SOUTH FLORIDA WATER MANAGEMENT DISTRICT

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 Technology Performance, Design and Operational Factors

Influence of Seepage on the Stormwater Treatment Area 3/4 Periphyton-based Stormwater Treatment Area Cell's Treatment Performance

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EXECUTIVE SUMMARY

This report presents an analysis of water surface elevation (i.e., stage) and water quality data collected from January 2012 to September 2015 to evaluate the influence of groundwater/surface water seepage on the treatment performance of the Stormwater Treatment Area (STA) 3/4 Periphyton-based Stormwater Treatment Area (PSTA) Cell. The analysis includes water level and water quality measurements from wells installed along the PSTA Cell's east and west perimeter levees, stage elevations, and water quality measurements in the PSTA Cell and adjacent water bodies, and chemical composition of surface water and groundwater in the vicinity of the PSTA Cell. Groundwater and surface water samples were analyzed for phosphorus fractions and major ion concentrations. Results were evaluated and interpreted in the context of the local hydrogeology.

The PSTA Cell's construction included the removal of most of the soil substrate down to the caprock to reduce a potential source of phosphorus flux to the water column and discourage growth of emergent macrophytes. As a consequence of soil removal, the floor of the PSTA Cell became approximately a foot lower than the ground elevation of the adjacent treatment cells in STA-3/4. In addition, the PSTA Cell stage was maintained generally lower than stages of the surrounding water bodies by an outflow pump station. The resulting head differences across the levees separating the PSTA Cell from the adjacent water bodies produced constant seepage into the PSTA Cell. In April 2013, the PSTA Cell target stage was increased by 0.5 feet to reduce the volume of seepage flowing into the PSTA Cell. A water budget analysis confirmed that the amount of seepage inflow to the PSTA Cell was reduced after the target stage was increased (Zhao et al. 2015).

An analysis of major ion concentrations, stage, and water level data in the PSTA Cell's surface water, surrounding surface water, and groundwater in wells adjacent to the PSTA Cell indicated possible interactions between the surface water in the PSTA Cell and groundwater. However, this analysis suggests that the contribution of lateral seepage through the levee between the Lower Submerged Aquatic Vegetation (LSAV) Cell and the PSTA Cell was greater than the upward movement of groundwater into the cell.

Data suggests that the lateral seepage from the LSAV Cell could be elevating the surface water total phosphorus concentrations within the PSTA Cell. In contrast, the STA-3/4 Discharge Canal surface water appeared not to have any impact on the PSTA Cell total phosphorus concentrations.

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INTRODUCTION AND BACKGROUND

The concept of using periphyton to reduce phosphorus (P) concentrations in stormwater prior to entering the Everglades has been investigated by the South Florida Water Management District (District or SFWMD) scientists and other researchers for over twenty years. Periphyton communities are complex assemblages of cyanobacteria, eubacteria, diatoms, and other eukaryotic algae found in lakes, streams, and wetlands, including the marshes of the Everglades (McCormick and O'Dell 1996). Several characteristics of periphyton communities make them well suited for biological treatment of surface waters in wetlands. Periphyton growth is associated with surfaces (e.g., attached to macrophytes or the sediment surface). Periphyton typically has a high affinity for P and responds to P inputs more rapidly than other wetland components (e.g., macrophytes and soils) and thus is important in the uptake and storage of P (McCormick et al. 1996, Noe et al. 2001). The presence of highly productive periphyton communities in P-limited systems has been linked to the increased uptake efficiency and rapid recycling of nutrients, due to the close association of autotrophic and heterotrophic microbial components (Wetzel 1996). Floating and benthic calcareous periphyton mats are a key component of the ultra-oligotrophic Everglades marshes (Browder et al. 1994), and are thought to be capable of reducing water column total phosphorus (TP) to extremely low levels.

A field-scale periphyton-based stormwater treatment area (PSTA) project was constructed in Stormwater Treatment Area (STA) 3/4 in 2005 for the purpose of addressing uncertainties associated with large-scale implementation of the PSTA treatment technology. The entire STA-3/4 PSTA Project is on a 400-acre (ac) site that is comprised of the 200-ac Upper Submerged Aquatic Vegetation (USAV) Cell, the 100-ac Lower Submerged Aquatic Vegetation (LSAV) Cell, and the 100-ac PSTA Cell.

There were complications in interpreting the PSTA Cell's treatment performance over the first four operational periods from Water Year 2008 (WY2008; May 1, 2007–April 30, 2008) to WY2011. First, the accuracy of the flow data at the inflow structures to the PSTA Cell was in question. Second, the amount of seepage entering the PSTA Cell from surrounding water bodies (i.e., the adjacent cells and the STA-3/4 Discharge Canal) was not known but was assumed to be quite large as evidenced by higher outflow than inflow water volumes. Third, the concentration of TP in the seepage water entering the PSTA Cell was not known.

An important difference between the PSTA Cell and adjacent treatment cells is that most of the soil in the PSTA Cell was removed down to the caprock to reduce a potential source of P flux to the water column and discourage growth of emergent macrophytes. As a consequence of the soil removal, the floor of the PSTA Cell is about one foot lower than the ground elevation of the adjacent treatment cells. To maintain water depths optimal for periphyton growth, the PSTA Cell was operated at a lower stage than those in the adjacent cells, which created a head difference between the PSTA Cell and surrounding waters. For this reason, the PSTA Cell received seepage water through its perimeter levees, in particular, the levee between the PSTA and the LSAV Cells. Additionally, there were assumptions that the surface water within the PSTA Cell may have been influenced by groundwater upwelling.

Therefore, to improve the accuracy of the PSTA Cell's treatment performance estimates, SFWMD implemented various structural, monitoring, and operational improvements in WY2012–WY2014 (Zhao et al. 2015). This report summarizes an analysis of the quantity, quality, and sources of seepage associated with the PSTA Cell during the operational periods from WY2008 to WY2014.

OBJECTIVES

The objective of the PSTA Cell seepage analysis is to determine the influence of seepage on the P removal performance of the PSTA Cell. More specifically, the analysis was conducted to address Hypothesis #6 from the PSTA Study Detailed Study Plan within the *Science Plan for the Everglades Stormwater Treatment Areas* (SFWMD 2013; www.sfwmd.gov/rs_scienceplan). Hypothesis #6 states shallow water depths (and a low surface water level compared to surrounding water levels) increase groundwater interaction, which in turn has led to low outflow TP concentrations for the STA-3/4 PSTA Cell. The efforts taken to determine the influence of seepage included the following:

1. Verifying the average ground elevations of the PSTA and LSAV Cells.
2. Evaluating the effects of head differences between the PSTA Cell and surrounding water bodies on seepage.
3. Measuring changes in groundwater elevations in wells installed along the PSTA Cell's east and west perimeter levees in response to changes in stages of adjacent water bodies.
4. Analyzing the chemical composition of surface water and groundwater within the PSTA region.
5. Evaluating the sources of seepage water entering the PSTA Cell and understanding their interaction using ionic fingerprinting.

This report also includes a brief discussion of the water budget analysis developed using the SFWMD Water Budget Tool previously reported in Zhao et al. (2015).

METHODS

GEOLOGIC SETTINGS

The majority of soils in the central and southern Everglades Agricultural Area (EAA) were previously classified as Pahokee muck ranging from 3 to 4 feet (ft) in thickness (McCollum et al. 1978). A more recent survey classified soils in the same areas as Dania muck ranging from 1 to 2 ft in thickness (Cox et al. 1988). Beneath these organic soils lies a layer between 0 to 6 ft in thickness consisting of a light gray, calcareous mud, and fresh water known as the Lake Flirt Marl (Parker et al. 1955). This layer overlies the surficial aquifer system in Broward County and southwest Palm Beach County, which is divided into two permeable units known as the Biscayne Aquifer and Gray Limestone Aquifer (Parker et al. 1955, Fish 1988, Harvey and McCormick 2009).

The Biscayne aquifer extends westward from the Atlantic coastal ridge becoming thinner and disappearing beneath the central Everglades (Harvey and McCormick 2009). The Gray Limestone Aquifer is found beneath the Biscayne Aquifer and is separated by a semi-confining layer in the western areas of Broward and southwest Palm Beach County (Fish 1988). The Biscayne Aquifer is primarily composed of limestone of marine origin with thin layers of brackish and freshwater limestone known as the Fort Thompson Formation and extends to a depth of approximately 80 ft below sea level (Fish 1988). The semi-confining layer separating the Gray Limestone Aquifer from the Biscayne Aquifer is known as the Tamiami Formation, which is primarily made of less permeable sand, limestone, silt, and clay (Fish 1998). The Gray Limestone Aquifer is lightly to moderately cemented consisting of sandy clayed limestone with abundant carbonate sands (**Figure 1**).

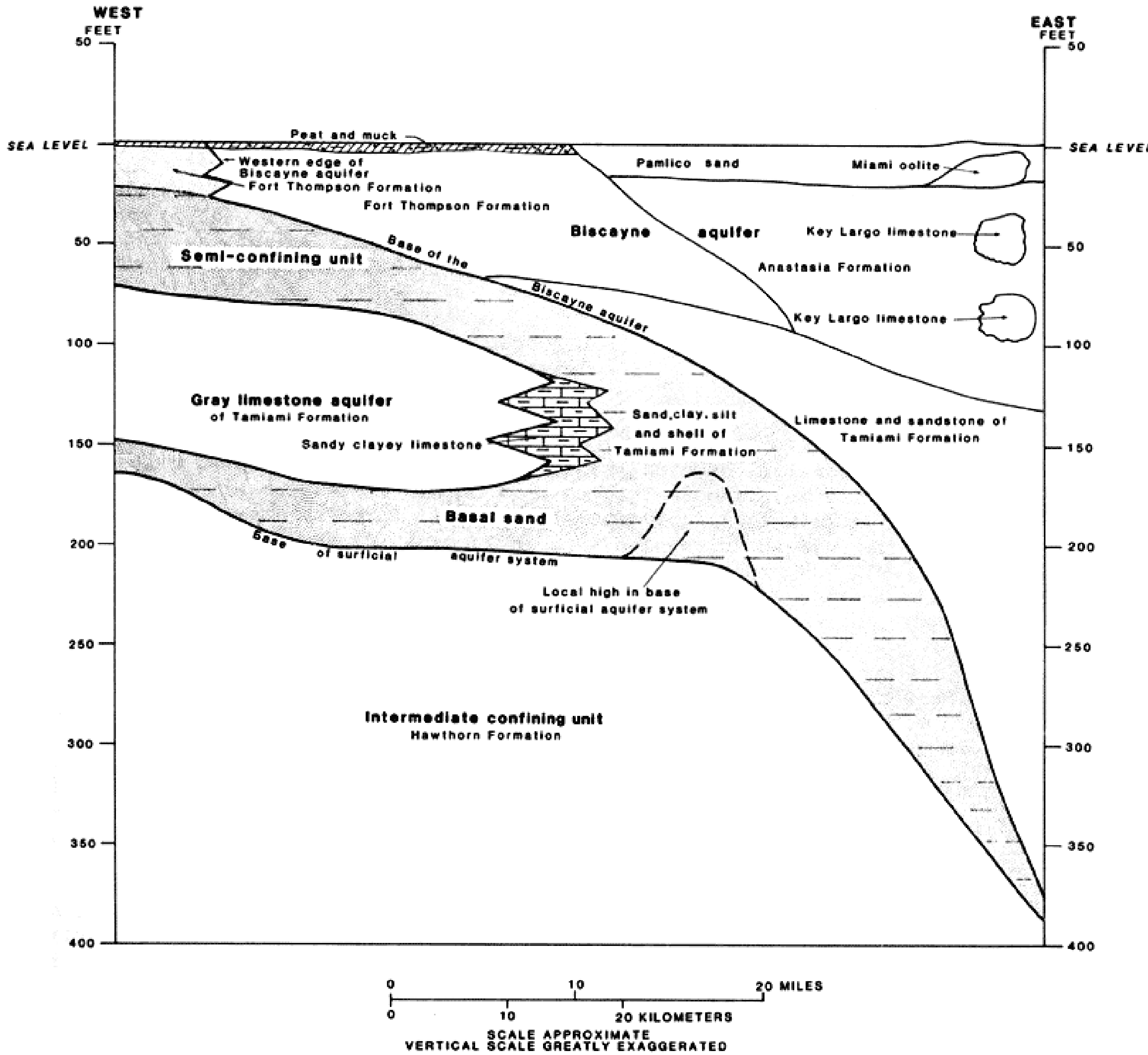


Figure 1. Schematic of geologic formations, aquifers and confining units of the surficial aquifer across Broward County and southwest Palm Beach County near the county line (Fish 1988).

Montgomery Watson Americas, Inc. (1999) characterized the lithology within the STA-3/4 footprint (top to bottom profile) to a depth of approximately 90 ft below ground level as follows: 1 to 2 ft of organic dark brown muck, followed by approximately 9 ft of hard caprock consisting of well-indurated limestone, mixed with shell and sand, and, finally, a layer of less indurated gray to white limestone that extended to a depth of 90 ft. During the construction of STA-3/4 in 2003, borings obtained from the southwestern edge of STA-3/4 next to the current PSTA Cell showed that the upper 25 ft was primarily composed, from top to bottom, of a layer of dark brown peat with organic silt and clay (ranging from 8 to 11 ft National Geodetic Vertical Datum 29 (NGVD29), followed by a gray, brown, and tan limestone with silty calcareous sand from 7 to -15 ft NGVD29 (Nova Consulting Inc. 2003). Hydrogeological cross-sections showing the hydrostratigraphic layers beneath the PSTA Cell can be found in **Appendix A**.

SITE DESCRIPTION

STA-3/4 is located in western Palm Beach County between the North New River Canal to the east, the Holey Land Wildlife Management Area (WMA) to the west and north of the Broward County line. STA-3/4 is situated on lands that were previously farmed as part of the EAA. The STA-3/4 PSTA Project was constructed within a 400-ac section of Cell 2B in STA-3/4 and is comprised of the 200-ac USAV Cell, the 100-ac LSAV Cell, and the 100-ac PSTA Cell (Chimney 2014). The PSTA Cell is situated between the LSAV Cell to the east, and the STA-3/4 Discharge Canal to the west, and is north of the former Griffin Rock Pit (**Figure 2**). The PSTA Cell receives surface water inflow from the USAV Cell through the G-390A and B structures and discharges through the G-388 pump station (Chimney 2015). The G-388 outflow pump station consists of two pumps (referred to as Pump #1 and Pump #2) with a capacity of 100 and 60 cubic feet per second (cfs), respectively. The outflow pumps run on automatic mode through a float switch programmed to turn the pumps on and off to achieve the target stage. Also, unlike adjacent cells, most of the soil in the PSTA Cell was removed down to the caprock. The adjacent LSAV Cell to the east has two inflow structures (G-389A and B) on the north and one outflow structure (G-379E) in the southwestern corner.

Eight monitoring well clusters (C1-C8) were installed in 2005 along the two perimeter levees that separate the PSTA Cell from the LSAV Cell and the STA 3/4 Discharge Canal, with four clusters (C1-C4) in the east perimeter levee and four clusters (C5-C8) in the west perimeter levee. The even numbered clusters have three wells at depths of 8. 20 and 36 feet, while the odd numbered clusters have two wells at depths of 8 and 38 feet. A well construction schematic is provided in Appendix B.

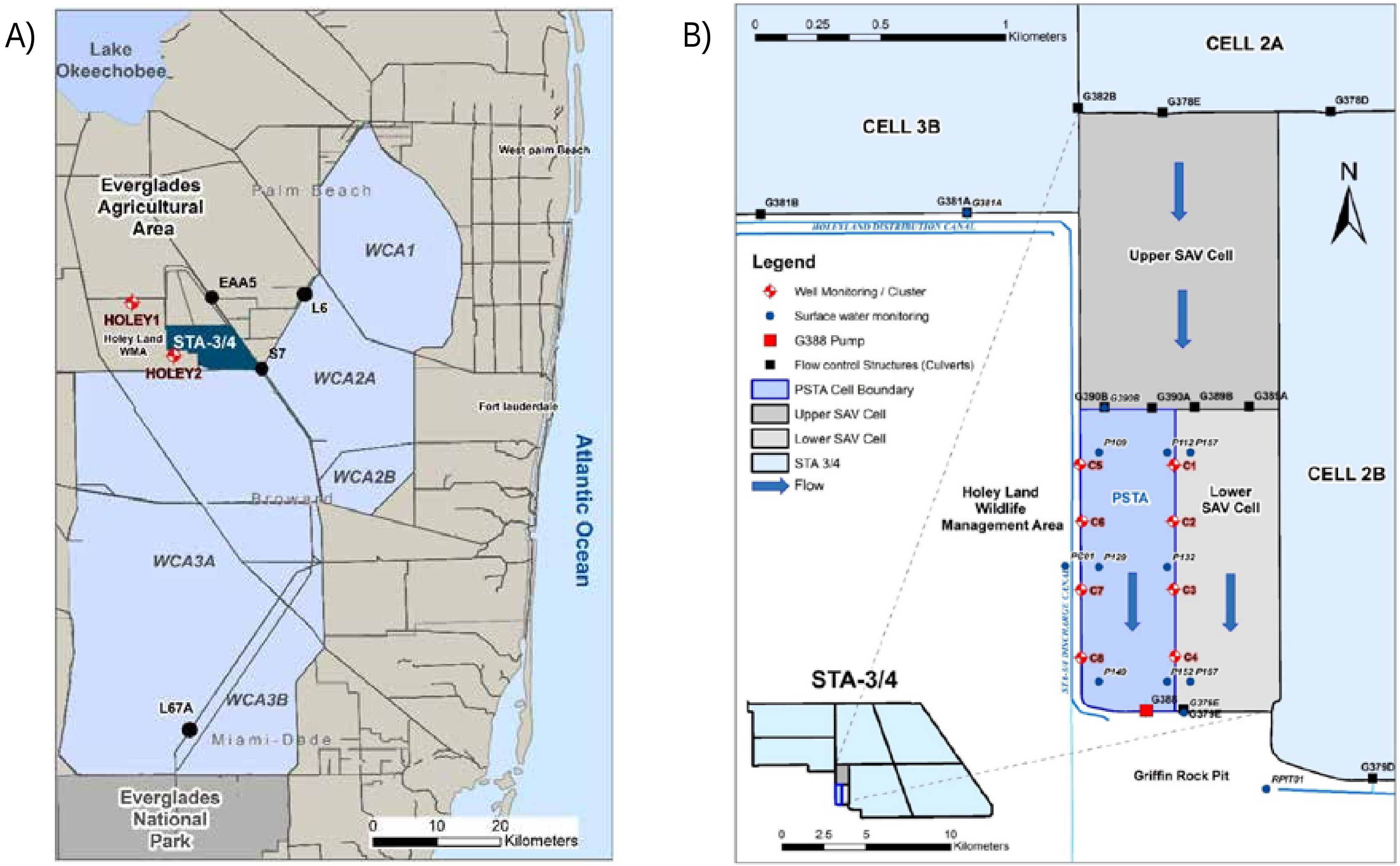


Figure 2. A) Map of the study area showing STA-3/4 and selected rainfall and regional groundwater monitoring stations. B) Map of STA-3/4 showing the PSTA, USAV, and LSAV Cells; related water control structures; monitor well clusters (C1 through C8); and surface water stations. (Note: SAV – Submerged Aquatic Vegetation and WCA – Water Conservation Area.)

TOPOGRAPHIC AND WELL SURVEYS

During the first 5 years of operations (WY2008–WY2012), the PSTA Cell was assumed to have had an average water depth of approximately 2 ft based on a target stage of 10.0 ft NGVD29 within the cell and an average caprock elevation of 8.1 ft NGVD29 specified in the 2003 design document by Nova Consulting Inc. However, after conducting some manual water depth measurements in 2012, it was discovered that the actual water depths in the PSTA Cell were noticeably less than the assumed depth of 2 ft.

To resolve this apparent discrepancy, a new topographic survey was conducted in the PSTA and LSAV Cells in August 2013 by GCY Professional Surveyors & Mappers, Inc. As shown in **Appendix C**, a total of 63 points were surveyed throughout the PSTA Cell, including 24 points on vegetation strips and 39 points on the caprock surface. Another 24 evenly spaced points were surveyed in the LSAV Cell. All horizontal measurements were based on the North American Datum of 1983 (NAD83) and all vertical measurements were based on the North American Vertical Datum of 1988 (NAVD88), which was then converted to NGVD29. The average caprock elevation in the PSTA Cell and ground elevation in the LSAV Cell were estimated using the digital elevation model (DEM) technique and the Spline interpolation method in ARCGIS 10.1 (Esri, Redlands, California).

Results of the 2013 survey showed that the average caprock elevation in the PSTA Cell was actually 8.8 ft NGVD29 and not the previously assumed elevation of 8.1 ft NGVD based on preconstruction data. This new elevation data confirmed the manual field observations that average water depths inside the PSTA Cell were less (by 0.7 ft) than the assumed 2.0 ft when the stage was 10.0 ft NGVD29. The survey also reported that the elevations of the vegetation strips in the PSTA Cell ranged from 9.2 ft to 10.6 ft NGVD29 with an average elevation of 9.8 ft NGVD29, while the average ground elevation in the LSAV Cell was 9.7 ft NGVD29.

In addition to the topographic survey, elevation surveys were conducted on each of the 20 monitoring wells (or 8 well clusters) located along the PSTA Cell's east and west perimeter levees, the results of which are reported in **Table 1**. The survey measurements revealed that the elevation of the wells located in the west levee were on average 1.8 ft higher than the wells located in the east levee of the PSTA Cell. As a result, the bottoms of the four shallow (8-ft) wells in the west levee are at an elevation above the average stage in both the STA-3/4 Discharge Canal and the PSTA Cell. Consequently, the groundwater levels in these shallow wells could not be used to assess possible interactions or seepage between the PSTA Cell and the STA-3/4 Discharge Canal. Cross-sections showing the relative stages in the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal along with groundwater elevations in the perimeter wells are included in **Appendix A**.

Table 1. Elevation survey (2013) results for each monitoring well located along the STA-3/4 PSTA Cell east and west levees, and the locations and depths of pressure transducer deployment.

