Technical Presentation
EMA # 394
(For presentation at ASCE Wetlands Engineering and River Restoration Conference 2001, August 27-31, 2001, Reno, Nevada)

# Hydrologic Performance of a Large-Scale Constructed Wetland: The Everglades Nutrient Removal Project

April 2001

by


Wossenu Abtew
Tim Bechtel

Hydro Information Systems and Assessment Department
Environmental Monitoring & Assessment Division
South Florida Water Management District
West Palm Beach, FL 33406

# Hydrologic Performance of a Large-Scale Constructed Wetland: The Everglades Nutrient Removal Project

Wossenu Abtew* and Tim Bechtel**

*Lead Engineer, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406; PH (561) 682-6326; FAX (561) 682-6442; email:wabtew@sfwmd.gov
**Sr. Supervising Environmental Scientist, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406; PH (561) 682-6392; FAX (561) 682-6442; email:tbechtel@sfwmd.gov

*Abstract*

The Everglades Nutrient Removal Project was a 1544 hectare (ha) constructed wetland that was operated from August 1994 to July 1999 as a flow-through treatment system to reduce phosphorus (P) levels in agricultural drainage/runoff. It was designed and operated as a prototype for planned stormwater treatment areas of more than 16,000 ha that are being built to reduce P load from the Everglades Agricultural Area into the Everglades Protection Area in South Florida. The wetland had a distribution (buffer) cell (55 ha) and a pair of parallel treatment systems with two cells in each. The eastern treatment train consisted of Cell 1 (525 ha) and Cell 3 (404 ha) and the western treatment train consisted of Cell 2 (414 ha) and Cell 4 (146 ha). Spatial and temporal average surface cover was mainly cattails (41%), open water (33%), mixed vegetation (24%) with the remainder covered by algae and floating aquatics. The average inflow and outflow pumping rates were 39.76 and 39.35 ha-m day$^{-1}$, respectively. The average hydraulic loading rate was 2.57 cm day$^{-1}$ with average depth of 55.6 cm and average hydraulic retention time of 22 days. The average inflow and outflow total P concentrations were 105 μg L$^{-1}$ and 22 μg L$^{-1}$, respectively. The constructed wetland achieved a total P reduction of over 75 percent demonstrating its treatment ability. 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 although the construction of wetlands for purpose of water treatment only started in the 1950s (Kadlec and Knight, 1996). The net removal of phosphorus 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). The Everglades Forever Act, enacted in 1994, requires that phosphorus (P) in drainage/runoff waters be reduced through the use of large-scale constructed wetlands before it is discharged to the Everglades Protection Area.

The Everglades Nutrient Removal Project (ENR) was a 1,544 ha constructed wetland, designed and operated to demonstrate the feasibility of large-scale phosphorus reduction from agricultural drainage/runoff. The project is located in South Florida (26° 38' N, 80° 25' W) at the eastern edge of the Everglades Agricultural Area (Figure 1). The Everglades Agricultural Area

(EAA) is a 240,000 ha highly productive irrigation/drainage basin with sugarcane as the major crop. Ecological changes in the Everglades have been partially attributed to an increase in phosphorus concentrations in the inflow waters. Local, state and federal initiatives have been taken to reduce total P loads in the agricultural drainage/runoff. EAA agricultural drainage/runoff flows to the south and southeast through four primary canals (Miami, North New River, Hillsboro, West Palm Beach).

