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

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

Analysis of Effects of Sustained Moderate Flow at the Stormwater Treatment Area 3/4 Periphyton-based Stormwater Treatment Area

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EXECUTIVE SUMMARY

The Stormwater Treatment Area (STA) 3/4 Periphyton Stormwater Treatment Area (PSTA) cell was designed to receive water from an upstream STA and discharge ultra-low (≤ 13 micrograms per liter [µg L^{-1}]) total phosphorus (TP) concentrations to the Everglades. A previous study, evaluating TP measurements taken at two or three-hour intervals with remote phosphorus analyzers (RPAs), indicated that the lowest discharge TP concentrations occurred on days when discharge flows averaged 63.6 x 10^3 cubic meters per day (m^3 d^{-1}) or 0.74 cubic meters per second (m^3 s^{-1}) (James 2015). This current study was developed to answer the following questions: (1) can the PSTA cell be actively managed at “moderate” (e.g. ± 20% of 63.6 x 10^3 m^3 d^{-1} or 50.9 to 76.3 x 10^3 m^3 d^{-1}) 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 ≤ 13 micrograms total phosphorus per liter (µg TP L^{-1}), and (4) can this moderate flow regime achieve better results than a lower flow regime (below 50.0 x 10^3 m^3 d^{-1}) when comparing TP removal and TP concentration in the discharging waters?

From September 18 to October 8, 2015, PSTA cell discharge was maintained above 50.9 x 10^3 m^3 d^{-1}. On nine of these days, the flow volume exceeded the high desired flow of 76.3 x 10^3 m^3 d^{-1}, but the average flow for the 21 days was within the desired range: 76.1 m^3 d^{-1}. Based on the size of the PSTA cell (40.8 hectares or 100.75 acres) the hydraulic loading rate (HLR) was between 12.3 and 25.7 centimeters per day. Inflow from the upstream STA was approximately 25% less than the discharge. The South Florida Water Management District’s STA Water Budget Application was used to create hydrologic budgets and estimates of seepage. These seepage estimates accounted for most of the difference between outflow and inflow. A TP budget of the PSTA cell indicated that the PSTA cell removed TP over the 21-day period. All 86 individual RPA measurements taken when there was discharge flow were at or below 10 µg P L^{-1}.

A review of the 2012 to 2015 record (when RPA data were available) revealed two similar periods of continuous flow within moderate ranges. During these periods, flows were within the desired range 81 and 86% of the time, respectively. Both of these periods (one in 2012 the other in 2014) produced similar results to the managed press test: all individual RPA measurements taken when there was discharge during these two periods were at or below 11 µg TP L^{-1}. Budgets of these moderate flow periods indicated a removal of TP.

The 2012 to 2015 record also was 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 (between 4.9 and 46.9 x 10^3 m^3 d^{-1}) 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 µg L^{-1}. During the managed press test, daily mean surface inflow TP declined from 13 µg L^{-1} to near 4 µg L^{-1}, while outflow concentrations remained within daily average values between 6 and 8.5 µg L^{-1}. Also, there were no individual RPA measurements above 10 µg L^{-1}. These observations suggest that there is a limit to TP removal by the PSTA cell (an equilibrium phosphorus concentration, EPC) close to 9 µg TP L^{-1}. These three moderate flow periods, which occurred over four years, suggest that this limit for removal of phosphorus (EPC) has not changed and the PSTA cell still has capacity to achieve ultra-low TP concentrations.

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 μg L^{-1}, the PSTA cell removes TP under moderate flow conditions. Management of the PSTA at moderate flows is as good, or better, than management at low flows.

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INTRODUCTION

Stormwater Treatment Area (STA) 3/4 contains a 40.77-hectare (100.75-acre) periphyton-based stormwater treatment area (PSTA) cell (**Figure 1**). The cell receives water from an upstream submerged aquatic vegetation (SAV) cell through the G-390A and G-390B 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 2.68 meters (m; 8.8 feet [ft]) National Geodetic Vertical Datum of 1929 (NGVD29). This cell was designed to treat stormwater runoff to ultra-low total phosphorus (TP)—≤ 13 micrograms per liter ($\mu g\ L^{-1}$)—concentrations prior to discharge to the downstream Everglades Protection Area. Past studies have shown that this PSTA cell met this performance objective under various flow regimes (Zamorano 2015, Zhao et al. 2015).