Site Name	Well Cluster	Coordinate NAD83 High Accuracy Reference Network (HARN) State Plane Florida East		Depth of Well (ft)	Top of the Well Casing (E) Elevation [a] (ft NGVD29)	Elevation at Bottom of Well Screen (z) (ft NGVD29)	Continuous Water Levels Pressure Transducer Deployment Depth (D) (ft)
		Easting (ft)	Northing (ft)				
C1-36	C1	776573.22	733325.43	36	17.0	-19.0	
C1-8	C1	776573.34	733330.49	8	17.0	9.0	
C2-20	C2	776579.22	732601.79	20	16.7	-3.4	
C2-36	C2	776574.28	732596.54	36	16.8	-19.3	
C2-8	C2	776574.77	732606.96	8	16.6	8.6	6.8
C3-36	C3	776581.95	731704.48	36	16.6	-19.4	33.3
C3-8	C3	776581.35	731709.84	8	16.6	8.6	6.9
C4-20	C4	776586.22	730822.42	20	16.5	-3.5	
C4-36	C4	776580.96	730817.14	36	16.5	-19.5	
C4-8	C4	776581.34	730827.07	8	16.5	8.5	
C5-36	C5	775364.04	733317.42	36	18.8	-17.2	
C5-8	C5	775363.95	733322.52	8	18.7	10.7	
C6-20	C6	775366.24	732596.36	20	18.4	-1.6	17.2
C6-36	C6	775370.86	732591.52	36	18.3	-17.7	33.4
C6-8	C6	775370.86	732600.98	8	18.2	10.2	
C7-36	C7	775370.86	731702.91	36	18.6	-17.4	
C7-8	C7	775371.07	731708.08	8	18.7	10.7	
C8-20	C8	775379.15	730805.5	20	18.2	-1.8	
C8-36	C8	775373.5	730811.22	36	18.2	-17.8	33.3
C8-8	C8	775379.07	730816.02	8	18.1	10.1	

a. Elevations are from the 2013 topographic survey (GCY Professional Surveyors & Mappers Inc. 2013).

SURFACE WATER STAGE AND WATER BUDGET CALCULATION

Daily stages for the PSTA and LSAV Cells were estimated by averaging the daily average stage at the inflow tailwater (TW) and outflow headwater (HW) locations of the associated water control structures for each cell (**Figure 2**). The daily stage for the STA-3/4 Discharge Canal was estimated by averaging the daily TW stages at the G-381B and G-379D structures. Daily surface water stages and groundwater elevations were also obtained from two monitoring sites in the Holey Land WMA, HOLEY1/HOLEY1_G and HOLEY2/HOLEY2_G (**Figure 2**). The PSTA Cell average daily flow values at the inflow and outflow structures were used to estimate the surface water volumes in and out of the cell. Rainfall from nearby stations S7_R and EAA5 was used to evaluate the influence of precipitation on stages and were presented as annual averages in terms of water year. All data were obtained using the preferred DBKEYs from SFWMD's DBHYDRO database listed in **Table 2**. The annual water budgets for the PSTA Cell for each of the water years from WY2008 through WY2014 were estimated using the District's web-based Water Budget Tool (Zhao et al. 2015).

Table 2. Description of flow, stage, rainfall, and evapotranspiration data database or DBKeys used.

DBKey	Station	Data Type	Data Description	Units	Associated Area	Feature Location
T1056	G379D_T	Stage	TW Stage	ft NGVD	STA-3/4 Cell 2B	On-site
TZ226	G379E_H	Stage	HW Stage	ft NGVD	STA-3/4 LSAV Cell	On-site
AL717	G379E_T	Stage	TW Stage	ft NGVD	STA-3/4 LSAV Cell	On-site
T1063	G381B_T	Stage	TW Stage	ft NGVD	STA-3/4 Cell 3B	On-site
TZ219	G-388_H	Stage	HW Stage	ft NGVD	STA-3/4 PSTA Cell	On-site
V2504	G-388_P	Flow	Daily Flow	cfs	STA-3/4 PSTA Cell	On-site
UA604	G389B_T	Stage	TW Stage	ft NGVD	STA-3/4 LSAV Cell	On-site
V8861	G390A_C	Flow	Daily Flow	cfs	STA-3/4 PSTA Cell	On-site
V8862	G390B_C	Flow	Daily Flow	cfs	STA-3/4 PSTA Cell	On-site
UA609	G390B_T	Stage	TW Stage	ft NGVD	STA-3/4 PSTA Cell	On-site
VW978	HOLEY1	Stage	Surface Water Stage	ft NGVD	Holey Land WMA	Off-site
VW980	HOLEY1_G	Well	Groundwater Stage	ft NGVD	Holey Land WMA	Off-site
W1923	HOLEY2	Stage	Surface Water Stage	ft NGVD	Holey Land WMA	Off-site
W1925	HOLEY2_G	Well	Groundwater Stage	ft NGVD	Holey Land WMA	Off-site
VN317	S7_R	Rain	Rainfall	inches	Water Conservation Area (WCA) 2A	Off-site
VN030	EAA5	Rain	Rainfall	inches	EAA	Off-site

STATIC WATER LEVELS IN WELLS

Static groundwater level measurement were collected in the shallow (8-ft), intermediate (20-ft) and deep (36-ft) wells located in the east and west levees of the PSTA Cell. Measurements were taken using a Solinst® Model 102M Water Level Indicator (Solinst Canada Ltd., Georgetown, Ontario, Canada) on a regular basis during the dry and wet seasons from February 2012 to July 2014. Groundwater elevations were determined for each well by subtracting the static depth to water level measurement from an elevation reference point measured at the top of casing for each well during the 2013 elevation survey (**Table 1**).These measurements were converted to groundwater elevations in ft NGVD29 using the 2013 reference elevations at the top of the well casings (**Table 1**) so that they could be compared to the adjacent surface water stages in the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal. Because the water levels were the same in both the intermediate and deep wells, the intermediate wells were not used in the analysis. The differences between the groundwater elevations in the wells and the stages in the adjacent surface water were evaluated independently prior to and after the PSTA Cell target stage was changed from 10.0 ft NGVD29 to 10.5 ft NGVD29 on April 2, 2013 (see **Figures 6A** and **6B** in the *Results and Discussion* section below). Summary statistics of the groundwater elevations in all the perimeter levee wells before and after the target stage modification are included in **Appendix E**.

CONTINUOUS WATER LEVEL IN WELLS

Water pressure transducers (Solinst® LTC Leveloggers) were deployed in three wells (C2-8, C3-36, and C3-8) located in the east levee and three wells (C6-20, C6-36, and C8-36) in the west levee of the PSTA Cell from August 21 through October 29, 2015 (**Table 1**). The Leveloggers collected absolute water pressure and temperature measurements every 30 minutes. To calculate groundwater elevation, the raw water level pressure is temperature compensated; the compensated water level data was then corrected for barometric pressure that was measured with a Solinst® Edge Barologger positioned above the water. All raw data was processed by the Data Wizard utility in the Solinst® Levelogger Software 4 (Version 4.1.0). The barometrically corrected water level data (H) was then loaded into an Excel spreadsheet. That information was post-calibrated to the Levelogger deployment depth (D) to obtain the depth to water (**Equation 1**). The revised groundwater level data was referenced back to a known datum based on the original survey of the top of casing (**Equation 2**) conducted on August 2013 to obtain the hydraulic head or groundwater elevation.

The depth to water (d_w) in each of the PSTA wells was calculated using the corrected data from the Leveloggers as follows:

$$d_w = D - H \tag{1}$$

where:

d_w = depth to water surface (ft)

D = deployment depth, i.e., length of the wire (ft) from the top rim of the well casing (hanging point) to the pressure sensor

H = barometrically corrected Levelogger depth within the well (ft)

The hydraulic head (h) at each well was calculated as the difference between the land surface elevation and the depth to water in the well:

$$h = E - d_w \tag{2}$$

where:

h = hydraulic head (ft)

E = top rim of the well casing elevation reference point (ft NGVD29)

The horizontal hydraulic gradient between two wells (Well 1 and Well 2) was calculated as the change in hydraulic head over a distance between two reference points:

$$\frac{\mathrm{dh}}{\mathrm{dl}} = \frac{\mathrm{h}_2 - \mathrm{h}_1}{\mathrm{L}} \tag{3}$$

where:

dh/dl = horizontal hydraulic gradient
h_2 = hydraulic head at Reference Point 2 (ft)
h_1 = hydraulic head at Reference Point 1 (ft)
L = horizontal distance between the wells (ft)

The vertical hydraulic gradient between two wells was calculated as the difference in hydraulic head over the vertical distance between the two wells:

$$\frac{\mathrm{dh}}{dl_v} = \frac{\mathrm{h}_2 - \mathrm{h}_1}{\mathrm{z}_2 - \mathrm{z}_1} \tag{4}$$

where:

dh/dl_v = vertical hydraulic gradient
h_2 = hydraulic head in Well 2 (ft)
h_1 = hydraulic head in Well 1 (ft)
z_1 = elevation head in Well 1 or the elevation at the bottom of the well (ft NGVD29)
z_2 = elevation head in Well 2 or the elevation at the bottom of the well (ft NGVD29).

Surface water stages for Holey Land WMA, PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal, and the Holey Land WMA groundwater elevations were obtained on a 30-minute frequency using the Interval Value Generator utility in SFWMD's corporate environmental database, DBHYDRO (**Table 1**).

WATER QUALITY

Groundwater samples were collected in February and June 2012; in February, June, and September 2013; and in September 2015 from four shallow (8-ft) wells and four deep (36-ft) wells in well clusters C2, C3, C4, C6, and C8 within the east and west levees. Groundwater samples were collected from intermediate (20-ft) wells in C4 and C8 once in September 2015 (**Figure 2B**). In addition, surface water samples were collected in June 2012, 2013, and 2014 and September 2015 to characterize major ions and nutrient concentrations during the wet season. Surface water samples were collected following the SFWMD *Field Sampling Quality Manual* (SFWMD-FIELD-QM-001-08.2; SFWMD 2015), and groundwater samples were collected in accordance with the Florida Department of Environmental Protection Standard Operating Procedure FDEP SOP 001/01 FS2200 (FDEP 2014).

The groundwater wells were purged using a variable speed peristaltic pump connected to a flow-through chamber. Water samples were collected on the same day after purging a minimum of one well volume and only after reaching stabilization of field parameters (pH, specific conductance, temperature, and dissolved oxygen) to assure that the samples were representative of the groundwater formation. Surface water samples were collected and field measurements were conducted at preselected sites in the PSTA Cell and surrounding water bodies (**Figure 2B**). Grab samples at the inflow and outflow structures were collected at a depth of 0.5 meters (1.64 ft) below the water surface. Samples collected inside the PSTA and LSAV Cells were collected at one-half the total depth. Water samples were collected using an intermediate sample bottle as a collection device before processing the samples. All samples were processed and preserved in the field and then transported on ice in a cooler to the District's Chemistry Laboratory for analysis.

Groundwater and surface water samples were analyzed for calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), alkalinity, TP, total dissolved phosphorus (TDP), and soluble reactive phosphorus (SRP). Particulate phosphorus (PP) was determined by subtracting TDP from TP, and dissolved organic phosphorus (DOP) was calculated as the difference between TDP and SRP. Ion concentrations were expressed as milliequivalents per L (me L^{-1}) to calculate the ionic balance. The cation to anion concentration ratio was determined to validate the analytical measurements, since the ratio should equal 1 in an electrically neutral solution. The percent charge balance error (%CBE) was calculated for each sample using total cation and anion concentrations following Frazee (1982). A balance error of less than 5% was considered acceptable:

$$\%CBE = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \text{ x } 100 \qquad (5)$$

The major ionic composition of groundwater and surface water in and around the PSTA Cell was graphically represented using trilinear Piper diagrams with cations and anions plotted as percent me L^{-1}. Water quality data were analyzed and graphed with AquaChem Version 10 (Waterloo Hydrogeologic Inc., Kitchener, Ontario, Canada). Results were used to identify the geochemical characteristics and interactions of groundwater and surface water. The classifications of Florida waters by Frazee (1982) and Upchurch (1992) were used to determine the possible sources of waters sampled within the PSTA region (**Table 3**). The chemical characteristics of the water were also compared with Harvey and McCormick's (2009) and Parker et al.'s (1955) classification of Lake Okeechobee surface water and the EAA surface water and groundwater. Major ions were measured in rainwater samples collected from two monitoring sites, L6 and L67A, located east and south of STA-3/4, respectively (**Figure 2A**). Data from these sites were obtained from SFWMD's DBHYDRO database.

Summary statistics were generated for each chemical parameter by sampling location (**Appendix D**). Values were plotted to determine central tendency and variability in terms of means, medians, interquartile ranges, and the 10th and 90th percentiles. None of the continuous variables met all the assumptions for parametric analysis; therefore, a nonparametric Kruskal-Wallis rank-sum test was used to examine differences among sampling locations at $\alpha = 0.05$. Multiple comparison tests (Dwass, Steel, and Critchlow-Fligner tests) were used to examine which pairs were significantly different. All statistical analyses were performed with JMP statistical software Version 11.2.0 (SAS Institute Inc., Cary, North Carolina).

Table 3. Chemical characteristics of different water types observed in and around the PSTA Cell according to the classification of Florida waters by Frazee (1982) and Upchurch (1992).

Frazee (1982)			Upchurch (1992)		
Water Type	**Criteria [a]**	**Characteristics**	**Water Type**	**Criteria**	**Characteristics**
FW-I	Ca-HCO_3	Rapid infiltration through sand column.	A1	Calcium-bicarbonate water	Derived from rainfall, interaction with peat, sand and carbonate layers over a short period. Dissolution of limestone.
FW-II	Ca-HCO_3 with Na-SO_4-Cl	Less rapid infiltration through sand and clay lens column.			
FW-IV	Ca-Mg-SO_4, low Cl	Vertical infiltration insignificant, older form of freshwater formation Type III or Type II.	B2	Calcium-magnesium bicarbonate-sulfate	Fresh formation derived from fresh recharge, longer contact with soils and aquifer sediments.
TW-I	HCO_3-SO_4, mixing zone with increasing Cl	Source water dominates balance, mixing of two or more end members.	F6	Calcium-sodium bicarbonate-Chloride	Mixing of fresh recharge water and older relict water.
			G1	Mixed-cation bicarbonate water	Derived from interactions with aquifer sediments. Rainfall-driven recharge through agricultural soil.
			G6	Mixed-cation bicarbonate-chloride water	Fresh-salt mixture, inputs of magnesium and sulfate.

a. Ca – calcium; cl – chloride; HCO_3 – bicarbonate ion; Mg – magnesium; Na – sodium; and SO_4 – sulfate.

RESULTS AND DISCUSSION

SURFACE INFLOW AND OUTFLOW

During the last month in WY2012 and throughout WY2013, the daily average stage in the PSTA Cell was lower than the daily average stages in the adjacent LSAV Cell and STA-3/4 Discharge Canal (**Table 4**). The water budget estimates for the PSTA Cell from April 6 to July 3, 2012 (**Figure 3**), show that while the inflow structures to the PSTA Cell were closed, the G-388 outflow pump station discharged a daily mean flow of 899 acre-feet (ac-ft) or 5.3 cfs, indicating water movement into the PSTA Cell in the form of lateral seepage from the LSAV Cell and STA-3/4 Discharge Canal, and/or possible groundwater upwelling through the floor of the PSTA Cell. During this period, direct rainfall did not contribute significantly to the water level in the PSTA Cell and was matched by a comparable amount of evapotranspiration (ET).

Table 4. Minimum, maximum and daily average stages in the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal during WY2013 and WY2014.

	Stage (ft NGVD29)					
	WY2013			WY2014 [a]		
	PSTA	LSAV	Canal	PSTA	LSAV	Canal
Minimum	10.1	10.1	9.8	10.1	10.2	9.1
Maximum	11.0	11.8	11.9	11.0	11.8	12.0
Average	10.2	10.7	10.6	10.6	10.7	10.4

a. Target stage for the PSTA Cell was increased from 10.0 to 10.5 ft NGVD29 on April 2, 2013.

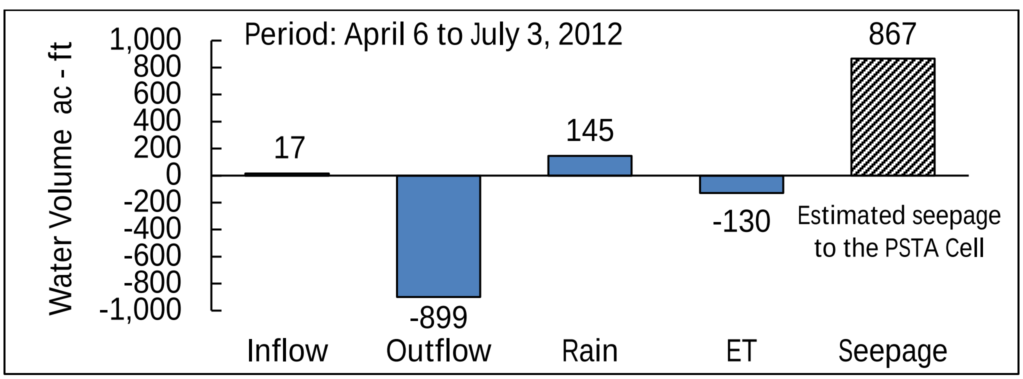


Figure 3. Water budget estimates for the PSTA cell, including total volume of inflow, outflow, rainfall, ET and seepage from April 6 to July 3, 2012.

From April 6 to April 19, 2012, the daily average stages in the STA-3/4 Discharge Canal and the groundwater elevations in the Holey Land WMA were comparable to those observed in the PSTA Cell, while the daily average stages in the LSAV Cell were higher than in the PSTA Cell (**Figure 4**). During this period, the daily average outflow from the PSTA Cell was approximately 3.7 cfs, which suggested that water was added by way of seepage from the LSAV Cell. On April 20, 2012, there was an increase in the Holey Land WMA stage, which was followed by a gradual increase in the average stage in both the STA-3/4 Discharge Canal and the LSAV Cell (**Figure 4**). Consequently, outflow from the PSTA Cell increased to

9 cfs and maintained a daily average of 5.8 cfs from April 20 to July 3, 2012, likely as a result of increased seepage into the PSTA Cell from all surrounding water bodies. Stage fluctuations observed in the STA-3/4 Discharge Canal and LSAV Cell were likely the result of increased precipitation along with increased surface water runoff and seepage into the PSTA Cell. During this period, the seepage contribution from the surrounding bodies (i.e., LSAV Cell and STA-3/4 Discharge Canal) to the PSTA Cell increased as a result of the large head difference between the PSTA Cell and surrounding waters.

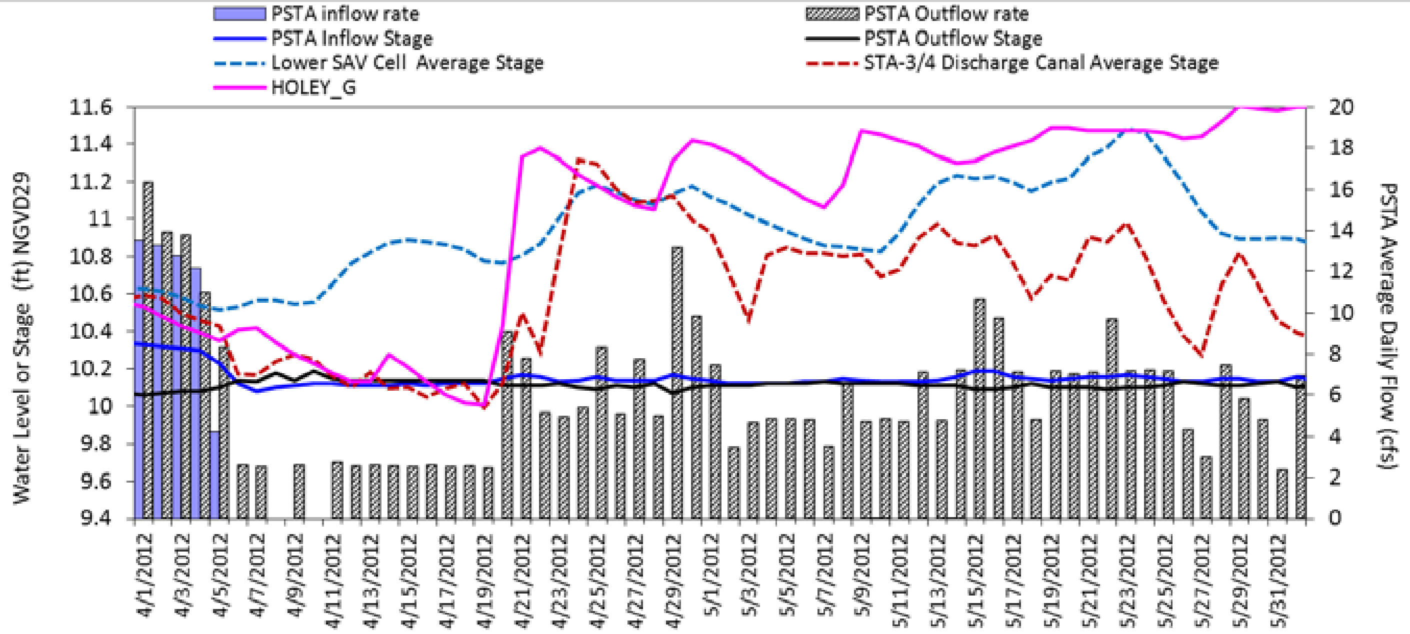


Figure 4. Daily average stages in the LSAV Cell, STA-3/4 Discharge Canal, and Holey Land WMA, and at the PSTA Cell inflow and outflow locations together with daily average PSTA Cell inflow and outflow rates from April 1 to June 2, 2012.

On July 3, 2012, the G-390B structure was opened approximately 1 ft to allow for surface water inflows to the PSTA Cell while the second inflow structure G-390A remained closed for a majority of the period analyzed (Zamorano 2015). Based on the annual water budget (Zhao et al. 2015), differences between total inflows and total outflows confirmed that in addition to the structure inflows and rainfall, the PSTA Cell continued to be influenced by lateral seepage and possibly vertical groundwater upwelling.

Beginning on April 2, 2013, the target stage for the PSTA Cell was increased by 0.5 ft to reduce the amount of seepage entering the PSTA Cell that had occurred at the 10.0 ft NGVD29 target stage. The change reduced the head differences between the PSTA Cell and surrounding waters. During WY2014, stage values in the PSTA Cell were more comparable to stage values in the LSAV Cell, but still remained slightly lower (**Figure 5**).

Figure 5 also shows that stages in the STA-3/4 Discharge Canal fluctuated more frequently than those in the PSTA and LSAV cells. During the second quarter of WY2014, stages in the STA-3/4 Discharge Canal were lower than stages in the surrounding areas, suggesting there was no contribution of seepage from the STA-3/4 Discharge Canal to the PSTA Cell. During this period, seepage direction was likely reversed, with water seeping from the PSTA Cell to the STA-3/4 Discharge Canal. The minimum, maximum and average annual stages for the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal for WY2013 and WY2014 are summarized in **Table 4**.

