

Appendix 5C-2: L-8 Flow Equalization Basin Operational Guidance

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SUMMARY

The primary purposes of the L-8 Flow Equalization Basin (FEB) are to attenuate peak stormwater flows and temporarily store stormwater runoff to improve inflow delivery rates to Stormwater Treatment Area 1 East (STA-1E) and Stormwater Treatment Area 1 West (STA-1W). The FEB was not expected to reduce total phosphorus (TP) concentrations along the flow path but when several brief periods of higher TP concentrations at the outflow than inflow were found, a study was initiated to determine the source of the elevated TP during these periods.

This study found that large inflow events can elevate TP concentrations in the FEB. Inflow events are periods of continuous flow or near continuous flow typically lasting a few days to few weeks. Specific findings are as follows:

- Monthly surface water monitoring of TP concentrations in cells nearest the inflow spillway were strongly and inversely correlated with the number of days since the inflow rate was greater than 500 cubic feet per second (cfs), indicating that these large inflow events may raise TP in FEB waters.
- High frequency monitoring of a large inflow event found that TP increased six-fold in the FEB cell closest to the inflow structure and more than doubled in the FEB cell furthest away from the inflow structure.
- Increases of TP concentration in the L-8 FEB could not be solely explained by high TP concentrations of the incoming water. FEB TP concentrations also increased after inflows ceased, exceeding inflow TP concentrations.
- Scouring immediately below the inflow spillway indicates that sediments resuspend from this area of high flow velocity.
- Laboratory resuspension test found that benthic FEB sediments increased TP concentration in the overlying water column to extremely high levels that diminished over time but remained very high for over a week.
- High frequency monitoring of a large inflow event found that TP concentrations declined to one-third from their peak within 3 weeks in the top of the water column.

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The key findings from this study with the largest implications for FEB operations are (1) large inflow events result in increased TP concentrations in the FEB especially nearest the G-538 inflow structure; (2) these elevated TP concentrations diminish with time, but TP remains higher than pre-event levels for over 3 weeks; (3) accrued sediment in the FEB is likely resuspended during flow events increasing already high TP concentrations from inflow; and (4) discharge via the G-539 pump station did not elevate TP concentrations.

Over the last three water years, the FEB has been a sink for phosphorus (P), which is beneficial to the downstream Everglades Stormwater Treatment Areas (STAs) by reducing P loading. Typical operation of the FEB over the period of record (POR) included large inflow events that quickly filled the FEB towards the end of the wet season followed by a slow discharge from the FEB over the dry season and into the next wet season. This sequence worked well to sequester P in the FEB over the last three water years. The high P concentrations in inflows during these high discharge events resulted in large load events. Since early 2019, L-8 FEB TP discharge concentrations have been lower than the inflow concentrations. It may be possible, weather permitting, to further optimize this operational pattern of wet season inflows and dry season discharges to further increase P retention and thus reduce P load to downstream STAs.

INTRODUCTION

The L-8 FEB, a component of the *Restoration Strategies Regional Water Quality* (SFWMD 2012) is a 366-hectare (950-acre) former rock mine capable of storing approximately 45,000 acre-feet (15 billion gallons) of water. The FEB depth typically changes dramatically throughout the year, ranging from just over 12.3 to 56.3 ft over the study period. It is located approximately 20 miles west of West Palm Beach, immediately west of the L-8 canal and approximately 1 mile north of Southern Boulevard/State Road 80 (**Figure 1**). Prior to incorporation into the South Florida Water Management District's (SFWMD's or District's) *Restoration Strategies Regional Water Quality Plan* (SFWMD 2012), the L-8 FEB was part of the Comprehensive Everglades Restoration Program (CERP) and was referred to as the L-8 Reservoir. The facility consists of six interconnected cells in series, an inflow spillway structure (G-538), and an outflow pump station (G-539), which delivers water to and from the L-8 canal. Details of additional structures and facility components are provided in the *L-8 Reservoir/Flow Equalization Basin Draft Project Operational Manual* (SFWMD 2015).

The primary purpose of the L-8 FEB is to attenuate peak stormwater flows and temporarily store stormwater runoff to improve inflow delivery rates to STA-1E and STA-1W. Improved control over water deliveries to the STAs enhances operational flexibility that should improve STA P removal performance to achieve state water quality standards in the Everglades Protection Area. For example, water from the L-8 FEB may be used to maintain minimum water levels in the STAs and reduce the frequency of dry out conditions within STA-1E and STA-1W, helping to sustain P treatment performance. The L-8 FEB Operational Cycle Testing Evaluation phase began in June 2017 and routine operations began in December 2017. Unless explicitly stated otherwise, the POR for this report begins June 1, 2017, and concludes at the end of Water Year 2021 (WY2021; May 1, 2020–April 30, 2021).

The design criteria for the L-8 FEB assumed no nutrient removal would occur. Therefore, marked reductions in FEB water column P concentrations were not expected. However, in WY2018, mean outflow TP concentrations were significantly higher than inflow TP concentrations (Xue 2019). In WY2019, there also were some outflow TP samples that were greater than inflow concentrations (DBE 2020a), suggesting that the L-8 FEB could have been a source of TP during those periods (**Figure 2**). Despite these higher outflow TP samples, the annual flow-weighted mean of outflow TP concentration was less than the inflow TP concentration in WY2019 (Xue 2020). This lower annual flow-weighted mean concentration of outflow TP also was observed in WY2020 and WY2021 (Xue 2021, 2022).

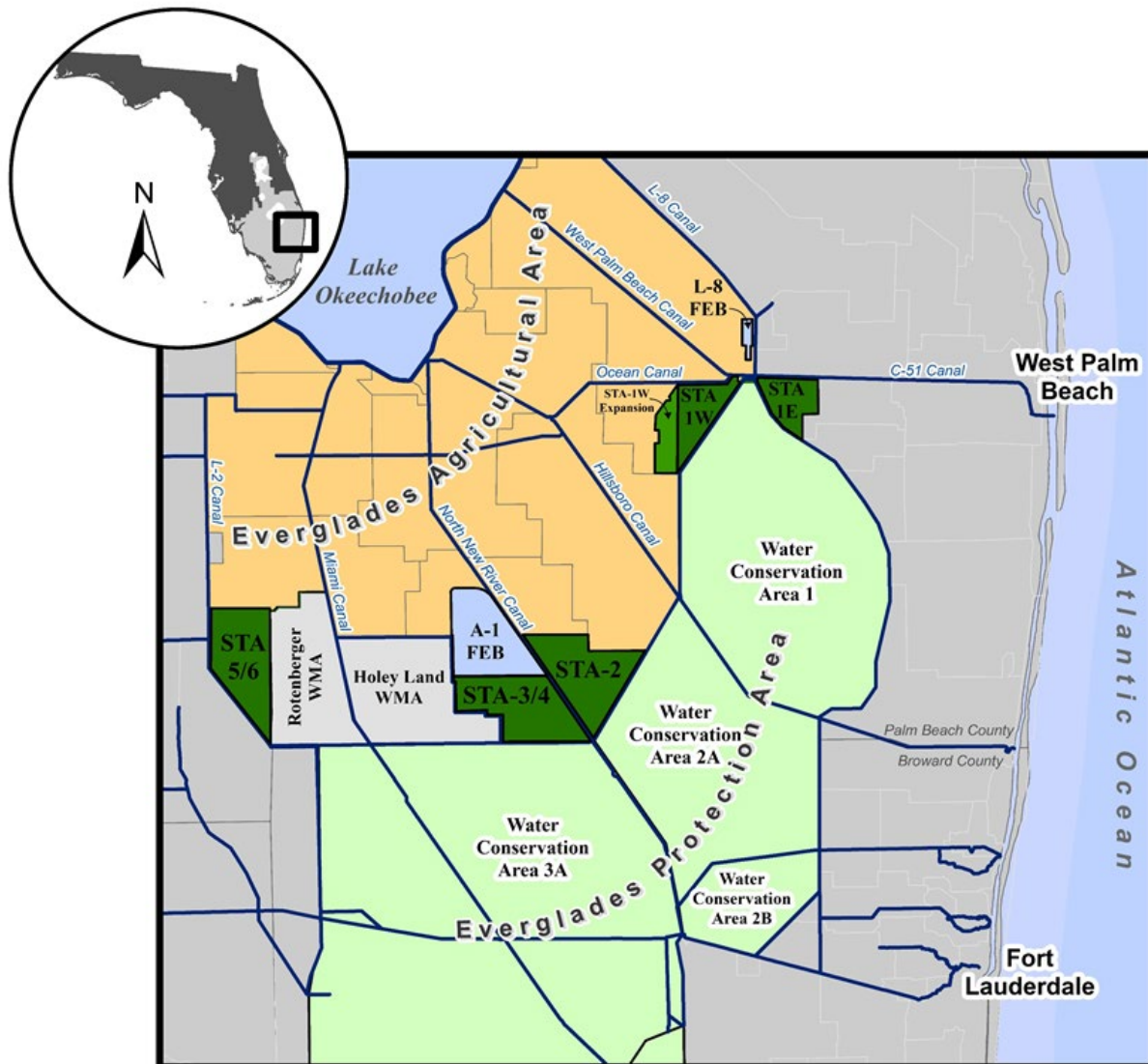


Figure 1. Schematic map of major water control features of Southeast Florida.
(Note: WMA – Wildlife Management Area.)

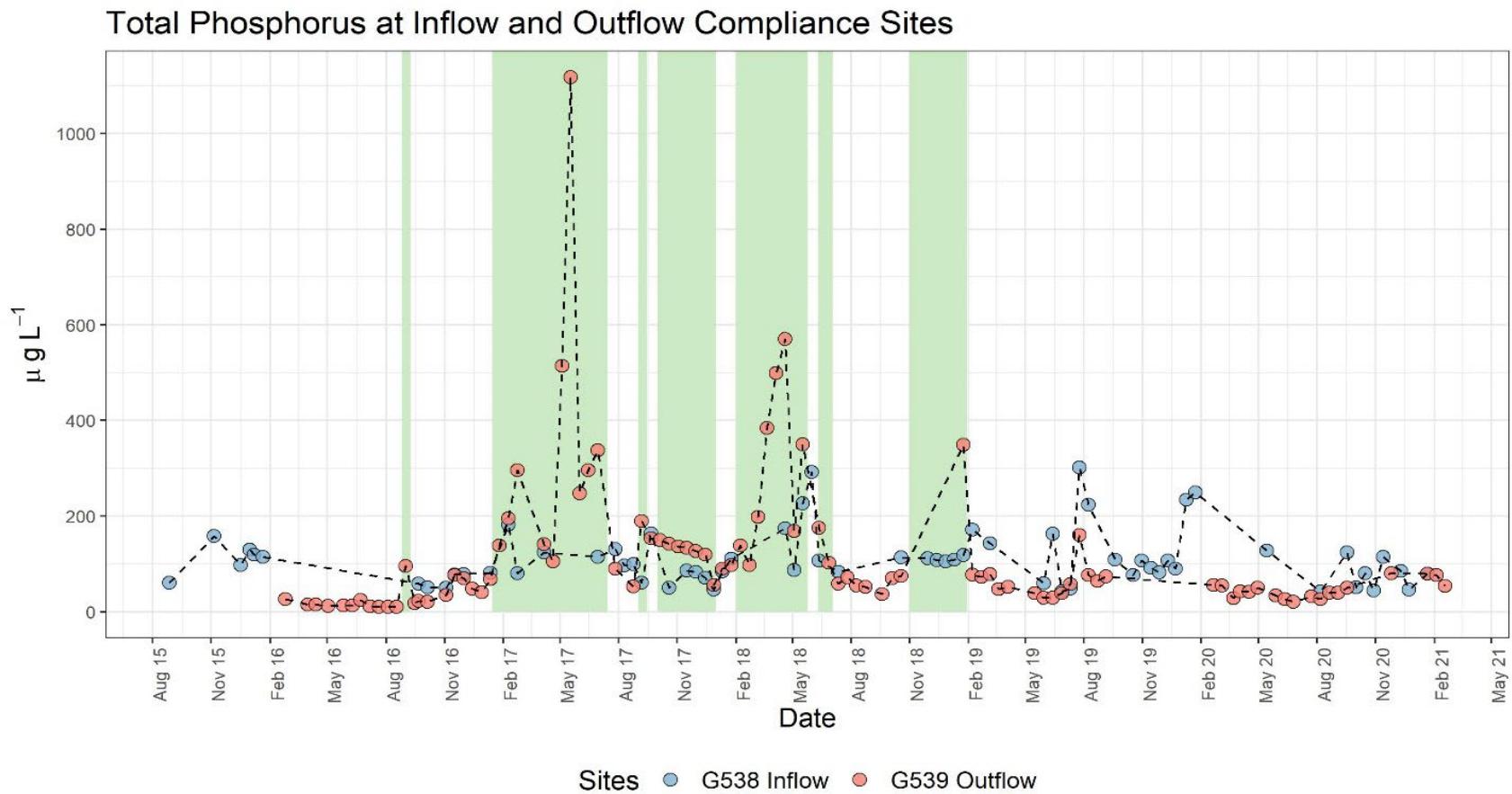


Figure 2. TP concentrations in microgram(s) per liter ($\mu\text{g L}^{-1}$) over time at G-538 (inflow) and G-539 (outflow). Shaded areas are periods when interpolated TP is greater at outflow than inflow.

Four hypotheses were proposed to explain the relatively high TP concentrations at outflow compared to inflow:

- Hypothesis I: High TP groundwater (relic seawater) flows into the FEB during low stages.
- Hypothesis II: Runoff induces erosion of levee sediments inside the FEB, which contributes to an increase in allochthonous P loading.
- Hypothesis III: At lower FEB stages, benthic sediments are more easily resuspended, resulting in high TP concentrations in the water column.
- Hypothesis IV: Rapid reductions in stage disrupt selected biological components inside the FEB, resulting in increases in internal P loading.

In Phase I of the study, initial baseline data were collected in the L-8 cells and surrounding wells to characterize the chemical composition of the water column and groundwaters associated with the L-8 FEB. Comparison of surface water and groundwater composition and quantity was used to evaluate Hypothesis I. Phase II is ongoing and focuses on Hypotheses II and III by sampling surface water of the FEB under specific flow conditions and analysis of sediment and soils from in and around the FEB. This study is subject to STOP/GO decision in September 2021. If continued, Hypothesis IV may be evaluated in a subsequent phase.