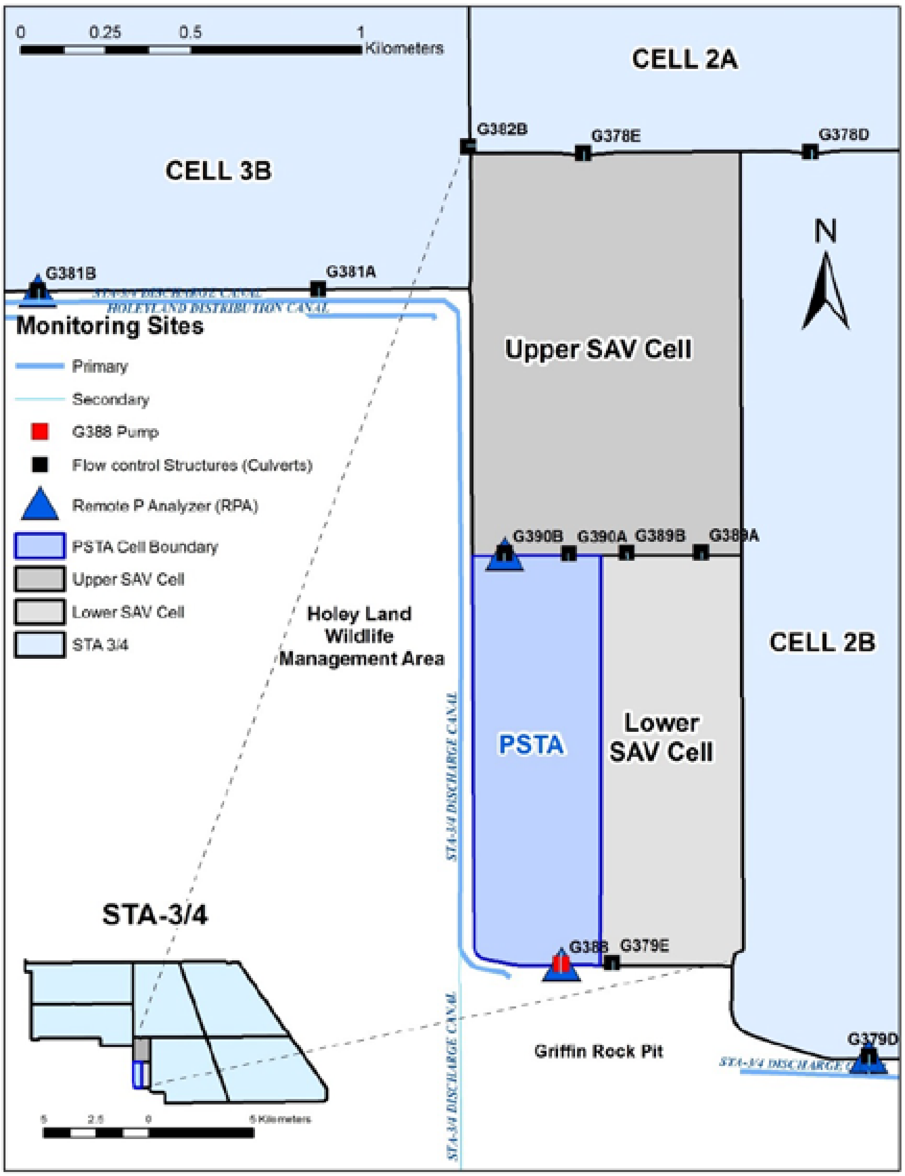

Figure 1. Map of the STA-3/4 PSTA cell showing inflow structures (G390A and G390B) and the discharge pump (G388). RPAs were located at G390B and G388.

A previous analysis of TP measured at the G-388 outflow structure (pump station) at 2- or 3-hour intervals, using remote phosphorus analyzers (RPAs), indicated that the lowest discharge concentration occurred when daily flow averaged 63.6 x 10^3 cubic meters per day (m^3 d^{-1}; 0.74 cubic meters per second [m^3 s^{-1}]; James 2015). Previously, there have been three short-term (3- to 4-day) pulse tests at or above 146.9 x 10^3 m^3 d^{-1} (1.70 m^3 s^{-1}) 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 have been maintained for short periods of time (3 to 4 days). However, moderate flow conditions (e.g. 63.6 x 10^3 m^3 d^{-1}) likely could be maintained over longer periods of time (21 days), but this has not been evaluated.

The objectives of this study were to answer these questions: (1) can the PSTA cell be actively managed at "moderate" (e.g. ± 20% of 63.6 x 10^3 m^3 d^{-1} or 50.9 to 76.3 x 10^3 m^3 d^{-1}) 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 ≤ 13 µg L^{-1}, and 4) can this moderate flow regime achieve better results than a lower flow regime (below 50 x 10^3 m^3 d^{-1}) 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 m^3 s^{-1} (50.9 x 10^3 m^3 d^{-1}, or a hydraulic loading rate [HLR] of 12.5 centimeters per day [cm d^{-1}]) from September 18 to October 9, 2015, and to allow discharge pumping at this moderate rate (**Figure 2A** and **Table 1**). During this 21-day managed "press" test, the average stage was 3.20 m NGVD29.

TP has been measured in-situ, from 2012 to present, using RPAs (SFWMD 2012) near the inflow (G-390B) and outflow (G-388) structures of the PSTA cell (**Figure 1**). The monitoring sites are G390B and G388, respectively, which are located at or near the structures. These TP measurements were taken every three hours with breaks due to power loss, equipment failure, or system maintenance. From November 22, 2013, to October 2, 2014, the sampling frequency at G390B was increased to every two hours.

Daily flow measurements were obtained from the South Florida Water Management District's (SFWMD's) corporate environmental database, DBHYDRO, for database keys (DBKEYS) V8861 (G390A), 90405 (G390B), and W3981 (G388)[1]. A review of this data for Calendar Years 2012 to 2015 (the period when the RPAs were operational) revealed two additional periods of 20 or more days with daily discharges at or above 50.9 x 10^3 m^3 d^{-1} (**Table 1** and **Figures 2B** and **2C**) and at least 40 TP measurements at G388 (**Table 2**). These two periods were from September 13 to October 2, 2012 (moderate flow 2012, stage of 3.05 m NGVD29), and September 14 to October 4, 2014 (moderate flow 2014, stage of 3.20 m NGVD29).

Low flow periods, when the flows through the PSTA cell were consistently below 50.9 x 10^3 m^3 d^{-1}, 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) flow on all included days, (3) daily discharge less than 50.9 x 10^3 m^3 d^{-1}, (4) within 2.5 months of the moderate flow periods, and (5) at least 7 days in duration. The comparison periods (2012, 2014, and 2015 low flows) were shorter in length (**Table 2** and **Figures 2D**, **2E**, and **2F**), and much lower flow than the moderate flow periods (**Table 1**). Because the 2012 moderate flow and 2012 low flow periods occurred when the water level in the PSTA cell was 15.2

[1] DBHYDRO is accessed at http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu. Data was pulled from the database on November 10, 2015.

centimeters (cm) lower (one-half foot) than the other tests, the turnover time (calculated from mean volume divided by mean outflow) was also shorter (**Table 1**).

