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Constructed Wetlands for Water Quality Improvement in Surface Water Discharges to the Everglades: Stormwater Treatment Areas

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by

Wossenu Abtew
Tracey Piccone
Kathleen Pietro

South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33406

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Wossenu Abtew[1], Tracey Piccone[2] and Kathleen Pietro[3]

[1] South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406; PH (561) 682-6326; FAX (562) 682-6051: email:wabtew@sfwmd.gov
[2] South Florida Water Management District; email:tpiccone@sfwmd.gov
[3] South Florida Water Management District; email:kpietro@sfwmd.gov

Abstract

Everglades Stormwater Treatment Areas (STAs) are constructed freshwater wetlands designed for reducing phosphorus concentration and load from drainage waters that flow into the Everglades. Currently, six stormwater treatment areas with a total effective treatment area of 16,098 ha are under operation. Operation of the STAs started in 1994 with a 1,544 ha prototype constructed wetland, the Everglades Nutrient Removal Project, and additional STAs were constructed over the following years. For the period of operation of the STAs, the average total phosphorus (TP) concentration was 140 ppb in the inflow and 43 ppb in the outflow. The average phosphorus load reduction was about 70 percent. Hydraulic loading rate, TP loading rate and hydraulic retention time are recognized as factors that affect TP removal efficiency. Since the start of operation of the Everglades Nutrient Removal Project and the subsequently constructed additional stormwater treatment areas, about 826,540 ha-m of water has been treated and 810.3 mt of total phosphorus have been removed. An additional expansion of the STA treatment system by another 2,389 ha is currently in progress.

Introduction

Natural wetlands have been used for wastewater treatment as far back as 100 years ago, while the use of constructed wetlands for the same purpose started in the 1950s (Kadlec and Knight, 1996). Constructed freshwater wetlands known as the Everglades Stormwater Treatments Areas (STAs) have been adopted as a treatment method to reduce phosphorus (P) concentrations from agricultural drainage and other waters that flow into the Everglades Protection Area (EPA) from the Everglades Agricultural Area (EAA) and surrounding basins in South Florida. The mechanism of phosphorus removal by wetlands is the cumulative result of sediment accretion and uptake by growing vegetation (Kadlec and Newman, 1992). The ability of wetlands to assimilate phosphorus is a critical component of the Everglades restoration program. Based on the work of Walker (1995) and Kadlec and Knight (1996), phosphorus removal within the STA is postulated to be represented by a first-order equation:

$$R = k\,A\,C \qquad (1)$$

Where R = removal rate, g/yr; k = settling rate as determined from past or existing comparable wetlands, m/yr; A = effective treatment area, m^2 and C = water column concentration of phosphorus, g/m^3. The design parameters for sizing wetland treatment systems are settling rate (k), inflow phosphorus concentration (C_i), target outflow phosphorus concentration (C_o), inflow rate (Q_i) and outflow rate (Q_o). Hydraulic Loading Rate (HLR in cm/day) characterizes the inflow application rate over the wetland surface area and is equated as follows.

$$HLR = 100 * \frac{Q}{A} \tag{2}$$

Where Q is average daily inflow rate in m^3/d and A is wetland area in m^2.

Settling rate (k), for existing wetland systems can be computed as follows (Kadlec and Knight, 1996).

$$k = -HLR * \ln \frac{(C_o - C^*)}{(C_i - C^*)} \tag{3}$$

Where C_i = inflow P concentration (mg/L); C_o is outflow P concentration (mg/L); C* is irreducible background concentration (mg/L) and HLR is hydraulic loading rate (m/yr). Hydraulic Retention Time characterizes the residence time of water in the wetland and it is a function of inflow rate, outflow rate, area and depth as represented by the following equation.

$$HRT = \frac{A.d}{Q^*} \tag{4}$$

Where Q* is the average of inflow and outflow (m^3/day); A is area in m^2; d is average depth in m and HRT is in days. Total Phosphorus loading rate (TPLR) characterizes the inflow water concentration and inflow rate as presented below:

$$TPLR = \frac{Q_i C_i}{A} \tag{5}$$

Where Q_i is inflow rate (m^3/yr); C_i is inflow TP concentration (gm/m^3); A is STA area in m^2 and TPLR is in mg/m^2/yr. The performance of wetlands in phosphorus removal is measured by the removal efficiency in percent (E) and is computed as follows:

$$E = 100 \frac{(Q_i C_i - Q_o C_o)}{Q_i C_i} \tag{6}$$

Initially, a 1,544 ha prototype constructed wetland, the Everglades Nutrient Removal (ENR) Project, was constructed and operated from 1994 to 1999 (Abtew and Bechtel, 2001). Currently, six STAs totaling about 16,098 ha of effective treatment area are under operation (STA-1E, STA-1W, STA-2, STA-3/4, STA-5 and STA-6) shown in Figure 1. An additional expansion of 2,389 ha of effective treatment area is currently under construction consisting of a 770-ha expansion to STA-2, a 1,036-ha expansion to STA-5 and a 583-ha expansion to STA-6. Each STA has different cell sizes and configurations dictated by the shape of the available land, topography, orientation to inflow sources and discharge points, and desired treatment performance. Table 1 shows the start-up and operational timeline for each of the STAs.