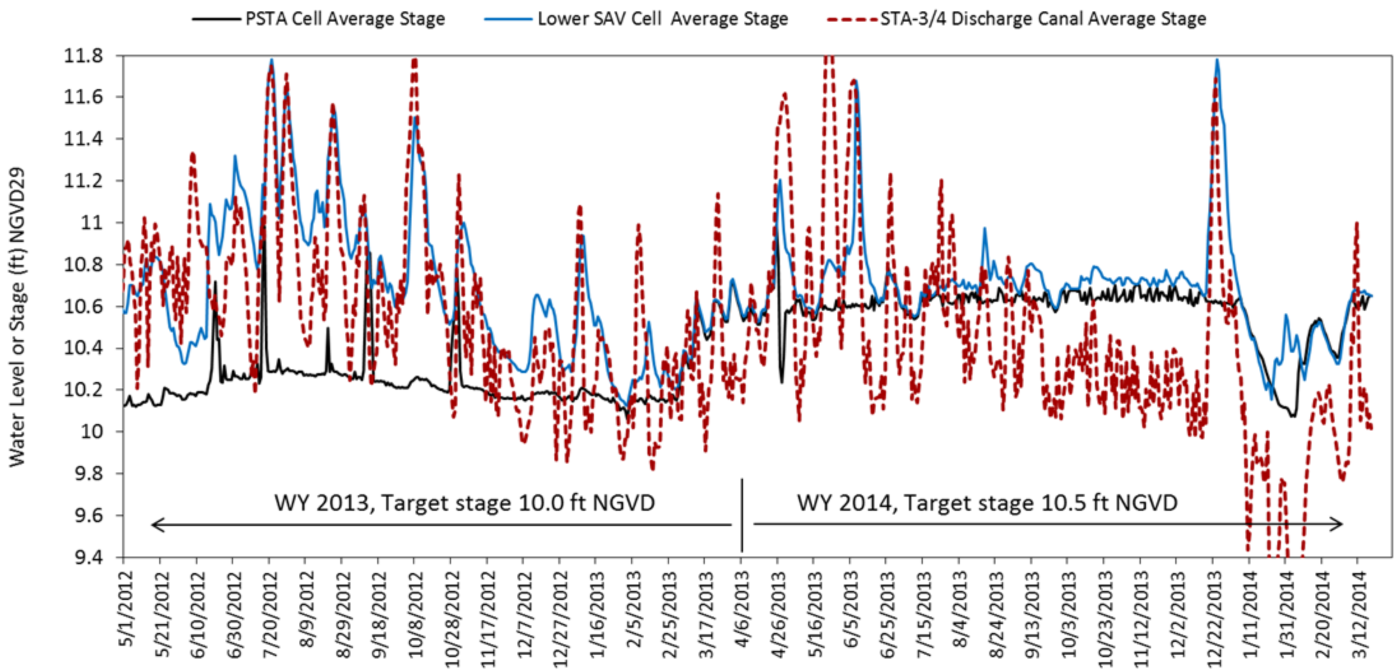


Figure 5. Daily average stages in the LSAV Cell, STA-3/4 Discharge Canal, and PSTA Cell during WY2013 and WY2014, before and after the target stage increase from 10.0 ft NGVD29 to 10.5 ft NGVD29.

STATIC WATER LEVEL DATA

Figure 6A shows that daily average stages in the LSAV Cell were generally higher than daily average stages in the PSTA Cell from January 1, 2012, to April 2, 2013, while the groundwater elevations in the shallow and deep wells on the east levee fell between those stages. Groundwater elevations in the shallow wells showed a north to south horizontal gradient with elevations highest near the inflow structures of the PSTA Cell and lowest near the G-388 PSTA outflow pump station. This trend, however, was not observed in the deeper wells. During this period, G-388 was operated to maintain the PSTA Cell at the 10.0 ft NGVD29 target stage. The operation of the pump likely contributed to the southward hydraulic gradient at the shallower depth.

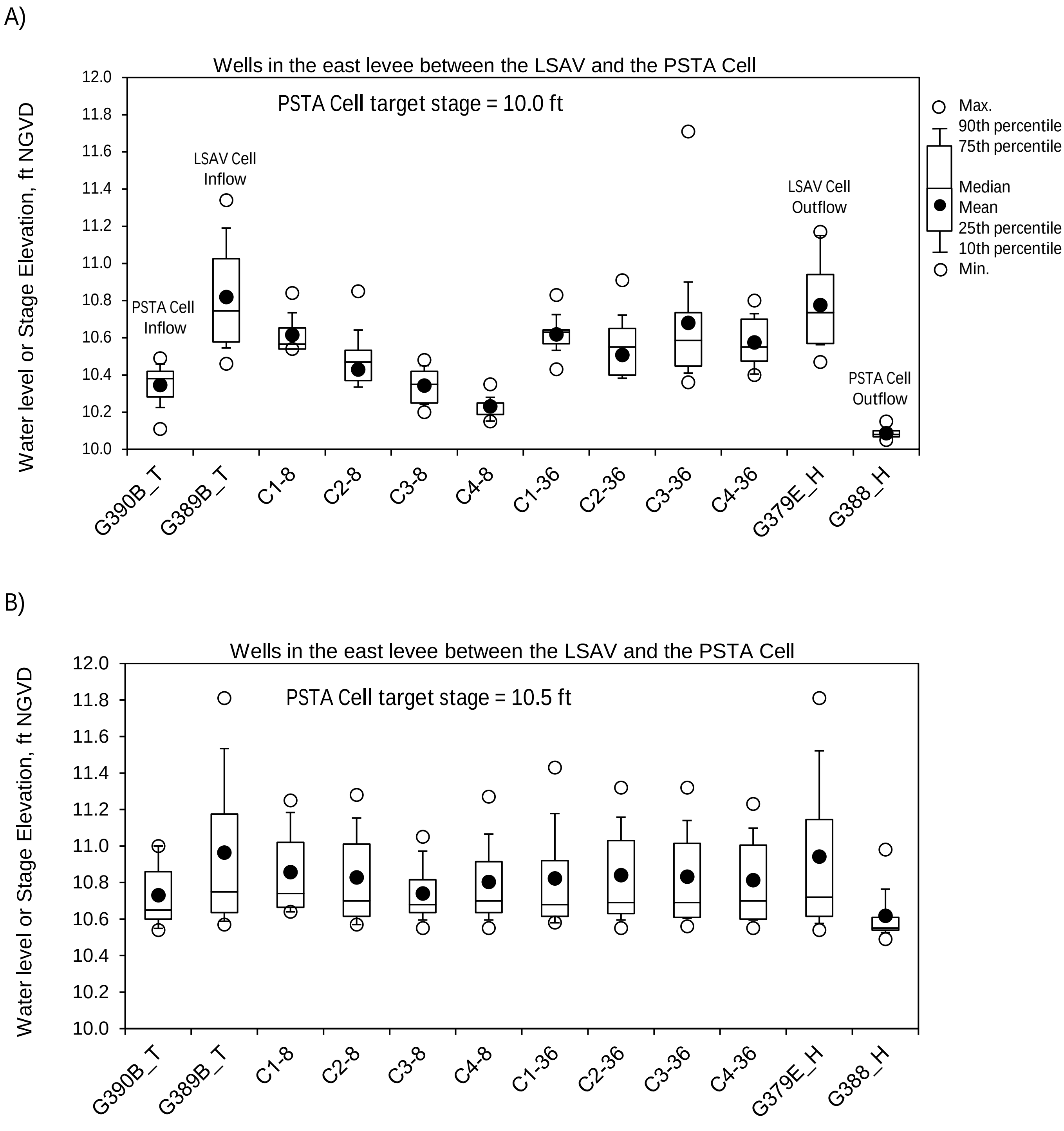


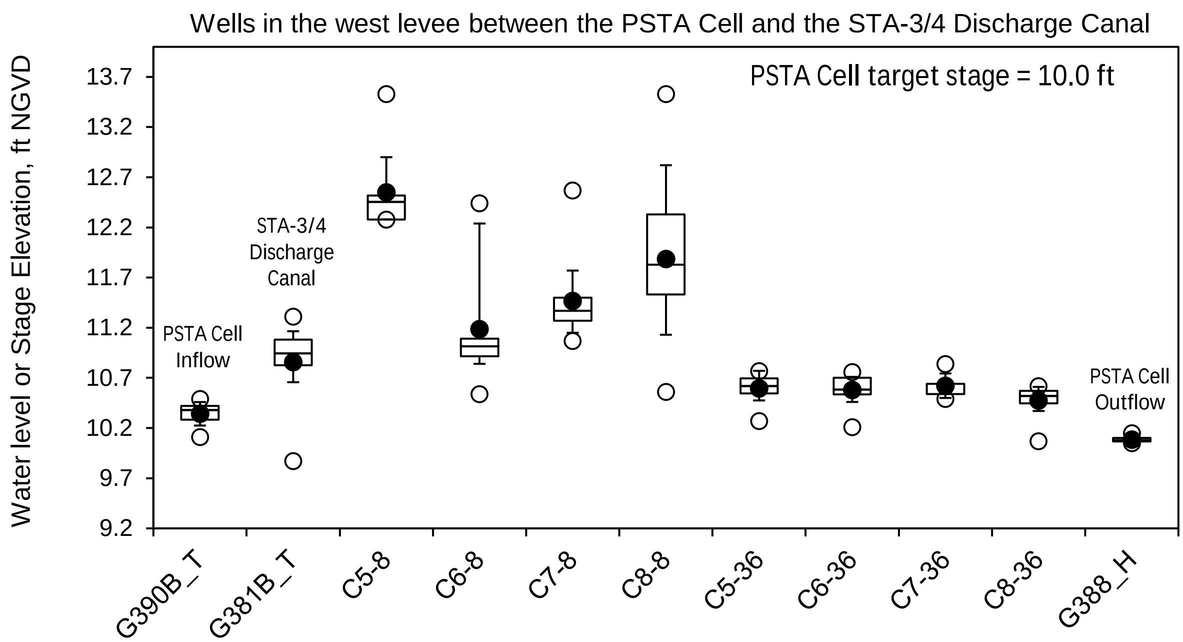
Figure 6. Comparison of groundwater elevations in the shallow (8-ft) and deep (36-ft) wells located in the levee between the LSAV and PSTA Cells prior to (A) and after (B) increasing the target stage.

When the target stage was increased to 10.5 ft NGVD29 after April 2, 2013, the groundwater elevations in both the shallow and deep wells and the stages in the PSTA and LSAV cells were almost equivalent (**Figure 6B**) and the gradient at the shallower depth disappeared. Therefore, in the period prior to April 2, 2013, when differences and rapid changes in water levels were more apparent between the shallow and deep wells and between the LSAV and PSTA cells, it is likely that there was greater lateral seepage of water into the PSTA Cell through the relatively permeable levee, and these differences were particularly evident in the shallow wells located closer to the G-388 outflow pump station.

In contrast to groundwater elevations in the wells in the east levee, groundwater elevations in the shallow wells in the west levee were consistently higher and more variable than daily average surface water stages in the PSTA Cell and the STA-3/4 Discharge Canal before (**Figure 7A**) and after (**Figure 7B**) the PSTA Cell target stage was raised. As explained earlier, these west levee wells are on average 1.8 ft higher in elevation than the east levee wells (**Table 1**) so that the bottom of the west levee shallow wells are above the daily average stage in the PSTA Cell and the STA-3/4 Discharge Canal, and consequently cannot capture seepage movement between the PSTA Cell and the STA-3/4 Discharge Canal. The water contained in these shallow wells likely came from rainwater and surface water runoff that slowly percolated through the highly compacted levee soil over time. Measurements obtained from the nearby EAA5 and S7_R rainfall sites suggest that, with some lag time, there was possible influence of rainfall on water levels in these shallow wells. In addition, the chemistry of the water samples collected from these shallow wells is similar to that of rainwater (see the *Water Quality* section).

Groundwater elevations measured in the deep wells in both the east and west levees were more stable over time and more in line with daily average stages observed in the LSAV Cell, PSTA Cell, and STA-3/4 Discharge Canal than groundwater elevations in the shallow wells (**Figures 6** and **7**). Changes in stages in the LSAV Cell and STA-3/4 Discharge Canal coincided with the wet and dry seasons. Similarly, groundwater elevations in the deep and shallow wells in both the east and west levees appeared to follow stage changes in the LSAV Cell and the STA-3/4 Discharge Canal with respect to seasonal changes. However, groundwater elevation changes in the shallow wells may have been primarily influenced by rainfall and surface runoff associated with the wet season, while those in the deeper wells could have been more influenced by upwelling during groundwater recharge.

A)



B)

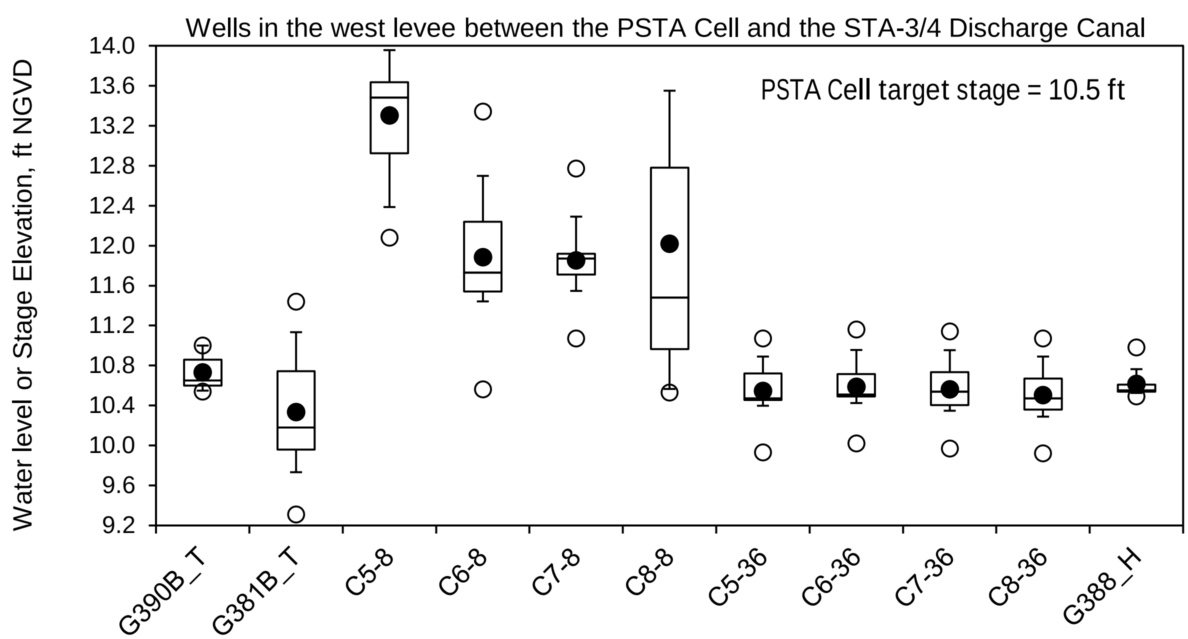


Figure 7. Comparison of groundwater elevations in the shallow (8-ft) and deep (36-ft) wells located in the levee between the STA-3/4 Discharge Canal and PSTA Cell prior to (A) and after (B) increasing the target stage. See **Figure 6** for a description of the box plots.

CONTINUOUS WATER LEVEL DATA

Hydrographs showing surface water stages for the Holey Land WMA (HOLEY), PSTA Cell (G388_H and G390_T), LSAV Cell (G389B_T), and STA-3/4 Discharge Canal (G381B_T) along with groundwater elevations in the PSTA Cell's east and west perimeter levee wells indicate a hydraulic connection between the groundwater and the surface water (**Figure 8**). Groundwater elevations in two shallow wells and one intermediate well in the east levee (C2-8', C3-8', and C3-36') responded to stage changes in the LSAV Cell at G389B (**Figure 8A**), while groundwater elevations in one intermediate and two deep wells in the west levee (C6-20', C6-36', and C8-36') responded primarily to stage changes in the STA-3/4 Discharge Canal at G381B (**Figure 8B**). The LSAV Cell discharge structure (G-379E) was maintained closed. This structure was purposely closed to focus flows from the USAV Cell to the PSTA Cell during the study period.

From August 24 to October 29, 2015, the TW stage at G-389B (inflow structure of the LSAV Cell) was consistently higher than the TW stage at G-390B (inflow structure of the PSTA Cell). This was likely due to the combined closure of the LSAV Cell discharge structure and the operation of the G-388 outflow pump station that lowered the stage in the PSTA Cell (**Figure 8A**). Greater variation in stage was observed in the STA-3/4 Discharge Canal. The stage in the STA-3/4 Discharge Canal measured at the TW of the G-381B outflow structure was typically lower than the G-390B TW stage in the PSTA Cell (**Figure 8B**) suggesting that surface water flow was predominantly westerly through the levee toward the STA-3/4 Discharge Canal. The estimated seepage into the PSTA Cell for this period was 261 ac-ft, which accounted for 11% of the total inflow (**Figure 9**).

Surface water stage and groundwater elevations (HOLEY2 and HOLEY2_G) in the southeastern region of the Holey Land WMA (approximately 2.5 miles west of the PSTA Cell) showed the same hydrologic trend from August 24 to October 29, 2015. Holey Land WMA surface water stage and groundwater elevations were also considerably higher than the stages in the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal, and higher than the groundwater elevations in the PSTA Cell's perimeter levee wells (**Figures 8A** and **B**). Having higher stages in the Holey Land WMA than those in the STA-3/4 Discharge Canal would suggest some eastward groundwater flow from the Holey Land WMA into the STA-3/4 Discharge Canal.

The differences between stages in the Holey Land WMA and those in the STA-3/4 Discharge Canal, LSAV Cell, and PSTA Cell, and the groundwater elevations in the PSTA Cell's perimeter levee wells indicate the presence of two potential hydraulic gradients. Daily average vertical head gradients between the Cluster 3 wells (C3) on the east levee were as low as -0.018 ft with the vertical gradient primarily in the downward direction (**Figure 10**). The downward gradient in C3 was greater during periods in which the TW stage at G-389B was higher. Daily average head differences in the C3 wells, in relation to changes in TW stages at G-389B and at G-390B, indicate that changes in stage at these structures greatly influenced the east levee wells. This suggests that the negative head difference or downward gradient in C3 was likely the result of water moving from the LSAV Cell into the PSTA Cell (**Figure 10**). In addition, operation of the G-388 outflow pump and possible drawing water from near the surface of the PSTA Cell may have promoted the vertical downward gradient at C3.

Unlike C3, the vertical gradient at the Cluster 6 wells (C6) on the west levee was consistently in the upward direction with daily average differences slightly greater than 0.01 ft (**Figure 10**). Data indicate that the small upward gradient at C6 is influenced by stage changes in the STA-3/4 Discharge Canal as a result of discharges from the STA-3/4 Cell 3B through G-381B (**Figure 10**). This suggests a possible interaction or mixing of groundwater with surface water beneath the STA-3/4 Discharge Canal. Overall, larger vertical head differences in C3 and C6 were observed during periods when stages were high at the inflow of the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal.

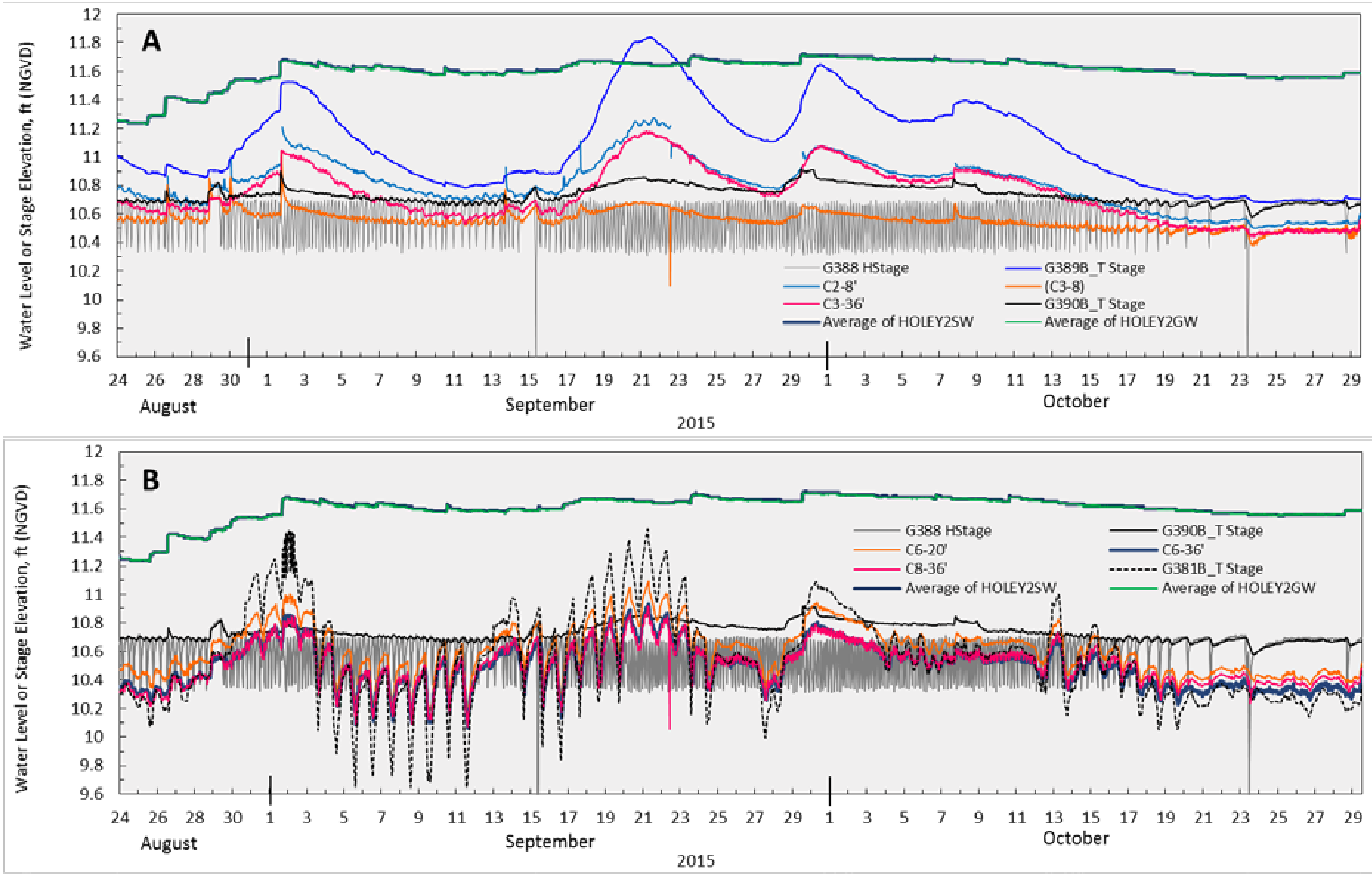


Figure 8. Hydrographs of surface water stages and groundwater elevations at 30-minute intervals for (A) the PSTA Cell, LSAV Cell, Holey Land WMA, and wells in the PSTA Cell's east levee, and (B) the PSTA Cell, STA-3/4 Discharge Canal, Holey Land WMA, and wells in the PSTA Cell's west levee from August 24 to October 29, 2015. (Note: HStage – headwater stage and TStage – tailwater stage.)

