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**Restoration Strategies Regional Water Quality Plan –
Science Plan for the Everglades Stormwater Treatment Areas:**

Investigation of STA-3/4 Periphyton-based Stormwater Treatment Area (STA) Technology Performance, Design and Operational Factors

Effects of Pulse Flow Events on the STA-3/4 PSTA Cell's Phosphorus Treatment Performance

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EXECUTIVE SUMMARY

This report presents an analysis of the effects of pulse flow events on the STA-3/4 Periphyton-based Stormwater Treatment Area (PSTA) Cell's phosphorus (P) treatment performance. This analysis was conducted in support of Hypothesis #4 from the PSTA Study's Detailed Study Plan (SFWMD, 2014): *Low outflow total phosphorus (TP) concentrations result from the moderation of hydraulic loads and P loading to the PSTA Cell. Higher P loads will compromise treatment efficacy and result in increased outflow TP concentrations.*

Three managed flow pulse events were conducted: Pulse 1 (August 1–3, 2012); Pulse 2 (October 24–26, 2012); and Pulse 3 (June 24–26, 2014). The data evaluated for each of the pulse events included periods prior to, during, and after each pulse. Hydraulic loading rate (HLR), phosphorus loading rate (PLR), and hydraulic residence time (HRT) for each pulse event were compared. TP concentrations were measured every three hours using remote phosphorus analyzers (RPAs) at the G-390B inflow culvert and the G-388 outflow pump station were used in the analyses.

Daily average depths in the PSTA Cell during Pulses 1 and 2 increased by approximately 0.6 ft compared to the daily average depths at the 10.0 ft National Geodetic Vertical Datum (NGVD) target stage. Daily average depths during Pulse 3 increased by 0.2 ft compared to the daily average depths at the 10.5 ft NGVD target stage. Water depths in the PSTA Cell returned to pre-pulse depths about 1 to 3 days after the pulses were completed.

Average flow rates for the PSTA Cell during the pulses (53 cfs for Pulse 1, 57 cfs for Pulse 2, and 74 cfs for Pulse 3) were about three to four times higher than the average historical flow rate (approximately 18 cfs). Pulses 1 and 2 produced 3-day maximum HLRs (28.5 and 32.1 cm day^{-1}, respectively) comparable to STA-3/4 Cell 2B historical 3-day maximum average HLRs (24.7 to 31.5 cm/day), while Pulse 3 resulted in a 3-day maximum HLR (43.4 cm day^{-1}) that was about 1.5 times greater than the 3-day maximum HLRs experienced historically at STA-3/4 Cell 2B. High flow rates during the pulses resulted in shorter HRTs (1 to 2 days) compared to HRTs (4 to 5 days) during normal operational periods in the PSTA Cell. Daily PLRs sharply increased for all three pulses, with the highest PLR (6.4 g m^{-2} day^{-1}) observed during Pulse 3.

TP concentrations at the PSTA Cell outflow location after the pulses were generally lower than or similar to outflow TP concentrations before the pulses. Overall, study results indicate that pulse flow events and associated higher P loads had no adverse effect on the PSTA Cell's P treatment performance thereby disproving Hypothesis #4. The results also suggest that inflow TP concentrations greater than 22 µg L^{-1} generally did not result in TP concentrations lower than 13 µg L^{-1} at the outflow.

INTRODUCTION

The STA-3/4 Periphyton-based Stormwater Treatment Area (PSTA) facility was constructed by the South Florida Water Management District (SFWMD or District) to address uncertainties associated with large-scale implementation of the PSTA treatment technology. An important difference between the PSTA Cell and adjacent 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 phosphorus (P) flux back to the water column. As a result, the floor of the PSTA Cell is about 1 ft lower than the ground elevation of the adjacent treatment cells. Based on a 2013 elevation survey (GCY Professional Surveyors & Mappers Inc., 2013), the average caprock elevation in the PSTA Cell is 8.8 ft National Geodetic Vertical Datum (NGVD).

The PSTA Cell has shown promising treatment performance by discharging water with very-low TP concentrations. During the first five years of operation in Water Years 2008 –2012 (WY2008–WY2012; May 1, 2007–April 30, 2012), the PSTA Cell's outflow flow-weighted mean (FWM) total phosphorus (TP) concentrations ranged from 8 to 12 micrograms per liter [$\mu g\ L^{-1}$, or parts per billion (ppb)]. In 2013, the SFWMD identified several key studies to be included in the Restoration Strategies Science Plan (SFWMD, 2013). One of these studies is the Investigation of STA-3/4 PSTA Performance Design and Operational Factors (PSTA Study), which includes the implementation of several short hydraulic pulses in the PSTA Cell to evaluate the effect of high flow rates on the cell's performance. While the historical (WY2008–WY2012) annual HLRs for the PSTA Cell were generally within the range of rates observed for STA-3/4 Cell 2B (the adjacent full-scale treatment cell), the peak 3-day HLR in the PSTA Cell was lower than that observed in Cell 2B. Therefore, there was concern that the flows delivered to the PSTA Cell during its period of superior performance did not adequately represent hydraulic conditions that occur in full-scale STA treatment cells.

This report includes analyses conducted in support of Hypothesis #4 from the PSTA Study's Detailed Study Plan available online at www.sfwmd.gov/rs_scienceplan

> ***Hypothesis #4:*** *Low outflow total phosphorus (TP) concentrations result from the moderation of hydraulic loads and P loading to the PSTA Cell. Higher P loads will compromise treatment efficacy and result in increased outflow TP concentrations.*

The analysis of three managed pulse flow events in the PSTA Cell are summarized in this report. The data for each pulse event was 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. The HLR, PLR, and HRT for each pulse and the associated pre- and post-pulse periods were compared. TP concentrations measured using remote phosphorus analyzers (RPAs) at the G-390B inflow culvert and the G-388 outflow pump station were used in the analyses.

In addition, the PSTA Cell experienced high inflows and stages resulting from Tropical Storm Isaac (August 26–27, 2012). Limited analysis of the data associated with T.S. Isaac is included; however, a full side-by-side comparison with the managed pulses was not conducted due to the overlap of T.S. Isaac with Pulse 1, and due to a failure of the G-388 outflow pump station that occurred during the storm.

METHODS

STUDY AREA

Stormwater Treatment Area 3/4 (STA-3/4) is located in western Palm Beach County between the North New River Canal to the east and the Holey Land Wildlife Management Area to the west, and north of the Broward County line. STA-3/4 was built on land that prior to construction was farmed as part of the Everglades Agricultural Area (EAA). The STA-3/4 PSTA Project is a 400-acre section of Cell 2B in

STA-3/4 comprised of a 200-acre Upper Submerged Aquatic Vegetation (SAV) Cell, a 100-acre Lower SAV Cell, and a 100-acre PSTA Cell (**Figure 1**; Andreotta et al., 2014). The PSTA Cell is situated between the Lower SAV Cell to the east, the STA-3/4 Discharge Canal to the west, and north of the former Griffin rock pit. Water from the Upper SAV Cell enters the PSTA Cell through two inflow gated culverts (G-390A and B), moves southward through the cell, and is then discharged by the G-388 outflow pump station. The G-390A inflow structure consists of a 6-ft by 6-ft concrete box gated culvert, while the G-390B inflow structure consists of a 36" diameter aluminum pipe installed inside a 6-ft by 6-ft concrete box gated culvert (Zhao et al., 2015). The G-388 outflow pump station consists of two pumps (Pump #1 and Pump #2), with a capacity of 100 and a 60 cubic feet per second (cfs), respectively. The outflow pumps run on automatic mode through a float switch programmed to turn the pumps on and off to achieve the target stage.

PULSED FLOWS

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 10.0 ft NGVD during both Pulses 1 and 2, and 10.5 ft NGVD for Pulse 3. Normal operation of the inflow culverts is based on a design flow of approximately 20-30 cfs (Zhao et al., 2015). To achieve this flow rate, the G-390B culvert gate opening is maintained at 1 ft, while the gate at G-390A is kept closed. During each of the three pulses, the G-390A and B gate openings and G-388 automatic on/off settings were modified to accommodate the additional flows through the cell. The maximum 3-day average HLRs (ranging from 24.7 to 31.5 cm/day) observed in STA-3/4 Cell 2B for the period WY2009–WY2012 were used to develop the target flow rates for the PSTA Cell flow pulses.

PHOSPHORUS ANALYSIS

Surface water flows and stages are routinely monitored by the SFWMD at the PSTA Cell's inflow (G-390A and B) and outflow (G-388) structures (**Figure 1**). RPA units located at G-390B and G-388 were programmed to collect and analyze water samples for TP every three hours. All data analyses presented in this report utilized the RPA TP data.