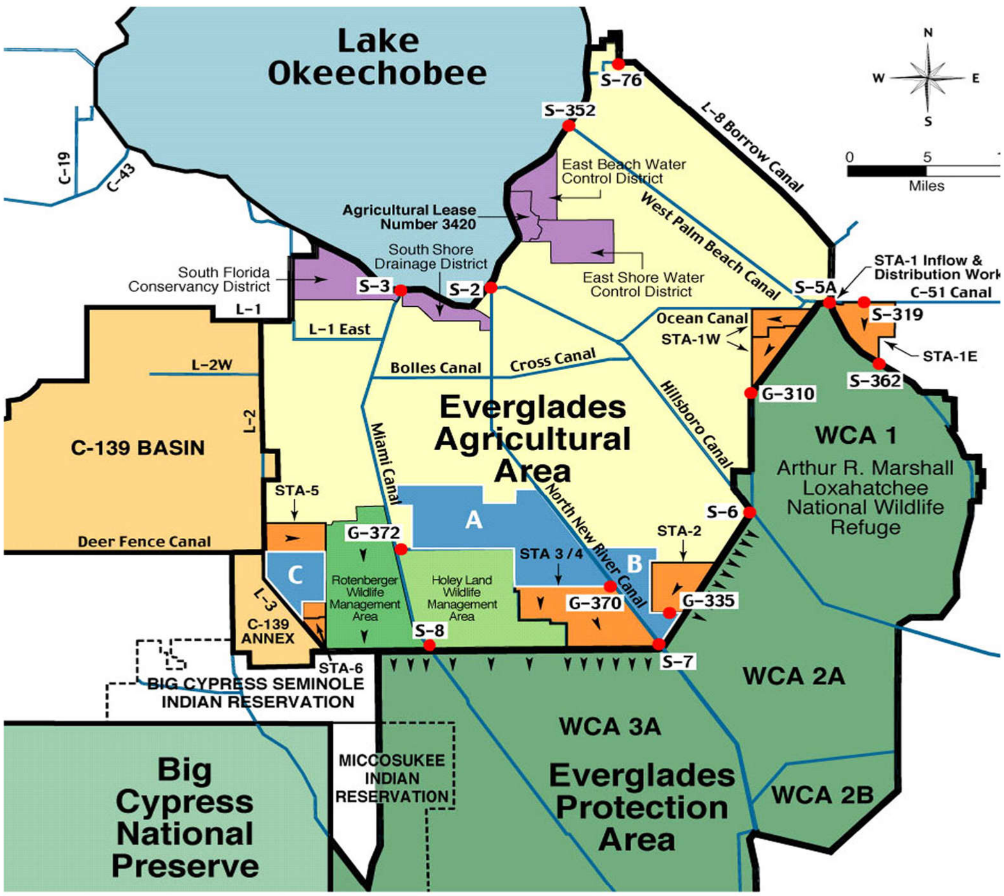

Figure 1. The Everglades Agricultural Area and Stormwater Treatment Areas.

Table 1. Start-up and operational timeline for the Stormwater Treatment Areas.

STA Operational Dates													
	Water Years (May - April)												
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
STA-1E											■	■	■
ENR Section of STA-1W	■	■	■	■	■	■							
STA-1W							■	■	■	■	■	■	■
STA-2							■	■	■	■	■	■	■
STA-3/4											■	■	■
STA-5						■	■	■	■	■	■	■	■
STA-6					■	■	■	■	■	■	■	■	■

Stormwater Treatment Area 1 East

STA-1E is an eight-cell STA with three parallel treatment trains and a total effective treatment area of 2,078 ha (Figure 2). STA-1E began start-up in 2004. Inflow into STA-1E is through two pump stations (S-319 and S-361) and a gated spillway (G-311). The source of water is mainly runoff/drainage from the C-51W Basin, consisting of residential and agricultural land uses. Outflow of treated water is into the Loxahatchee National Wildlife Refuge. The 31-year long-term average annual simulated hydraulic loading rate for this STA is 2.06 cm/d and the simulated total phosphorus loading rate is 1.33 $g/m^2/yr$. The major vegetation coverage in STA-1E is submerged aquatic vegetation (SAV) and mixed emergent vegetation. The performance of STA-1E for water year 2006 (May 1, 2005 to April 30, 2006) is shown in Table 2. During water year 2006, Cells 1 and 2 were off-line for construction of a large-scale demonstration project that utilizes periphyton to remove phosphorus.