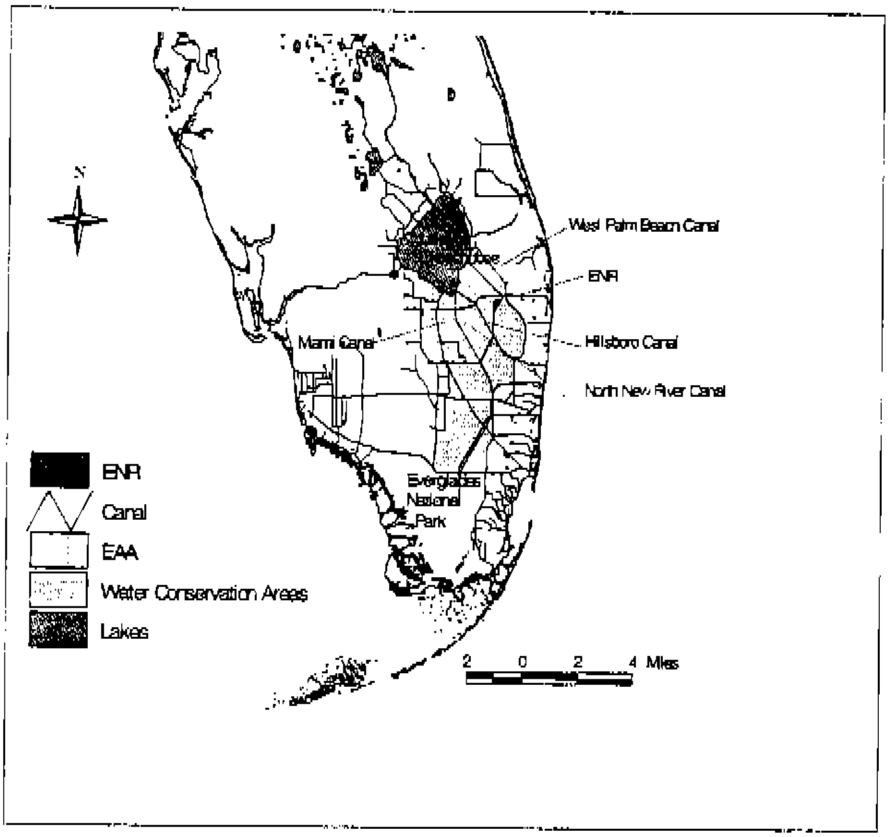


**Figure 1. Location of the Everglades Nutrient Removal Project in South Florida**

A minimum of 25 percent of the total P load in agricultural drainage/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). The ENR project was a field scale prototype for the large-scale STAs. It was built on farmland owned by the State of Florida and previously leased (until 1988) to Knight's Farm for sugarcane and corn production. Originally, the land was part of the Everglades, which consisted of wetland prairies, sloughs and stands of custard apple. ENR project construction started in August 1992 and was completed in October 1993. The inflow and outflow pumps started operation in August 1994. The ENR project was operated for five years before being incorporated into the larger Stormwater Treatment Area 1 West (STA-1W) in July 1999. In the first quarter of 2001, three of six planned Stormwater Treatment Areas were in operation.

The ENR Project area is primarily covered by Okeechobee muck soils with very low topographic relief and an average ground elevation of 3 meters (m) NGVD (Table 1). A 1 to 2 m layer of peat overlies several meters of carbonate rock. To the east, the L-7 levee separates the ENR Project from the Loxahatchee National Wildlife Refuge (Water Conservation Area 1). The northern and western sides of the ENR project are bounded by a seepage canal and levee that separates the ENR project from agricultural fields. The narrow, southern ENR project levee runs along Knight's Farm, which is not under cultivation. A 12-km levee surrounds the ENR project and internal levees separate the five interior cells. The Project consisted of two parallel treatment trains of two cells each and a buffer (distribution cell). As shown in Figure 2, the upper two cells, Cells 1 and 2, were treatment cells. The lower two cells, Cells 3 and 4, were polishing cells. The eastern treatment train carried water from the Buffer Cell to Cell 1, then to Cell 3 and finally to the outflow pump. The western treatment train carried water from the Buffer Cell to Cell 2, then to Cell 4 and finally to the outflow pump.

As part of the ENR project monitoring plan, temporal and spatial changes of vegetation were documented using aerial photography taken quarterly prior to 1995 and semiannually thereafter. The dominant covers were cattail (41%), open water/submerged macrophytes (33%), mixed vegetation (24%), with the remaining covered by algae and floating macrophytes. Significant temporal variation in coverage was observed (SFWMD, 2000).

**Table 1. ENR project site characteristics and average water depth (1994-1999).**

| Cell | Area (ha) | Ground elev. (m NGVD) | Avg. depth (cm) | Dominant cover |
|---|---|---|---|---|
| Buffer Cell | 55 | 3.14 | 58 | cattails/floating macrophyte |
| Cell 1 | 525 | 3.08 | 55 | cattails/open water/submerged macrophyte |
| Cell 2 | 414 | 2.88 | 76 | cattails |
| Cell 3 | 404 | 3.16 | 32 | other emergent macrophytes/cattail |
| Cell 4 | 146 | 2.94 | 63 | open water/submerged macrophyte |

### *System Hydraulics*

West Palm Beach canal water that would otherwise be pumped into the Water Conservation Area 1 (WCA1) via the S5-A Pump Station was partially diverted to the ENR project through five culverts and a 3.4 km supply canal. Inflow into the constructed wetland, outflow from the constructed wetland, and seepage recycling were performed with lift pumps. The inflow pump station (G250) had six identical pumps with a total capacity of 16.98 $m^3\ s^{-1}$. The inflow pumps lifted water from the delivery canal into the Buffer Cell. The outflow pump station (G251) had six identical pumps with a total capacity of 12.74 $m^3\ s^{-1}$. The outflow pumps lifted treated effluent from the ENR project into the Loxahatchee National Wildlife Refuge. Seepage from the seepage canal was pumped into the Buffer Cell by three identical pumps (G250S) with a total capacity of 5.66 $m^3\ s^{-1}$ . Water can be recirculated through the seepage canal from Cell 2 and Cell 4 via culverts G258 and G259, respectively. Water surface elevation was monitored by automated stage recorders and staff gages supplemented stage readings for operational purposes.

Inter-cell flow was regulated with risers through 16.7 m long and 1.83 m diameter culverts. In the eastern treatment train, water flowed from the Buffer Cell into Cell 1 through 10 culverts (G252A-J) and from Cell 1 to Cell 3 through 10 culverts (G253A-J). Water from Cell 3 flowed to the outflow pump through collection canals.