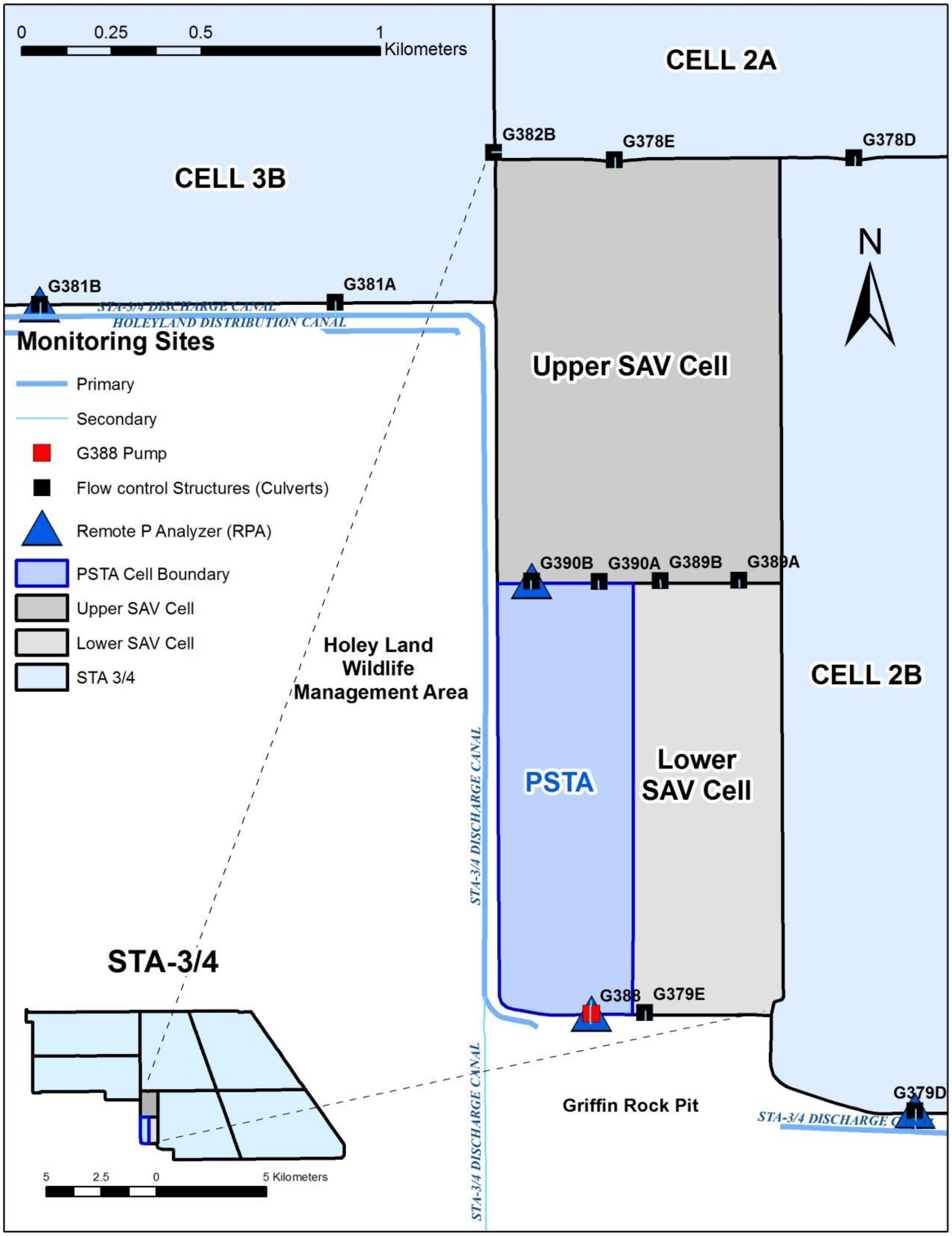

Figure 1. Stormwater Treatment Area 3/4 (STA-3/4) locations of the inflow (G-390A and B) and outflow (G-388) structures in the PSTA Cell and features of the surrounding area.

CALCULATION OF PARAMETERS

The PSTA Cell average daily flow was used to estimate daily inflow and outflow water volumes. Stage readings at G-390B and G-388 were used to calculate daily average stages in the PSTA Cell. All flow and stage data were obtained using the preferred DBKEYs from the SFWMD's DBHYDRO database (**Table 1**).

Table 1. Periphyton-based Stormwater Treatment Area (PSTA) Cell flow and stage data preferred DBKEYs.

DBKEY	Station	Data Type	Data Description
TZ219	G388_H	STG	Headwater Stage
V2504	G388_P	FLOW	Daily Flow
V8861	G390A_C	FLOW	Daily Flow
V8862	G390B_C	FLOW	Daily Flow
UA609	G390B_T	STG	Tailwater Stage

The daily average stage (H) in the PSTA Cell was estimated by calculating the arithmetic average of the daily mean stage at the G-390B tailwater (TW) and the G-388 headwater (HW) locations.

Daily mean water depth was calculated as:

$$h = H - G \tag{1}$$

where:
h = mean water depth (ft),
H = average stage at the inflow and outflow of the PSTA Cell (ft NGVD), and
G = average ground caprock elevation in the PSTA cell (8.8 ft NGVD).

The daily surface HLR was calculated using the following equation:

$$\text{HLR} = \frac{Q_{in}}{\text{A}} \text{ x } 100 \tag{2}$$

where:
HLR = surface-water hydraulic loading rate (cm day^{-1}),
Q_{in} = average daily surface-water inflow rate (m^3 day^{-1}),
A = PSTA Cell surface area (m^2).

Daily nominal HRT was calculated by dividing the water volume in the PSTA Cell by the average of the inflow and outflow flow rates:

$$\text{HRT} = \frac{\text{V}}{(\text{Q}_{\text{in}} + \text{Q}_{\text{out}})/2} \tag{3}$$

where:

HRT = nominal hydraulic residence time (day),
V = PSTA Cell's average storage volume (m^3)[1],
Q_{in} = average daily surface-water inflow rate (m^3 day^{-1}), and
Q_{out} = average daily surface-water outflow rate (m^3 day^{-1}).

Daily PLR was calculated using the following equation:

$$PLR = \frac{[(C_{in})(V_{in})]}{A} \text{ x } 10^{-3} \tag{4}$$

where:

PLR = phosphorus loading rate (g m^{-2} day^{-1}),
C_{in} = surface-water inflow FWM TP concentration recorded by the RPA (mg m^{-3})
V_{in} = daily surface-water inflow volume (m^3),
A = PSTA Cell surface area (m^2)

DATA ANALYSIS

The HLR, PLR, and HRT for each of the managed pulse events 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 TP outflow was lagged by 4 days from the inflow TP data collection to account for HRT. Summary statistics were calculated (means, medians, interquartile ranges, and 10th and 90th percentiles of the data distributions) and displayed using box plots to examine central tendencies and variability in the data. 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 of all analyses was evaluated at $\alpha = 0.05$. All statistical analyses were performed with JMP® statistical software (version 11.2.0; SAS Institute Inc. 2013, Cary, NC).

[1]Throughout this report, water volumes and flow rates have been converted from metric to imperial units and are presented as acre-feet (ac-ft) and cubic feet per second (cfs), respectively.

RESULTS AND DISCUSSION

STAGE AND DEPTH

Daily average stage within the PSTA Cell was evaluated from January 2012 through mid-August 2014. Stage fluctuations were observed as a result of drought periods, tropical storms, rain events, and managed pulse events. Stage also fluctuated due to failure of the G-388 outflow pump station that occurred during T.S. Isaac. The highest daily average stage occurred during Pulse 2 (10.9 ft NGVD) followed by Pulse 3 (10.8 ft NGVD) and Pulse 1 (10.7 ft NGVD). Soon after Pulse 1 was completed, the PSTA Cell experienced the effects of T. S. Isaac. During this period, the PSTA Cell inflow and outflow structures had been returned to the normal settings; however, failure of the G-388 outflow pump station during the storm event resulted in a temporary increase in stages causing the highest daily average stage (11.0 ft NGVD) recorded during the period of record (**Figure 2**).

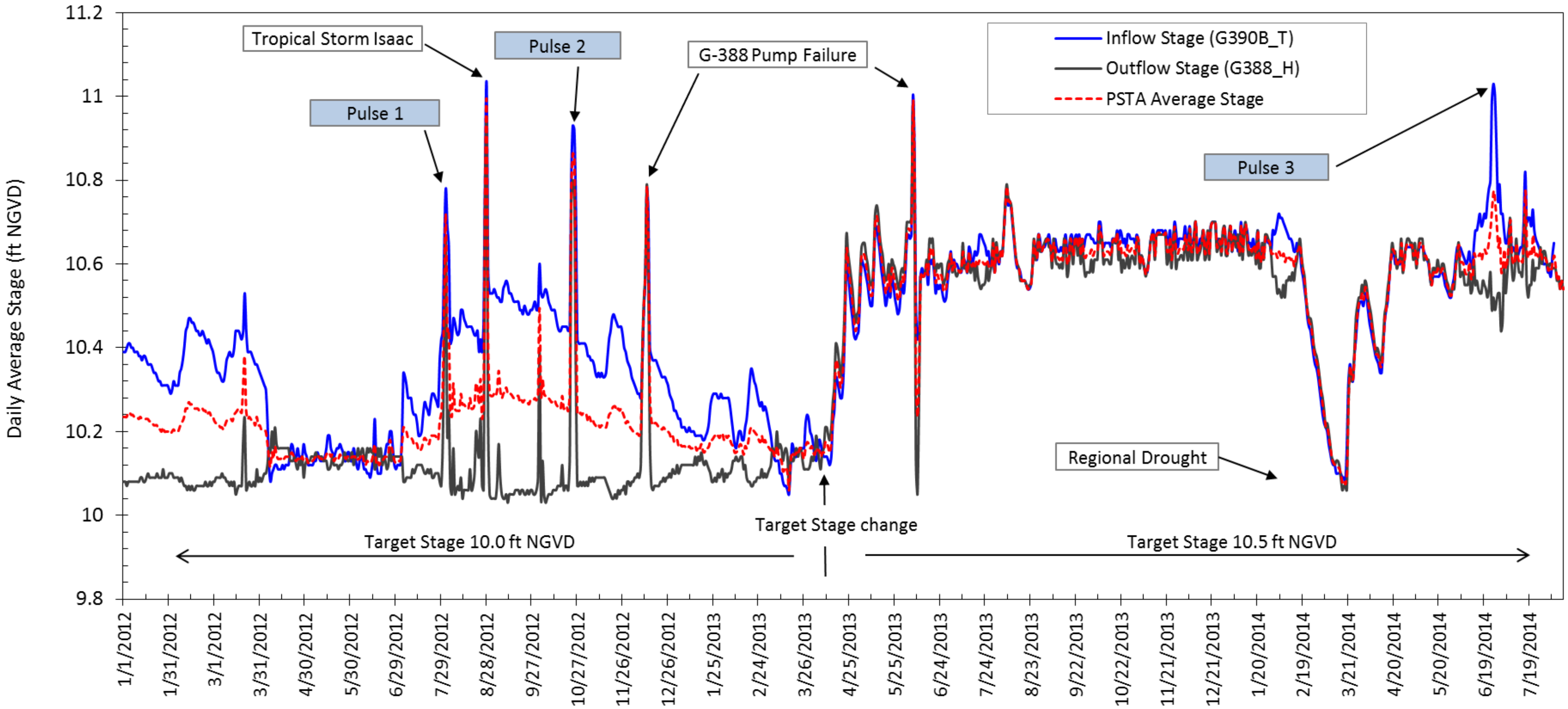

Figure 2. Daily inflow and outflow stage and water depths in the PSTA Cell from January 2012 to August 2014. Timelines for the three pulse flow events, Tropical Storm Isaac, and the target stage increase from 10.0 to 10.5 feet National Geodetic Vertical Datum (ft NGVD) are also depicted. Average ground elevation in the PSTA Cell is 8.8 ft NGVD.