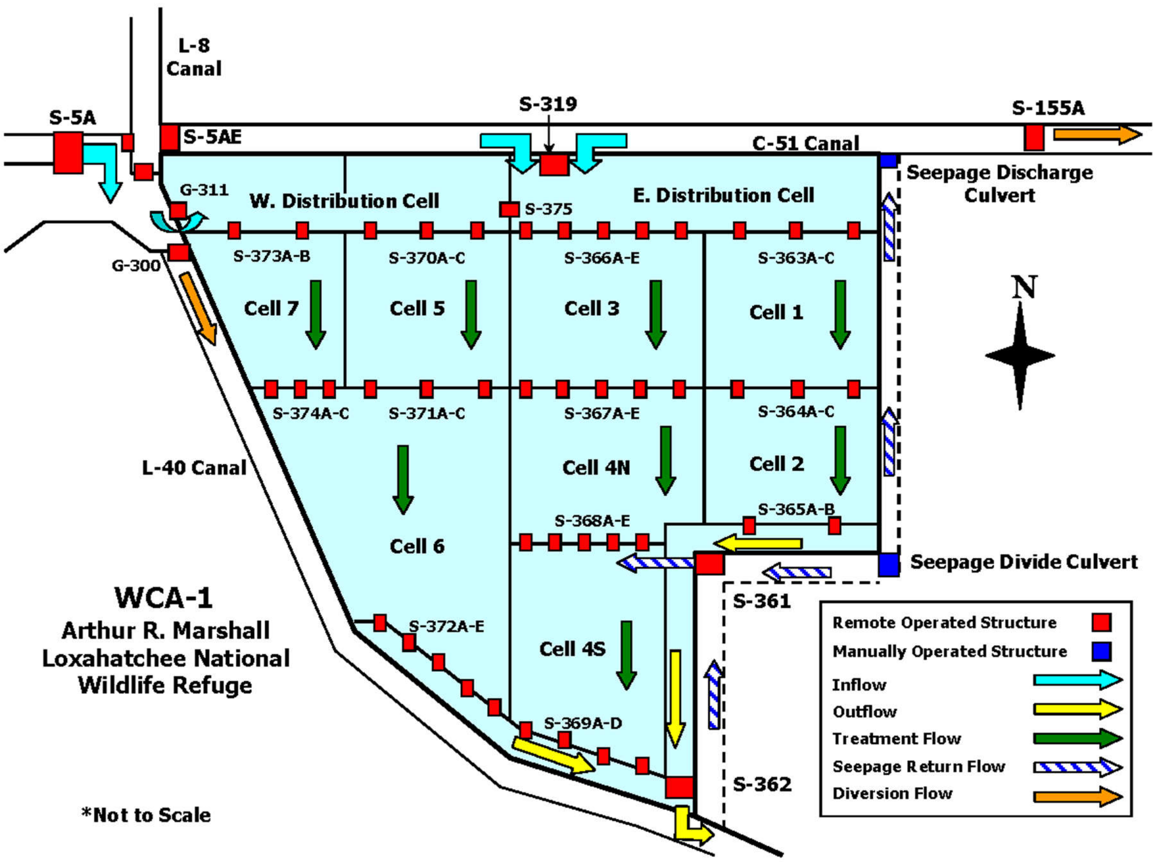

Figure 2. Stormwater Treatment Area 1 East (STA-1E).

Stormwater Treatment Area 1 West

STA-1W is a 2,700-ha STA consisting of seven cells arranged in three parallel flow-ways as shown by the directional arrows in Figure 3. Upon completion of a new internal levee in Cell 1, the STA will be an eight-cell STA. Full flow-through operations in Cells 1 through 4 have occurred since August 1994, when these cells were part of the original prototype STA, the Everglades Nutrient Removal (ENR) Project. When Cell 5 was added and became operational in July 2000, the project was then referred to as STA-1W. The source of inflow into STA-1W is mainly runoff/drainage from the Everglades Agricultural Area pumped into the Inflow and Distribution Basin through a pump station (S-5A). Outflow from STA-1W is into the Loxahatchee National Wildlife Refuge. STA-1W contains 14 miles of levees, several large gated spillways and numerous culverts. The 31-year long-term average annual simulated hydraulic loading rate for STA-1W is 2.0 cm/d and the simulated total phosphorus loading rate is 1.01 $g/m^2/yr$. The major plant communities in the upstream receiving cells are emergent vegetation dominated by cattails, while the downstream cells are dominated by submerged aquatic vegetation. The performance of STA-1W for water year 2006 is shown in Table 2. During water year 2006, only a part of the STA was operational because some of the treatment cells were off-line for structural enhancements and for recovery of plant communities damaged by recent hurricanes.

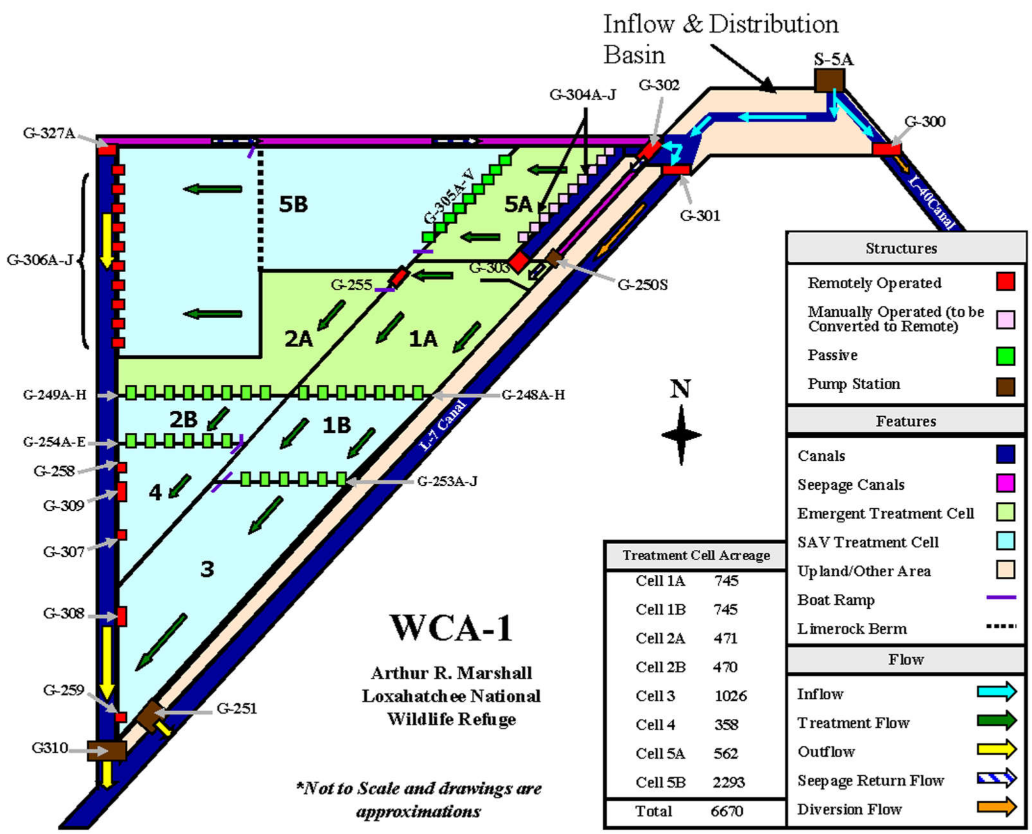

Figure 3. Stormwater Treatment Area 1 West (STA-1W).

Stormwater Treatment Area 2

STA-2 is a 2,603-ha STA with three cells operating in parallel (Figure 4). Construction of STA-2 included about 28 miles of levees, numerous remote controlled structures and an outflow pump station (G-335). STA-2 started operation in 2000. The source of inflow into STA-2 is mainly runoff/drainage from the Everglades Agricultural Area and outflow is into Water Conservation Area 2A. The 31-year long-term average annual simulated hydraulic loading rate for STA-2 is 3.02 cm/d and the simulated total phosphorus loading rate is 1.11 $g/m^2/yr$. The major vegetation coverage in Cell 1 and Cell 2 can be characterized as cattails, sawgrass and mixed emergent vegetation, while Cell 3 is dominated by submerged aquatic vegetation. The operation and performance of STA-2 for water year 2006 during which all treatment cells were operational is shown in Table 2. Construction of a 70-ha expansion (new Cell 4) for STA-2 was underway in water year 2006 and is now substantially completed.

