Chapter 4B: STA Optimization and Advanced Treatment Technologies

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SUMMARY

- A new sediment and vegetation monitoring program was initiated in all the Stormwater Treatment Areas (STAs) during WY2003. The new program greatly expands on past monitoring efforts and will provide a database that is consistent across all STAs.
- Flow-weighted mean outflow total phosphorus (TP) concentration for the operational period of record in each STA was highly correlated with corresponding flow-weighted mean inflow TP concentration and areal TP loading. Treatment performance in STA-2 and STA-6 exceeded expectations predicted by the STA design model in all operational years. STA-1 West did not meet its design expectation in the first operational year, but it did so in the following two years. STA-5 had outflow higher TP concentrations than predicted by the model in two of the three years it has been in operation.
- Decreased treatment performance in some of the STAs (east and north flow-ways in STA-1 West, STA-5 north flow-way) was attributed to hydraulic overloading and excess phosphorus released after herbicide applications for vegetation management.
- Continued monitoring of the STA-1 West test cells indicated that some of the technologies, such as the Periphyton-Based Stormwater Treatment Area (PSTA) and chemical treatment/ solids separation (CTSS) can reduce outflow TP concentrations to very low levels on a long-term basis. However, none of these technologies as implemented in the test cells consistently reduced outflow TP to 10 micrograms per liter (µg/L).
- Two studies of other aquatic systems, the Lake Panasoffkee Sediment Study and the Florida Lake and River Survey, indicated that Florida lakes and rivers systems dominated by submerged aquatic vegetation (SAV) can store phosphorus (P) in their sediments on a long-term basis.
- Field-scale research of the PSTA technology indicated that while a PSTA system built on a limerock or caprock substrate can reduce outflow TP concentrations, peat-based systems are not effective. Additionally, a PSTA system that maximizes the aspect ratio, which increases the flow path and substantially improves system hydraulics, may provide the best overall TP concentration reduction.
- The South Florida Water Management District (SFWMD or District) has proposed conducting a full-scale, side-by-side demonstration of PSTA and SAV technologies in STA-3/4.
- Everglades restoration is now focused on developing biologically based, or "green," technologies to the maximum extent possible. Research has indicated that wetlands

dominated by SAV or periphyton (PSTA) have the potential to reach target TP levels on a consistent basis. Scenarios for improving STA performance envision reconfiguring the STAs to contain cells dominated by emergent macrophytes followed by cells dominated by SAV and/or PSTA. The Process Development and Engineering component of the District's Conceptual Plan for Achieving Long-term Water Quality Goals will continue to investigate green technologies for use in Everglades restoration.

INTRODUCTION

The 1994 Everglades Forever Act (Section 373.4592, Florida Statutes [F.S.]) requires the South Florida Water Management District to build and operate the Stormwater Treatment Areas as part of the Everglades restoration. The Everglades Forever Act (EFA) further stipulated that the District must

> … continue [conducting] research seeking to optimize the design and operation of STAs and to identify other treatment and management methods that are superior to STAs in achieving optimum water quality and water quantity for the benefit of the Everglades.

The District's efforts to comply with this mandate during the past nine years have been organized into two separate programs. STA Optimization refers to the research, monitoring, and other activities that have focused on understanding how the STAs function as treatment systems, with the goal of maximizing their performance through improved management strategies. The Advanced Treatment Technologies (ATT) program comprises experiments and demonstration projects that evaluate the applicability of other treatment technologies and modifications to the original STA design concept, i.e., wetlands dominated by emergent aquatic vegetation. Descriptions of the studies that comprised these two programs, their goals and objectives, results, and key findings were provided in Chapters 6 and 8 of the *Everglades Interim Report* (Chimney and Moustafa, 1999; Gray and Coffelt, 1999, respectively). They were also covered in various chapters of previous Everglades Consolidated Reports (ECRs) (Chimney et al., 2000; Gray and Coffelt, 2000; Nungesser et al., 2001; Coffelt at al., 2001; Jorge et al., 2002; Newman et al., 2003) as well as in individual project reports posted on the District's "Ecological Technologies Reports" Website.[1]

The objective of Chapter 4B in this year's Everglades Consolidated Report is to summarize analyses and new findings from the STA Optimization and ATT programs that were completed since the *2003 Everglades Consolidated Report* was written and to update ongoing studies. This chapter generally covers data collected during Water Year 2003 (WY2003) (May 1, 2002 through April 30, 2003). Results from the STA Optimization and ATT programs have been reported in separate chapters in previous ECRs. Because all STA Optimization and ATT research projects have been completed, resulting in fewer data to report this year, both programs are discussed in a single chapter in this year's ECR. The *2004 Everglades Consolidated Report* will bring the ATT program to closure. In addition, the research portion of the STA Optimization program has been integrated into the Process Development and Engineering (PDE) component of the District's Plan for Achieving Long-Term Water Quality Goals (Burns & McDonnell, 2003; also discussed in Chapter 8A of this report) and will be reported in that section of the *2005 Everglades Consolidated Report*. All statistics presented in this chapter were calculated using the following computer software: SAS (Release 8.2, SAS Institute Inc., Cary, NC), SAS JMP® (Version 5), or SigmaPlot (Version 8.0, SPSS Inc., Chicago, IL). The level of statistical significance (α) was set at 0.05 in all analyses.

[1] www.sfwmd.gov/org/erd/ecp/etweb/main_template/report.html

STA OPTIMIZATION MONITORING

The STA Optimization program comprises research, monitoring, and other activities that improve the understanding of how the STAs function as wetland treatment systems, collectively contributing to the goal of developing management strategies to achieve optimum performance in the STAs. These efforts include the following:

- Gaining practical experience in the day-to-day operation of the STAs (the four currently operating STAs are STA-1 West, STA-2, STA-5, and STA-6, each described in Chapter 4A of this report)
- Analysis of long-term performance data from the operating STAs, including performance of the individual treatment cells
- Monitoring changes in STA sediment chemistry, sediment accretion rates, and species composition of the plant communities
- Analysis of data from other comparable aquatic systems
- Experiments conducted in the STA-1 West test cells

Evaluations of STA performance, including analyses of total phosphorus (TP) load reduction, concentration reduction, and removal efficiency during WY2003 are presented in Chapter 4A of the *2004 Everglades Consolidated Report*. The focus of this chapter is on analyses of long-term trends in STA performance.

The District initiated a new sampling program in WY2003 to monitor interior water quality; sediment physicochemical characteristics and accretion rates; and vegetation community composition, biomass, and tissue nutrient content annually in the operating STAs. Data in each STA will be collected at sample sites uniformly distributed over the entire wetland. The objectives are to develop a baseline database and to document changes in the vegetation community and sediments at the same temporal and spatial resolution among all the STAs. These new data will be used as correlates in future analyses of long-term STA treatment performance and will support the District's PDE initiative. They also will provide basic information on the structure and functioning of the STAs, which is needed for informed management decisions. The detailed scope of work for this project is presented in Appendix 4B-1. This new program supplants the different vegetation and sediment sampling programs that the District has conducted to date in each STA. However, because only limited data are available from this new program at this time, an analysis has been deferred until there is sufficient information for a comparison across all STAs. The data presentations that follow should be regarded as preliminary in nature.

Past ECRs have provided annual water and TP mass balance budgets for the treatment cells that comprised the Everglades Nutrient Removal Project (ENRP), which is now part of STA-1W. These were part of the analysis of treatment performance, which also included a discussion of flow-weighted TP concentrations. The goal is to provide similar information for all treatment cells within the other STAs. To that end, the District is installing flow monitoring and automated sample collection equipment at the inflow and outflow of all treatment cells in the operating STAs. With the addition of many more sampling sites, it became necessary to redesign the software used for these calculations. However, software development and equipment installation in some of the STAs (STA-5, STA-6, and Cells 5A and 5B in STA-1W) are still ongoing.[2] Because flow and/or autosampler TP data needed to calculate flow-weighted TP concentrations

[2] In the interim, the District collected grab samples biweekly during WY2003 from all sites scheduled for autosampler installation.

were unavailable for some interior sites, STA treatment performance was evaluated using geometric mean TP concentrations calculated from either grab sample or autosampler data. Unless otherwise noted, all discussions of mean TP concentrations in the STAs are based on geometric means. It is anticipated that water and TP budgets and flow-weighted mean TP concentrations for all STA treatment cells will be provided in next year's ECR.

STA-1 WEST

STA-1W consists of three treatment trains (**Figure 4B-1**): Cells 1 and 3 comprise the east flow-way, Cells 2 and 4 comprise the west flow-way, and Cells 5A and 5B comprise the north flow-way. These cells collectively encompass 2,699 ha (6,670 acres). The east and west flow-ways (the former ENRP) have been operating since 1994. The north flow-way began treating water in July 2000. Surface inflow to STA-1W originates at the S-5A pump station and enters the wetland through the G-302 lift gates. Part of this flow is directed westward through culverts in the G-304 levee (the primary inflow into the north flow-way), while the rest passes through the G-303 gates into the east and west flow-ways. Water exits the north flow-way through 10 culverts in the G-306 levee and leaves STA-1W through the G-310 pump station. Water from the east and west flow-ways exits STA-1W via the G-251 pump station. Cells 3 and 4 have multiple outflow points: Cell 3 releases water from its south end and can discharge from two upstream structures, G-259 and G-308; Cell 4 discharges at its south end through G-256 and can release water through two upstream structures, G-258 and G-309. All discharge from STA-1W ultimately flows into Water Conservation Area 1 (WCA-1), which is part of the Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge).

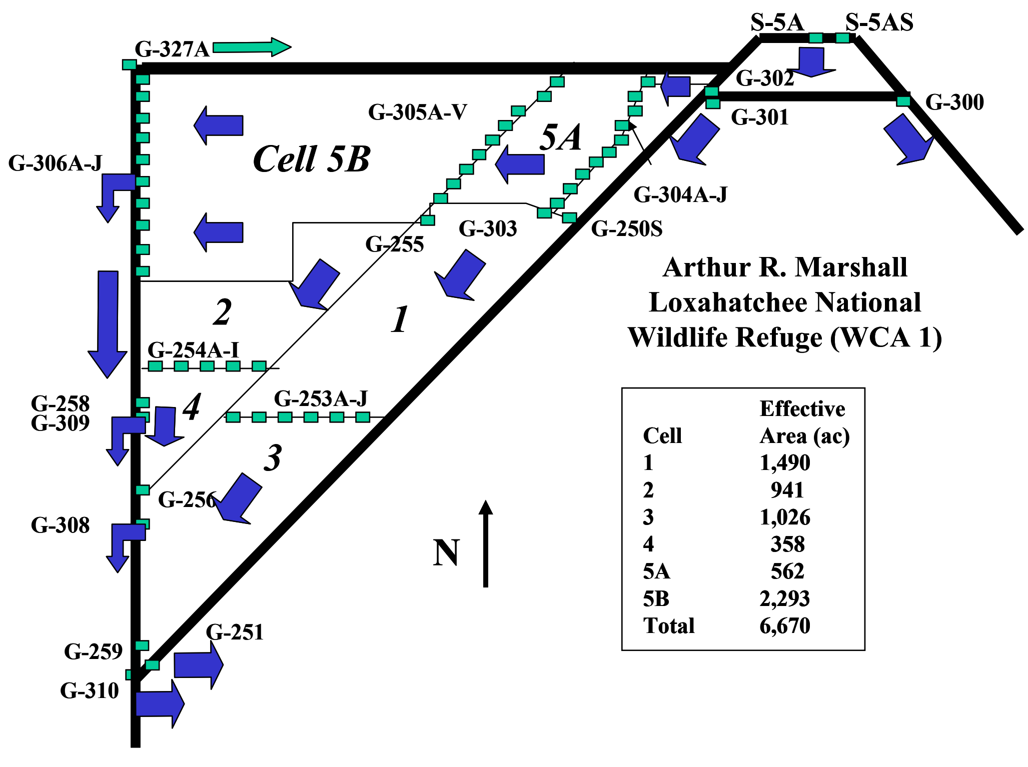


Figure 4B-1. Map of Stormwater Treatment Area 1 West (not to scale). Arrows indicate direction of flow.

Aerial photography and ground-truthing surveys monitored changes in the plant community within the former ENRP (Chimney et al., 2000; Nungesser at al., 2001). However, information on standing crop biomass for dominant species had not been collected since the winters of 1995 and 1996. The District contracted to sample vegetation in the east and west flow-ways during winter (February) and summer (May/June) 2002. The focus of the project was to (1) document changes in plant species composition, biomass, and tissue nutrient content along the downstream nutrient gradient in these cells, (2) determine if there were any seasonal changes in plant biomass or nutrient content, and (3) determine if cattail (*Typha* spp.) biomass and tissue nutrient content has changed since similar data were collected in winter 1995.

In March 2003, the north flow-way was closed for construction of a limerock berm across the width of Cell 5B, and it remained closed through the end of WY2003. This effort was part of a three-year project funded by the Florida Department of Environmental Protection (FDEP) to demonstrate the benefits of improved hydraulics through increased cell compartmentalization on TP removal. The project is described in Appendix 4B-2. A water quality monitoring plan for the limerock berm project is being prepared by the District and should be underway by the time the *2005 Everglades Consolidated Report* is written.

TREATMENT PERFORMANCE

Analysis and discussion of past treatment performance in the STA-1W flow-ways (and its predecessor, the ENRP) appear in previous ECRs (Chimney et al., 2000; Nungesser et al., 2001; Jorge et al., 2002; Newman et al., 2003). Summary statistics for all water quality parameters monitored at interior sampling stations in STA-1W during WY2003 are provided in Appendix 4B-3. Time series plots of weekly inflow and outflow TP concentrations and daily inflow water load for the north, east, and west flow-ways in STA-1W are presented in **Figure 4B-2**.

Total P concentrations in the inflow to the STA-1W flow-ways are monitored at three separate locations. Water quality into the north flow-way is measured at G-302 (**Figure 4B-1**). Mean TP concentrations at this structure averaged 137 µg/L for WY2003 (**Table 4B-1**).[3] The entrance to the east flow-way is through the G-303 structure, which is downstream from G-302. Total P concentrations at G-303 averaged 132 µg/L for the year. The entrance to the west flow-way is through G-255, which had a mean TP concentration of 129 µg/L.

[3] Note: 1 µg/L = 1 ppb (part per billion).

