South Florida Water Management District

Evaluation of Remote Phosphorus Analyzer Measurements and Hydrologic Conditions of the STA-3/4 Periphyton-based Stormwater Treatment Area

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EXECUTIVE SUMMARY

This report evaluates remote phosphorus analyzer (RPA) measurements of total phosphorus (TP) from a periphyton-based stormwater treatment area (PSTA)—a 100-acre cell located in Stormwater Treatment Area (STA)-3/4, downstream of the upper submerged aquatic vegetation (SAV) cell. Initially, muck was scraped from this cell, which was designed to treat stormwater to ultra-low TP concentrations prior to discharge to the Everglades. This analysis evaluates factors that may contribute to the PSTA cell's ability to produce very low TP concentrations at the PSTA cell discharge. The factors evaluated include flow, two different operational stages, inflow concentration, season, and time of day.

The RPA data that were evaluated excluded pulse tests, Tropical Storm Isaac, and an anomalous period of record (November 3 to 14, 2012) that included extremely high TP values attributed to vegetation management in the PSTA cell. Of the remaining data, values taken during flow (e.g., when the G-388 discharge pump was operating) indicate that the PSTA cell retained TP when inflow TP concentrations were above 10 parts per billion (ppb). Discharged TP concentrations were lower during the 10.0-foot National Geodetic Vertical Datum of 1929 (ft NGVD) operational stage (average water depth of 1.3 feet, prior to April 22, 2013) than at the 10.5-ft NGVD operational stage (average water depth of 1.8 feet of water depth after April 22, 2013). However, this result is complicated by the strong relationship between inflow and outflow TP concentrations and the significantly higher TP concentrations during the 10.5-ft NGVD operational stage. The higher concentrations are attributed to non-optimal conditions occurring in the upstream STA flowway.

Despite the significant difference between the inflow concentrations of the two operational stages, an analysis of weekly flow-weighted concentrations showed that the linear relationship between inflow and outflow concentrations was not significantly different between operational stages. This result suggests that the two different operational stages did not directly influence the TP removal rate from the PSTA cell. Continued collection of RPA measurements at the 10.5-ft NGVD operational stage will allow for more comparable inflow concentration measurements as the upstream STA flowway returns to normal operations.

A few factors appeared to influence retention of TP in the PSTA cell. While time of day did not affect outflow TP concentrations, lower TP was observed during the wet season—May to October—under the 10.0-ft NGVD operational stage. Comparing weekly inflow and outflow concentrations indicates that discharge concentrations less than 15 ppb occurred when inflow concentrations were less than 20 ppb. The percentages of TP measurements in discharge from the PSTA cell that were below concentrations of 10, 13, or 15 ppb were different under different flow and stage conditions. For the 10.0-ft NGVD operational stage, a pump operation of 642 minutes per day (outflow estimate of 27 cubic feet per second [cfs] and a turnover time of 2.4 days) resulted in the greatest percentage of values below these concentrations, while at the 10.5-ft NGVD operational stage, the greatest percentage of values below these concentrations occurred at a pump operation category of 594 minutes (26 cfs and a turnover time of 3.4 days). Further tests of the PSTA cell operations are warranted to determine if these conditions can maintain low TP concentrations for extended periods.

INTRODUCTION

Stormwater Treatment Area (STA)-3/4 contains a 100-acre periphyton-based stormwater treatment area (PSTA) cell (**Figure 1**). The cell receives water from the upper submerged aquatic vegetation (SAV) cell through the G-390A and B structures and discharges through the G-388 pump station (Chimney 2015). The PSTA cell was constructed by removing muck down to the caprock (e.g., bedrock) of the cell. This resulted in an average floor elevation of 8.8 feet National Geodetic Vertical Datum of 1929 (ft NGVD). This cell was designed to treat stormwater runoff to ultra-low total phosphorus (TP) concentrations prior to discharge to the downstream Everglades Protection Area.

The study presented here evaluates TP concentrations measured by remote phosphorus analyzers (RPAs) located at the G-388 structure outflow and the G-390B structure inflow (Struve et al. 2008). The study objective was to determine the conditions that consistently produce lower TP concentrations during discharge events. In particular, the effect of two different operational stages, season, time of day, flow rate, and inflow TP concentrations are evaluated against outflow TP concentrations. Results may provide the basis for design and operational guidelines to optimize PSTA treatment performance at low inflow TP concentrations.
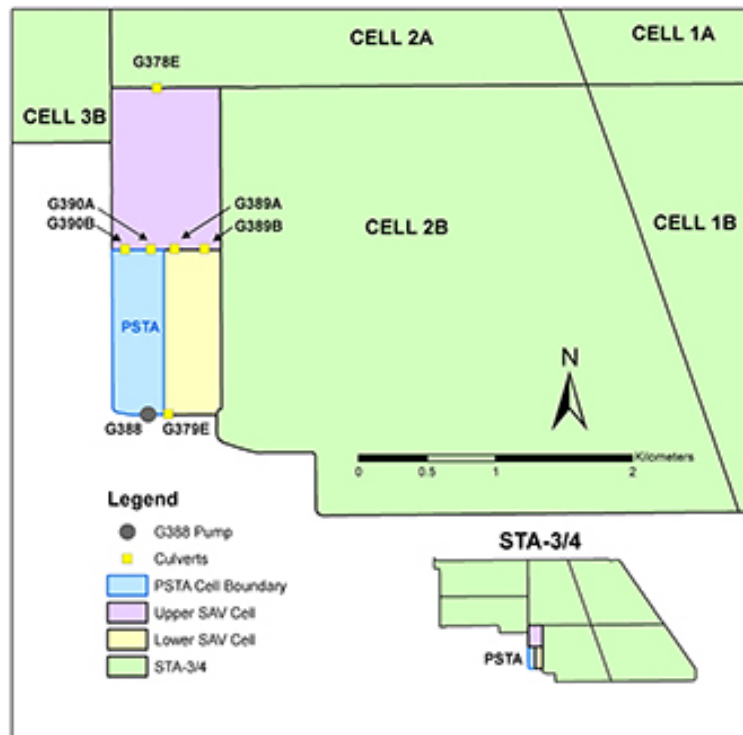
Figure 1. Map of the STA-3/4 PSTA cell showing inflow structures (G-390A and G-390B) and the discharge pump station (G-388). RPA were located at G-390B and G-388.

METHODS

RPA TP measurements (SFWMD 2012) were obtained for the period March 30, 2012 to October 20, 2014 at the inflow (G-390B) and outflow (G-388) structures of the PSTA cell (**Figure 1**). TP was measured continuously every three hours with breaks due to power loss, equipment failure, or system maintenance (**Table 1**). From November 22, 2013 to October 2, 2014, the sampling frequency at G-390B was increased to every two hours. Data obtained during pulse tests (August 1 to 3, 2012; October 25 to 26, 2012; and June 24 to 27, 2013), Tropical Storm Isaac (August 31, 2012), and from November 3 to 14, 2012—due to high TP concentrations related to herbicide treatments for plant management—were removed.

Table 1. Offline dates for RPAs for more than four days from March 2012 to October 2014.