For Hypothesis I, groundwater seepage was posited as a potential explanation for relatively high TP in outflows based on elevated TP concentrations near the outflow pump station that were recorded from May to June 2017 and April 2018. These measurements occurred when little flow entered the FEB and water levels were low. A concomitant increase in specific conductance levels was also observed during those periods, which may indicate the influence of groundwater seepage (Xue 2019). When the FEB is at low stage, groundwater seepage increases proportionally with the difference in hydraulic head from the surrounding surficial aquifer. Prior to initiating this study, the composition of groundwater was not well known and was thought to possibly contain high concentrations of TP. However, groundwater samples from wells of different depths surrounding the L-8 FEB contained lower TP concentrations in the water than in the surface water of the FEB. Additionally, a greater proportion of groundwater P was in the form of soluble reactive phosphorus (SRP) than FEB surface water, which was primarily composed of particulate phosphorus (PP). These observations don't support Hypothesis I. The higher percentage of PP in surface water suggested Hypotheses II or III may be more likely explanations for any high TP concentrations in the L-8 FEB.

The results from Phase I led to the initiation of Phase II, which expanded and continued the study into 2020 (DBE 2021). The focus of Phase II was to assess Hypotheses II and III as possible explanatory theories for the high TP concentration and the composition of that high TP observed in the L-8 FEB. Runoff is known to induce erosion (Hypothesis II, in the sense of Daroub et al. 2002). Resuspension of sediments occur through wind-waves (Bloesch 1995), flow (Salim et al. 2017), or low water levels (Shantz et al. 2004) and can result in elevated TP (Hypothesis III). To address these two hypotheses, Phase II activities included additional surface water sampling during inflow and outflow pumping events at both high and low water levels in the FEB, and sediment sampling from within the FEB, L-8 canal, and soils from the banks of the FEB to determine their potential to contribute to water column PP and to FEB TP export (DBE 2021). Monitoring of surface water within the FEB continues in WY2022 as an ongoing component of Phase II, with a focus on collecting samples during inflow events at low water levels in the FEB. In addition, sediment samples from within the FEB were collected and analyzed for their potential to be resuspended and elevate water column TP.

SURFACE WATER AND GROUNDWATER MONITORING

METHODS

Groundwater was sampled from well clusters surrounding the L-8 FEB three times between January 2019 and September 2019 (**Figure 3**). All wells were purged, and the samples collected according to the Florida Department of Environmental Protection’s standard operating procedures (SOP) for groundwater sampling (FS 2200 in FDEP 2017). The L-8 FEB monitoring well clusters were purged using the minimum volume method, which places the submersible pump within the screened interval of the well. This allows for a representative groundwater sample to be collected while only purging three equipment volumes. PZ5A was dry during the sampling period so data was could not be used, nor could it be used from wells PZ5B, PZ5C, and PZ5D due to scale buildup in the wells.

Surface water was sampled monthly from January 2019 through January 2020 except for September and November 2019 for a total of 11 events. Surface water was collected from each of the six cells in the FEB at three different depths: a “top” sample from 0.5 meters (m) below surface, a “mid” sample from half the water column depth, and a “bottom” sample collected 0.5 m above the benthic surface. Water samples were collected according to the SFWMD Water Quality Monitoring Section’s *Field Sampling Manual* (SFWMD 2019b) and were analyzed for total nitrogen, TP, total dissolved phosphorus, soluble reactive phosphorus, nitrate + nitrite, ammonia, chloride, sulfate, alkalinity, total suspended solids, and dissolved organic carbon, calcium, magnesium, sodium, and potassium. Samples were analyzed according to the SFWMD Analytical Services Section’s *Chemistry Lab Quality Manual* (SFWMD 2019a).

Data analysis was completed using R 4.0.0 (R Core Team 2020) with the following packages:

- *dbhydroR* (Stachelek 2017) and *readr* (Wickham et al. 2018) for data importation
- *dplyr* (Wickham et al. 2019), *tidyr* (Wickham and Henry 2019), *stringr* (Wickham 2019), and *lubridate* (Grolemund and Wickham 2011) for arranging and calculations
- *ggplot2* (Wickham 2016), *viridis* (Garnier 2018), and *scales* (Wickham 2018) for figure creation

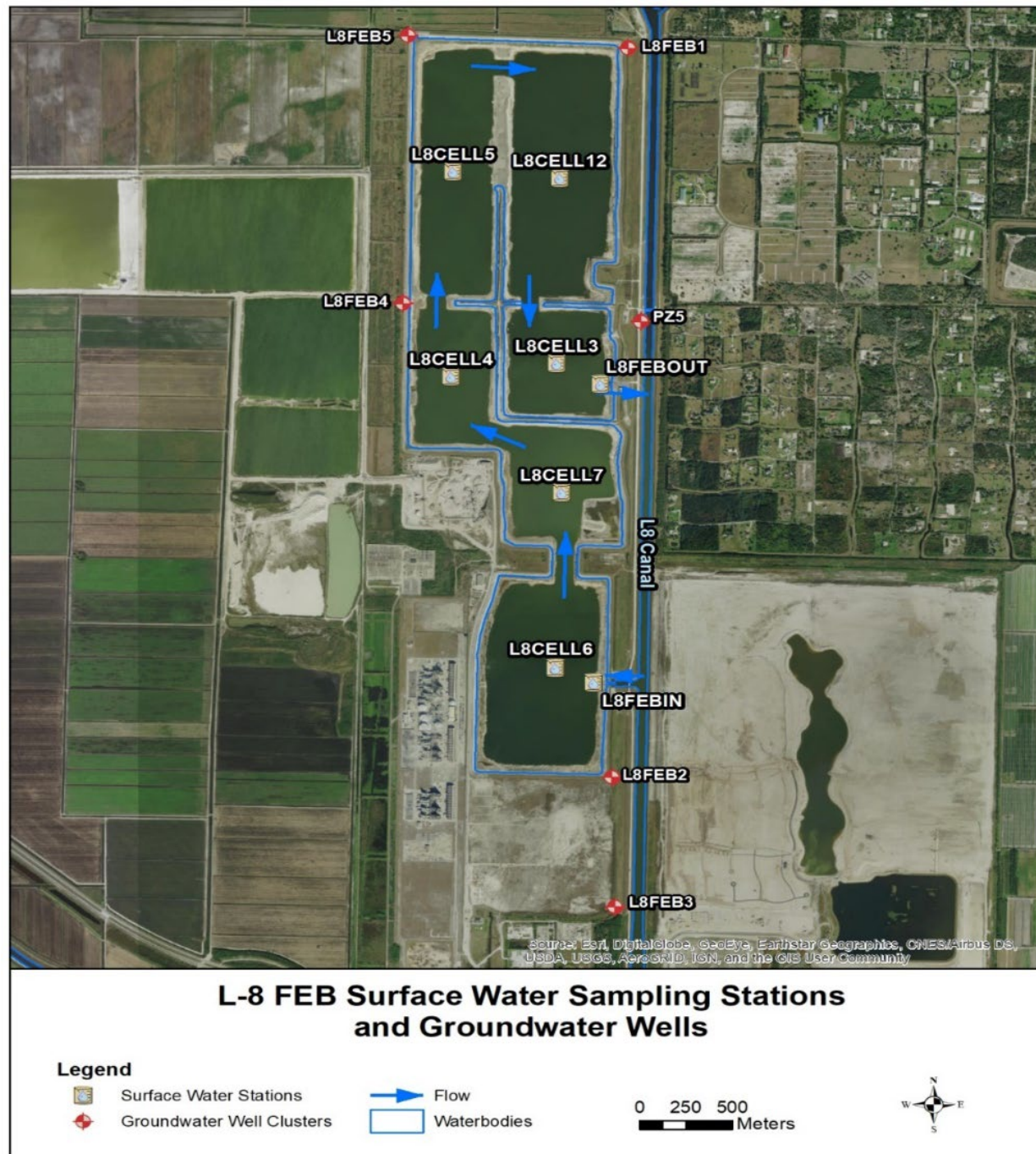


Figure 3. L-8 surface water sampling stations and groundwater wells.

RESULTS

Surface Water

Surface water TP is very dynamic within the L-8 FEB, changing temporally, spatially, and in composition. The range of TP concentrations in the surface water was much wider than the range in groundwater (**Figures 3 and 4**). Surface water TP concentrations fluctuated greatly over time, most TP samples from January measured well over 200 micrograms per liter ($\mu\text{g/L}$ or $\mu\text{g L}^{-1}$) compared to below 50 $\mu\text{g/L}$ in June then back up to well over 100 $\mu\text{g/L}$ for most cells (**Figure 5**). The composition of P also changed over time. The dominant form of P from January 2019 through July 2019 was PP and from August 2019 through January 2020 was SRP. Surface water was more dynamic than groundwater and it was found to have much higher mean TP concentration (105 $\mu\text{g/L}$) than groundwater (27 $\mu\text{g/L}$, **Table 1**). Surface water TP concentrations also changed with depth (**Figure 5**). Of the three surface water samples collected at each site, the deepest sample collected at 0.5 m from the bottom almost always had the highest TP concentrations. The median ratio TP in bottom depth samples was 1.4 times that of top depth samples and 1.3 times that of mid depth samples (**Figure 6**). Relative to surface water, groundwater remained much more stable in overall TP concentration and in the forms of P (**Figure 7**). PP accounted for approximately 67% of TP in surface water compared to 45% of TP in groundwater compared to groundwater where SRP comprises 18% of the TP in the surface water and 43% of the TP in the groundwater. Average TP concentrations were higher in surface water than in groundwater (**Table 1**) and was far more dynamic temporally, spatially, and in composition (**Figures 4 through 7**). Additionally, surface water had many positive outliers skewing data to the right. These extreme TP values represent values over 200 $\mu\text{g/L}$ that occurred in January and February 2019. The samples collected on January 29 coincided with inflow of over 10,000 acre-feet (ac-ft) into the FEB between January 27 and February 1. The next month, samples were collected February 27 and extreme values were only found in the samples collected 0.5 m from the bottom (**Figure 5**). TP concentrations diminished from February through June with the bottom depth samples remaining relatively high compared to the top and mid depth samples. In July, TP increased moderately at all three depths, but concentrations remained far lower than in January. August samples showed an increase in overall TP from July and a decreasing trend in TP along the flow path. TP concentrations were highest nearest the inflow structure and decreased in each cell along the flow path. This trend was consistent at each sampling depth and most pronounced in the bottom depth samples.

Table 1. Mean and standard error of P concentrations in micrograms per liter ($\mu\text{g/L}$) in groundwater and surface water from monitoring sites in and around the L-8 FEB.

Analyte	Units	Groundwater			Surface Water		
		Sample Size	Mean	Standard Error	Sample Size	Mean	Standard Error
Total Phosphorus	$\mu\text{g/L}$	48	27.1	2.3	219	105.4	6.1
Soluble Reactive Phosphorus	$\mu\text{g/L}$	48	11.6	1.0	218	27.9	2.4
Dissolved Organic Phosphorus	$\mu\text{g/L}$	48	3.1	0.2	218	6.3	0.2
Particulate Phosphorus	$\mu\text{g/L}$	48	12.3	1.9	219	71.1	5.9

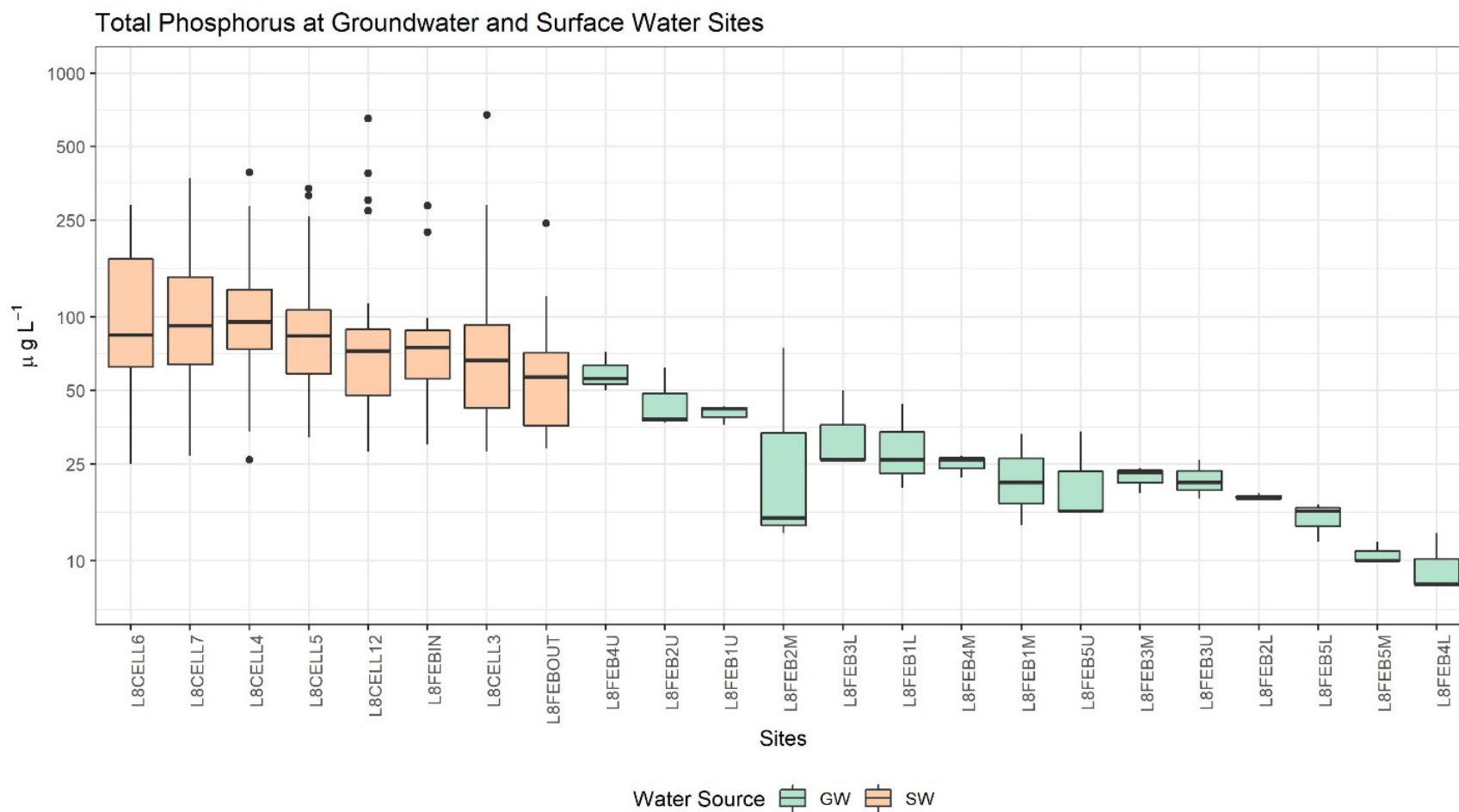


Figure 4. Boxplot of TP results from groundwater and surface water stations (see **Figure 3** for monitoring station locations).