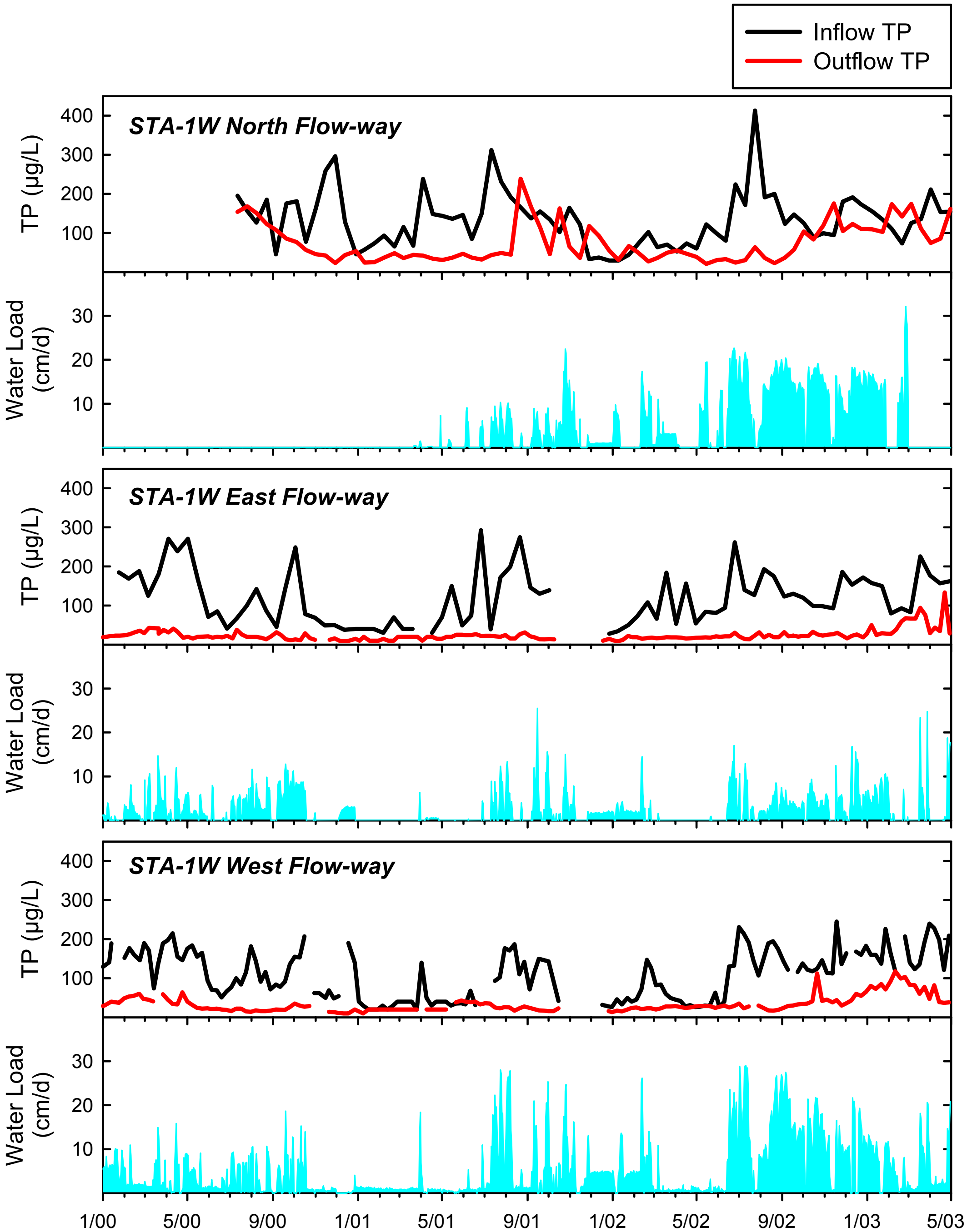


Figure 4B-2. Time series of inflow and outflow weekly total phosphorus (TP) concentrations and daily water load for the north, east and west flow-ways of Stormwater Treatment Area 1 West. Stations and collection methods for TP as follows: North FW inflow at G-302, grab samples; North FW outflow at G-306C and G-306G, grab samples; East FW inflow at G-303, grab samples; East FW outflow at ENR305 and ENR306, time-proportioned autosamplers; West FW inflow at G-255, time-proportioned autosampler, West FW outflow at G-256, time-proportioned autosampler.

Table 4B-1. Annual geometric mean inflow and outflow total phosphorus (TP) concentrations and TP concentration reduction based on these means for the east, west, and north flow-ways of STA-1W during WY2003.

	Mean Inflow TP (µg/L)	Mean Outflow TP (µg/L)	TP Conc. Reduction (%)
East flow-way	**132**	**28[a]/40[b]**	**78.8[a]/69.7[b]**
Cell 1	132	63	52.3
Cell 3	63	28[a]/40[b]	55.6[a]/36.5[b]
West flow-way	**129**	**42[c]/71[d]**	**67.4[c]/45.0[d]**
Cell 2	129	110	14.7
Cell 4	110	42[c]/71[d]	61.7[c]/35.5[d]
North flow-way	**137**	**82**	**40.1**
Cell 5A	137	150	-9.5
Cell 5B	150	82	45.3

[a] outflow at the south end of Cell 3
[b] outflow through G308
[c] outflow through G256 at the south end of Cell 4
[d] outflow through G309

The east flow-way had a higher TP concentration reduction during WY2003 (79-percent reduction at the south end of Cell 3 and 70-percent reduction through G-308; mean outflow TP = 28 and 40 µg/L, respectively; G-259 was not operated during WY2003) compared to the west flow-way (67-percent reduction through G-256 and 45-percent reduction through G-309; mean outflow TP = 42 and 71 µg/L, respectively; G-258 was not operated during WY2003) or the north flow-way (40-percent reduction; mean outflow TP = 82 µg/L) (**Table 4B-1**). A statistically significant difference in outflow TP concentration was detected among flow-ways (Kruskal-Wallis test, Chi-square $p < 0.0001$); the median value for the north flow-way was significantly different from the east and west flow-ways, while the east and west flow-ways did not differ from each other. Historically, the west flow-way has had the lowest mean outflow TP concentrations; levels often were less than 20 µg/L. The better treatment performance by the west flow-way in the past was attributed to greater treatment efficiency of the submerged aquatic vegetation (SAV) community that dominated Cell 4, despite the fact that the west flow-way had a greater hydraulic load than the east flow-way. (Approximately 60 percent of the hydraulic load to the old ENRP was processed by the west flow-way.) Water released through G-308 and G309 did not transit the entire length of Cells 3 and 4, respectively, and therefore received only partial treatment. This resulted in the higher TP concentrations and lower TP concentration reductions at these structures compared to values for water released from the bottom of each respective cell. It stands to reason then that operation of G-308 and G-309 reduced the overall treatment performance of Cells 3 and 4 to some extent.

The reduced treatment performance of STA-1W in WY2003 (i.e., higher weekly outflow TP concentrations compared to previous years) (**Figure 4B-2**) was attributed to the combined effects of herbicide application to control vegetation and hydraulic overloading of the system. Large mats of water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*) in Cell 2 were sprayed in calendar years 2002 and 2003. In addition, a decision was made to eliminate the floating cattail islands from this cell using herbicide application followed by mechanical removal. Both efforts were intended to promote SAV growth in Cell 2 and improve the treatment performance of the west flow-way. The loss of living vegetation and corresponding reduction in nutrient uptake, the release of P from decaying plants, and disturbance of the sediments by harvesting activities appear to have had the opposite effect in the short-term. There was little net decrease in the annual mean TP concentration in Cell 2 during WY2003 (**Table 4B-1**). Reduced treatment performance in the north flow-way also coincided with herbicide applications for vegetation management in these cells and increased hydraulic loading. Based on a visual comparison of daily inflow, the water load to the north and west flow-ways in STA-1W was substantially higher in WY2003 than in previous years (**Figure 4B-2**).

VEGETATION

Submerged and Floating Aquatic Vegetation

Two dominant SAV species, southern naiad (*Najas quadalupensis*) and coontail (*Ceratophyllum demersum*), and two dominant species of floating aquatic vegetation (FAV), water lettuce and water hyacinth, were sampled during February and May/June 2002 at multiple sites located along the downstream nutrient gradient in the east and west flow-ways of STA-1W. Four replicate subsamples of plant material were collected at each site. SAV was collected using a 1-m^2 box corer and FAV with a 1-m^2 PVC frame. Plant percent cover was assessed in each quadrat. All plant samples were returned to the laboratory and analyzed for wet and dry weight and tissue P, nitrogen (N), carbon (C), and ash content. Methods and materials used for this sampling program are detailed in DBEL (2002) (see Appendix 4B-4).

There were no consistent spatial trends observed among species for standing crop biomass. Differences between inflow and outflow plant biomass and tissue nutrient content were generally more pronounced in the east flow-way, which had the longer flow path and greater concentration reductions than in the west flow-way. Coontail and water hyacinth exhibited greater inflow-to-outflow differences in tissue nutrient content than southern naiad or water lettuce in both flow-ways. Standing crop biomass of SAV and FAV was higher in the summer than in the winter. However, tissue nutrient levels displayed the opposite trend: P and N levels typically were higher in the winter than during the summer (DBEL, 2002).

Cattail

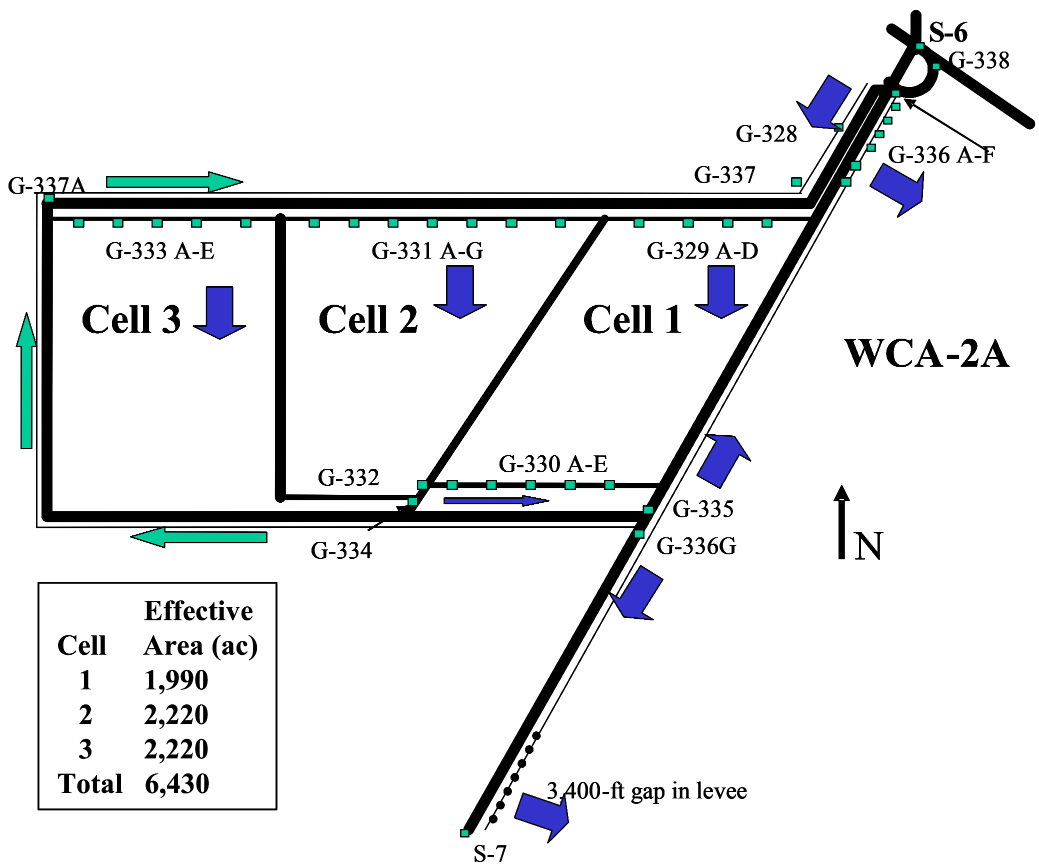
Cattail was collected only during February 2002 using a 0.5-m^2 PVC frame at three sites located along the downstream nutrient gradient in the east and west flow-ways. Four subsamples were collected at each site. Plant samples were separated into aboveground live, aboveground dead, and belowground tissue types and were analyzed for wet and dry biomass and tissue P, N, C, and ash content. Methods and materials used for this sampling program are detailed in DBEL (2002) (see Appendix 4B-4).

In general, cattail total biomass was highest at the inflow locations, with the bulk of the standing crop occurring as aboveground dead tissue. Changes in the tissue nutrient content of belowground tissues typically correlated most closely with the downstream nutrient gradient in each flow-way (DBEL, 2002). Two sites in this project corresponded to stations where cattail was sampled by the District in winter 1995. Standing crop biomass for all tissue types was higher in winter 2002 than in winter 1995. Conversely, the tissue P and N content at the inflow to the east flow-way was much lower than levels observed in winter 1995.

STA-2

STA-2 consists of three parallel treatment cells that together encompass 2,602 ha (6,430 acres) (**Figure 4B-3**). Each cell functions as a separate flow-way and will be evaluated as such in this chapter. Water enters STA-2 at the S-6 and G-328 pump stations and is distributed to the north end of each treatment cell via a distribution canal. Water then flows by gravity to the south, enters another collection canal, and is discharged to WCA-2A via the G-335 pump station. The vegetation community differed among treatment cells. Cell 1 was allowed to develop as an emergent macrophyte marsh dominated by cattail. Cell 3 has been actively managed for SAV, and a large portion of Cell 2 was the former Brown's Farm Wildlife Management Area and now has a large area of standing dead wood.

STA-2 began releasing treated water in June 2001. However, flow-through operation of Cell 1 was delayed until August 2002 as part of the District's effort to mitigate mercury release (see Chapters 2B and 4A). A topographic survey of ground elevations within STA-2 was completed this year. Efforts (aerial photography and ground-truthing surveys) to produce a vegetation base map are underway.



Cell	Effective Area (ac)
1	1,990
2	2,220
3	2,220
Total	6,430

Figure 4B-3. Map of Stormwater Treatment Area 2 (not to scale). Arrows indicate direction of flow.

TREATMENT PERFORMANCE

This is the first ECR that presents treatment performance data for the individual cells of STA-2. Summary statistics for all water quality parameters monitored at interior sampling stations during WY2003 are provided in Appendix 4B-5. Time series plots of weekly inflow and outflow TP concentrations and daily inflow water load for each of the three flow-ways in STA-2 are presented in **Figure 4B-4**.

Inflow TP concentrations for STA-2 were low compared to inflow concentrations at the other STAs (compare inflow TP concentrations in **Figure 4B-4** with time series plots for the other STAs); mean TP levels at S-6 and G-328 during WY2003 were 45 µg/L and 29 µg/L, respectively (**Table 4B-2**). The plant community in Cell 3 was dominated by SAV, while Cells 1 and 2 primarily had an emergent macrophyte community. Despite differences in the plant assemblages, TP concentration reduction in each of the treatment cells was similar (47- to 51-percent reduction). Mean outflow TP concentrations from these cells ranged from 16 to 18 µg/L. No significant difference in outflow TP concentration was detected among flow-ways (Kruskal-Wallis test, Chi-square $p = 0.2192$).