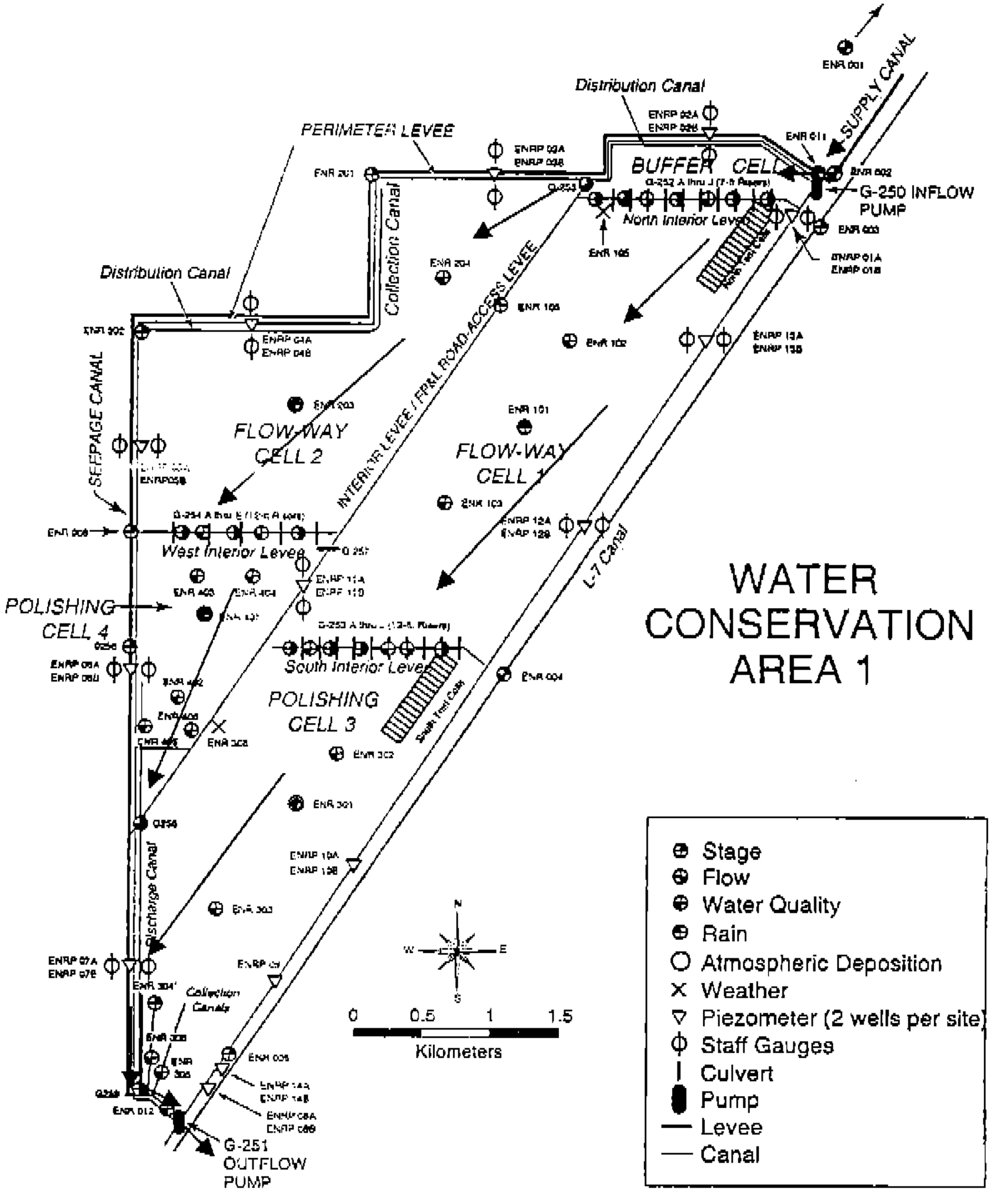


**Figure 2. ENR project structures and monitoring sites.**

In the western treatment train, water flowed from the Buffer Cell into Cell 2 through five culverts (G255A-E) and from Cell 2 to Cell 4 through five culverts (G254A-E). Outflow from Cell 4 flowed through five culverts (G256A-E) into a discharge canal that led to the outflow pump station. ENR project structure locations and monitoring sites are shown in Figure 2.

*Operation*

The seepage pump started operation in December 1993. Pumping was mainly to recirculate water from the seepage canal and reroute water from cell to cell. The inflow and outflow pumps started operating on August 19, 1994, marking the beginning of full-scale operation of the ENR project. The recommended depths in each cell ranged from 46 to 67 cm. Inflow and outflow operations were based on many conditions, such as the stage in each cell, S-5A pump station status, seepage tests, construction operations, pump maintenance and others. Through the five years of operation, the mean depths in the Buffer Cell and Cells 1, 2, 3 and 4 were 58, 55, 76, 32 and 63 cm, respectively. Water could be recirculated from Cell 2 and Cell 4 via the seepage canal by being released through culverts (G258 and G259, respectively) in the western levee. Water could be transferred from Cell 1 to Cell 4 through culvert G257 when necessary.

