Stormwater Treatment Areas: Constructed Wetlands for Phosphorus Removal in South Florida Surface Waters

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Abstract

Stormwater Treatment Areas (STAs) in South Florida are large-scale constructed wetlands operated as flow-through treatment systems to reduce phosphorus levels entering the Everglades in order to promote ecological restoration. The removal mechanism is through vegetation and periphyton uptake and sediment accretion. As part of the Everglades Construction Project, 16,800 hectares (ha) of constructed wetlands are being built to reduce phosphorus load from stormwater runoff and Lake Okeechobee discharges into the Everglades Protection Area in South Florida. At this time, four constructed wetlands with a total area 7,930 ha are operating, while construction is nearing completion in the remaining two totaling 8,864 ha. This study presents the performance of STA-1 West from May 1, 1999 through April 30, 2003, corresponding to the fifth through eighth year of operation. This was a transition period for the STA, encompassing the start-up of an 1,150 ha treatment cell, the addition of a significantly larger outflow pump station, a significant drought and a year with excessive inflows from Lake Okeechobee. The 2,700 ha constructed wetland has five cells with three parallel treatment systems. The eastern treatment train consists of Cell 1 (603 ha) and Cell 3 (415 ha), and the western treatment train consists of Cell 2 (381 ha) and Cell 4 (145 ha). Cell 5 (1150 ha) comprises the northern flow-way and is operated in parallel to the other four cells; Cell 5 began flow-through operation in July 2000. Surface vegetation cover consists mainly of cattails, submerged aquatic vegetation, open water and other mixed vegetation. The annual inflow during this time period ranged from 116 cubic hectometers (hm^3) (93,800 acre feet) to 730 hm^3 (592,000 acre feet), with an associated range in hydraulic loading from 1.17 to 7.41 cm/day. The corresponding annual inflow phosphorus loads ranged from 17.1 to 112 metric tons, with an associated nutrient loading rate range from 0.63 to 4.16 $g/m^2/yr$. Annual flow-weighted mean inflow concentrations ranged from 111 to 154 µg/L. The annual outflow during this time period ranged from 112 to 735 hm^3 (90,900 to 596,000 acre feet). The corresponding annual outflow phosphorus loads ranged from 3.67 to 38.7 metric tons, with an associated phosphorus removal rate range from 0.48 to 2.72 $g/m^2/yr$. The annual flow-weighted mean outflow concentrations ranged from 25 to 53 µg/L. The constructed wetland achieved a total phosphorus load reduction of 71 percent during this 4-yr period. STAs, functioning in combination with other elements of the Everglades Construction Project and EAA best management practices, are intended to produce a long-term, flow-weighted average P concentration of 50 µg/L. This paper summarizes the hydrologic performance, mass balance and treatment efficiency of one of the largest constructed wetlands in the world.

Introduction

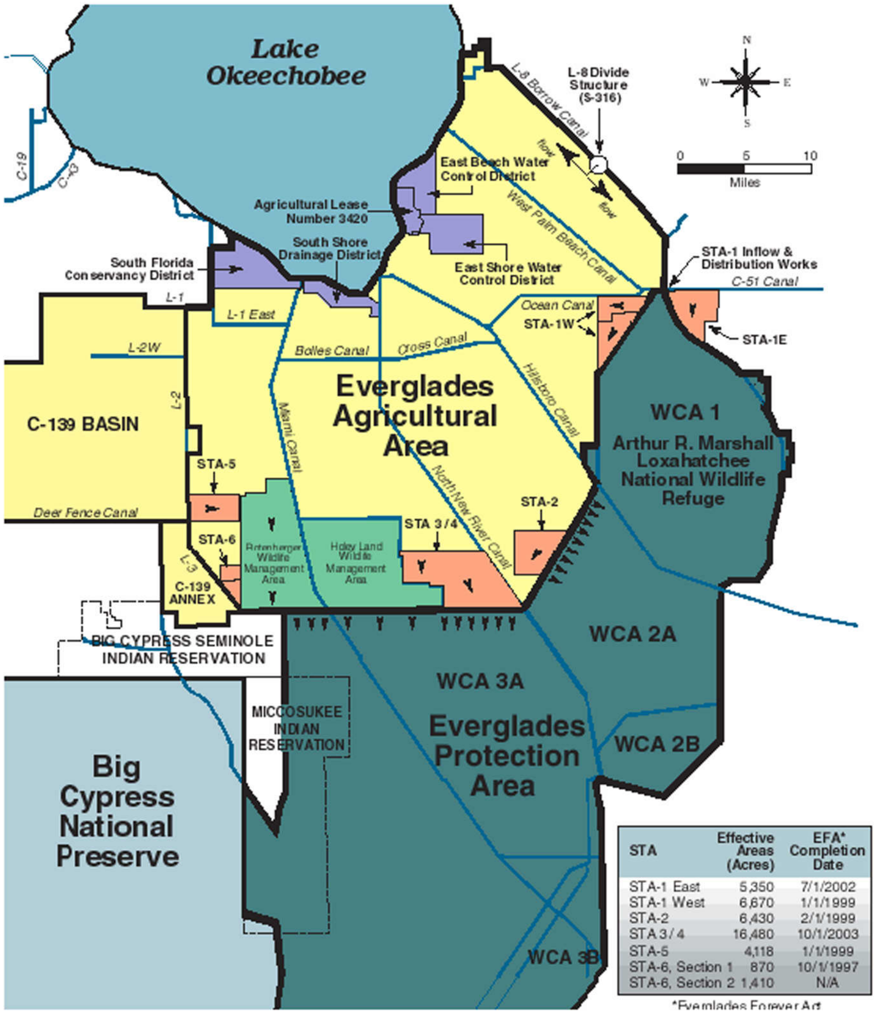
Natural wetlands have been used for wastewater treatment as far back as 100 years, while the construction of wetlands for the purpose of surface water treatment started only in the 1950s (Kadlec and Knight, 1996). The net removal of phosphorus (P) by constructed wetlands is the sum of sediment accretion, leaching, and uptake by growing biomass (Kadlec and Newman, 1992). The Everglades ecosystem has been impacted by both natural and anthropogenic factors.