Station	Stop Date	Restart Date	Days Offline
G-388	6/14/2012	6/20/2012	6
	9/5/2012	9/13/2012	8
	10/4/2012	10/9/2012	5
	8/7/2014	8/14/2014	7
	8/23/2014	8/28/2014	5
	9/15/2014	9/24/2014	9
G-390B	5/4/2012	5/29/2012	25
	6/5/2012	6/13/2012	8
	6/20/2012	7/6/2012	16
	1/20/2013	1/25/2013	5
	7/22/2013	8/3/2013	12
	8/3/2013	9/13/2013	41
	12/11/2013	12/19/2013	8
	12/25/2013	1/12/2014	18
	1/30/2014	2/21/2014	22
	5/12/2014	5/19/2014	7
	8/4/2014	8/14/2014	10
	8/20/2014	8/27/2014	7
	8/28/2014	9/3/2014	6

Hourly breakpoint flow data were obtained from the South Florida Water Management District's (District's) Breakpoint Flow Data Generator Parameter Screen webpage (SFWMD 2015a) for G-390 (DCVP station ID G390B-1 and G390A-1). Instantaneous breakpoint revolutions per minute (rpm) data were obtained from the District's corporate environmental database, DBHYDRO, menu webpage for the G-388 pumps (G388_P, DBKEYS: TZ221, TZ222; SFWMD 2015b). 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-390 (a sum of the flows at G390B_C DBKEY: 90405 and G390A_C DBKEY: V8861) and G-388 (DBKEY: W3981). Daily averaged stage data were obtained for G-388 (DBKEY: TZ219) and 8.8 feet was subtracted from this to obtain the average daily water column depth.

RPA TP data were subset into two stage operation periods: a 10.0-ft NGVD stage operation that occurred prior to April 22, 2013 and a 10.5-ft NGVD stage operation that occurred from this date forward (**Figure 2**). Histograms and percent cumulative frequencies of these two subsets were compared to evaluate TP flowing into and discharging from the PSTA cell. Histograms and cumulative frequencies were developed with the FREQ procedure of the statistical package SAS (SAS Institute Inc 2006). Changes between TP at G-390 and G-388 during flow for the two stage operation subsets were analyzed using a non-parametric Kruskal-Wallis Test of the NPAR1WAY procedure of SAS (SAS Institute Inc. 2004). The outflow concentrations at G-388 were also analyzed using the same method to determine any significant differences for the two stage operating periods. These subsets of outflow concentrations at the two stage operation periods also were analyzed by time of day (three-hour intervals starting at midnight), and season (dry: November to April and wet: June to October) using the Kruskal-Wallis Test.
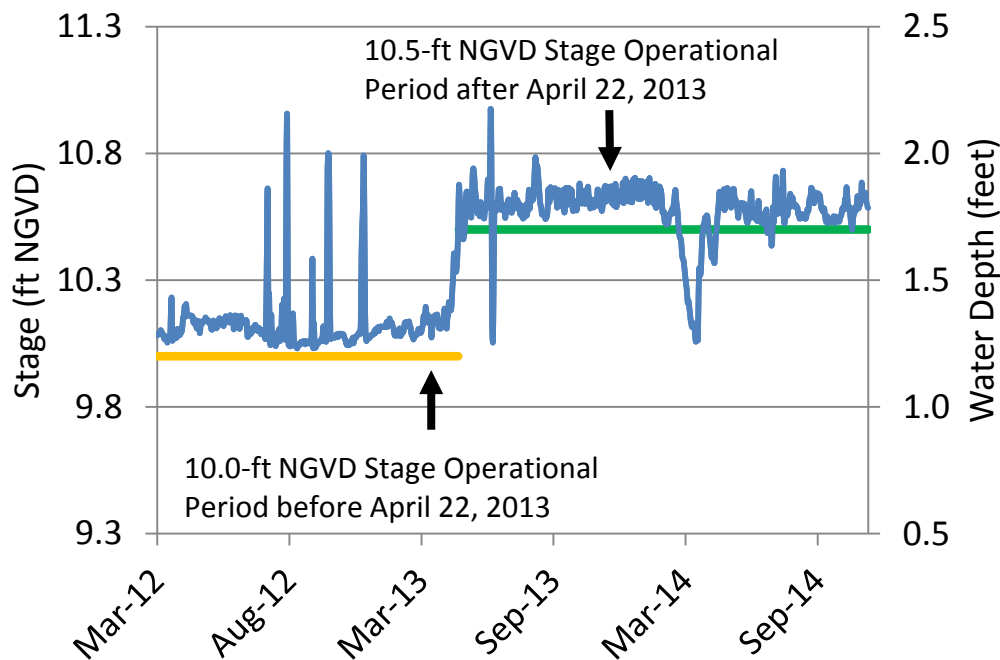
Figure 2. Daily average water depth in the PSTA cell before and after April 22, 2013 (based on G-388 headwater [DBKEY: TZ219]).

Parameter studies beyond TP were not possible for RPA data because the device only measures ortho-phosphorus and TP.

Inflow G-390 RPA TP measurements were average weighted by day using the hourly flow data. Outflow G-388 RPA TP measurements were average weighted by day using the breakpoint data for pump speed. These daily average weighted values were then weighted by the appropriate daily flow observations to obtain weekly flow-weighted mean concentrations. An Analysis of Covariance (ANCOVA) technique using the GLM procedure of SAS (SAS Institute Inc 1992) determined if weekly outflow concentrations co-varied with weekly inflow concentrations and if this co-variation differed between the two stage operation periods.

To evaluate the effects of flow on treatment performance more thoroughly, the two stage operational data subsets were examined separately. Each data subset was ordered by daily minutes of pump operation and then divided into five equal bins of TP data points (e.g., counts in each bin were within one value of each other). Daily minutes of pump operation was used instead of flow due to three factors: 1) flow is estimated for each day based primarily on pump speed and

minutes of operation, 2) the pumps cycled on and off during days of discharge to regulate stages, thus flow was discontinuous, and 3) the pump operation could be set at four different configurations. Minutes of pump operation per day were normalized to a pump configuration of 224 rpm. The number of TP samples within each bin that were at or below 10 parts per billion (ppb), 13 ppb, and 15 ppb were counted. These counts were divided by the total number of TP samples in the data set to determine the percent of samples for each TP value in each bin. These percentages were compared to the minutes of pumping for each bin. A Kruskal-Wallis Test of the NPAR1WAY procedure of SAS (SAS Institute Inc. 2004) was performed to test if the counts in each bin were equal or unequal.

RESULTS

From March 30, 2012 to October 20, 2014, 6,512 measurements of TP were sampled at G-390B, and 6,121 at G-388 (**Figure 3a**). Of these, 183 and 180 measurements, respectively, were removed due to pulse tests, Tropical Storm Isaac, and vegetation management activities in the PSTA cell (**Figure 3b**). Of the 6,329 and 5,941 measurements remaining, 5,531 and 881 measurements, respectively, occurred during positive flow periods (**Figure 3c**). The discontinuous nature of pump operations at G-388 (see below) resulted in the smaller number of TP measurements during outflow. Most RPA TP measurements at G-388, especially during outflow, were less than those at the G-390 inflow structure.

Of 5,531 measurements taken during flow at G-390, 2,117 were taken before April 22, 2013 and 3,414 were taken from this date through October 20, 2014. The stage increased from 10.0 ft NGVD (average water depth 1.3 feet) to 10.5 ft NGVD (average water depth 1.8 feet) on April 22, 2013 (**Figure 2**). The operational protocol allowed water levels to exceed the schedule by 0.2 of a foot at which time the pump at G-388 would turn on. Once water levels returned to the scheduled value, the pump was turned off. When water flowed into the PSTA cell, this pumping protocol resulted in numerous cycles per day, and produced daily averaged stage values of 0.2 feet or less above the operational schedule. Stages did exceed the 0.2-feet limit during storm and or onset of the pulse test events. During the 10.5-ft NGVD stage operation schedule, there was a period where water levels declined to stage of 10.0 feet NGVD due to dry conditions with limited available inflow from the upper SAV cell.

The variation and skewness of the RPA data are different between G-390 inflow and G-388 outflow (**Figure 4**). During flow, data at G-390 are skewed substantially to the right (**Figure 4A** and **Table 2**). While the skewness and variance (as standard deviation) of the G-388 data are more difficult to visualize because of few data points (**Figure 4B**), both are less than those from flowing G-390 TP values (**Table 3** versus **Table 2**).