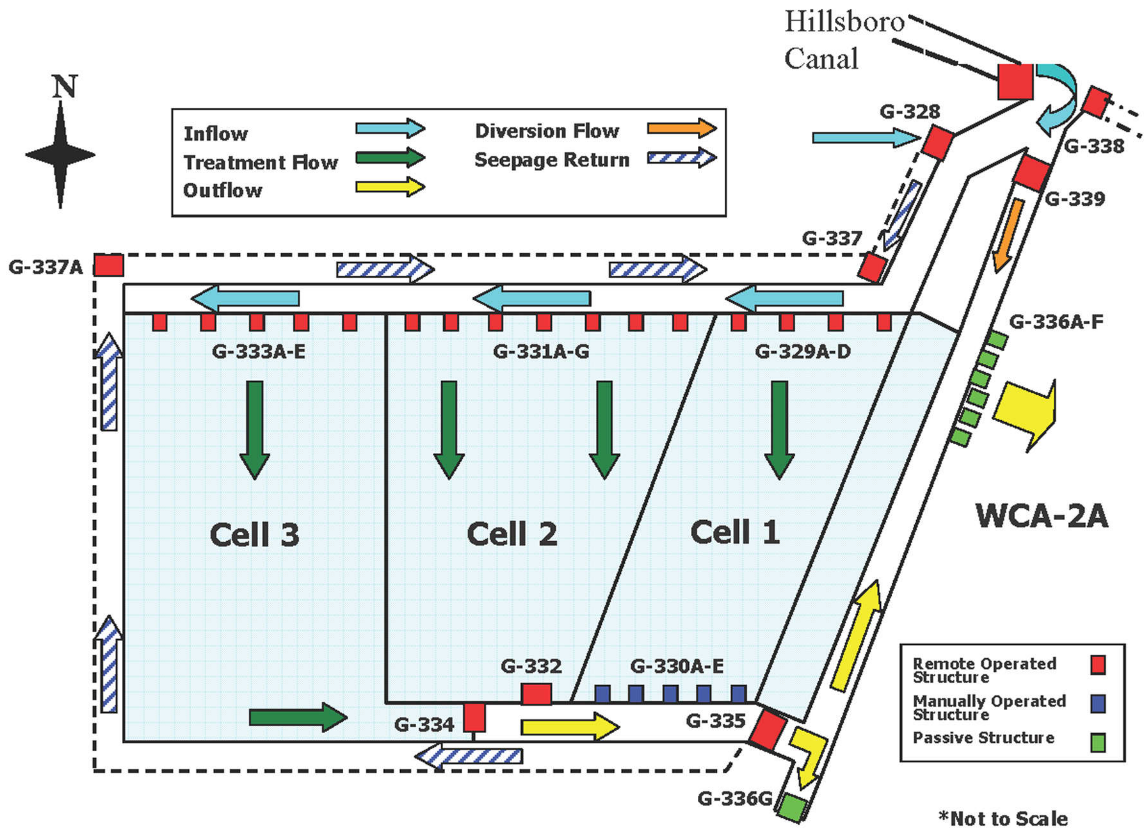

Figure 4. Stormwater Treatment Area 2 (STA-2).

Stormwater Treatment Area 3/4

STA-3/4 is a 6,698-ha, six-cell STA consisting of three parallel treatment flow-ways each with two cells in series (Figure 5). STA-3/4 started operation in 2004. The source of inflow into STA-3/4 is runoff/drainage from the Everglades Agricultural Area and Lake Okeechobee releases through the Miami and North New River canals. Outflow from STA-3/4 is into Water Conservation Area 3A. The 31-year long-term average annual simulated hydraulic loading rate for STA-3/4 is 3.32 cm/d and the simulated total phosphorus loading rate is 1.07 g/m^2/yr. The major vegetation coverage in the upstream receiving cells can be characterized as cattails, sawgrass, and mixed emergent vegetation, while the downstream cells are, or are planned to be, dominated by submerged aquatic vegetation. The performance of STA-3/4 for water year 2006 is shown in Table 2. During part of water year 2006, Cell 3 was off-line for construction of structural enhancements.