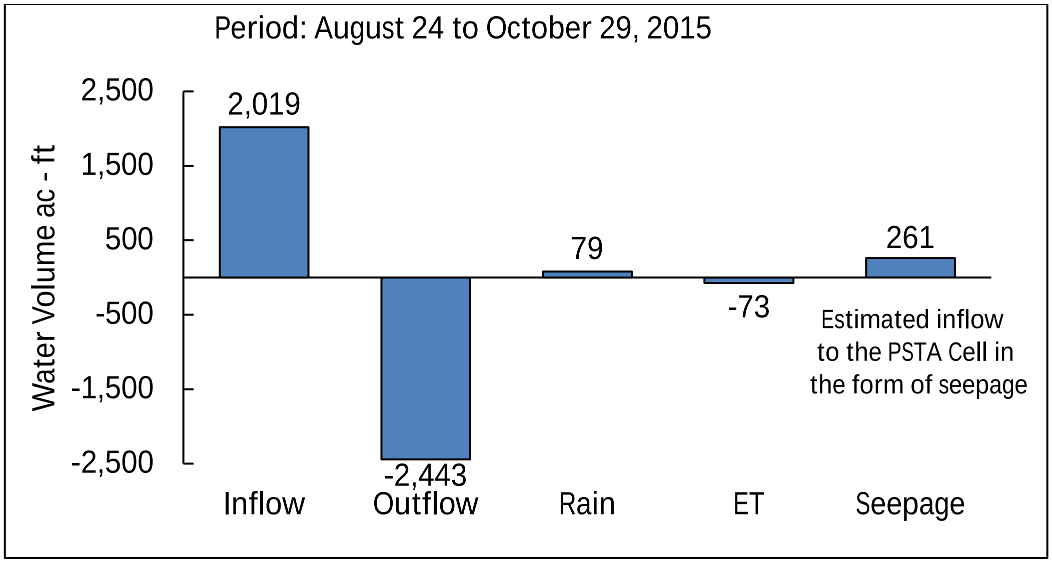


Figure 9. Water budget estimates for the PSTA Cell, including total volume of inflow, outflow, rainfall, ET, and seepage from August 24 to October 29, 2015.

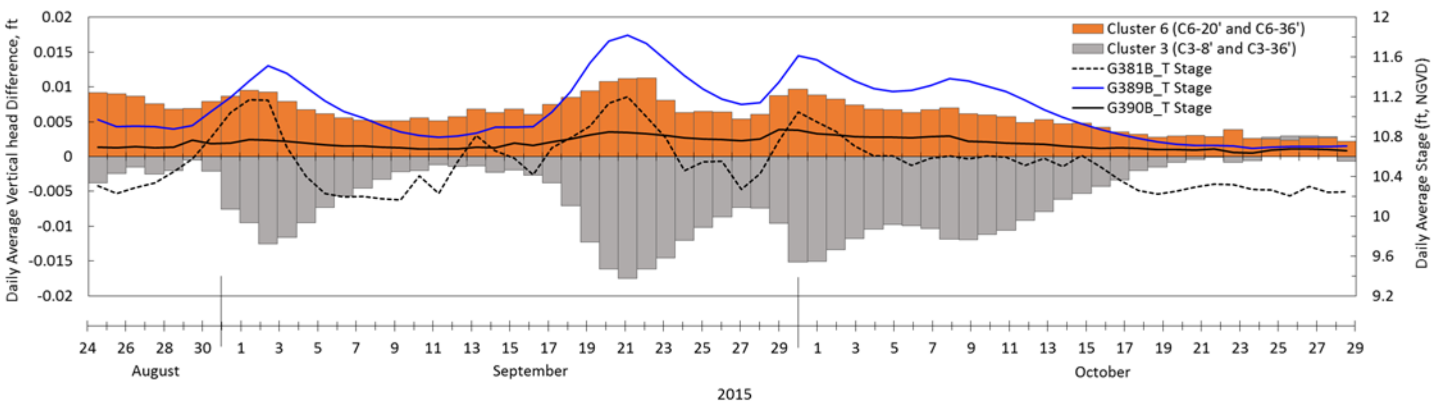


Figure 10. Daily average head differences in well clusters C3 (east levee) and C6 (west levee) in relation to the TW stage (T Stage) at G-389B (inflow to the LSAV Cell), TW stage at G-390B (inflow to the PSTA Cell), and TW stage at G-381B (outflow from STA-3/4 Cell 3B) into the STA-3/4 Discharge Canal. Positive and negative head differences indicate upward or downward hydraulic gradients, respectively.

Differences between the PSTA Cell inflow stage (G-390B TW) and the hydraulic head in the wells in the east and west levees varied with time and location. Differences among the wells located between the LSAV and the PSTA Cell suggest that seepage into the PSTA Cell likely occurred during periods when the LSAV Cell stage was higher than 11.0 ft NGVD29 (**Figure 11A**). Head differences between wells C2-8' and C3-36' and the PSTA Cell inflow stage suggests that the wells consistently responded to changes in stage in the LSAV Cell measured at G-389B TW. However, data suggest that water levels in the C3-8' well were influenced by factors other than the LSAV Cell stage based on head differences between the PSTA Cell and the C3-8' well, which may indicate influence from the G-388 pump drawing water and possibly greater seepage through the levee near C3 (**Figure 11A**).

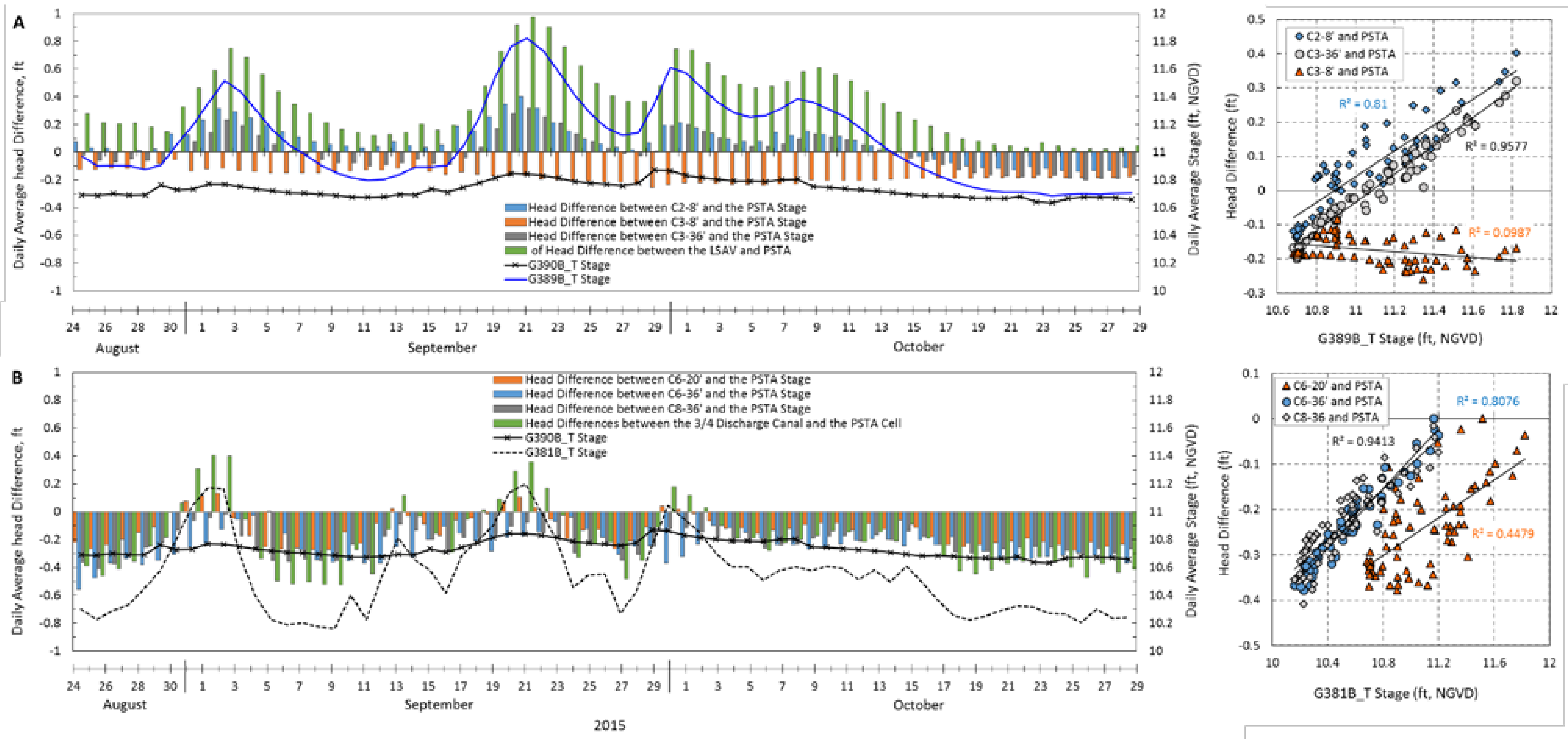


Figure 11. Daily average differences between stages in the PSTA Cell and the groundwater elevations in (A) the PSTA Cell's east levee wells (C2-8', C3-8', and C3-36') and (B) the PSTA Cell's west levee wells (C6-20', C6-36', and C8-36'). Negative head differences indicate that groundwater elevations in the wells were lower than the PSTA Cell stage, while positive head differences indicate that groundwater elevations in the wells were higher than the PSTA Cell stage. Scatterplots show the effect of stages in the LSAV Cell (G389_T) and STA-3/4 Discharge canal (G381B_T) on head differences between perimeter wells and the PSTA Cell.

Head differences in the west levee wells, and between the PSTA Cell and STA-3/4 Discharge Canal suggest that seepage water generally moved from the PSTA Cell into the STA-3/4 Discharge Canal, but seepage into the PSTA Cell also occurred during periods when the STA-3/4 Discharge Canal stage was greater than 11.0 ft NGVD29 (**Figure 11B**). Head differences between the C6-36' and C8-36' wells and the PSTA Cell suggest that these wells responded to changes in stage elevation in the STA-3/4 Discharge Canal measured at G-381B TW. However, differences in head between C6-20' and the PSTA Cell inflow stage suggests that in addition to the STA-3/4 Discharge Canal influence other factors may be contributing to higher stages at C6-20' especially during periods in which the canal stage appears the lowest (**Figure 11B**).

Horizontal head differences between the Holey Land WMA groundwater well (HOLEY2_G) and the west levee well C6-20' suggest a west to east hydraulic gradient. However, horizontal head differences between the C6-20' well and the STA-3/4 Discharge Canal suggest a hydraulic gradient in the opposite direction (east to west) from the PSTA and LSAV cells (**Table 5**). The estimated mean horizontal gradient was lower between wells west of the PSTA Cell (HOLEY2_G and C6-20') than between wells on both sides of the PSTA Cell (C6-20' and C2-8'), suggesting more localized seepage between the PSTA Cell and either the LSAV Cell or the STA-3/4 Discharge Canal than the PSTA Cell and Holey Land WMA (**Table 5**).

Table 5. Horizontal groundwater hydraulic gradients derived from head differences in wells surrounding the PSTA Cell from August 24 to October 29, 2015.

Western Well	Eastern Well	Head Difference (ft) [a]			Distance Between Wells (miles)	Mean Horizontal Water Level Gradient (vertical ft per linear ft)
		Mean	Minimum	Maximum		
HOLEYG2	C6-20'	0.99	0.55	1.46	2.50	7.6×10^{-5}
C6-20'	C2-8'	-0.14	-0.73	0.05	0.23	1.1×10^{-4}

a. Positive values indicate a west to east gradient; negative values indicate an east to west gradient.

Finally, the large hydraulic head difference between the Holey Land WMA and the wells between the PSTA and LSAV cells suggests a possible underflow component from the Holey Land WMA to the PSTA and LSAV cells that passes to and under the STA-3/4 Discharge Canal and comes up into the PSTA Cell. The mixing of waters from the Holey Land WMA and PSTA Cell may have an effect on the water quality but not as much on the water level. Further water quality sampling in the Holey Land WMA groundwater wells may help provide insight on the water quality beneath the Holey Land WMA and its potential influence on the PSTA Cell's water quality.

WATER BUDGETS

Seepage into and out of the PSTA Cell was estimated as part of annual water budgets that were developed for WY2008 through WY2014 using the District's web-based Water Budget Tool (Zhao et al. 2015). Over the first six years of operation, annual volumes at the G-388 outflow pump station were notably higher than inflow at the G-390A and G-390B structures (**Table 6**), and large annual seepage inflow volumes were attributed to head differences between the PSTA Cell and the adjacent water bodies. In April 2013, the PSTA Cell target stage was increased by 0.5 ft and the estimated net seepage (the difference between seepage in and seepage out) in the PSTA Cell for WY2014 (196 ac-ft) was substantially reduced compared to the previous years. Over the period of record, the annual net seepage, as a percentage of the total PSTA Cell inflow, ranged from 0.1% to 38.5%, with the lowest percentage observed in WY2014.

Table 6. Annual water budget summaries for the PSTA Cell from WY2008 to WY2014 in ac-ft (Zhao et al. 2015).

Water Year	Inflow Structures	Seepage In	Rain	Total Inflow	Outflow Pump	Seepage Out	ET	Total Outflow	Change in Storage	Remainder	Error %
WY2008	2,922 [a]	1,821	402	5,145	4,905	31	446	5,382	119	355	6.8
WY2009	3,298 [a]	2,108	448	5,854	6,405	2	458	6,864	-66	945	14.9
WY2010	7,020 [a]	2,339	504	9,864	10,080	17	448	10,545	-7	675	6.7
WY2011	3,289 [a]	885	340	4,515	3,965	124	464	4,554	-9	30	0.7
WY2012	7,452	2,122	431	10,005	9,848	29	453	10,331	-7	318	3.2
WY2013	9,322	2,436	516	12,275	11,219	12	450	11,681	32	-561	-4.6
WY2014	4,030	432	413	4,875	3,794	236	449	4,479	20	-376	-8
Total	**37,334**	**12,144**	**3,054**	**52,533**	**50,216**	**450**	**3169**	**53,835**	**82**	**1,385**	**2.7**

a. Flow data for the PSTA Cell inflow structures (G-390A & B) for the period from May 1, 2007 through December 31, 2010 were revised by the District. The revised flow estimates were considered to have remaining uncertainties associated with flow measurements at the structures that could not be resolved.

WATER QUALITY

Chloride

Ratios of Na and Cl were relatively constant from February 2012 to September 2015. A scatterplot of Na and Cl shows that most samples collected fall on or close to the line defined by sodium chloride (NaCl) (**Figure 12**). These values revealed a significant positive linear relationship between samples collected in the PSTA region from the groundwater wells, surrounding surface water, and rainwater from the L6 and L67A station. The average monthly concentration of NaCl in rainwater was low compared to the surface water and groundwater sites and not a significant source of Cl to the PSTA Cell or the shallow wells in the east and west levees. Instead, precipitation may have diluted the concentration of Cl in surface waters (**Figure 12**). Concentration differences among sampling locations were evaluated with the non-parametric Kruskal-Wallis rank-sum test ($\alpha = 0.05$). Cl concentrations were significantly different among the rainwater, the PSTA Cell surface water, and groundwater in both the deep and shallow wells located in the west levee of the PSTA Cell ($p < 0.05$). Cl concentrations in the shallow wells in the east levee and the PSTA Cell surface water were very similar suggesting a strong linkage between these hydrologic components. Cl concentrations in the deep wells in the east levee were substantially higher than those observed at any other sampling location (**Figure 13**).

Higher Cl concentrations in the east levee deep wells compared to lower Cl concentrations in the PSTA Cell suggest less interaction between the PSTA Cell surface water and the deep groundwater beneath the PSTA region. However, groundwater level data from the same deep wells show an upward hydraulic gradient coinciding with seasonal recharge of the aquifer, suggesting that some upwelling of groundwater to the PSTA Cell primarily occurs during the wet season. Cl concentrations in the west levee deep wells were slightly lower or similar to the PSTA Cell and STA-3/4 Discharge Canal surface water, suggesting interaction or mixing of surface and groundwater through the PSTA Cell's west levee. Similar interactions have been previously reported in canals adjacent to Everglades National Park where the main drivers for Cl fluctuations are surface and groundwater exchange and dilution by rainfall (Muñoz-Carpena et al. 2005).

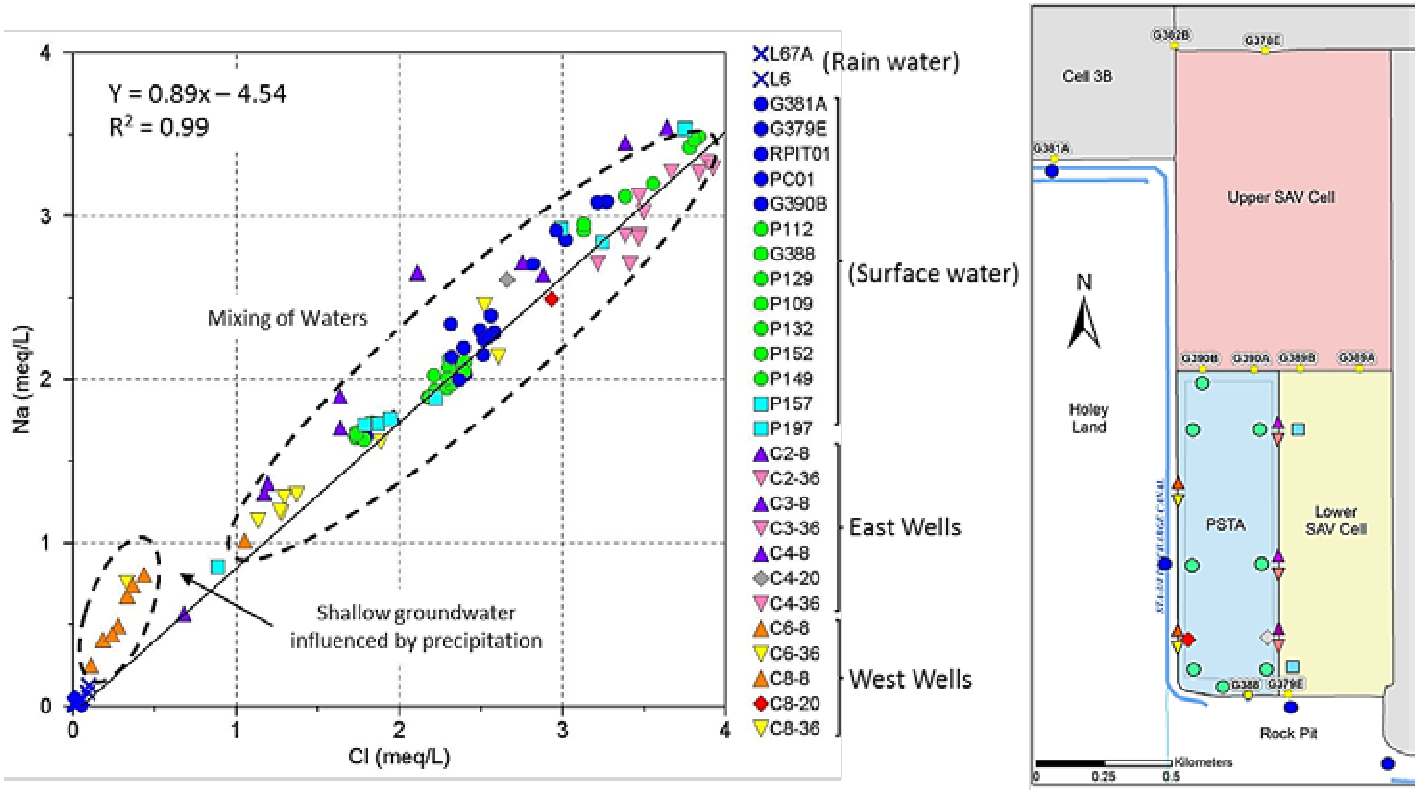


Figure 12. Scatterplot of Na and Cl concentrations in water quality samples in milliequivalents of solute per liter of solvent (meq/L) collected from surface water in the PSTA Cell, groundwater in the shallow (8-ft), intermediate (20-ft), and deep (36-ft) wells located along the PSTA Cell's east and west levees, and rainwater at stations L6 and L67A (see **Figure 2**).

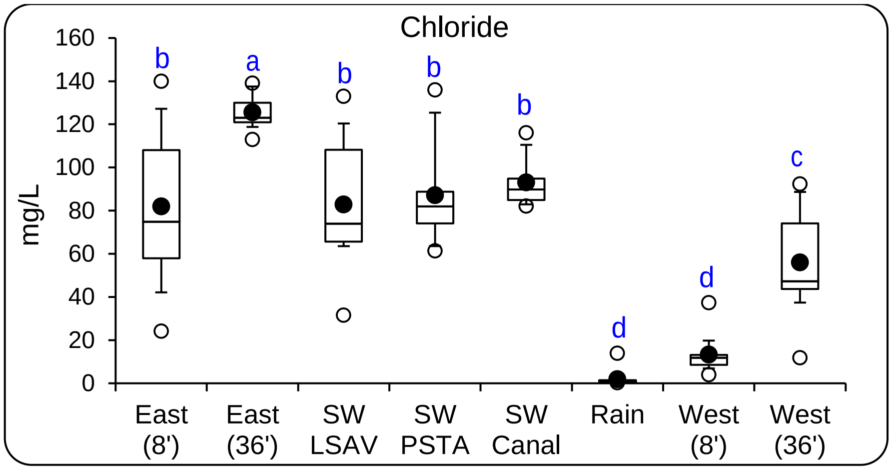


Figure 13. Comparison of Cl concentrations in rainwater, surface water in the LSAV and PSTA cells, and the STA-3/4 Discharge Canal, and groundwater from the shallow (8-ft) and deep (36-ft) wells in milligrams per liter (mg/L) along the PSTA Cell's east and west levees.
See **Figure 6** for a description of the box plots.
Box plots with the same letters are not significantly different ($p > 0.05$).