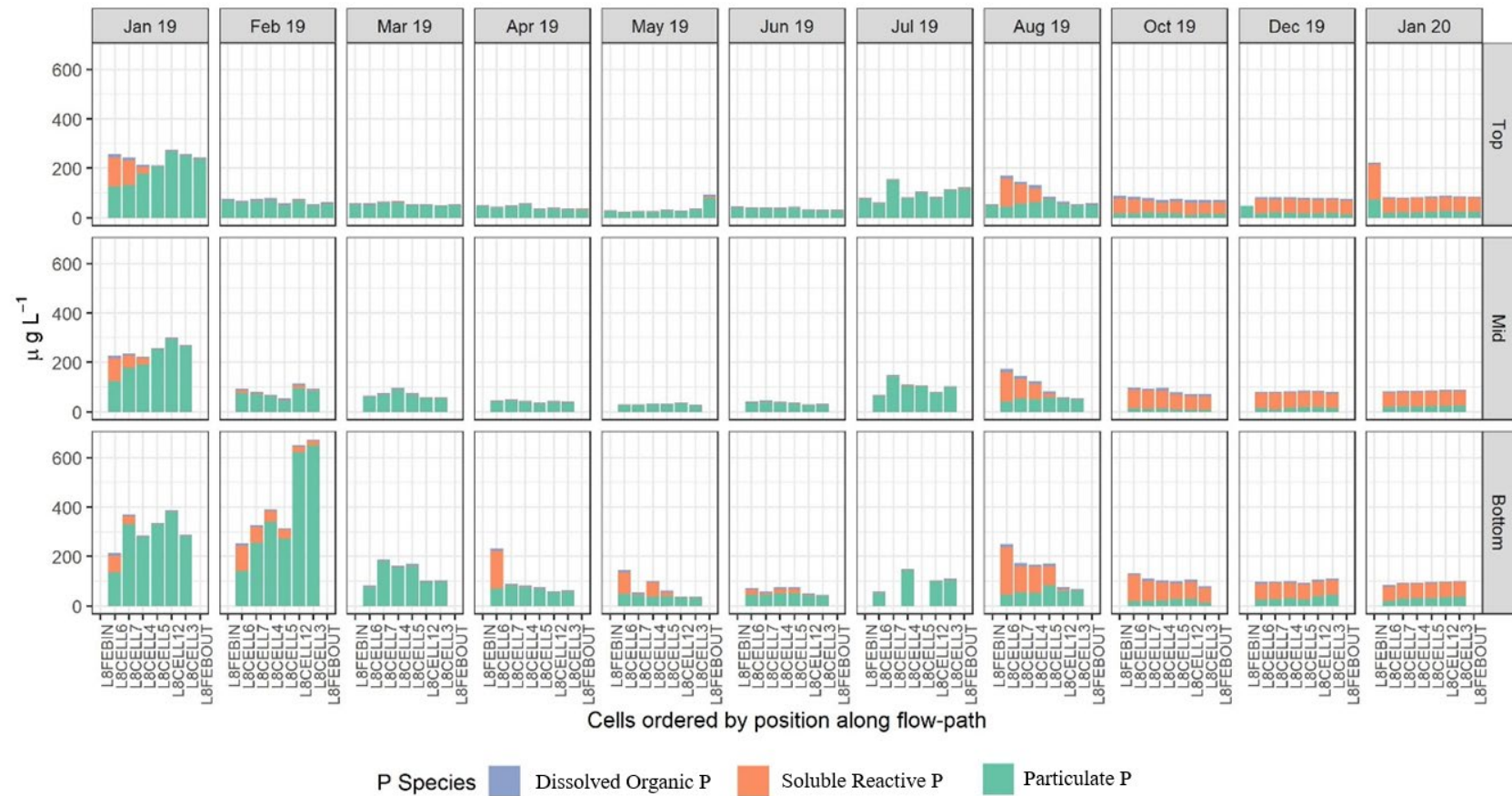


Figure 5. P forms in surface water over time along the flow path.

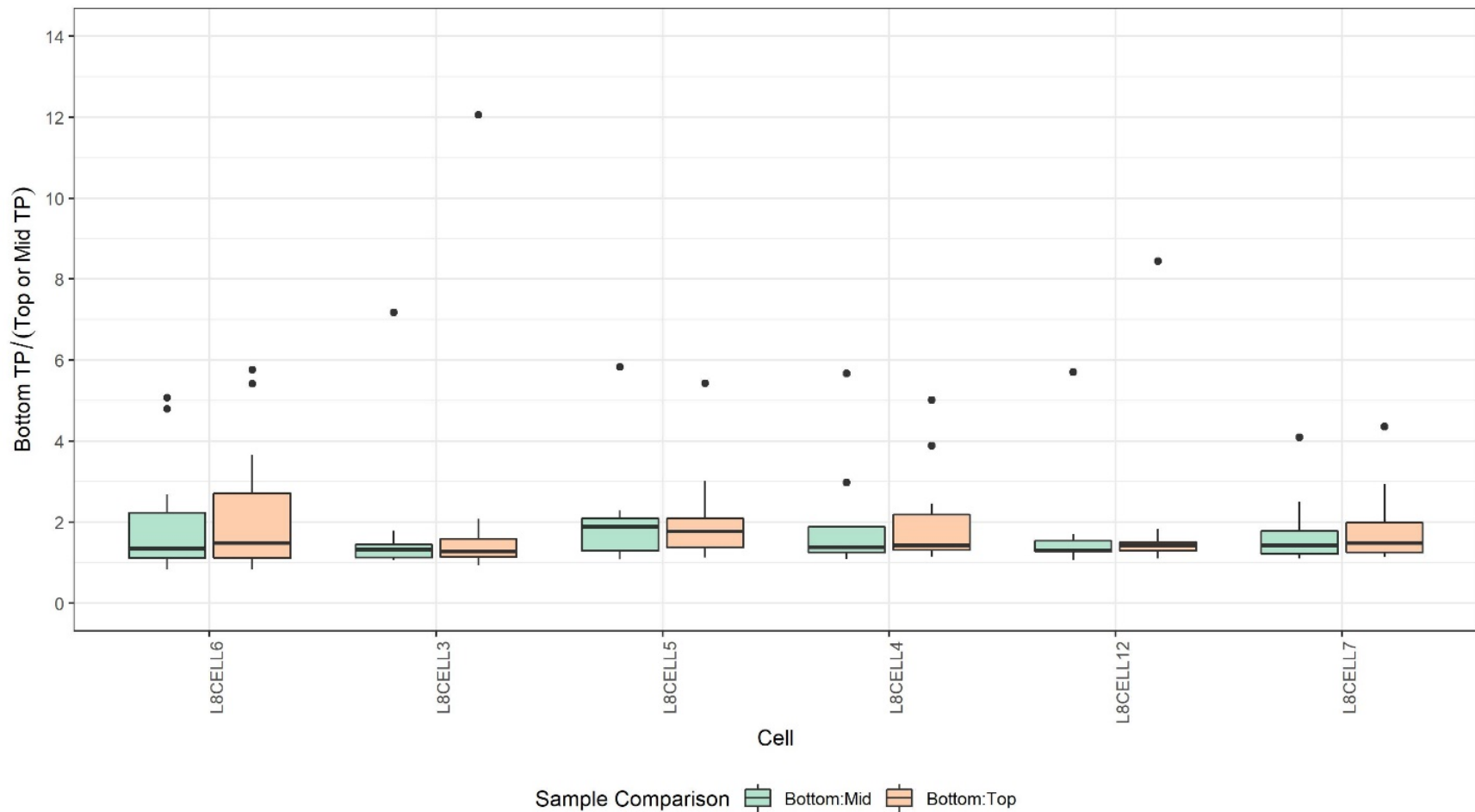


Figure 6. Ratio of TP samples collected 0.5 m from bottom to samples collected 0.5 m from surface and mid water column depth.

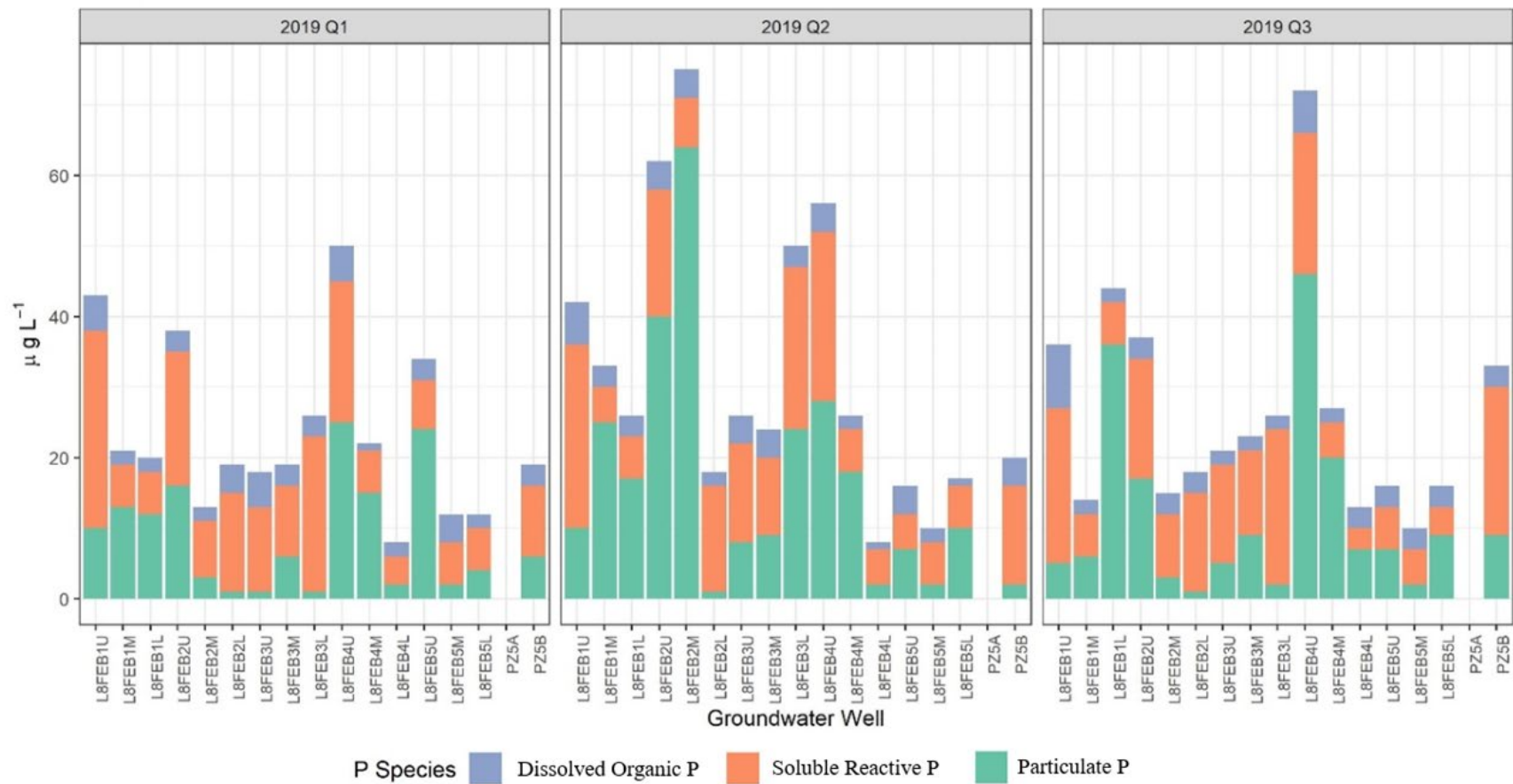


Figure 7. P forms in groundwater wells over time.

Samples were collected on August 15 following another inflow event of over 9,500 ac-ft that occurred between August 2 and 8. The August sample collected at L8FEBIN was collected from the bridge above the G-538 spillway in efforts to keep samplers safe from dangerous flows down the spillway should the structure open. The composition of P changed during this period. Before the August sampling, PP was the dominant form, however after the August sampling, SRP became the dominant form of P, and this trend carried through to the last sampling event in January 2020. TP concentrations were higher in the bottom depth samples than top or mid depth samples (**Figure 6**). This trend was consistent spatially, similar in every cell, but varied between months. This variation can be observed in January samples from the bottom, mid, and top depths, which have roughly the same TP values, but changed in February, when TP was much higher in the bottom depth samples than the top or mid depth samples (**Figure 5**).

Groundwater

Groundwater TP concentrations were much lower on average than in surface water. The highest measured groundwater TP values was 75 µg/L, compared to the 105 µg/L mean TP concentration of L-8 FEB surface water. Groundwater samples displayed a narrower range of TP concentrations than the L-8 FEB surface water samples (**Figures 3 and 4**). The composition of TP in groundwater also was different than in surface water. While surface water had two distinct periods where different forms of P were dominant (PP January–July, 2019 and SRP August 2019–January 2020, **Figure 5**), the composition of P in groundwater samples was more consistent (**Figure 7**). The proportion of P forms remained relatively stable at most wells. At L8FEB2U and L8FEB2M, there was a large increase in PP between quarters 1 and 2 collections and at L8FEB4U between quarter 2 and 3. Data from samples collected at the PZ5B, PZ5C, and PZ5D wells were not included in the analysis because of scale buildup in the wells. PZ5A was dry during the sample collection period.