Changes in the flora and fauna observed over the last several decades are attributed to alteration of the natural hydroperiods and increased nutrient levels in the inflow waters (Davis, 1991; Koch and Reddy, 1992). Florida's 1994 Everglades Forever Act requires that phosphorus in drainage/runoff and other waters be reduced before it is discharged to the Everglades Protection Area (EPA). The Everglades Agricultural Area (EAA) is a 224,000 ha highly productive irrigation/drainage basin with sugarcane as the major crop. EAA agricultural drainage/runoff and Lake Okeechobee discharges flow to the south and southeast through four primary canals (Miami, North New River, Hillsboro and West Palm Beach). A minimum of 25 percent of the P load in EAA runoff is required to be removed at the farm level through the application of various agricultural Best Management Practices. Additional removal of P is to be achieved through constructed wetland treatment systems known as Stormwater Treatment Areas (STAs) (Walker, 1995). Six constructed wetlands with a total area of 16,800 ha are being built to reduce P load from three basins and Lake Okeechobee discharges into the EPA in South Florida. At this time, four constructed wetlands with a total area 7,930 ha are operating, while construction is nearing completion in the remaining two totaling 8,864 ha. This paper presents the second four years of performance of Stormwater Treatment Area 1 West (STA-1W), a 2,700 ha constructed wetland.

Initially, a 1,544 ha prototype treatment wetland, the Everglades Nutrient Removal (ENR) Project, was constructed and operated from 1994 to 1999 to demonstrate the feasibility of large-scale constructed wetlands for P reduction from agricultural drainage/runoff. A 75-percent reduction in P load and concentration was achieved (Chimney et al., 2000; Abtew and Bechtel, 2001). The treatment system was expanded to an area of 2,700 ha in 1999, and the entire area became known as STA-1W. STA-1W is located in South Florida (26^{o} $38^{'}$ N, 80^{o} $25^{'}$ W) at the eastern edge of the EAA (Figure 1). Spatial and vegetative characteristics of STA-1W are presented in Table 1.

Table 1. STA-1W cell characteristics (1999 to 2003).

Cell	Area (ha)	Ground elevation (m NGVD)	Dominant surface cover
Cell 1	603	3.13	cattails/floating macrophyte/submerged aquatic vegetation
Cell 2	381	2.94	floating aquatics/ submerged aquatic vegetation/periphyton
Cell 3	415	3.10	cattails/mixed emergent vegetation
Cell 4	145	3.00	submerged aquatic vegetation/periphyton
Cell 5	1,150	2.90	mixed vegetation/ submerged aquatic vegetation/floating aquatics/periphyton



STA	Effective Areas (Acres)	EFA* Completion Date
STA-1 East	5,350	7/1/2002
STA-1 West	6,670	1/1/1999
STA-2	6,430	2/1/1999
STA 3 / 4	16,480	10/1/2003
STA-5	4,118	1/1/1999
STA-6, Section 1	870	10/1/1997
STA-6, Section 2	1,410	N/A

*Everglades Forever Act

Figure 1. Location of Stormwater Treatment Area 1 West.

System Hydraulics and Operation

Basin runoff and Lake Okeechobee discharges are pumped into the STA-1 Inflow Basin, located adjacent to the north boundary of the Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge). Water from the Inflow Basin is directed into STA-1W via the G-302 spillway (see Figure 2). STA-1W consists of five cells comprising three flow-ways: Cells 1 and 3 form the eastern flow-way; Cells 2 and 4 form the western flow-way and Cells 5A and 5B make up the northern flow-way. Discharges from G-302 move into the northern flow-way via ten culverts (G-304) and into the eastern and western flow-ways through the G-303 spillway. The seepage pump (G-250S) controls stages in the seepage canal north of Cell 5, and returns the collected seepage into Cell 1. Cell 2 receives flow from Cell 1 through six culverts (G-255). From Cell 1, water flows to Cell 3 through the ten G-253 culverts. Water delivery between Cell 2 and Cell 4 is through the nine G-254 culverts. Outflow from STA-1W into the Refuge is through pump stations G-251 (12.7 m^3/s or 450 cfs capacity) and G-310 (86 m^3/s or 3,040 cfs), which also serve to control seepage along the western boundary of the STA. The STA-1 Inflow Basin also includes diversion structures G-300 and G-301, used when the S-5A inflow pump exceeds the G-

302 capacity of 92.5 cubic meters per second (3,250 cfs). When completed, STA-1E, located to the east of the Inflow Basin, will receive this excess flow. Full flow-through operations in Cells 1 through 4 have occurred since August 1994. Full flow-through operations in Cell 5 have occurred since July 2000. Additional details on the design, operational plan and early performance of STA-1W are available (Goforth, 2000; Chimney et al., 2000; SFWMD 2001).