*ENR Project Hydrologic Monitoring*

***Rainfall.*** South Florida has a subtropical climate with relatively high rainfall frequency of occurrence and magnitude. On the average, 34% of the annual rainfall occurs in the dry season (November to May), with the remaining 66% occurring in the wet season (June to October). Mean annual rainfall for the area is 133 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-gage rainfall network was established as a pilot network to evaluate the optimum gage density needed for the project area. Network analysis of the first wet season daily rainfall showed that five gages were sufficient for the area (Abtew et al., 1995). As a result, three gages were removed. However, a seven-gage network was maintained because two of the gages were associated with two weather stations, and four gages (one at the middle of each cell) were part of the monitoring network required by the operating permit. Areal average rainfall on the project site was computed as a Thiessen-weighted average of the stations. The daily distribution of areal average rainfall for the study period (August 19, 1994 to June 30, 1999) is depicted by Figure 3. The total areal rainfall for ENR project (August 19, 1994 to June 30, 1999) was 705 cm. Annual rainfall is shown in Table 2.

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

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

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 $\lambda$ is latent heat of vaporization of water in MJ kg$^{-1}$. The daily distribution of ET for the study period (August 19, 1994 to June 30, 1999) is depicted by Figure 3. The total areal ET for ENR project was 635 cm. Annual ET is shown in Table 2.

***Flows and Water Levels.*** Inflow to the ENR project was through pump station G250 with a capacity of 16.98 $m^3 s^{-1}$. On 75 percent of the days there was inflow with a daily average