Plots of RPA data during flow and histograms of this data indicate that G-388 outflow TP concentrations are less than G-390 inflow concentrations (**Figures 3** and **4**). This is further indicated by comparing the cumulative percent frequency of TP concentrations that show curves further to the left for G-388 during outflow as compared to G-390 inflow (**Figure 5**). When evaluating only samples taken when water was flowing, a Kruskal-Wallis test verifies that TP is significantly reduced at G-388 as compared to G-390 (**Table 4**, P < 0.0001).

TP concentrations during discharge events at G-388 are significantly different between the 10.0- and 10.5-ft NGVD stage operations based on a Kruskal-Wallis test (**Table 3**, P < 0.0001). During the 10.0-ft NGVD stage operations, 48% of these RPA samples are at or below 10 ppb of TP while only 31% of the samples are at or below 10 ppb of TP during the 10.5-ft NGVD stage operation (**Figure 5A** and **Table 3**). During flow, 85 and 71% of the samples are at or below 15 ppb TP during 10.0- and 10.5-ft NGVD stage operations, respectively. For flow conditions,

the mean, median, and 25th and 75th percentiles are lower for the 10.0-ft NGVD stage operation than the 10.5-ft NGVD stage operation by one to two ppb of TP.
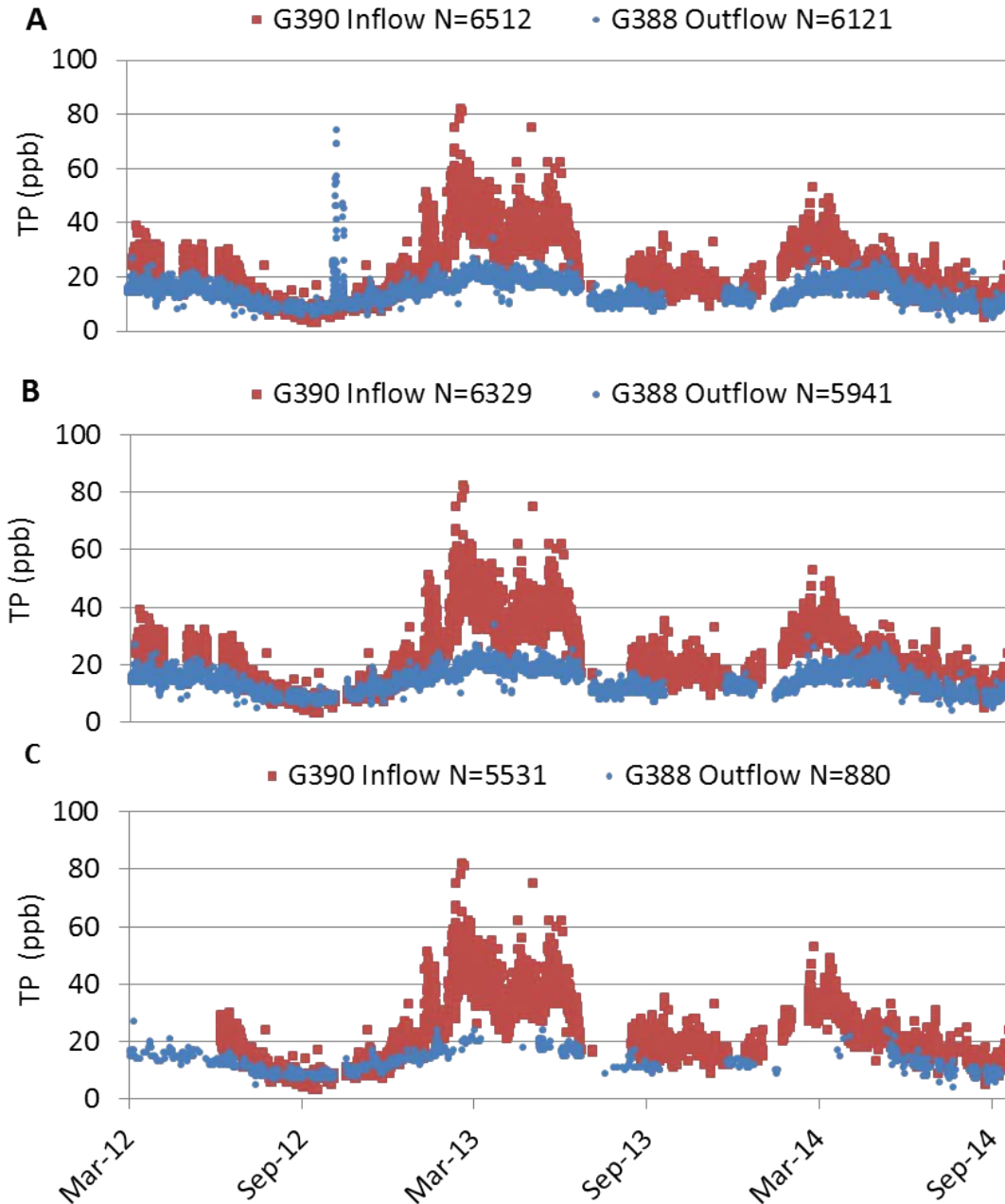
Figure 3. RPA TP measurements taken at the G-390 (inflow) and G-388 (outflow) structures from March 2012 to October 2014 for A) all data, B) pulse tests, Tropical Storm Isaac, and November 2012 outliers removed, C) flow only measurements from B**.**
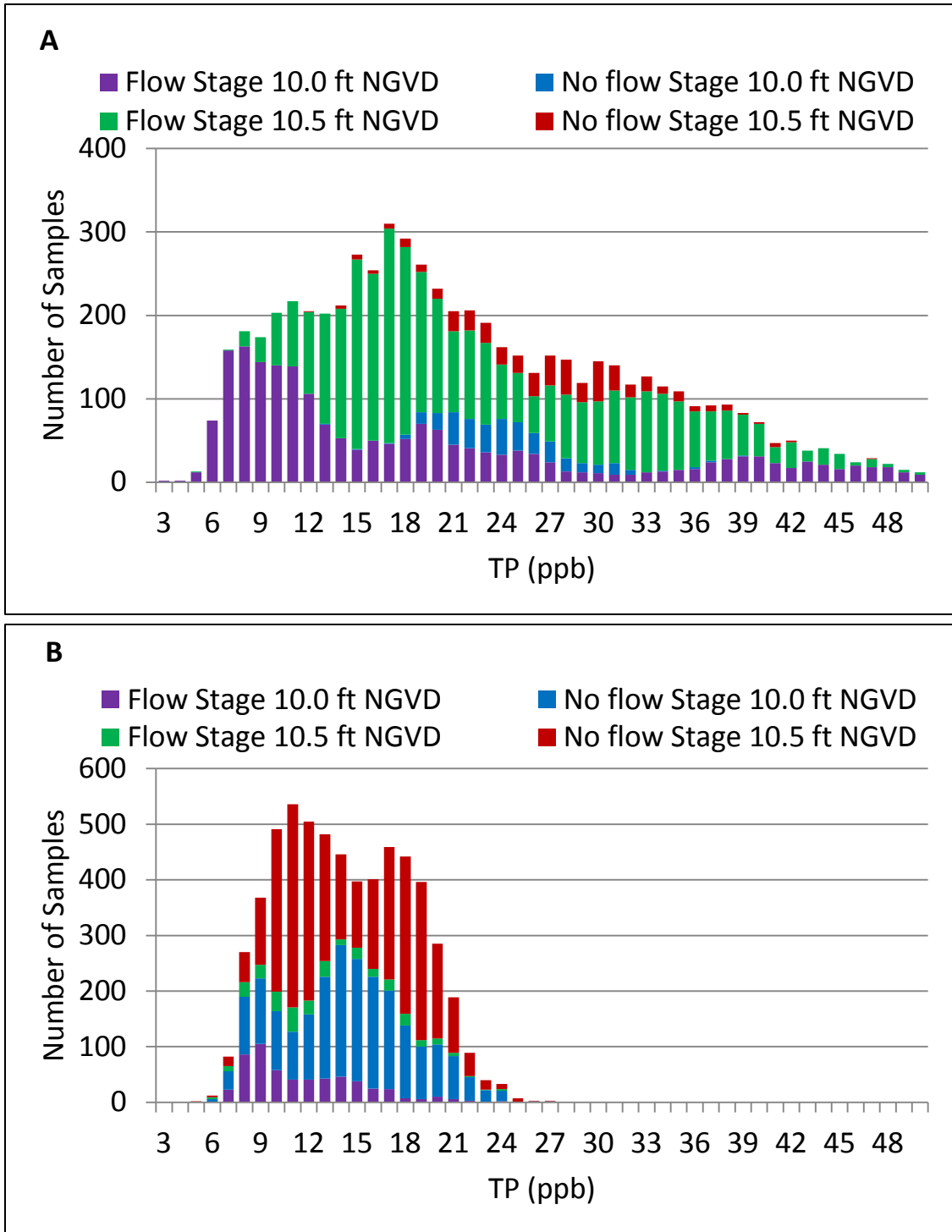
Figure 4. Histograms of RPA TP measurements for the 10.0- or 10.5-ft NGVD operational stages and flow or no flow conditions with pulse tests, Tropical Storm Isaac, and a vegetation management period removed for A) inflow G-390A (N = 6329) and B) outflow G-388 (N = 5941).

