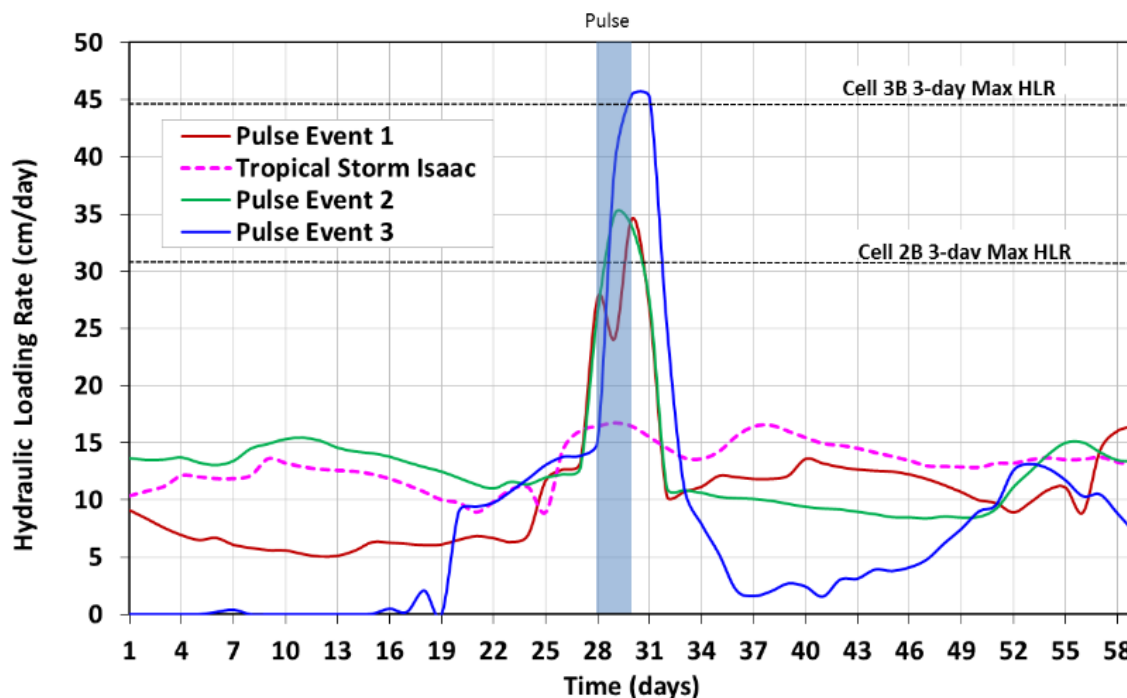


Figure 8. Daily average HLRs in the PSTA Cell during the three pulse flow events, 28 days before and 28 days after each pulse, and during Tropical Storm Isaac. (Note: Max – maximum.)

High flow rates during the pulses resulted in short HRTs (1–2 days) compared to typical operations (4–5 days). There was no significant increase in outflow TP concentrations during or after the pulses compared to pre-pulse concentrations except for the 28-day period after Pulse 2. High outflow TP concentrations of up to 63 $\mu\text{g/L}$ following Pulse 2 were likely a result of herbicide treatment and subsequent decomposition of spikerush (*Eleocharis* spp.) that occurred immediately after the pulse. In addition, the daily PLRs sharply increased for all three pulses with the highest PLR (6.4 $\text{g/m}^2/\text{day}$) observed during Pulse 3 (**Figure 9**).

While differences between pre-pulse and post-pulse outflow TP concentrations during Pulses 1 and 3 were statistically significant (probability [p] < 0.05), the concentration differences were minimal and within the laboratory's practical quantitation limit (8 $\mu\text{g/L}$). Further evaluation of TP data suggested that when inflow TP concentrations exceeded 22 $\mu\text{g/L}$, outflow concentrations generally exceeded 13 $\mu\text{g/L}$. Evaluation of the entire daily average TP concentration data for the period from April 2012 to August 2014 produced similar results (**Figure 10**).

In summary, results indicated that the high flow rates at the outflow pump station during pulses did not result in higher TP concentrations compared to pre- and post-pulse periods. Similarly, increased flow at the inflow culvert during the pulses did not result in higher inflow TP concentrations. TP concentrations at the PSTA Cell outflow location after the pulses generally were lower than or similar to outflow TP concentrations before the pulses. The results indicate that pulse flow events had no adverse effect on the PSTA Cell's P treatment performance.

