SURMOUNTING THE ENGINEERING CHALLENGES OF EVERGLADES RESTORATION

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ABSTRACT

The South Florida Water Management District, in partnership with other agencies and stakeholders, is undertaking one of the world's largest ecosystem restoration programs. The foundation of the nutrient control program for the Everglades is a set of six large constructed wetlands, referred to as Stormwater Treatment Areas (STAs). The initial treatment goal is to reduce phosphorus entering the Everglades to 50 parts per billion. The STAs comprise almost 17,000 hectares, with a capital cost of approximately $700 million. Approximately 4,720 hectares are currently operational, another 2,600 hectares are in the start-up phase, and construction is just getting underway on the remaining areas.

Throughout the design process, engineers and scientists collaborated to capture the best available information on wetland treatment systems, and to develop the most appropriate design criteria. Some of the more challenging issues included characterizing stormwater inflows and phosphorus loads, determining appropriate nutrient removal performance characteristics, and estimating hydraulic design parameters relating to densely-vegetated systems.

The design process combined in-house staff with engineering consultants, construction contractors, external review groups and independent peer-review. This paper summarizes major design aspects and key assumptions, and sets the stage for addressing future challenges associated with achieving long-term water quality goals of Everglades restoration.

KEYWORDS

Constructed wetlands, environmental engineering, Everglades, phosphorus removal, restoration, stormwater treatment areas

INTRODUCTION

Background. The South Florida Water Management District (District), in partnership with other state and federal agencies and stakeholders, is undertaking one of the largest ecosystem restoration programs in the world. Florida's 1994 Everglades Forever Act (Act) set into action a plan for restoring a significant portion of the remaining 618,000-ha Everglades ecosystem through a program of construction, research, and regulation activities. The Act addressed water quality, water quantity (including hydroperiod), and the invasion of exotic plant species in the Everglades ecosystem. The Act also establishes both interim and long-term water quality goals to ultimately achieve restoration and preservation of the Everglades. The interim goal of the restoration program is to reduce phosphorus (P) concentrations entering the Everglades to 50 parts per billion (ppb). The foundation of the interim phosphorus control program is the Everglades Construction Project (ECP) which encompasses six strategically located constructed wetlands, referred to as Stormwater Treatment Areas, or STAs (see Figure 1). In addition to the STAs, significant phosphorus load reductions have been achieved through best management practices (BMPs) within the adjacent Everglades Agricultural Area (EAA). The long-term goal is to combine point-source, basin-level and regional solutions in a system-wide approach to ensure that all waters discharged to the Everglades Protection Area achieve final water quality goals by December 31, 2006. With respect to nutrients, the long-term goal is to reduce nutrient discharges to levels that do not cause an imbalance in natural populations of aquatic flora or fauna, however, the numerical interpretation of this narrative standard has not yet been determined. Additional background information can be found in Chimney and Goforth (2000).

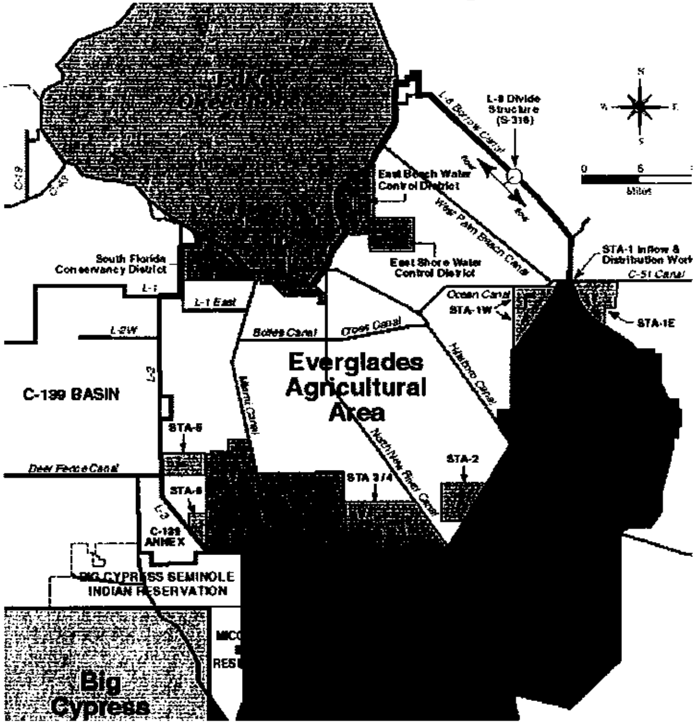


Figure 1. Overview of the Everglades Construction Project.