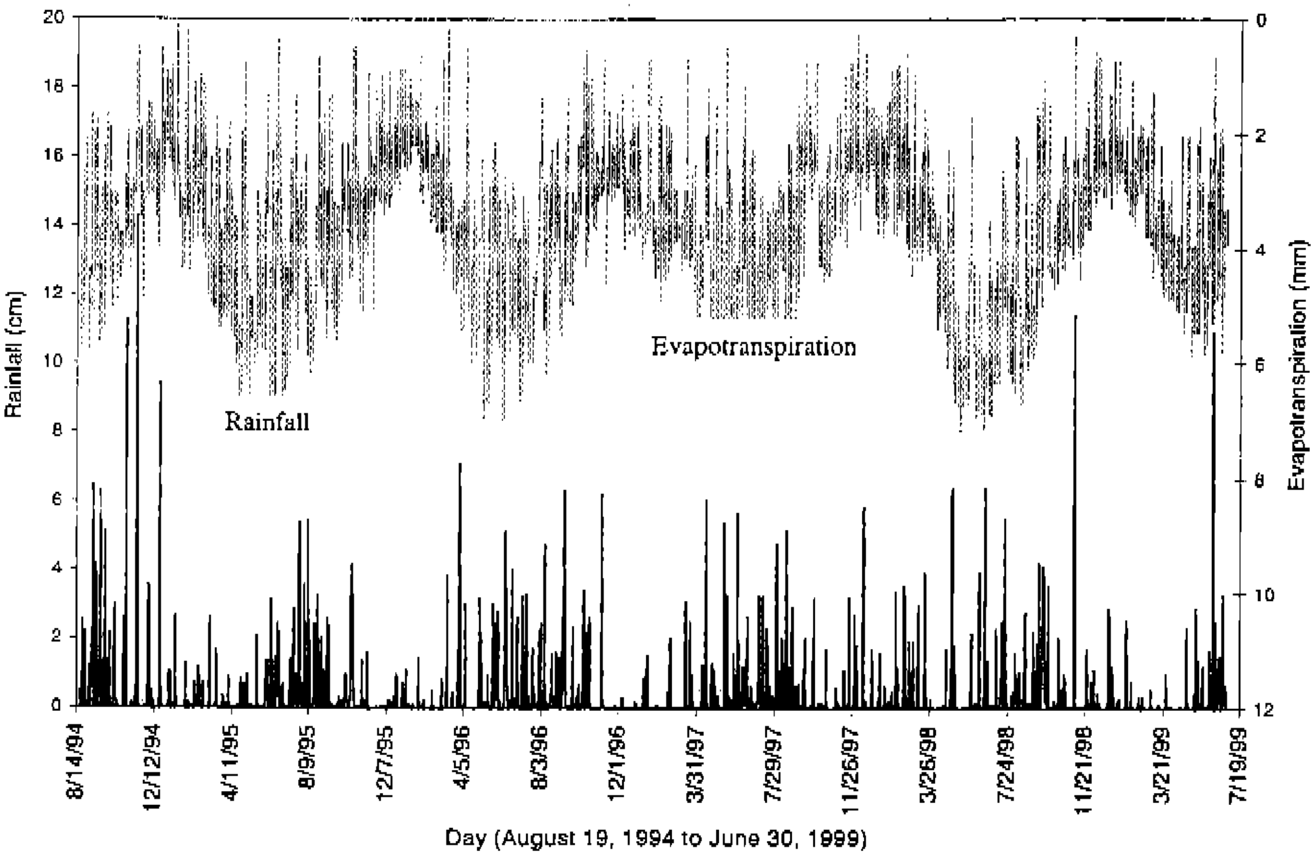


**Figure 3. Daily areal rainfall and evapotranspiration in ENR project (August 19, 1994 to June 30, 1999).**

pumping of 6.16 $m^3 s^{-1}$. Outflow was through pump station G251 with a capacity of 12.74 $m^3 s^{-1}$. On 96 percent of the days there was outflow with a daily average discharge of 4.73 $m^3 s^{-1}$. Surface seepage inflow from Water Conservation Area 1, which has water surface elevation higher than ENR project, was 0.183 $m^3 s^{-1}$. The seepage recirculation pump station G251S operated the entire period, except three days, at a rate of 1.41 $m^3 s^{-1}$. The seepage collection canal which encompasses the western and northern perimeters of the ENR project was maintained at an average water surface elevation of 2.44 m NGVD while the adjacent (western) cells of the ENR project maintained 3.63 m NGVD average water surface elevation.

For the study period, the total inflow pumping from the supply canal was 70,573 ha-m, which resulted in an average hydraulic loading rate of 2.57 cm $day^{-1}$. The total effluent outflow pumping was 69,826 ha-m. The temporal and spatial averaged depth was 55.6 cm with variation between cells and seasons. The average hydraulic retention time in days (HRT) was computed as follows:

$$HRT = \frac{A \times d}{Q_{avg}} \tag{2}$$

where A is wetland area, d is average depth and $Q_{avg}$ is daily average flow. Monthly flows and average water depth are depicted in Figure 4.