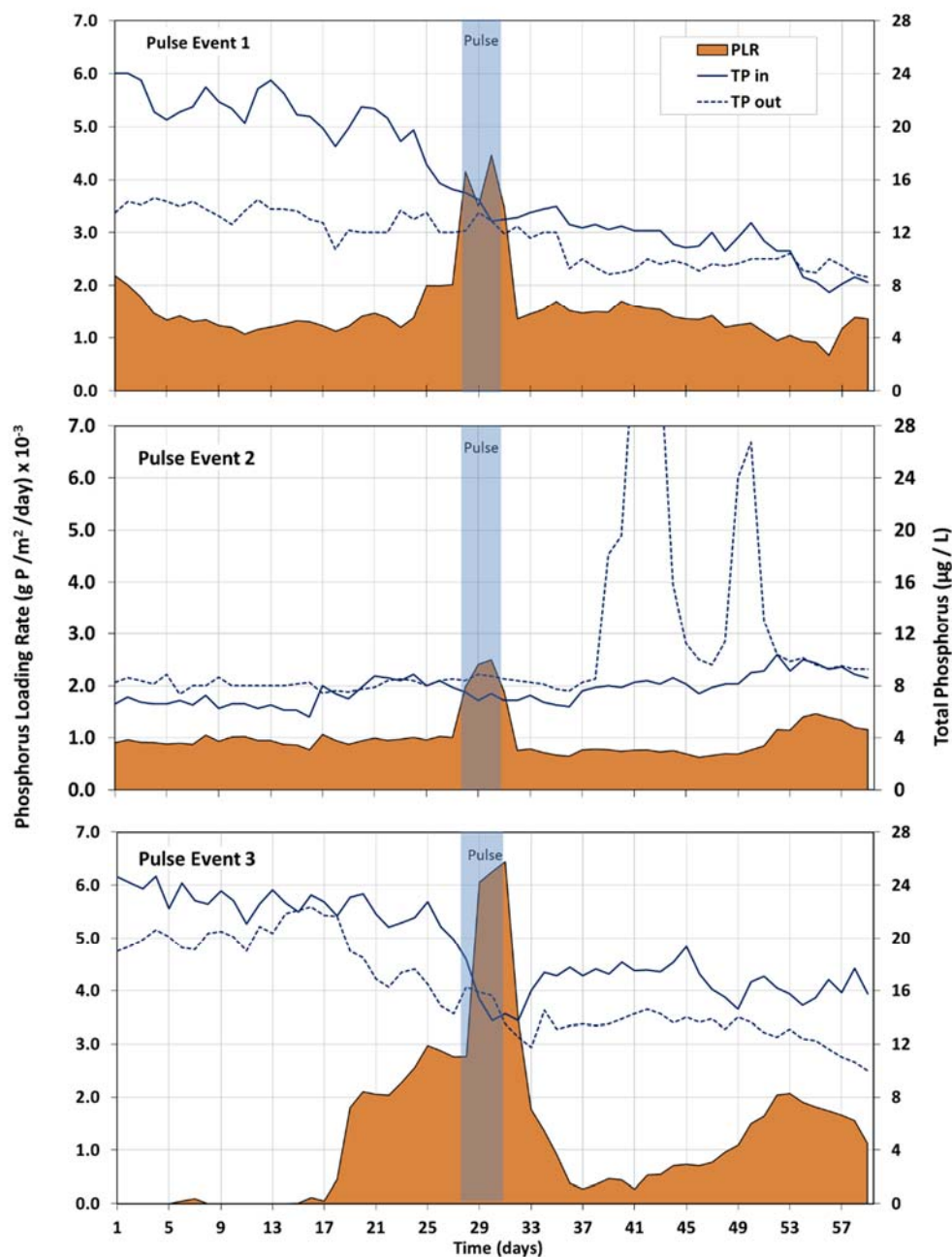


Figure 9. Daily TP loading rates and daily average inflow and outflow TP concentrations in the PSTA Cell during the 3-day flow pulse, and the 28-day pre- and post-pulse periods for Pulse 1 (top), Pulse 2 (middle), and Pulse 3 (bottom).
(Note: g P / m² / day – grams phosphorus per square meter per day.)

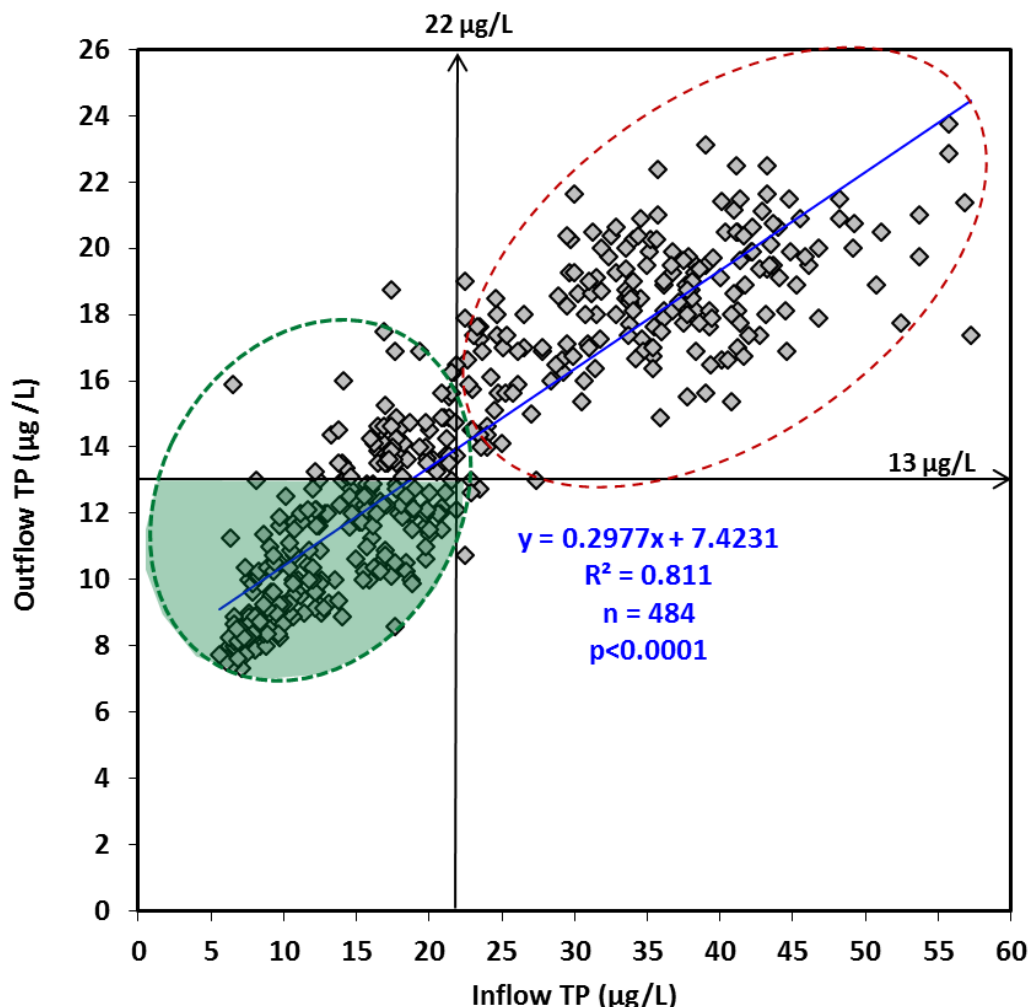


Figure 10. Relationship between PSTA Cell inflow and outflow daily average TP concentrations from April 2012 to August 2014. Optimal performance is indicated by the green-shaded area.