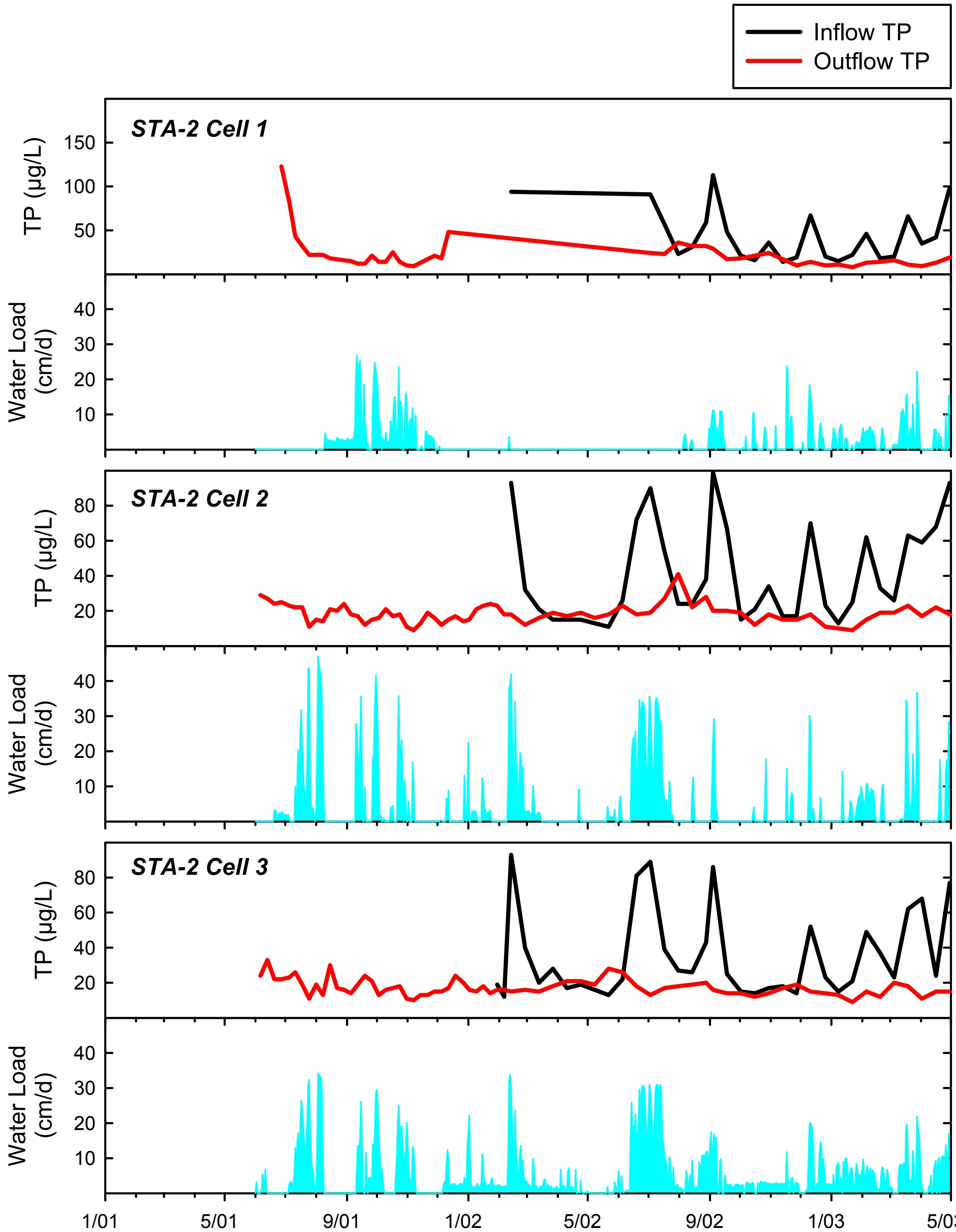


Figure 4B-4. Time series of inflow and outflow weekly total phosphorus concentrations and daily water load for Cells 1, 2 and 3 of Stormwater Treatment Area 2. Stations and collection methods for TP as follows: Cell 1 inflow at G-329, grabs; Cell 1 outflow at G-330A, grab samples; Cell 2 inflow at G-331D, grab samples; Cell 2 outflow at G-322, grab samples; Cell 3 inflow at G-333C, grab samples, Cell 3 outflow at G-334, grab samples.

Table 4B-2. Annual geometric mean inflow and outflow total phosphorus (TP) concentrations and TP concentration reduction based on these means for STA-2 during WY2003.

	Mean Inflow TP (μg/L)	Mean Outflow TP (μg/L)	TP Conc. Reduction (%)
STA inflow (S-6)	45	--	--
STA inflow (G-328)	29	--	--
Cell 1	35	17	51.4
Cell 2	35	18	48.6
Cell 3	30	16	46.7

STA-5

STA-5 consists of four treatment cells arranged into two parallel flow-ways. Together these cells encompass 1,663 ha (4,110 acres). The north flow-way is comprised of Cells 1A and 1B, while the south flow-way consists of Cells 2A and 2B (**Figure 4B-5**). Water enters STA-5 from the L-2 canal and flows eastward, where it is discharged to the Rotenberger Water Management Area and the Miami Canal. Water levels in Cells 1A, 2A, and 2B have been managed to promote the establishment of an emergent macrophyte plant community dominated by cattail, while Cell 1B was managed for SAV.

The District began monitoring vegetation, sediment, and water quality at sites throughout STA-5 in calendar year 2001. This effort has included surveys of plant biomass, plant community composition, and sediment nutrient and physical properties. To establish sampling sites, a grid pattern was projected over a map of STA-5 that divided the wetland into 112 equal-sized grid cells (approximately 16 ha in size). Then, 56 grid cells were randomly selected and sampled during each survey. Vegetation was collected from permanent 1-m^2 quadrats established within the grid cells. Sediment and water quality samples were collected at locations that were randomized within each grid. Six surveys have been conducted as of this report: five for vegetation, one for sediment, and three for water quality. The plant and sediment data are discussed in Jorge et al. (2002) and Newman et al. (2003).

TREATMENT PERFORMANCE

Analysis and discussion of past treatment performance in the STA-5 flow-ways appears in Newman et al. (2003). Summary statistics for all water quality parameters monitored at interior sampling stations in STA-5 during WY2003 are provided in Appendix 4B-6. Time series plots of weekly inflow and outflow TP concentrations and daily inflow water load for the north and south flow-ways in STA-5 are presented in **Figure 4B-6**.

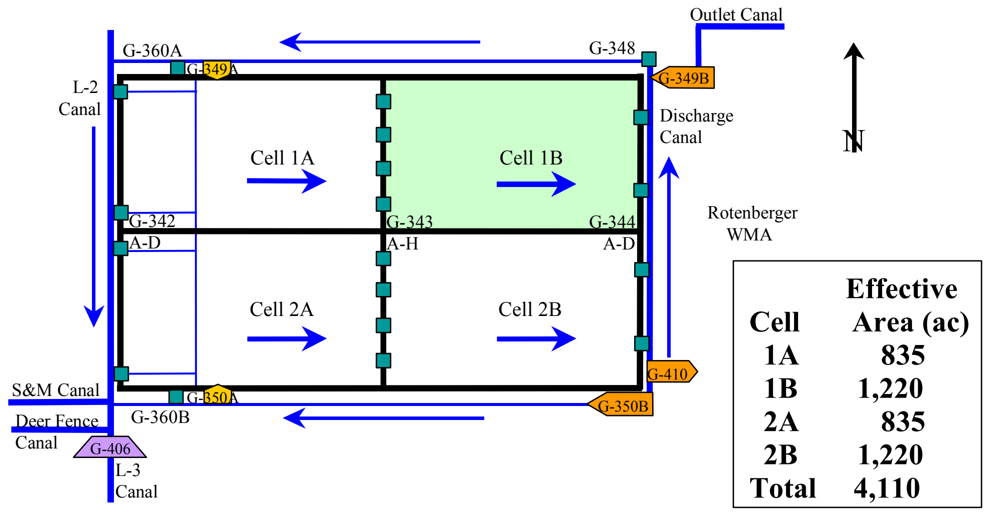


Figure 4B-5. Map of Stormwater Treatment Area 5 (not to scale). Arrows indicate direction of flow.

Over the past three water years, the annual mean TP inflow concentration to STA-5 has been high (range of 156 to 178 µg/L), relative to the other STAs. STA-5 also had some of the highest weekly inflow TP concentrations (compare inflow TP concentrations in **Figure 4B-6** with time series plots for the other STAs). The mean inflow TP concentration to the south flow-way during WY2003 was markedly higher than the mean concentration to the north flow-way (173 and 139 µg/L, respectively; **Table 4B-3**). The south flow-way had a 43 percent TP concentration reduction, while the north flow-way actually had slightly higher mean outflow TP (-1 percent reduction). However, despite these differences, outflow TP concentrations were not statistically significant between flow-ways (Kruskal-Wallis test, Chi-square p = 0.2805). The downstream cell in each flow-way (Cells 1B and 2B) had higher mean outflow TP concentrations for the year compared to their inflows. This apparent net export of P was attributed to the management of FAV in STA-5 (see discussion in the Vegetation section below). As the plants decomposed, they released large amounts of P into the water column, which affected the overall treatment performance of STA-5. For example, we observed a "correlation" between the dates when herbicide was applied in the north flow-way and spikes in weekly outflow TP levels that occurred shortly thereafter (some exceeding 300 µg/L) in July/August 2002, November 2002, January 2003, and February/March 2003 (**Figure 4B-6**).

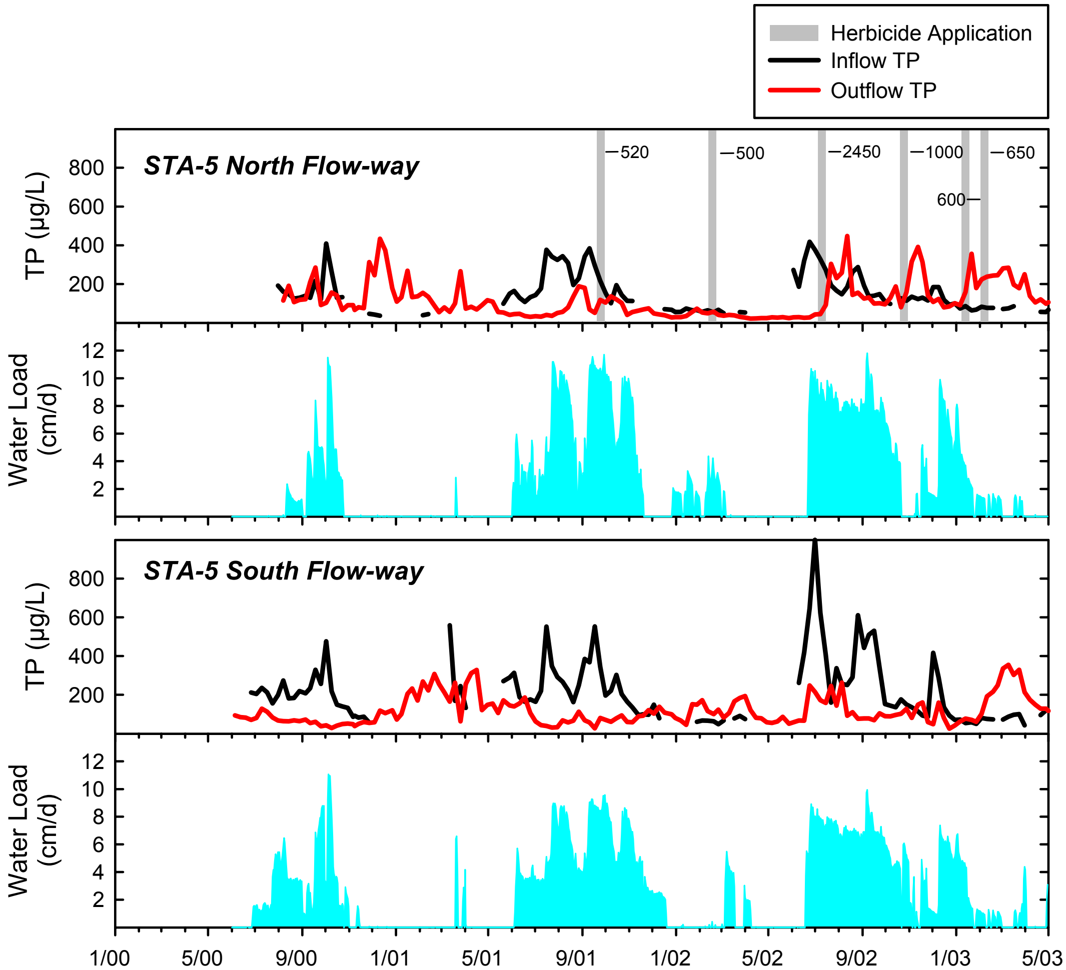


Figure 4B-6. Time series of inflow and outflow weekly total phosphorus concentrations and daily water load for the north and south flow-ways of Stormwater Treatment Area 5. Stations and collection methods for TP as follows: North FW inflow at G-342A and G-342B, flow-proportioned autosamplers; North FW outflow at G-344A and G-344B, flow-proportioned autosamplers; South FW inflow at G-342C and G-342D, flow-proportioned autosamplers; East FW outflow at G-344C and G-344D, flow-proportioned autosamplers. Gray bars indicate timing of herbicide applications in north flow-way; numbers indicate total acreage treated during each application.

Table 4B-3. Annual geometric mean inflow and outflow total phosphorus (TP) concentrations and TP concentration reduction based on these means for STA-5 during WY2003.

	Mean Inflow TP (µg/L)	Mean Outflow TP (µg/L)	TP Conc. Reduction (%)
North flow-way	**139**	**141**	**-1.4**
Cell 1A	139	109	21.6
Cell 1B	109	141	-29.3
South flow-way	**173**	**99**	**42.8**
Cell 2A	173	92	46.8
Cell 2B	92	99	-7.6

VEGETATION

Observations made during aerial and ground surveys in STA-5 indicated that the areal coverage of cattail is still increasing in Cells 1A, 2A, and 2B, while the abundance of SAV in Cell 1B decreased from the coverage observed in previous years. Large mats of water hyacinth and water lettuce have become established in this cell and have shaded out much of the SAV underneath. To reverse this trend, the District began controlling FAV in WY2003 in an attempt to restore the SAV community. As of June 2003, there have been four aerial and two ground herbicide applications in Cell 1B. The most recent vegetation survey in January 2003 found reduced FAV coverage and an increase in SAV, notably an increase in Hydrilla (*Hydrilla verticillata*).