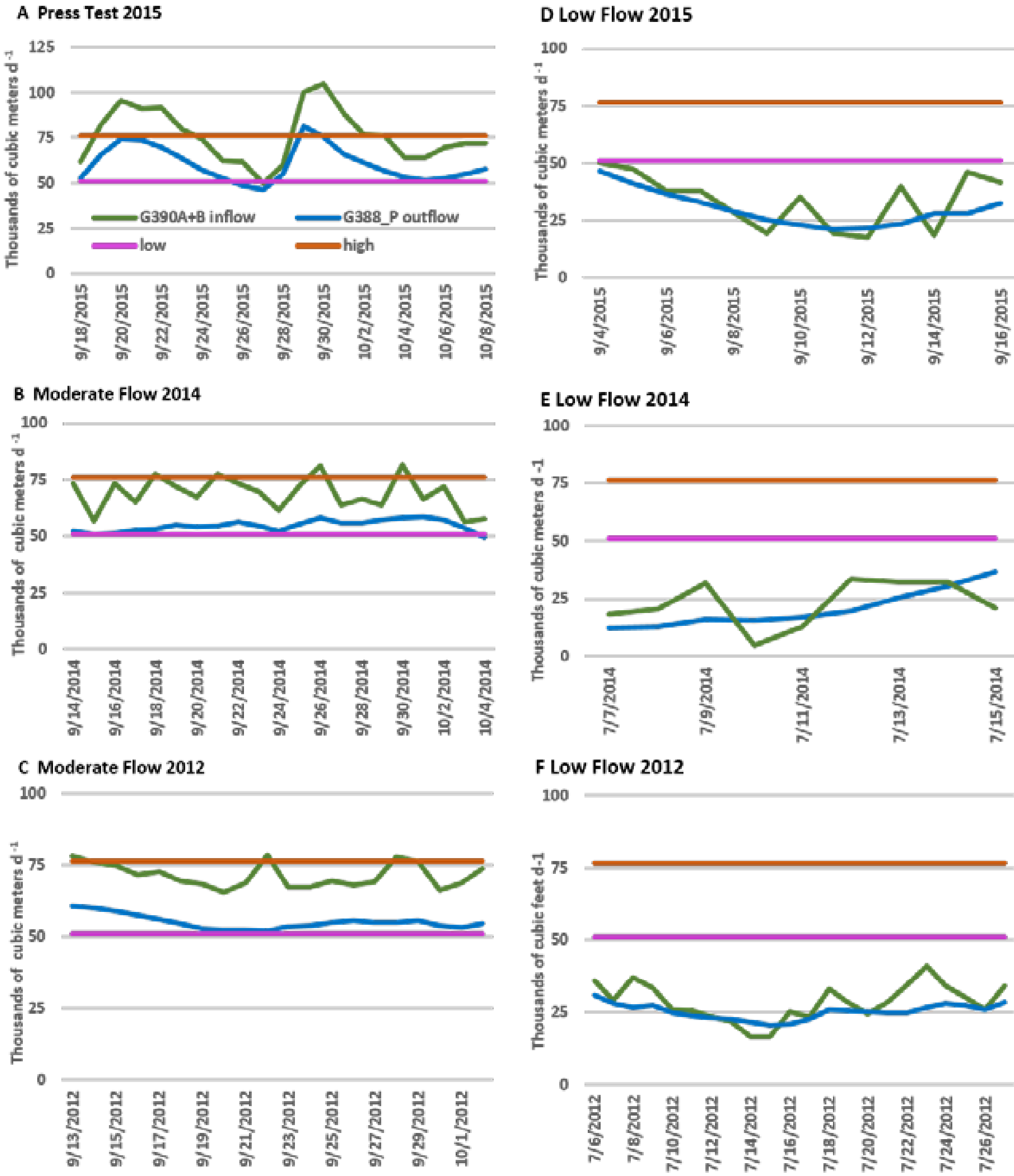

Figure 2. Daily volume inflow, outflow, and desired flow range (low and high) for three moderate flow periods (A, B, and C) and three low flow periods (D, E, and F).

Table 1. Inflow and outflow daily volume statistics for the PSTA cell for the moderate and low flow periods.

Year	Period	Average Cell Volume ($x10^3$ of cubic meters)	Number of Days	Flow Type	Daily Flow Volume ($x10^3$ m^3 d^{-1}) Mean	Minimum	25th Percentile	Median	75th Percentile	Maximum	Coefficient of Variation	Hydraulic Loading Rate (cm d^{-1})	Turnover Time (days)
2015	Press Test Moderate Flow	232.2	21	inflow	60.5	46	52.7	57.5	67.9	81.2	20.1	14.8	
				outflow	76.1	50	62.9	74	89.4	104.8	23.7	18.7	3.0
	Low Flow	230.0	12	inflow	28.4	21.1	22.9	28	32.8	41.0	27.2	7.0	
				outflow	32.2	17.3	18.5	36.4	41.3	46.9	43.6	7.9	7.1
2014	Moderate Flow	232.2	21	inflow	54.7	49.7	52.6	54.7	56.8	58.7	5.9	13.4	
				outflow	69.3	56.7	64.1	69.1	74.0	81.4	13.3	17.0	3.4
	Low Flow	226.2	9	inflow	20.6	12.4	14.1	16.8	27.9	36.7	50.6	5.1	
				outflow	22.9	4.9	15.4	21	32.1	33.3	54.8	5.6	9.9
2012	Moderate Flow	184.9	20	inflow	55.2	52.3	53.3	54.8	56.1	60.8	5.5	13.5	
				outflow	71.6	65.4	68.1	69.7	76.2	78.9	7.2	17.6	2.6
	Low Flow	170.9	16	inflow	24.2	20.6	22.7	24.8	25.7	28.2	11.3	5.9	
				outflow	26.8	16	23.4	25.9	32.4	37.0	27.0	6.6	6.4

Table 2. Moderate and low flow periods, dates, number of days, number of samples, and number of missing days of remote phosphorus analyzer TP measurements.