EFFECTS OF SUSTAINED MODERATE FLOW

R. Thomas James and Manuel F. Zamorano

INTRODUCTION

Analysis of TP measured at the G-388 outflow structure (pump station) at 2- or 3-hour intervals using RPAs indicated that the lowest discharge concentration occurred when daily flow averaged $63.6 \times 10^3 \text{ m}^3/\text{d}$ ($0.74 \text{ m}^3/\text{s}$) (James 2015). Three short-term (3 to 4 day) pulse events at or above $146.9 \times 10^3 \text{ m}^3/\text{d}$ ($1.70 \text{ m}^3/\text{sec}$) were conducted in 2012 and 2014, which determined the capability of the PSTA cell to provide TP reduction treatment at high flow rates (Zamorano 2015). These high flow conditions were maintained only for short periods of time (3 to 4 days). However, moderate flow conditions (e.g. $63.6 \times 10^3 \text{ m}^3/\text{day}$), which likely could be maintained over longer periods of time (21 days), had not been evaluated.

The objectives of this study were to answer these questions (see James and Zamorano 2017): (1) can the PSTA cell be actively managed at “moderate” (e.g. $\pm 20\%$ of $63.6 \times 10^3 \text{ m}^3/\text{d}$ or 50.9 to $76.3 \times 10^3 \text{ m}^3/\text{d}$)

flows over an extended period of time, (2) will discharge concentrations remain at ultra-low TP values over this extended period, (3) given moderate flows over an extended period (a managed “press” test), can the PSTA cell remove TP even when inflow concentrations are at or below $\leq 13 \mu\text{g/L}$, and (4) can this moderate flow regime achieve better results than a lower flow regime (below $50 \times 10^3 \text{ m}^3/\text{d}$) when comparing TP removal and TP concentration in the discharging waters?

METHODS

To obtain a moderate flow regime, inflow gates to the PSTA cell were opened with enough head difference to exceed a flow of $0.59 \text{ m}^3/\text{s}$ ($50.9 \times 10^3 \text{ m}^3/\text{d}$, or a HLR of 12.5 cm/d) from September 18 to October 9, 2015, and to allow discharge pumping at this moderate rate (**Table 3**). During this 21-day managed “press” test, the average stage was 3.20 m NGVD29.

Low flow periods, when the flows through the PSTA cell were consistently below $50.9 \times 10^3 \text{ m}^3/\text{d}$, were found for comparison to the managed press test and the two other moderate flow periods based on the following criteria: (1) RPA data were available, (2) no days of no flow, (3) no days with discharge exceeding $50.9 \times 10^3 \text{ m}^3/\text{d}$, (4) within 2.5 months of the moderate flow periods, and (5) at least 7 days in duration. The comparison periods (Low Flow 2012, Low Flow 2014, and Low Flow 2015) were shorter in length (**Table 3**), and much lower flow than the moderate flow periods. Because Moderate Flow 2012 and Low Flow 2012 periods occurred when the water level in the PSTA cell was 15.2 centimeters (cm) lower (one-half foot) than the other tests, the turnover time (calculated from mean volume divided by mean outflow) was also shorter.

Daily flow measurements were obtained from DBHYDRO on November 10, 2015, and daily water budgets for the period of May 2012 to October 2015 were calculated using the Water Budget Tool (BPC Group Inc. 2008) and the methods and data sources used by Zhao et al. (2015).

RESULTS AND DISCUSSION

The 2012 to 2015 record was also reviewed to find periods of low constant daily flows (as comparisons to determine if such periods could achieve similar or better results than the moderate flow regimes). The three low flow comparison periods had higher discharge TP concentrations than the moderate flow periods. These results were somewhat equivocal because the inflow concentrations also were higher in the low flow, as compared to the moderate flow periods, so higher discharge concentrations were expected.

For the managed press test and two other moderate flow periods, daily mean outflow concentrations were higher than the daily mean inflow concentrations only when daily mean inflow concentrations were below $9 \mu\text{g/L}$. During the managed press test, daily mean surface inflow TP declined from $13 \mu\text{g/L}$ to near $4 \mu\text{g/L}$, while outflow concentrations remained within daily average values between 6 and $8.5 \mu\text{g/L}$. Also, there were no individual RPA measurements above $10 \mu\text{g/L}$. These observations suggest that there is a limit to TP removal by the PSTA cell (an equilibrium P concentration, EPC) close to $9 \mu\text{g/L}$.

Based on these results, the PSTA cell can be operated at moderate flow levels for extended periods of time without affecting its ability to maintain ultra-low TP concentrations in the discharge. At average daily inflow TP concentrations above $9 \mu\text{g/L}$, the PSTA cell removes TP under moderate flow conditions (**Table 3**). Management of the PSTA at moderate flows is as good, or better than, management at low flows.

Table 3. Summary of inflow and outflow daily volumes, RPA TP measurements for the moderate and low flow periods.

Year	Period	Average Cell Volume (m ³ x 1,000)	Number of Days	Flow Type	Hydraulic Loading Rate (cm/d)	FWM TP (µg/L)	Rate (mg/m ² /d)	Turnover Time (d)
2015	Press Test Moderate Flow September 18–October 8	232.2	21	inflow	14.8	7.1	1.05	
				outflow	18.7	7.4		3
	Low Flow September 5–September 16	230	12	inflow	7	9.4	0.66	
				outflow	7.9	8		7.1
2014	Moderate Flow September 14–October 4	232.2	21	inflow	13.4	11	1.48	
				outflow	17	8.9		3.4
	Low Flow July 7–July 15	226.2	9	inflow	5.1	16.6	0.84	
				outflow	5.6	13		9.9
2012	Moderate Flow September 13–October 2	184.9	20	inflow	13.5	7.4	1	
				outflow	17.6	8.4		2.6
	Low Flow July 7–July 22	170.9	16	inflow	5.9	21	1.26	
				outflow	6.6	12.4		6.4

EVALUATION OF RPA RESULTS AND HYDROLOGIC CONDITIONS

R. Thomas James

INTRODUCTION

This task includes the evaluation of TP concentrations measured by Remote P Analyzers (RPAs) located at the G-388 outflow and the G-390B inflow of the PSTA Cell (James 2015). The objective was to determine the conditions that consistently produced lower TP concentrations during discharge events. In particular, the effect of two separate stage operational periods, season, time of day, flow rate, and inflow TP concentrations were evaluated against outflow TP concentrations. Results may provide the basis for design and operational guidelines to optimize PSTA treatment performance.