SEDIMENT

A sediment survey of STA-5 was conducted in August 2002. The old agricultural soil (0–10 cm) and newly accreted floc layers were analyzed separately for bulk density, organic content, TP, total N (TN), total C (TC), and iron. The floc layer was also analyzed for inorganic and organic P fractions.

Preliminary results indicate that the old agricultural soil layer has 3 to 6 times the P content, when corrected for bulk density, than the floc layer. The highest P concentrations in both the floc and soil layers occurred in Cell 2B. Approximately 50 percent of the TP stored in the floc layer was in recalcitrant forms.

STA-6

STA-6 consists of two treatment cells (Cells 3 and 5) that together encompass 352 ha (870 acres). It is located in the southwestern corner of the Everglades Agricultural Area (EAA), adjacent to the Rotenberger Wildlife Management Area (**Figure 4B-7**). Each cell functions as a separate flow-way. Water enters STA-6 via the G-600 pump station into a canal that supplies the treatment cells. Cell 5 receives inflow through two weirs (G-601 and G-602); Cell 3 receives inflow through one weir (G-603). Treated water is discharged to the L-4 borrow canal. STA-6 became operational in December 1997.

Plant and soil surveys were conducted in STA-6 during July 2002. Field and laboratory methods are discussed in Newman et al. (2003).

TREATMENT PERFORMANCE

Analysis and discussion of past treatment performance in STA-6 appears in previous ECRs (see Jorge et al., 2002; Newman et al., 2003). Summary statistics for all water quality parameters monitored at interior sampling stations in STA-6 during WY2003 are provided in Appendix 4B-7. Time series plots of weekly inflow and outflow TP concentrations for Cells 3 and 5 and daily inflow water for STA-6 at G-600 are presented in **Figure 4B-8**.

The mean inflow TP concentration to STA-6 during WY2003 was 61 µg/L (**Table 4B-4**). Mean outflow TP concentrations from Cells 3 and 5 for the year were 28 and 19 µg/L, respectively; these differences were not statistically significantly (Kruskal-Wallis test, Chi-square p = 1.000). The corresponding mean TP concentration reduction for Cells 3 and 5 were 54 and 69 percent, respectively. The difference in TP concentration reduction was attributed to differences in hydraulic loading rate (HLR); Cell 3 received considerably higher loading (4.9 cm/d) than Cell 5 (2.5 cm/d) in WY2003. Hydraulic residence time (HRT) is inversely related to the HLR; increasing HLR reduces HRT and can promote hydraulic short-circuiting, both of which may reduce wetland treatment performance. It is not clear at this time whether other factors such as differences in vegetation community type were also responsible for the difference in TP concentration reduction between Cells 3 and 5.

Phosphorus speciation data indicate that 75 percent of inflow TP to STA-6 was in the form of particulate phosphorus (PP) (Appendix 4B-7). The mean concentration of soluble reactive phosphorus (SRP) was about the same as total dissolved phosphorus (TDP), suggesting that dissolved organic phosphorus (DOP) levels were negligible. Weekly outflow SRP concentrations in both cells were often at or below the analytical detection limit of 4 µg/L.

Cell	Effective Area (ac)
3	245
5	625
Total	870

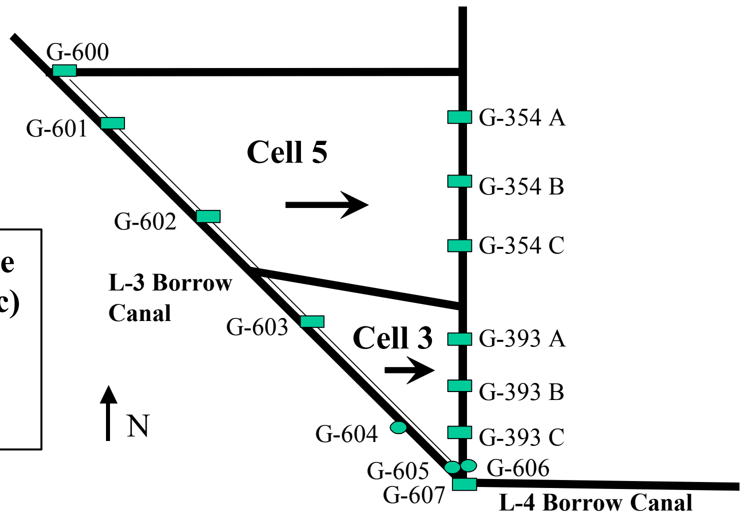


Figure 4B-7. Map of Stormwater Treatment Area 6 (not to scale). Arrows indicate direction of flow.

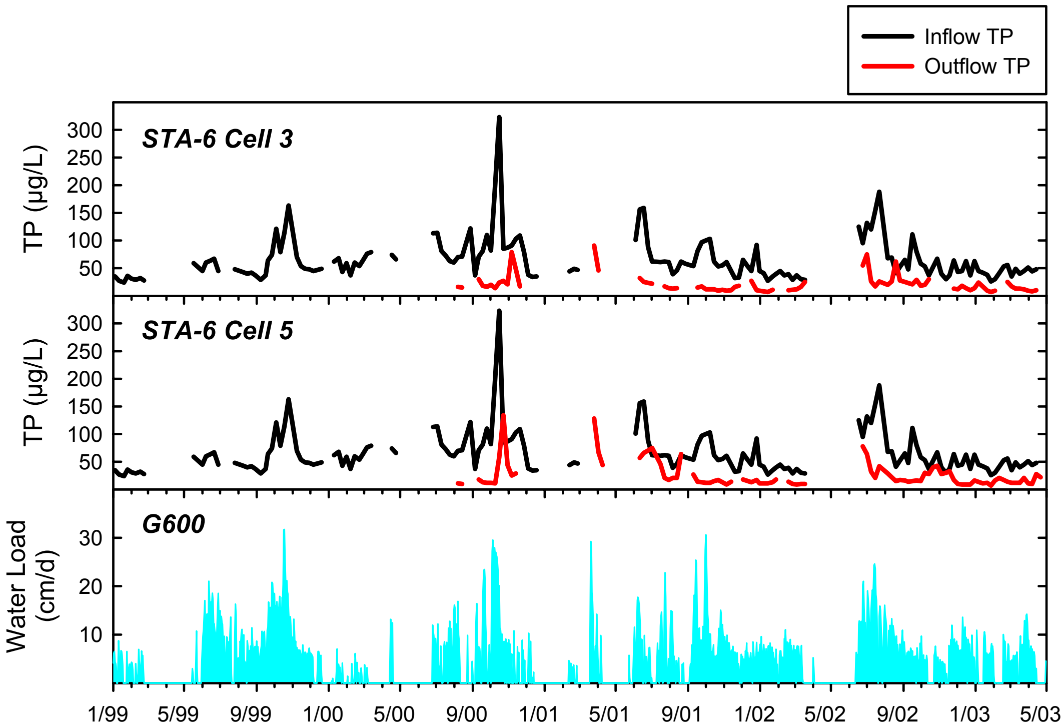


Figure 4B-8. Time series of inflow and outflow weekly total phosphorus concentrations and daily water load for the Cells 3 and 5 of Stormwater Treatment Area 6. Stations and collection methods for TP as follows: Cell 3 inflow and Cell 5 inflow at G-600, flow-proportioned autosamplers; Cell 3 outflow at G-393B, flow-proportioned autosamplers; Cell 5 outflow at G-354C, flow-proportioned autosamplers.

Table 4B-4. Annual geometric mean inflow and outflow total phosphorus (TP) concentrations and TP concentration reduction based on these means for STA-6 during WY2003.

	Mean Inflow TP (µg/L)	Mean Outflow TP (µg/L)	TP Conc. Reduction (%)
STA inflow (G-600)	61	--	--
Cell 3 outflow (G-393B)	--	28	54.1
Cell 5 outflow (G-354C)	--	19	68.8

VEGETATION

A vegetation survey of STA-6 conducted in July 2002 found that the species composition of the plant community has changed little since this wetland began operation in December 1997 (Pietro, in prep.). Cell 5 was dominated by maidencane (*Panicum hemitomon*), torpedograss (*Panicum repens*), switch grass (*Panicum virgatum*), and paragrass (*Brachiaria mutica*), with lesser amounts of smartweed (*Polygonum* spp.), climbing hempweed (*Mikania* spp.), and cattail. Open-water areas of this cell had an abundance of floating periphyton. Cell 3 was dominated by a dense sawgrass (*Cladium jamaicense*) community interspersed with willow (*Salix* spp.). Other species, such as duck potato (*Sagittaria lancifolia*), milk vine, and pickerelweed (*Pontederia cordata*), also were present. The dense periphyton mat common throughout Cell 5 was not present in Cell 3.

Results of chemical analysis of macrophytes collected from STA-6 in July 2002 are presented in **Table 4B-5**. The tissue C content was quite similar among species. Conversely, there was a threefold difference in tissue N content and a tenfold difference in tissue P content among species. Sawgrass, followed by cattail, had the lowest tissue P and N levels of the species examined.

Sediment

The TP content of the floc layer was two to four times higher than that of the underlying sediment in both Cells 5 and 3 (**Table 4B-6**). This indicated that STA-6 was storing P in the floc at far higher concentrations than historic P levels in the underlying sediment. Inspection of the data also revealed differences between cells in sediment nutrient content. The TP and TN content of the floc layer in Cell 5 were higher than in Cell 3. These results agreed with the water quality data, which showed that Cell 5 removed more nutrients from the inflow water than Cell 3.

Table 4B-5. Means and standard deviations for total phosphorus (TP), total nitrogen (TN), and total carbon (TC) content of plant tissue for selected macrophyte species collected from STA-6 in July 2002 (data source: Pietro, in prep.).

			TP (mg/kg)		TN (mg/kg)		TC (g/kg)	
		N	Mean	SD	Mean	SD	Mean	SD
Cell 5	Switchgrass	3	713	296	9330	2029	451.3	16.5
	Paragrass	4	1131	1355	12060	1832	437.0	13.5
	Cattail	1	650	--	8730	--	439.0	--
	Climbing hempweed	1	3380	--	22800	--	435.0	--
Cell 3	Sawgrass	3	313	32	6230	770	454.3	1.5
	Climbing hempweed	1	1170	--	19200	--	448.0	--
	Pickerel weed	1	1820	--	20800	--	408.0	--
	Duck potato	1	1370	--	19300	--	430.0	--
	Willow	1	1200	--	16300	--	491.0	--

Table 4B-6. Means and standard deviations for physical and chemical characteristics of sediment collected from STA-6 in July 2002 (data source: Pietro, in prep.).

	Cell 5		Cell 3	
	Floc layer	**10-30 cm**	**Floc layer**	**10-30 cm**
Bulk density (g/cm^3)	0.10 (0.04)	0.67 (0.19)	0.09 (0.02)	0.35 (0.12)
TP* (mg/kg)	1243 (286)	281 (283)	909 (304)	370 (124)
TN (g/kg)	29 (2)	11 (7)	26 (2)	18 (10)
TC (g/kg)	401 (35)	198 (117)	420 (29)	230 (134)

*TP = total phosphorus; TN = total nitrogen; TC = total carbon.

LONG-TERM TRENDS IN THE STAS

There is sufficient operational data from the STAs available at this time to support an evaluation of long-term trends in treatment performance. Two analyses were performed: (1) flow-weighted outflow TP concentrations from the STAs and the ENRP were regressed against corresponding inflow-weighted outflow TP concentrations and areal TP loading, and (2) annual outflow TP concentrations in these systems were compared with design expectations predicted by the steady-state STA design model (Burns & McDonnell, 1983).

Kadlec (2003) found a strong positive correlation between outflow TP concentration and TP loading in an analysis of data from 283 different wetland systems that spanned four orders of magnitude in concentration and loading. District analysis found similar relationships in the STAs and the ENRP using mean data that represented the operational period of record (POR) for each system. Variance in flow-weighted outflow TP concentration was almost entirely accounted for by the corresponding flow-weighted inflow TP concentration (r^2 = 0.9706) and TP areal loading (r^2 = 0.8948) (**Figure 4B-9**). Inflow TP concentrations in these systems exhibited a fivefold range across these wetlands, while outflow concentrations varied by only a factor of three. These results indicate that the long-term performance of the STAs is almost entirely a function of inflow TP concentration and load and is insensitive to differences in other hydrologic and biogeochemical factors. However, this finding is based on limited operational experience with the STAs and should be considered preliminary. Also, analyses of treatment performance at shorter time-steps (e.g., annual, monthly, etc.) indicate that inflow TP concentration and load account for less variance, suggesting that other factors are important in the short-term.

Treatment performance in STA-2 and STA-6, as measured by annual flow-weighted outflow TP concentrations, exceeded expectations predicted by the STA design model in all water years. That is, annual flow-weighted mean outflow TP concentrations all were less than the corresponding outflow TP concentrations predicted by the model (**Table 4B-7**). The old ENRP also exceeded model predictions of annual treatment performance throughout its operational life. Treatment performance in the other two STAs has not been as consistent. STA-1W did not meet the design expectation in its first operational year, but it did so in the following two years. STA-5 produced higher outflow TP concentrations than predicted by the model in two of the three years the wetland has been in operation.

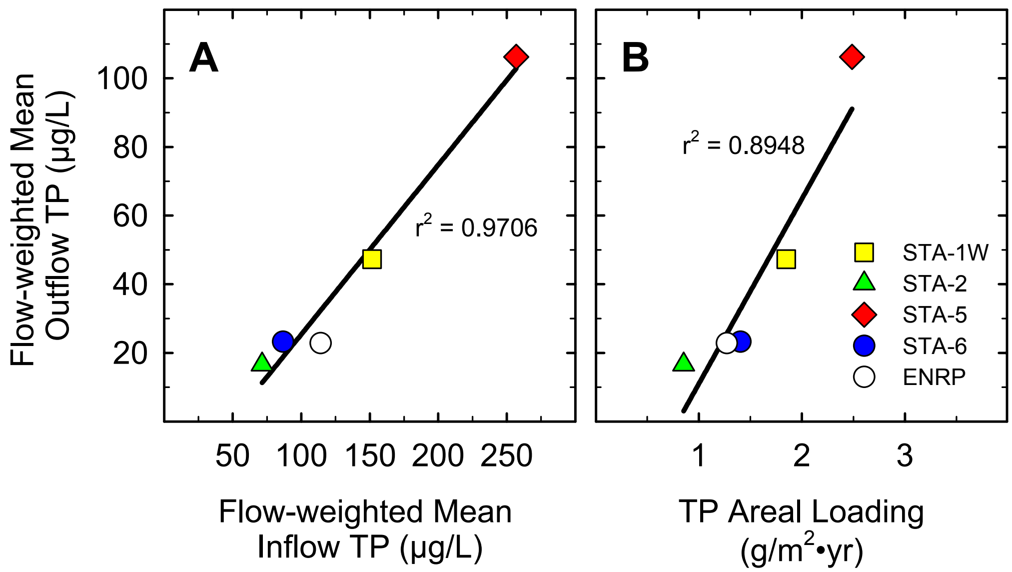


Figure 4B-9. Long-term performance of the Stormwater Treatment Areas and the Everglades Nutrient Removal Project. Relationship of flow-weighted mean outflow total phosphorus (TP) concentration with (A) flow-weighted mean TP inflow concentration and (B) TP areal loading. Period of record for each dataset: STA-1W, STA-5, and STA-6 = WY2001 to WY2003; STA-2 = WY2002 to WY2003; ENRP = WY1995 to WY2001.