Seepage

The influence of groundwater on surface water chemistry depends on the quantity and quality of groundwater that seeps into the FEB. This amount of seepage is contingent upon the difference in stage between the FEB and the groundwater table, known as hydraulic head difference. Seepage estimates can be made by dividing the change in storage (ΔS) in the FEB during a period of no surficial inflow (SW_{in}) or outflow (SW_{out}) in acre-ft by the hydraulic head (H) and length of time between volume measurements (t) in days and surface area of the FEB (A) in **Equations 1 through 3** below where GW is groundwater, P is precipitation, and ET is evapotranspiration.

$$GW = \Delta S - SW_{in} + SW_{out} - P + ET \quad (1)$$

$$GW = \Delta S + ET \quad (2)$$

$$\text{Seepage Rate} = \frac{GW}{H * A * t} \quad (3)$$

In 2009, a seepage test was conducted between February 11 and March 10, 2009, finding a seepage rate of 0.038 inches per day per foot (in/d/ft) of head (MacVicar, Federico and Lamb, Inc. 2009). This seepage test was conducted when there was very little rainfall and no inflow or outflow from the FEB. At that time, the mean water surface of the basin was 0.34 feet (ft) National Geodetic Vertical Datum of 1929 (NGVD29), and the mean canal stage was 11.72 ft NGVD29, equaling a mean stage difference of 11.40 ft. This was used to estimate a flow rate of 1.5 cfs per foot of head in subsequent reports (Archer Western/Jacobs 2013).

A similar methodology was used to estimate seepage rates during the study period, however instead of making an estimate based on a single period, many individual daily seepage estimates were made, and the median of these estimates was used as the estimated seepage rate in water balance and P mass balance calculations (**Figure 8**).

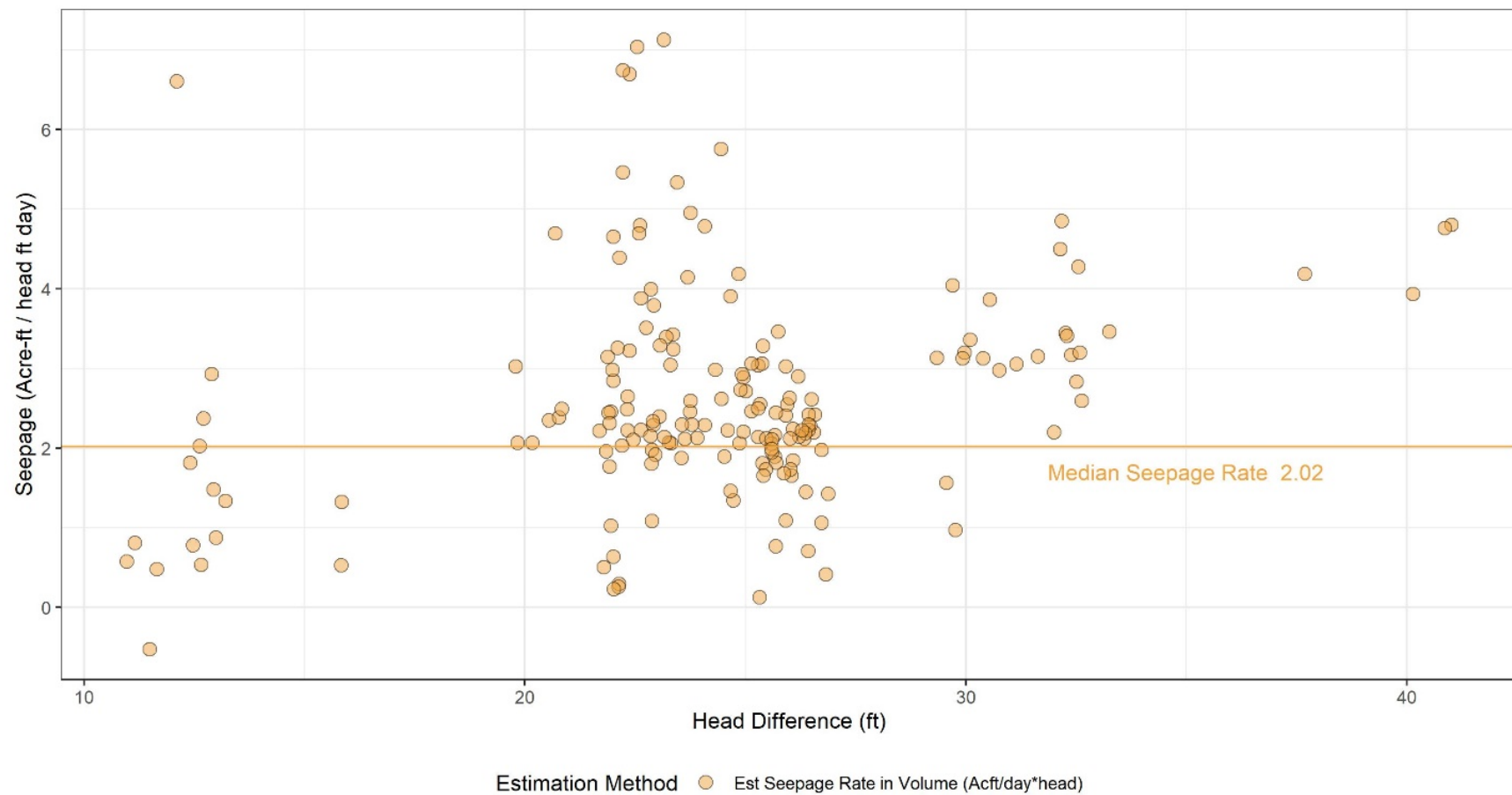


Figure 8. Daily estimated seepage rates.

To create daily seepage estimates, a database was created of every day in the POR without inflow or outflow on that day or the preceding day. Days when precipitation (P) exceeded 0.1 inches were excluded. Daily evapotranspiration (ET) was estimated as 70% of the measured ET at the LOXWS weather station. This 70% scaling factor was used in the 2009 seepage test and was thought to represent the relative ET in the FEB compared the weather station at S-5A. The LOXWS station was used in this current study because the S-5A data set used in the 2009 MacVicar, Federico and Lamb, Inc., study was incomplete for the POR. Seepage in ac-ft (GW) was calculated using **Equation 1**. Because SW_{in} , SW_{out} , and P were near zero for the selected days of this data set, the equation was simplified (**Equation 2**). Seepage rate was calculated by dividing GW by H and the surface area of the FEB (A) and time (t) (**Equation 3**).

Using this method, seepage rate was estimated for every day during the POR, and the median of these estimates was 2.02 ac-ft per day per ft of head (ac-ft/d/ft) or 0.025 in/d/ft of head. This result was used as the seepage rate when calculating GW influence in subsequent water and phosphorus mass balances. This estimate is slightly lower than the estimate from the 2009 seepage test, which were admittedly conservative (Archer Western/Jacobs 2013). There is a slight positive trend to seepage rate that increases with hydraulic head (**Figure 8**). However, the median of these daily seepage rates was used to keep water and P mass balances from becoming overly complex.

TP CORRELATION WITH HYDRAULIC OPERATIONS AND CONDITIONS

We see in **Figure 5** that TP is spatially heterogenous by cell and water depth over time. What explains this heterogeneity? Could hydraulic operations of the FEB affect TP concentrations? It may seem obvious that inflow would have an effect on TP concentrations especially if incoming water contained a different concentration TP than FEB waters, but would this inflow affect all the cells in the FEB equally? Would this effect be evident at all depths? And what inflow rate is required to affect TP? Would other hydraulic operations such as outflow and conditions such as FEB depth affect TP? If high frequency TP data were available from every cell in the FEB at multiple depths for every hydraulic operation over time, these effects could be observed directly but due to resource restraints, this level of data collection was not possible. However, monthly TP data was collected in every cell at multiple depths. Using this monthly water quality data, we can calculate TP correlation with days since a hydraulic event occurred and make inferences about where in the FEB (cell and depth) TP is affected by a hydraulic event. Additionally, for inflow and outflow operations, we can make an inference about the flow rate required to affect TP. The relative strength of the relationships between these hydraulic operations and conditions and TP as measured by correlation provides insight into the TP dynamics in the FEB that would not be possible using other methods.

TP CORRELATION WITH INFLOW

Methods

To investigate a potential effect that inflow may have on FEB TP, the correlation between time since inflow and TP was calculated. Flow was measured at the G-538 inflow structure and was converted to daily average cfs. Time since inflow is defined as the number of days since flow of a certain rate passed through the G-538 structure. The number of days since four different rates (125, 250, 500, and 1,000 cfs) were tallied for every TP measurement in the FEB. The strength of the relationship between days since flow for each flow rate category to TP concentration was measured with the non-parametric Spearman's correlation. Spearman's correlation is a measure of monotonic relationship and does not imply linearity and statistical significance is denoted with an asterisks (*) in **Figure 9**.

Results

There is an overall negative correlation at every cell at every depth between days since inflow and TP (**Figure 9**). This indicates that TP is highest during an inflow event or recently following an inflow event into the FEB and decreases with time after the event. The highest correlation occurs in Cell 6, the cell where the G-538 spillway is located. The correlation declines along the flow path with distance from inflow. This trend is stronger in the top and mid depth samples where correlation decreases from approximately -0.85 in L8CELL6 to approximately -0.3 in L8CELL3. This flow path trend is not as evident in the bottom depth samples. Correlation is also stronger in bottom depth samples for the 500- and 1,000-cfs inflow rates than the 250- and 125-cfs inflow rates.

The strong negative correlations between time since flow and TP indicate that inflow does influence TP concentrations. The stronger correlation nearest the inflow indicates that this influence of flow is greatest nearest the spillway. Finally, the stronger correlation in bottom depth samples for inflow rates of 500 cfs and above suggest that higher inflow rates affect TP concentrations in the FEB but only for the lower depths of the FEB and upper reaches of water column are affected by all flow rates analyzed.

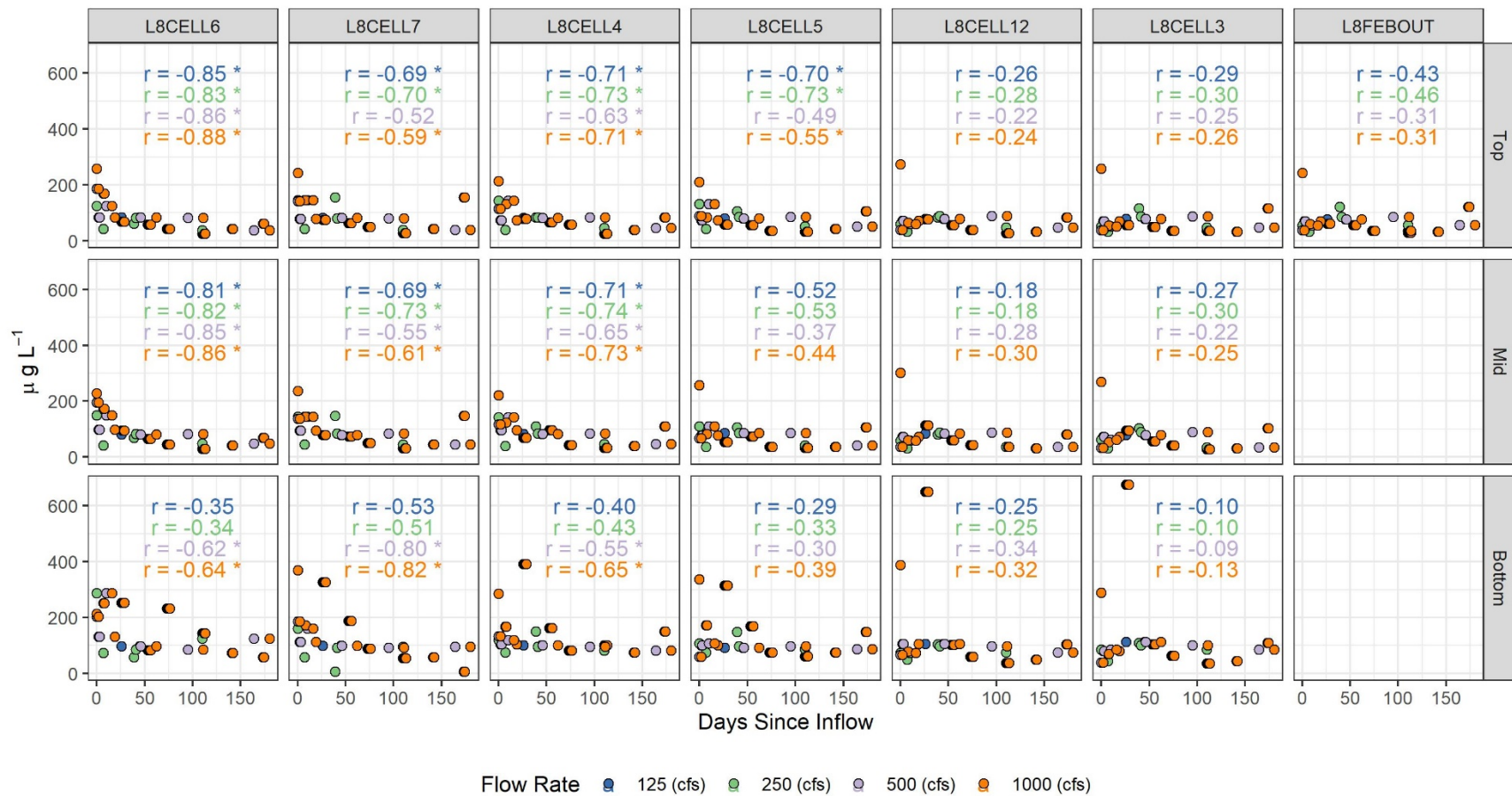


Figure 9. TP correlation to days since different inflow rate events measured at G-538 pump station.