Flow Rate	Start Date	End Date	Number of Days	G390B Number of Samples	G390B Number of Missing Days	G388 Number of Samples [a]	G388 Number of Missing Days
Moderate	9/18/2015	10/8/2015	21	164	0	86	0
Low	9/5/2015	9/16/2015	12	96	0	19	2
Moderate	9/14/2014	10/4/2014	21	242	0	40	0
Low	7/7/2014	7/15/2014	9	104	0	10	2
Moderate	9/13/2012	10/2/2012	20	160	0	66	1
Low	7/7/2012	7/22/2012	16	124	0	23	2

a. Includes only samples taken when the pump was running.

Daily water budgets for the period of May 2012 to October 2015 were calculated using the STA Water Budget Application (BPC Group, Inc. 2008) and the methods and data sources used by Zhao et al. (2015). In addition to the daily flows at G390A, G390B, and G388, daily rainfall was obtained for station EAA5 (DBKEY VN030) located 10 kilometers (km) north-northeast of the PSTA cell and evapotranspiration was obtained for weather station ROTNWX (DBKEY RW486) located 24.5 km west of the PSTA cell. PSTA volume was estimated from stage values at G388 (DBKEY TZ219) and G390A (DBKEY UA609) using the following formula:

$$Volume_{PSTA} = \left[\frac{(G388_h + G390A_t)}{2} - 2.68\right] * 44770$$

Where $G388_h$ and $G390A_t$ are the headwater and tailwater stages (in meters) at G388 and G390A, respectively. 2.68 m is the average floor elevation of the PSTA cell, and 44,770 square m is the area of the PSTA cell. The daily positive and negative residuals were determined from the difference of the net inflows (rain + inflow + seepage – outflow - evapotranspiration) and the change in volume on a daily basis. These residuals were included in the analysis as additional seepage inflow or outflow (see below).

The inflow load was determined from daily averaged RPA measurements multiplied by the flow volume. The outflow load was estimated from the daily averaged RPA measurements collected when the pump was operating (determined from breakpoint pump speeds obtained for DBKEYS TZ221 and TZ222 at G388_P), and then multiplied by the flow volume. If daily average TP values were not available, they were estimated by linear interpolation between the previous and next daily average. Atmospheric deposition was based on the estimate of 30 milligrams phosphorus per square meter per year (mg P m^{-2} yr^{-1}; Redfield 2002). This equates to an estimated 0.033 kilograms phosphorus per day (kg P d^{-1}) of atmospheric phosphorus (P) load to the PSTA cell. The mass estimate of TP in the cell was calculated by multiplying the daily estimated water volume by the average of the inflow and outflow concentrations each day. The seepage was calculated using a formula developed by Zhao et al. (2015) that included the difference between the PSTA and the adjacent water body, the levee length, and a coefficient of seepage. Loadings to the PSTA cell through seepage were estimated by assuming the TP concentration in seepage water was either 10 or 20 µg TP L^{-1} (Zhao et al. 2015) The TP values in the lower SAV and in the 2.44-m (8-ft) wells between the PSTA and lower SAV cell were within this range (Zamorano et al. 2017). Positive daily residuals were assumed to be inflow seepage and loading was estimated by multiplying the value by 10 or 20 µg L^{-1}. Negative daily residuals were assumed to be seepage out of the cell and loading was estimated by multiplying this seepage out by the daily concentration at G388 (at or near the outflow pump).

RESULTS

The managed press test exceeded the high flow target for discharge by as much as 33% on 9 of the 21 days (**Figure 2A**). However, the mean discharge (76.1 x 10^3 m^3 d^{-1}) was within the desired range of flow (**Table 1**). The mean daily discharges for the 2012 and 2014 moderate flow periods were lower than this 2015 managed press test with little day-to-day variation in the inflow, and modest day-to-day variation in the discharge (**Figures 2B** and **2C**). Flows for these two periods were outside of the desired range for only a few days. The average discharges for 2012 and 2014 were similar (71.6 x 10^3 and 69.3 x 10^3 m^3 d^{-1}, respectively; **Table 1**).

For all periods evaluated in this study, the discharges were greater than the surface inflow (**Table 1**). This is observed both in the mean daily flows and the HLR estimates, which were higher for outflow than inflow in the managed press test and the two other moderate flow periods by 3.5 cm. The average daily water budgets for the moderate flow periods and the managed press test were similar with discharge exceeding inflow by more than 25% (**Figure 3**). The low flow periods had smaller mean daily inflows and outflows, with discharge exceeding the inflow by 11 to 13%. Seepage, which made up for most of this difference, was higher in the moderate flow than the low flow periods. Additionally, the negative residuals (e.g. additional seepage out) were larger in the low flow periods than in the moderate flow periods, while the positive residuals (additional seepage into the cell) were larger for the moderate flow periods. Rainfall and evaporation were minor compared to these other flows. During each moderate flow period, over 159 TP measurements were made at the inflow structure (G390B) with no missing days, and over 39 measurements were made at G388 when the outflow pump was operating with only one missing day of samples for the 2012 period (**Table 2**).