Design Objectives. Through a process of scientific research and evaluation, litigation, mediation, legislation, and consensus building, the design objectives of the ECP have evolved to include the following:

1. to reduce the phosphorus concentration entering the Everglades to an interim target of 50 ppb (measured as total phosphorus); this objective will be achieved in conjunction with the BMPs of upstream landowners;
2. to increase the supply of water to the Everglades;
3. to improve the spatial distribution and timing of inflows to the Everglades;
4. to improve the flood control of an adjacent urban watershed while maintaining flood protection in the other basins;
5. to reduce harmful discharges of freshwater to coastal estuaries; and
6. to the extent possible, reduce phosphorus loading to Lake Okeechobee from local drainage districts along the southern and eastern shores.

Location. The STAs are located along the northern boundary of the Everglades Water Conservation Areas (WCAs) (see Figure 1), and in most cases are adjacent to existing major flood control pump stations that have been in operation since the late 1950s. In addition to taking advantage of the existing pump stations, these locations allow for improvement in the spatial distribution of water entering the Everglades, changing the hydraulic regime from discrete point sources to a linear distribution that approaches sheetflow. Almost 19,300 ha of agricultural lands (primarily sugar cane, citrus, sod, vegetables and pasture) and remnant wetlands were acquired for the project.

Project costs. An additional design consideration was available finances. The estimated capital cost for the ECP is approximately $700 million, with approximately $183 million for land acquisition, $498 million for design and construction, and $16.3 million for program management and related costs. Individual STA design and construction costs varied considerably, as each of the STAs has a unique configuration of existing and new components (levees, pump stations, etc.), with variations in size, prior land use and topography. Overall, the design and construction costs averaged approximately $23,800/ha, with a range of $9,600/ha to $58,000/ha. Excluding the 3,400 ha of state-owned land incorporated into the STAs, the acquisition cost ranged from $6,900/ha to $26,150/ha and averaged $14,000/ha. Revenue sources include annual agricultural privilege taxes (approximately $61/ha for the EAA and $10/ha for the C-139 Basin), ad valorem property taxes, state land acquisition funds, mitigation funds from a regional electric utility, and toll revenues from a highway crossing the southern Everglades. In addition, the U.S. Army Corps of Engineers is cost-sharing the design and construction of STA-1 East. Complete expense and revenue information is available on the ECP website: http://www.sfwmd.gov/org/erd/ecp/3_ecp.html.

MAJOR DESIGN ASPECTS

The design process

Numerous alternative treatment systems were evaluated during the 1980s and early 1990s leading to the decision to utilize constructed wetlands for phosphorus reduction. By 1994, alternatives investigated included source control (e.g., BMPs), algal raceways, chemical treatment, and aquifer storage and retrieval. Once the decision was made to use constructed wetlands, the design of the STAs proceeded in three phases:

1. A **Conceptual Design** for the entire ECP was completed by the consulting firm of Burns & McDonnell in March 1992 (Burns and McDonnell, 1992). This conceptual design was later revised in February 1994, as a result of mediation among the District, state and federal agencies and other stakeholders (Burns and McDonnell, 1994).

2. **General Design Memoranda** for individual ECP components were prepared by Burns & McDonnell between 1994 and 1996; and

3. **Detailed Design Reports** and associated plans and construction contract specifications were prepared by multiple consulting firms, including Hutcheon Engineers (STA-1 West), Stanley Engineers (STA-1 Inflow and Distribution Works), Brown & Caldwell (STA-2), Prescott-Follett (outflow pump stations for STA-1 West and STA-2), and Burns & McDonnell (STA-5 and STA-6). In addition to these larger works, multi-discipline engineering services were provided by several consultants, including Metcalf & Eddy, Peer Consultants, Nodarse, Sverdrup Civil, Milian Swain, Weidener Surveying, and Muniz/Hazen & Sawyer. Also, District staff engineers completed the design for several of the smaller facilities. Detail design is currently underway for STA-3/4 by Burns and McDonnell and STA-1 East by the Corps.

Throughout the design process, the District encouraged review by stakeholders and technical experts, independent peer-review, and construction contractors' value engineering as part of a formal partnering process. In addition to improving the designs, these activities led to considerable cost savings, including the use of refurbished 10-cylinder diesel engines in place of new engines for two 970-cfs pumps (cost saving: approximately $1.5 million), and resizing the outflow pump station for STA-2 (cost savings: approximately $3 million).

Inflow characteristics

The inflows to the STAs will include runoff from seven hydrologic basins that previously discharged untreated water into the northern Everglades. The following design decisions and assumptions were made:

1. The 10-yr period from October 1978 to September 1988 was selected as the basis of design for average and peak stormwater runoff and discharges from Lake Okeechobee.
2. The STAs were sized to capture and treat all basin flows that occurred during the 1978-1988 period of record without hydraulic bypass;
3. The 10-yr period of record flows were modified to reflect implementation of BMPs within the EAA, with an assumed 25% reduction in phosphorus load. With the recognition that increased on-farm retention of stormwater would be a major BMP, it was assumed that the annual volume of runoff would be reduced by 20%.
4. An amount of water equivalent to the reduction due to BMPs would need to be delivered to the Everglades during the dry season, when it was assumed that sufficient capacity would be available in the STAs.
5. It was assumed that an additional 29,100 ha-m of water would be released from Lake Okeechobee as a result of implementation of a new lake regulation schedule.
6. To optimize the size of the STAs, the transfer of water between adjacent basins would be encouraged.