METHODS

TP measurements (SFWMD 2012) were obtained for the period from March 30, 2012, to October 20, 2014, at the inflow (G-390B) and outflow (G-388) structures of the PSTA Cell. Measurements were done continuously by the RPAs every 3 hours with a few breaks due to power loss, equipment failure, or system maintenance. From November 22, 2013, to October 2, 2014, the sampling frequency at G-390B was increased to every 2 hours. The measurements that were evaluated excluded pulse tests (see previous section), Tropical Storm Isaac, and an anomalous period of record (November 3–14, 2012) that included extremely high TP values attributed to vegetation management in the PSTA Cell.

Hourly flow data were obtained from the breakpoint flow data generator web page of DBHYDRO on March 18, 2015, for G-390A and G-390B, and instantaneous breakpoint revolutions per minute (rpm) data were obtained from the DBHYDRO on February 4, 2014, for the G-388 pumps. The breakpoint data were used to separate out RPA data based on flow or no-flow conditions. Daily flow measurements also were obtained for G-390A, G-390B, and G-388. Daily averaged stage data were obtained for G-388, and daily water depth was determined by subtracting 2.7 m from this daily stage. TP data were subset into two stage operation periods: a 3.05-m NGVD29 stage operation that occurred prior to April 22, 2013, and a 3.2-m NGVD29 stage operation that occurred from this date forward. Histograms and percent cumulative frequencies of these two subsets were compared to evaluate TP entering and discharging from the PSTA Cell.

RESULTS AND DISCUSSION

RPA measurements during flow (e.g. when the G-388 discharge pump was operating) show that the PSTA Cell retained TP when inflow TP concentrations were greater than 10 $\mu\text{g/L}$. Discharged TP concentrations were lower during the 3.05-m NGVD29 stage operations (average water depth of 0.39 m prior to April 22, 2013) than at the 3.2-m NGVD29 stage operation (average water depth of 0.55 m of water depth after April 22, 2013, **Figure 11**). However, this result is complicated by the strong relationship between inflow and outflow TP concentrations and the significantly ($p < 0.0001$) higher TP concentrations during the 3.2-m NGVD29 stage operation period. The higher concentrations are attributed to vegetation rehabilitation activities occurring in the upstream STA flow-way.

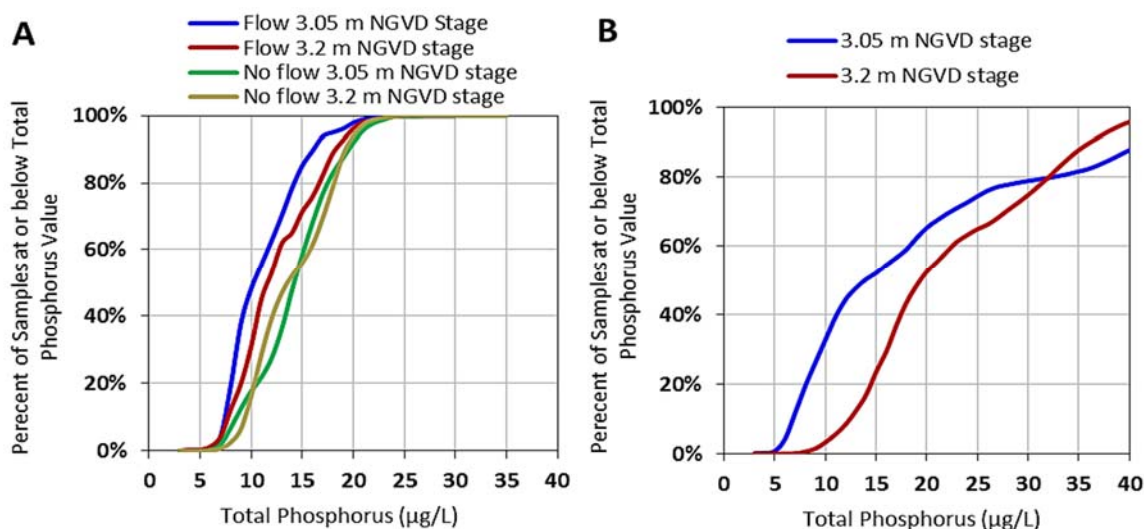


Figure 11. Percent cumulative frequencies of RPA TP concentrations with pulse tests, Tropical Storm Isaac, and vegetation management period removed. (A) G-388 for 3.05-m and 3.2-m NGVD29 stage operations for flow and no flow conditions. (B) G-390A during 3.05-m and 3.2-m NGVD29 stage operations for flow conditions.

Despite the significant difference ($p < 0.0001$) between the inflow concentrations of the two stage operational periods, an analysis of weekly FWM TP concentrations showed that the linear relationship between inflow and outflow concentrations was not significantly ($p = 0.76$) different between stage operations. This result suggests that the two different stage operations did not directly influence the TP removal rate from the PSTA Cell (**Figure 2**).

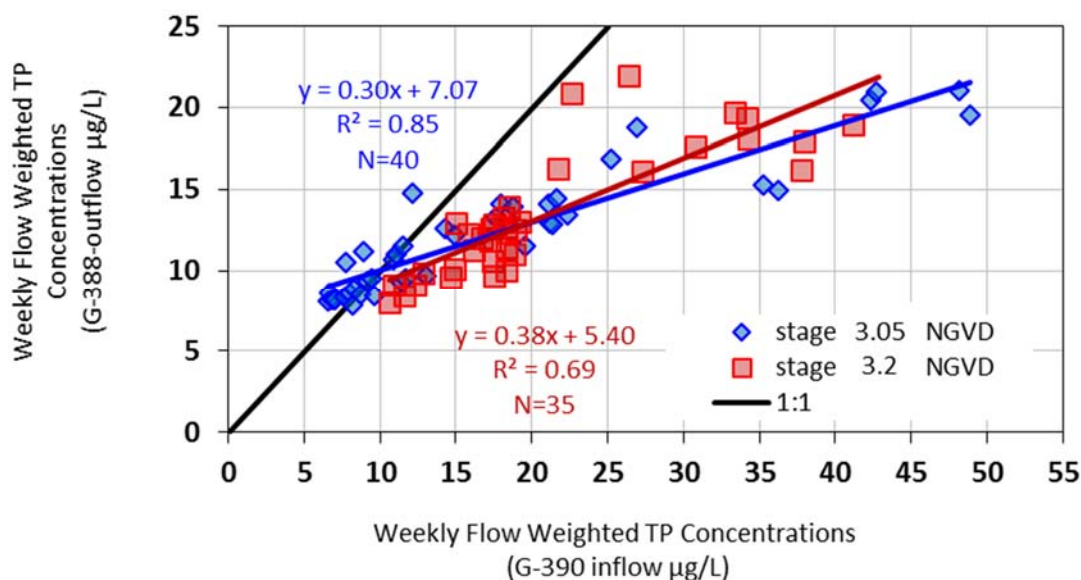


Figure 12. Linear regression of weekly FWM TP concentration (computed from daily flow averaged RPA results) at G-390A against G-388 for 3.05-m and 3.2-m NGVD29 stage operations.