Table 2. Summary statistics for RPA TP measurements collected at G-390B from April 2012 to October 2014 under various stage and flow regimes.

Statistic	No flow 10.0-ft NGVD Stage	No flow 10.5-ft NGVD Stage	Flow 10.0-ft NGVD Stage	Flow 10.5-ft NGVD Stage
Mean	24.4	27.2	19.4	23.0
Standard deviation	3.8	5.7	13.9	9.5
Sample size (N)	339	459	2117	3414
Median	24	27	13	20
25th percentile	22	23	9	16
75th percentile	27	31	25	31
Percent samples at or below 15 ppb	1%	2%	52%	24%
Percent samples at or below 13 ppb	0%	0%	48%	12%
Percent samples at or below 10 ppb	0%	0%	33%	3%
Skewness	0.66	0.09	1.2	0.79
Kurtosis	0.91	0.12	0.62	0.10
Kruskal-Wallis test				
Sum of scores			4,827,295	10,471,451
Expected under H_o = Not significantly different			5,855,622	9,443,124
Mean score			2,280	3,067
Chi-square				317.73
Pr > Chi-square				<0.0001

Table 3. Summary statistics for RPA TP measurements collected at G-388 from April 2012 to October 2014 under various stage and flow regimes.

Statistic	No flow 10.0-ft NGVD Stage	No flow 10.5-ft NGVD Stage	Flow 10.0-ft NGVD Stage	Flow 10.5-ft NGVD Stage
Mean	14.7	14.6	11.7	13.0
Standard deviation	4.0	3.9	3.6	4.0
Sample size (N)	2072	2988	566	315
Median	15.0	14.0	11.0	12.0
25th percentile	12.0	11.0	9.0	10.0
75th percentile	17.0	18.0	14.0	16.0
Percent samples at or below 15 ppb	58%	56%	85%	71%
Percent samples at or below 13 ppb	36%	47%	70%	62%
Percent samples at or below 10 ppb	18%	16%	48%	31%
Skewness	0.11	0.20	0.93	0.49
Kurtosis	-0.27	-1.00	0.56	-0.56
Kruskal-Wallis test				
Sum of scores	5,283,836	7,520,494	231,387	157,135
Expected under H_o = Not significantly different	5,243,196	7,561,134	249,606	138,915
Mean score	2,550	2,517	409	499
Chi-square		0.64		25.6
Pr > Chi-square		0.43		<0.0001

Table 4. Kruskal-Wallis test comparing TP concentrations at G-388 and G-390 during flow and at 10.0- and 10.5-ft NGVD operational stages.

Operational Schedule and Stage	Sample Size	Sum of Scores	Expected under H_0	Standard Deviation under H_0	Mean Score or Probability
10.0-ft NGVD Stage Operation					
G-388	566	581,533	759,572	16,346	1,027
G-390	2117	3,019,054	2,841,014	16,346	1,426
Kruskal-Wallis Chi-square					118.6
Pr > Chi-Square					<.0001
10.5-ft NGVD Stage Operation					
G-388	315	220,351	587,475	18,267	700
G-390	3414	6,734,235	6,367,110	18,267	1,973
Kruskal-Wallis Chi-square					403.9
PR > Chi-square					<0.0001
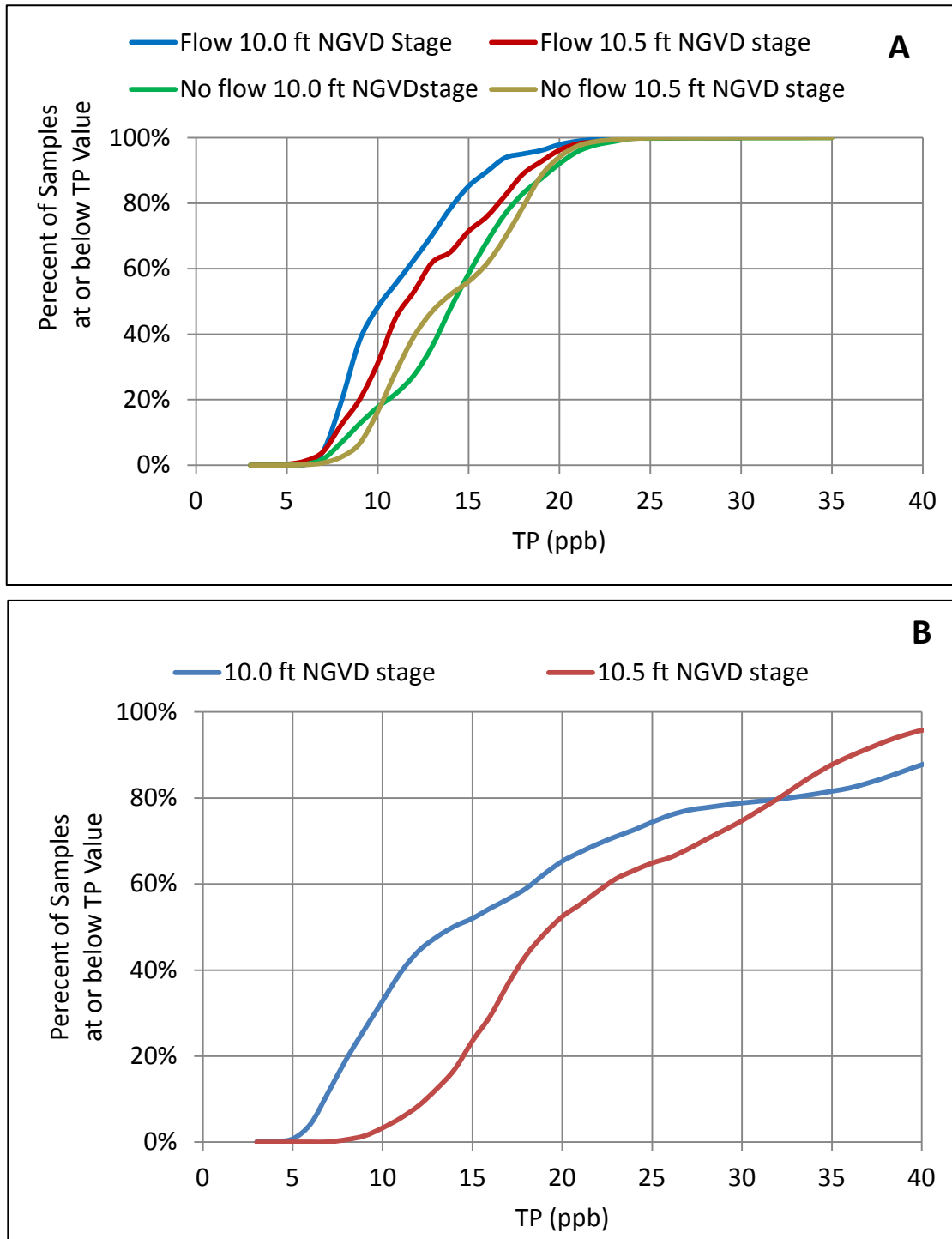
Figure 5. Percent cumulative frequencies of RPA TP measurements with pulse tests, Tropical Storm Isaac, and a vegetation management period removed for A) G-388 for 10.0- and 10.5-ft NGVD stage operations for flow and no flow conditions and B) G-390A during 10.0- and 10.5-ft NGVD operational stages for flow conditions.