The STA inflows are primarily stormwater, hence there is considerable variability on a day-to-day basis in both flow volumes and phosphorus concentrations. Examples of this variability are presented in the Figures 2 and 3 representing calendar year 1979 for STA-2 (Walker, 1999).

Figure 2. Simulated 1979 flow for STA-2 (1 acre ft =0.1233 ha-m).

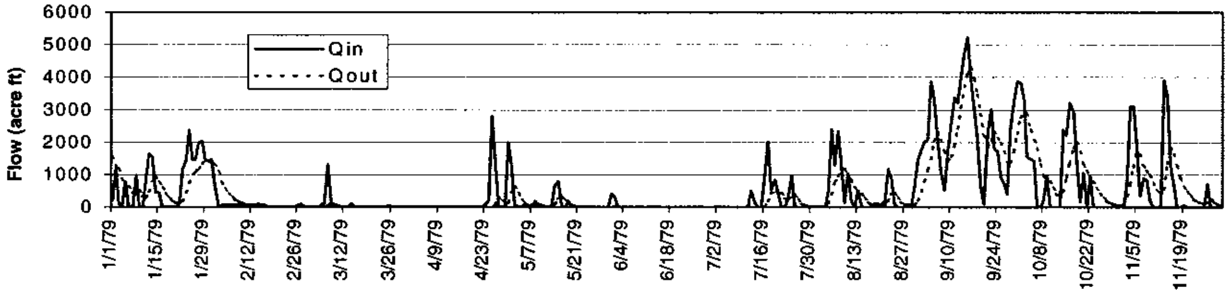
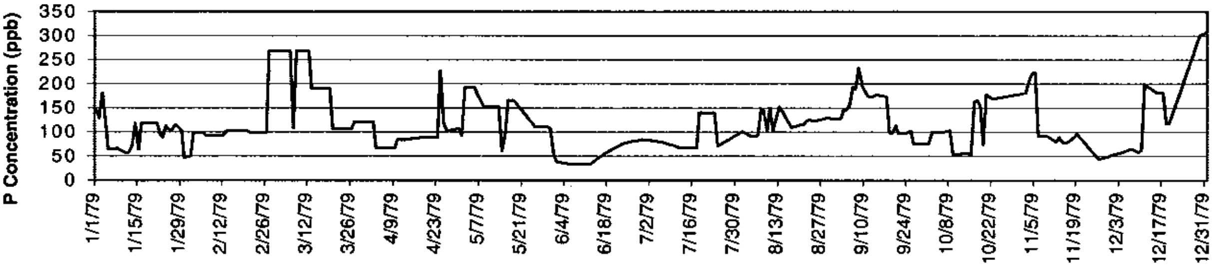


Figure 3. Simulated 1979 phosphorus concentrations for STA-2.



A summary of the projected STA inflows is presented in Table 1.

Table 1. Summary of STA Hydraulic and Phosphorus Inflows (revised)

STA	Average annual flow (acre-feet)	Peak daily flow (cfs)	Average daily flow (cfs)	Ratio of peak : average flow	Average P load (metric tons/yr)
STA-1 East	124,876	4,050	185	21.8	29.4
STA-1 West	142,860	3,250	200	16.3	37.7
STA-2	174,641	3,370	244	13.8	33.8
STA-3/4	604,655	5,840	841	6.9	87.3
STA-5	78,340	2,510	110	22.9	25.3
STA-6	53,877	2,090	74	28.1	13.2
Total	1,179,240	21,110	1,629	13.0	227

Notes: 1 acre-feet = 0.1233 ha-m; 1 cfs = 0.0283 cubic meter per second

Nutrient removal performance and sizing of the STAs

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

$$R = K\,A\,C$$

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;
3. there is negligible interaction between the STA and groundwater;
4. the apparent background phosphorus concentration within the STA is equal to zero; and
5. 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):

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

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^3
N = long-term average annual difference between rainfall and evapotranspiration, m^3/yr
C_p = long-term average annual phosphorus concentration of atmospheric deposition, mg/l
A = area required to achieve the target outflow phosphorus concentration, m^2

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). This increase in the effective settling rate yielded smaller estimates of required treatment area, reflecting the observation that keeping the soil wet will increase phosphorus removal performance. The effective treatment areas resulting from this equation and associated loading rates are summarized in Table 2. The areas in Table 2 are effective treatment areas; an additional 2,620 ha was required for levee footprints and other ancillary components.