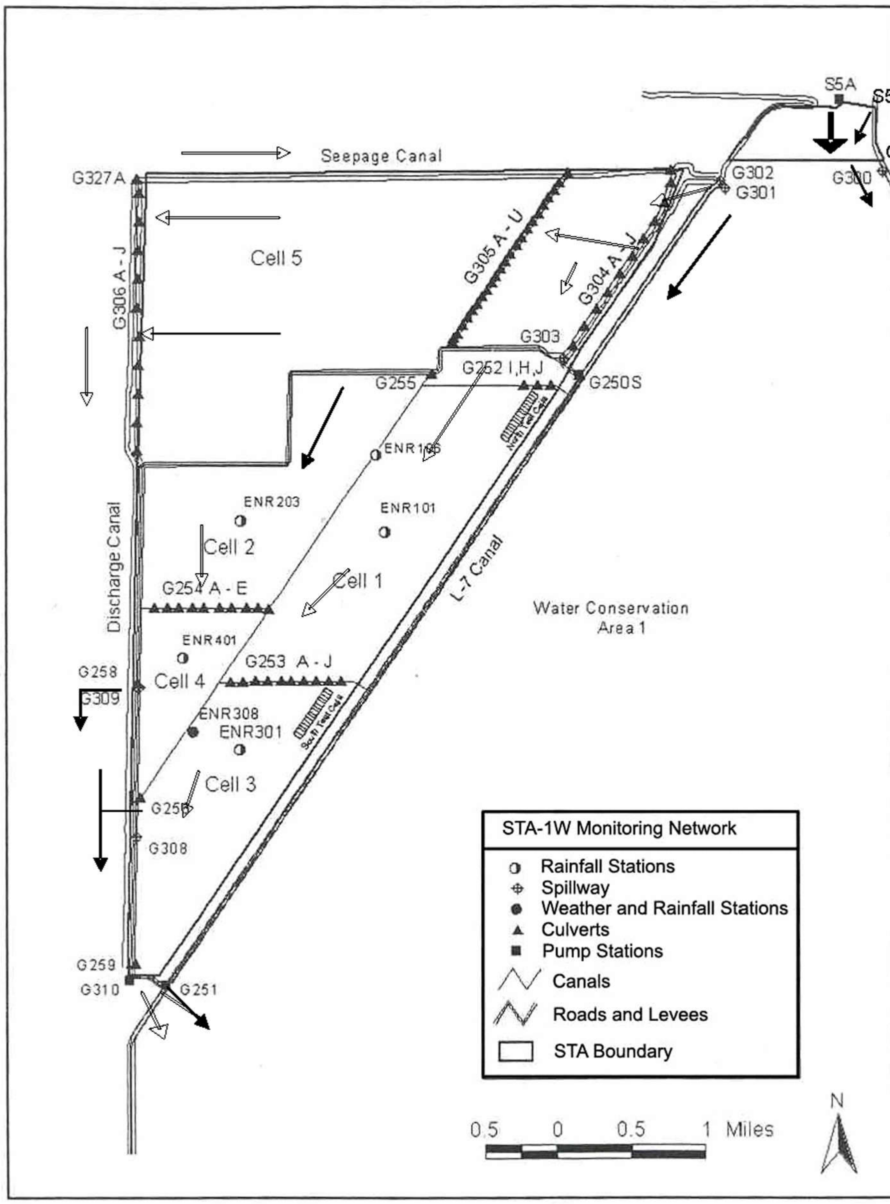


Figure 2. STA-1W structure and monitoring network.

Hydrologic Monitoring

Rainfall. South Florida has a subtropical climate with a relatively high rainfall frequency and magnitude. On the average, 34 percent of the annual rainfall occurs in the dry season (November to May), with the remaining 66 percent occurring in the wet season (June to October). Mean annual rainfall for the region is 134 cm. Frontal rainfalls occur in the dry season and have relatively lower spatial variation. Rainfall during the wet season is associated with daily convective and tropical systems, which have high spatial variation.

Based on the high variation of summer rainfall observations in the area, a ten-gauge rainfall network was established as a pilot network to evaluate the optimum gauge density needed for the ENR Project. Network analysis of the first wet season daily rainfall showed that five gauges were sufficient for the area (Abtew et al., 1995). As a result, four gauges were removed. The same network is being used for STA-1W. Areal average rainfall on the project site was computed as a Theissen-weighted average of the stations. The daily distribution of areal average rainfall for the study period (May 1, 1999 to April 30, 2003) is depicted by Figure 3. The total rainfall was 462 cm. Rainfall for the water year (May through April) is shown in Table 2.

Evapotranspiration. For the first two years of the ENR Project, evapotranspiration (ET) was measured with a lysimeter installed in Cell 1 (cattail), Cell 3 (mixed vegetation) and Cell 4 (open water algae) with the respective coverage. Following the lysimeter study, calibrated ET models were applied to estimate evapotranspiration from high resolution weather parameters (Abtew, 1996). The simplest ET estimation model currently used is:

$$ET = K_1 \frac{R_s}{\lambda} \tag{1}$$

where ET is evapotranspiration in mm day^{-1}, K_1 is a dimensionless coefficient (0.53), R_s is solar radiation in MJ m^{-2} day^{-1} and λ is latent heat of vaporization of water in MJ kg^{-1}. The daily distribution of ET over STA-1W as computed from solar radiation data collected at the weather station is depicted in Figure 3. The total areal ET for the study period was 537 cm. Yearly ET is shown in Table 2.

Flows and Water Levels. For the reporting period, 56 percent of the days had inflow with a daily average inflow rate of 11 m^3 s^{-1}. Seventy-two percent of the days had outflow pumping from either or both pump stations with daily average discharge of 10.5 m^3 s^{-1}. Surface seepage inflow from the Refuge, which has a water surface elevation higher than STA-1W, was 0.14 m^3 s^{-1}. For the operating period, the total inflow through the G-302 spillway was 1,389 hm^3, which resulted in an average hydraulic loading rate of 3.4 cm day^{-1}. The total outflow was 1,327 hm^3. The temporal and spatial averaged depth was 57 cm with variation between cells and seasons.