Table 4B-7. Evaluation of long-term treatment performance in the Stormwater Treatment Areas and the Everglades Nutrient Removal Project based on comparisons of observed annual average outflow total phosphorus concentrations with design expectations predicted by the STA design model.[a]

		C_{in} (µg/L)	R (m)	ET (m)	Q_{in} (hm^3)	C_r[b] (µg/L)	k (m/yr)	A (m^2)	Obs. C_{out} (µg/L)	Pred. C_{out} (µg/L)
STA-1W	WY2001	148	0.890	1.424	112.1	11	10.2	26,992,532	***39***	***13***[c]
STA-1W	WY2002	148	1.145	1.370	292.0	11	10.2	26,992,532	38	59
STA-1W	WY2003	154	1.075	1.298	582.7	11	10.2	26,992,532	53	97
STA-2	WY2002	77	1.145	1.370	262.5	11	10.2	26,021,287	16	29
STA-2	WY2003	67	1.075	1.298	348.7	11	10.2	26,021,287	17	32
STA-5	WY2001	231	0.922	1.260	71.8	11	10.2	16,632,580	***105***	***22***[c]
STA-5	WY2002	244	0.922	1.260	203.2	11	10.2	16,632,580	78	108
STA-5	WY2003	278	0.922	1.260	209.0	11	10.2	16,632,580	***136***	***126***[c]
STA-6	WY2001	138	1.328	1.423	35.7	11	10.2	3,520,765	31	52
STA-6	WY2002	68	1.201	1.335	65.9	11	10.2	3,520,765	16	40
STA-6	WY2003	78	1.265	1.379	69.4	11	10.2	3,520,765	26	47
ENRP	WY1995	105	1.674	1.200	177.4	11	10.2	15,454,279	23	43
ENRP	WY1996	100	1.498	1.293	265.3	11	10.2	15,454,279	22	55
ENRP	WY1997	78	1.301	1.294	170.4	11	10.2	15,454,279	19	32
ENRP	WY1998	99	1.360	1.320	150.9	11	10.2	15,454,279	21	36
ENRP	WY1999	70	1.291	1.322	125.9	11	10.2	15,454,279	19	21
ENRP	WY2000	184	1.195	1.372	192.8	11	10.2	15,454,279	26	83

[a] $C_{out} = (r\ C_r) + (C_{in} - r\ C_r) \times (1 + a\ A) \exp - (1 + k / [R - ET])$ (Burns & McDonnell, 1993).

where:

- C_{out} = predicted flow-weighted average outflow total phosphorus concentration
- C_{in} = observed flow-weighted average inflow total phosphorus concentration
- C_r = long-term median rainfall total phosphorus concentration
- R = annual rainfall
- ET = annual evapotranspiration
- Q_{in} = annual inflow
- k = net settling rate
- A = wetland treatment area
- r = R / (R-ET + k)
- a = (R-ET) / Q_{in}

[b] The median concentration of total phosphorus in rainfall at the ENRP (March 1992 to July 1997) was used for all wetlands.

[c] Observed average annual outflow total phosphorus concentration exceeded predicted value.

STA-1W TEST CELL RESEARCH

The District has conducted research in the STA-1W test cells since June 1998 to evaluate ways of improving STA treatment performance. These projects were part of either the STA Optimization or ATT programs. All these studies were completed as of January 2002. Results were published in previous ECRs, and project reports were posted on the District's "Ecological Technologies Reports" Website (see previous citation). The District has continued monitoring 12 test cells at a reduced effort to document long-term trends in treatment performance for the following technologies: emergent macrophyte-dominated wetlands, SAV-dominated wetlands, periphyton-dominated wetlands (Periphyton-Based Stormwater Treatment Areas [PSTA]), and chemical treatment/solids separation (CTSS) that coupled a pilot-scale chemical treatment plant to an SAV-dominated test cell (CTSS-SAV). One of the concerns raised about using chemical treatment for Everglades restoration is that the process will change water quality parameters other than TP and that these changes may adversely affect the ecosystem. Monitoring of CTSS-SAV has continued in order to document how much the treatment plant altered water quality and to what degree the downstream wetland reconditioned the water. This section presents updated operational and TP removal data from these 12 test cells for the period January 1, 2002 to April 30, 2003.

The test cells are small, rectangular 0.2-ha (0.5-acre) wetlands isolated hydrologically from each other and arranged into two groups of 15 units: one group is located at the north site in Cell 1 (north test cells) and the other at the south site in Cell 3 (south test cells) of STA-1W. Refer to Chimney et al. (2000) for a more complete description of the test cells. Five of the north test cells and seven of the south test cells were selected for continued monitoring. These cells were operated at a HLR of 2.6 cm/d and a mean depth of 60 cm, except the PSTA cells, which were operated at a mean depth of 30 cm (**Table 4B-8**). The pilot-scale chemical treatment plant used aluminum chloride ($AlCl_3$) and Cytec polymer in its treatment process. See Newman et al. (2003) for background information on the operation of the CTSS-SAV test cell.

Grab samples were collected biweekly at the common inflow to each group of test cells and at the outflow from each test cell. They were analyzed for TP, SRP, TDP, total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_4-N), nitrite+nitrate-nitrogen (NO_x-N), and chloride (Cl). Unless otherwise noted, means discussed in this section are geometric means. Differences in outflow TP concentrations from the test cells were compared using analysis of variance analysis (ANOVA) of log_{10}-transformed data followed by post-hoc mean comparison tests (Tukey-Kramer HSD).

Table 4B-8. Description of the STA-1W test cells monitored since January 1, 2001.

Test Cell Designation	Vegetation Type (dominant species)	HLR* (cm/d)	Depth (cm)	Treatment
E-N1	Emergent (*Typha domingensis*)	2.6	60	Peat substrate
E-N2	Emergent (*Typha domingensis*)	2.6	60	Peat substrate
SAV-N	Submerged (*Chara* sp.)	2.6	60	Peat substrate
SAVLR-N	Submerged (*Chara* sp.)	2.6	60	Peat substrate with a limerock berm
CTSS-SAV	Submerged (*Najas guadalupensis*)	2.6	60	Peat substrate receiving chemically treated water
E-S1	Emergent (*Typha domingensis*)	2.6	60	Peat substrate
E-S2	Emergent (*Typha domingensis*)	2.6	60	Peat substrate
SAV-S	Submerged (*Chara* sp.)	2.6	60	Peat substrate
SAVLR-S	Submerged (*Chara* sp.)	2.6	60	Peat substrate with a limerock berm
P-1	Periphyton (*Eleocharis* sp.)	2.6	30	Shell rock substrate
P-2	Periphyton (*Eleocharis* sp.)	2.6	30	Shell rock substrate
P-P	Periphyton (*Eleocharis* sp.)	2.6	30	Peat substrate

*Hydraulic loading rate.

NORTH TEST CELLS

The adjusted root mean square error was approximately 50 percent for all ANOVAs. All mean TP concentrations at the outflow from the north test cells were significantly lower than the inflow mean value (68 µg/L); mean outflow TP concentrations ranged from 13 µg/L at CTSS-SAV to 31 µg/L at SAV (**Figure 4B-10**). None of the north test cells has achieved an outflow TP concentration of 10 µg/L for any period of time. The mean TP outflow concentration from CTSS-SAV was significantly lower than outflow from the other test cells. Keep in mind that the inflow to the SAV-wetland portion of CTSS-SAV was effluent from the pilot-scale chemical treatment plant, which had very low TP levels (mean = 8 µg/L). These data indicate that the SAV-wetland portion of CTSS-SAV exported a small amount of P. The pattern of differences identified among test cells for mean TDP concentrations were identical to those observed for TP: mean TDP levels at all outflows were significantly lower than at the inflow, and outflow from CTSS-SAV (6 µg/L) was significantly lower than outflow from the other test cells (13 to 15 µg/L). Mean SRP concentrations at all outflows were significantly lower than at the inflow. Although the mean comparison test for this ANOVA grouped the test cells somewhat differently, the general pattern was similar to the groupings for TP and TDP. Mean outflow SRP ranged from a low of 4 µg/L at CTSS-SAV to 9 µg/L at emergent test cell 2 (E-N2).

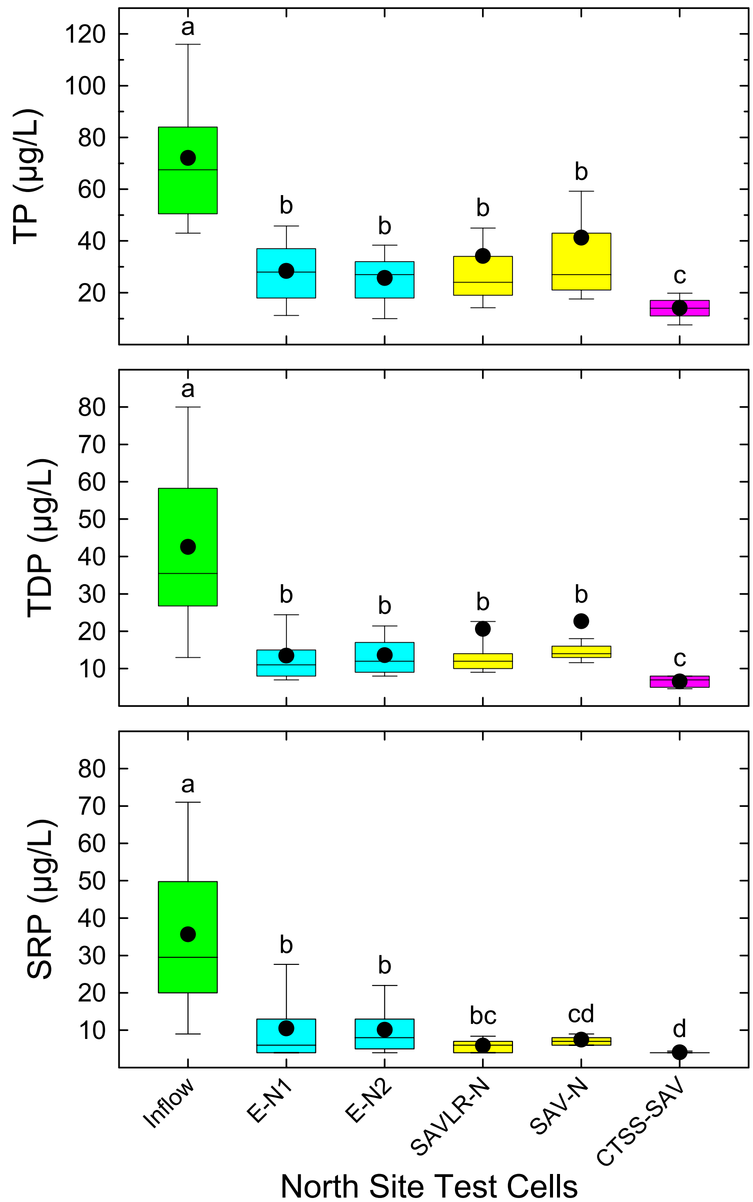


Figure 4B-10. Variation in inflow and outflow total phosphorus (top panel), total dissolved P (middle panel), and soluble reactive P (bottom panel) concentrations for emergent-dominated (E), SAV-dominated (SAV), and CTSS-SAV test cells located at the north site of STA-1W, January 2002 to April 2003. Test cells with different letter designations are significantly different from each other at $\alpha = 0.05$. Description of box plots: top and bottom of box = 75th and 25th percentiles, respectively; mid-line in box = median; ends of whiskers = 10th and 90th percentiles; closed circles = arithmetic means.

Mean Al and Cl concentrations in effluent from the pilot-scale chemical treatment plant (620 and 235 mg/L, respectively) were approximately 10 and 2 times higher than corresponding levels at the plant inflow (58 and 139 mg/L, respectively; **Table 4B-9**). Conversely, the treatment process reduced the alkalinity of the effluent water by almost half that of the inflow. The downstream SAV wetland dramatically reduced Al levels; the mean concentration at the test cell outflow (20 mg/L) was far below even inflow levels to the plant. However, the SAV wetland had no discernable treatment effect on either alkalinity or Cl levels.

Table 4B-9. Geometric means for alkalinity, aluminum, and chloride in the CTSS-SAV test cell from January 1, 2002 to April 30, 2003. Water samples were collected at the inflow to the pilot-scale chemical treatment plant, outflow from the plant and inflow to the test cell, and outflow from the test cell.

	Pilot plant Inflow	Test Cell Inflow	Test Cell Outflow
Alkalinity (mg $CaCO_3$/L)	235.4	124.6	117.0
Aluminum (mg/L)	57.9	619.6	20.4
Chloride (mg/L)	139.0	228.8	234.6

SOUTH TEST CELLS

The adjusted root mean square error was approximately 50 percent for all ANOVAs, except for the ANOVA performed on SRP outflow concentrations, where only 40 percent of the total variance was explained by differences between test cells. The mean inflow TP concentration to the south test cells (32 µg/L) was substantially lower than at the north test cells (mean inflow TP = 68 µg/L), because the source water to the south site received more treatment as it traveled down the east flow-path of STA-1W. Not all mean outflow TP concentrations at the south site were significantly lower than the inflow mean TP concentration; one SAV-dominated (SAV) test cell and the PSTA test cell based on peat (P-P) were not significantly different from the inflow, while one emergent-dominated (ES-1) test cell was significantly higher (**Figure 4B-11**). Both PSTA test cells lined with shellrock (P-1, P-2) had significantly lower mean outflow TP concentrations (13 µg/L and 14 µg/L, respectively) than the other test cells. None of the south test cells ever achieved an outflow TP concentration of 10 µg/L for any period of time. The data indicate that P-P and E-S1 were net P exporters. It is unclear why E-S1 had such high outflow TP values during this period, while the other emergent-dominated test cell (E-S2) did not.