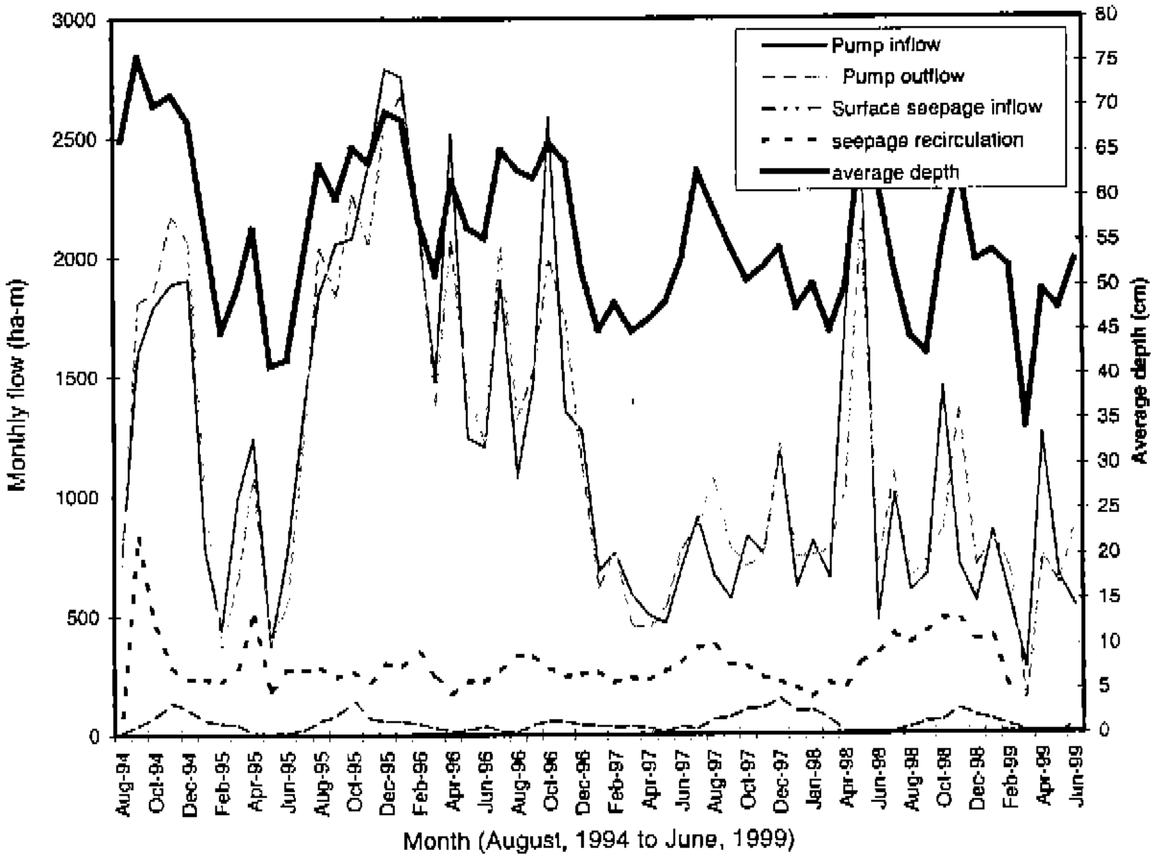


**Figure 4. Monthly flows and average water depth in ENR project (1994 to 1999).**

*Seepage.* Seepage inflows and outflows occurred into and out of the ENR project in the form of surface, lateral subsurface and vertical subsurface seepage (Guardo and Prymas, 1998; Guardo, 1999; Choi and Harvey; 2000). Surface seepage inflow was from Water Conservation Area 1 through the eastern perimeter of the ENR project. The water surface elevation of WCA1 was higher than the ENR project with an average difference in water level of 1.4 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 higher than the water level in the seepage canal. Lateral subsurface seepage outflow would also occur through the southern levee. The apparent subsurface seepage was to the seepage canal through the western and northern levees of the ENR project. In this study, recirculation pumping from the seepage canal through pump station G251S (16, 296 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 occurred through the ENR project increasingly as it went to the west (Choi and Harvey, 2000). Estimates for surface seepage from WCA1 to the ENR project (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 or remainders in the water budget computation.

***Water Budget.*** Water flow model for the ENR project was originally developed and annual water budgets for the constructed wetland were reported previously (Guardo, Abtew, Fink and Cadogan, 1996; Abtew and Mullen, 1997; Abtew and Downey, 1998; Guardo, 1999; Abtew, Raymond and Imru, 2000). A schematic model of the ENR project is shown in Figure 5 and the water balance is expressed by the following equation.

$$\Delta S = G250 + R + L7a + L7b - G251 - ET \pm L_{seep} \pm V_{seep} \pm \varepsilon_t \qquad (3)$$

where $\Delta S$ is change in storage; G250 is pump inflow; R is rain; L7a is surface seepage flow from Water Conservation Area 1 through Levee L7; L7b is subsurface seepage inflow from Water Conservation Area 1 through Levee L7; G251 is pump outflow; ET is evapotranspiration; $L_{seep}$ is subsurface lateral seepage; $V_{seep}$ is subsurface vertical seepage and $\varepsilon_t$ is errors. The water budget terms are summarized in Table 2.

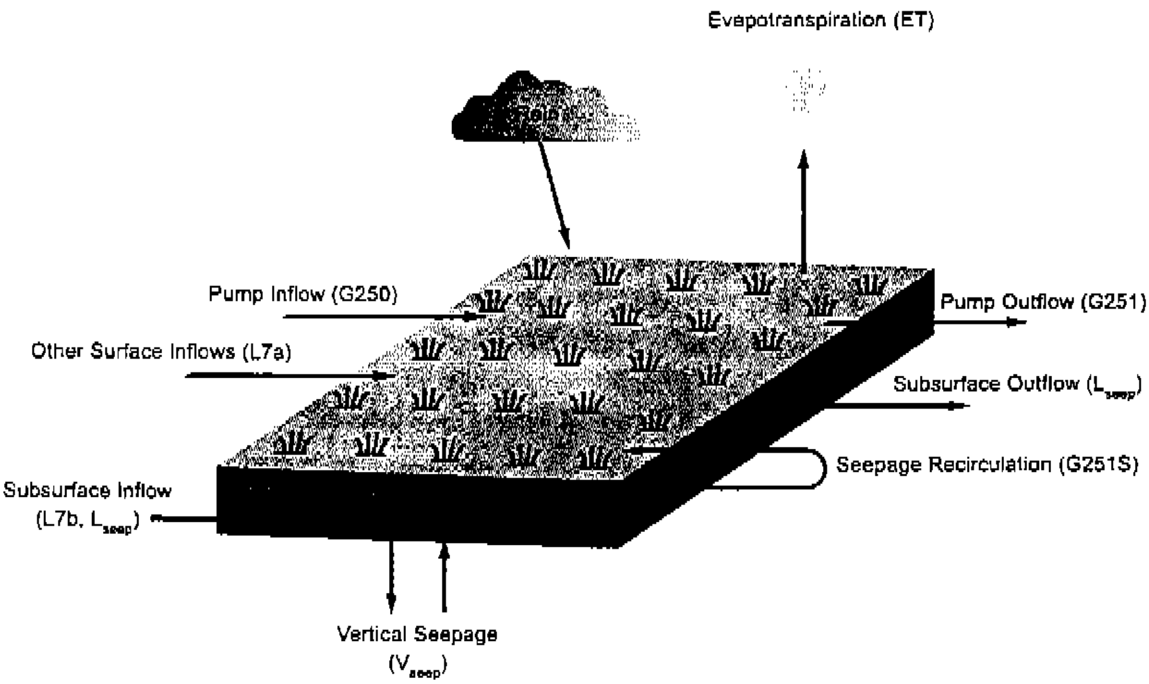


**Figure 5. Schematic model of the ENR project hydrology.**

The main hydrologic components were the inflow (G250) and outflow (G251) pumping which were 83.6% and 82.7% of the total input and output of the system, respectively. Rainfall (R) was 12.9% and surface seepage from L7 Levee (L7a) was 3.3% of total input to the system. Evapotranspiration accounted for 11.6% of the total output from the system, while change in storage accounted for 0.2% of the output (Figure 6). The Remainders, which account for lateral, vertical seepage and errors, were 5.7% of the total output from the system (Figure 6).