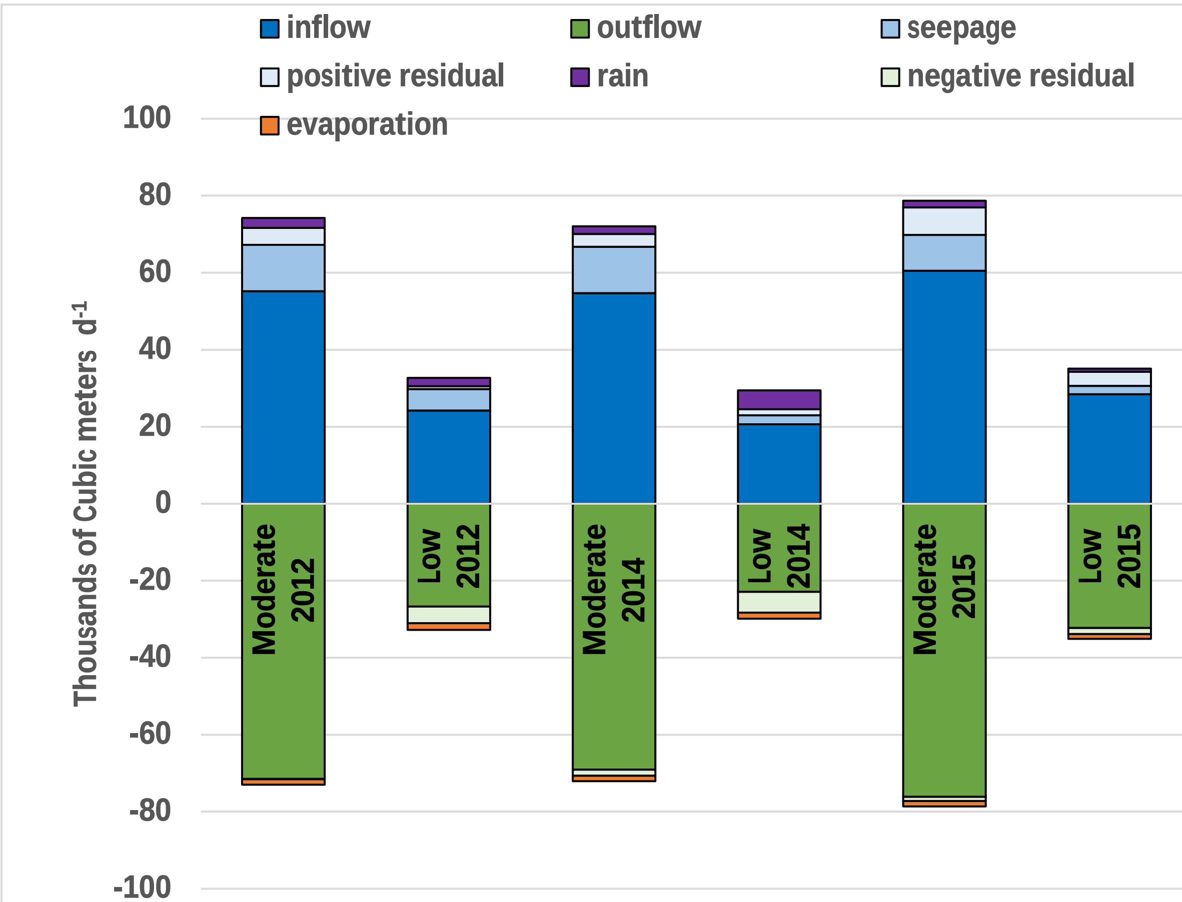

Figure 3. Daily averaged water budgets of the PSTA cell for three moderate flow periods and three low flow periods.

Daily TP concentrations at the inflow for low flow periods were higher and varied more than the inflow for moderate flow periods (**Table 3** and **Figure 4**). The inflow concentrations also varied to a greater extent than outflow concentrations. The low flow period inflow concentrations were greater than the moderate flow inflow concentrations. Inflow and outflow concentrations for the 2012 and 2015 moderate flow periods varied much less than the managed press test in 2015. The latter inflow concentration declined to the lowest values of any period (**Figure 4A**). Despite this decline, the daily outflow concentration of the managed press test remained between 6 and 8 $\mu g\ L^{-1}$.

Table 3. Phosphorus loading rate (PLR) and selected statistics for inflow and outflow RPA TP measurements and for the PSTA cell during the moderate and low flow periods.

Year	Period	Flow Type	RPA TP measurements (µg L^{-1}) [a]								PLR (mg m^{-2} d^{-1})
			Flow-weighted Mean Concentration	Minimum	25th Percentile	Median	75th Percentile	Maximum	Standard Deviation	Coefficient of Variation	
2015	Press Test Moderate Flow	inflow	7.1	3	6	7	9	13	1.9	27%	1.05
		outflow	7.4	4	7	7	8	10	1.2	16%	
	Low Flow	inflow	9.4	4	8	9	10	15	1.7	18%	0.66
		outflow	8.0	6	7	8	9	12	1.4	17%	
2014	Moderate Flow	inflow	11.0	5	10	11	12	18	1.7	16%	1.48
		outflow	8.9	6	8	8	9	11	1.3	14%	
	Low Flow	inflow	16.6	11	15	17	19	27	2.8	17%	0.84
		outflow	13.0	11	12	13	14	17	1.9	14%	
2012	Moderate Flow	inflow	7.4	4	7	7	8	15	1.2	17%	1.00
		outflow	8.4	7	8	8	9	11	0.9	10%	
	Low Flow	inflow	21.0	15	19	21	23	30	2.7	13%	1.26
		outflow	12.4	11	12	13	14	16	1.3	11%	

a. Flow-weighted mean concentrations are based on daily averages of flow and concentration measurements. All other statistics are based on individual RPA measurements during the test and comparison periods as defined in **Table 2**.