The target stage in the PSTA Cell was maintained at 10.0 ft NGVD by the outflow pump station during the first portion of the analysis period (i.e., from January 2012 to April 2013). The target stage was increased to 10.5 ft NGVD in April 2013 to reduce the volume of seepage into the PSTA Cell that was occurring under the 10.0 ft NGVD target stage (Zhao et al., 2015). Excluding the pulse events, differences between the inflow and outflow stage were more pronounced under the 10.0 ft NGVD target stage than under the 10.5 ft NGVD target stage (**Figure 2**). This is most likely due to reduced hydraulic resistance as a result of the increased target stage, which allowed water to flow more easily over the vegetation strips[2].

Daily average depths in the PSTA Cell during Pulses 1 and 2 increased by approximately 0.6 ft compared to the daily average depths at the 10.0 ft NGVD target stage. Daily average depths during Pulse 3 increased by 0.2 ft compared to the daily average depths at the 10.5 ft NGVD target stage (**Figure 3**). Water depths in the PSTA Cell returned to pre-pulse depths about 1 to 3 days after the pulses were completed.

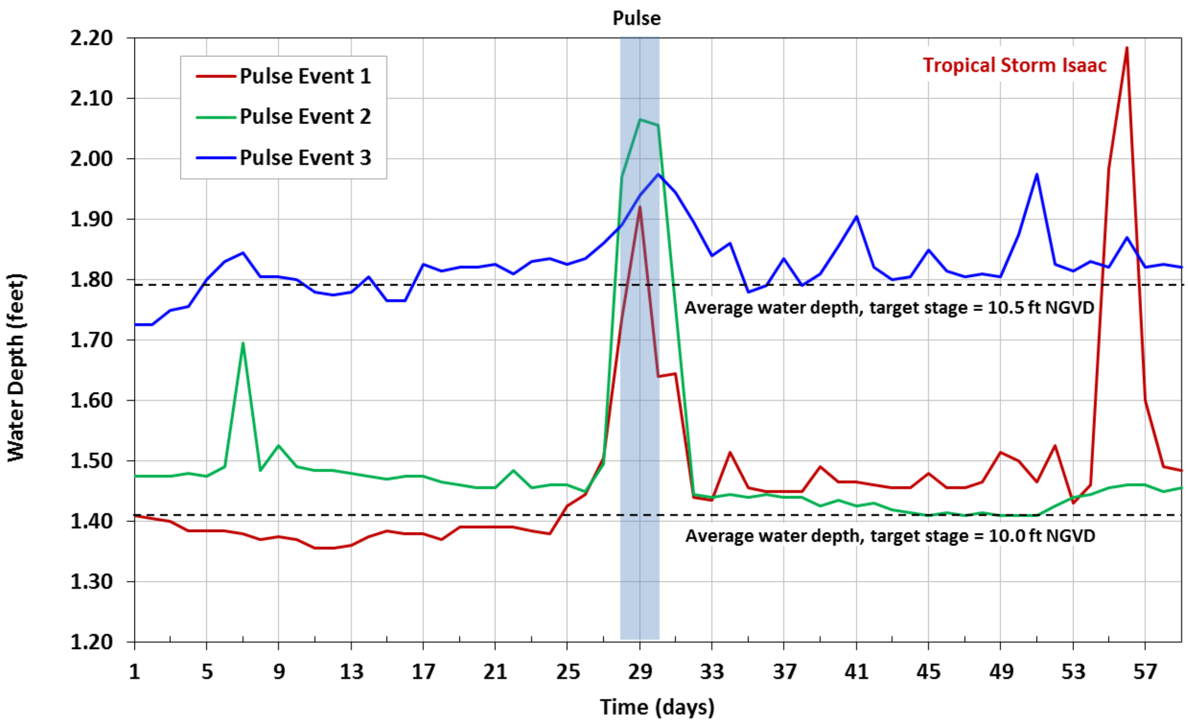

Figure 3. Daily average water depth in the PSTA Cell 28 days before, during, and 28 days after the three pulse flow events under two different target stage regimes. Note that Pulse 3 was conducted after the target stage was increased to 10.5 ft NGVD.

[2]When the PSTA Cell was constructed, although most of the peat was scraped and removed, a portion of the scraped peat material was left on site and reconfigured into twelve vegetation strips (each 18"- 24" high) oriented perpendicular to flow. The vegetation strips are being evaluated under a separate effort (SFWMD, 2014).

FLOW RATE

Under normal operating conditions, surface inflow to the PSTA Cell is controlled by maintaining the G-390B culvert gate opening at 1 ft, while the gate at G-390A is kept closed. During the three managed pulse events, gate openings at both G-390A and B were increased to facilitate the conveyance of higher flows into the PSTA Cell. The daily average inflow and outflow rates for the pre- and post-pulse periods were similar for all three pulses, while the highest inflow and outflow rates occurred during Pulse 3 (**Figure 4**). Under normal operating conditions, the daily average surface inflow to the PSTA Cell is approximately 14 cfs. The target inflow rate for the pulsed flow events was 60 to 75 cfs at the inflow structures. Pulse 1 and Pulse 2 produced a 3-day average inflow rate of 47 and 53 cfs, respectively. During Pulse 3, the high end of the flow target range was achieved, with a 3-day average inflow rate of 72 cfs (**Table 2**). Surface inflow rate during the managed three pulses was three to five times higher than historical inflow rates.

During all three managed pulses, slightly higher flow rates were observed at the outflow than the inflow mainly as a result of the over-sizing of the outflow pump station with respect to the design inflow capacity[3] (**Figure 5**). During T.S. Isaac, the PSTA Cell experienced a 3-day average inflow rate of 28 cfs however failure of the outflow pump station during the storm resulted in a short period of little to no outflow followed by a short period of relatively high flows immediately after the pump station became operational again (**Figure 5**, panel B). Average flow rates for the PSTA Cell during the pulses (53 cfs for Pulse 1, 57 cfs for Pulse 2, and 74 cfs for Pulse 3) were about three to four times higher than the average historical flow rate (approximately 18 cfs).

[3]The two pumps in the G-388 pump station were salvaged from another SFWMD pump station as a cost-saving measure with the understanding that they were relatively oversized in comparison to the approximate 20–30 cfs design flow for the PSTA Cell (Zhao et al., 2015).

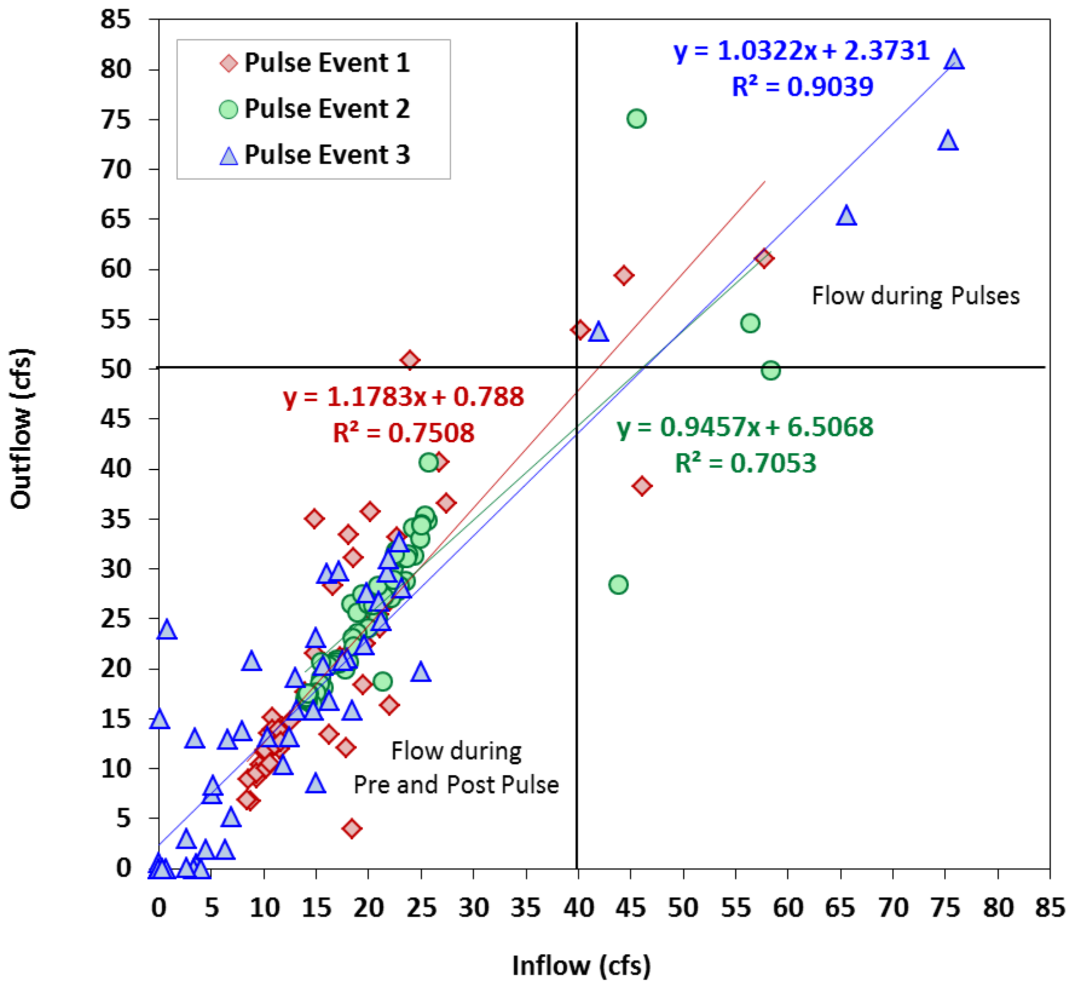

Figure 4. Daily average flow rates in cubic feet per second (cfs) at inflow and outflow for three pulse flow events conducted in the PSTA Cell covering periods 28 days before pulse, 3-day pulse, and 28 days after pulse.