TP CORRELATION WITH OUTFLOW

Methods

To investigate a potential effect that outflow may have on FEB TP, the same methodology as described above for the inflow events was applied to outflow events. Spearman's correlation was calculated for the number of days since an event for five different outflow rates. Outflow rate is defined here as the daily average cfs pumped out of the FEB by the G-539 pump station. The rates were tallied for every TP measurement in the FEB. The strength of the relationship between days since flow for each flow rate category to TP concentration was measured with the non-parametric Spearman's correlation. Spearman's correlation is a measure of monotonic relationship and does not imply linearity. The statistical significance is denoted with an asterisks (*) in **Figure 10**.

Results

A moderate to weak positive correlation was found between days since outflow and TP in the top and mid depth samples and a weak negative correlation in the bottom depth samples (**Figure 10**). The weak correlation in the bottom depth samples was slightly stronger at higher flow rates. There was no trend between distance along the flow path and correlation in the top and mid depth samples. A positive relationship as shown in the top and mid depth samples indicates that TP concentrations are lowest immediately following outflow and increase with days since outflow. Because it is highly unlikely that the process of discharge is lowering TP in the FEB, or that not operating the discharge pump station for many days increases TP in the FEB, this correlation is most likely spurious.

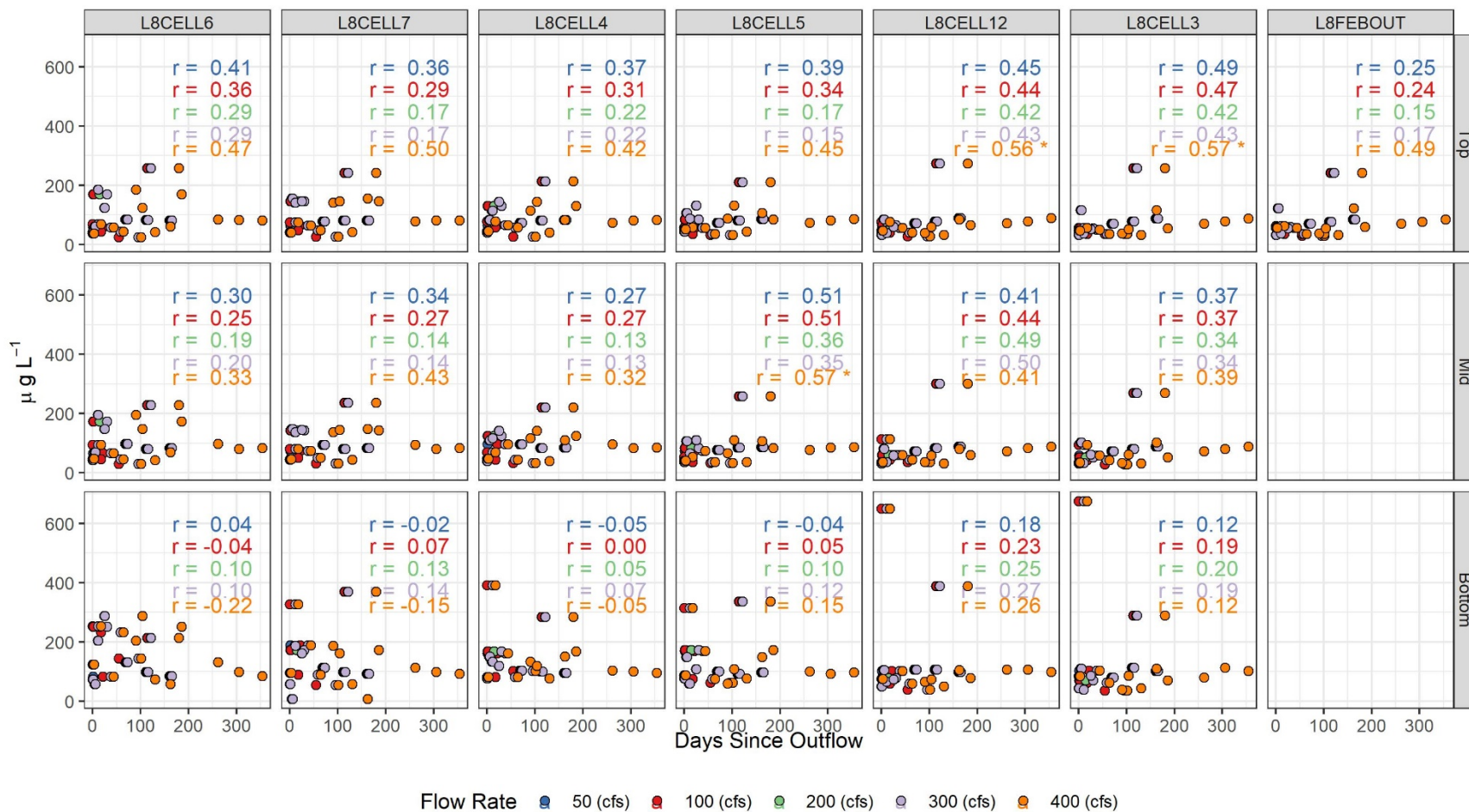


Figure 10. TP correlation to days since flow of different outflow rates measured at the G-539 pump station.

TP CORRELATION WITH FEB DEPTH

Methods

To investigate a potential effect that FEB depth might have on TP concentrations, Pearson's correlation was calculated for every sample in each cell at the top, mid, and bottom depths (**Figure 11**). Additional TP samples in L8CELL3 were collected for regulatory permit compliance.

Results

Only weak correlations and a single statistically significant correlation were found between stage and FEB depth in either the research or compliance data sets. Results collected from research and compliance data sets were in reasonable agreement increasing confidence of the findings of this analysis. FEB daily average stage ranged from -28.7 to 16.3 ft NGVD29 during this study. FEB depths were calculated from the stage using an average bottom elevation of -40.6 ft NGVD29 (SFWMD 2015). This bottom elevation is approximate because the bottom of the FEB varies among cells due to the accumulation of sediments and slight differences in the level at which these cells were excavated. As water levels changed greatly over the course of sample collection, the relatively small error from using an approximate bottom elevation is thought to be negligible. Given the estimates, FEB calculated depth ranged from 12.3 ft when samples were collected in July to a depth of 56.3 ft in August. Although FEB depth did not correlate with TP, it should not be assumed that this will hold true if water levels in the FEB were to drop below lowest levels at which samples were collected for this analysis.

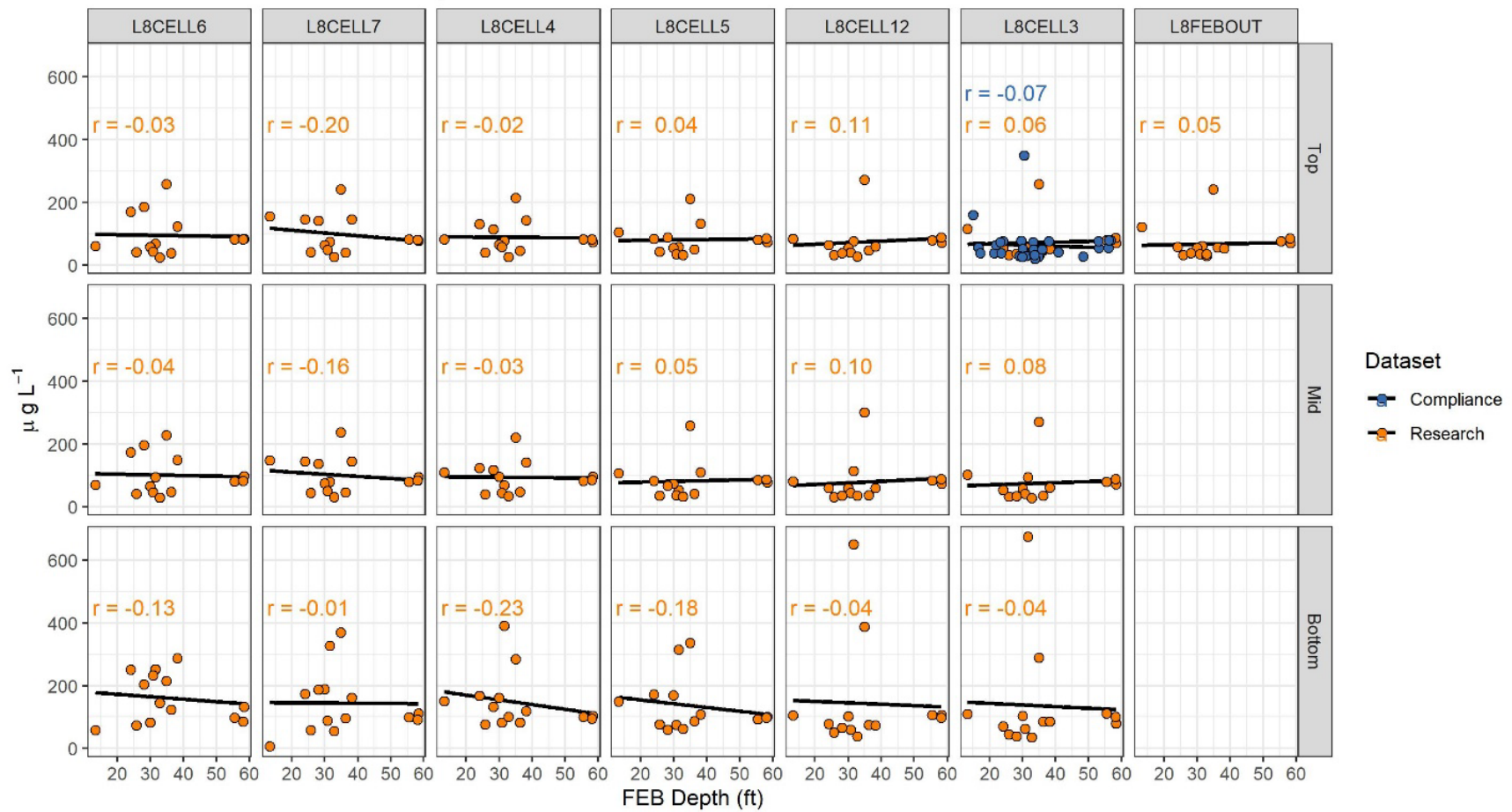


Figure 11. TP correlation to FEB depth.

WATER BALANCE

METHODS

A cumulative water mass balance was developed from the start of FEB operations in June 2017 through the end of WY2021 using **Equation 4**. This water balance was used to create a subsequent P mass balance and characterize the operational flow patterns.

$$\Delta S = SW_{in} - SW_{out} + P + GW_{in} - GW_{out} - ET \quad (4)$$

The quantity of surficial flow in (SW_{in}) and discharge (SW_{out}), groundwater in (GW_{in}) and out (GW_{out}), precipitation (P), and evapotranspiration (ET) of the FEB were estimated daily and cumulative totals were recorded.

Rain data were missing at the S-5A weather station between October 29 and November 6, 2017. For this period of missing data, a zero value was substituted for daily average rain measurement in the water balance calculations. Stage data for the period between October 2, 2018 and November 25, 2018, were also missing. For this period, values between the nearest existing measurements were linearly interpolated to estimate stage. Outflow measurements were made at G539TOT when data were available; data collected from G539P was substituted when it was not. Seepage measurements, GW_{in} and GW_{out} were estimated by multiplying the head difference between the L-8 canal and FEB with a seepage rate of 2.02 ac-ft per day. To calculate the change in volume ΔS when stage changes, the wetted area of the FEB must be considered. Because the banks of the FEB are inclined, the FEB covers a much larger area when the stage is high than when stage is low. To accurately measure volume, a volume stage curve was used to estimate the volume based on stage (**Figure 12**). Original curve datum was in North American Vertical Datum of 1988 (NAVD88) but this was transformed to NGVD29 when used in calculations for this study.

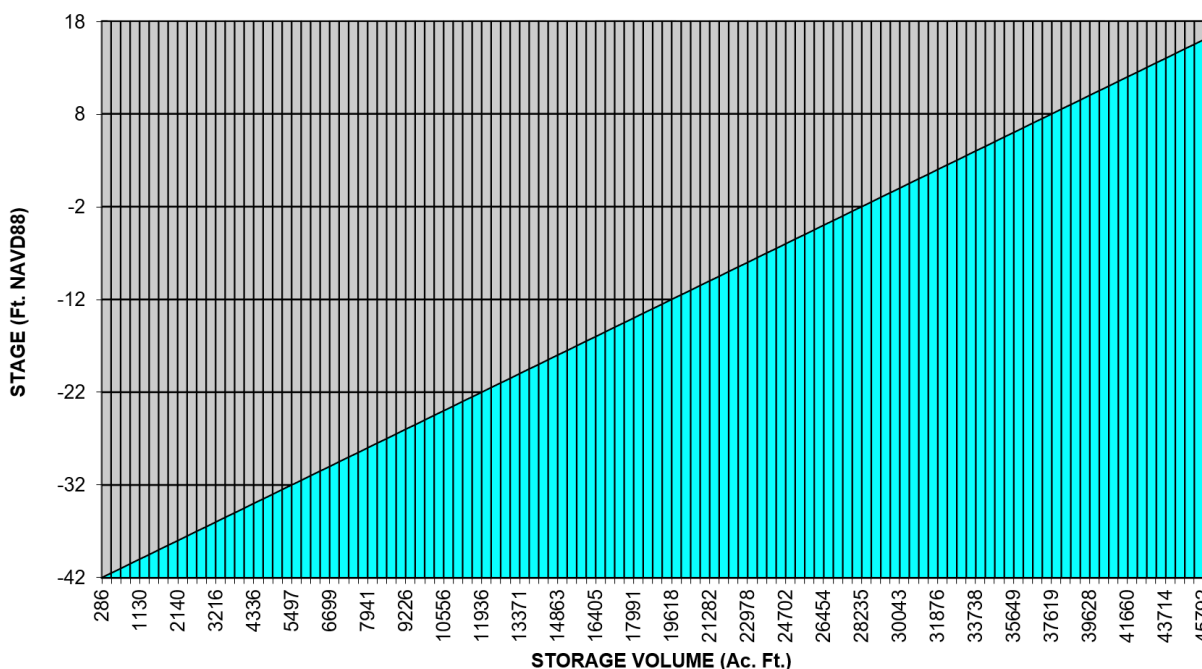


Figure 12. Volume stage curve developed from a data elevation model.