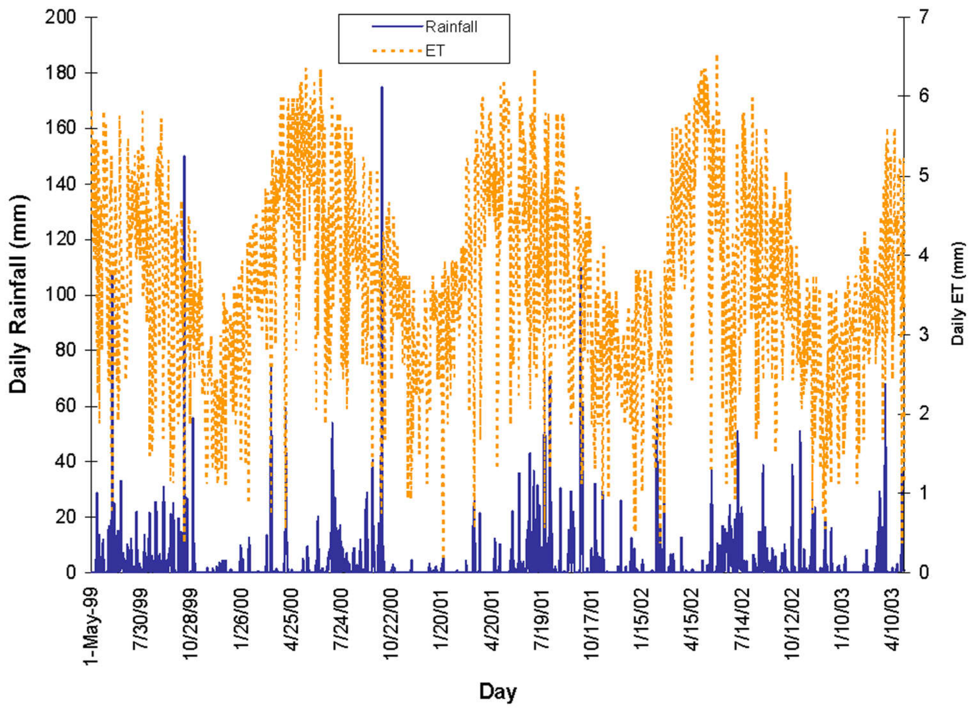


Figure 3. Daily areal rainfall and evapotranspiration in STA-1W (1999 to 2003).

Table 2. Water year (May to April) water budget and hydraulic parameters (cm) for STA-1W (May 1, 1999 to April 30, 2003).

Water Year	WY2000	WY2001	WY2002	WY2003	Total	Average
No. of days	366	365	365	365	1461	---
Rain (R)	132.26	89	133.63	107.44	462.33	---
Spillway inflow (G-302)	529.49	428.63	1273.99	2703.93	4936.04	---
Surface seepage (L7a)	22.39	10.68	16.3	14.65	64.02	---
Change in storage (ΔS)	-5.97	-41.24	18.62	23.88	-4.71	---
Seepage recirculation (G-250S)	202.77	125.41	53.65	53.01	434.85	---
ET	131.05	142.34	134	129.68	537.07	---
Pump outflow (G-251+G-310)	552.44	413.54	1222.68	2722.9	4911.56	---
Residuals	-43.66	-12.25	-48.61	51.03	-53.14	---
Average depth	54	53	58	61	---	57
Hydraulic loading rate (cm/d)	1.45	1.17	3.49	7.41	---	3.4
Hydraulic residence time (d)	36	46	17	8	---	17

Hydraulic loading rate (HLR) is expressed in Equation 2.

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

where Q is surface water inflow in ha-m day^{-1}, A is area of the constructed wetland in ha and HLR is hydraulic loading rate in m day^{-1}. The average annual hydraulic loading for the 2,700-ha STA contemplated during design is 2.2 cm day^{-1}, although considerable year-to-year variability is expected (SFWMD, 2001). The average HLR for the 4-yr period was 3.4 cm day^{-1}.

Hydraulic residence time, HRT, is expressed in Equation 3.

$$HRT = \frac{A \times d}{Q_*} \tag{3}$$

where Q_* is the average of the surface water inflow and outflow in ha-m day^{-1}, A is area of wetland in ha and d is average depth in m. The average HRT for the 4-yr period was 17 days. Table 2 summarizes annual estimates of hydraulic loading rates and hydraulic residence times.

Seepage. Seepage inflows and outflows occur into and out of STA-1W in the form of surface, lateral subsurface, and vertical subsurface seepage (Guardo and Prymas, 1998; Guardo, 1999; Choi and Harvey, 2000). Surface seepage inflow is from the Refuge through the eastern perimeter of STA-1W. The water surface elevation of the Refuge was higher than the eastern STA-1W water level with an average difference of 1.26 meters resulting in surface and subsurface seepage. Lateral subsurface seepage inflow and outflow potentially occurred into or from the agricultural area in the west when water levels were significantly varied from the water level in the delivery canal. The seepage recirculation pump station G-250S operated 92 percent of the days at an average rate of 0.93 m^3 s^{-1}. The seepage collection canal, which encompasses the northern perimeter of STA-1W, was maintained at an average water surface elevation of 2.36 m NGVD, at G-327_C tailwater, while the adjacent cell (Cell 5) maintained an average water surface elevation of 3.39 m NGVD. Recirculation pumping from the seepage canal through pump station G-250S (11,741 ha-m) was not considered as an input or output of the system for water budget computations but a recirculation in the system. Vertical seepage outflow increased from east to west through the previous ENR Project (Choi and Harvey, 2000). Estimates for surface seepage from the Refuge to STA-1W (L7a) were made based on estimation equations presented in Guardo (1999). Subsurface lateral and vertical seepage were lumped with error terms and presented as residuals in the water budget computation.