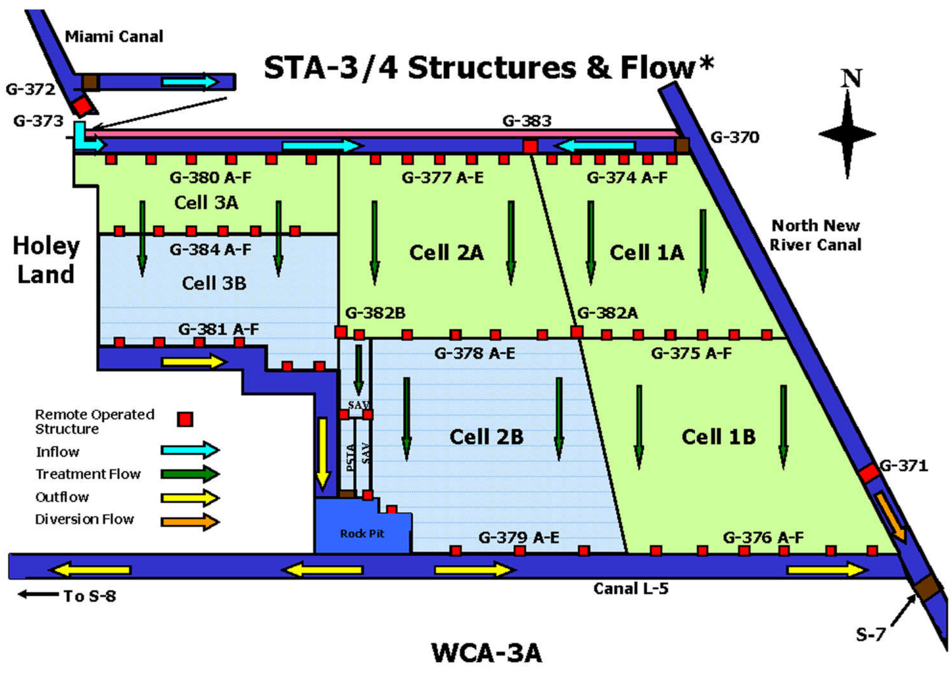

Figure 5. Stormwater Treatment Area 3/4 (STA-3/4).

Stormwater Treatment Area 5

STA-5 is a 1,667-ha, four-cell STA consisting of two parallel treatment flow-ways each with two cells in series (Figure 6). STA-5 started operation in 1999. The source of inflow into STA-5 is runoff/drainage from the C-139 Basin discharged through the L-2 Canal. Outflow from STA-5 is into the Miami Canal, while some discharge is made to the Rotenberger Wildlife Management Area. The 31-year long-term average annual simulated design hydraulic loading rate for STA-5 is 2.62 cm/d and the design total phosphorus loading rate is 1.69 g/m^2/yr. The major coverage in the upstream receiving cells can be characterized as being dominated by cattails and other emergent vegetation, while the downstream cells are dominated by submerged aquatic vegetation. The operation and performance of STA-5 for water year 2006 is shown in Table 2. During water year 2006, portions of each of the flow-ways were off-line for construction of structural enhancements. Construction of a two-cell, 1,036-ha, additional treatment flow-way for STA-5 was also underway in water year 2006 and is now substantially completed.

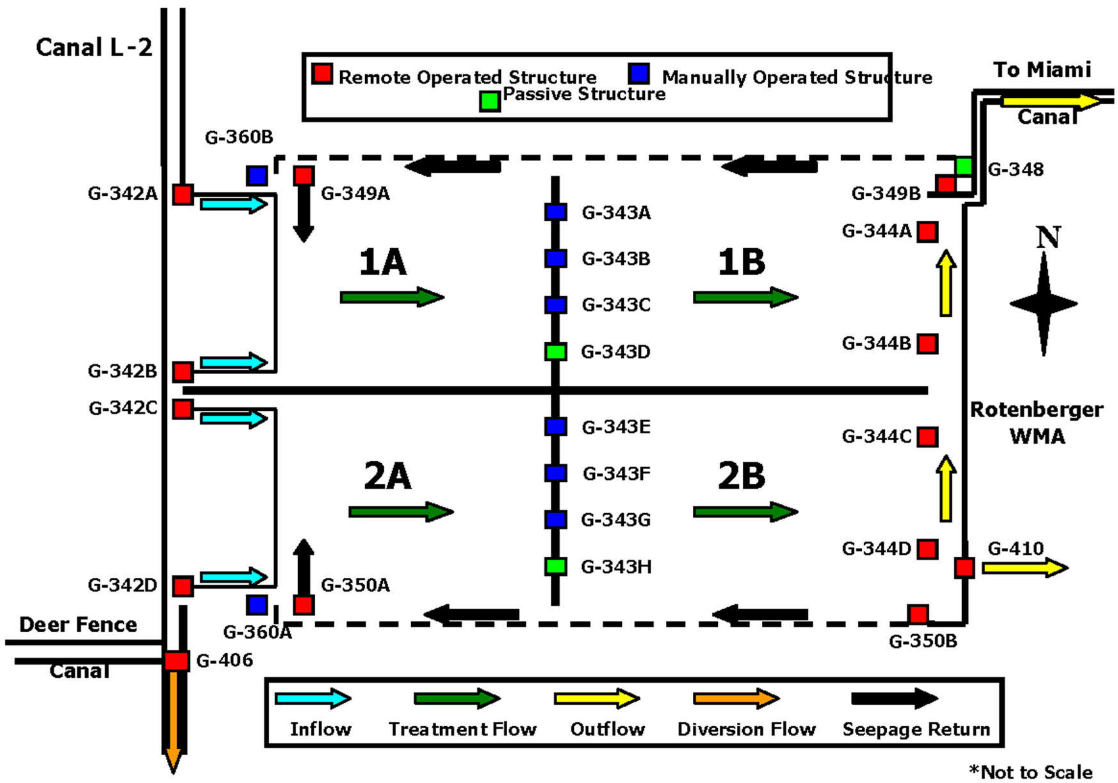

Figure 6. Stormwater Treatment Area 5 (STA-5).

<u>**Stormwater Treatment Area 6**</u>

STA-6, Section 1, is a 352-ha STA consisting of two cells operating in parallel (Figure 7). STA-6 started operation in 1997. Historically, the source of inflow into STA-6 was runoff/drainage from the agricultural area north of the STA pumped via the G-600 pump station into the supply canal. In 2005, farming operations north of the STA ended and the inflow facilities were used minimally to regulate stages in the tributary area to facilitate construction of the STA expansion. Outflow from STA-6 is through the box-weir culverts (G-354A-C and G-393A-C). The 31-year long-term average annual simulated hydraulic loading rate for STA-6 is 1.32 cm/d and the simulated total phosphorus loading rate is 0.42 g/m^2/yr. The major vegetation coverage in STA-6 can be characterized as mixed graminoids, willows, cattails and sawgrass. The performance of STA-6 for water year 2006, during which both treatment cells were operational, is shown in Table 2. STA-6, Section 2, a 583-ha expansion was underway in water year 2006 and is now substantially completed.