There are a few factors that appeared to influence retention of TP in the PSTA Cell. Time of day did not affect TP concentrations, but lower TP concentrations were observed during the wet season (May to October) under the 3.05-m NGVD29 stage operation period. Comparing weekly inflow and outflow concentrations indicates that discharge concentrations less than $15 \mu\text{g/L}$ occurred when inflow concentrations were less than $20 \mu\text{g/L}$. The percentages of TP measurements in the discharge from the PSTA Cell that were below concentrations of 10, 13, or $15 \mu\text{g/L}$ were different under different flow and stage conditions. For the 3.05-m NGVD29 stage operation, a pump operation of 642 minutes per day (outflow estimate of $0.76 \text{ m}^3/\text{s}$ and a turnover time of 2.4 days) resulted in the greatest percentage of values below these concentrations. At the 3.2-m NGVD29 stage operation, the greatest percentage of values below $15 \mu\text{g/L}$ occurred at a pump operation category of 594 minutes, $0.74 \text{ m}^3/\text{s}$, and a turnover time of 3.4 days (Figure 13).

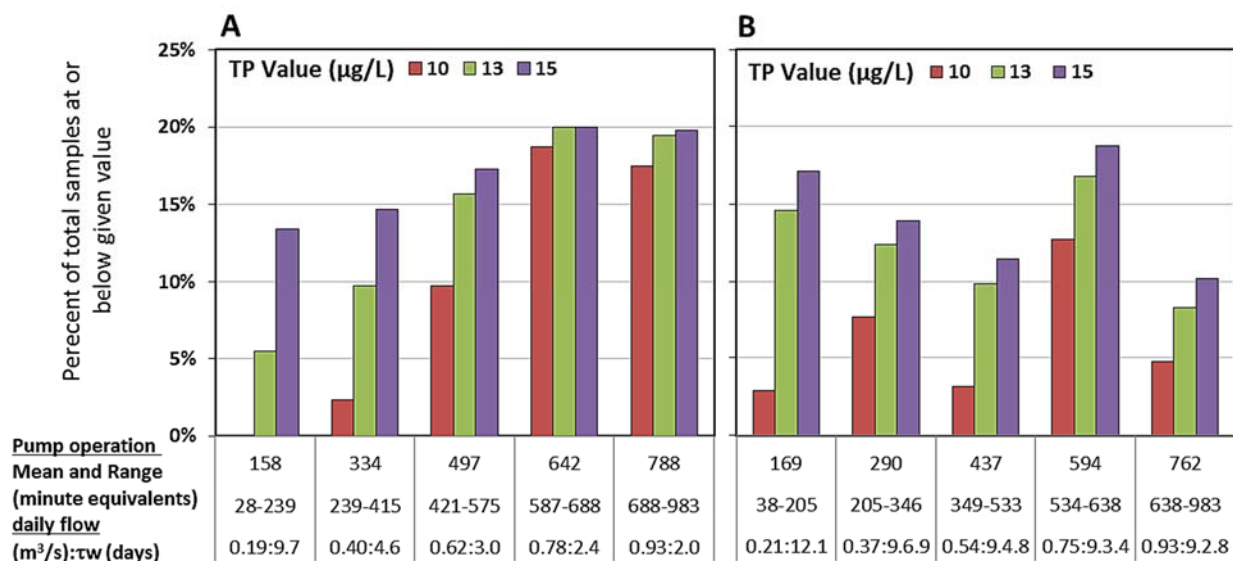


Figure 13. Percent of RPA TP results at or below 10, 13, and 15 µg/L under various flow categories: pump operation (minutes), flow (m³/s) and τ_w (turnover time in days); with equal number of samples in each category at (A) 3.05-m NGVD29 stage operation (sample size [n] = 113 per category) and (B) 3.2-m NGVD29 stage operation (n = 63 per category). (Note: All comparisons of TP versus pump operation are significant [Kruskal-Wallis Chi-square p < 0.05].)

EVALUATION OF LIMEROCK CAP AS AN ALTERNATIVE TO SCRAPING OF MUCK TO ACHIEVE ULTRA-LOW P CONCENTRATION

Kevin Grace¹ and Tom DeBusk¹

INTRODUCTION

A principal design element of PSTA systems has been that a calcareous substrate is thought to be necessary to promote the low-P periphyton community that has adapted to grow in a low nutrient environment and is able to efficiently and reliably remove recalcitrant P from already low P surface waters. Calcareous periphyton grows well in some areas of the Everglades that are least affected by surficial nutrient loading, such as the interior of Water Conservation Area (WCA) 2A. It also grows well in parts of the Everglades where short hydroperiod and frequent drying of the marsh have completely oxidized organic soil matter. In these locations, the wetland substrate is exposed limestone bedrock.

Removal of the organic muck soils from STA outflow regions to expose the underlying rock can provide a calcareous substrate. The STA-3/4 PSTA Cell is a prime example of this approach. In some locations, however, the depth of muck may preclude periphyton-based treatment from consideration. A more cost-effective approach may be to apply limerock (LR) gravel to the ground surface to provide a calcareous substrate. To evaluate the effectiveness of LR as a cap above muck soils, replicated experiments were conducted at the STA-1 West research facility.