For "no flow" conditions at G-388, there is no significant difference of TP between the two operational stages (**Figure 5A** and **Table 3**, Kruskal-Wallis test P = 0.43). Just 18 and 16% of the samples at 10.0- and 10.5-ft NGVD operational stages, respectively, are at or below 10 ppb of TP and 58 and 56% of the samples, respectively, are at or below 15 ppb.

The significant difference of TP at G-388 between the 10.0- and 10.5-ft NGVD stage operations during flow is complicated by the inflowing TP concentrations at G-390 that are strongly related to outflow TP concentrations (**Figure 6**). For TP measurements at G-390 during flow and at the 10.0-ft NGVD operational stage, 33% of the samples were at or below 10 ppb and 52% at or below 15 ppb (**Table 2** and **Figure 5B**). This contrasts markedly with the 10.5-ft NGVD operational stage with less than 3% of the samples at or below 10 ppb and only 24% of the samples at or below 15 ppb. The difference between these two periods was significant (**Table 2**, Kruskal-Wallis test P < 0.0001). The median values during flow at G-390 differed by 7 ppb: 13 ppb for the 10.0-ft NGVD operational stage and 20 ppb for the 10.5-ft NGVD operational stage.
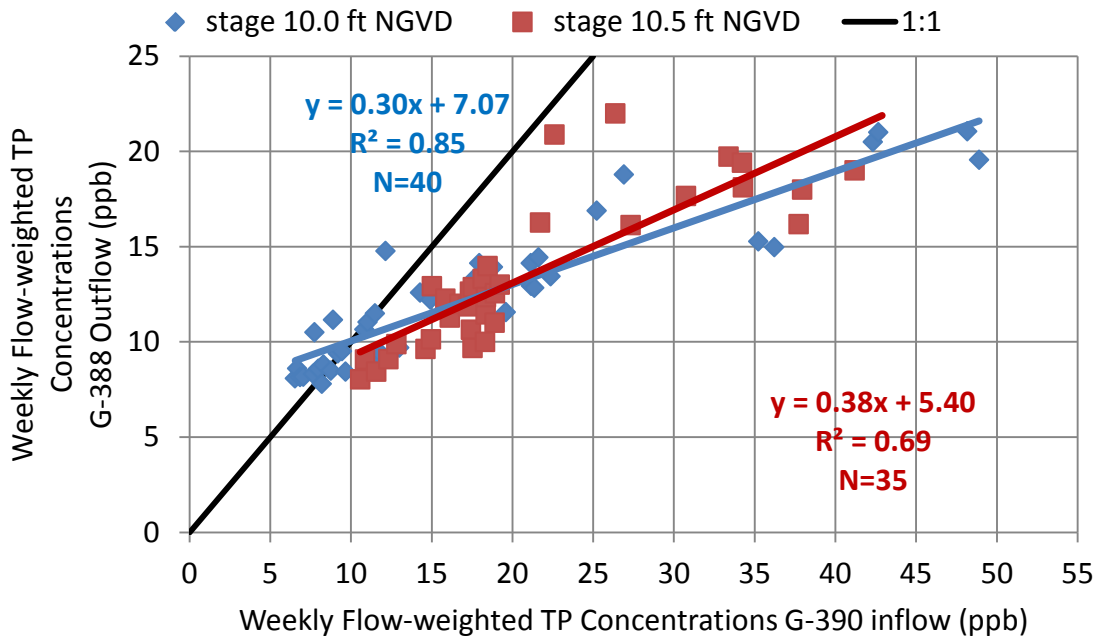
Figure 6. Linear regression of weekly flow-weighted mean TP concentrations (computed from daily flow averaged RPA) at G-390A against G-388 for the 10.0- and 10.5-ft NGVD operational stages.

An ANCOVA comparing outflow (G-388) to inflow (G-390A) and stage operation indicates a strong relationship between weekly inflow and outflow flow-weighted TP concentrations, but there is no significant difference between the two operational stages (**Figure 6** and **Table 5**). A comparison of the weekly inflow-outflow pairs of flow-weighted concentration to the 1:1 line shows that outflow is lower than inflow when inflow exceeds 10 ppb, with one exception. When inflow concentrations are at or below 20 ppb (33 weekly pairs) outflow concentrations are at or below 15 ppb. Based on the linear regressions, an inflow concentration of 25 ppb would result in outflow concentrations of 14.6 and 14.9 ppb for the 10.0- and 10.5-ft NGVD operational stages for the PSTA cell, respectively.

Table 5. ANCOVA statistics for weekly flow-weighted mean TP concentrations at G-388 versus operational stage.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Operational Stage	1	8.05	8.05	2.32	0.1324
G-390 TP	1	773.98	773.98	223.09	<0.0001
G-390 TP x Operational Stage	1	11.65	11.65	3.36	0.0712

| Least Square Means	G-388	Standard Error	H_0:LSMean1= LSMean2 Pr > |t|
10.0-ft NGVD stage	12.88	0.31	0.76
10.5-ft NGVD stage	13.01	0.32	

Time of day did not significantly affect the concentration of phosphorus at G-388 for either stage operational period (**Figure 7**, Kruskal-Wallis Chi-square P > 0.05). The values and the percent cumulative frequencies were very similar among the different three-hour time classes. Conversely, the seasonal data for the 10.0-ft NGVD operational stage were significantly different with lower values during the wet season (**Figure 8a**, Kruskal-Wallis Chi-square P < 0.0001). For the 10.5-ft NGVD operational stage, there was no significant difference (**Figure 8b**, Kruskal-Wallis Chi-square P = 0.73). TP concentrations were significantly higher in the 10.5-ft NGVD operational stage for the wet season (**Figure 8**, Kruskal Wallis Chi-square P < 0.0001).