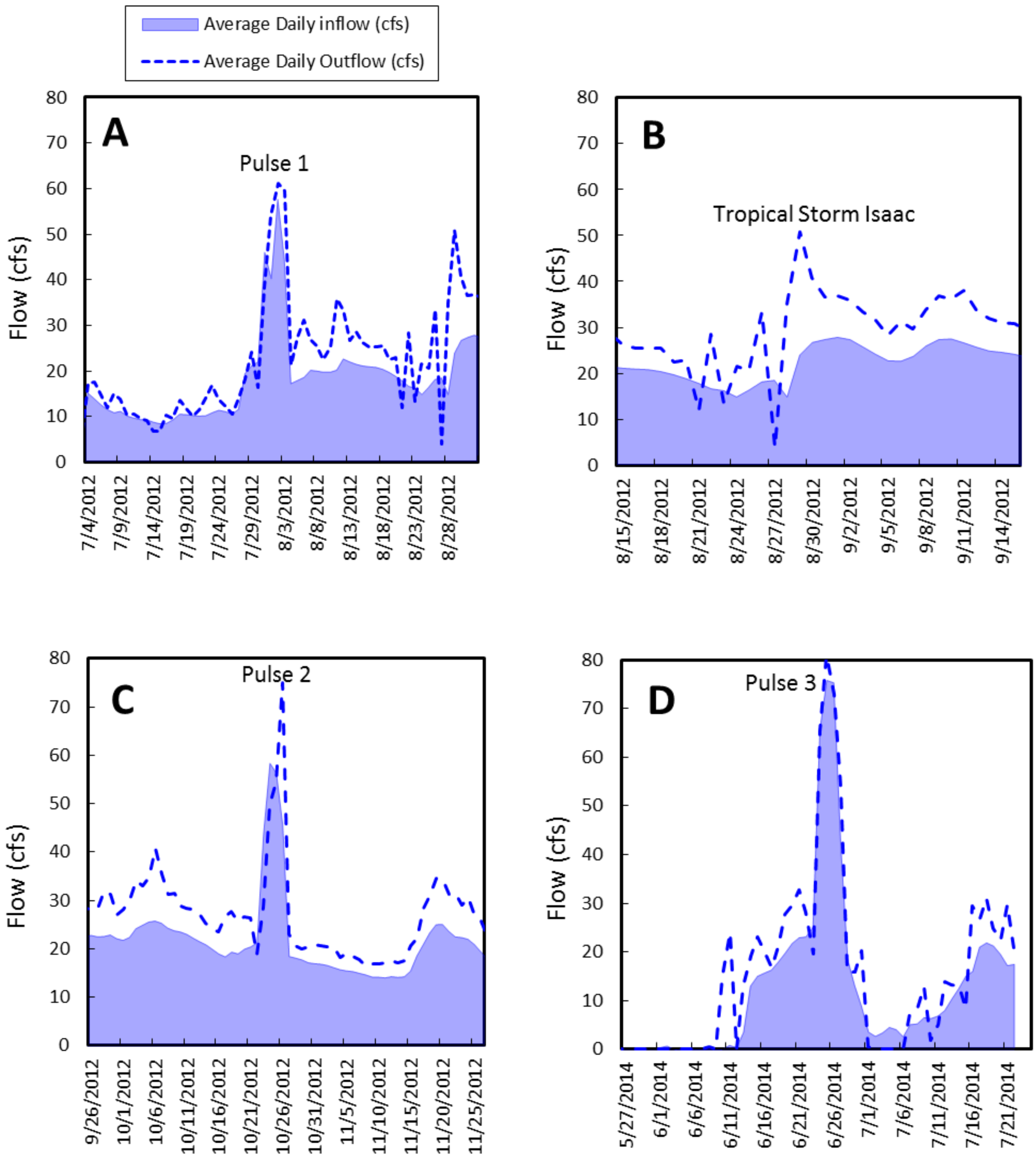

Figure 5. PSTA Cell daily average inflow and outflow flow rates for Pulse 1 (A), Tropical Storm Isaac (B), Pulse 2 (C), and Pulse 3 (D).

Table 2. Comparison of PSTA Cell surface inflow and outflow flow rates during three flow pulses and Tropical Storm Isaac.

Event	Period	Peak Inflow (cfs)	3-day Average Inflow (cfs)	Peak Outflow (cfs)	3-day Average Outflow (cfs)	Average Flow (cfs)	3-day Average Flow (cfs)
Pulse 1	Aug 1 - Aug 3, 2012	58	47	61	58	59	53
T.S. Isaac	Aug 28 - Sep 2, 2012	28	28	51	43	37	39
Pulse 2	Oct 24 - Oct 26, 2012	58	53	75	60	60	57
Pulse 3	Jun 24 - Jun 26, 2014	76	72	81	73	78	74

Flow = average of surface inflow and outflow

HYDRAULIC LOADING RATE

The intent of the flow pulses was to subject the PSTA Cell to a maximum 3-day HLR that was similar to or greater than the maximum 3-day average HLR experienced in STA-3/4 Cell 2B, which ranged from 24.7 to 31.5 cm day^{-1} (**Table 3**). The target flow rate of 75 cfs for the PSTA Cell was selected to achieve a 3-day HLR of approximately 45 cm day^{-1}.

Under normal operating conditions, HLRs in the PSTA Cell ranged from approximately 6 to 14 cm/day. The 3-day HLR for Pulses 1, 2, and 3 was 28, 32, and 43 cm day^{-1}, respectively (**Table 3**). During the 28-day pre-pulse periods for Pulses 1, 2, and 3, the PSTA Cell experienced daily HLRs ranging from 5 to 28, 11 to 26, and 0 to 15 cm day^{-1}, respectively (**Figure 6**). In the 28-day post-pulse period for Pulses 1 and 2, the PSTA Cell had daily HLRs ranging from 9 to 16 and 8 to 15 cm day^{-1} respectively, while Pulse 3 HLRs ranged from 2 to 25 cm day^{-1} (**Figure 6**). Daily HLRs immediately after the three pulses were comparable to those observed under normal operating conditions.

HLRs in the PSTA Cell during and after T.S. Isaac were about three times lower than the maximum 3-day HLRs observed during the pulses and nearly two times lower than the maximum 3-day HLRs observed in Cell 2B (**Figure 6**). This was a result of the outflow pump station failure that occurred during the storm. The managed pulses, however, generated HLRs approximately three times higher than those observed under normal operating conditions for the PSTA Cell. Pulses 1 and 2 produced 3-day maximum HLRs (28.5 and 32.1 cm day^{-1}, respectively) comparable to STA-3/4 Cell 2B historical 3-day maximum average HLRs (24.7 to 31.5 cm day^{-1}), while Pulse 3 resulted in a 3-day maximum HLR (43.4 cm day^{-1}) that was about 1.5 times greater than the 3-day maximum HLRs experienced historically in STA-3/4 Cell 2B.

Table 3. Maximum 3-day average hydraulic loading rates (HLRs) in STA-3/4 Cell 2B during four water years and in the PSTA Cell during the three pulse flow events and Tropical Storm Isaac.

AREA	Period	Max 3-day Average HLR (cm day^{-1})
STA-3/4 Cell 2B	WY2009	27.6
	WY2010	31.5
	WY2011	24.7
	WY2012	25.6
PSTA Cell	Pulse 1	28.5
	T.S. Isaac	16
	Pulse 2	32.1
	Pulse 3	43.4

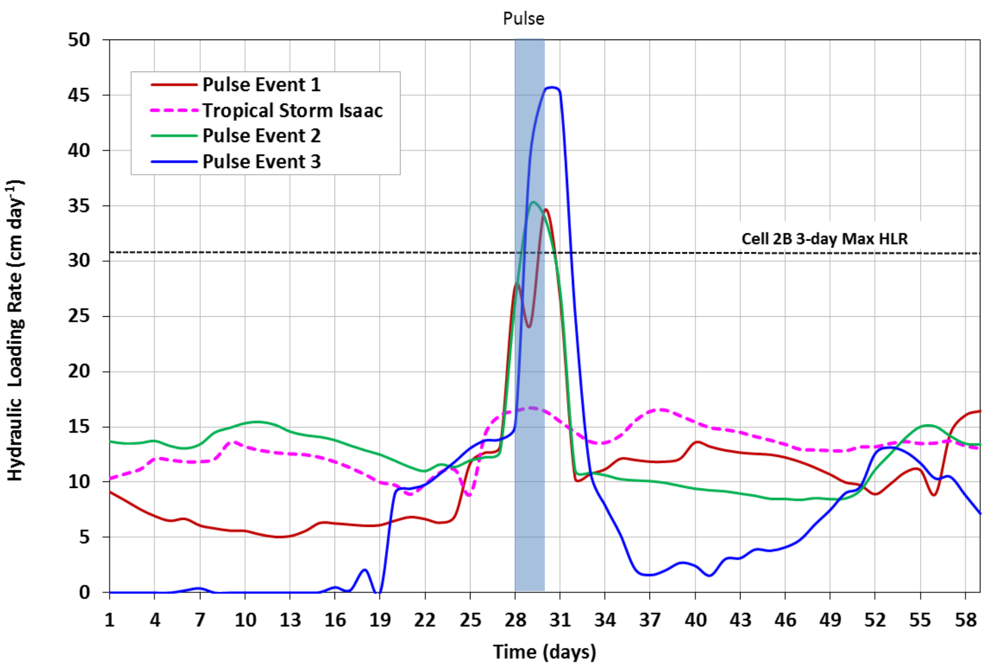

Figure 6. Daily average HLRs in the PSTA Cell during the three pulse flow events, 28 days before and 28 days after each pulse, and during Tropical Storm Isaac.

HYDRAULIC RESIDENCE TIME

The hydraulic residence time (HRT) for each of the three pulse flow events was estimated for periods covering the 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.