Unlike the deep wells, Cl concentrations in the west levee shallow wells were consistently low and similar to values observed in rainwater, which likely percolated into the wells through the semipermeable levee material (**Figure 13**). As previously discussed, because the bottom of the west levee shallow wells were higher in elevation than the average stages in the PSTA Cell and STA-3/4 Discharge Canal, no seepage or exchange between the two water bodies was captured that would affect Cl concentrations (**Figure 13**).

Overall, Cl concentrations indicated the interaction of surface water in the PSTA Cell with the LSAV Cell and the groundwater (based on deep well data) forming a transitional region beneath the ground surface. Data indicates greater interaction via seepage through the levee between the LSAV and PSTA cells with possible smaller contributions from groundwater upwelling during the wet season. In previous studies, Cl concentrations greater than 100 milligrams per liter (mg L^{-1}) have been considered as indicative of freshwater and groundwater interaction (Hittle 1999). Parker et al. (1955) and Harvey and McCormick (2009) found Cl concentrations ranging from 100 to 500 mg L^{-1} in shallow wells (21- to 55-ft depth) within the EAA. High Cl values in samples obtained in the surface water and groundwater associated with the PSTA and LSAV cells confirmed this possible interaction. In addition, mining activities in the EAA such as those that occurred in the rock pit south of the PSTA Cell prior to the construction of STA-3/4 have increased the interaction of groundwater and surface water (Naja et al. 2011). In general, the surface water and groundwater in the PSTA region are slightly lower than the EAA Cl levels. which averaged 182 mg L^{-1} in shallow wells and 1,011 mg L^{-1} in deeper wells (Naja et al. 2011) with the exception of the shallow and a few of the deep wells located in the west levee.

Calcium Bicarbonate, Specific Conductance, and pH

Concentrations of Ca and HCO_3^- had a positive linear relationship with concentrations of calcium bicarbonate [$Ca(HCO_3)_2$] gradually increasing from surface water to groundwater. Ca concentrations in all samples ranged from 25 to 260 mg L^{-1}, while bicarbonate (HCO_3^-) levels ranged from 93 to 959 mg L^{-1} (**Figure 14A**).

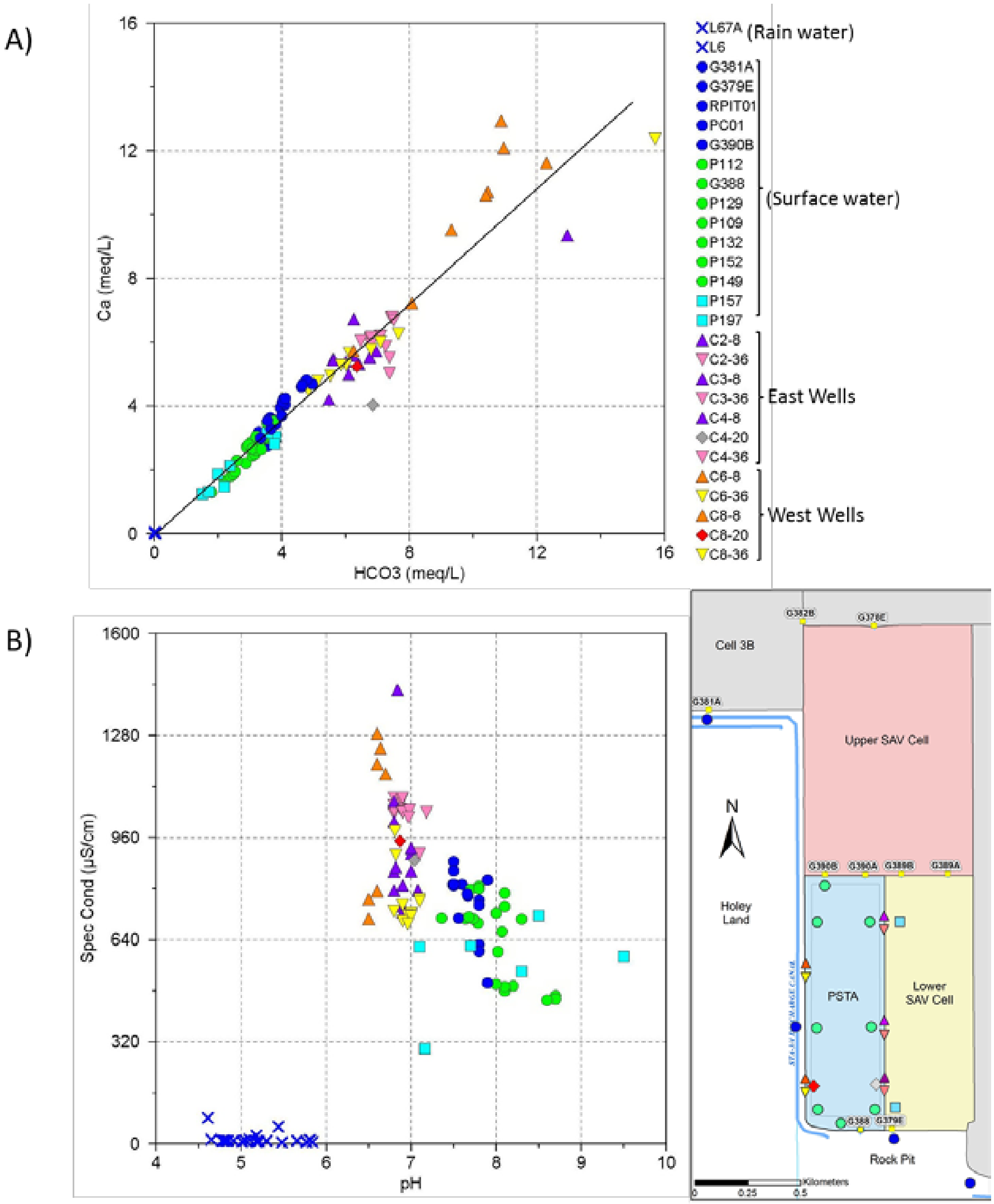


Figure 14. Scatterplots of (A) Ca and HCO_3 concentrations, and (B) specific conductance (Spec Cond) and pH in water quality samples collected from surface water in the PSTA Cell, groundwater in the shallow (8-ft), intermediate (20-ft), and deep (36-ft) wells along the PSTA Cell's east and west levees, and rainwater at stations L6 and L67A (see **Figure 2**).

Specific conductance in the perimeter levee wells and surface water ranged from 700 to 1,423 microsiemens per centimeter ($\mu S\ cm^{-1}$) and 298 to 885 $\mu S\ cm^{-1}$, respectively. Specific conductance in the surface water was consistently higher in the STA-3/4 Discharge Canal and the rock pit area located south of the PSTA Cell than the LSAV Cell and more comparable to the PSTA Cell. Rainwater pH at station L6 and L67A was consistently low, ranging from 4.6 to 5.8. The pH in the perimeter levee wells, the PSTA Cell, and other surrounding surface water ranged from 6.5 to 7.2 and 7.1 to 9.5, respectively, with consistently higher pH observed in the PSTA Cell (**Figure 14B**).

Ca concentrations were consistently higher in the shallow 8-ft wells in the west levee than in the other shallow and deep wells (**Figure 13**). Ca concentrations in all surface water were lower than concentrations in all the wells. However, significantly higher Ca concentrations observed in the water from the STA-3/4 Discharge Canal than in the PSTA and LSAV cells suggest that surface water in the canal could be influenced by groundwater upwelling (**Figure 15**).

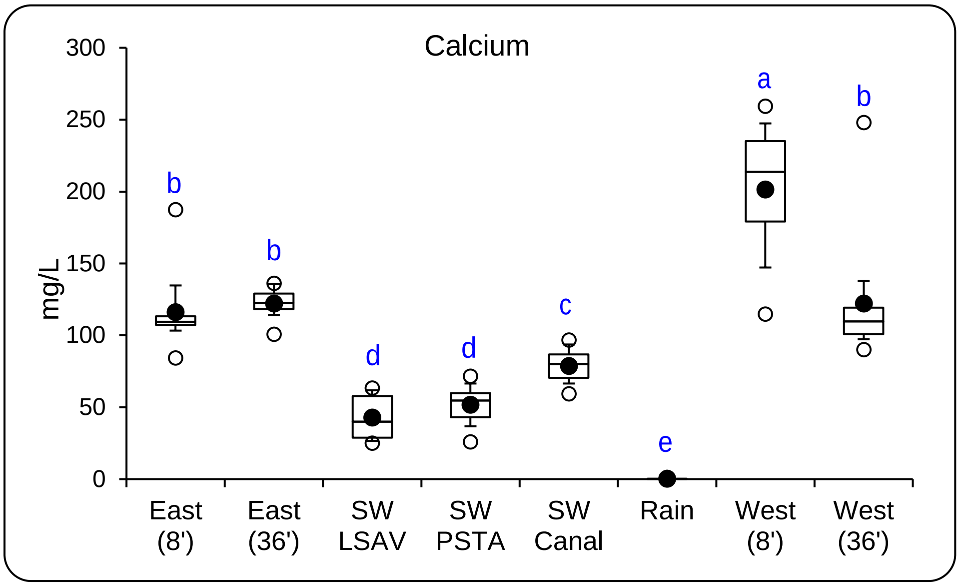


Figure 15. Comparison of Ca concentrations in rainwater, surface water in the LSAV and PSTA cells, and groundwater from shallow (8-ft) and deep (36-ft) wells along the PSTA Cell's east and west levees. See **Figure 6** for a description of the box plots. Box plots with the same letters are not significantly different ($p > 0.05$).

Overall, data suggests that the composition of surface water surrounding the PSTA Cell is highly influenced by the presence of calcium bicarbonate [$Ca(HCO_3)_2$], which is typical of Ca-enriched groundwater associated with the surficial aquifer located beneath the EAA (Harvey and McCormick 2009). Lower concentrations of $Ca(HCO_3)_2$ in the PSTA Cell surface water suggests higher precipitation of calcium carbonate ($CaCO_3$) within the PSTA region resulting from high consumption of carbon dioxide (CO_2) during photosynthetic activity and high pH conditions generated by the dense submerged aquatic vegetation (SAV) mats (Gleason 1972, Dierberg et al. 2002, Kadlec and Wallace 2009). Higher concentrations of carbonates found in the groundwater suggest higher dissolution of $CaCO_3$, which is the primary mineral in limestone. The dissolution process occurs as rainwater reacts with CO_2 to form carbonic acid, which comes into contact with the $CaCO_3$ in limestone resulting in the release of Ca^{2+} and HCO_3^- ions (Upchurch 1992).

Sulfate

SO_4 concentrations in surface water from the PSTA and LSAV cells ranged from 7 to 50 mg L^{-1}, while concentrations in the STA-3/4 Discharge Canal and the rock pit area located south of the PSTA Cell ranged from 44 to 60 mg L^{-1} (**Figure 16**). SO_4 concentrations in the shallow wells were markedly higher than in deep wells. However, SO_4 concentrations in most of the PSTA wells were considerably lower than concentrations observed in the EAA (Naja et al. 2011). SO_4 concentrations in deep wells were comparable to concentrations observed in rainwater. SO_4 concentrations in the west levee shallow wells displayed greater variability with consistently higher concentrations in C8, ranging from 86 to 188 mg L^{-1}, than all other shallow and deep wells (**Figures 16** and **17**).

High concentrations of SO_4 have been observed in farm canals (Bates et al. 2002) and in shallow wells beneath the EAA (Naja et al. 2011). Higher SO_4 found in the EAA may have resulted from the oxidation of naturally occurring sulfur in peat soils and the dissolution of fertilizer additives such as gypsum used in the EAA (Bates et al. 2002, Orem 2007, Harvey and McCormick 2009). SO_4 in groundwater can also result from the oxidation of pyrite (Naja et al. 2011). In addition, naturally present SO_4 in deep groundwater can potentially migrate to shallow aquifers and surface waters as a result of rock mining activities within the EAA (Naja et al. 2011). However, higher SO_4 concentrations in the west levee shallow wells may have resulted from the dissolution of localized minerals containing SO_4, which could have been included in the material used to construct the levees. Finally, since the bottoms of the shallow wells in the west levee were higher in elevation than the average stage in the STA-3/4 Discharge Canal and PSTA Cell, the west levee wells were not able to capture any seepage between the PSTA Cell and STA-3/4 Discharge Canal.

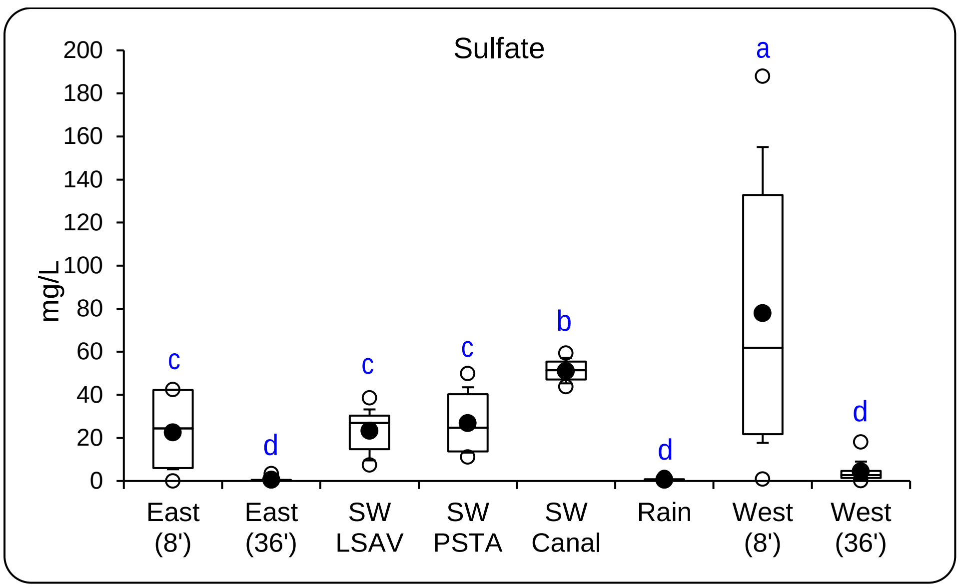


Figure 16. Comparison of SO_4 concentrations in rainwater, surface water in the LSAV and PSTA cells, and groundwater from shallow (8-ft) and deep (36-ft) wells along the PSTA's Cell east and west levees. See **Figure 6** for a description of the box plots. Box plots with the same letters are not significantly different ($p > 0.05$).

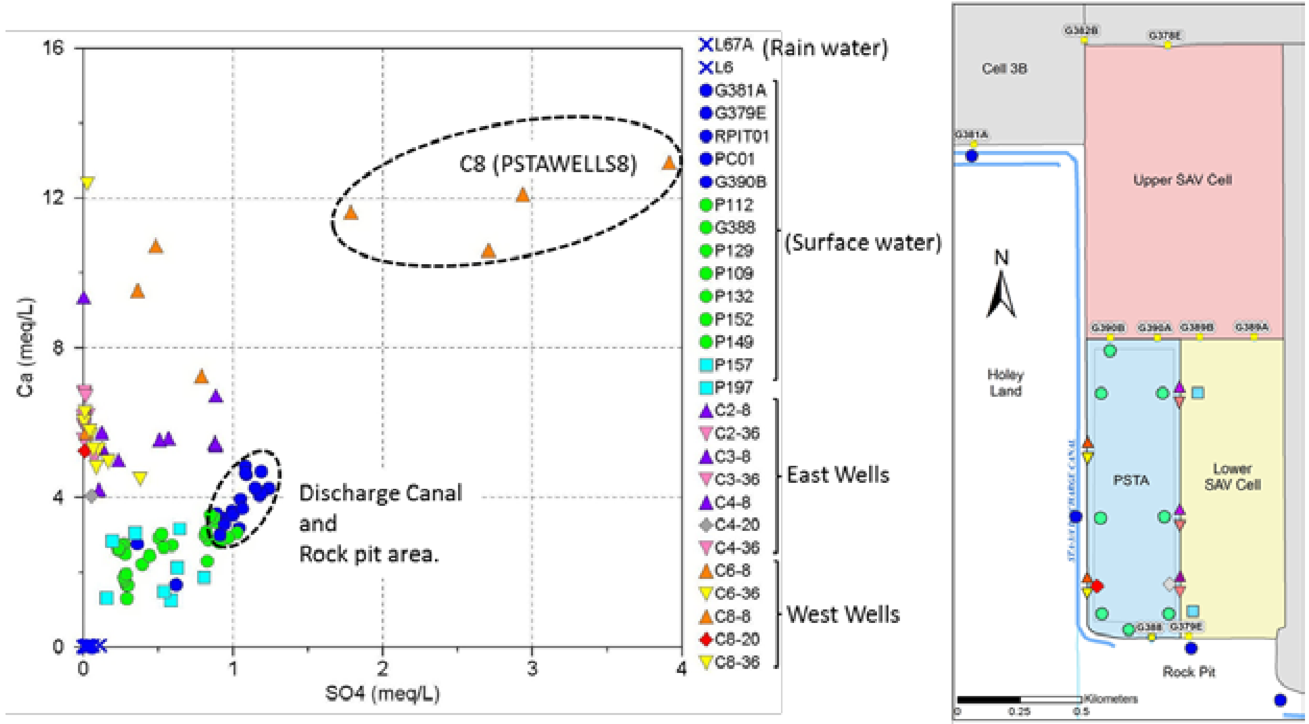


Figure 17. Scatterplot of Ca and SO_4 concentrations in water quality samples collected from surface water in the PSTA Cell, groundwater in the shallow (8-ft) and deep wells (36-ft) along the PSTA Cell's east and west levees, and rainwater at stations L67A and L6 (see **Figure 2**).

Phosphorus

From 2012 to 2015, surface-water TP concentrations in the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal ranged from 5 to 39 μg L^{-1} with slightly higher values at the G-390B structure and interior sites in the LSAV Cell. Concentrations of SRP in surface water consistently measured at the 2-micrograms per liter (μg L^{-1}) method detection level (**Figure 18**). TP in the shallow wells ranged from 10 to 393 μg L^{-1} while SRP ranged from 4 to 183 μg L^{-1}, with the highest concentrations for both parameters observed at the C6 location. TP concentrations in the deep wells were highest at the C3 location. The high TP value of 587 μg L^{-1} at the C3 deep well is believed to have resulted from contamination by resuspension of sediment at the bottom of the well while purging the well during sampling. SRP concentrations were consistently low in all deep wells in comparison to the shallow wells. Shallow wells had higher SRP concentrations than deeper wells with highest concentration in samples collected from C6 (**Figure 19**).

Surface water sampled inside the PSTA Cell and surrounding areas had higher concentrations of PP in comparison to DOP and SRP (**Figure 20**). Higher PP concentrations were observed at all three well depths at C4 and in the shallow well at C6 (**Figure 21**). Moderate PP concentration in the deep well at C3 accounted for the majority of P fraction in the well. The DOP concentration in most of the wells and surface water was below 5 μg L^{-1}. The higher PP levels in these wells could be an indication of sample contamination caused by poor recharge and purging during sampling events and/or soil erosion around the well casing near the screen.

As discussed in the *Static Water Levels in Wells* section, the shallow wells located in the west levee were not able to capture seepage between the PSTA Cell and STA-3/4 Discharge Canal through the levee. Therefore, the P concentrations observed in these wells cannot be included in the estimate for the P concentration in west levee seepage for the PSTA Cell P budgets. High TP concentrations were observed primarily in shallow wells in the east levee (**Figure 21**). Moderate to low TP concentrations were observed in most of the deep wells with the exception of the deep well in C3, which consistently exhibited high TP values.

Most of the TP concentrations in surface water were lower inside the PSTA Cell and STA-3/4 Discharge Canal than in the LSAV Cell and in groundwater sampled in the PSTA Cell perimeter levee wells especially in the shallow wells. As indicated in previous work (Muñoz-Carpena et al. 2005), P concentrations in shallow groundwater can be influenced by prior land use, accumulation of nutrients in the underlying soils, and vertical or lateral exchanges between surface water and groundwater. This could explain why TP concentrations were higher in the LSAV Cell and the east levee wells, considering that the nutrient-rich farm soil remained in the LSAV Cell and was used to construct the east levee.

Overall, TP concentrations were generally higher in the LSAV Cell surface water and the shallow (8-ft) wells in the levee between the LSAV and PSTA cells compared to generally lower TP concentrations in the PSTA Cell and the deep wells (36-ft). This suggests that the PSTA Cell's performance was impacted by TP enrichment from seepage water coming from the LSAV Cell. In contrast, TP concentrations in the STA-3/4 Discharge Canal surface water and the deep wells in the levee between the PSTA Cell and STA-3/4 Discharge Canal were comparable to TP concentrations in the PSTA Cell, suggesting no impact of seepage to the PSTA Cell from the STA-3/4 Discharge Canal.

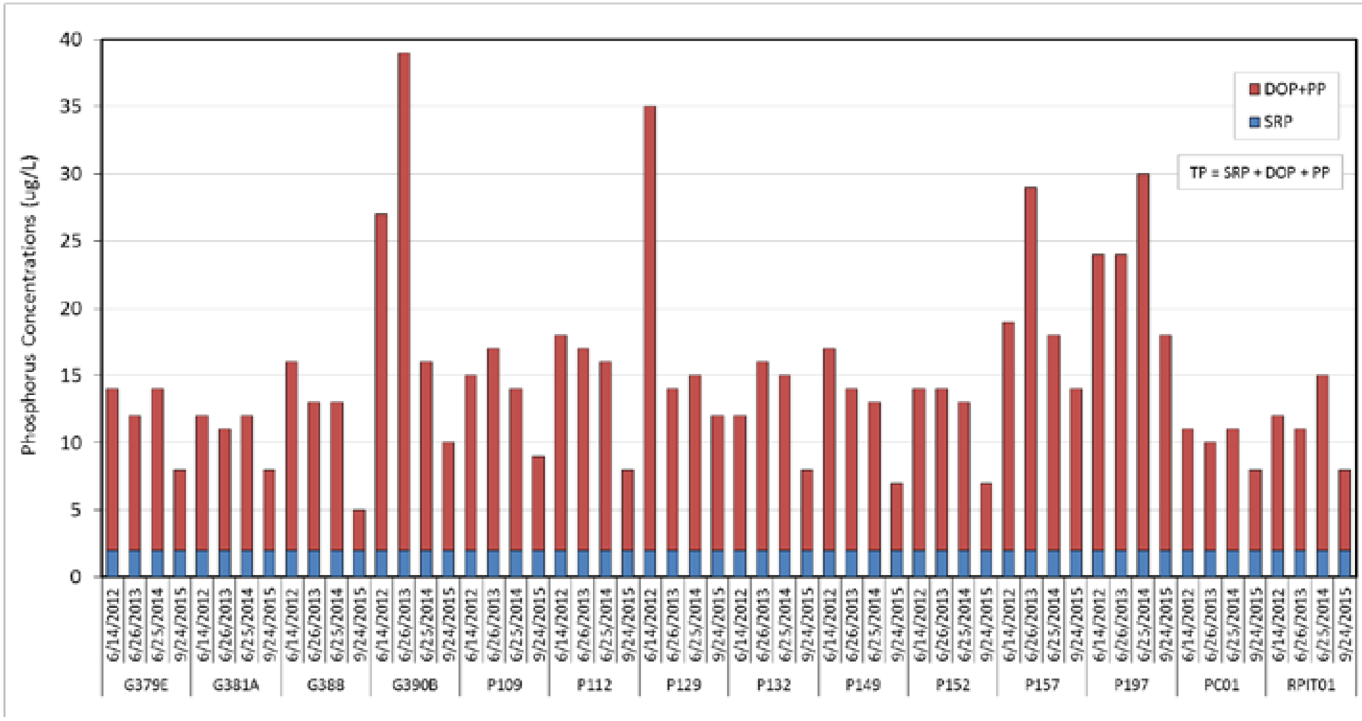


Figure 18. TP and SRP concentrations in surface water samples collected from sites within the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal.
(Note: µg/L – micrograms per liter.)