Water Budget. Annual water budget analysis for the ENR Project was reported through its five-year operation (Guardo, et al., 1996; Abtew and Mullen, 1997; Abtew and Downey, 1998; Guardo, 1999; Abtew et al., 2000). Water budget analysis for STA-1W has been reported on an annual basis (Abtew et al., 2000; 2001; 2002; Abtew and Reardon, 2003). A schematic model of STA-1W is shown in Figure 4. The water balance is expressed by the following equation:

$$\Delta S = G302 + R + L7a + L7b - G251 - G310 - ET \pm SEEPAGE \pm \varepsilon_t \quad (4)$$

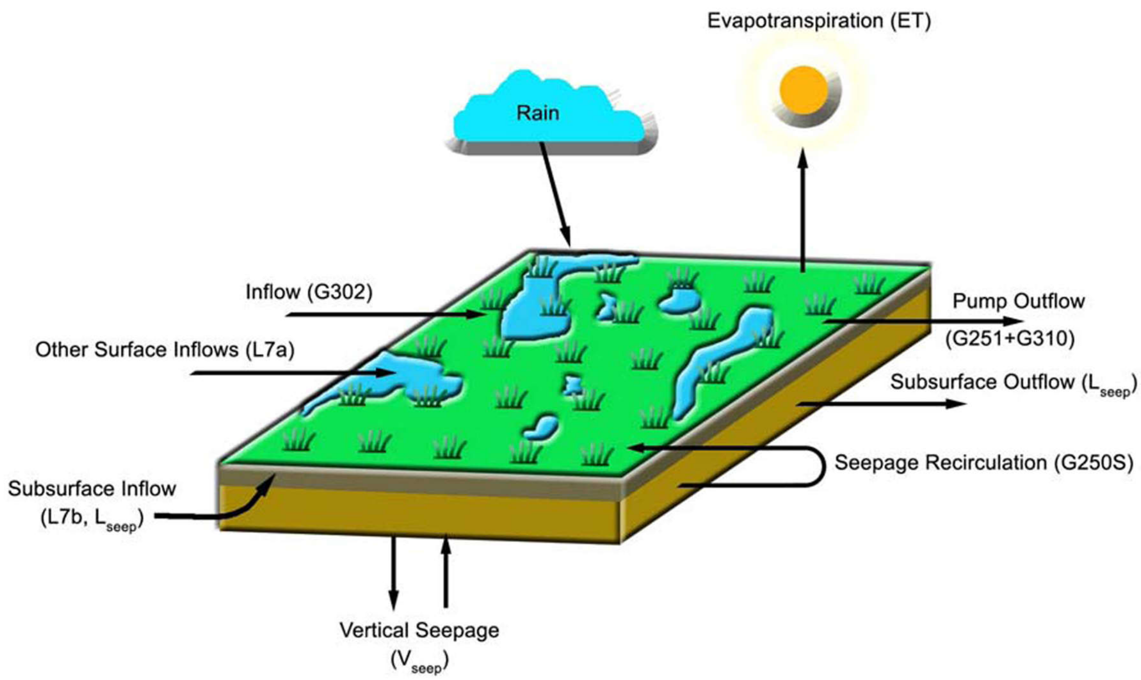


Figure 4. Schematic model of the STA-1W hydrology.

where ΔS is change in storage; G302 is spillway inflow; R is rain; L7a is surface seepage inflow from the Refuge through Levee L7; L7b is subsurface seepage inflow from the Refuge through Levee L7; G251 and G310 are pump outflows; ET is evapotranspiration; L_{seep} is subsurface lateral seepage; V_{seep} is subsurface vertical seepage and ε_t is the error term.

The water budget is summarized in Table 2. The main hydrologic components are the inflow (G-302) and outflow (G-251 and G-310), which were 90.7 percent and 89.2 percent of the total input and output of the system, respectively. Rainfall (R) was 8 percent and surface seepage from L7 Levee (L7a) was 1.1 percent of total input to the system. Evapotranspiration accounted for 9.7 percent of the total output from the system, while change in storage accounted for 0.2 percent of the output (Figure 5). The residuals, which account for lateral and vertical seepage plus errors, were 1.2 percent of the total output from the system.

Between July 2002 and February 2003, approximately 407 hm^3 (330,000 ac-ft) of Lake Okeechobee releases were diverted to STA-1W for treatment prior to discharge into the Refuge. These inflows accounted for over one-half of the STA-1W inflows during the water year. The decision to send lake releases to STA-1W was based on a federally authorized regulation schedule for the lake. This schedule, referred to as Water Supply and the Environment (WSE), is designed to balance regional factors by (1) controlling water levels and potential impacts to the lake and Everglades ecosystems, (2) minimizing damaging freshwater discharges to the Caloosahatchee Estuary and the St. Lucie Estuary, and (3) providing flood control and water supply to tributary basins. Because the Refuge was the only water conservation area where the water level was below its operating schedule for most of the year, the WSE schedule dictated sending the majority of the excess water to the Refuge. Generally, the District prefers to treat any water it sends to the Water Conservation Areas, so these lake releases were diverted to STA-1W. These deliveries were terminated in February 2003, when data indicated that the annual outflow concentrations of P from STA-1W might exceed the target of 50 µg/L. The lowest hydraulic residence time of 8 days occurred in water year 2003. In the near future, lake releases are not to be directed to STA-1W until water quality and biological data indicate that the treatment area has recovered from the high phosphorus loading created by this diversion. STA-3/4 was designed to capture and treat approximately 308 hm^3/yr (250,000 ac-ft per year) of lake releases. When construction is completed, it is expected to handle the majority of any required lake releases. Also, the EAA Storage Reservoir will provide regional water storage in the future. Finally, it is possible that STA-1E could have provided some additional storage and treatment capability had it been operational.