RESULTS

Of the estimated 265,000 ac-ft of flow volume into the FEB over this time, surface water flow (SW_{in}) contributed approximately 75% of the total (**Figure 13**). Sources of surface water included agricultural and urban runoff as well as lake Okeechobee discharges. Although these sources could not be separated the overall contribution of Lake Okeechobee was estimated at 10,200 ac-ft in WY2017, 7,600 in WY2018, 100 ac-ft in WY2019, 15,700 ac-ft in WY2020, and 7,600 in WY2021. Groundwater inflow (GW_{in}) was the next largest contributor with almost 20%, and precipitation (P) contributed the remaining 5% of the total. Outflows from the FEB total over 253,000 ac-ft, of which 96% were pumped out by the G-539 pump station (SW_{out}), and the remainder left through evapotranspiration (ET) and groundwater outflow (GW_{out}) with groundwater outflow accounting for only 0.2%.

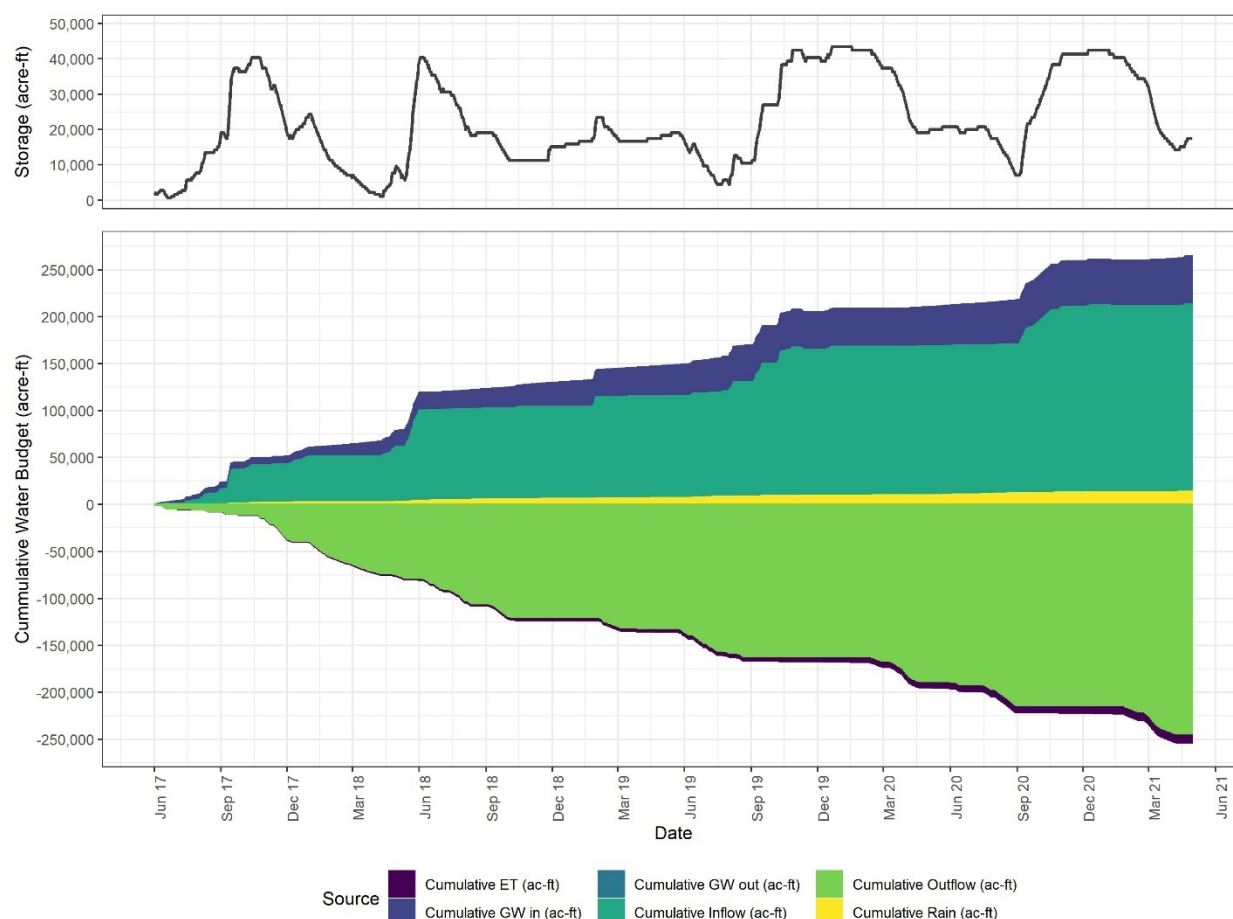


Figure 13. Daily volume and cumulative water mass balance of the L-8 FEB.

Since the FEB became operational the annual hydropattern has been characterized by relatively brief periods of high inflow during the summer months that contribute most of the annual water balance and then a longer drawdown period where withdrawals are almost entirely from G-539 (**Table 2**). Discharge also can occur through the G-538 inflow spillway when FEB stage is higher than the L-8 canal and the structure is open. This is called “reverse flow” and is rare occurring just 17 days and accounting for 4,326 ac-ft over the POR. Groundwater inflow does become the largest source of water when the FEB stage is low, and there are little to no inflows. Groundwater outflow is relatively rare accounting for less than 0.25% of total

outflow. Precipitation is a relatively consistent inflow contributor around 5% annually. Evapotranspiration contributes between 2.4 to 4.5% of total annual outflow volume.

Table 2. L-8 FEB water balance table by water year and POR.

Period	Total Inflow (acre-ft)	Proportion of Total Inflow (%)			Total Discharge (acre-ft)	Proportion of Total Discharge (%)		
		SW_{in}	GW_{in}	P		SW_{out}	GW_{out}	ET
6/1/17 to 4/30/18 (part of WY2018)	78,700	72.2	21.8	5.9	76,100	97.6	0.01	2.4
WY2019	68,800	72.3	21.6	5.9	59,600	96.2	0.07	3.7
WY2020	62,800	79.6	15.4	4.9	59,300	95.1	0.68	4.2
WY2021	54,600	75.8	17.5	6.6	58,500	95.2	0.26	4.5
POR	265,000	74.8	19.4	5.8	253,600	96.1	0.2	3.6

PHOSPHORUS MASS BALANCE

METHODS

A P mass balance of the FEB was created to evaluate relative size of P sources and discharges (Equation 5).

$$\Delta NP = SW_{in} * C_{in} - SW_{out} * C_{FEB} + P * C_p + GW_{in} * C_{GW_{in}} - GW_{out} * C_{FEB} + DD \quad (5)$$

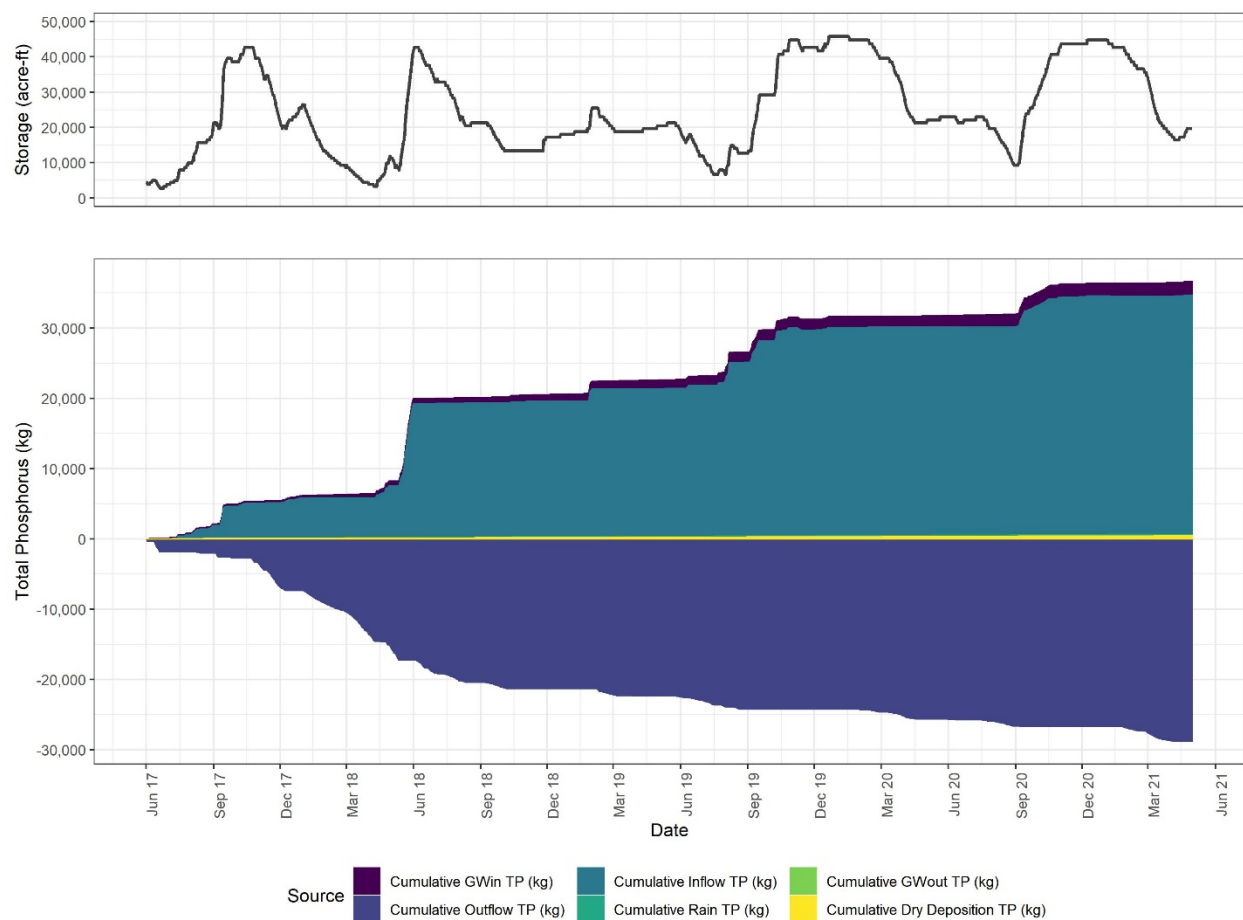
where ΔNP is the change in net P. C_{in} , C_{FEB} , C_p , and $C_{GW_{in}}$, are estimates of P concentration from inflow canal, the FEB, rainwater, and the mean of groundwater measurements, respectively. P loads were calculated by multiplying these concentrations with their associated flows from the water balance (Equation 4). Dry deposition (DD) of P estimated at 82.2 micrograms phosphorus per square meter per day ($\mu\text{g P/m}^2/\text{d}$) (Ahn and James 1999) was added to this total to complete the mass balance.

RESULTS

Surface water inflow is the primary source of P for the FEB (Table 3 and Figure 14). Groundwater, rain, and dry deposition contributed small amounts of P combined for the POR. Although groundwater was roughly 20% (Table 2) of total inflow for the POR, it contributed just 5.3% of TP import to the FEB because the mean P concentration ($C_{GW_{in}}$) was much lower than the measured and interpolated concentrations at the G-538 inflow (C_{in}). Similarly, rain contributed 5.8% of total inflow but just 0.5% of P load due to the low P concentration in rainwater (C_{in}). Dry deposition contributed about 1.1% of total P over the POR. Export of P from the FEB was almost entirely through discharge from the G-539 pump station at 99.8% for the POR. There were periods where the FEB was staged higher than surrounding water when P was exported through groundwater seepage in trivial amounts, estimated at approximately 0.2%.

Table 3. P mass balance table by water year and POR.

Period	Total P Import (kg)	Proportion of P Inflow (%)				Total P Export (kg)	Proportion of P Export (%)	
		SW_{in}	GW_{in}	P	DD		SW_{out}	GW_{out}
6/1/17 to 4/30/18 (part of WY2018)	8,195	90.0	7.9	0.7	1.2	15,132	99.9	<0.1
WY2019	14,326	95.3	3.6	0.3	0.7	7,196	99.9	<0.1
WY2020	9,069	94.9	3.6	0.4	1.1	3,295	99.1	0.9
WY2021	4,922	89.5	7.5	0.9	2.2	3,188	99.5	0.5
POR	36,635	92.9	5.3	0.5	1.1	28,813	99.8	0.2

**Figure 14.** Daily volume and cumulative water phosphorus balance of the L-8 FEB.

HIGH FREQUENCY EVENT MONITORING

INFLOW EVENT

Methods

Inflow and outflow events in this study are defined as continuous periods of flow either in or out of the FEB. Inflow events typically occur towards the end of the wet season when water managers want to increase storage in the FEB for supply later but these events can occur anytime there is an excess of water in the regional basin. This excess water is typically precipitation driven surficial runoff but the FEB will also receive Lake Okeechobee discharge occasionally. Because the design capacity of the inflow spillway is much larger than the G-539 pump station, inflow events move larger volumes of water over a shorter time period than outflow events. To evaluate the effect that large inflow events can have on TP within the FEB, high frequency monitoring data were collected for an inflow event in September 2020. Autosamplers were placed on floating platforms to collect a sample every 3 hours. These samples were composited into a daily sample. Samples were collected in the cells nearest the inflow (L8CELL6) and outflow (L8CELL3, **Figure 3**). Samples were taken at 0.5 m from the surface and 0.5 m from bottom. To reduce the amount of laboratory analysis work, only every third day's sample were analyzed. Grab samples were collected from all cells during the event and after peak inflow.

Results

Baseline TP preceding the inflow event was below 50 µg/L from top depth samples collected near the inflow and outflow (**Figure 15**). Samples collected 0.5 m from bottom for both cells were more variable during the time preceding the inflow event, varying between 20 and 50 µg/L, with most samples below 100 µg/L. TP response to inflow from the G-538 spillway was immediate in L8CELL6. TP concentrations increased to over 200 µg/L in top depth samples during the peak of the flow event and reached a maximum value over 350 µg/L a few days after peak inflow. Bottom depth samples in L8CELL6 also increased dramatically from 50 µg/L to over 200 µg/L during peak inflows. This was followed by an additional increase to almost 300 µg/L following peak inflows. The response to the inflow event was less apparent in L8CELL3, which is furthest from the spillway. There was little response in the top depth samples until three weeks after peak inflow when TP concentrations slowly climbed from 50 µg/L to almost 100 µg/L.