METHODS

A pair of mesocosm studies were established to explore the effectiveness of an LR cap as an alternative to muck removal. In the first study, SAV and periphyton communities were established on low-P muck soils (TP = 170 milligrams per kilogram [mg/kg]), while in the second study a more P-enriched muck soil (TP = 679 mg/kg) was used (DBE 2015b, 2016). In both studies, triplicate flow-through mesocosms were established, with or without a LR cap (3 to 5 cm thick) above the muck, and with a mixed community of rooted (e.g. *Potamogeton illinoensis*) and non-rooted (*Chara* sp.) SAV species. The latter study also had a 15-cm LR cap treatment above the high-P muck soil. The TP concentrations of the inflow and outflow waters were then monitored to evaluate P removal performance. Note that the first study (low P muck) was concluded in 2015 after nearly four years of operation, while the second study (higher P muck), which began in December 2015, is still ongoing.

RESULTS AND DISCUSSION

The performance of the PSTA Cell supports the concept of periphyton-based P removal at very low levels, reducing inflow TP concentrations (11 to 24 $\mu\text{g/L}$) to even lower levels (8 to 13 $\mu\text{g/L}$) (**Table 1**). The initial mesocosm study demonstrated that muck soil with P content that is sufficiently low (and chemically stable) can also produce ultra-low P concentrations, with or without a calcareous substrate. In that experiment, long-term (period of record = 3.8 years) average TP concentrations were 15 ± 1 , 11 ± 1 , and 12 ± 0 $\mu\text{g/L}$, for the inflow, LR-capped outflow, and control outflow, respectively (**Figure 14**).

Most current and future STA locations, however, are underlain by previously farmed soils with soil P concentrations higher than in the preliminary study. Initial results from the second, ongoing mesocosm study demonstrate that P removal below approximately 15 $\mu\text{g/L}$ by wetlands established on P-enriched muck soils is limited, but improved by a 15-cm thick LR cap.

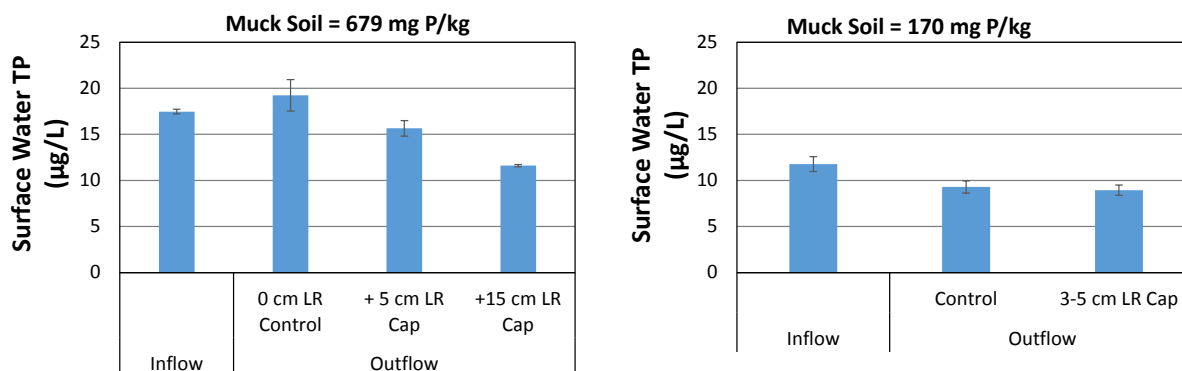


Figure 14. Average TP concentrations in the inflow and outflow waters of mesocosms operated with or without a LR cap. Data represent fourteen months of flow-through operations for mesocosms established on high-P muck (February 10, 2016, to April 5, 2017, left) and low-P muck (May 5 to September 6, 2011, right). Values represent the average ($\pm$ standard error) of duplicate inflows or triplicate outflows under each treatment. (Note: mg P/kg – milligrams phosphorus per kilogram.)

During fourteen months of operations, average inflow and outflow TP concentrations were 17 ± 0 $\mu\text{g/L}$ and 16 ± 1 $\mu\text{g/L}$, respectively, in mesocosms with 5-cm LR-capped high P muck soils, while mesocosms without LR (i.e. “controls”) produced outflow concentrations of 19 ± 2 $\mu\text{g/L}$ (**Figures 14 and 15**). These average outflow TP concentrations are within the range of background concentrations reported for well-performing STAs on previously farmed muck soils (Juston and DeBusk 2011). By contrast, the 15-cm LR cap produced outflow concentrations with an average of 12 ± 0 $\mu\text{g/L}$, within the range observed for the muck-scraped STA-3/4 PSTA Cell.

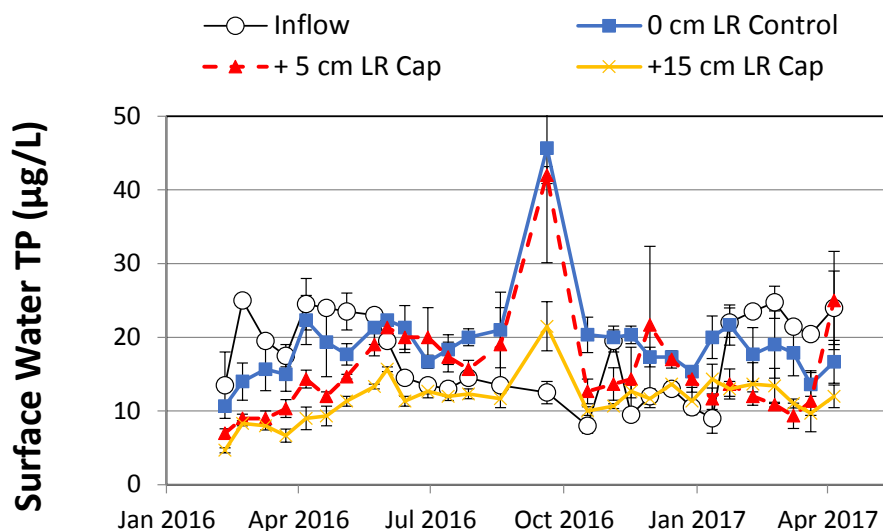


Figure 15. Average TP concentrations in the inflow and outflow waters of mesocosms established on high P muck soils with or without a LR cap (either 5- or 15-cm thickness), during a 14-month period of record (February 10, 2016, to April 5, 2017).