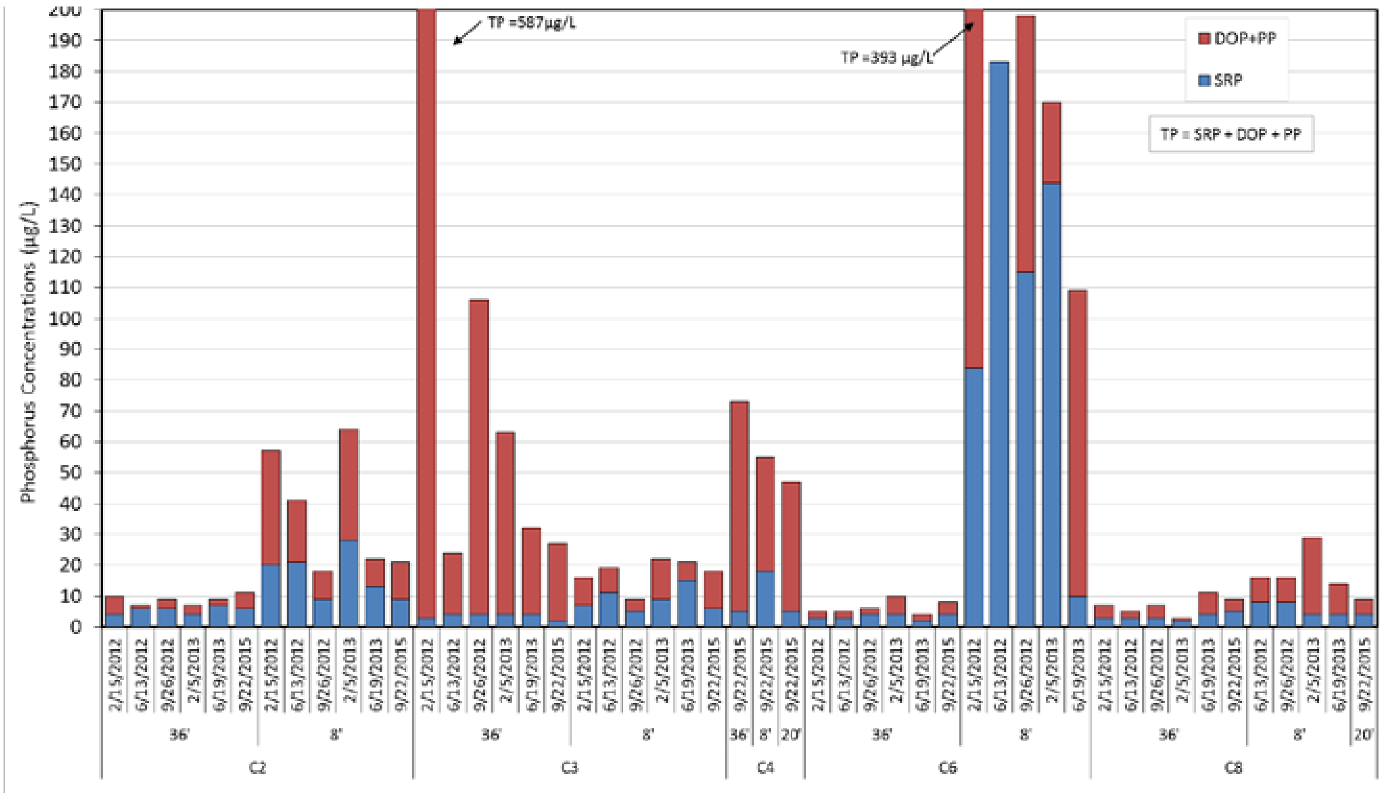


Figure 19. TP and SRP concentrations in groundwater samples collected from the shallow (8-ft) and deep (36-ft) PSTA Cell's levee wells. C2 and C3 are in the east levee between the LSAV Cell and PSTA Cell; C6 and C8 are in the west levee between the PSTA Cell and STA-3/4 Discharge Canal.

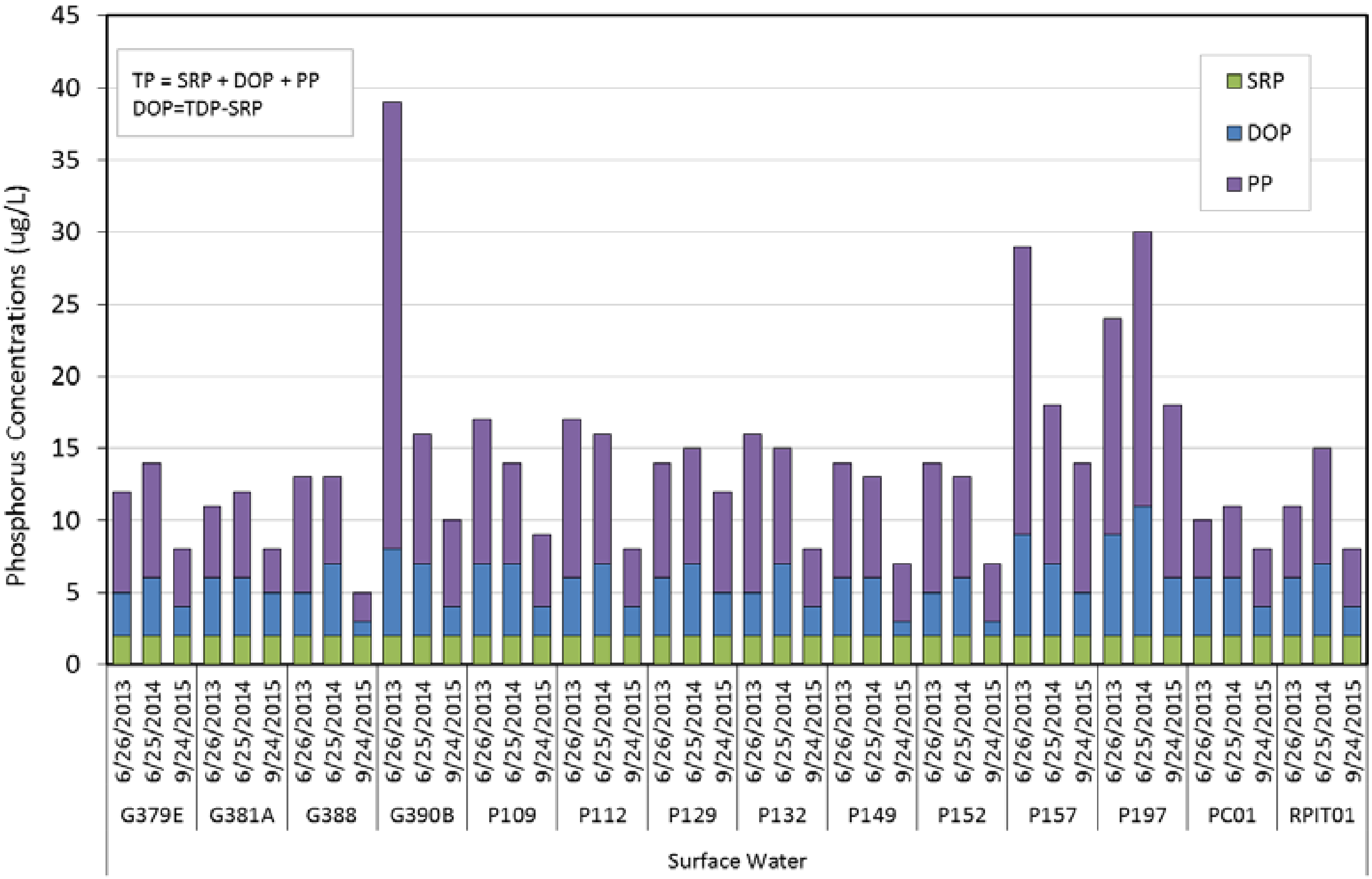


Figure 20. TDP and PP concentrations in surface water samples collected from sites within the PSTA Cell, LSAV Cell, and STA-3/4 Discharge Canal.

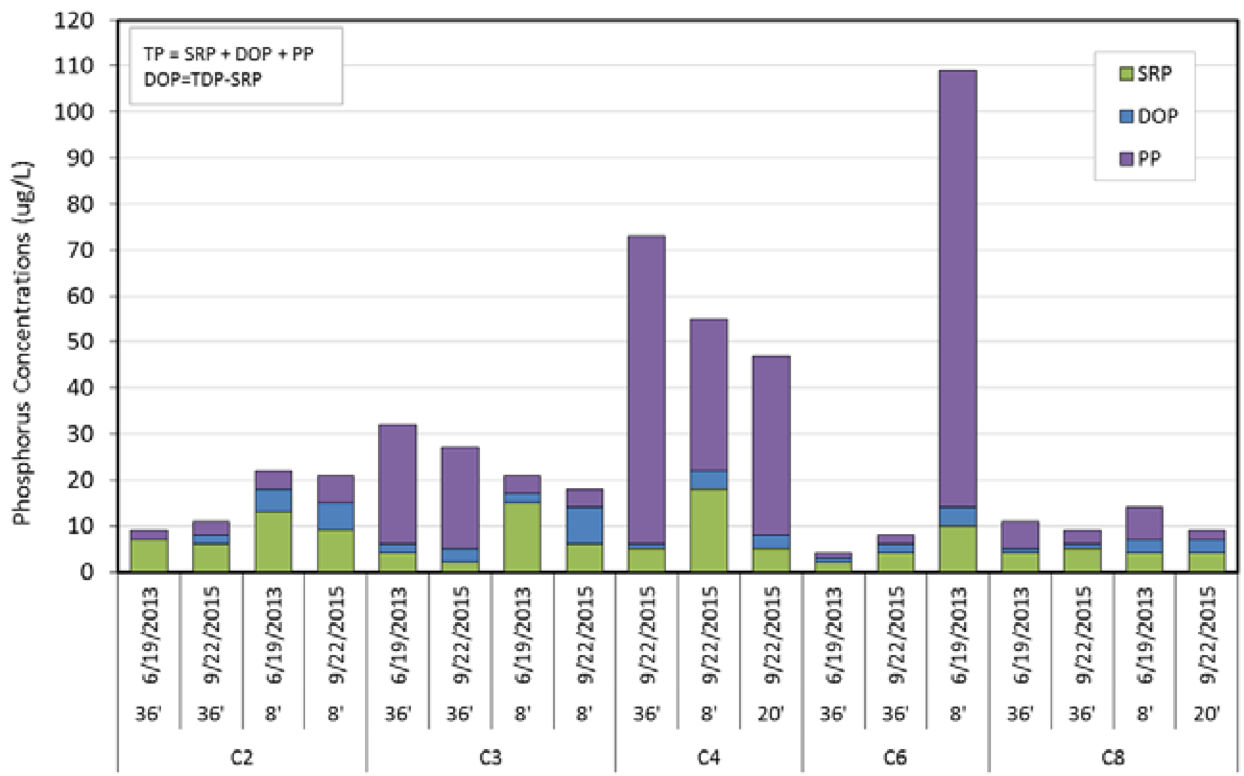


Figure 21. TDP and PP concentrations in groundwater samples collected from the shallow (8-ft) and deep (36-ft) PSTA Cell's levee wells. C2, C3, and C4, are in the east levee between the LSAV and PSTA cells; C6 and C8 are in the west levee between the PSTA Cell and STA-3/4 Discharge Canal.

Major Ions

Estimation of the major cation (K^+, Ca^{2+}, Mg^{2+}, and Na^+) to anion (Cl^-, SO_4^{2-}, and HCO_3^-) ratios in and around the PSTA Cell detected a slight deviation in three data points that were associated with samples from the shallow well at C8. The average anion to cation ratio for all samples collected was 1.04, which is a good indication of the electroneutrality in the water (**Figure 22**). Since the charge balance error for the three data points was only slightly greater than the target 5% error, these values were not considered to be outliers and were included in the analysis.

Analysis of major ions using a Piper diagram, to distinguish between surface water, shallow wells and deep wells, indicated two water types or water sources within the vicinity of the PSTA Cell based on Frazee's (1982) and Upchurch's (1992) classifications: freshwater recharge (FW-I and FW-II) or A1 primarily from rainfall and/or surface runoff in contact with sediments, sands, and limestone; and transitional water (TW-I) or more specifically F6 which is derived from mixed-fresh water recharge and older water, G1, derived from interactions with aquifer sediments and agricultural soil, and G6, which is highly influenced by magnesium and sulfate mixtures. The FW-I, FW-II, and TW-I water types were predominant in the wells while the TW-I water type appeared only in the surface water and in groundwater from selected wells (**Figure 23**).

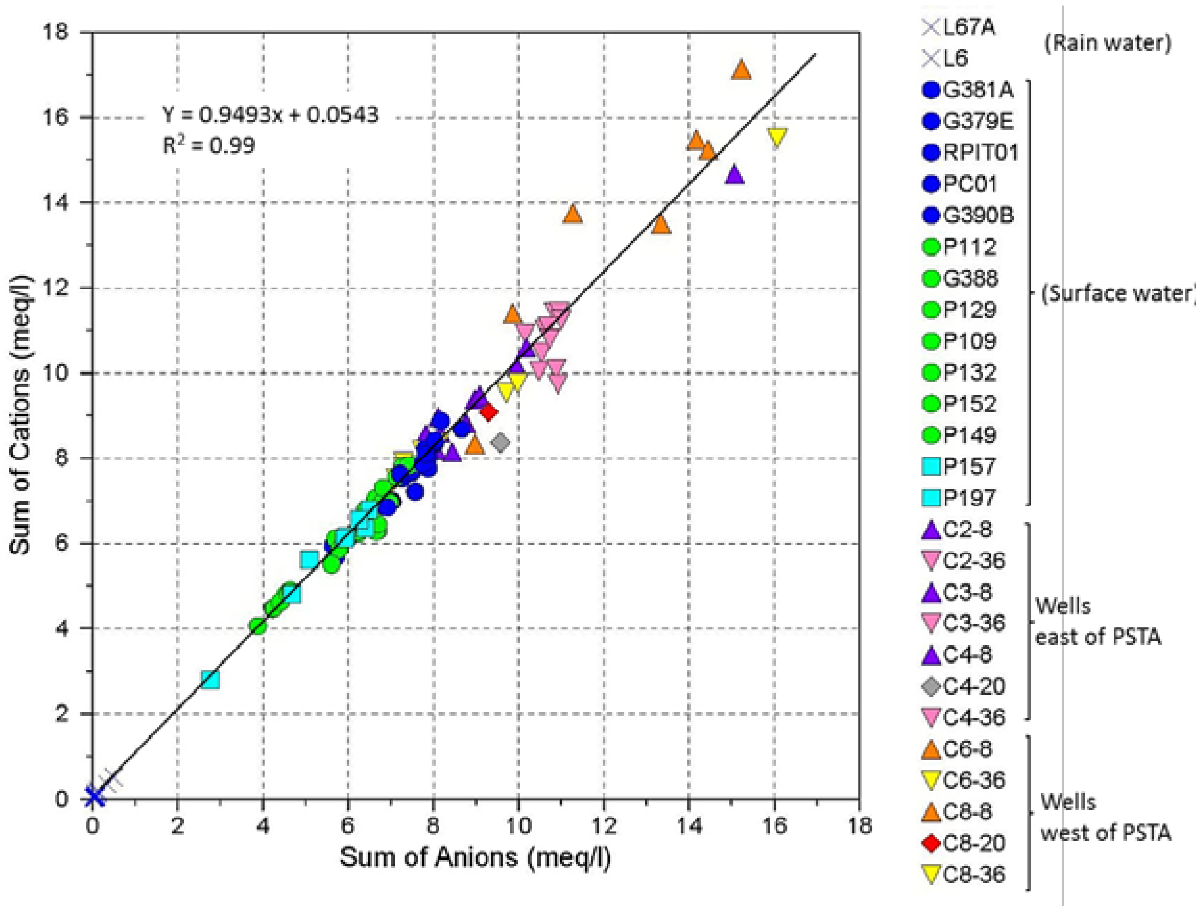


Figure 22. Scatterplots of cation and anion concentrations of rainwater, surface water collected from the PSTA Cell and water control structures, and groundwater from the wells along the PSTA Cell's perimeter levees.

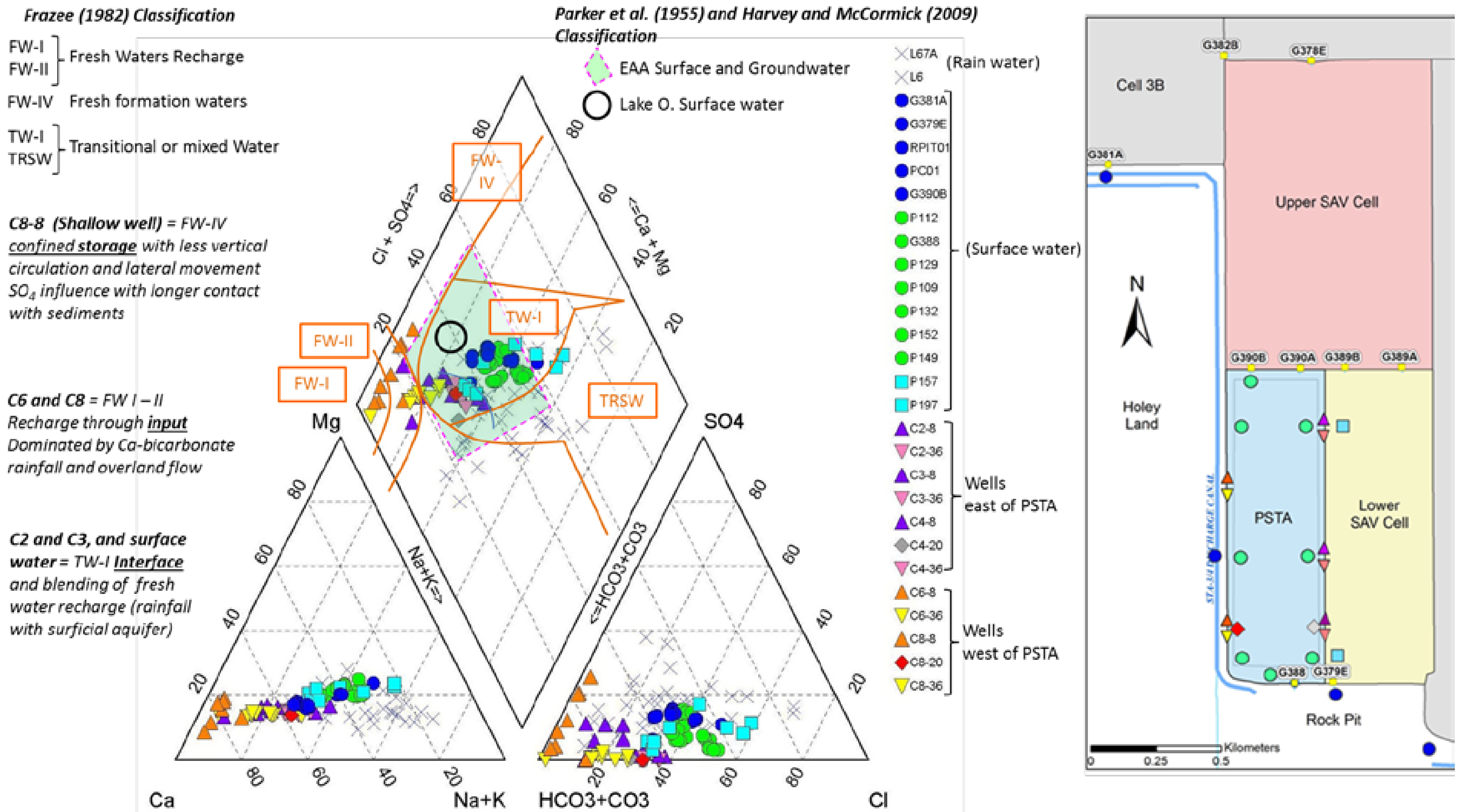


Figure 23. Piper diagram showing the chemical composition of rainwater, surface water, and groundwater collected from specific locations in the vicinity of the PSTA Cell indicating the areas of freshwater recharge (FW-I and FW-II), transitional or mixed water (TW-I) and freshwater confinement (FW-IV).

Most of the data for water in the east levee's deep and shallow wells and all the data for surface water within and surrounding the PSTA Cell indicates transitional water (TW-I), which is in part influenced by a mixture of runoff, rainwater, Lake Okeechobee water, and EAA groundwater (Harvey and McCormick 2009). However, data for water collected from the east levee's shallow wells during the dry season indicates water type FW-II. Water in the west levee's deep and shallow wells was primarily fresh water recharge (FW-I and FW-II). This fresh water recharge is primarily derived from rainwater recharge to the aquifer and overland flow, and is characterized by higher $Ca(HCO_3)_2$ content resulting from the dissolution of limestone rock (Harvey et al. 2002). In addition, a few samples from the west levee's deep wells appeared as transitional water (TW-I), likely as a direct result of water exchange between groundwater and the STA-3/4 Discharge canal water through the west levee (**Figure 23**).