The 3 and 7-day pre-pulse periods were characterized by gradual increases in flow rates at the G-390B and the G-388, including increases in storage volume within the PSTA Cell, as operational changes were made to produce the flow pulses. In comparison, the periods after the 3-day pulses showed a slight reduction in flow rates and storage volume particularly during the first 3 days with inflow and outflow rates remaining constant for up to 28 days after Pulses 1 and 2. Pulse 3 experienced a substantial decline in flow rates through the PSTA Cell during the 28-day post-pulse period. The reduction in flow to and from the PSTA Cell immediately after Pulse 3 resulted in longer HRTs that were more representative of periods associated with low flows and stagnant conditions (**Table 4**). Flow Pulse events 1, 2, and 3 had HRTs of 1.7, 1.8, and 1.4 days, respectively. These were approximately two times shorter than HRTs for the 3 days prior to and after each pulse (**Table 2**). In comparison to Pulse 1 and 2, Pulse 3 had the highest flow rate and the shortest HRT.

High flow rates experienced during the pulses resulted in shorter HRTs (1 to 2 days) compared to the normal operational periods for the PSTA Cell (approximately 4 to 5 days). It was theorized that the reduced HRTs might adversely affect the treatment performance of the PSTA Cell. However, this did not appear to be the case, as no substantial increases in outflow TP concentration occurred during or after the pulses.

Table 4. Comparison of PSTA Cell's mean hydraulic residence time (HRT), average storage volume, and flow rates prior to, during, and after the three pulses.

Pulse Event / Period (days)	Time Interval	Mean Volume (ac-ft)	Mean flow rate (inflow and outflow) (cfs)	Mean HRT (days)
Pulse Event 1				
Pre Pulse (28)	Jul 4 - Jul 31	141	13	6.0
Pre Pulse (7)	Jul 25- Jul 31	148	20	4.5
Pre Pulse (3)	Jul 29 - Jul 31	157	28	3.1
Pulse (3)	Aug 1- Aug 3	175	53	1.7
Post Pulse (3)	Aug 4 - Aug 6	147	21	3.5
Post Pulse (7)	Aug 4 - Aug 10	147	22	3.4
Post Pulse (28)	Aug 4 - Aug 31	153	23	3.6
Pulse Event 2				
Pre Pulse (28)	Sep 26 - Oct 23	151	26	3.0
Pre Pulse (7)	Oct 17 - Oct 23	155	24	3.2
Pre Pulse (3)	Oct 21 - Oct 23	165	27	3.2
Pulse (3)	Oct 24 - Oct 26	197	57	1.8
Post Pulse (3)	Oct 27 - Oct 30	145	20	3.7
Post Pulse (7)	Oct 27 - Nov 23	145	19	3.8
Post Pulse (28)	Oct 27 - Nov 23	144	20	3.4
Pulse Event 3				
Pre Pulse (11) *	Jun 13 - Jun 23	182	10	5.1
Pre Pulse (7)	Jun 17 - Jun 23	185	26	4.2
Pre Pulse (3)	Jun 21 - Jun 23	188	28	3.8
Pulse (3)	Jun 24 - Jun 26	197	74	1.4
Post Pulse (3)	Jun 27 - Jun 29	188	28	4.7
Post Pulse (7)	Jun 27 - Jul 3	184	14	**
Post Pulse (18)	Jul 7 - Jul 24	185	15	8.4

* No flow observed at inflow and outflow before this period
** No outflow recorded 3 days after the pulse

PHOSPHORUS CONCENTRATIONS AND LOADING RATES

The daily average TP data at the inflow and outflow structures of the PSTA Cell varied among the three pulse flow events. Daily inflow TP concentrations ranged from 15 to 24 µg L^{-1} during the 28-day period prior to Pulse 1 and Pulse 3, while inflow TP concentrations prior to Pulse 2 were ultra-low with an average of 8 µg L^{-1} (**Figure 7**). The average daily PLR for the 28-day period prior to Pulse 1 and 2 was 1.5 and 1 mg P m^{-2} day^{-1}, respectively, while the average daily PLR for the 11-day period prior to Pulse 3 was 2.2 mg P m^{-2} day^{-1} (**Figure 7**). Furthermore, 17 days prior to Pulse 3, the PSTA Cell experienced a period of stagnation with no substantial flow into or out of the cell. For this reason, calculated values presented only include the 11-day period prior to Pulse 3.

For all three of the flow pulses, the TP concentrations entering the PSTA Cell gradually decreased to levels comparable to TP concentrations at the outflow. The daily PLRs sharply increased for all three pulses with the highest PLR (6.4 g m^{-2} day^{-1}) observed during Pulse 3 (**Figure 7**). After the pulses, the TP concentrations at the inflow and outflow continued to decline for Pulse 1 and 3, but remained constant for Pulse 2 (**Figure 7**).

There were significant positive linear relationships between inflow and outflow TP concentrations for Pulse 1 (R^2= 0.753, $P < 0.0001$), Pulse 2 (R^2=0.469, $P < 0.0001$) and Pulse 3 (R^2=0.738, $P < 0.0001$). The weaker relationship for Pulse 2 was due to the very low and similar inflow and outflow TP concentrations, with the exception of spikes in TP concentration at the outflow during the post-pulse period (**Figure 8**). These spikes in outflow TP concentrations were not included in the analysis since they were likely a result of herbicide application during the first week of November 2012 to control the expansion of spikerush within the PSTA Cell. The resulting vegetation die-off and decomposition may have also played a role in the observed spike in outflow TP concentrations.

The ANCOVAs of outflow TP concentrations 3 days before and after each pulse showed a statistically significant concentration reduction for Pulse 1 (df = 2, 28; F = 31.2 $p < 0.0001$) and 3 (df = 2, 45; F = 8.71 $p = 0.0006$), while 3-day pre- and post-pulse outflow TP concentrations for Pulse 2 were unchanged. Similar results were observed when comparing outflow TP concentrations 7 days before and after each the pulse; there were significant concentration reductions for Pulses 1 (df = 2, 88; F = 64.5 $p < 0.0001$) and 3 (df = 2, 105; F = 35.4 $p < 0.0001$), but not for Pulse 2. Analysis of TP concentrations 28 days before and after each pulse indicated significant concentration reductions for Pulse 1 (df = 2, 323; F = 284.3. $p < 0.0001$) and 3 (df = 2, 429; F = 390.4 $p < 0.0001$), while there was a significant increase in outflow concentration after Pulse 2 (df = 3, 317; F = 47.2 $p < 0.0001$). As stated above, this TP increase was likely due to herbicide application and subsequent vegetation die-off conducted one week after Pulse 2 was completed. Figure 9 show the differences between pre- and post-pulse TP outflow concentrations.

While many of the reductions between pre- and post-pulse outflow mean TP concentrations noted above were statistically significant, the magnitude of these differences in all cases was within the practical quantification limit (PQL) for TP (8 µg L^{-1})[4] and often close to the method detection limit (MDL) of 2 µg L^{-1}. Further evaluation of the pulse data suggested that inflow TP concentrations greater than 22 µg L^{-1} generally did not result in outflow TP concentrations lower than (13 µg L^{-1}) [5] (**Figure 8**). To confirm this observation, the daily average inflow and outflow RPA TP concentrations for the period from April 2012 to August 2014 were evaluated. Results of this evaluation also suggested that inflow concentrations greater than 22 µg L^{-1} did not result in outflow concentrations below 13 µg L -1 (**Figure 10**). In summary, increased PLR resulting from high flow pulse events did not negatively affect the PSTA Cell's outflow TP concentrations.

[4] The PQL is the lowest measurement level that can be reliably achieved within the limits of routine analytical precision and accuracy; the PQL = 4 × MDL. The MDL is the minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero.

[5] 13 µg L^{-1} is shown as a reference to the STA annual discharge limit described in the Restoration Strategies Science Plan (SFWMD, 2013).

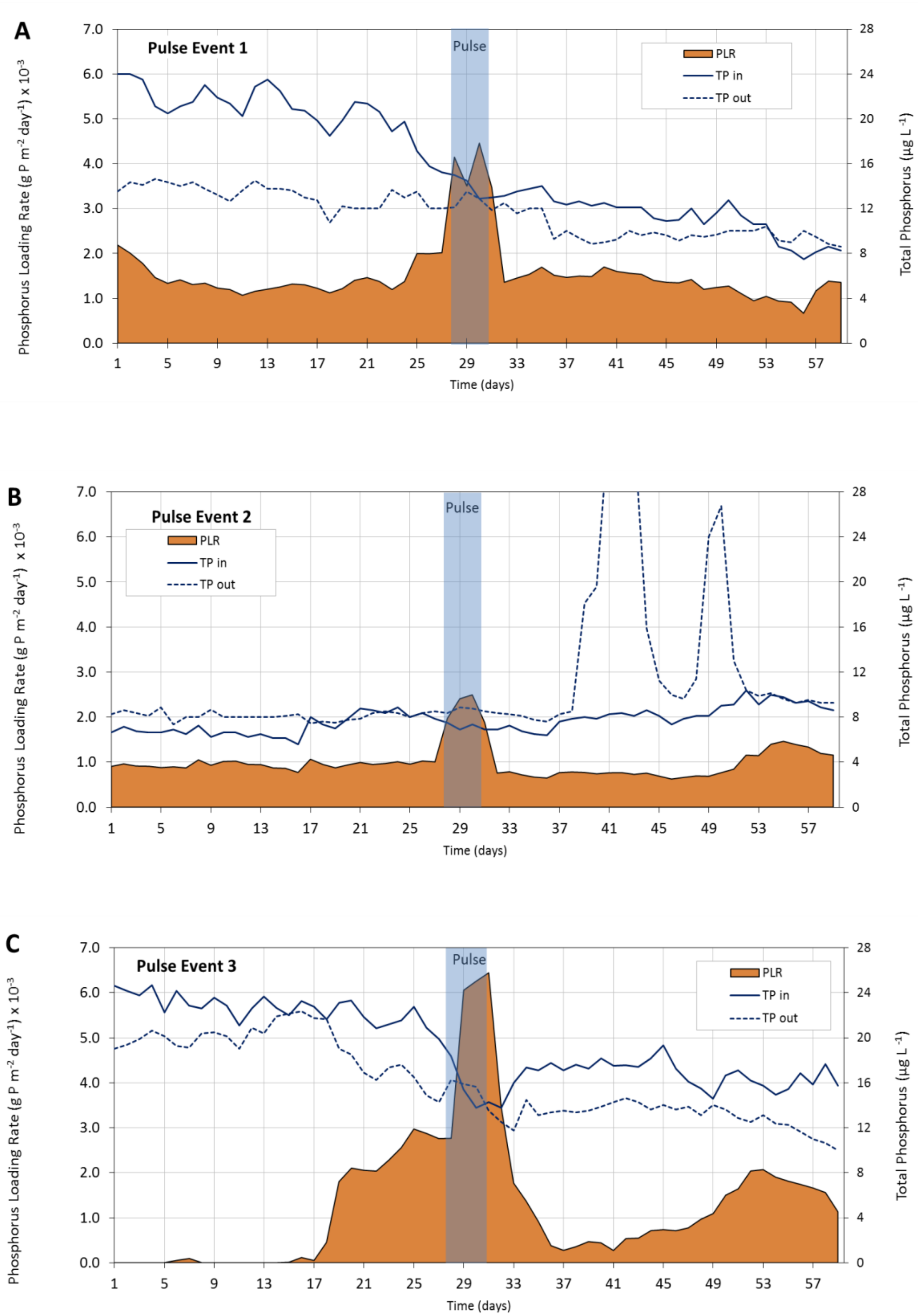

Figure 7. Daily total phosphorus (TP) loading rates and daily average inflow and outflow TP concentrations in the PSTA Cell during the three-day flow pulse, and the 28-day pre- and post-pulse periods for (A) Pulse 1, (B) Pulse 2, and (C) Pulse 3.