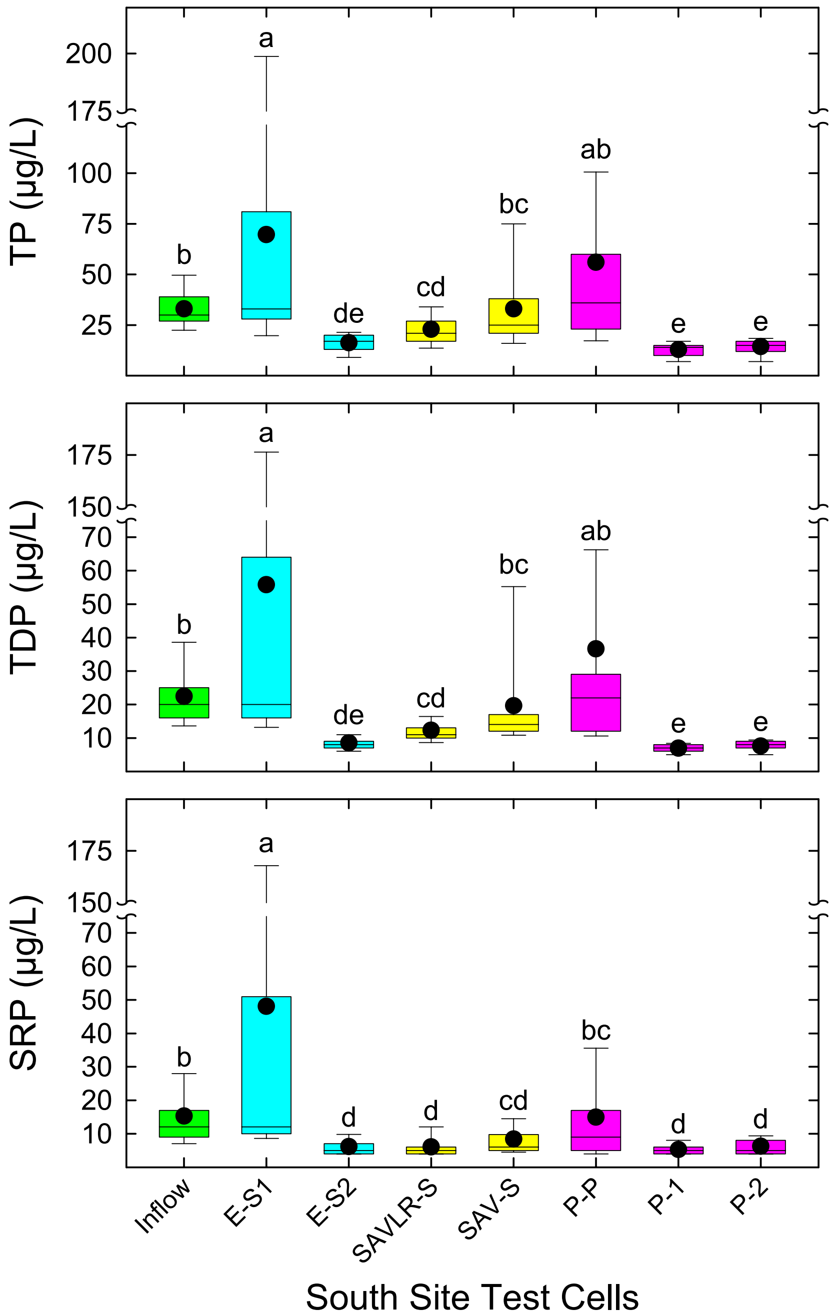


Figure 4B-11. Variation in inflow and outflow total phosphorus (top), total dissolved P (middle), and soluble reactive P (bottom) concentrations for emergent-dominated (E), SAV-dominated (SAV), and periphyton-dominated (P) test cells located at the south site of STA-1W, January 2002 to April 2003. Test cells with different letter designations are significantly different from each other at $\alpha = 0.05$. Description of box plots: top and bottom of box = 75th and 25th percentiles, respectively; midline in box = median; ends of whiskers = 10th and 90th percentiles; closed circles = arithmetic means.

ANALYSIS OF OTHER AQUATIC SYSTEMS

Data from constructed and natural wetlands in the region, such as the Water Conservation Areas, Iron Bridge (Orlando, FL), and Boney Marsh (Kissimmee, FL), were evaluated to gain insight into the long-term treatment performance that might be expected from subtropical wetlands and to help establish design criteria for the STAs (Kadlec and Newman, 1992; Walker, 1995). As part of STA Optimization, the District performed additional analyses of treatment performance in Boney Marsh[4] (Moustafa, 1997, 1998, 1999; Moustafa et al., 1996, 1998). Results from these analyses are summarized in Chimney and Moustafa (1999).

The District's experience with SAV-dominated wetlands, both in STA treatment cells dominated by SAV and in the Submerged Aquatic Vegetation/Limerock research project conducted under the ATT program (see Advanced Treatment Technology section, below), indicates that this plant community is capable of reducing TP to very low levels (Chimney et al., 2000; Gu et al., 2001; Nungesser et al., 2001; Dierberg et al., 2002; Jorge et al., 2002; Newman et al., 2003). However, there is a question about the long-term viability of P storage in such wetlands. To address this issue, the District commissioned two studies of long-term P storage in Florida systems that historically have been dominated by SAV: the Lake Panasoffkee Sediment Study and the Florida Lake and River Survey.

LAKE PANASOFFKEE SEDIMENT STUDY

Lake Panasoffkee (LP) is a shallow (mean depth = 1.3 m), mesotrophic (mean TP = 27 µg/L) hard-water lake located in Sumter County, FL that historically has supported extensive SAV beds. Currently, 94 percent of the lake bottom is covered by SAV, including the genera *Ceratophyllum*, *Hydrilla, Chara*, *Vallisneria,* and *Najas*. The upper 20 cm of the sediments may be described as a marl or calcitic mud, characterized by high calcium content (approximately 70 to 80 percent $CaCO_3$), moderate to high TP content (approximately 300 to 600 mg/kg), and low organic content (loss on ignition approximately ≤ 25 percent). This system was well suited for a study of the long-term importance of SAV in P sequestration in the sediments. The objectives of this study were to use paleolimnological techniques to reconstruct the history of SAV abundance in LP, to identify the dominant sources of organic matter in the sediment, and to evaluate how sediment P accumulation has changed over time relative to SAV abundance.

Sediment cores were collected from two sites in LP in May and December 2001. They were sectioned and then analyzed for C, N, P, and stable C isotope content (Hodell et al., 2002; see Appendix 4B-8). These data suggested that prior to the 1890s, the predominant source of organic C in the sediments was emergent macrophytes, not SAV. Several lines of evidence suggested that the abundance of SAV began to increase in LP starting in the late 1800s and continued to the early 20th century. First, several biogeochemical indicators suggested increased plant productivity and SAV abundance, i.e., an increase in organic C and N concentrations, a decrease in C/N ratios, and increases in the $\delta^{13}C$ (C 13 isotope) and $\delta^{15}N$ (N 15 isotope) in the buried organic matter. Second, the abundance of sediment macrofossils from SAV species, including stem nodes, strands, and seeds (especially for southern naiad), increased over the same period. Third, the alga *Pediastrum*, generally associated with the presence of SAV, increased in abundance beginning in the late 1800s.

[4] Boney Marsh was a small treatment wetland (48 ha) built by the District on the Kissimmee River floodplain in Highlands County, FL. It was operated from 1976 to 1987 (Davis, 1981; Mierau and Trimble, 1988) to evaluate the effectiveness of overland flow as a means of improving water quality.

This study concluded that increased nutrient loading to LP during the last century stimulated the growth of SAV and associated microflora (e.g., periphytic algae). This new plant biomass was a sink for P that eventually became deposited in the sediments. Sediment P concentrations increased in conjunction with increased SAV biomass. The long-term stability of this storage compartment is difficult to access because most of the P was stored in the upper 10 cm of sediment and potentially subject to diagenesis and release back to the water column. However, we do not know that there is any appreciable return flux of sediment P in this system. Phosphorus bound to calcitic sediments is usually considered very stable.

FLORIDA LAKE AND RIVER SURVEY

The objective of this study was to analyze historical data available in the literature and from other sources for selected Florida SAV-dominated lakes and rivers to address two questions: (1) have these systems effectively removed P on a long-term basis and at what rates, and (2) how do these systems respond to changes in TP loading, hydraulic loading, and changes in the species composition of the SAV community. Results of this study have recently been published in *Ecological Engineering* (Knight et al., 2003; see Appendix 4B-9).

Knight et al. (2003) analyzed data from eleven lakes (Harney, Hellen Blazes, Isotokpoga, Kissimmee, Myakka, Panasoffkee, Poinsett, Rodman Reservoir, Sawgrass, Seminole, and Tarpon) and two rivers (Wekiva and Withlacoochee). Each system had at least 20 percent SAV areal coverage in one or more years based on surveys conducted from 1983 to 1995. *Hydrilla* was the dominate SAV species in all systems except for Lake Harney, Panasoffkee, and the Wekiva River, where *Vallisneria* was dominant. Substrate composition differed among systems and included clay, sand, gravel, marl, and organic detritus. These systems had an average POR for water quality and flow data of 30 yrs (range from 18 to 45 yrs). Ten systems exhibited net TP removal over their POR. Mean TP uptake for the lakes (1.2 $g/m^2 \cdot yr$) and rivers (3.7 $g/m^2 \cdot yr$) was similar to STA-1W Cell 4, an SAV-dominated wetland (1.3 $g/m^2 \cdot yr$; Nungesser et al., 2001). This was despite the fact that inflow TP concentrations, hydraulic loading, and TP loading in the Florida systems were higher, sometimes markedly so, than in Cell 4. The likely long-term sink for TP removed from the water column in the Florida systems was accretion to the sediments. Knight et al. (2003) surmised that the Florida systems operated under the same biogeochemical principles as constructed treatment wetlands and found that after decades of operation, the Florida systems continued to remove TP at rates comparable to the STAs.

ADVANCED TREATMENT TECHNOLOGY

The District's Advanced Treatment Technology (ATT) program evaluated the eight treatment technologies listed below to determine critical design criteria, such as performance efficacy, hydrologic operating characteristics, start-up capital, operating costs, and identification of potential environmental impacts:

- Periphyton-Based Stormwater Treatment Areas (PSTA)
- Submerged Aquatic Vegetation/Limerock (SAV)
- Managed Wetlands Treatment Systems (MWTS)
- Low-Intensity Chemical Dosing (LICD)
- Chemical Treatment/Solid Separation (CTSS) coupled with (a) Direct Filtration, (b) High-Rate Sedimentation, (c) Dissolved-Air Flotation, and (d) Microfiltration

The PSTA and SAV technologies are based on managing constructed wetlands to establish a plant community dominated by either SAV or periphyton and are referred to as biological, or "green," technologies. All the CTSS technologies are based on conventional wastewater treatment strategies. The primary differences among the CTSS technologies were the chemical(s) used to precipitate the phosphorus (aluminum or iron salts combined with organic polymers) and the method used to remove the floc from the water. The MWTS and LICD technologies are hybrids that combined wetlands with some level of chemical treatment. Both MWTS and LICD were classified as chemical-based technologies. All projects conducted experiments and/or demonstration projects at various spatial scales that focused primarily on removing P from Everglades Agricultural Area (EAA) runoff and/or effluent from the STAs. Each project had an independent scientific review panel. Results also were reviewed by the Florida Department of Environmental Protection (FDEP), other state and federal agencies, and interested stakeholders. All projects were completed as of January 2002. Extensive descriptions of each project and summaries of the results and conclusions can be found in Coffelt et al. (2001), Jorge et al. (2002), and Newman et al. (2003). Project reports for each study are available on the District's "Ecological Technologies Reports" Website (cited previously). The District has continued monitoring the PSTA field-scale test facility (see below) and the PSTA, SAV, and CTSS experiments in the STA-1W test cells (discussed above under STA-1W Test Cell Research) at a reduced effort to document long-term trends in P removal in these wetlands. In addition, the District has proposed conducting a side-by-side demonstration of SAV and PSTA at full-scale in STA-3/4 as a final effort to obtain design information for these two technologies.

PSTA FIELD-SCALE TEST FACILITY

Experimental Cells

The District's PSTA field-scale test facility (PSTA test facility) is located adjacent to STA-2 and consists of four 2-ha (5-acre) experimental cells (**Figure 4B-12**) with different substrates. The peat substrate in Cells 1 and 2 was covered with 60 cm of shellrock, the peat in Cell 3 was removed to expose the underlying caprock (limestone), and the peat in Cell 4 was left unamended (**Table 4B-10**). Cells 1, 3, and 4 have a length-to-width ratio of 5:1, while Cell 2 was constructed using a sinuous pathway, resulting in a length-to-width ratio of 43:1. Additional information about the physical characteristics and hydrology of the experimental cells is provided in **Tables 4B-10** and **4B-11** and in Newman et al. (2003). The inflow water to the PSTA test facility is pumped from Cell 3 of STA-2.

The PSTA test facility began operation in August 2001. Inflow to the experimental cells was stopped from April 22, 2002 to July 30, 2002 due to a severe drought in South Florida and lack of water in STA-2. Other short-term disruptions in operation occurred due to vegetation maintenance and pump outages. The experimental cells had a target water depth of 30 cm and a nominal hydraulic retention time (HRT) of five days (**Table 4B-11**). However, actual water depth varied in all experimental cells throughout the POR (April 2001 to March 2003; **Figure 4B-13**). Generally, the peat-based cell (Cell 4) had the lowest water depth due to higher seepage loss compared to the other experimental cells. The water budget for each experimental cell is summarized in Appendix 4B-10.