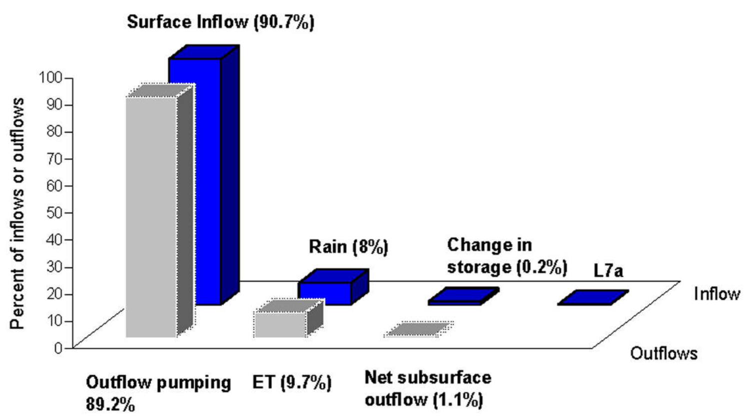


Figure 5. Summary of STA-1W water budget parameters (1999 to 2003).

Water Quality

Water quality monitoring at STA-1W encompasses many parameters that are required for permit compliance. Details of monitoring and data analysis are provided in previous reports (Goforth et al., 2002; 2003; 2004). The primary water quality parameter, total phosphorus (P), is monitored with grab samples at the G-302 spillway, although a time-proportioned auto-sampler was recently installed. STA-1W, functioning in combination with other elements of the Everglades Construction Project and EAA best management practices, is intended to produce a long-term, flow-weighted average P concentration of 50 µg/L prior to discharge to the Refuge (SFWMD, 2001). Enhancements are currently under design to further reduce the outflow concentrations (Piccone et al., 2003). Outflow pumps G-251 and G-310 are sampled with flow-proportional auto-samplers. Weekly composite flow-proportional samples are collected from each auto-sampler along with grab samples. Figure 6 a,b,c depicts annual inflow and outflows, P loads and P concentrations at the G-302 inflow station and through the G-251 and G-310 pump outflow stations. The average inflow and outflow flow-weighted mean total P concentrations were 146 μg/L and 45 μg/L, respectively. P load is computed as a product of total flow and flow-weighted concentration. The constructed wetland achieved a P load reduction of 71% percent during this 4-yr period.

Treatment Efficiency

The long-term phosphorus removal mechanism within the STAs is the creation of plant biomass and subsequent accretion of this organic material onto the sediment. The initial estimates of the effective treatment area required for each of the STAs were based on the work of Walker (1995) and Kadlec and Knight (1996). Phosphorus removal within the STA was assumed to be represented by a first-order equation:

$$R = k\,A\,C \qquad (5)$$

where R = removal rate, g/yr
k = effective settling rate, m/yr
A = effective treatment area, m^2
C = water column concentration of phosphorus, g/m^3

Integration of the differential equations describing the water and phosphorus mass balances, with the following assumptions:

1. the flow in the STA can be represented as plug flow;
2. the STA will remain wet all year long; there is negligible interaction between the STA and groundwater;
3. the apparent background phosphorus concentration within the STA is equal to zero; and
4. the effective settling rate is constant and independent of hydraulic and nutrient loading rates

and solving for area, yields the following equation for determining the effective treatment area required for each STA (Walker, 1995):

$$A = \frac{Q\left\{\frac{(N\,C_i + k\,C_i - P\,C_p)}{(N\,C_o + k\,C_o - P\,C_p)}\right\}^{[1/(1+k/N)]} - Q}{N} \qquad (6)$$

Where C_o = target long-term average annual outflow phosphorus concentration, mg/l
C_i = long-term average annual inflow phosphorus concentration, mg/l
Q = long-term average annual inflow, m^3/yr
P = long-term average annual rainfall, m/yr
N = long-term average annual difference between rainfall and evapotranspiration, m/yr
C_p = long-term average annual phosphorus concentration of atmospheric deposition, mg/l
K = effective settling rate, m/yr