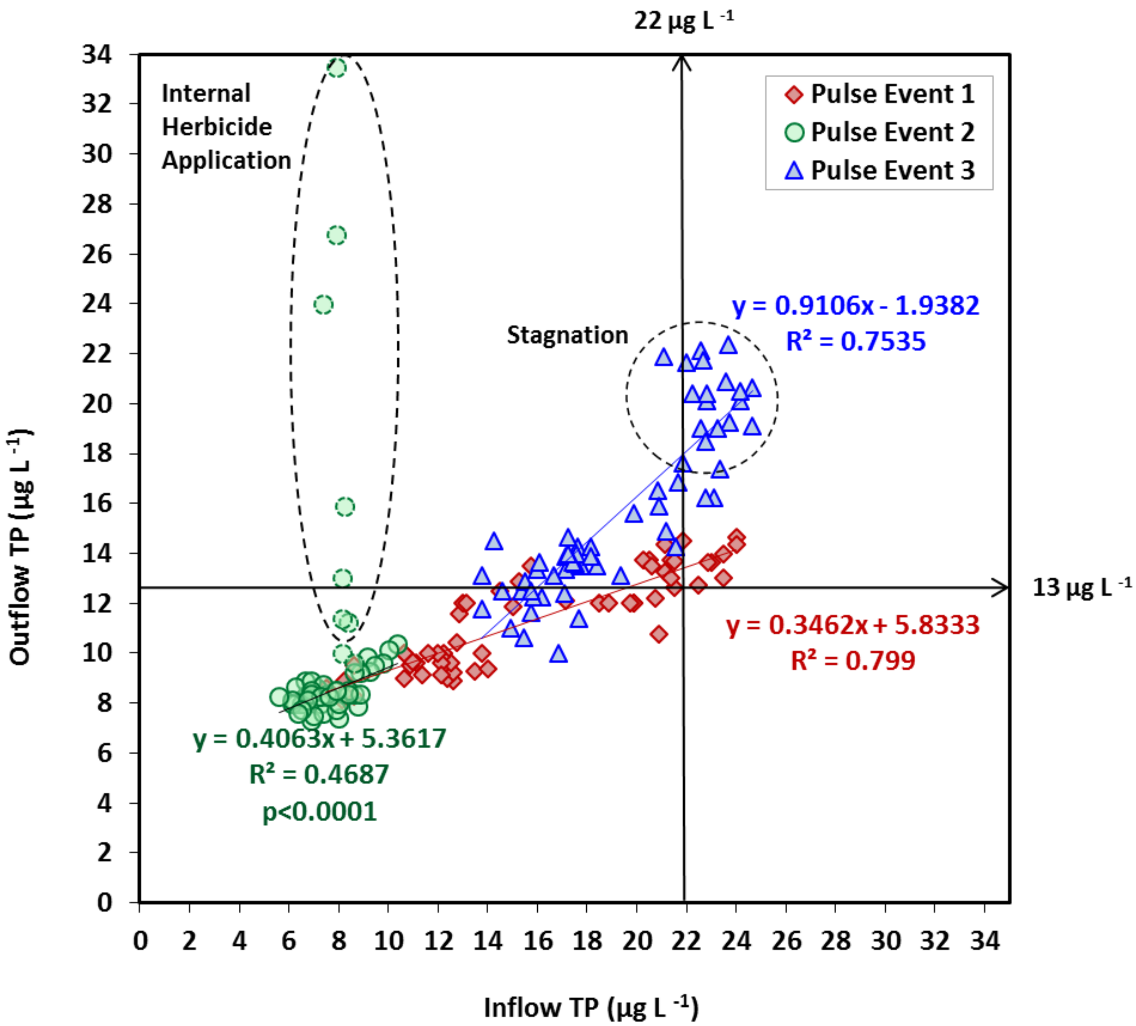

Figure 8. Relationship of PSTA Cell daily average inflow and outflow TP concentrations during pre-pulse, pulse, and post-pulse periods for each of the three flow pulses.

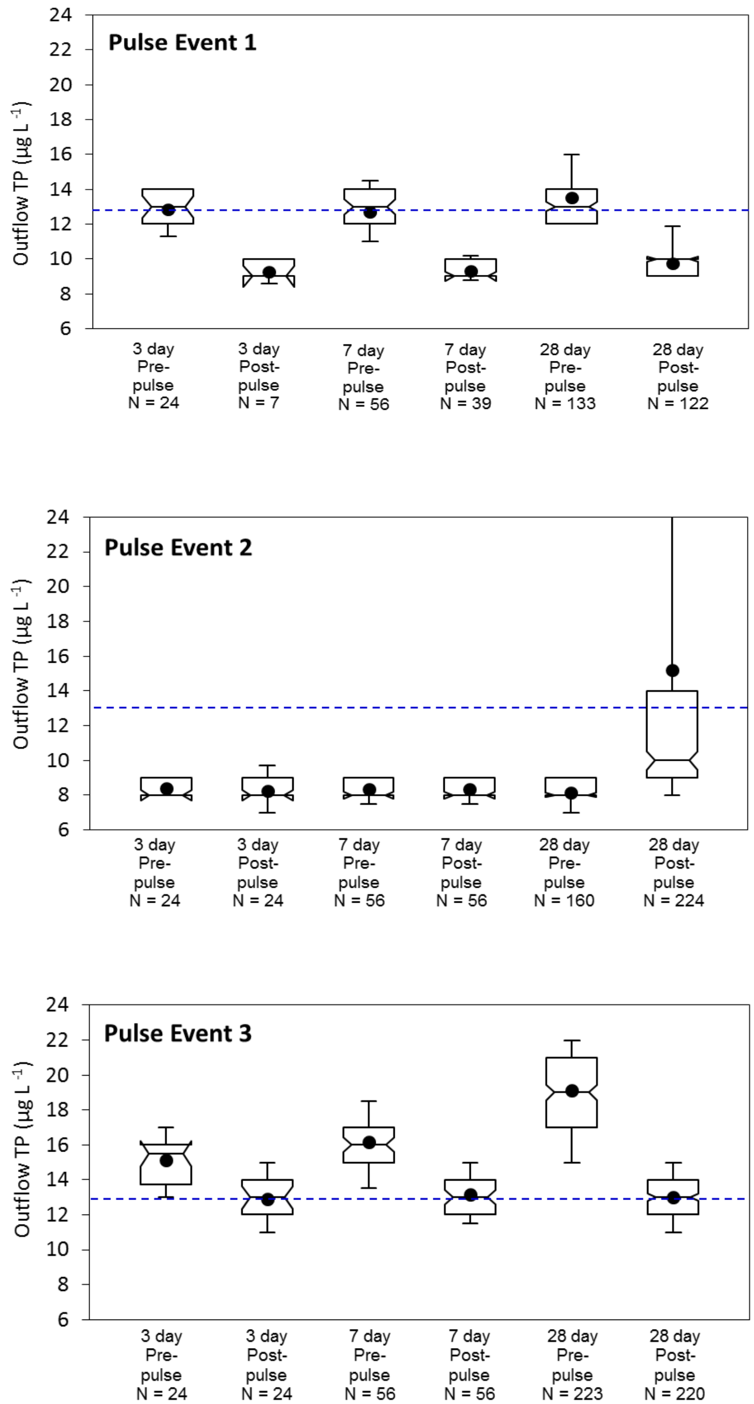

Figure 9. Comparison of average TP concentrations of samples collected every three hours at the PSTA Cell outflow 3, 7, and 28 days before and after each flow pulse. Dashed lines indicate the 13 µg L^{-1} shown as a reference to the STA annual discharge limit. The top and bottom of each box represent the 1st and 3rd quartiles; horizontal lines within boxes represent the median; solid circles represent the mean, and the vertical whiskers extend to the 10th and 90th percentile.