It is not yet known whether the performance benefit of a LR cap on high P muck can be sustained long term. Performance during the initial fourteen months of operations for the low P muck mesocosms, when average TP concentrations were reduced from 12 ± 1 µg/L in the inflow to 9 ± 1 µg/L at the outflows of the both the LR-capped muck treatment and control (uncapped muck) (**Figures 15 and 16**), was similar to the long-term performance in that study. With P-enriched soils more typical of the STAs, however, it is possible that rooted macrophytes will, over time, begin to access the nutrients below the LR layer and increase P concentration in outflow waters. An understanding of the macrophyte “nutrient pump” mechanism of internal loading is critical to replicating the success of the PSTA Cell and to fully evaluate the LR cap as an alternative to permanent removal (i.e. scraping) of muck soils in PSTA systems. The current mesocosm study will continue to provide insight into this question.

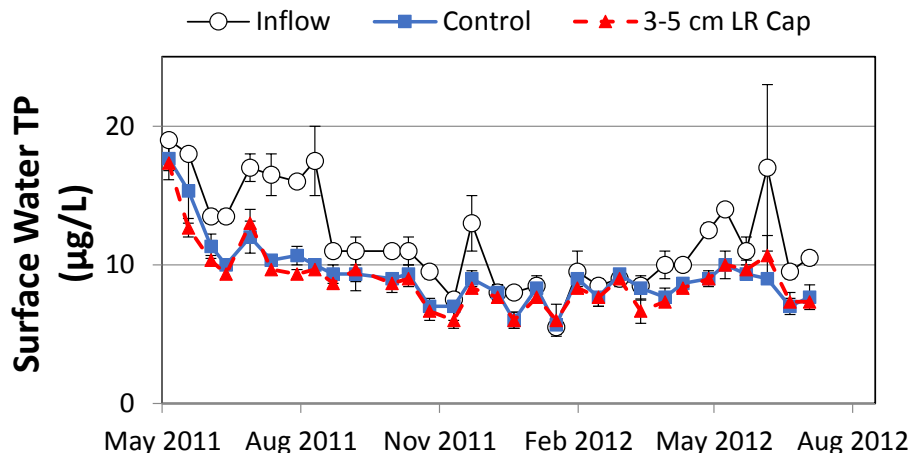


Figure 16. Average TP concentrations in the inflow and outflow waters of mesocosms established on low P muck soils with or without a LR cap, during a 14-month period of record (May 5, 2011, through July 3, 2012). Values represent the average ($\pm$ standard error).

EVALUATION OF THE SUSTAINABILITY OF PSTA TREATMENT PERFORMANCE THROUGH ANALYSIS OF SEDIMENT ACCRUAL AND VEGETATIVE NUTRIENT CONTENTS

Kevin Grace¹ and Tom DeBusk¹

INTRODUCTION

The previous section showed that substrate conditions are important factors for P removal performance of SAV/periphyton systems operated under low P conditions. There is concern that through typical operations, a PSTA system will accrue new sediment material that is different from the LR substrate, and the sustainability of the performance benefit provided by the LR will be compromised.

Sediments enriched with P can contribute to internal loading (Fisher and Reddy 2001), which may affect P removal performance. It is well documented that gradients in P content of wetland soils and macrophyte tissues can become established by flows of nutrient-enriched surface waters. (DeBusk et al. 1994, Juston et al. 2013). Both nutrient storages are in dynamic equilibrium with water column nutrients. Thus, increases in the P content of sediments or plants within an STA increase the likelihood of a higher water column P concentration. On the other hand, P content below a certain threshold could indicate minimum potential for P release and even net uptake potential.

Sediment P stability and release potential from PSTA sediments were compared to other muck-based substrates in use within Everglades STAs (DBE 2014). Core studies from DBE (2014) provided evidence that muck soils can provide more P to macrophytes than an exposed LR substrate or sediments from the PSTA Cell. DBE (2014) showed that macrophyte tissue P contents are quite low in the PSTA Cell compared to other STAs. Low tissue nutrient contents are likely to limit internal P loading from senescent vegetation. The best indicator of internal P loading may be alkaline phosphatase activity (APA), as measured in surface water, periphyton, or sediments (DBE 2014).

To assess the sustainability of performance in the PSTA Cell, gradients in sediment accrual depth and P content are compared to gradients in macrophyte tissue P content, and to long-term average water TP concentrations and APA rates. These comparisons directly address the following hypothesis: over time, accrued sediments in a PSTA Cell become a source of P to the water column and result in increased outflow TP concentrations compared to the initial condition when the cell bottom was mainly composed of LR substrate. Accumulation of sediment will result in elevated outflow TP concentrations compared to a bare LR substrate.

METHODS

The sampling and analytical methods for internal surveys of sediments, vegetation, and surface waters within the PSTA Cell have been described elsewhere (DBE 2015a, b, c) and are summarized as follows. The depth of the newly accrued marl sediment layer was quantified at 39 locations in the PSTA Cell during four surveys by retrieving intact cores and visually determining the transition from marl to remnant muck soil. The surveyed stations were evenly distributed throughout the cell, with three stations located along each of 13 transects (A through M) that ran perpendicular to flow and between vegetated berms that compartmentalize the PSTA Cell's 40-ha treatment area. In addition, the P content of the newly accrued sediment layer was quantified on three dates, May 2012, May 2014, and November 2016, for three stations within each of three regions of the PSTA Cell: near the inflow (B-transect), middle (G-transect), and outflow (L-transect).

On four occasions (July 2014, February 2015, June 2015, and September 2015), SAV was collected in the PSTA Cell from three stations within each region (inflow, middle, and outflow). A grab sample of aboveground tissues of the dominant SAV, along with associated epiphytic periphyton, was collected from each station. Periphyton was separated from the host plant, and both the periphyton and host SAV tissues were analyzed for TP content. Surface water samples were collected along 5 internal transects within the PSTA Cell, at 3 stations per transect, on 21 occasions between May 2012 and October 2015. Each water sample was analyzed for TP concentration and APA rates. Values for each parameter were averaged across all events for each station, then reported as a transect average ($\pm$ standard error across the three stations per transect).

RESULTS AND DISCUSSION

Sediment accretion varied locally within the cell, but accrual depth showed no consistent gradient from inflow to outflow (**Figure 17**). Newly accrued sediments in the PSTA Cell were low in P (typically < 300 mg/kg), as were the underlying muck soils (where present), when compared to soils in muck-based cells (Chimney 2014, DBE 2014). There was no difference in sediment P content between inflow and outflow regions of the PSTA Cell. By contrast, macrophyte tissues and periphyton showed decreasing P content with distance through the PSTA Cell. STA-3/4 PSTA Cell SAV communities generally had lower tissue P content relative to SAV communities at the outflow region of P-enriched muck-based STA cells (DBE 2014, 2015a, b). This gradient was coincident with reductions in surface water TP concentrations along the gradient from inflow to outflow in the cell, and increases in enzyme activity.