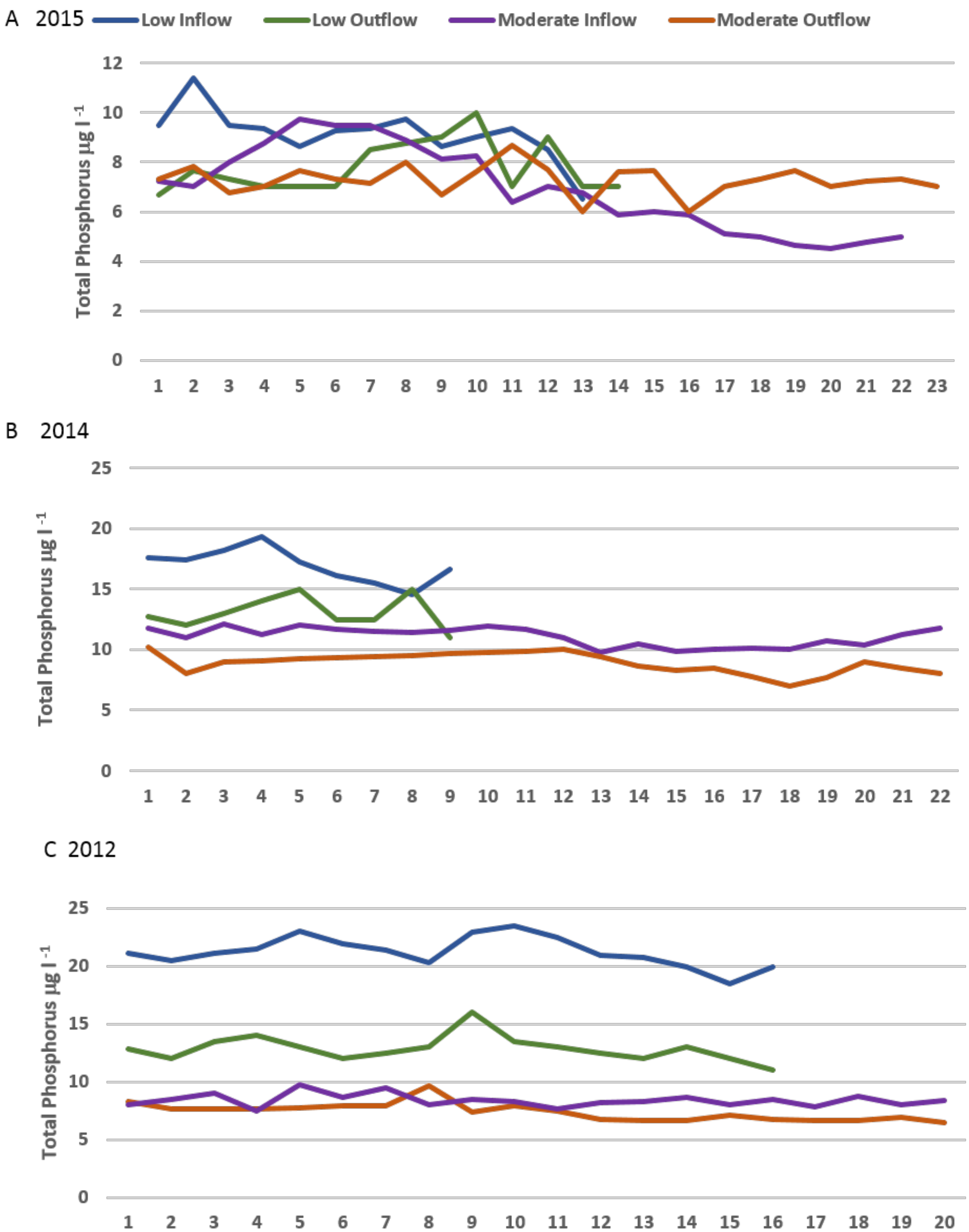

Figure 4. Mean daily inflow and outflow concentrations for low and moderate flow periods for Calendar Years (A) 2015, (B) 2014, and (C) 2012.

For all periods, the TP flow-weighted mean concentration (FWMC) discharge was at or below 13 mg L^{-1} (**Table 3**). For the moderate flow periods, the FWMC discharge was less than the low flow periods. Maximum individual RPA measurements of discharge TP in the moderate flow periods were at or below 11 mg TP L^{-1} while the maximum individual RPA TP measurements at the discharge for the low flow periods were 16, 17, and 12 mg TP L^{-1} for the 2012, 2014, and 2015 periods, respectively.

FWMC inflow values ranged from 7.1 mg L^{-1} for the press test in 2015 to 21 mg L^{-1} for the 2012 moderate flow period (**Table 3**). For these two periods, the discharge FWMC was greater than the inflow FWMC, however the maximum values in the outflow were less than the maximum values in the inflow. Overall, the coefficients of variation in the outflow TP concentrations were less than the coefficients of variation for the inflow TP concentrations.

Despite the similarity in overall hydrologic budgets of the moderate flow periods, the inflow surface load for the 2012 moderate flow period (0.41 kilograms per day [kg d^{-1}]) was lower than the 2014 moderate flow period load (0.60 kg d^{-1}), which was much higher than the 2015 managed press test load (0.43 kg d^{-1}; **Figure 5**). The phosphorus loading rate (PLR) for the three moderate flow periods were 1.00, 1.48, and 1.05 milligrams phosphorus per square meter per day (mg P m^{-2} d^{-1}), respectively, while the PLR for the low flow periods were 1.26, 0.84, and 0.66, respectively (**Table 3**). The lower PLR in the 2012 moderate flow period as compared to the 2012 low flow period is attributed to higher TP inflow concentrations during the low flow period. Despite differences of inflow TP load to the PSTA cell, the discharge TP loads for the moderate flow periods were quite similar (0.60, 0.62, and 0.56 kg d^{-1} for 2012, 2014, and 2015, respectively). TP discharge loads from the PSTA cell for the low flow periods were lower than the moderate flow periods (0.34, 0.30, and 0.26, respectively), despite the higher TP FWMCs, because of the lower water volume discharged.