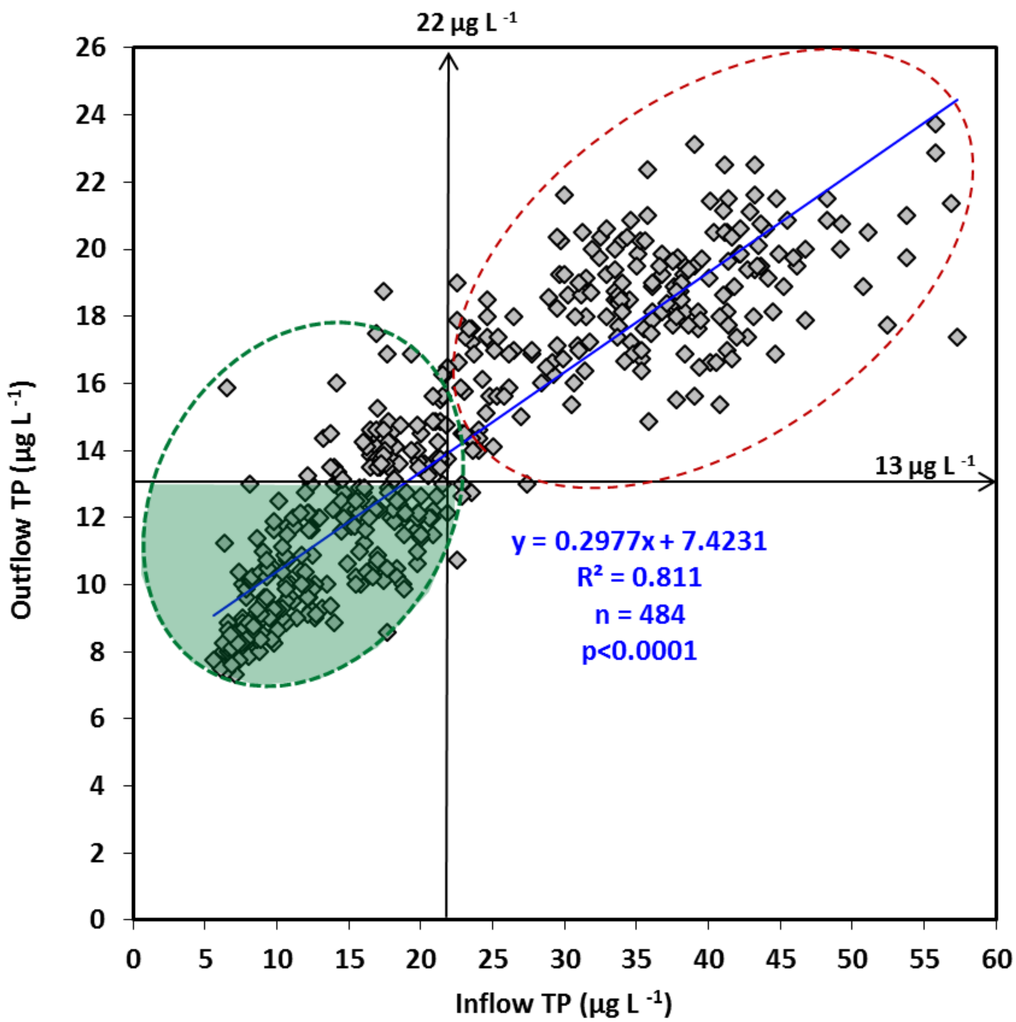

Figure 10. Relationship between PSTA Cell inflow and outflow daily average TP concentrations from April 2012 to August 2014.

FLOW RATES AND PHOSPHORUS CONCENTRATIONS

During the flow pulses, PSTA Cell flow rates were increased markedly compared to the historical flow rates. Daily average flow during the pulses ranged from 40 to 76 cfs at the inflow (**Figure 11**), and 49 to 81 cfs at the outflow with the highest flow rates occurring during Pulse 3 (**Figure 12**). Average flow rates during the 3-day pulses were approximately three to four times higher than the daily average flow rate under normal operating conditions (approximately 18 cfs).

It was theorized that the high flow at the PSTA Cell inflow and outflow structures may result in short-term increase of TP concentrations in the water column. Evaluation of the flow and TP concentrations data suggests that the high inflow and outflow rates during the pulses did not result in higher TP concentrations at the outflow compared to outflow TP during the pre- and post-pulse periods (**Figures 11** and **12**).

Similarly, increased flow at the inflow culvert during the pulses did not result in higher inflow TP concentrations (**Figure 13**). As indicated previously, high TP concentrations at the outflow following Pulse 2 (**Figure 9**) were likely a result of herbicide treatment and subsequent decomposition of spikerush that occurred immediately after the pulse.

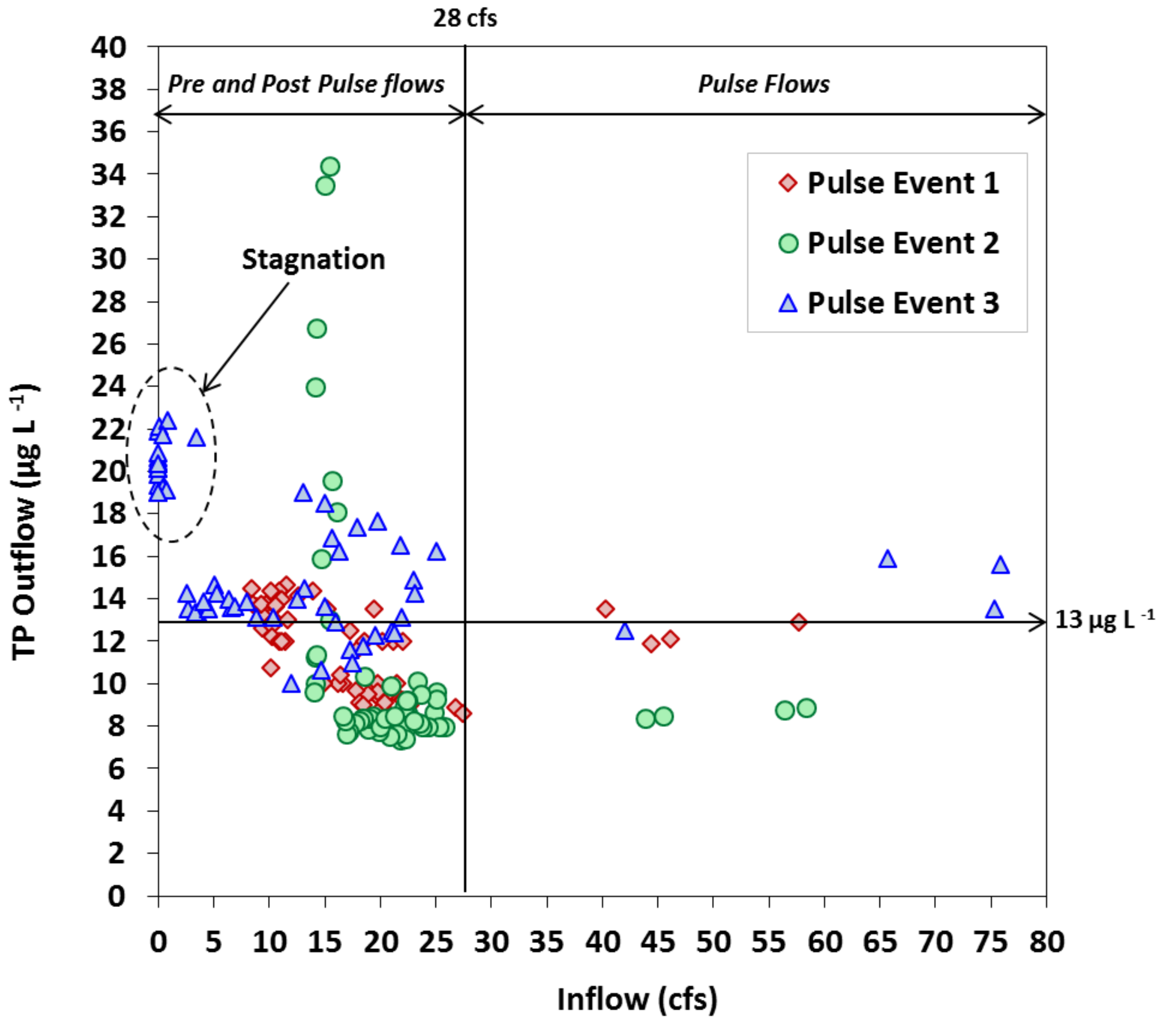

Figure 11. Daily average PSTA Cell outflow TP concentrations in relation to daily inflow flow rates during pre-pulse, pulse, and post-pulse periods for each flow pulse.

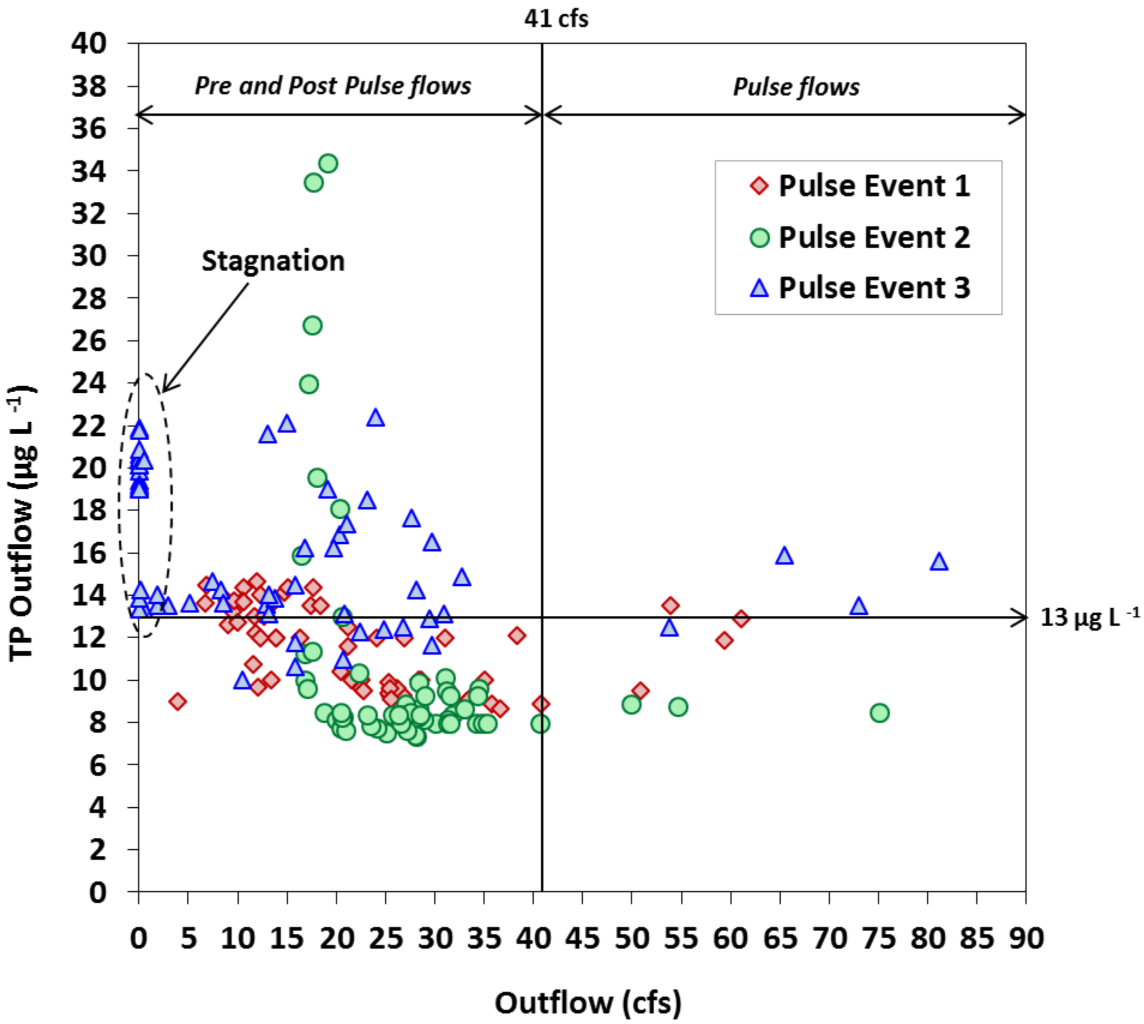

Figure 12. Daily average PSTA Cell outflow TP concentrations in relation to daily outflow flow rates during pre-pulse, pulse, and post-pulse periods for each flow pulse.