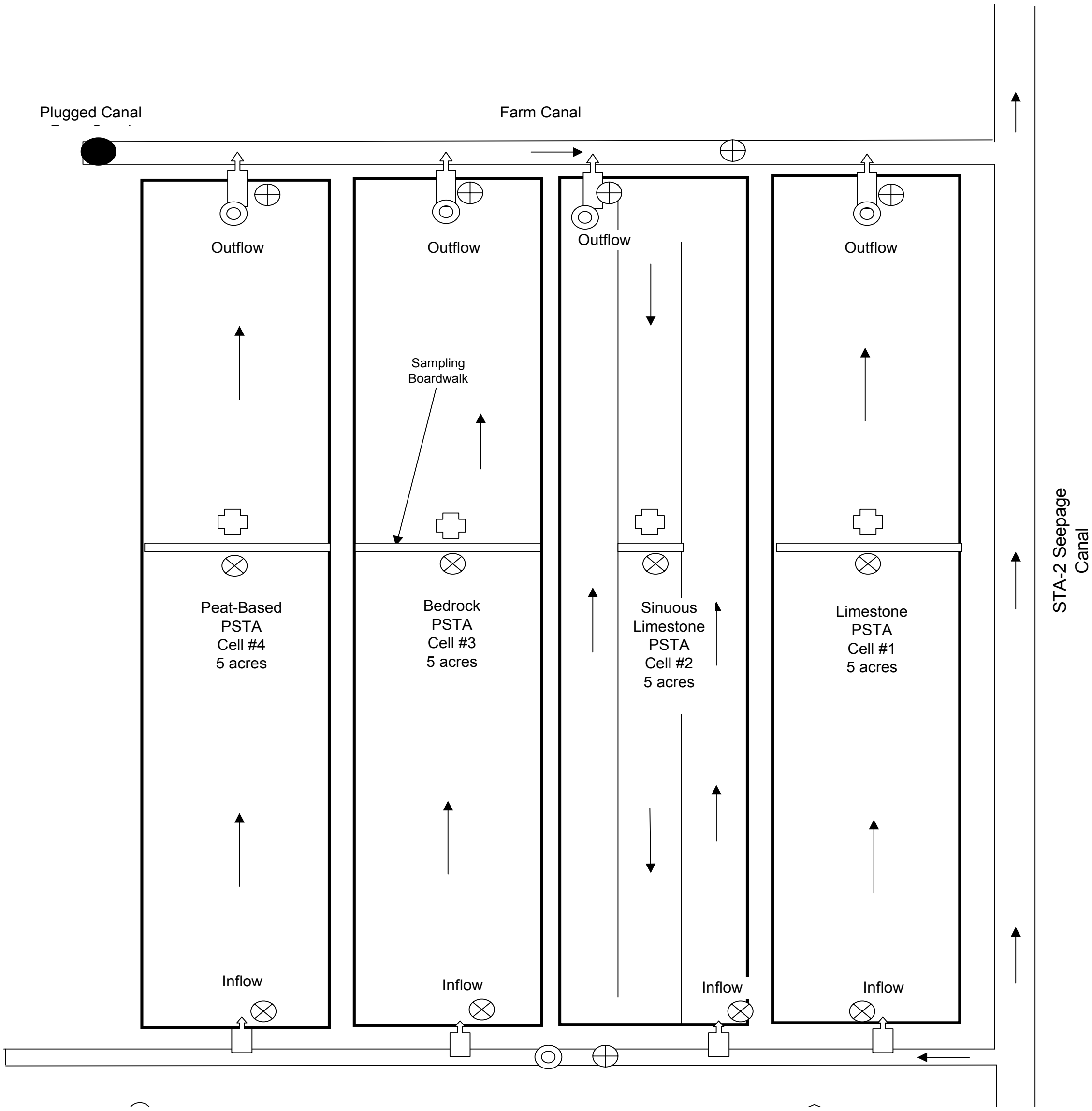


Figure 4B-12. Schematic of the Periphyton-Based Stormwater Treatment Area field-scale test facility. The site is located along the western boundary of STA-2. Arrows indicate direction of flow.

Table 4B-10. Substrate type and physical characteristics of experimental cells in the Periphyton-Based Stormwater Treatment Area (PSTA) field-scale test facility (data source: CH2MHill, 2003).

	Cell 1	**Cell 2**	**Cell 3**	**Cell 4**
Substrate type	Limerock over peat	Limerock over peat	Caprock	Peat
Cell length (m)	315	945	315	315
Cell width (m)	66	22	66	66
Length:width aspect ratio	5:1	43:1	5:1	5:1
Nominal linear velocity (m/d)	63	189	63	63

Table 4B-11. Design parameters and hydraulic operating criteria for the Periphyton-Based Stormwater Treatment Area field-scale test facility (data source: CH2MHill, 2003).

Flow (m^3/d) – average	1250
Flow (m^3/d) – maximum	2500
Flow (m^3/d) – minimum	0
Surface area (m^2)	20790
Average operational water depth (m)	0.30
Average operational water volume (m^3)	6237
Nominal hydraulic residence time (d) under average flow and depth	5.0
Hydraulic loading rate (cm/d) under average flow and depth	6.0
Average design total phosphorus influent concentration (µg/L)	25
Average total phosphorus mass loading (g/m^2/yr)	0.55

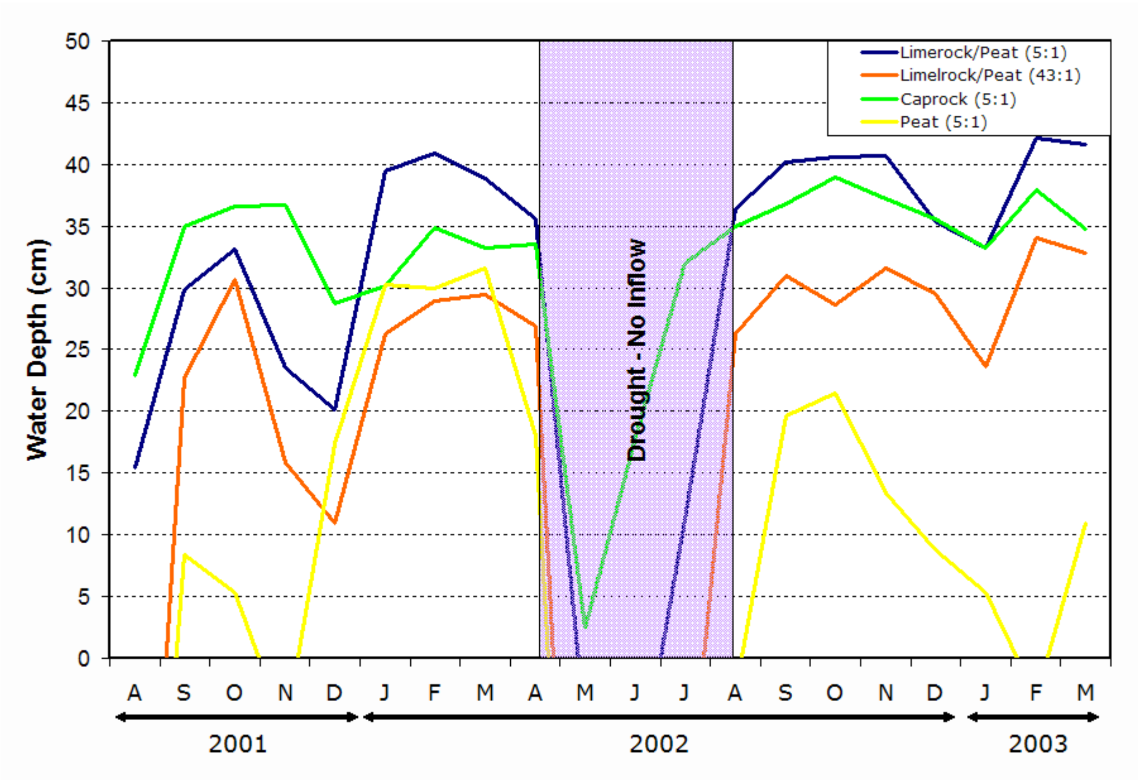


Figure 4B-13. Monthly mean water depth in each of the experimental cells in the Periphyton-Based Stormwater Treatment Area field-scale test facility, April 2001 to March 2003. The inflow pumps were shut down in December 2001 and 2002 during vegetation management and from April through July 2002 due to a severe drought in South Florida.

Cells 1, 2, and 3 had a mean TP concentration reduction during the POR of 5 to 7 µg/L. Mean outflow TP values during this period were 18, 14, and 15 µg/L, respectively (**Table 4B-12**). The sinuous cell (Cell 2) had the lowest individual mean outflow TP concentration (13 µg/L in WY2003). Conversely, the peat-based cell had a net increase in outflow mean TP. Mean inflow and outflow SRP concentrations in all experimental cells were at or close to the method detection limit of 2 µg/L. This indicated that DOP was the predominate form of dissolved P in these wetlands. Cell 1 reduced a larger proportion of inflow SRP concentration (30 percent) and actually exported DOP, while Cells 2 and 3 were more efficient at reducing inflow PP concentration (39 percent and 43 percent, respectively) **(Table 4B-13**). The peat-based wetland (Cell 4) exported all P fractions. Summary statistics for water quality parameters monitored in each experimental cell are presented in Appendix 4B-11.

Hydraulic dye tracer studies were conducted in Cells 2 and 4 from March 11, 2002 and April 1, 2002, and in Cells 1 and 3 from October 29, 2003 to November 13, 2003 using rhodamine WT dye and lithium (Li) (CH2MHill, 2003). Substantial leakage of dye was observed between Cells 1 and 2 and from Cells 1 and 2 back to the inflow canal. No dye was found in the groundwater wells that surrounded the site. This indicated that the direction of seepage was primarily horizontal through the levees rather than vertical through the cell floors. The mass of Li recovered in Cells 1, 2, 3, and 4 was 46 percent, 45 percent, 101 percent, and 6 percent, respectively, indicating that Cell 4 had the highest seepage rate (**Table 4B-14**). The measured HRTs ranged from 2.5 d in Cell 2 to 5.1 d in Cell 1 and were comparable to the nominal HRTs calculated for each experimental cell. The sinuous cell (Cell 2), which had the largest aspect ratio, had the highest tank-in-series (TIS) estimate of 25.0, while the other experimental cells had TIS estimates that ranged from 4.5 to 9.3.

Table 4B-12. Geometric mean concentrations of total phosphorus, total dissolved P, and soluble reactive P at the inflow and outflow of each experimental cell in the Periphyton-Based Stormwater Treatment Area field-scale test facility for the period of record (POR) and by water year (WY2002 and WY2003).

	Cell 1		Cell 2		Cell 3		Cell 4	
	In	Out	In	Out	In	Out	In	Out
Total Phosphorus (µg/L)								
POR	23	18	21	14	21	15	20	25
WY2002	22	19	21	15	20	14	19	20
WY2003	23	17	21	13	22	15	20	30
Total Dissolved Phosphorus (µg/L)								
POR	11	8	11	9	9	8	10	12
WY2002	9	7	9	9	8	7	9	10
WY2003	13	9	13	10	10	9	12	13
Soluble Reactive Phosphorus (µg/L)								
POR	2	2	3	2	3	2	3	3
WY2002	2	2	3	2	2	2	4	3
WY2003	3	3	3	3	3	2	2	3

Table 4B-13. Concentration reduction of particulate phosphorus (PP), soluble reactive P (SRP), and dissolved organic phosphorus P (DOP) for each experimental cell in the Periphyton-Based Stormwater Treatment Area field-scale test facility. Concentration reduction was calculated using the inflow and outflow geometric means for the entire period of record (August 2001 through April 2003).

	Cell 1	Cell 2	Cell 3	Cell 4
PP (%)	11.5	39.0	43.4	-65.1
SRP (%)	30.4	13.4	0.8	-7.0
DOP (%)	-21.5	3.5	13.8	-28.8

Table 4B-14. Summary of hydraulic conditions and results from a lithium tracer study conducted in the experimental cells in the Periphyton-Based Stormwater Treatment Area field-scale test facility (data source: CH2MHill, 2003).

	Cell 1	Cell 2	Cell 3	Cell 4
Study period	Oct-Nov 2002	Mar-Apr 2002	Oct-Nov 2002	Mar-Apr 2002
Average Depth (m)	0.41	0.29	0.38	0.31
Average Volume (m^3)	8337	5868	7753	6273
Average Flow (m^3/d)	2875	2084	3160	1445
Nominal HRT* (d)	2.9	2.8	2.5	4.3
Actual HRT (d)	5.1	2.5	3.0	4.2
No. of tanks-in-series	9.0	25.0	4.5	9.3
Volumetric Efficiency (%)	177	89	124	97
Mass Recovery (%)	46	45	101	6

* hydraulic retention time.

Mesocosms

Measurement of TP removal in the PSTA test facility and the STA-1W test cells indicated that peat-based cells did not perform as well as cells in which the peat had been removed or capped with limerock. We attributed these differences to the continued flux of P from the peat to the overlying water column in the peat-based cells. A mesocosm study was conducted to determine if soil amendments, other than capping with limerock, would improve the performance of the peat-based cells. Based on a literature review of the use of soil amendments in wetlands (CH2MHill, 2003), the District selected Poly-aluminum chloride (PACL), ferric chloride ($FeCL_3$), and hydrated lime (lime) for use in this study. Each amendment was incorporated into the peat in duplicate 1.14 m^2 mesocosms at two different application rates (low and high). The peat in one mesocosm was left unamended and was run as a control. The peat in the mesocosms was treated with chemicals on August 13, 2002 and allowed to equilibrate in batch mode before flow-through operation began on October 22, 2002. Data collection continued from this date until December 18, 2002 (CH2MHill, 2003).

Hydraulic loading to the mesocosms ranged from 5.6 to 7.3 cm/d. Inflow TP concentrations averaged 21 µg/L. Mean outflow concentrations for all P fractions, except SRP, were higher than the corresponding inflow mean concentration in all treatments, including the control (**Table 4B-15**). Mean outflow SRP concentrations were 1 to 2 lower µg/L than the inflow mean in all but one treatment (PACL – low). These results indicate that the application rates used for PACL, $FeCl_3$, and lime were not effective at eliminating P flux from the sediment to the water column.

Table 4B-15. Average concentrations of phosphorus species at the inflow and outflow of peat-based mesocosms treated with soil amendments at different application rates, October 22 to December 18, 2002 (data source: CH2MHill, 2003). Mesocosms were located at the Periphyton-Based Stormwater Treatment Area (PSTA) field-scale test facility. See text for description of soil amendments.

	Application Rate (g/m^2)	Average Concentration (µg/L) TP*	TDP	SRP	TPP	DOP
PSTA Inflow		21	10	6	11	4
Control	none	33	15	5	18	10
$FeCl_3$ - High	47.8	27	15	4	12	12
$FeCl_3$ – Low	12.2 & 12.5	27	14	4	12	10
Lime – High	344.7 & 345.6	53	27	5	25	22
Lime – Low	88.5	37	19	5	19	14
PACL – High	23.3	27	14	4	12	10
PACL – Low	6.0	28	16	6	13	10

* TP = total phosphorus; TDP = total dissolved phosphorus; SRP = soluble reactive phosphorus; TPP = total particulate phosphorus; DOP = dissolved organic phosphorus.

STA-3/4 PSTA DEMONSTRATION

The STA Optimization and ATT programs have demonstrated that the green technologies (SAV and PSTA) can reduce P to very low levels. These two technologies are preferred by the District and the FDEP for use in Everglades restoration over chemical-based wastewater treatment technologies. At this time, it is envisioned that the final design for the STAs will incorporate upstream cells dominated by emergent macrophytes coupled with downstream SAV or PSTA cells. However, uncertainty remains about the treatment efficiency and/or cost of both SAV and PSTA. The District has investigated SAV and PSTA at a variety of spatial scales, but each technology was studied in separate research/demonstration projects, and only SAV has been implemented at full-scale. Both technologies have achieved outflow total P concentrations that consistently approached 10 µg/L, but only in small-scale implementations. In addition, the cost of implementing PSTA at full-scale has been estimated to be as high as $30,000/acre. An evaluation of all PSTA research studies conducted by the District and other parties has been made by Robert Kadlec and William Walker (Kadlec and Walker, 2003; see Appendix 4B-12). This document provided the scientific basis for the conceptual plan outlined below.