Seepage was a substantial factor of the inflow loads and the PSTA budget. Assuming a TP concentration of 10 mg L^{-1}, seepage contributed between 11 to 29% of the TP inflow load (**Table 4**). Assuming a TP concentration of 20 mg L^{-1} seepage contributed between 19 and 45% of the TP load. The budgets show the effect of this seepage through the calculation of TP removal by the PSTA cell. The removal was estimated by the difference between net loads (inflow loads - outflow loads) and the change TP over time (in terms of mass) within the PSTA cell (**Figure 5**).

Assuming a seepage inflow concentration of 10 micrograms phosphorus per liter (mg P L^{-1}), the amount of TP removed for the 2012, 2014, and 2015 moderate flow periods was 0.01, 0.16, and 0.07 kg P d^{-1}, respectively, and for the low flow periods, 0.25, 0.10, and 0.09 kg P d^{-1}, respectively (**Figure 5**). Assuming a seepage inflow concentration of 20 mg P L^{-1}, removal increased to 0.17, 0.32, and 0.23 kilogram total phosphorus per day (kg TP d^{-1}) for the moderate flow periods, and 0.31, 0.14, and 0.15 kg d^{-1} for the low flow periods, respectively. A higher percentage of the total inflow load was removed at low flow than moderate flow periods for all but one comparison (2014 at 20 mg P L^{-1}), in part because there was less load during the low flow periods (compare **Figure 5** and **Table 4**).

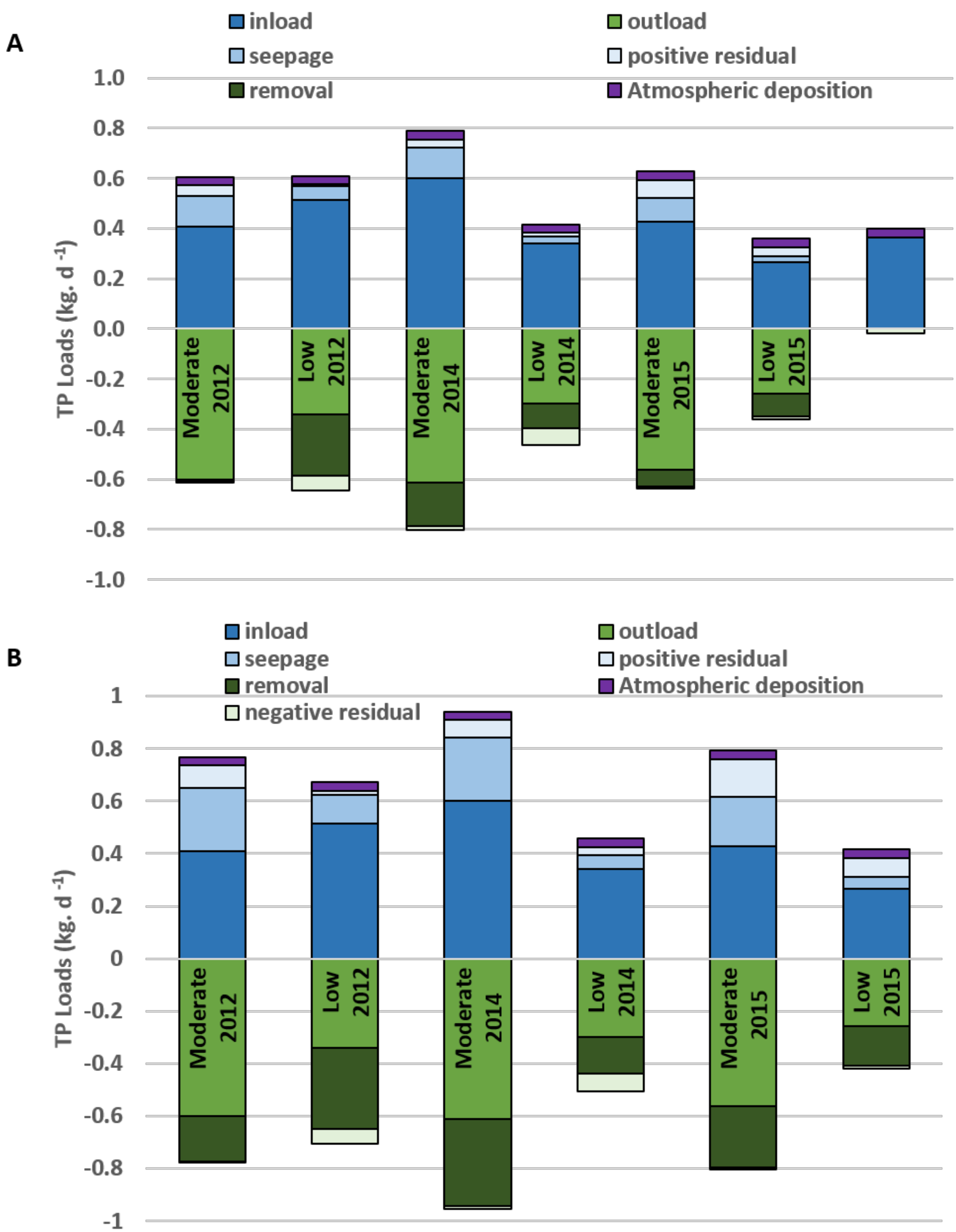

Figure 5. P budgets of the PSTA cell for three moderate and three low flow periods assuming (A) a seepage P concentration of 10 mg L^{-1} and (B) a seepage P concentration of 20 mg L^{-1}).

Table 4. Percent of TP load contributed by seepage and removed by the PSTA cell each moderate and low flow period.