A = area required to achieve the target outflow phosphorus concentration, m^2

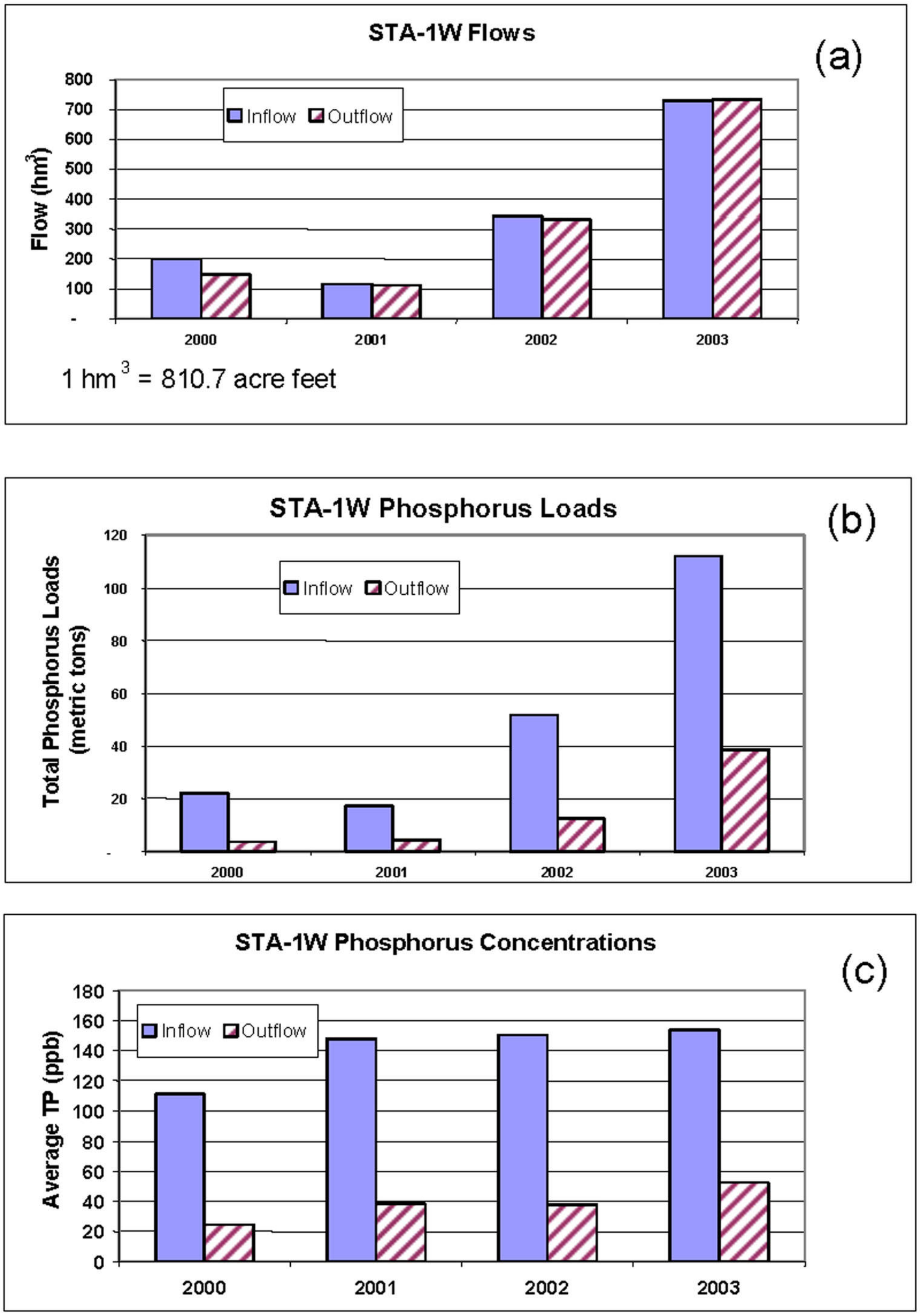


Figure 6. STA-1W inflow (G-302) and outflow (combined G-251 and G-310) total phosphorus levels.

Using soil and water column phosphorus data from WCA-2A, a value of 8 m/yr was initially estimated for the effective settling rate (Burns and McDonnell, 1992). Later analysis excluded droughts from the periods in which phosphorus removal is assumed to occur, and the effective settling rate increased to 10.2 m/yr (Walker, 1995).

Annual estimates of the effective settling rate, k, can be derived from the STA-1W data using Equation 7 (Chimney and Moustafa, 1999).

$$k = \ln (C_i / C_o) \times [(Q_{in} + Q_{out})/2A] \quad (7)$$

Where Q_{in} = annual inflow, m^3
Q_{out} = annual outflow, m^3
C_i = flow-weighted influent TP concentration, kg/m^3
C_{out} = flow-weighted effluent TP concentration, kg/m^3

In addition, the P removal efficiency can be expressed in Equation 8.

$$\text{Removal efficiency} = (\text{Inflow load} - \text{Outflow load}) / \text{Inflow load} \quad (8)$$

Annual estimates of the effective settling rate and the removal efficiencies for STA-1W are presented in Figure 7.

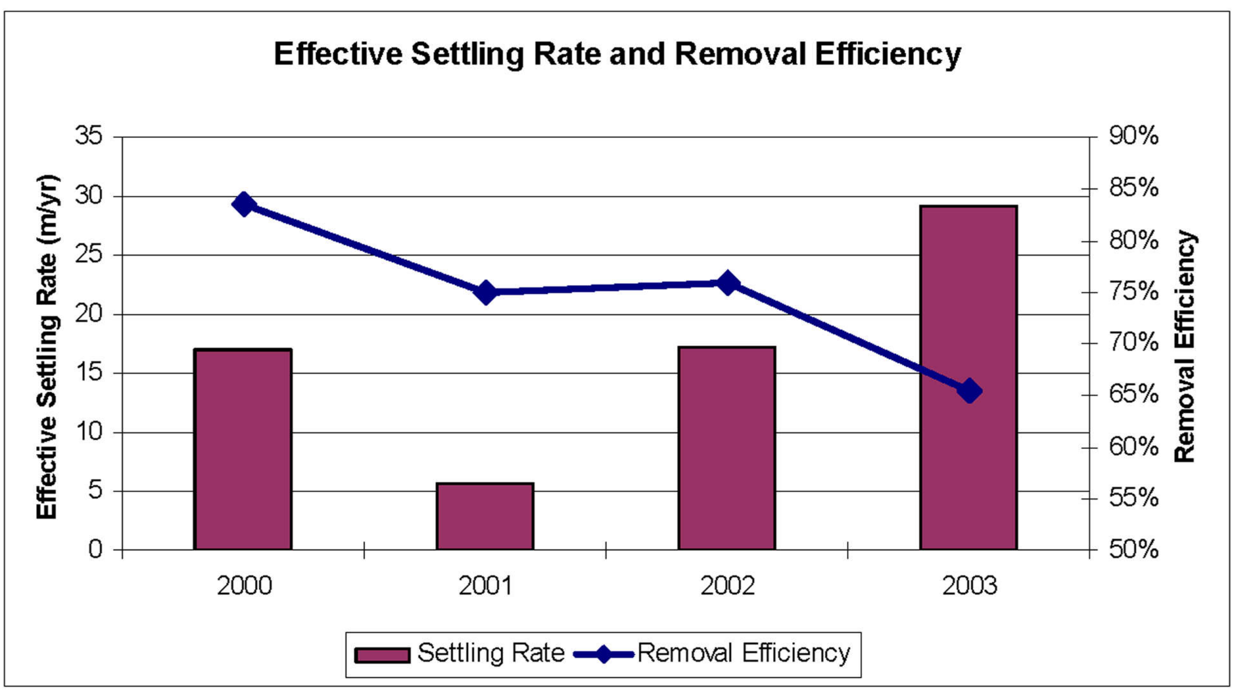


Figure 7. Annual STA-1W effective settling rates and removal efficiencies.