Over the monitoring period, the PSTA Cell demonstrated exponentially decreasing surface water TP concentrations over the length of the cell, as is typical for treatment wetlands (Kadlec and Wallace 2009). Clearly, internal P loads from accrued sediment must be sufficiently low as to allow P uptake mechanisms to exceed both internal and external P loads, resulting in net P removal from the water column, even after 10 years of operation and 7 to 10 cm of new sediment accretion. The contrast in longitudinal profiles of P concentration in the sediments and plants/periphyton is noteworthy (**Figure 17**). The enrichment of plant tissue P in the inflow region indicates a source of P not available to plants in the middle and outflow regions. The similarity of sediment P concentrations from inflow to outflow suggests that the sediments were not the source. Furthermore, the increasing APA down the flow path suggests increasing P limitation, and that the accrued PSTA sediments do not contribute substantial P loading to the water column directly or indirectly via the plants. In concert, these trends do not support the hypothesis that accrued sediment in a PSTA system becomes a P source that results in elevated outflow TP concentrations. By contrast, the PSTA Cell appears to have produced sediment that is sufficiently low in P and chemically stable to sustain a high level of P removal performance after 10 years of operation.

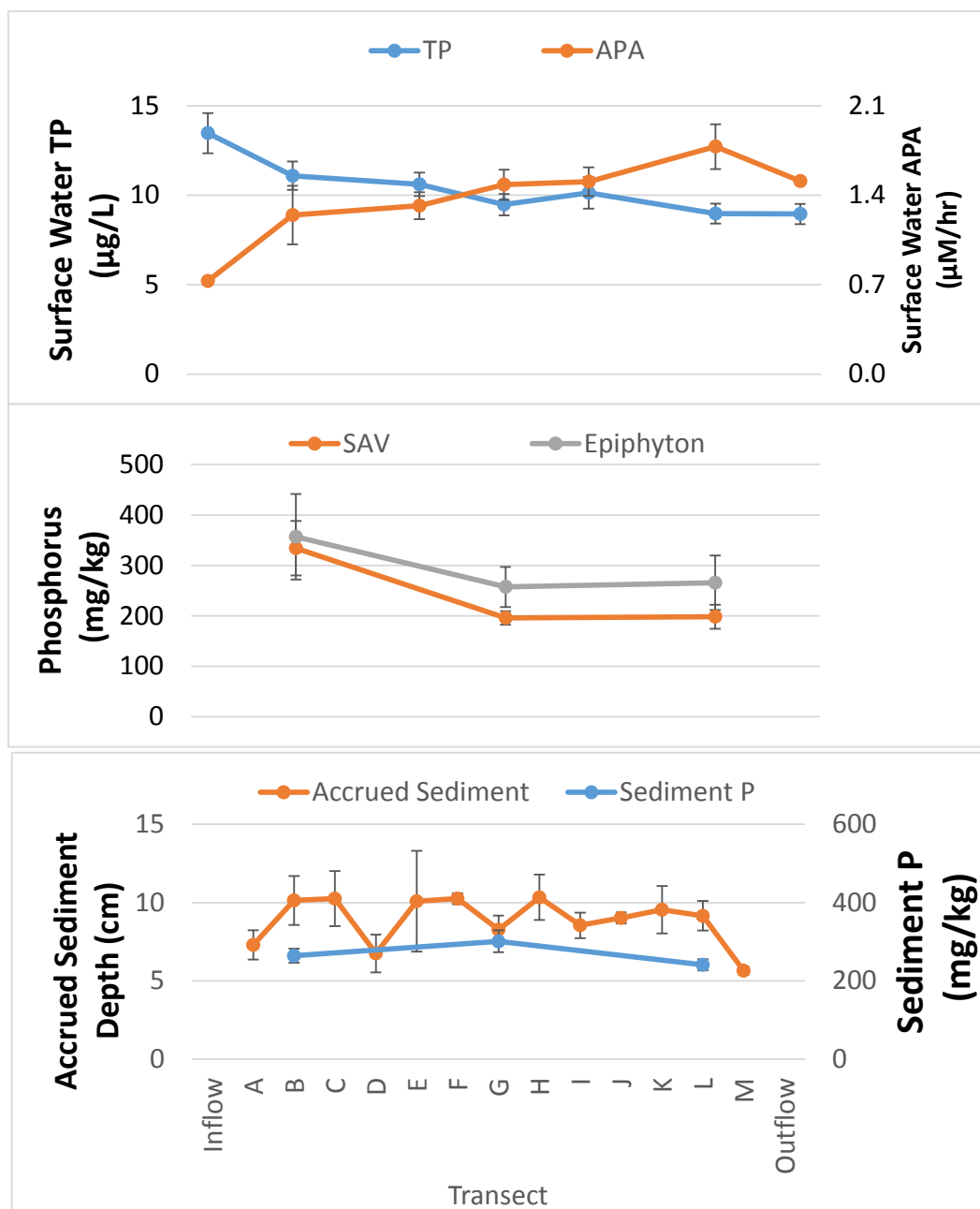


Figure 17. Gradients in water P content and APA, and vegetation, periphyton, and sediment P content within the STA-3/4 PSTA Cell. (Top) Average surface water TP concentrations and APA rates from 21 sampling events between May 2012 and October 2015. (Middle) Average periphyton and macrophyte tissue P contents along inflow, middle, and outflow region transects within the PSTA Cell, on four dates (July 7, 2014, February 25, 2015, June 24, 2015, and September 30, 2015). (Bottom) Depth of accrued sediment layer in the PSTA Cell for three stations along each of 13 internal transects within the PSTA Cell, averaged across four events (November 8, 2012, May 14, 2014, December 3, 2014, and December 8, 2016), and average sediment P content on three dates (May 31, 2012, May 14, 2014, and November 30, 2016). All values represent the mean ($\pm$ standard error) of three stations along each internal transect.

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