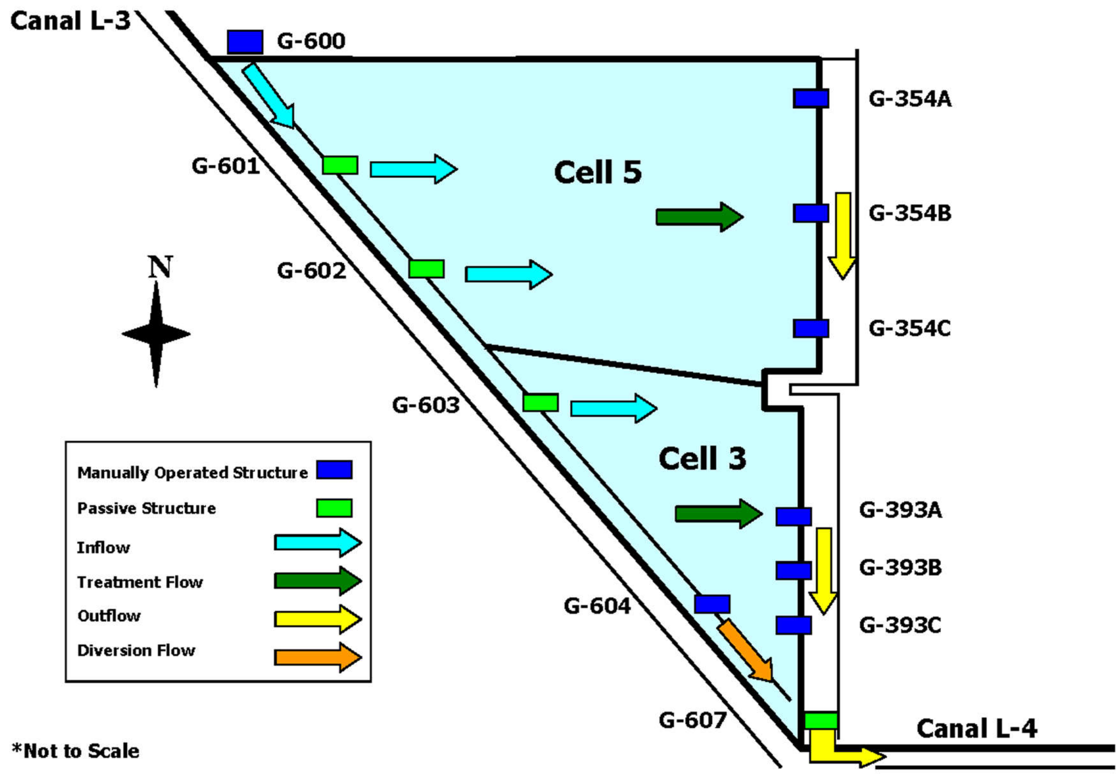

Figure 7. Stormwater Treatment Area 6 (STA-6).

Hydraulics and Operation

Due to the low relief topography of the area, inflow and outflow from the STAs is generally achieved through pump stations, although some of the STAs receive inflow through gated structures or culverts. Cell-to-cell flows are typically by gravity and some cell-to-cell flows are controlled by gated culverts. In most cases, inflows and outflows into and from the STAs are on an automated remote-controlled water management system. Dry out of STAs is discouraged and maintaining a minimum water level of 15 cm is recommended (SFWMD, 1999). STA operations are influenced by surface water runoff/drainage, rainfall in the tributary basins, evapotranspiration and seepage.

Each STA has an operation plan in which target water levels are specified and operational guidelines are provided. A typical STA operation plan includes guidelines for start-up phase operations, normal operations and extreme hydrologic operations. The general range of water depths in the STAs is between 15 cm and 120 cm. Operational challenges include hydrologic extremes, increases in inflow TP concentrations, hurricane wind impacts, controlling undesirable vegetation types and maintaining treatment capacity during implementation of STA enhancements.

Table 2. STA performance for water year 2006 (May 1, 2005 to April 30, 2006).

Stormwater Treatment Area	STA-1E**	STA-1W	STA-2	STA-3/4	STA-5	STA-6	All STAs WY2006
Average Effective Treatment Area for WY2006* (ha)	1,629	1,693	2,603	5,768	1,304	352	13,350
Inflow							
Total Inflow Volume (ha-m)	6,431	17,600	36,681	85,997	26,708	4,992	178,408
Hydraulic Loading Rate (HLR) (cm/day)	1.08	2.85	3.86	4.08	5.61	3.88	3.99
Flow-weighted Mean Inflow TP (ppb)	188	213	120	123	199	104	144
TP Loading Rate (TPLR) ($g/m^2/yr$)	0.74	2.21	1.69	1.83	4.07	1.47	2.23
Total Inflow TP Load (mt)	12.1	37.4	44	105.4	53	5.2	257.2
Outflow							
Total Outflow Volume (ha-m)	5,005	17,009	39,757	92,403	24,807	3,246	182,226
Flow-weighted Mean Outflow TP (ppb)	146	113	21	23	96	26	44
Total Outflow TP Load (mt)	7.3	19.3	8.2	21.6	23.7	0.8	80.9
Hydraulic Residence Time (HRT) (days)	41	13	15	14	6	13	18
TP Retained (mt)	4.8	18.2	35.8	83.8	29.3	4.3	176.2
TP Removal Rate ($g/m^2/yr$)	0.31	1.21	1.38	1.25	1.76	1.23	1.32
Load reduction (%)	40	49	81	80	55	84	69

* average effective area reflects treatment cells off-line for plant rehabilitation or Cell enhancement construction.