With over eight years of Stormwater Treatment Area performance data available from the ENR project and STA 1-W, a brief synopsis of phosphorus removal performance may be insightful. Of particular focus is the envelope of STA performance under high nutrient loading rates, as experienced during Water Year 2003. Figure 8 summarizes the annual removal rate (expressed as grams per square meter per year) in relation to the annual nutrient loading rate (also expressed as grams per square meter per year). A very strong correlation is observed, with about 99% of the variance in removal rate explained by variance in the nutrient loading rate. The strong linear relationship reflects the underlying first-order removal process that occurs in biological treatment systems (see Equation 5). The proposed enhancements to the STAs (discussed in Piccone et al., 2004) have been designed using a forecast model based on this relationship.

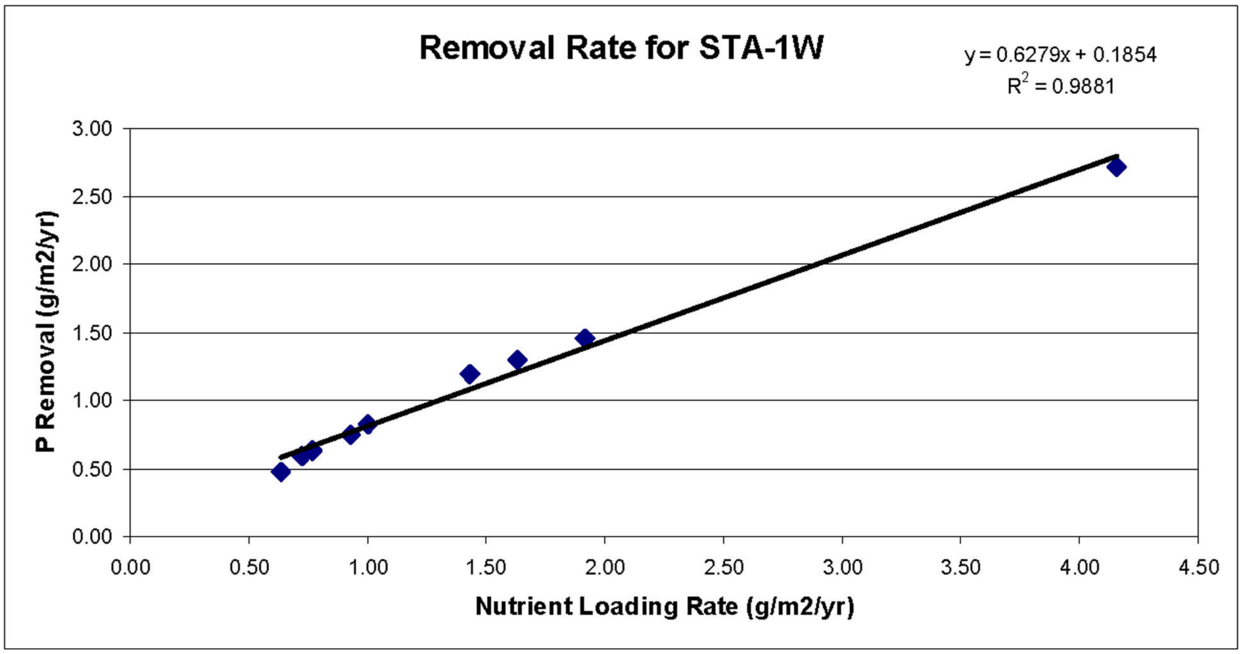


Figure 8. STA-1W P removal rate as a function of P loading rate.

Summary

Stormwater Treatment Areas have become the primary regional methods of P removal from runoff and other sources in South Florida. The first of the six large-scale constructed wetlands, STA-1W has been in operation for over eight years. Periodic water budget, hydraulic, and treatment performance analysis is essential to optimize operation and advance design parameters for constructed wetlands. In the second four years of operation, wide ranges of hydraulic and nutrient loading have been experienced. The annual inflow during this time period ranged from 116 to 730 hm^3 (93,800 to 592,000 acre feet), with an associated range in hydraulic loading from 1.17 to 7.41 cm/day. The corresponding annual inflow phosphorus loads ranged from 17.1 to 112 metric tons, with an associated nutrient loading rate range from 0.63 to 4.16 $g/m^2/yr$. The average hydraulic loading rate was 3.4 cm day^{-1} with an average depth of 57 cm and average hydraulic residence time of 17 days. Annual flow-weighted mean inflow concentrations ranged from 111 to 154 μg/L. The annual outflow during this time period ranged from 112 to 735 hm^3 (90,900 to 595,999 acre feet). The corresponding annual outflow phosphorus loads ranged from 3.67 to 38.7 metric tons, with an associated phosphorus removal rate range from 0.48 to 2.72

$g/m^2/yr$. The annual flow-weighted mean outflow concentrations ranged from 25 to 53 µg/L. The constructed wetland achieved a total P load reduction of 71 percent during this 4-yr period.

Acknowledgements

The authors would like to thank Violeta Ciuca and Christopher King for the wetland water budget model schematic drawing and Kathy Pietro for assistance in STA-1W data analysis. Linda Lindstrom, Jana Newman and Martha Nungesser are acknowledged for reviewing and providing useful comments. Hedy Marshall and Stacey Efron are acknowledged for their editorial review.

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