Bottom depth samples did increase from a little over 50 µg/L to roughly 100 µg/L during the event and increased to 150 µg/L approximately three weeks from the event. TP concentrations drifted back towards pre-event baselines in a matter of weeks in top depth samples, but high frequency monitoring was discontinued before baseline concentrations had returned completely. Bottom depth sample TP drifted downwards albeit more slowly than the top depth samples in L8CELL6 but had yet to reach pre-baseline levels when monitoring stopped. L8CELL3 bottom depth samples had yet to exhibit any downward momentum by the end of monitoring. Grab samples collected the same day as autosampler composites agreed very closely with autosampler data giving a high degree of confidence in the accuracy of these results (**Figure 15**).

Samples collected by autosampler upstream of the FEB at the S-5A pump station during the flow event on September 8 and 15 measured TP at 198 and 234 µg/L, respectively. These values, while higher than TP in the FEB before the inflow event, were not as high as peak TP values in the FEB after the event.

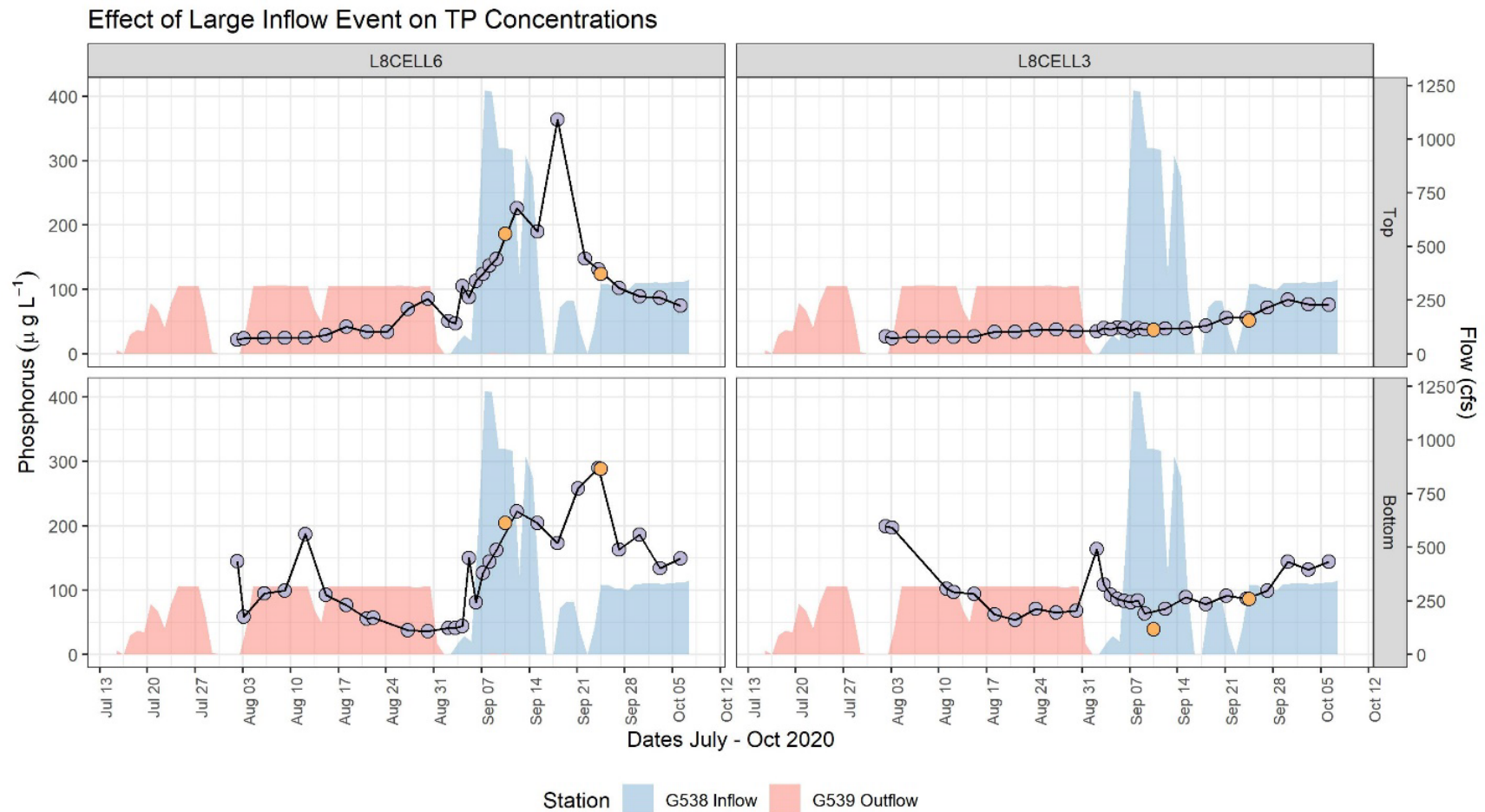


Figure 15. Effects of a large inflow event on TP concentrations in the L-8 FEB. Samples collected by autosampler are in blue and grab samples are in orange.

OUTFLOW EVENT

Methods

To evaluate the effect that large outflow events had on TP within the FEB, high frequency monitoring samples also were collected for an outflow event that occurred from March to April 2020. Autosamplers were placed on floating platforms to collect a sample every 3 hours. These were composited into a daily sample. Samples were collected in the cells nearest the inflow, L8CELL6, and outflow, L8CELL3, at 0.5 m from the surface and 0.5 m from bottom. Data collected by the autosamplers at 0.5 m from the bottom were contaminated with benthic sediments and were not used. The intake tubing apparatus was redesigned for subsequent autosampler collections with better results. Grab samples were also collected from all cells during the event and after peak outflow.

Results

Peak discharge rate from the FEB via the G-539 outflow pump station was over 400 cfs during the high frequency monitoring. The design of the pump station only allows a maximum flow rate of 450 cfs. At the time discharge started on March 10, FEB stage measured almost 11 ft NGVD29, and by the time outflow ended on April 21, stage was at -9.3 ft NGVD29. During this period, there was little change in TP concentrations in surface samples (**Figure 16**). At G-539, where flow is thought to be most influential, there was little to no response in TP concentration. Prior to this flow event, compliance monitoring measured TP concentration of just 55 µg/L on March 5, 2020, in Cell 3. When TP concentrations were first measured in early April as part of this study, top depth sample concentrations were approximately 50 µg/L, and they remained there for the duration of the event. Although there was only a single data point collected from both cells at the bottom via grab sample, the TP concentrations were around 100 µg/L, comparable to the levels measured in bottom depth samples during the 2019 monthly monitoring during months without large inflow events (**Figure 5**). At L8CELL6, there was a brief fluctuation upwards in TP in the top depth sample; this is unlikely to be related to the outflow event as no response was seen in L8CELL3, which is located much closer to the pump station. Because stage did not drop below -9.3 NGVD29 during the monitoring period, we cannot discern if there would be an effect from pumping at lower stages.

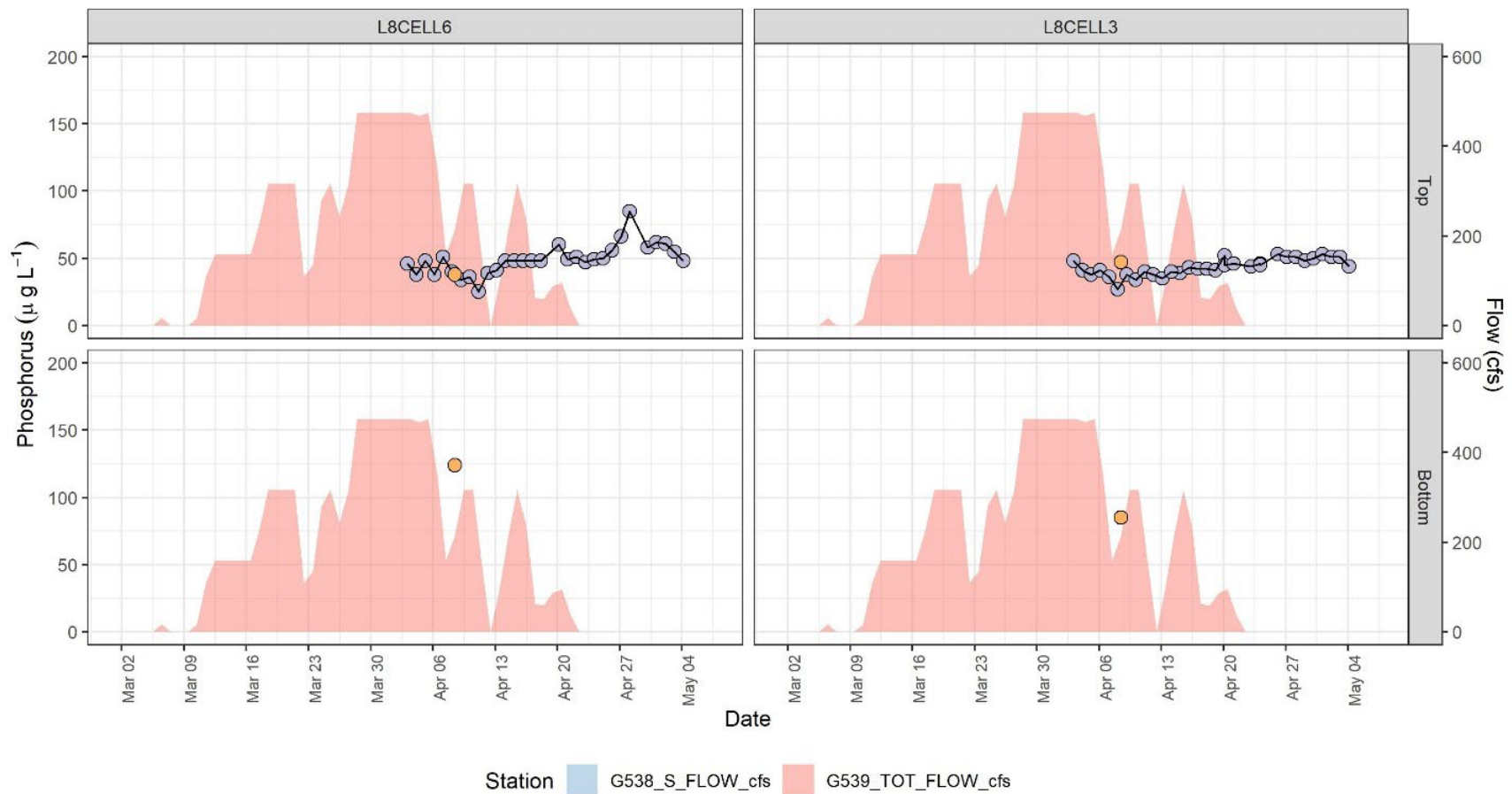


Figure 16. Effects of a large outflow event on TP concentrations in the L-8 FEB. Samples collected by autosampler are in blue and grab samples are in orange.

SEDIMENT AND SOIL RESUSPENSION

METHODS

Sediment samples from the L-8 canal and FEB and soil samples from the FEB banks were collected to evaluate their potential for resuspension and release of TP to the overlying water column (DBE 2020b). Samples were transported to a laboratory where they were agitated and aliquots of the overlying water were analyzed for TP at 1 hour, 24 hours, and 1 week.

RESULTS

Overall samples from FEB sediments had much higher initial TP concentration than canal sediments with median concentration of 15,900 $\mu\text{g/L}$ compared to 1,395 $\mu\text{g/L}$ for bank soils and 1,020 $\mu\text{g/L}$ for canal sediments (**Figure 17**). After 24 hours, FEB samples were highest with median values of 2,130 $\mu\text{g/L}$ compared to 167 $\mu\text{g/L}$ for bank soils and 119 $\mu\text{g/L}$ for canal sediments. TP remained the highest in FEB samples with values of 425 $\mu\text{g/L}$, followed by bank soils 75 $\mu\text{g/L}$ and canal sediments at 127 $\mu\text{g/L}$.

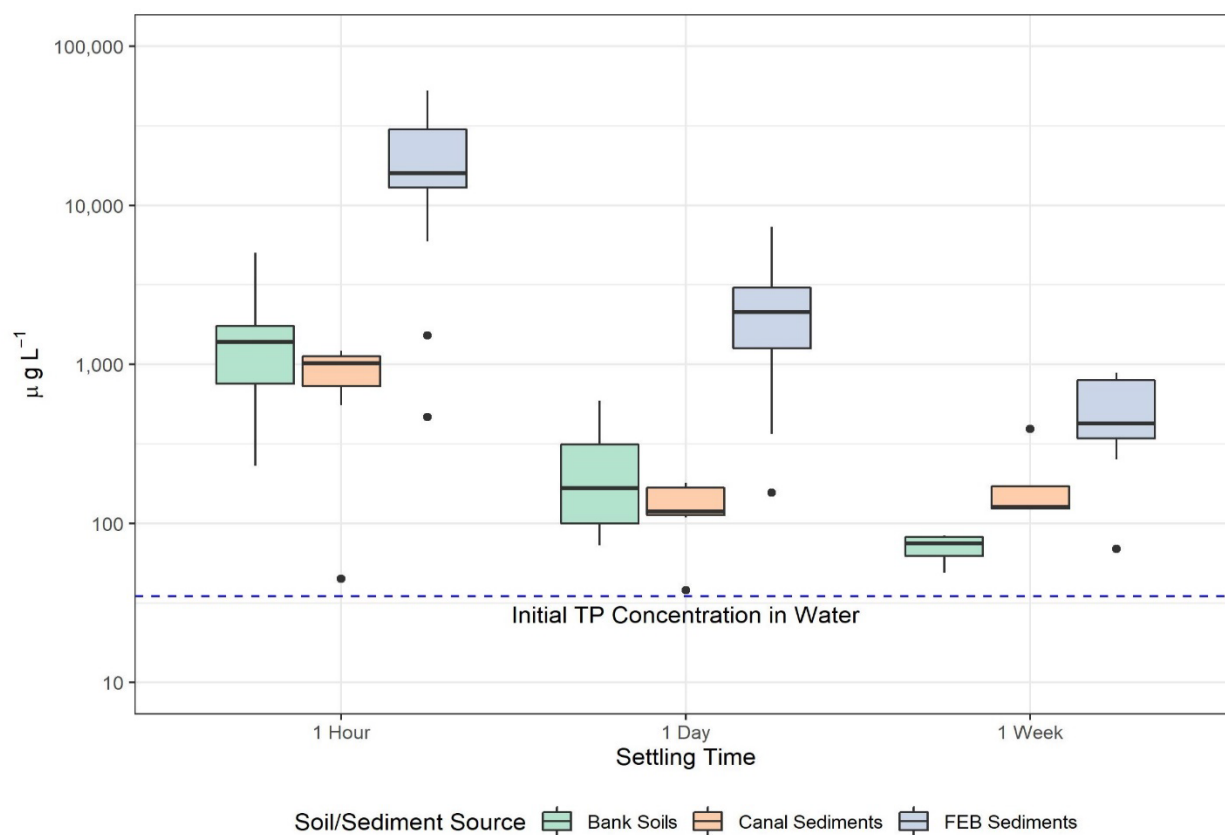


Figure 17. TP in water column after resuspension.