**Table 2. Calendar year water budget and hydraulic parameters (cm) for ENR project (August 19, 1994 to June 30, 1999).**

| Year | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | Total | Average |
|---|---|---|---|---|---|---|---|---|
| No. of days | 135 | 365 | 366 | 365 | 365 | 181 | 1777 | --- |
| Rain (R) | 109.7 | 119.33 | 142.82 | 135.08 | 148.92 | 49.3 | 705.15 | --- |
| Pump inflow (G250) | 515.02 | 1105.77 | 1359.91 | 559.28 | 762.83 | 267.97 | 4570.78 | --- |
| Surface seepage (L7a) | 23.65 | 39.34 | 27.82 | 44.44 | 38.1 | 8.84 | 182.19 | --- |
| Change in storage (ΔS) | -3.27 | 5.9 | -29.73 | 11.93 | -5.02 | 10.48 | -9.71 | --- |
| Seepage recirculation (G251S) | 122.08 | 213.82 | 208.36 | 213.5 | 258.92 | 38.46 | 1055.14 | --- |
| ET | 43.44 | 132.29 | 125.73 | 127.4 | 142.27 | 84.14 | 635.27 | --- |
| Pump outflow (G251) | 559.01 | 1037.88 | 1343.07 | 582.35 | 747.64 | 252.48 | 4522.43 | --- |
| Remainders | -49.19 | -89.37 | -91.48 | -17.12 | -64.96 | 0.99 | -310.13 | --- |
| Average depth | 71 | 55.7 | 60.4 | 51.6 | 52.6 | 48.3 | --- | 55.6 |
| Hydraulic loading rate (cm/d) | 3.81 | 3.03 | 3.72 | 1.53 | 2.09 | 1.48 | --- | 2.57 |
| Hydraulic retention time (d) | 18 | 19 | 16 | 33 | 25 | 33 | --- | 22 |

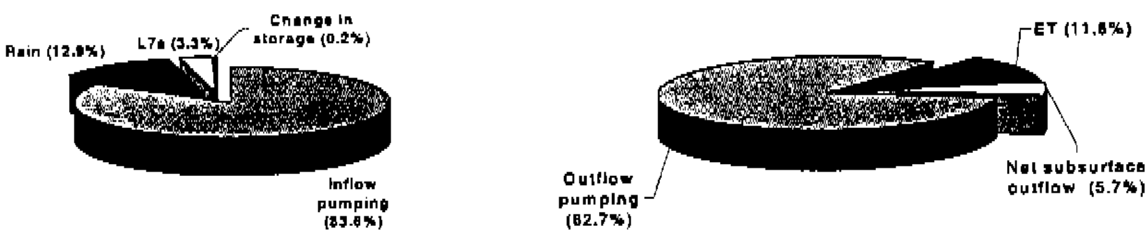


**Figure 6. Summary of ENR project water budget parameters (August 19, 1994 to June 30, 1999).**

*Water Quality*

Water quality monitoring at the ENR project encompassed many parameters that are required for permit compliance. Details of monitoring and data analysis are provided in the Everglades Consolidated Report (2000). The main water quality parameter, total phosphorus, was monitored at the inflow and outflow pumps in addition to other sites. Weekly composite flow proportional and grab samples were collected at these pumps. Based on a 12-month rolling average total phosphorus load analysis, a cumulative load reduction of 82% was reported (SFWMD, 2000). For this study period, the inflow and outflow total phosphorus concentration ranged from 28 μg/L to 227 μg/L and 6 μg/L to 57 μg/L, respectively with corresponding means of 105 μg/L and 22 μg/L. Figure 7 depicts inflow and outflow total P concentrations.

*Summary*

The ENR Project was a large constructed wetland designed as a prototype wetland to further reduce concentrations of total P in agricultural drainage/runoff. Five years of operation demonstrated that over 75% of load and concentration reduction was achieved. The demonstration showed that constructed wetlands are viable treatment systems for reducing P from agricultural drainage/runoff. The significance of seepage management and subsurface flows was demonstrated by the water budget analysis.