** STA-1E is a partial water year, October 2005-April 2006.

Performance

The performance of STAs can be impacted by antecedent soil type, soil phosphorus content, prior land use, vegetation cover, and major storm events. Hydraulic loading rate and temporal and spatial distribution of loading in the wetlands can also impact performance. In South Florida, 65 percent of the rainfall occurs in the wet season of June through October and surface water flows generally correspond with rainfall. An example of the monthly variation of hydraulic loading rate in a year is demonstrated at STA-6, where the wet season hydraulic loading rate is four times that of the dry season (Huebner, 2006). For this STA, for the period from May 1, 2004 to April 30, 2005 (water year 2005), the highest monthly hydraulic loading was 10.4 cm/d in August and the lowest was zero inflows in December. Variability in the hydraulic loading rate also occurred at other STAs. Extreme ranges of hydraulic loading occurred in STA-1W during the 2004 hurricane season, during which a hydraulic loading rate of 16.3 cm/d occurred in one month (September 2004) (Abtew, 2005). This extremely large loading rate, along with reduced hydraulic retention times, had a profound effect on the performance of the STA. Hydraulic loading rate generally has a negative correlation with STA TP load removal efficiency as shown in Figure 8.

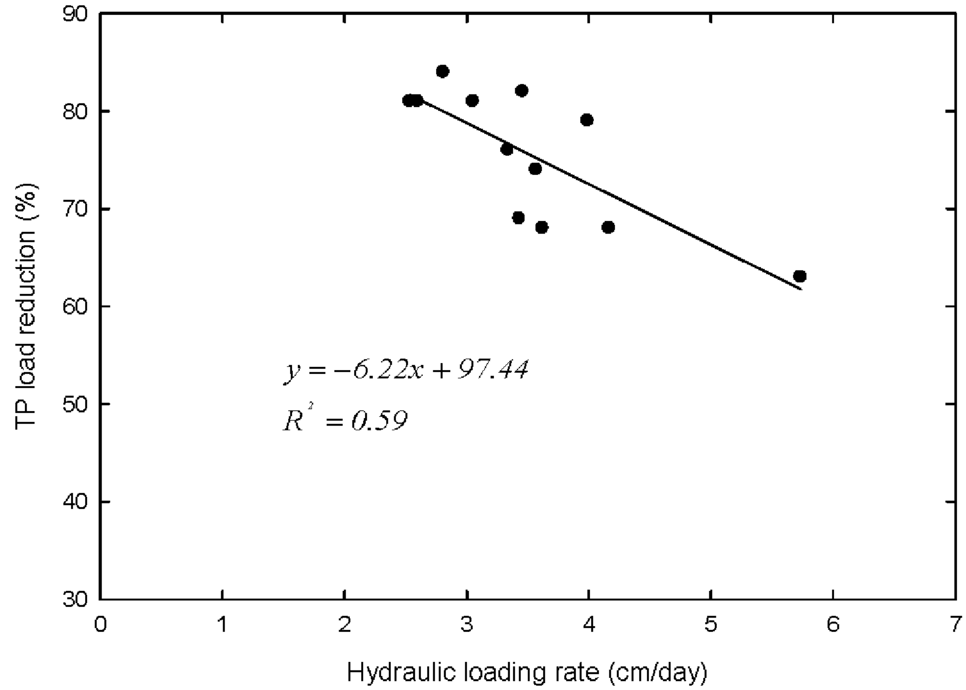

Figure 8. Hydraulic loading rate versus TP load reduction for all STAs (1995-2006).

Annual inflow flow-weighted mean TP concentrations for all of the STAs including the ENR (1995 to 2006), not including start-up periods, ranged from 53 ppb to 136 ppb, and annual outflow flow-weighted mean TP concentrations ranged from 11 to 136 ppb (Pietro, et al, 2007). For this same period, the average total phosphorus (TP) concentration was 140 ppb in the inflow and 43 ppb in the outflow. All of the STAs showed a net decrease in outflow concentrations as compared to inflows for this period. Figure 9 depicts inflow and outflow flow-weighted annual mean TP concentrations for all of the STAs.

Since the start of operation of the STAs, the total amount of phosphorus removed is about 810.3 mt with an average removal efficiency of 70 percent (Pietro et al., 2007). Hydraulic and TP loading rates vary among the STAs and from year to year (Pietro et al., 2007). TP loading rate has a negative relationship with performance efficiency as shown in Figure 10.

Residence time is one of the critical factors that affect the performance efficiency of wetland treatment systems. In general, residence time is expected to have a positive correlation with performance efficiency. Analysis of twelve years (1994-2006) of hydraulic residence times for the ENR and STA-1W indicates that residence time has a non-linear positive correlation with TP removal efficiency up to about 25 days. For this system, a residence time longer than 25 days does not seem to contribute to removal efficiency (Figure 11). While the general shape of the relationship of hydraulic residence time and TP removal efficiency may not change, the optimum number of days varies between STAs.

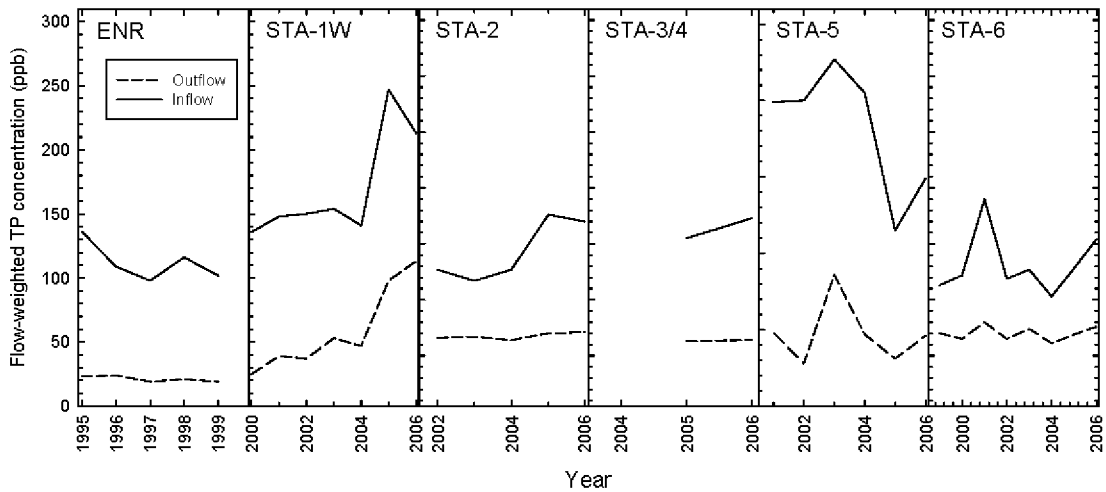

Figure 9. Inflow and outflow flow-weighted TP concentrations.