SEDIMENT ACCRUAL

METHODS

Benthic surveys of the L-8 FEB were conducted by E&CT Hydro in 2007 and by Whidden Hydro in 2018. In 2019, SFWMD conducted an exploratory survey of cells L8CELL3 and L8CELL6. This 2019 exploratory survey was not meant for construction or design purposes, and therefore all the requirements of a certified survey by Florida Administrative Code Rule 5J-17.051 were not met. Survey data did conform with data from depth measurements made during the water quality sampling, increasing the confidence in these results. Benthic elevations from these surveys were compared to estimate sediment accrual.

RESULTS

Accrual piles were evident in L8CELL6 near the levee banks. Erosion is evident on the banks as evidenced by gullies (**Figure 18**). Sediment accrual was evident from benthic elevation surveys conducted in L8CELL6 between 2007 and 2019 (**Figure 19**). Benthic elevation between these surveys increased by up to 7 ft in L8CELL6 near the G-538 inflow structure and accrued approximately 2 to 5 ft elsewhere in the cell. The erosive loss of soil is shown on the heatmap as blue and purple areas that ring the cell (**Figure 19**). Loss of elevation is also evident right below the G-538 structure's spillway. This could be from scouring during large inflow events. Just past the possible scouring, the highest accrual of sediment is found. It is possible that this is the result of alluvial process nearest the spillway where flow velocity would be highest.

L8CELL3 did not accumulate as much sediment as L8CELL6. There was elevation gained along the edges of the cell as in L8CELL6, but there was little to no elevation gain in the interior of the cell (**Figure 20**). This accrual along the edges is likely from bank erosion, and the longer distance from inflow means that larger particulates would likely settle earlier in the flow path before reaching L8CELL3.

There is loss of elevation near the G-539 pump station, but the cause of this loss is unknown. Because the construction of the pump station was completed after the 2007 survey, this loss could be from construction activities, but it is possible there could be scouring from the pump station itself.



Figure 18. Southern bank of Cell 6 in the L-8 FEB on April 14, 2020

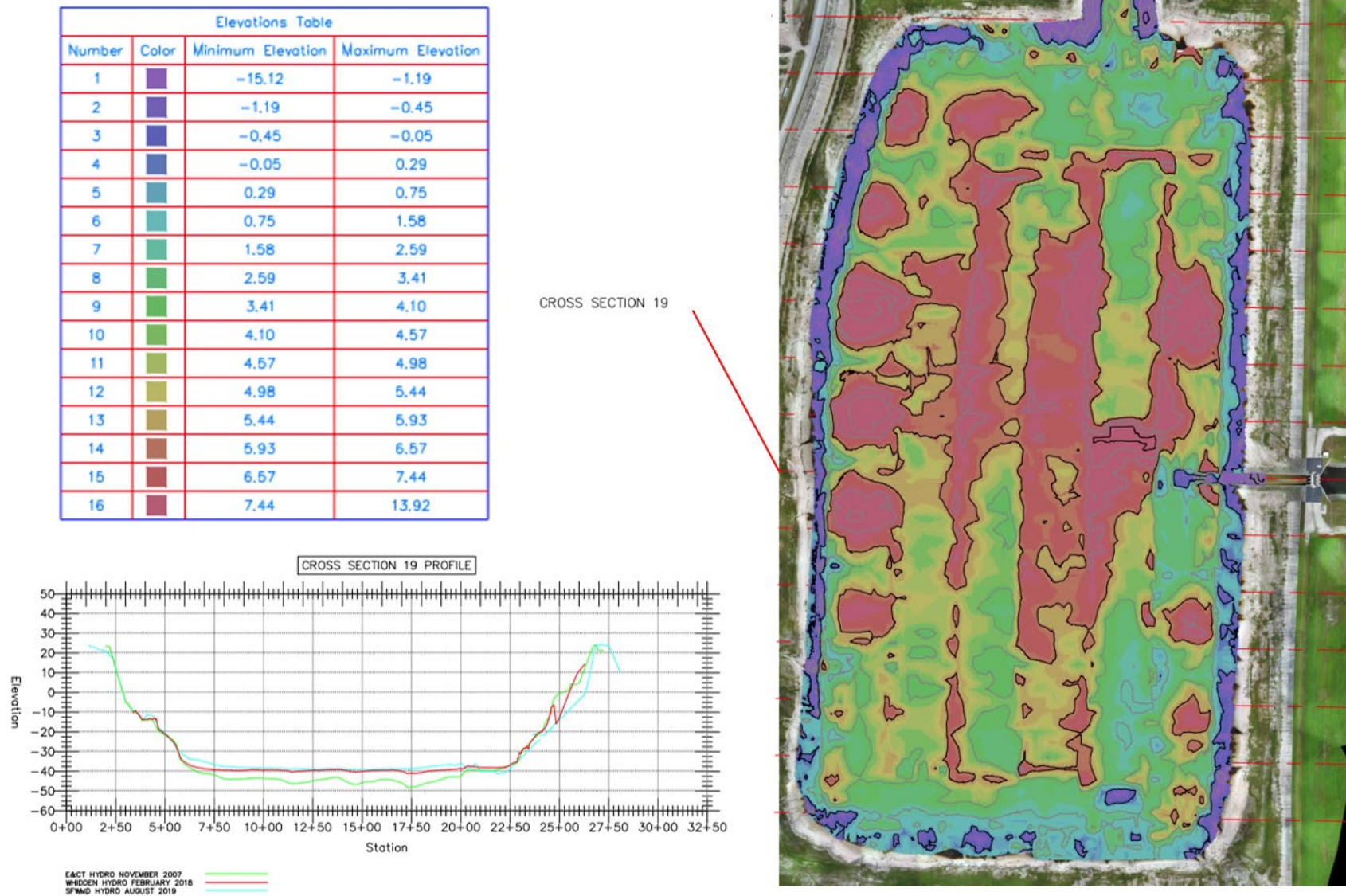


Figure 19. Changes in benthic elevation (ft) between 2007 and 2019 in L8CELL6.

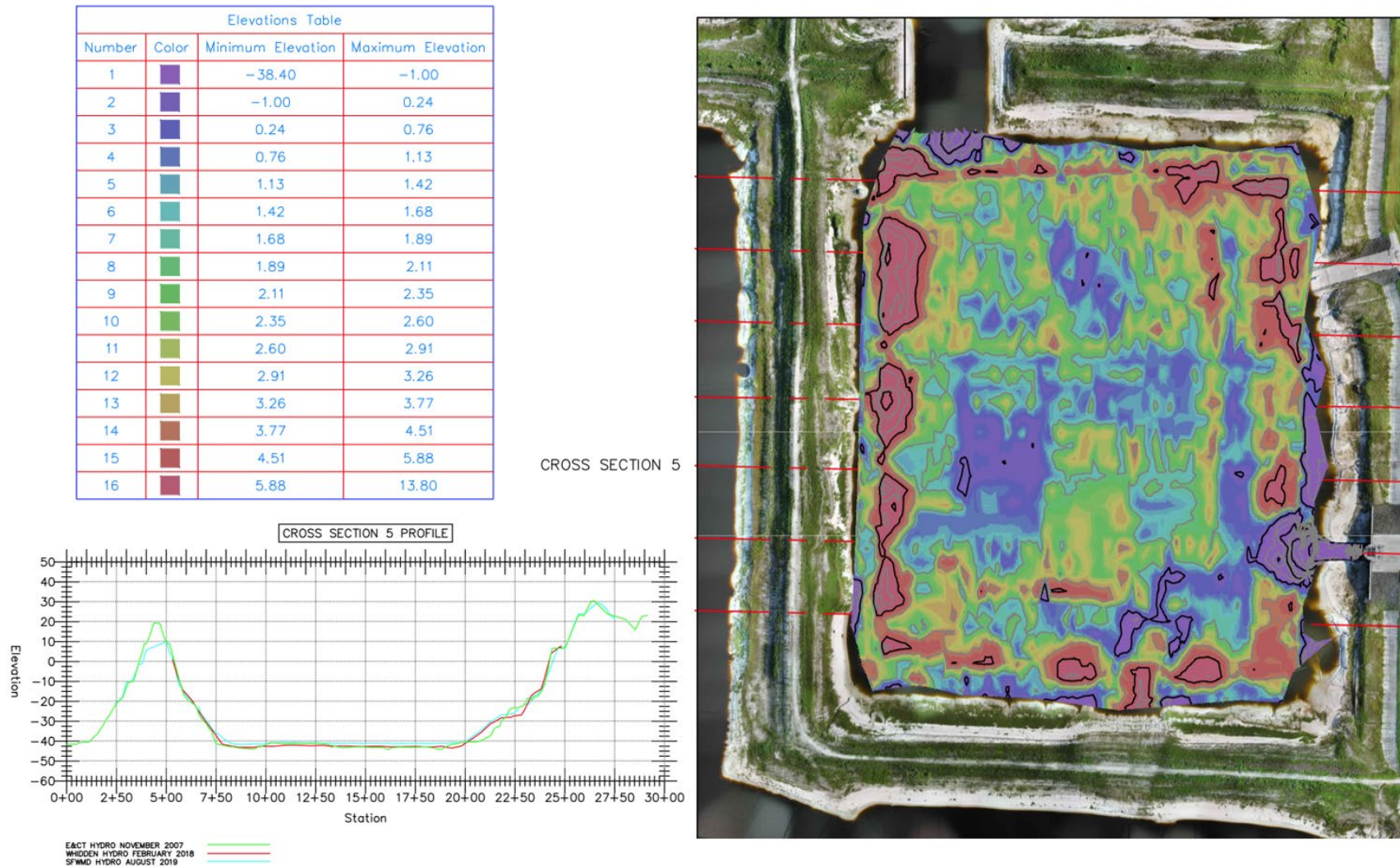


Figure 20. Changes in benthic elevation (ft) from between 2007 and 2019 in L8CELL3.

DISCUSSION AND CONCLUSIONS

Large inflow events resulted in elevated TP concentrations in the surface water in the FEB. From monthly surface water monitoring, TP concentration in the water column of cells nearest the inflow structure were strongly and inversely correlated with the number of days since the inflow rate was greater than or equal to 500 cfs indicating that large inflow events increase TP concentrations in the FEB. High frequency monitoring of a large inflow event found that TP increased sixfold in the FEB closest to the inflow structure and more than doubled in the FEB cell furthest away from the inflow structure. This increase in TP could not be solely explained by the high TP concentrations of the incoming water. After inflows ceased, TP concentrations continued to rise in the FEB, exceeding inflow TP concentrations. This suggests processes other than high inflow TP concentrations alone contributed to the relatively high TP concentrations in the FEB following and during large flow events.

Evidence does not support the hypothesis that groundwater is a source of P that results in periods of high TP in the FEB surface water discharges. Average TP concentrations in groundwater are lower than average TP concentrations in surface water discharged into FEB. Groundwater contributed approximately 10% of total inflow and 5% of the TP load during the period of record, much less than surface water inflows through the G-538 pump station. The composition of TP in groundwater was also different from the composition of TP in surface water in the FEB. On average PP made up less than half of groundwater TP but almost three quarters of surface water TP. Because of the low TP concentration, different P form, and low quantity compared to surface water inflows, groundwater is unlikely to be the source of high TP in the FEB.

It is unlikely that erosion of bank soils is responsible for high TP in the FEB due to the low P content in these soils. P content from sediments in the FEB and the L-8 canal were much higher than in the bank soils. Bank soils were also much heavier with greater mineral content than sediments making them less likely to resuspend. In the laboratory resuspension test, TP concentrations from bank soils were orders of magnitude less than concentrations from the FEB sediments.

Evidence does indicate that resuspension of benthic sediments is one process that can contribute to relatively high TP concentrations in the FEB during and after large flow events. The 2019 benthic survey of L8CELL6 reveals scouring immediately below the inflow structure, suggesting that sediments are resuspended from this area of high flow velocity. Sediment sample analyses showed that these benthic sediments have high P content. In a laboratory resuspension test, benthic sediments increased TP in the overlying water column, which diminished over time but remained elevated for over a week. This is consistent with findings from high frequency monitoring where TP concentrations diminished to one-third from their peak within 3 weeks. No evidence exists to date that stage affects TP concentrations in the FEB, although the FEB depth was not less than 12.3 ft during the period when data was collected for this analysis.

The key findings from this study are (1) large inflow events resulted in increased TP concentrations in the FEB especially nearest the G-538 inflow structure; (2) these elevated TP concentrations diminished with time, but TP remained higher than pre-event levels for over 3 weeks; (3) accrued sediment in the FEB is likely resuspending, exacerbating already high TP concentrations from inflow; and (4) discharge via the G-539 pump station did not elevate TP concentrations when stage was over -9.3 NGVD29.

Over the last three water years, the FEB has been a sink for P, which is beneficial to the downstream STAs by reducing P loading. Operation of the FEB over this period has included large inflow events that quickly fill the FEB towards the end of wet season and slow discharges from the FEB over the dry season and into the early part of the next wet season. This operational pattern has worked well to sequester P in the FEB for the last three water years. These large inflows events have been high in P concentration and load, and since early 2019, discharges have had lower TP concentration than inflow. It may be possible, weather permitting, to further optimize this operational pattern of wet season inflows and dry season discharges to further increase P retention and thus reduce P load to downstream STAs.

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