Comparing the percentage of samples reaching three selected phosphorus concentrations (10, 13, and 15 ppb) for the 10.0- and 10.5-ft NGVD operational stages for different pump operations shows different results (**Figure 9**). At the 10.0-ft NGVD operational stage, the number of samples reaching the various TP concentrations increases with increasing pump operation to a maximum of 642 minutes (estimated flow is 27 cubic feet per second [cfs] with a turnover time of 2.4 days). At the 10.5-ft NGVD operational stage, the pump operation with the greatest number of samples at or below the given values is at the second highest pump operation of 594 minutes (estimated flow is 25 cfs with a turnover time of 3.4 days). The lowest pump operation condition, 169 minutes (estimated flow of 8 cfs and a turnover time of 12.1 days), was the next best result for TP concentrations below 15 and 13 ppb. Overall, there is a significant difference of these TP concentration categories for both the 10.0- and 10.5-ft NGVD operational stage (**Table 6**).
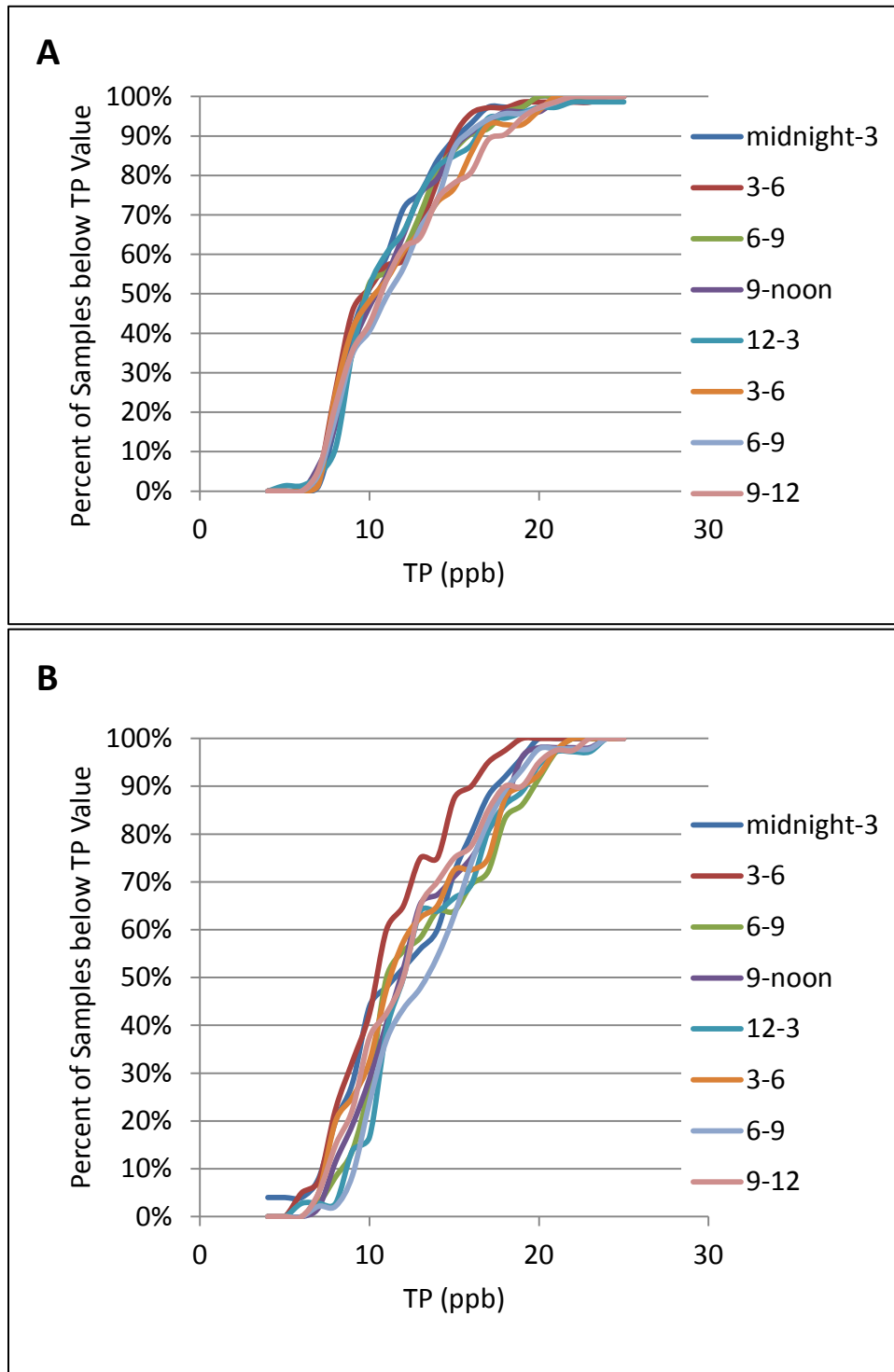
Figure 7. Percent cumulative frequency for G-388 RPA TP measurements while flowing based on time of day for A) 10.0-ft NGVD operational stage (Kruskal-Wallis Chi-square = 2.2, P = 0.95) and B) 10.5-ft NGVD operational stage (Kruskal-Wallis Chi-square = 10.2, P = 0.18).
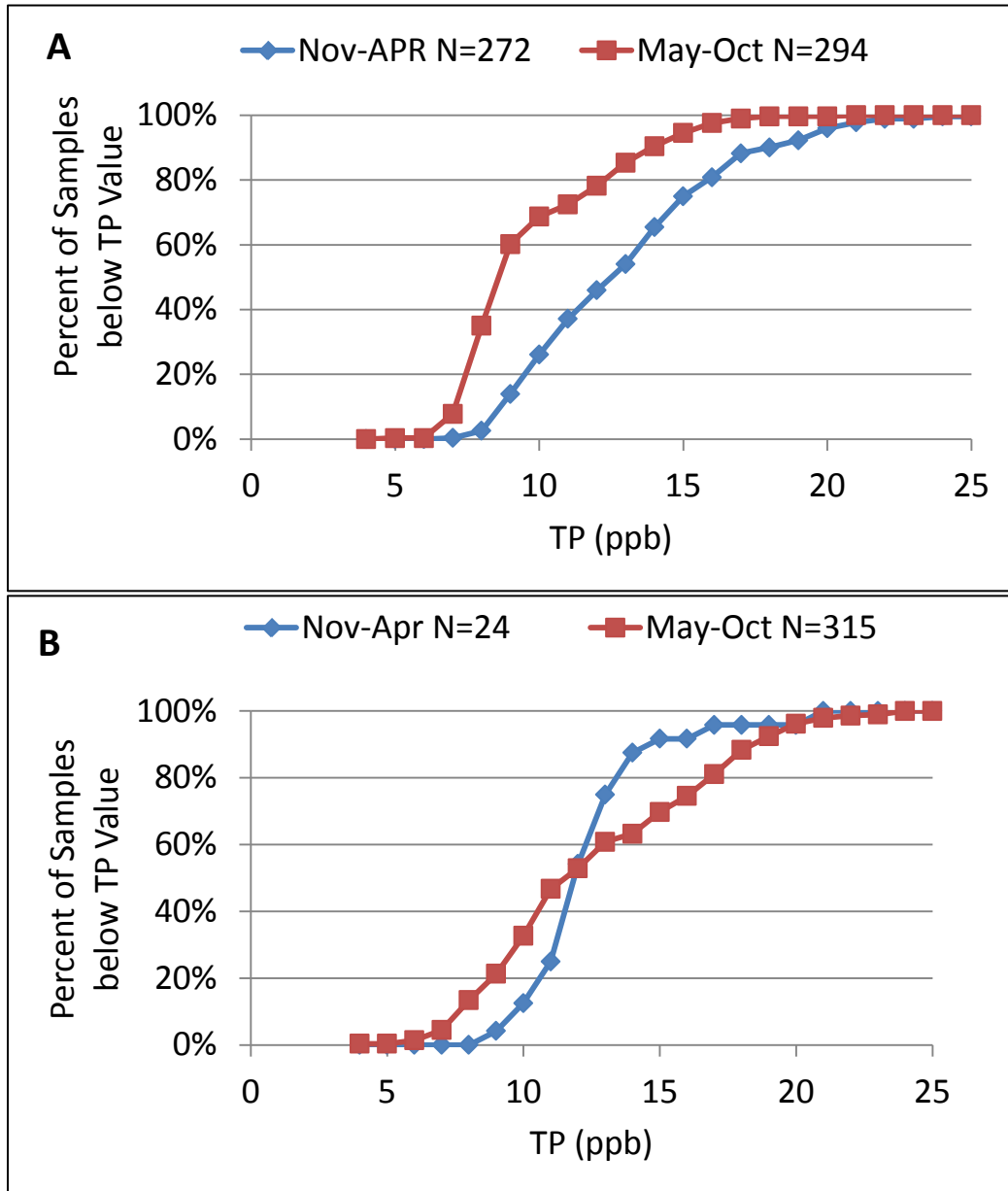
Figure 8. Percent cumulative frequency for G-388 RPA TP measurements based on season (dry: November to April, wet: May to October) for A) 10.0-ft NGVD operational stage (Kruskal-Wallis Chi-square = 136.9, P < 0.0001) and B) 10.5-ft NGVD operational stage (Kruskal-Wallis Chi-square = 0.1208, P = 0.73). Wet seasons at the different operational stages were significantly different (Kruskal-Wallis Chi-square = 87.5, P < 0.0001).
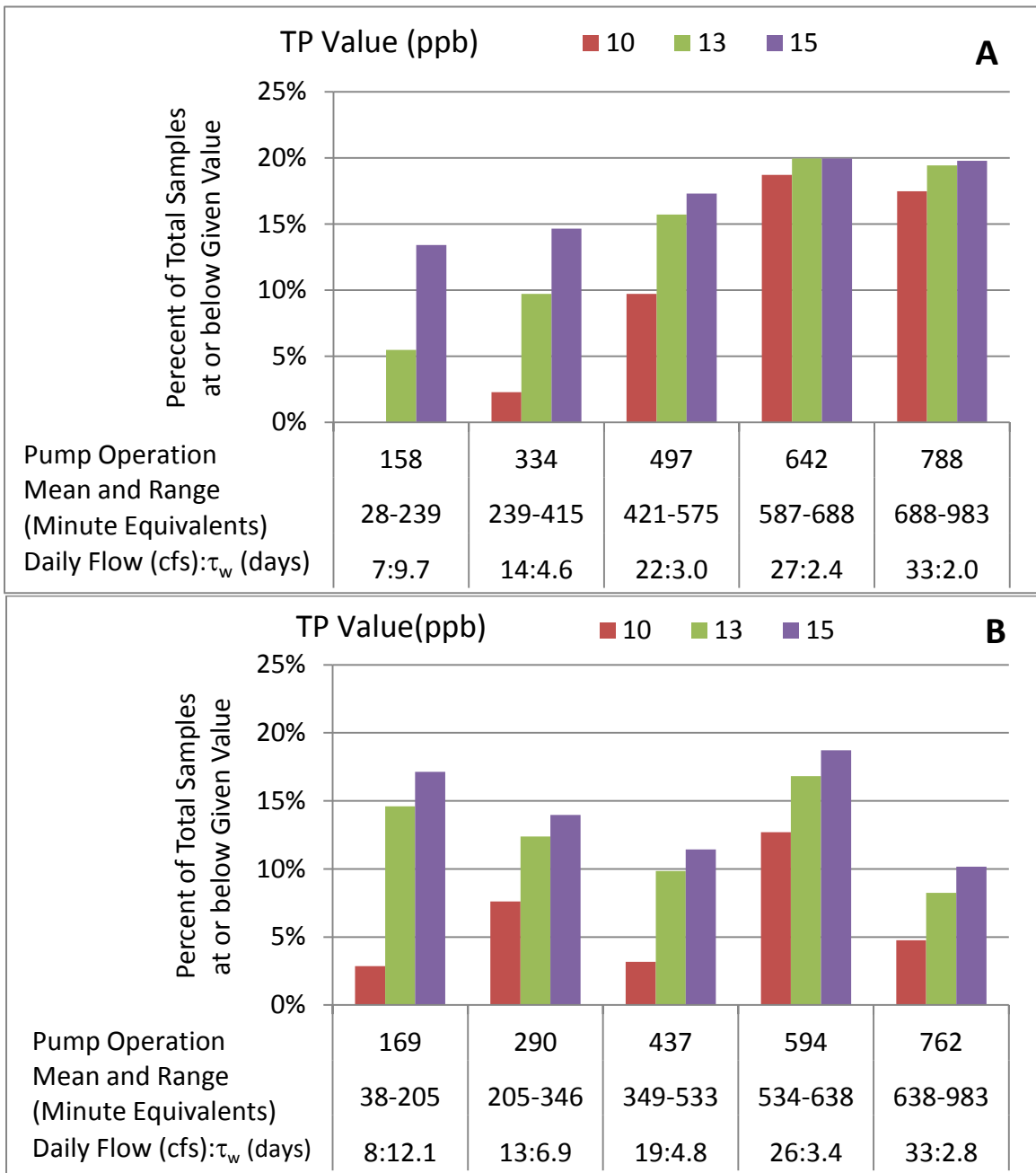
Figure 9. Percent of RPA TP samples at or below 10, 13, and 15 ppb TP under various flow categories—pump operation (minutes), flow (cfs) and τw (turnover time days)—with equal number of samples in each category for A) 10.0-ft NGVD operational stage N = 113 per category and B) 10.5-ft NGVD operational stage N = 63 per category (all comparisons of TP versus pump operation are significant (Kruskal-Wallis Chi-square $P < 0.05$).