The District proposes to conduct a side-by-side comparison of the treatment efficacy of SAV and PSTA at full-scale in an operating STA (STA-3/4). The conceptual design for this demonstration project is the product of a working group composed of agency representatives and several consultants. The PSTA working group benefited from the expertise of Robert Kadlec, Robert Knight, and William Walker on constructed wetlands, and Galen Miller on STA design and engineering. In summary, a 400-acre section in one of the treatment cells in STA-3/4 (Cell 2B) will be isolated by constructing new internal levees to form an upstream, 200-acre cell and two adjacent downstream 100-acre cells. The upstream cell will be managed for SAV and is intended only to condition the water. SAV will be established in one of the downstream cells; a periphyton community will be established in the other. The downstream cells will receive a hydraulic load that is proportionate to the load on the entire STA and consistent with its flood-control mission. Due to the scale and cost of this project, the downstream SAV and PSTA cells cannot be replicated. Therefore, this effort must be viewed as a demonstration project. Both cells will be monitored extensively to provide information on the relative treatment performance of SAV and PSTA at full-scale. The conceptual plan for the design and construction of this facility and a draft monitoring plan are summarized in **Table 4-16** and provided in Appendices 4B-13 and 4B-14.

Table 4B-16. Description and summary of major components of conceptual design for the STA-3/4 PSTA Demonstration Project.

Project Design	• 400 acres located on the west side of STA-3/4 Cell 2B configured as a 200 acre headcell (SAV dominated) followed by 2 adjacent 100 acres cells, one dominated by SAV and the other by PSTA • Project will receive water from upstream Cell 2A dominated by emergent macrophytes • Hydraulic loading to Project proportional to flood-control operation of STA-3/4, process ca. 20% of total flow through Cell 2B • Hydraulic load will be balanced between SAV and PSTA demonstration cells • Anticipate TP inflow to PSTA and SAV demonstration cells to be in the range of 25-30 µg/L • Survey of as-built bottom topography at ± 5 cm accuracy
Water Quality	• Routine water quality monitoring at inflow and outflow points to each cell. • Weekly sampling: total P (autosampler); total dissolved P and soluble reactive P (grab samples) • Monthly sampling: nitrite+nitrate-N, ammonia-N, total Kjeldahl-N, calcium, chloride, and total suspended solids (grab samples) • Continuous measurements for dissolved oxygen, temperature, pH, and conductivity • Intensive inflow-outflow TP monitoring if dryout occurs • Intensive inflow-outflow TP monitoring during several pumping events each year
Hydrology	• Flow measurements at all inflow and outflow points based on continuous headwater and tailwater stage measurements • Continuous depth measurements in each cell • Continuous meteorological data (rainfall, temperature, humidity, solar insolation) from weather station established in STA-3/4 • Annual hydraulic tracer test in each cell to determine hydraulic residence times and identify an areas of short circuiting • Seepage monitoring along dividing levees (if necessary)
Vegetation	• Periodic surveys in each cell for vegetation coverage (bimonthly), biomass (quarterly) and tissue nutrient content (quarterly); annual vegetation map of site produced as part of routine monitoring in STA-3/4
Sediment	• Monitor sediment accretion and annual sediment analysis with P fractionation at all inlet and outlet points

LINKAGE OF RESEARCH AND MONITORING TO STA MANAGEMENT

The numerous experiments and project demonstrations conducted as part of the STA Optimization and ATT programs over the past nine years can be categorized as belonging to two alternative treatment approaches: biological, or green, treatment (emergent wetlands, SAV, and PSTA) or chemical treatment (variants of CTSS, MWTS, LICD). As noted above, the CTSS technologies are all based on conventional wastewater treatment strategies. The primary differences among them are the chemicals used to precipitate the P (aluminum or iron salts combined with organic polymers) and the method used to sediment the floc from the water column. The MWTS and LICD technologies were hybrids that combined some level of upstream chemical treatment with a downstream wetland to condition the water. Neither MWTS nor LICD was judged effective at reducing TP levels to target levels. While some of the CTSS variants did achieve outflow TP concentrations that consistently approached 10 µg/L, serious concerns about high capital and operation costs, disposal of residuals, and the potential impact of the effluent from a chemical treatment plant on the Everglades ecosystem remain unresolved. Because of this uncertainty, the District and the FDEP have decided not to include chemical treatment in future plans for Everglades restoration and have stopped research on these technologies. Monitoring of the CTSS-SAV test cell will cease at the end of FY2003.

Everglades restoration is now focused on developing the green technologies to the maximum extent possible. This approach is based on manipulating hydrology together with selective vegetation management to create a wetland plant community dominated by emergent macrophytes, SAV, or PSTA. Research has indicated that SAV and PSTA have the potential to reach target TP levels on a consistent basis. One scenario for improving performance in the STAs envisions that these wetlands would be reconfigured internally to contain sequences of cells dominated by emergent macrophytes followed by cells dominated by SAV. Another possible scenario would sequence cells dominated by emergent macrophytes followed by SAV followed by PSTA. The PDE component of the Conceptual Plan for Achieving Long-Term Water Quality Goals is the mechanism whereby the District and the FDEP will continue to investigate ways to exploit green technologies for use in Everglades restoration.

The STA Optimization program has both direct and indirect linkages to STA management. For example, results from the ENRP validated the premise that treatment wetlands constructed on former agricultural land can effectively reduce TP levels in EAA runoff and achieve outflow concentrations less than the interim target level of 50 µg/L. Observations of the enhanced treatment performance of the SAV community in Cell 4 of STA-1W prompted the District to establish SAV in the other STAs. Treatment performance data from a number of platforms monitored by the STA Optimization program (e.g., ENRP, STAs, STA-1W test cells, SAV community in STA-1W Cell 4) were used to calibrate the Dynamic Model for the Stormwater Treatment Areas (DMSTA) model written by William Walker and Robert Kadlec (Walker and Kadlec, 2003; see brief description of DMSTA in Jorge et al, 2002). DMSTA was used to evaluate alternative combinations of treatment technologies as part of the Basin-Specific Feasibility Study recently conducted by the District (Burns & McDonnell, 2002; Brown and Caldwell, 2002; Goforth et al., 2003). DMSTA also will be used extensively in the PDE component of the Conceptual Plan for Achieving Long-Term Water Quality Goals (Chapter 8A of the 2004 ECR; Burns & McDonnell, 2003). Past monitoring of sediment and vegetation in the STAs provides baseline information to characterize similarities and differences among STAs. This information will be coupled with future monitoring efforts to model STA treatment performance.

LITERATURE CITED

Brown and Caldwell. 2002. Basin Specific Feasibility Studies, Everglades Stormwater Program Basins. Contract C-E024. Final report prepared for the South Florida Water Management District, West Palm Beach, FL.

Burns & McDonnell. 1993. Everglades Protection Project, Palm Beach County, Florida. Appendix A to Settlement Agreement, Conceptual Design of Mediated Technical Plan (Draft), November 5, 1993. 92-166-1-002

Burns & McDonnell. 1996. Everglades Construction Project STA-6, Section 1 Design Analysis. Report prepared for the South Florida Water Management District, West Palm Beach, FL.

Burns & McDonnell. 2002. Basin-Specific Feasibility Studies, Everglades Protection Area Tributary Basins, Evaluation of Alternatives for the ECP Basins. Contract No. C-E023. Report prepared for the South Florida Water Management District, West Palm Beach, FL.

Burns & McDonnell. 2003. Everglades Protection Area Tributary Basins, Conceptual Plan for Achieving Long-term Water Quality Goals. Report prepared for the South Florida Water Management District, West Palm Beach, FL.

CH2M Hill, Inc. 2003. PSTA Research and Demonstration Project Phase 1, 2, and 3 Summary Report. February 1999 to September 2002. C-E8624. Prepared for the South Florida Water Management District, West Palm Beach, FL.

Chimney M.J. and M.Z. Moustafa. 1999. Chapter 6: Effectiveness and Optimization of Stormwater Treatment Areas for Phosphorus Removal. Redfield, G., ed. In: *Everglades Interim Report*, South Florida Water Management District, West Palm Beach, FL.

Chimney, M.J., M. Nungesser, J. Newman, K. Pietro, G. Germain, T. Lynch, G. Goforth and M.Z. Moustafa. 2000. Chapter 6: Stormwater Treatment Areas - Status of Research and Monitoring to Optimize Effectiveness of Nutrient Removal and Annual Report on Operational Compliance. Redfield, G., ed. In: *2000 Everglades Consolidated Report*, South Florida Water Management District, West Palm Beach, FL.

Coffelt, G, J.M. Newman, T. Aziz, D. Campbell, B. Gu, J. Jorge, J. Lopez, K. Pietro and L. Wenkert. 2001. Chapter 8: Advanced Treatment Technologies for Treating Stormwater Discharges into Everglades Protection Area. Redfield, G., ed. In: *2001 Everglades Consolidated Report*, South Florida Water Management District, West Palm Beach, FL.

Davis, S.M. 1981. Mineral flux in the Boney Marsh, Kissimmee River: 1. Mineral retention in relation to overland flow during the three-year period following reflooding. Technical Publication 81-1, South Florida Water Management District, West Palm Beach, FL.

DB Environmental Laboratories, Inc (DBEL). 2002. Vegetation Biomass and Nutrient Analysis for Stormwater Treatment Area 1 West (STA-1W). Final report submitted to the South Florida Water Management District, West Palm Beach, FL.

Dierberg, F.E., T.A. DeBusk, S.D. Jackson, M.J. Chimney and K. Pietro. 2002. Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. *Water Research* 36:1049-1422.

Goforth, G., T.T. Piccone, S. Van Horn, D. Pescatore and C. Mo. 2003. Chapter 8A: Achieving Long-term Water Quality Goals. Redfield, G., ed. In: *2003 Everglades Consolidated Report*, South Florida Water Management District, West Palm Beach, FL.

Gray, S. and G.L. Coffelt. 1999. Chapter 8: Supplemental Technologies for Treating Stormwater Discharges into the Everglades Protection Area. Redfield, G., ed. In: *Everglades Interim Report*. South Florida Water Management District, West Palm Beach, FL.

Gray, S. and G.L. Coffelt. 2000. Chapter 8: Advanced Treatment Technologies for Treating Stormwater Discharges into Everglades Protection Area. Redfield, G., ed. In: *2000 Everglades Consolidated Report*, South Florida Water Management District, West Palm Beach, FL.

Gu, B., T. DeBusk, F.E. Dierberg, M. Chimney, K. Pietro and T. Aziz. 2001. Phosphorus removal from Everglades agricultural area runoff by submersed aquatic vegetation/limerock treatment technology: an overview of research. *Water Science and Technology* 44:101-108.

Hodell, D.A., M., Brenner, J.H. Curtis, W.F. Kenney and B.W. Leyden. 2002. Investigation of long-term stability and phosphorus accretion by an aquatic system with a long history of submerged aquatic vegetation dominance. Department of Geology, University of Florida and University and Department of Geology, South Florida Departments of Geology. Final report submitted to the South Florida Water Management District, West Palm Beach, FL.

Jorge, J., J.M. Newman, M.J. Chimney, G. Goforth, T. Bechtel, G. Germain, M.K. Nungesser, D. Rumbold, J. Lopez, L. Fink, B. Gu, R. Bearzotti, D. Campbell, C. Combs, K. Pietro, N. Iricanin and R. Meeker. 2002. Chapter 4: Stormwater Treatment Technologies. Redfield, G., ed. In: *2002 Everglades Consolidated Report*, South Florida Water Management District, West Palm Beach, FL.

Kadlec, R.H., 2003. Free surface wetlands for phosphorus removal: the position of the Everglades Nutrient Removal Project. Unpublished manuscript.

Kadlec, R.H. and S. Newman, 1992. Phosphorus removal in wetland treatment areas. DOR 106. Report prepared for South Florida Water Management District, West Palm Beach, FL.

Kadlec, R.H. and W.W. Walker. 2003. Technology review of periphyton stormwater treatment. Unpublished draft report.

Knight R.L., B. Gu, R.A. Clarke and J.M. Newman. 2003. Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. *Ecological Engineering* 20: 45-63.

Mierau, R. and P. Trimble. 1988. Hydrologic characteristics of the Kissimmee River Floodplain Boney Marsh Experimental Area. Technical Memo 9-88. South Florida Water Management District, West Palm Beach, FL.

Moustafa, M.Z. 1997. Graphical representation of nutrient removal in constructed wetlands. *Wetlands* 17: 493-501.

Moustafa, M.Z. 1998. Long-term equilibrium phosphorus concentrations in the Everglades as predicted by a Vollenweider-type model. *Journal of the American Water Resources Association* 34: 135-147.

Moustafa, M.Z. 1999. Analysis of phosphorus retention in free-water surface treatment wetlands. *Hydrobiologia* 392: 41-53.

Moustafa, M.Z., M.J. Chimney, T.D. Fontaine, G. Shih and S. Davis. 1996. The response of freshwater wetland to long-term “low level” nutrient loads – marsh efficiency. *Ecological Engineering* 7: 15-33.

Moustafa, M.Z., T.D. Fontaine, M. Gurado and R.T. James. 1998. The response of a freshwater wetland to long-term “low level” nutrient loads: nutrient and water budget. *Hydrobiologia* 364: 41-53.

Newman, J.M., G. Goforth, M.J. Chimney, J. Jorge, T. Bechtel, G. Germain, M.K. Nungesser, C. Pathak, D. Rumbold, J. Lopez, L. Fink, B. Gu, K. Cayse, R. Bearzotti, D. Campbell, C. Combs, K. Pietro, N. Iricanin, R. Meeker, G. West and N. Larson. 2003. Chapter 4: Stormwater Treatment Technologies. Redfield, G., ed. In: *2003 Everglades Consolidated Report*, South Florida Water Management District, West Palm Beach, FL.

Nungesser, M.K., J.M. Newman, C. Combs, T. Lynch, M.J. Chimney and R. Meeker. 2001. Chapter 6: Optimization Research for the Stormwater Treatment Areas. Redfield, G., ed. In: *2001 Everglades Consolidated Report*, South Florida Water Management District, West Palm Beach, FL.

Pietro, K. In Preparation. Stormwater Treatment Area 6 (STA-6) technical publication – Land use history, operation, hydrology, and nutrient removal performance. South Florida Water Management District, West Palm Beach, FL

Walker, W.W., Jr. 1995. Design basis for Everglades stormwater treatment areas. *Water Resources Bulletin* 31: 671-685.

Walker, W.W. and R. Kadlec. 2003. Dynamic Model for the Stormwater Treatment Areas. http://wwwalker.net/dmsta/index.htm.