Year	Flow Period	Percent of TP Load Attributed to Seepage for a Given Seepage Concentration		Percent P Load Removal for a Given Seepage Concentration	
		10 µg P L^{-1}	20 µg P L^{-1}	10 µg P L^{-1}	20 µg P L^{-1}
2015	Press Test Moderate Flow	29%	45%	11%	29%
	Low Flow	11%	20%	25%	36%
2014	Moderate Flow	20%	34%	21%	34%
	Low Flow	11%	19%	24%	31%
2012	Moderate Flow	28%	44%	1%	22%
	Low Flow	18%	30%	40%	46%

DISCUSSION

The three moderate flow periods were similar in their hydrologic budget, but were different in daily inflow and outflow patterns (**Figures 2** and **3**). In addition, the 2012 period occurred when water levels were approximately 15.2 cm (0.5 ft) shallower than during the other moderate flow periods. Seepage, which was estimated based on the head difference between the PSTA cell and the surrounding SAV cells (Zhao et al. 2015) was a substantial contributor of flow to the PSTA cell for the three moderate flow periods. In addition, the positive residuals for the water budgets were larger for these three periods than for the three low flow periods (**Figure 3**). These residuals could be attributed to the intermittent pumping at the G-388 structure, which occurred multiple times a day and rapidly affected the water levels in the PSTA cell. Because the STA Water Budget Application used daily average values to determine seepage, the intermittent changes in seepage, due to short-term fluctuations in water levels, are not accounted for in the calculations. Thus, the amount of water pumped out of the PSTA cell at the G-388 structure exceeded the flow into the PSTA cell through the G-390 culverts plus the estimated seepage based on daily average water levels. The remaining positive residual was assumed to be seepage from the short-term fluctuations.

No statistical analyses were performed for this study, in part because selections of the low flow periods were not random and the conditions (e.g. inflow concentrations and time periods), were not equivalent to the moderate flow periods. Assuming the TP concentration of seepage was 10 µg P L^{-1}, the 2014 moderate flow period was the only one of the three moderate flow periods that removed more P from the inflow waters than its comparison low flow (i.e. 2014) period **(Figure 4B** and **Table 4**). However, if the assumed seepage P concentration was 20 µg L^{-1}, (as indicated from well samples and water samples from the lower SAV cell taken during this year, unpublished data) then both the moderate flow periods in 2014 and 2015 removed more P on a daily basis than the low flow periods in 2014 and 2015 (**Figure 4b** and **4c**). While it is possible that the greater removal during the 2014 moderate flow period was a result of more constant flow (compared to the 2015 moderate flow period) and the deeper water column (compared to the 2012 moderate flow period), a confounding factor is the inflow TP concentration, which was highest during the 2014 moderate flow period (FWMC of 11 µg L^{-1}, **Table 3**) and lower than 8 µg L^{-1} in the other two moderate flow periods (FWMC of 7.4 and 7.1 µg TP L^{-1}, respectively).

While the inflow FWMC for the three moderate flow periods were different, all three had TP discharge concentrations of ≤ 13 µg L^{-1} (**Table 3**). Consequently, the discharge loads also were similar during these three periods (**Figure 5**). There were no individual TP measurements in the discharge during these periods that exceeded 11 µg TP L^{-1} (**Table 3**). The 2014 moderate flow period had the highest FWMC in the outflow (8.9 µg TP L^{-1}) and the greatest removal of TP (**Figure 5B**). When the FWMC of inflow was less than 9 µg TP L^{-1}, the daily outflow concentration was higher (**Figure 4**). The largest difference between the daily inflow and outflow concentrations occurred on day 19 for the 2015 managed press test, which were 4.6 µg TP L^{-1} and 7.7 µg TP L^{-1}, respectively. These inflow/outflow results suggest that there is an EPC (Belmont et al. 2009) for the PSTA cell close to 9 µg TP L^{-1}. When inflow was less than 9 µg TP L^{-1}, it appears that the PSTA cell released some P (e.g. from sediments or periphyton) or was affected by seepage water resulting in outflow concentrations near 9 µg TP L^{-1}. When inflow concentrations were above 9 µg TP L^{-1}, the PSTA cell removed TP resulting in outflow concentrations near 9 µg TP L^{-1}. The results of the three moderate flow periods that occurred over four years suggest that this limit for removal of phosphorus (EPC) has not changed and the PSTA cell still has capacity to achieve ultra-low TP concentrations.

Based on the nutrient budget calculations, the PSTA continued to remove TP for all moderate flow periods, albeit removal for the 2012 moderate flow period was very small (**Figure 5**). Given the assumptions made on seepage, seepage concentration, the water budget calculations, and the criteria used to estimate loads into and out of the cell, the PSTA cell also removed P under low inflow conditions at discharge flow loading rates from 22.9 to 32.2 x 10^3 m^3 d^{-1}. While the daily removal for low flow periods was on a par with the moderate flow periods, much less water and total load are processed at these lower flows.

In addition, the results indicate that TP FWMC of discharge was higher under low flow conditions as compared to moderate flow conditions (**Table 3**). This result supports the hypothesis that moderate flows (from 50.9 to 76.3 x 10^3 m^3 d^{-1}) are optimal in achieving the $\leq$ 13 µg L^{-1} discharge criteria.

CONCLUSIONS

The PSTA cell can be managed for moderate flows for extended periods of time. During moderate flow periods, the concentration in discharge water remains below 13 µg TP L^{-1}. The FWMC of TP in the discharge during these moderate flow periods was less than the FWMC in the discharge of comparison periods of low flow. Assuming a concentration in the seepage of 10 µg P L^{-1}, only one of the three periods (2014) resulted in more removal of TP than the companion low flow period. However, if the seepage was assumed to be 20 µg P L^{-1} then moderate flows in 2014 and 2015 removed more P than their companion 2014 and 2015 low flow periods. While daily flows and water levels were different among these three periods, the water budgets were very similar, with the largest difference being seepage estimates. This study indicates that the PSTA cell performs as expected, ultra-low TP concentrations in the discharge are maintained over extended periods of constant moderate flow.

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