Table 6. Kruskal-Wallis rank order tests for 10.0- and 10.5-ft NGVD operational stages comparing counts of TP at or below values of 10, 13, and 15 ppb for five categories of pump operation.

Stage Operation	Pump Operation (minutes)	Estimated Flow (cfs)	Turnover Time (days)	Sample Size (N)	Mean Scores		
					TP < 10	TP < 13	TP < 15
	158	7	9.7	113	147	162.14	232.84
	334	14	4.6	113	179.56	222.24	250.37
	497	22	3	113	284.74	307.39	287.93
10.0 ft NGVD	642	27	2.4	113	412.47	367.5	325.5
	788	33	2	114	392.76	357.57	320.54
	Chi-Square				327.81	213.53	76.14
	Pr > Chi-Square				<0.0001	<0.0001	<0.001
	169	8	12.1	63	131.5	175.5	180.5
	290	13	6.9	63	169	158	155.5
	437	19	4.8	63	134	138	135.5
10.5 ft NGVD	594	26	3.4	63	209	193	193
	762	33	2.8	63	146.5	125.5	125.5
	Chi-Square				48.81	32.07	40.94
	Pr > Chi-Square				<0.0001	<0.0001	<0.0001

DISCUSSION

The STA-3/4 PSTA cell removes phosphorus from the incoming surface water at low ambient inflow concentrations; this is especially true when inflow exceeds 10 ppb (**Figure 6**). At inflow values below 10 ppb, some export may occur as outflow values can exceed inflow values. When weekly inflow-weighted averaged values are at or below 20 ppb, all of the weekly outflow-weighted averaged values are below 15 ppb regardless of operational stage. Based on percent cumulative frequency, it appears that operation at the 10.0-ft NGVD operational stage had lower TP concentrations than the 10.5-=ft NGVD operational stage and would be preferred in future operations of the PSTA cell (**Figure 5a**). However, there are three issues that complicate this result: 1) the number of measurements during outflow for the 10.0-ft NGVD stage operation (566) is almost twice the number for the 10.5-ft NGVD stage operation (315), 2) the TP concentration of the inflowing water during the 10.0-ft NGVD stage operation was significantly

less than during the 10.5-ft NGVD stage operation (**Table 2** and **Figure 5b**), and 3) the inflow concentrations of TP are strongly related to the outflow concentrations (**Figure 6**) and stage operation does not significantly change this relationship (**Table 5** and **Figure 6**).