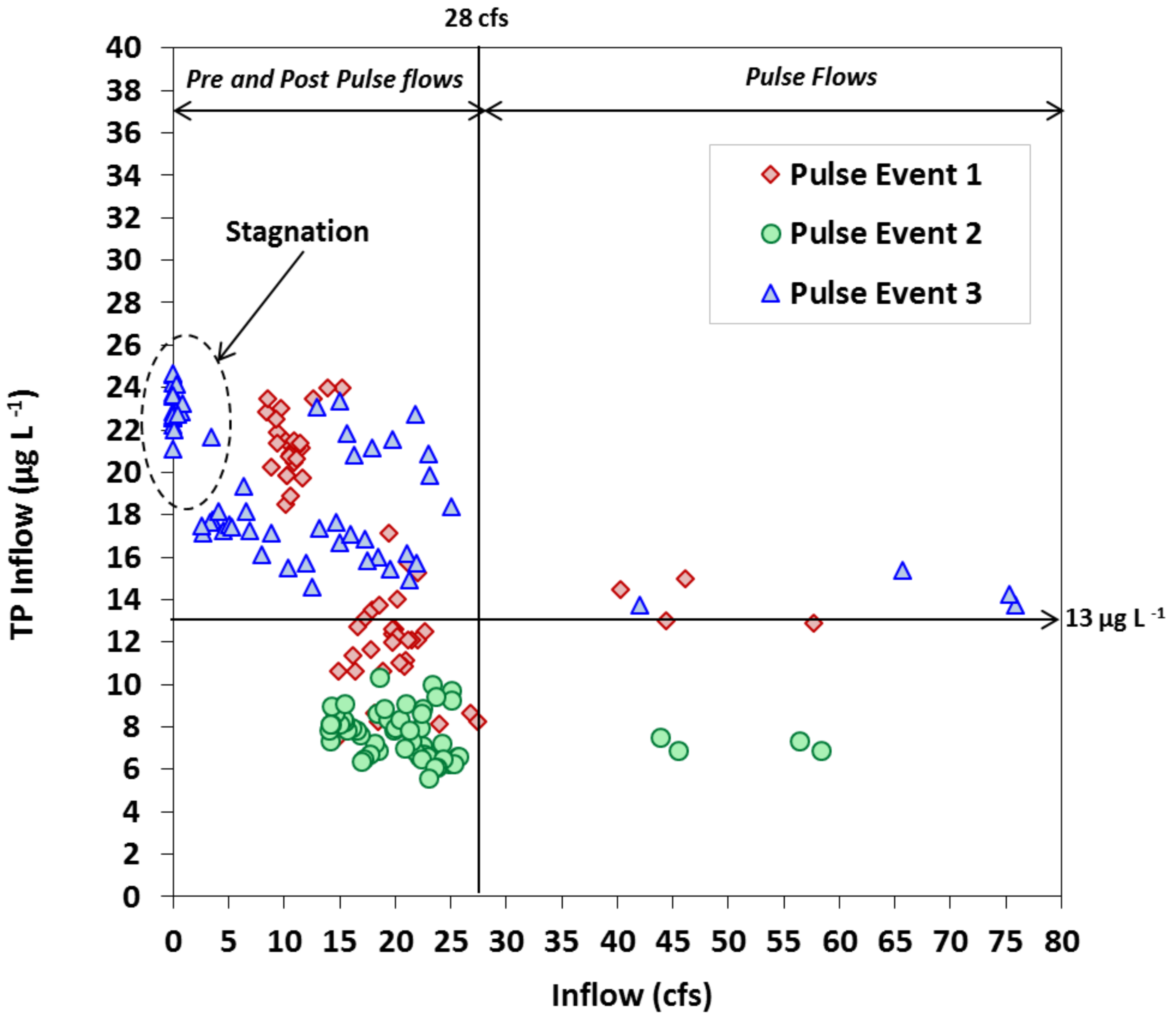

Figure 13. Daily average PSTA Cell inflow TP concentrations in relation to daily inflow flow rates during pre-pulse, pulse, and post-pulse periods for each flow pulse.

SUMMARY AND CONCLUSIONS

This report summarizes an analysis of stage, flow and TP data collected between January 2012 and August 2014 to address Hypothesis #4 from the PSTA Study's Detailed Study Plan, which states that low outflow TP concentrations result from the moderation of hydraulic and P loading to the PSTA Cell and that higher P loads will compromise treatment efficacy and result in increased outflow TP concentrations. During the study, three managed flow pulses were conducted: Pulse 1 (August 1–3, 2012); Pulse 2 (October 24–26, 2012); and Pulse 3 (June 24–26, 2014). Key findings and conclusions are summarized below.

- Daily average depths in the PSTA Cell during Pulses 1 and 2 increased by approximately 0.6 feet compared to the daily average depths at the 10.0 ft NGVD target stage. Daily average depths during Pulse 3 increased by 0.2 feet compared to the daily average depths at the 10.5 ft NGVD target stage. Water depths in the PSTA Cell returned to pre-pulse depths about 1 to 3 days after the pulses were completed.
- Average flow rates during the pulses (53 cfs for Pulse 1, 57 cfs for Pulse 2, and 74 cfs for Pulse 3) were three to four times higher than average historic flow rates (approximately 18 cfs) in the PSTA Cell which resulted in HLRs (28.5 – 43.4 cm day^{-1}) approximately three times higher than HLRs under normal operations. Pulses 1 and 2 produced 3-day maximum HLRs (28.5 and 32.1 cm day^{-1}, respectively) that were comparable to STA-3/4 Cell 2B historical 3-day maximum average HLRs (24.7 to 31.5 cm day^{-1}), while Pulse 3 resulted in a 3-day maximum HLR (43.4 cm day^{-1}) that was about 1.5 times greater than the 3-day maximum HLRs experienced historically at STA-3/4 Cell 2B.
- High flow rates during the pulses resulted in short HRTs (1 to 2 days) compared to normal operations (4 to 5 days). The reduced HRTs did not significantly increase 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 µg L^{-1} following Pulse 2 were likely a result of herbicide treatment and subsequent decomposition of spikerush that occurred immediately after the pulse.
- The daily PLRs sharply increased for all three pulses, with the highest PLR (6.4 g m^{-2} day^{-1}) observed during Pulse 3.
- While differences between pre-pulse and post-pulse outflow TP concentrations during Pulse 1 and 3 were statistically significant ($p < 0.05$), the concentration differences were minimal and within the laboratory's practical quantitation limit (8 µg L^{-1}). Further evaluation of TP data suggested that when inflow TP concentrations exceeded 22 µg L^{-1} outflow concentrations generally exceeded 13 µg L^{-1}. Evaluation of the daily average TP concentration data for the period from April 2012 to August 2014 produced similar results.
- Results indicate 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.
- Overall, TP concentrations at the PSTA Cell outflow location after the pulses were generally lower than or similar to outflow TP concentrations before the pulses. In conclusion, study results indicate that pulse flow events and associated higher P loads had no adverse effect on the PSTA Cell's P treatment performance thereby disproving Hypothesis #4.

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REFERENCES

Andreotta, H., M. Chimney, T. DeBusk, B. Garret, G. Goforth, K. Grace, D. Ivanoff, M. Jerauld, M. Kharbanda, N. Larson, S. Miao, D. Marois, W. Mitsch, T. Piccone, K. Pietro, N. Ralph, A. Ramirez, L. Schwartz, L. Toth, S. Xue, Y. Yan, M. Zamorano, L. Zhang and H. Zhao. 2014. Chapter 5B: Performance of the Everglades Stormwater Treatment Areas. In: *2014 South Florida Environmental Report – Volume I*, South Florida Water Management District, West Palm Beach, FL.

GCY Professional Surveyors & Mappers Inc. 2013. SFWMD: Infrastructure Management Bureau Survey and Mapping Section. Topographic Survey-Task I: Cell Elevations. Work Order No. 4600002692-WO05. STA-3/4 PSTA Section 15 & 22, Township 47 South, Range 37 East, Palm Beach County, Florida. Final Deliverable to the South Florida Water Management District, West Palm Beach, FL.

SFWMD. 2013. Restoration Strategies Regional Water Quality Plan: Science Plan for the Everglades Stormwater Treatment Areas. South Florida Water Management District, West Palm Beach, FL. June 2013. Available online at www.sfwmd.gov/rs_scienceplan

SFWMD. 2014. Restoration Strategies Regional Water Quality Plan: Science Plan for the Everglades Stormwater Treatment Areas, Detailed Study Plans, Fiscal Years 2013–2018. South Florida Water Management District, West Palm Beach, FL. June 2013. Available online at www.sfwmd.gov/rs_scienceplan

Struve, D., M. Zhou and T. Baber. 2005. Optimization and Operation of a Remote Phosphorus Analyzer in In-Situ Determination of Total and Reactive Phosphate in Water. Florida Water Resources Conference Proceedings.

Zhao H, T. Piccone and F. Zamorano. 2015. STA-3/4 Periphyton-based Stormwater Treatment Area (PSTA) Cell Water and Total Phosphorus Budget Analyses. Technical Publication WR-2015-001. South Florida Water Management District, West Palm Beach, FL. April 2015.