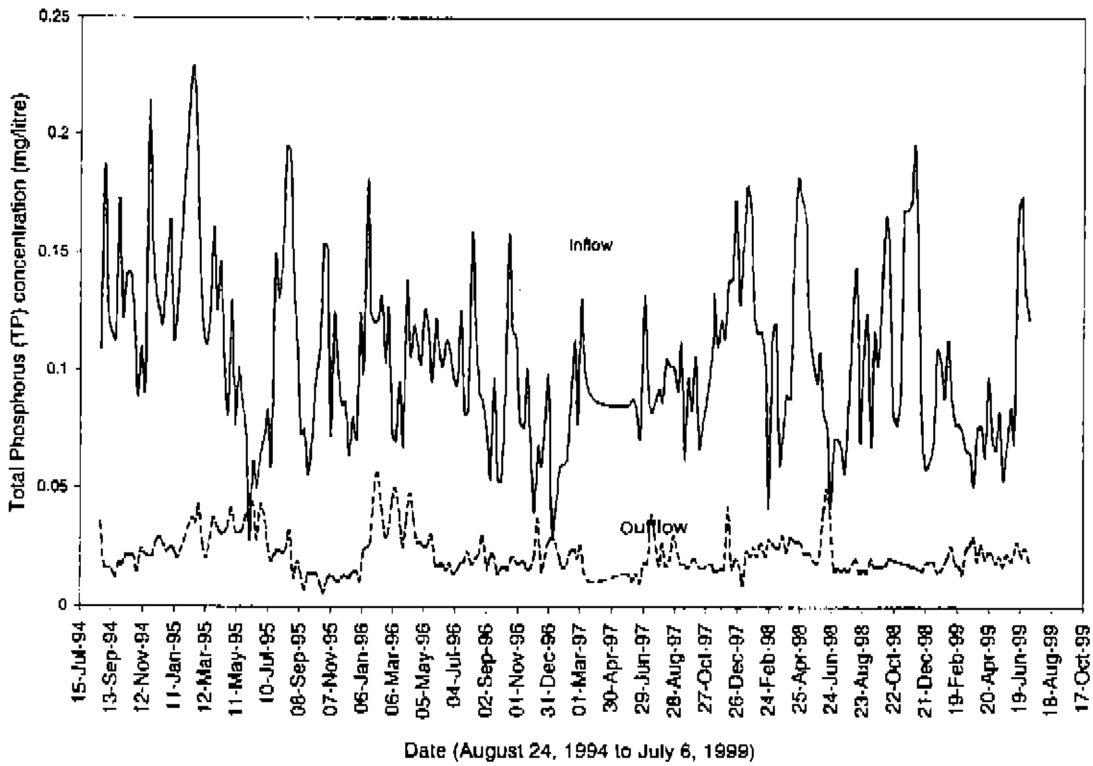


**Figure 7. ENR project inflow and outflow total phosphorus concentrations.**

*Acknowledgements*

The authors would like to thank Chris King for graphics work; Susan Bennett, Guy Germain, Mariano Guardo, Scott Huebner, Nagendra Khanal, Martha Nungesser, Chandra Pathak, John Raymond and Garth Redfield for reviewing the draft of the paper.

*References*

Abtew, W., Obeysekera, J. and Shih, G. (1995). Spatial variation of daily rainfall and network design. Transactions of ASAE 38(3):843-845.

Abtew, W. (1996). Evapotranspiration measurement and modeling for three wetland systems in South Florida. Journal of American Water Resources Association 33(3):465:473.

Abtew, W. and Mullen, V. (1997). Water budget analysis for the Everglades Nutrient Removal

Project (August 20, 1996 to August 19, 1997). Technical Memorandum WRE #354. South Florida Water Management District, West Palm Beach, FL.

Abtew, W. and Downey, D. (1998). Water budget analysis for the Everglades Nutrient Removal Project (August 20, 1997 to August 19, 1998). Technical Memorandum WRE #368. South Florida Water Management District, West Palm Beach, FL.

Abtew, W., Raymond, J. and Imru, M. (2000). Water budget analysis for the Everglades Nutrient Removal Project (August 20, 1998 to June 30, 1999). Technical Memorandum EMA #388. South Florida Water Management District, West Palm Beach, FL.

Choi, J. and Harvey, J. W. (2000). Quantifying time-varying ground-water discharge and Recharge in wetlands of the northern Florida Everglades. Wetlands, Vol. 20(3): 500-511.

Davis, S. M. (1991). Growth. Decomposition, and Nutrient Retention of Cladium jamaicense Cranz and Typha domingensis Pers. in the Florida Everglades. Aqua. Bot. 40:203:224.

Guardo, M., Abtew, W., Fink, L. and Cadogan, A. (1996). Water budget analysis for the Everglades Nutrient Removal Project (August 19, 1994 to August 19, 1996). Technical Memorandum WRE #347. South Florida Water Management District, West Palm Beach, FL.

Guardo, M. and Prymas, A. (1998). Calibration of steady-state seepage simulation to estimate subsurface seepage into an artificial wetland. Engineering Approach to Ecosystem Restoration Proceedings of the Conference, ASCE. March 22-27, 1998, Denver, CO.

Guardo, M. (1999). Hydrologic balance for a subtropical treatment wetland constructed for Nutrient removal. Ecological Engineering 12:315-337.

Kadlec, R. H. and Newman, S. (1992). Phosphorus Removal in Wetland Treatment Areas: Principles and Data. DOR 106. South Florida Water Management District, West Palm Beach, FL.

Kadlec, R. H. and Knight, R. L. (1996). Treatment Wetlands. New York, NY: Lewis Publishers, Inc.

Koch, M. S. and Reddy, K. R. (1992). Distribution of Soil and Plant Nutrients along a Trophic gradient in the Florida Everglades. Soil Sci. Soc. Am. J. 561:1492-1499.

South Florida Water Management District. (2000). Everglades Consolidated Report. South Florida Water Management District, West Palm Beach, FL.