Unlike other west levee wells, samples collected from the shallow well at C8 consistently showed characteristics associated with fresh water type IV (FW-IV) or B2. According to Frazee (1982), FW-IV type water is derived from older forms of water types FW-II or FW-III. Upchurch (1992) further describes B2 type of water as fresh-formation water that is influenced by Ca, HCO_3, Mg, and SO_4 ion composition resulting from longer contact with soils and aquifer sediments.

However, higher SO_4 in the west levee shallow wells may have resulted from the dissolution of localized minerals containing SO_4, which could have been included in the rock material used to construct the levees. Furthermore, SO_4 can result from the oxidation of naturally occurring sulfur in peat soils also used to construct the levee, the dissolution of fertilizer additives such as gypsum used in the EAA (Orem 2007, Harvey and McCormick 2009), and the oxidation of pyrite (Naja et al. 2011). In addition, the possible low permeability of the west levee, which can result in well confinement, could potentially trap rainwater in the wells for extended periods increasing the contact time between the soils and the water thus allowing for more dissolution and oxidation of minerals containing SO_4.

Overall, uncertainty associated with sample results from the west levee shallow wells indicated that these data could not be used to confirm or rule out groundwater interaction between the PSTA Cell and STA-3/4 Discharge Canal. Water sample data indicated that the ion distribution of the PSTA Cell and surrounding surface water, and water in the PSTA Cell perimeter wells was primarily within the EAA classification in accordance to the classification of South Florida waters by Frazee (1982), the classification of Lake Okeechobee surface water and the EAA surface water and groundwater by Parker et al. (1955) and Harvey and McCormick (2009). Major ions in the east levee shallow wells indicated the mixing of waters from both cells through the levee. Deep wells in the east levee showed the mixing of surface water and groundwater beneath the PSTA Cell while the west levee deep wells captured the direct exchange between groundwater and canal water (**Figure 23**).

SUMMARY AND CONCLUSIONS

The objective of this analysis was to evaluate the influence of seepage on the P removal performance of the STA-3/4 PSTA Cell. This report summarizes results from activities that have been under way to estimate the quantity, quality, and sources of seepage coming into and leaving the PSTA Cell.

The PSTA Cell's construction included the removal of most of the soil down to the caprock. Approximately 1 to 2 ft of the previously farmed soil was removed in an effort to reduce the possible diffusion of P from soils back to the water column and discourage the establishment of emergent macrophytes. As a consequence of soil removal, the floor of the PSTA Cell is approximately 1 ft lower than the ground elevations of the adjacent cells. The average caprock elevation in the cell is 8.8 ft NGVD29.

Since its inception, shallow water depths were maintained in the PSTA Cell to promote an SAV-periphyton based community. The PSTA Cell's lower stage resulted in considerable head differences between the PSTA Cell and the adjacent water bodies. However, because the G-388 outflow pump station was continuously operating to maintain the stage even though there was little or no surface water inflow through the G-390A and B structures, it was thought that water was moving into the PSTA Cell primarily by way of lateral seepage through the perimeter levees from adjacent water bodies and from vertical seepage (groundwater upwelling) through the caprock. In an attempt to reduce the head differences between the PSTA Cell and adjacent water bodies, and the amount of seepage entering the PSTA Cell, the PSTA target stage was increased 0.5 ft (i.e., from 10.0 to 10.5 ft NGVD29) at the end of WY2013. While this resulted in a reduction of the head differences between the PSTA Cell and adjacent water bodies and reduced seepage into the cell, the PSTA Cell stages remained generally lower than surrounding stages.

Data suggests that lateral seepage, primarily from the LSAV cell, contributed more water to the PSTA Cell than groundwater upwelling, which was more likely to occur during the wet seasons. Seepage from the LSAV Cell into the PSTA Cell was greater during periods when the LSAV Cell stage was higher than 11.0 ft NGVD29. Likewise, seepage into the PSTA Cell from the STA-3/4 Discharge Canal occurred during periods when its stage was greater than 11.0 ft NGVD29. On the other hand, during periods when the canal stage was lower than the PSTA Cell stage, seepage was in the opposite direction.

Differences between water levels in the Holey Land WMA (surface water and groundwater), the stages in the STA-3/4 Discharge Canal, PSTA Cell, and LSAV Cell; and the groundwater elevations in the perimeter levee wells indicated possible vertical and horizontal hydraulic gradients. The groundwater levels in the east levee wells showed a vertical gradient in the downward direction, which promoted lateral seepage into the PSTA Cell, while those in the west levee deep wells showed a very small vertical gradient in the upward direction. The horizontal head differences between the Holey Land WMA groundwater well (HOLEY2_G) and wells in the PSTA Cell levees indicate a regional west to east gradient. However, horizontal head differences between the LSAV Cell, the PSTA Cell perimeter levee wells, and the STA-3/4 Discharge Canal indicate a more localized seepage gradient in the opposite direction (east to west). Other factors such as the operation of the G-388 outflow pump station, and breaks in the aquifer confinement layers in the STA-3/4 Discharge Canal and the rock pit area could be contributing factors to the direction of seepage but would require further investigation to assess their importance.

The overall ionic composition of surface water and groundwater within and surrounding the PSTA Cell is typical of the EAA geochemical composition. Both surface water and groundwater within the vicinity of the PSTA Cell are primarily characterized by differences in the concentration of $Ca(HCO_3)_2$. Lower concentrations of $Ca(HCO_3)_2$ in the surface water suggest higher precipitation of $CaCO_3$ in the PSTA and LSAV cells as a result of high photosynthetic activity and high pH conditions generated by the dense SAV mats and associated periphyton. Higher concentrations of carbonates in the groundwater suggest the dissolution of $CaCO_3$, which is the primary mineral in limestone. While differences in $Ca(HCO_3)_2$ between the surface water and the groundwater suggest different water types, data indicate there is continuous interaction between the two forming a mixing zone of transitional water (TW-I). This is also confirmed by Cl concentrations and the presence of the mixed bicarbonate-chloride in the PSTA and LSAV cells' surface water and groundwater in the shallow and deep wells, which also indicates the mixing of waters beneath the ground forming a transitional region for mixing or transitional water (TW-I).

Furthermore, geochemical characteristics in the surface water within the LSAV and PSTA cells indicated that the two water bodies appeared to intersect in the shallow and deep wells in the levee between the LSAV and PSTA cells confirming the downward gradient observed in the continuous water level data. Characteristics of the surface water in the STA-3/4 Discharge Canal also indicate that it is transitional water, which result from a mixture of surface water runoff and the groundwater beneath the PSTA Cell. However, continuous water level data from wells in the levee between the PSTA Cell and the Discharge Canal show an upward gradient possibly driven by groundwater beneath the STA-3/4 Discharge Canal.

Findings regarding seepage into and out of the PSTA Cell, and TP concentrations in the STA-3/4 Discharge Canal, LSAV Cell, and PSTA Cell, suggest that TP concentrations within the PSTA Cell water column are impacted by TP enrichment from seepage water from the LSAV Cell. In contrast, data suggest that the STA-3/4 Discharge Canal surface water has no impact on the PSTA Cell surface water TP concentrations.

Finally, because of the apparent mixing of groundwater and surface water in the EAA including the PSTA Cell (especially during aquifer discharge and recharge associated with dry and wet seasons), uncertainties remain as to the magnitude of seepage influence from the LSAV Cell versus the groundwater upwelling. However, because the total estimated seepage into the PSTA Cell was only about 10% of the cell's overall water budget, and since the data suggest that most of the seepage into the cell is from the LSAV Cell, the effect of groundwater upwelling on the PSTA Cell's performance is likely negligible.

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APPENDIX A: HYDROGEOLOGIC CROSS-SECTION PROFILES

This appendix contains hydrogeologic cross-section profiles for the profiles and well clusters for which the location is shown in **Figure A-1**. **Figures A-2** through **A-5** present the profiles.

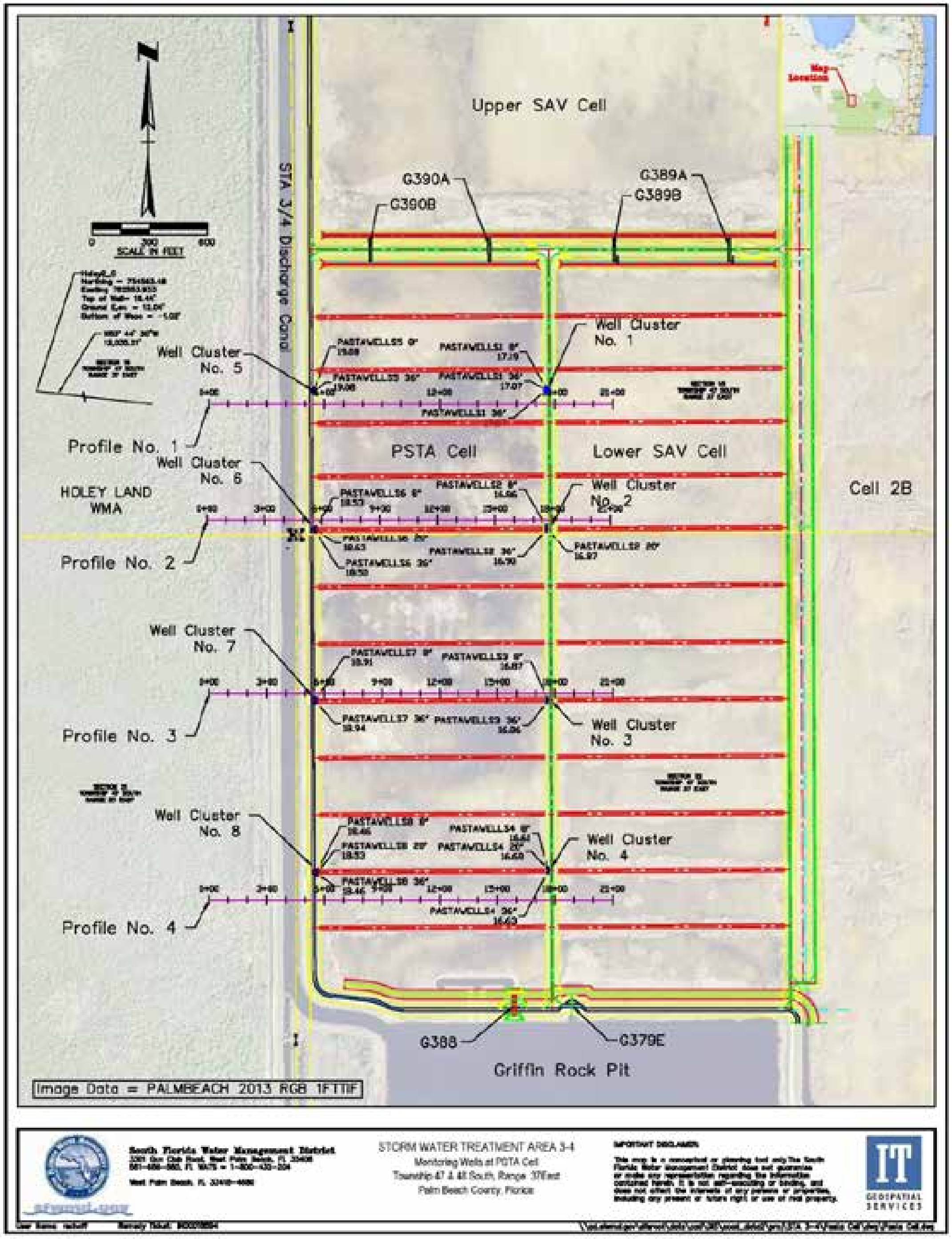

Figure A-1. Map of the STA-3/4 PSTA Project showing the Holey Land WMA, STA-3/4 Discharge Canal, PSTA Cell, USAV Cell, LSAV Cell, related water control structures, monitor well clusters (C1-C8); and locations of west to east hydrogeologic cross-section profiles (1-4) across the PSTA Cell.

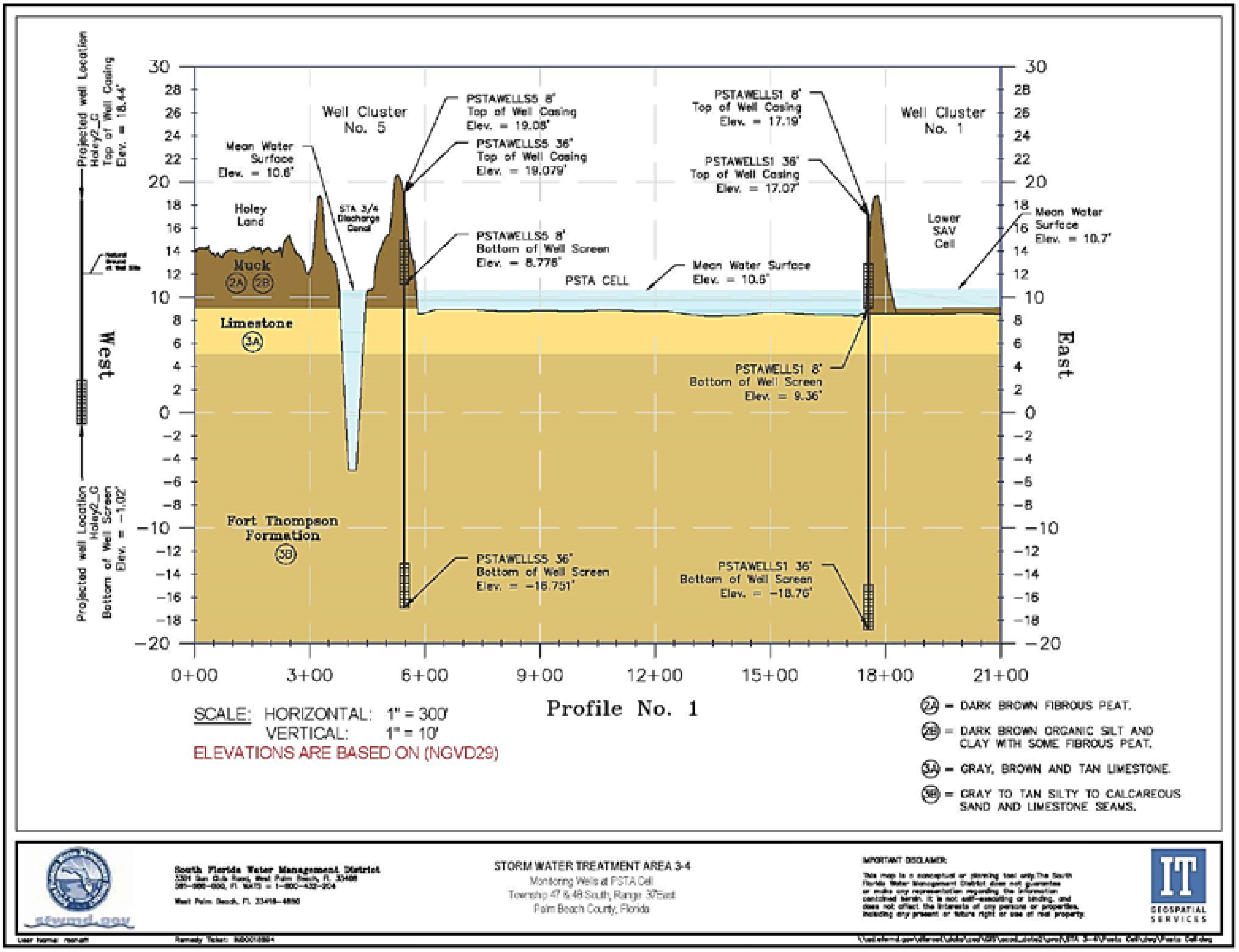

Figure A-2. West to east hydrogeologic cross-section profile through monitor well clusters C5 and C1 illustrating surficial aquifer formations underlying the Holey Land WMA, STA-3/4 Discharge Canal, PSTA Cell, and LSTA Cell.

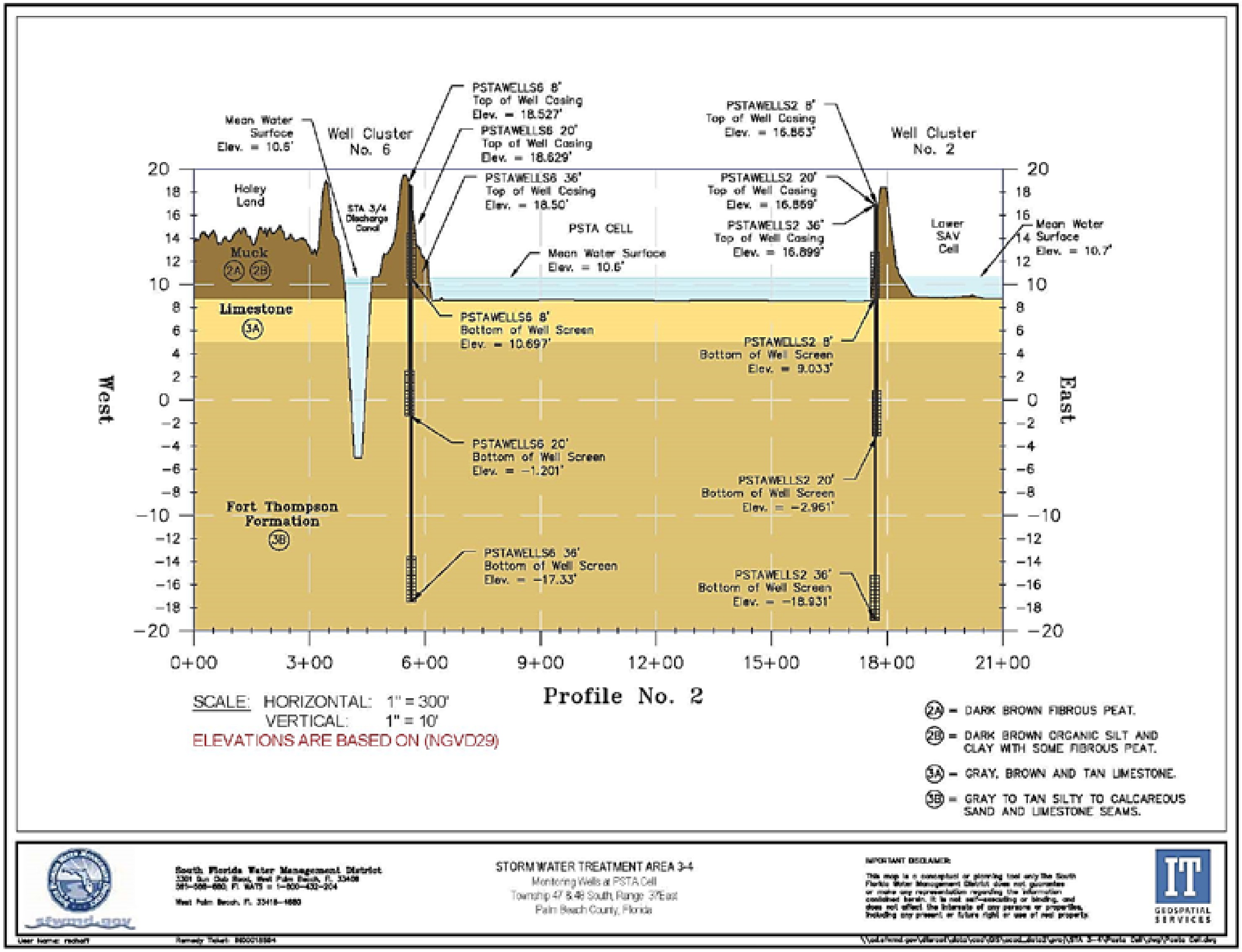

Figure A-3. West to east hydrogeologic cross-section profile through monitor well clusters C6 and C2 illustrating surficial aquifer formations underlying the Holey Land WMA, STA-3/4 Discharge Canal, PSTA Cell, and LSAV Cell.

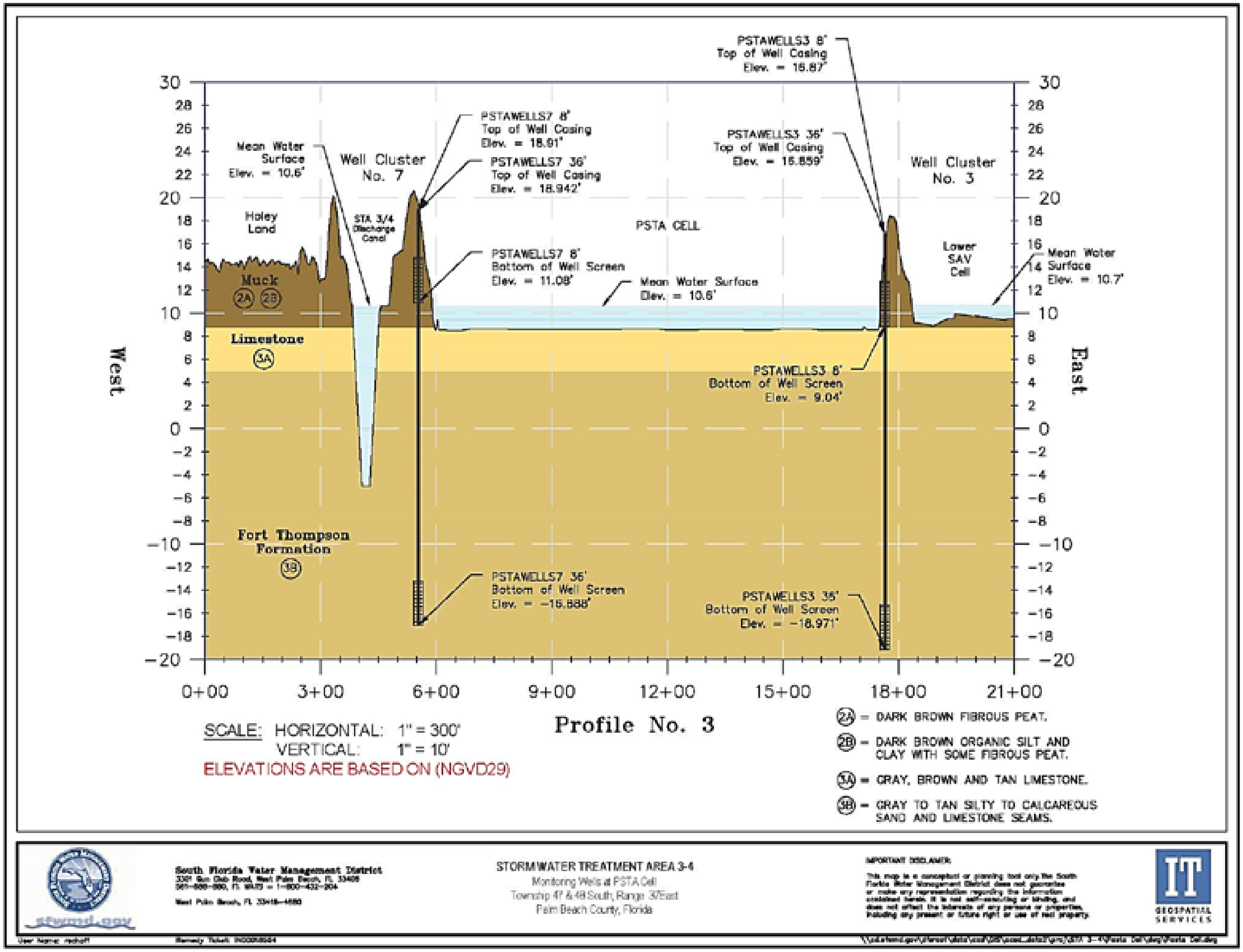

Figure A-4. West to east hydrogeologic cross-section profile through monitor well clusters C7 and C3 illustrating surficial aquifer formations underlying the Holey Land WMA, STA-3/4 Discharge Canal, PSTA Cell, and LSAV Cell.