To remove these complicating factors will require further monitoring. This will increase the number of comparisons, which will address the first factor. The second factor was attributed to vegetation management activities in Cell 2A—upstream of the PSTA cell—that resulted in less water release to the PSTA cell and likely resulted in the higher TP concentration at the PSTA inflow site G-390B. As these activities are completed, it is expected that inflow will increase and TP concentrations at G-390B will decline. Further monitoring at G-388 at the 10.5-ft NGVD stage with the expected lower inflow TP concentration should address the second factor and allow for a more robust comparison between 10.0- and 10.5-ft NGVD operational stages.

The third complicating issue may be extremely important. Because there was no significant difference in the relationship between TP in weekly averaged inflow and outflow concentrations at 10.0- and 10.5-ft NGVD operational stages, neither improved the ability of the PSTA cell to remove TP. This suggests that the range of operational stages (depths) evaluated does not influence the effectiveness of the PSTA cell. However, there is some degree of uncertainty that goes with this finding (e.g., the relationships explain 85 and 69% of the variability for the 10.0- and 10.5-ft NGVD operational stages, respectively (**Figure 6**). As more data are collected under the 10.5-ft NGVD operational stage, the results may or may not validate this issue.

Time of day did not influence the TP concentration discharge (**Figure 7**). However, there was a significant difference in the discharged TP concentrations based on wet and dry seasons for the 10.0-ft NGVD operational stage (**Figure 7A**). The wet season from May to October accounts for over 70% of the annual rainfall in the basin (Chimney 2015). The wet season also is warmer and has longer photoperiod than the dry season resulting in increased microbial activity and periphyton and aquatic plant production. Thus, the left shift of the curve in this wet season was expected as more phosphorus is transformed by biological processes. No difference could be determined in the 10.5-ft NGVD operational stage as the small number of samples in the dry season and the range of variation (N=24, **Figure 7B**) limit the power of this comparison. More samples with flow in the dry season are needed under the 10.5-ft NGVD operational stage, a further reason for continued monitoring under this operational stage.

One uncertainty that the 10.5-ft NGVD operational stage should have resolved is the concern that seepage influences the phosphorus loads associated with the PSTA cell. Under the 10.0-ft NGVD operational stage, seepage is thought to be a significant source of water to the PSTA cell (Zhao et al. 2015). This is due to 1) the lower level of the PSTA cell floor compared to the surrounding STA cells, 2) the lower stages in the PSTA cell compared to surrounding STA cells that results in a head difference and greater seepage and 3) pump operation that draws the water down near the discharge area creating a further head difference that can induce greater seepage. Once the PSTA cell's operational stage was increased by half a foot, the estimated amount of seepage declined (Zhao et al. 2015). If seepage was a significant source of relatively high concentration phosphorus, it would be expected that TP concentration would be higher in discharge at the 10.5-ft NGVD operational stage, especially during the wet season. If seepage were not a significant source of TP, (e.g., it had a dilution effect), then the expected outflow TP concentration would be higher in discharge at the 10.5-ft NGVD operational stage. While the significant difference between TP during the wet season is consistent with the hypothesis that seepage has a dilution effect at the 10.0-ft NGVD operational stage (**Figure 8**), because of the different conditions of the surface inflow TP concentrations, this comparison is inconclusive.

A second method to evaluate the effect of seepage is to compare wet versus dry season discharge at the 10.0-ft NGVD operational stage. If seepage is a significant source of phosphorus for the 10.0-ft NGVD operational stage (e.g., high concentrations of TP in seepage), it would be

expected that discharge TP concentrations from the PSTA cell would be higher in the wet season. This was not observed, in fact the exact opposite was observed, which supports a dilution effect of seepage (e.g., seepage TP concentration below 10 ppb).

A third method to determine if seepage is a significant source of TP or had a dilution effect on the discharge is provided in the ANCOVA between the inflow and outflow TP concentrations for 10.0- and 10.5-ft NGVD operational stages (**Table 4**). This analysis did show an effect of the TP flow-weighted concentration at G-390B (e.g., higher inflow produces higher outflow concentrations), but there was no significant difference with operational stage, and operational stage did not have a significant effect on the slope of G-390B to G-388 TP flow-weighted concentration (**Table 5** and **Figure 6**). This ANCOVA suggests that seepage did not have a significant effect on discharge TP concentration from the PSTA cell. Continued monitoring at the 10.5-ft NGVD operational stage should verify this conclusion given the expected lower inflow TP concentrations as vegetation management activities in Cell 2A are completed.

Evaluating the percent of samples that were at or below 10, 13, and 15 ppb under the two operational stages suggests slightly different mechanisms to reach these ultra-low TP concentrations, and also indicates potential future tests to evaluate these differences. For the 10.0-ft NGVD operational stage, as pump operation increased up to the fourth operation category (642 minutes) so did the percent of samples at or below these TP levels. Note that at this level all values were at or below 13 and 15 ppb (e.g., the maximum percentage in a given category for this analysis was 20%), thus the "leveling off" at the highest category (788 minutes). This could be a result of increased "dynamic" surface area between the flowing water and the periphyton/aquatic plants, (e.g., as water flows faster, the boundary layer surrounding the plant is smaller) allowing for more potential uptake of phosphorus. Conversely, the increased flow could reduce the stagnant areas of the water column where phosphorus could be more easily released to the water column. For the 10.5-ft NGVD operational stage, the highest percent of samples reaching the various TP levels also occurred at the second highest pump operation category evaluated. This was followed by the lowest pump operation category. Potential explanations for this could be attributed to the increased settling of particulates as the water takes longer to move through the cell due to the longer turnover times as compared to the 10.0-ft NGVD operational stage. It could also be attributed to more contact time between the periphyton/aquatic plants and the water column as there is less flow.

CONCLUSIONS

While there was discharge at the G-388 site, a majority of RPA measurements of TP were at or below 15 ppb. On a weekly averaged flow concentration basis, the discharge concentration at G-388 was at or below 15 ppb when inflow concentrations at G-390B were at or below 20 ppb. Operational stage and flow appeared to influence the percentage of outflow measurements at or below 15 ppb. At the 10.0-ft NGVD operational stage, the highest percent of measurements below 15 ppb occurred when the pump operated for 642 minutes per day (estimated daily flow of 27 cfs). At the 10.5-ft NGVD operational stage, the highest percent of measurements below 15 ppb occurred when the pump operated for 594 minutes per day (estimated daily flow of 26 cfs). Continued monitoring using the RPA should improve our understanding of this removal under various flow and stage regimes, particularly for the 10.5-ft NGVD operational stage. TP concentrations in PSTA cell discharge at the 10.0-ft NGVD operational stage were lower during the wet season than the dry season. Comparison of weekly inflow and outflow TP concentrations under 10.0- and 10.5-ft NGVD operational stages suggests that seepage was not a major contributor to the discharge TP concentration.

RECOMMENDATIONS

"Press" tests, e.g., constant flow for a period of one to two weeks minimum, are recommended to determine if a given pump/stage operation combination produce consistent low level TP discharge. Two different tests are indicated from this analysis: 1) 10.5-ft NGVD operational stage (average depth of 1.8 feet), and average pump operation of 594 minutes per day (range of 534–638 minutes per day), and 2) 10.0-ft NGVD operational stage (average depth of 1.3 feet) and pump operation of 642 minutes per day (range of 587–688 minutes per day). The 10.5-ft NGVD operational stage test should be implemented first since this is the current operational setup. This could begin sometime during the upcoming wet season. It would also be instructive to carry out similar tests during the dry season, if possible, to confirm the role of seepage. After the first press test is carried out, the second could be carried out the following wet season.

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