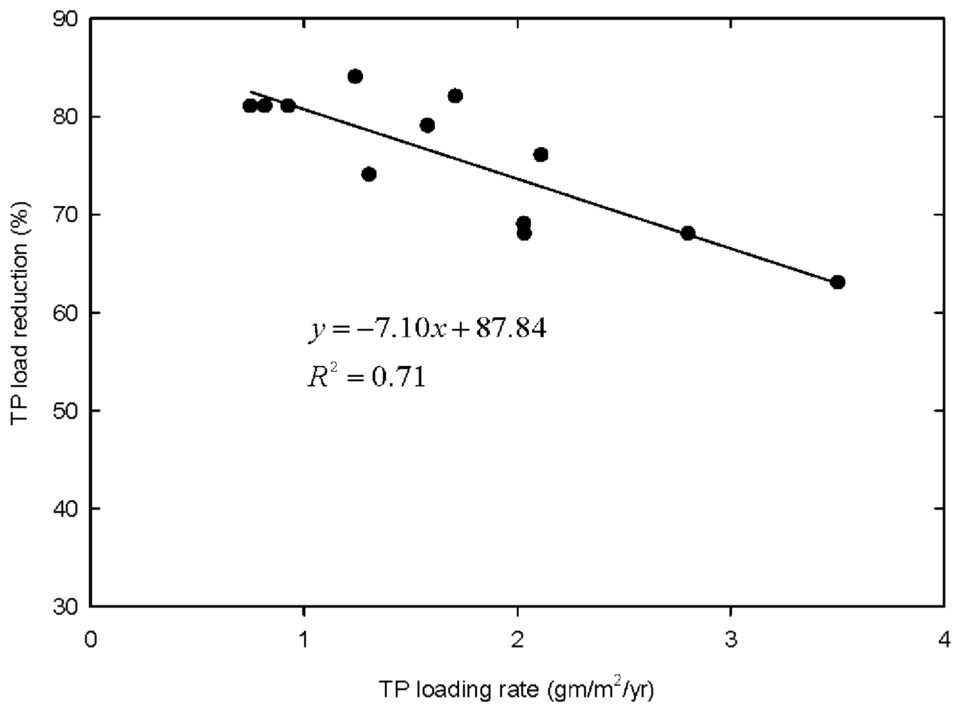

Figure 10. Annual average TP loading rate versus TP load reduction for all STAs (1995-2006).

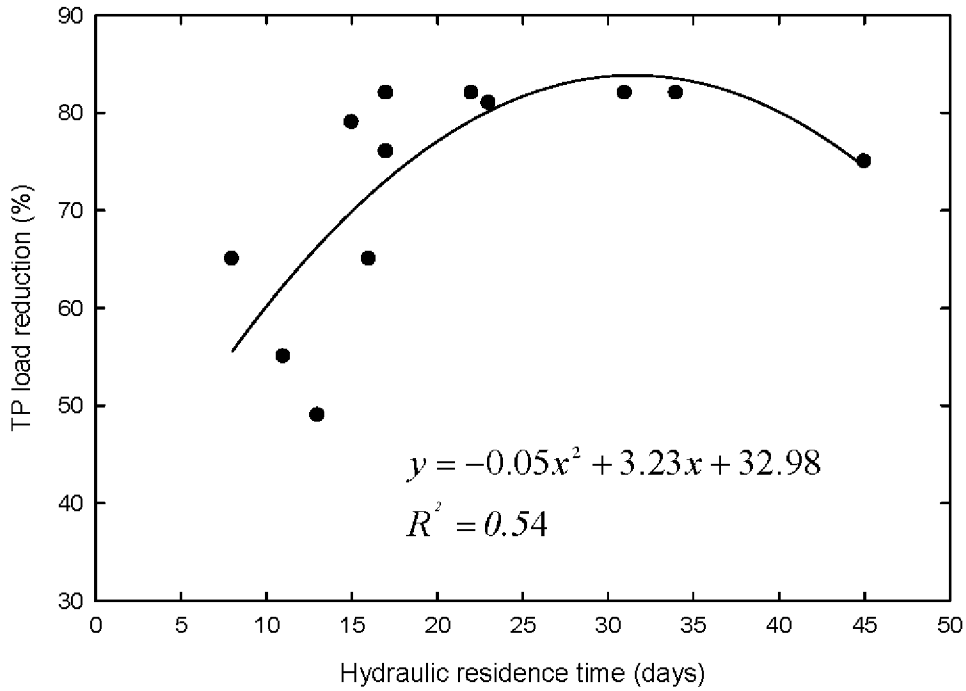

Figure 11. Hydraulic retention time versus TP load reduction for ENR and STA-1W (1995-2006).

Summary

Over their twelve years of operation, the STAs have demonstrated that significant phosphorus reduction can be achieved using constructed wetland treatment systems. So far, about 826,540 ha-m of water has been treated with 810.3 mt of total phosphorus removed and with an average treatment efficiency of 70 percent. For the period of operation of the STAs, the average total phosphorus (TP) concentration was 140 ppb in the inflow and 43 ppb in the outflow. Hydraulic loading rate, TP loading rate and hydraulic retention time are recognized as factors that affect TP removal efficiency. Operational challenges include hydrologic extremes, increases in inflow TP concentrations, hurricane wind impacts, controlling undesirable vegetation types and maintaining treatment capacity during implementation of STA enhancements.

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