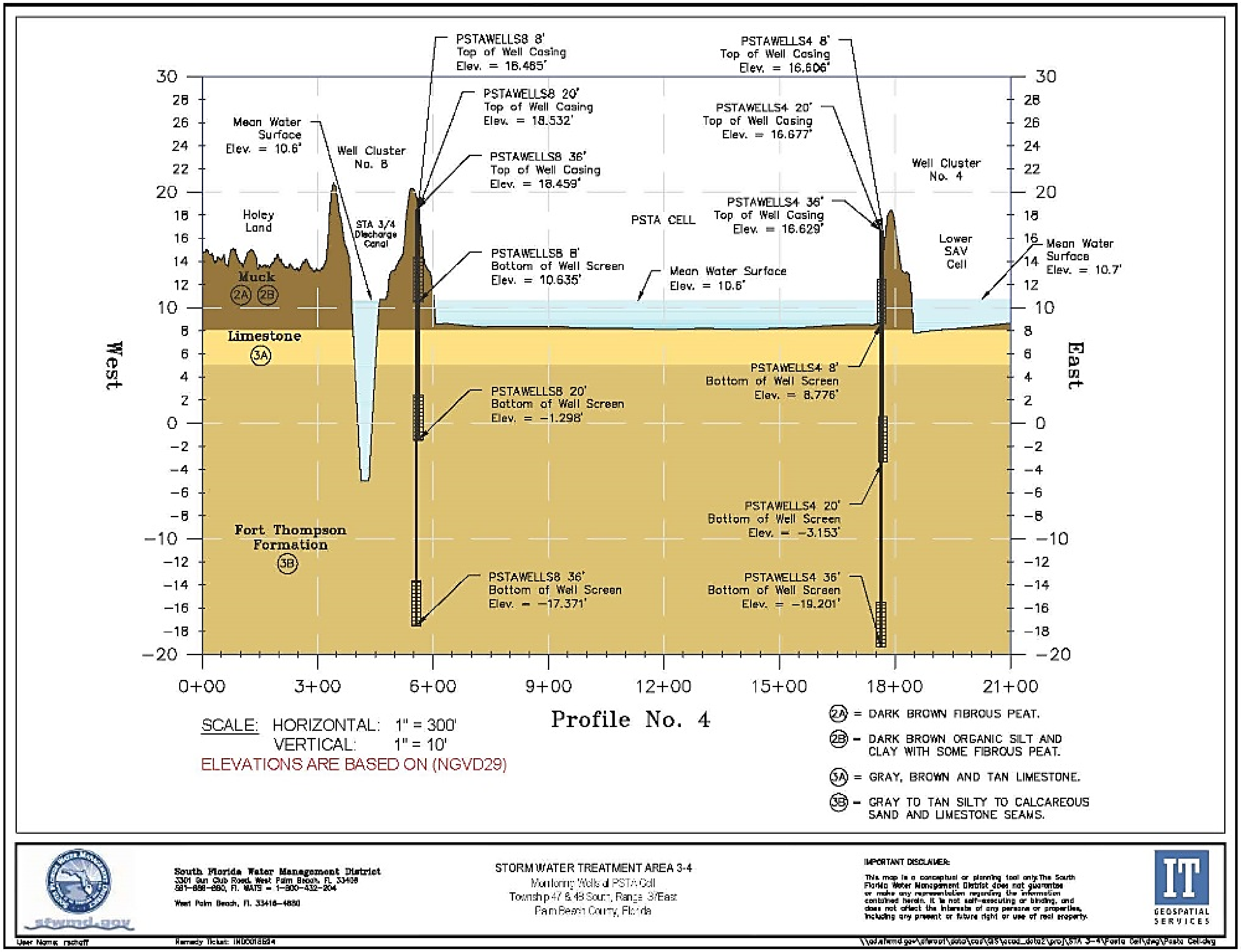

Figure A-5. West to east hydrogeologic cross-section profile through monitor well clusters C8 and C4 illustrating surficial aquifer formations underlying the Holey Land WMA, STA-3/4 Discharge Canal, PSTA Cell, and LSAV Cell.

APPENDIX B: CONSTRUCTION AND DESIGN DRAWINGS OF THE PSTA CELL'S PERIMETER LEVEE WELL CLUSTERS

Figure B-1 presents the construction and design drawing s of the PSTA cell's perimeter levee well clusters. These drawings were done by Nova Consulting, Inc. in 2003.

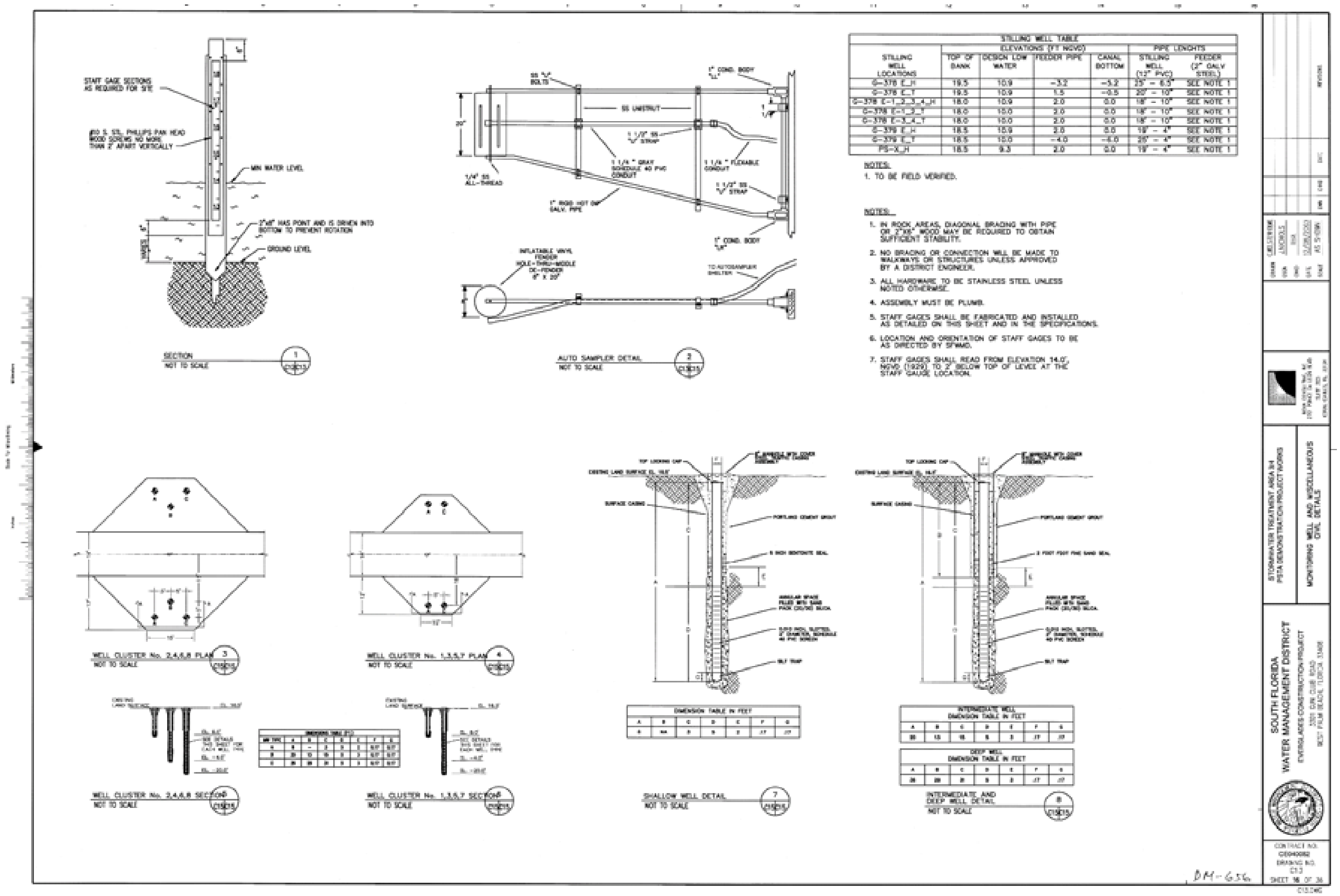

Figure B-1. Construction and design drawings of the PSTA cell's perimeter levee well clusters.

APPENDIX C: MAP OF THE STA-3/4 PSTA PROJECT SHOWING ELEVATION SURVEY POINTS

Figure C-1 is a map of the STA-3/4 PSTA Project showing elevation survey points measured within the PSTA and LSAV cells in August 2013.

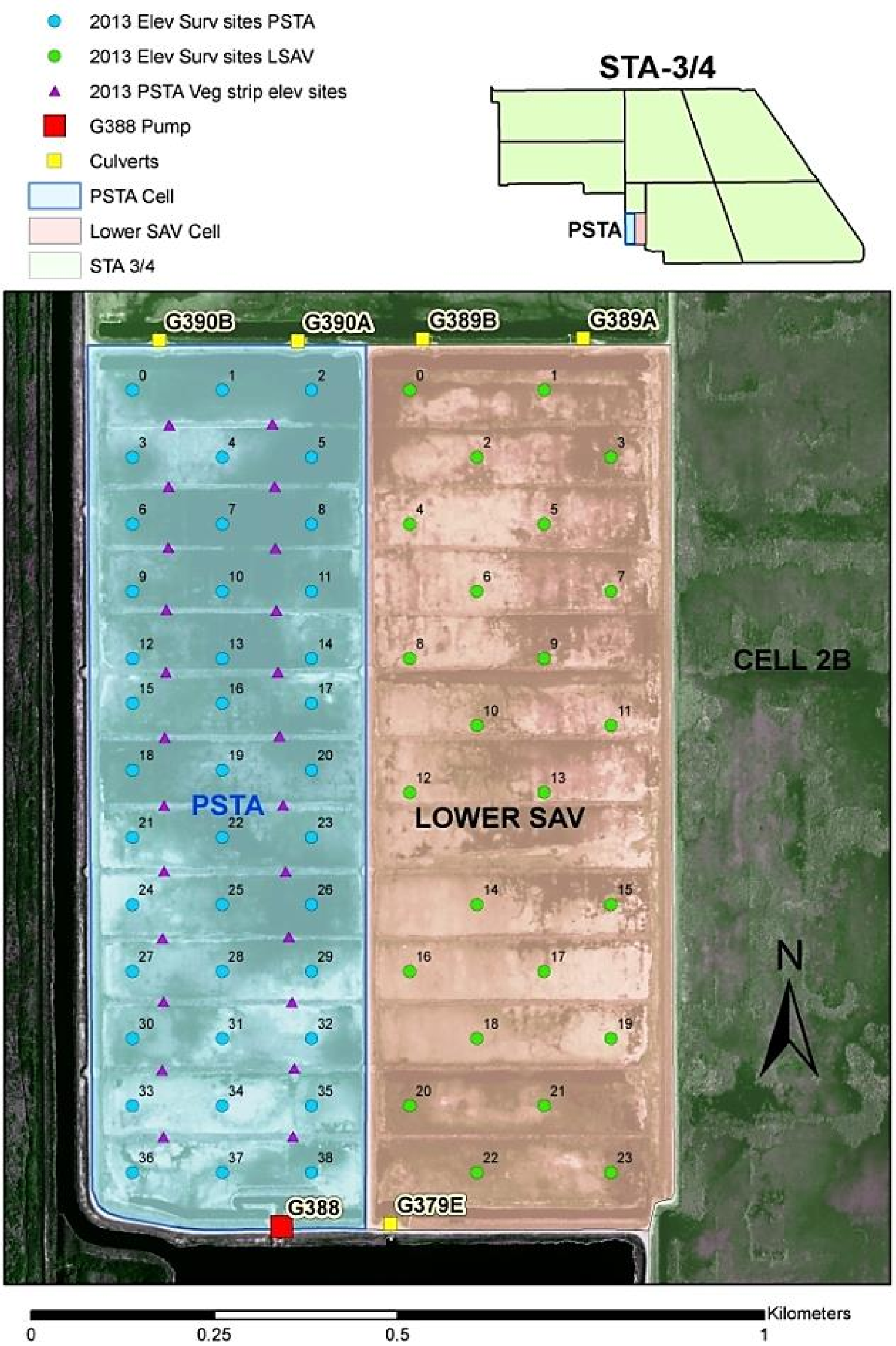

Figure C-1. Map of the STA-3/4 PSTA Project showing elevation survey points measured within the PSTA and LSAV cells in August 2013.

APPENDIX D: SUMMARY STATISTICS FOR CHEMICAL CHARACTERISTICS

Table D-1 provides summary statistics for select chemical characteristics of surface water, groundwater, and rainwater collected from sites within and surrounding the PSTA Cell.

Table D-1. Summary statistics for select chemical characteristics of surface water, groundwater, and rainwater collected from sites within and surrounding the PSTA Cell.

Parameter	Statistic	WELL DEPTH				Rain	Surface Water
		36 Feet		8 Feet			
		East	West	East	West		
Na (mg L^{-1})	Mean	70	31	55	14	1.1	54
	Standard Deviation	6	11	19	6	2.1	14
	Median	71	28	52	13	0.3	49
	Maximum	77	56	81	23	8.3	81
	Minimum	62	17	31	6	0.2	38
	Percentile 10	62	17	31	6	0.2	38
	Percentile 90	77	56	81	23	5.1	77
K (mg L^{-1})	Mean	2.3	3.1	5.5	4.7	0.1	5.9
	Standard Deviation	0.2	1.8	0.7	1.6	0.2	0.9
	Median	2.3	2.2	5.4	4.7	0.0	5.8
	Maximum	2.5	7.1	6.5	7.3	0.6	8.2
	Minimum	2.0	2.1	4.6	1.8	0.0	4.6
	Percentile 10	2.0	2.1	4.6	1.8	0.0	4.8
	Percentile 90	2.5	7.1	6.5	7.3	0.4	7.0
Ca (mg L^{-1})	Mean	127	122	106	202	0.2	57
	Standard Deviation	7	52	10	49	0.3	19
	Median	124	106	109	214	0.1	56
	Maximum	136	248	115	259	1.0	97
	Minimum	119	90	84	115	0.0	25
	Percentile 10	119	90	84	115	0.0	33
	Percentile 90	136	248	115	259	0.9	90
Mg (mg L^{-1})	Mean	19	15	18	25	0.1	16
	Standard Deviation	1	5	2	11	0.2	2
	Median	19	13	18	28	0.0	16
	Maximum	21	27	20	40	1.0	21
	Minimum	19	13	16	9	0.0	12
	Percentile 10	19	13	16	9	0.0	13
	Percentile 90	21	27	20	40	0.6	19

Table D-1. Continued.

Parameter	Statistic	WELL DEPTH				Rain	Surface Water
		36 Feet		8 Feet			
		East	West	East	West		
Cl (mg L^{-1})	Mean	127	50	92	13	1.9	91
	Standard Deviation	9	22	34	10	3.5	23
	Median	126	46	100	12	0.6	85
	Maximum	139	89	140	37	13.8	136
	Minimum	113	12	42	4	0.3	61
	Percentile 10	114	14	44	4	0.4	63
	Percentile 90	139	88	139	37	9.0	131
HCO_3/CO_3 (mg L^{-1})	Mean	352	350	303	492	.	163
	Standard Deviation	20	179	25	95	.	40
	Median	348	297	303	522	.	168
	Maximum	376	786	348	615	.	248
	Minimum	324	242	274	312	.	76
	Percentile 10	324	242	274	312	.	110
	Percentile 90	376	786	348	615	.	223
SO_4 (mg L^{-1})	Mean	0.4	5	23	78	1.1	30
	Standard Deviation	0.4	6	18	69	1.2	16
	Median	0.3	4	19	62	0.7	27
	Maximum	1.4	18	42	188	5.2	60
	Minimum	0.0	1	5	1	0.2	9
	Percentile 10	0.0	1	5	1	0.5	13
	Percentile 90	1.4	18	42	188	2.9	52
Specific Conductance (µmhos/cm)	Mean	1042	727	869	1019	16	667
	Standard Deviation	50	25	112	252	18	143
	Median	1045	722	854	1159	10	710
	Maximum	1085	766	1073	1285	81	885
	Minimum	910	689	726	705	5	450
	Percentile 10	922	690	728	705	6	463
	Percentile 90	1085	765	1067	1285	48	830
pH	Mean	6.9	7.0	6.9	6.6	5.2	8.0
	Median	6.9	7.0	6.9	6.6	5.2	7.9
	Maximum	7.1	7.1	7.1	6.7	5.8	9.5
	Minimum	6.8	6.8	6.8	6.5	4.6	7.1
	Percentile 10	6.8	6.8	6.8	6.5	4.7	7.5
	Percentile 90	7.1	7.1	7.1	6.7	5.8	8.7

APPENDIX E: SUMMARY STATISTICS FOR GROUNDWATER LEVEL MEASUREMENTS

Tables E-1 and **E-2** provide summary statistics for groundwater level measurements from wells located in the PSTA Cell's east and west, respectively, perimeter levees before and after the PSTA Cell target stage modification.

Table E-1. Summary statistics for groundwater level measurements from wells located in the PSTA Cell's east perimeter levee between the PSTA and LSAV cells before and after the PSTA Cell target stage modification.

Well Cluster	Depth (ft)	Statistic	PSTA Target Water Level: 10.0 ft	PSTA Target Water Level: 10.5 ft [a]
			Water Level (ft)	Water Level (ft)
1	36	Sample Size	8	7
		Mean	10.62	10.82
		Standard Deviation	0.12	0.31
		Minimum	10.43	10.58
		Maximum	10.83	11.43
	8	Sample Size	8	7
		Mean	10.62	10.86
		Standard Deviation	0.11	0.25
		Minimum	10.54	10.64
		Maximum	10.84	11.25
2	20	Sample Size	9	7
		Mean	10.47	10.83
		Standard Deviation	0.26	0.30
		Minimum	9.80	10.55
		Maximum	10.70	11.33
	36	Sample Size	12	7
		Mean	10.51	10.84
		Standard Deviation	0.27	0.29
		Minimum	9.80	10.55
		Maximum	10.91	11.32
	8	Sample Size	12	7
		Mean	10.43	10.83
		Standard Deviation	0.27	0.28
		Minimum	9.72	10.57
		Maximum	10.85	11.28

a. Change in PSTA Cell target stage implemented on April 2, 2013.

Table E-1. Continued.

Well Cluster	Depth (ft)	Statistic	PSTA Target Water Level: 10.0 ft Water Level (ft)	PSTA Target Water Level: 10.5 ft [a] Water Level (ft)
3	36	Sample Size	12	7
		Mean	10.68	10.83
		Standard Deviation	0.37	0.29
		Minimum	10.36	10.56
		Maximum	11.71	11.32
	8	Sample Size	12	7
		Mean	10.34	10.74
		Standard Deviation	0.09	0.18
		Minimum	10.20	10.55
		Maximum	10.48	11.05
4	20	Sample Size	8	7
		Mean	10.51	10.79
		Standard Deviation	0.15	0.26
		Minimum	10.37	10.57
		Maximum	10.77	11.26
	36	Sample Size	8	7
		Mean	10.58	10.81
		Standard Deviation	0.15	0.26
		Minimum	10.40	10.55
		Maximum	10.80	11.23
	8	Sample Size	8	7
		Mean	10.23	10.80
		Standard Deviation	0.07	0.25
		Minimum	10.15	10.55
		Maximum	10.35	11.27

a. Change in PSTA Cell target stage implemented on April 2, 2013.

Table E-2. Summary statistics for groundwater level measurements from wells located in the PSTA Cell's west perimeter levee between the PSTA Cell and STA-3/4 discharge canal before and after the PSTA Cell target stage modification.

Well Cluster	Depth (ft)	Statistic	PSTA Target Water Level	
			10.0 ft	10.5 ft [a]
			Water Level (ft)	Water Level (ft)
5	36	Sample Size	8	7
		Mean	10.60	10.55
		Standard Deviation	0.16	0.35
		Minimum	10.27	9.93
		Maximum	10.77	11.07
	8	Sample Size	8	7
		Mean	12.55	13.30
		Standard Deviation	0.42	0.80
		Minimum	12.28	12.08
		Maximum	13.53	14.43
6	20	Sample Size	8	7
		Mean	10.66	10.57
		Standard Deviation	0.12	0.37
		Minimum	10.42	9.97
		Maximum	10.77	11.17
	36	Sample Size	12	7
		Mean	10.58	10.59
		Standard Deviation	0.15	0.35
		Minimum	10.21	10.02
		Maximum	10.76	11.16
	8	Sample Size	12	7
		Mean	11.19	11.88
		Standard Deviation	0.59	0.86
		Minimum	10.54	10.56
		Maximum	12.44	13.34
7	36	Sample Size	9	7
		Mean	10.62	10.56
		Standard Deviation	0.11	0.37
		Minimum	10.49	9.97
		Maximum	10.84	11.14
	8	Sample Size	9	7
		Mean	11.47	11.85
		Standard Deviation	0.45	0.51
		Minimum	11.07	11.07
		Maximum	12.57	12.77

a. Change in PSTA Cell target stage implemented on April 2, 2013.

Table E-2. Continued.

Well Cluster	Depth (ft)	Statistic	PSTA Target Water Level	
			10.0 ft	10.5 ft [a]
			Water Level (ft)	Water Level (ft)
8	36	Sample Size	11	7
		Mean	10.47	10.50
		Standard Deviation	0.16	0.36
		Minimum	10.07	9.92
		Maximum	10.62	11.07
	8	Sample Size	11	7
		Mean	11.89	12.02
		Standard Deviation	0.87	1.47
		Minimum	10.56	10.53
		Maximum	13.53	14.63

a. Change in PSTA Cell target stage implemented on April 2, 2013.