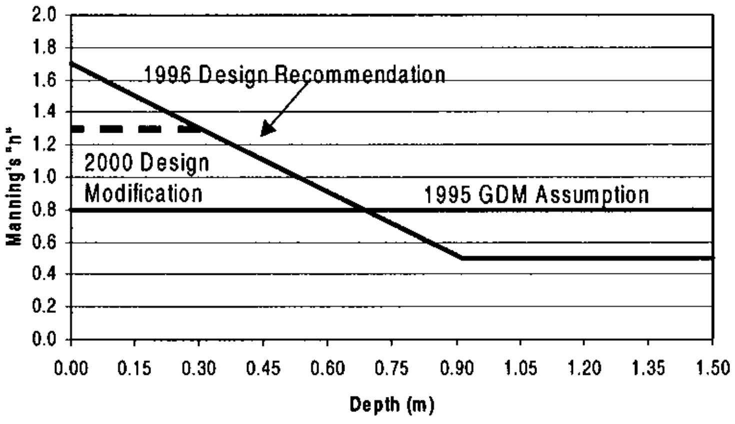
Table 2. Summary of STA Treatment Areas, Phosphorus Loading and Hydraulic Characteristics (revised)

STA	**Area required to achieve 50 ppb (ha)**	**Average nutrient loading rate ($g/m^2/yr$)**	**Estimated P removal (metric tons/yr)**	**Average hydraulic loading rate (cm/d)**	**Average hydraulic residence time (days)**
STA-1 East	2,170	1.36	23.0	1.95	31
STA-1 West	2,700	1.40	30.5	1.79	34
STA-2	2,600	1.30	24.5	2.27	27
STA-3/4	6,670	1.29	53.9	3.03	20
STA-5	1,670	1.52	21.4	1.59	38
STA-6	960	1.37	10.4	1.90	32
Total	16,770	1.35	164	2.37	26

STA hydraulics

Flow resistance due to vegetation. For design purposes, the hydraulic capacity of the STAs was estimated using various hydraulic routing models, all of which simulated the influence of vegetation on conveyance. The vegetation within the STAs plays a primary role in the efficacy of the treatment areas. The type and density of the vegetation within the treatment area influences the movement of water through the projects by imparting a resistance to flow, as commonly represented by the Manning's coefficient of roughness, or Manning's "n". The value of "n" varies with depth and surface conditions, including soil type and vegetation. Values for Manning's "n" vary from 0.023 for well-maintained canals to 0.045 for densely vegetated canals. During the general design of the STAs, a constant value for Manning's "n" of 0.8 was used. Subsequent field tests yielded values ranging from 0.2 to above 1.0 in Cell 4 of STA-1 West, suggesting the 0.8 value was a conservative design assumption for the higher flows and higher depths associated with extreme storm events (see Figure 4) (Brown and Caldwell, 1996; Kadlec, 1999). For the detail design of STA-2, Brown and Caldwell recommended the use of a depth-variant "n", with a value of 0.5 for depths greater than 1 meter, and a linear relationship below 1 m. As part of the STA-3/4 detail design, Burns & McDonnell modified the relationship to a constant "n" of 1.3 at or below 30 cm depth (Burns & McDonnell, 2000). Additional analyses are underway to differentiate the influence on "n" between cattail-dominated systems and areas with submersed aquatic vegetation.

Figure 4. Influence of depth on Manning's "n" for a cattail marsh



Operating guidelines. In addition to normal flow conditions, the design of the STAs evaluated extreme storm events and dry periods requiring supplemental water to avoid soil dryout. As part of the levee and structure design, storms up to the Standard Project Flood, estimated as 1.25 times the 100-year flood discharge, were analyzed. In addition, to protect against the release of phosphorus from the organic sediment following exposure to the air, the STAs were designed to avoid dryout. The target minimum average depth was established at 15 cm. All but one of the STAs will have the capability to introduce supplemental water to maintain this minimum depth. Based on a review of stage exceedence curves for natural wetland systems, and the best professional judgement of biologists, a maximum operating water depth of 137 cm, for no more than 10 days, was established for the STAs.

EARLY RESULTS

Over 4,720 ha of treatment areas (STA-1 West, STA-5 & STA-6) are operational, while STA-2 (2,600 ha) is in the start-up phase. Construction is underway on STA-1 East, and the initial construction contract for STA-3/4 should be awarded in early 2001. The initial phosphorus removal performance of the STAs has been better than the design criterion of 50 ppb. The initial 1,515-ha treatment area in STA-1 West has been fully operational since August 1994, and has consistently produced annual phosphorus concentrations less than 25 ppb (see Figure 5). Similarly, average discharge concentrations from the 352-ha STA-6 have remained below 25 ppb, despite receiving considerably greater inflow than estimated during design.

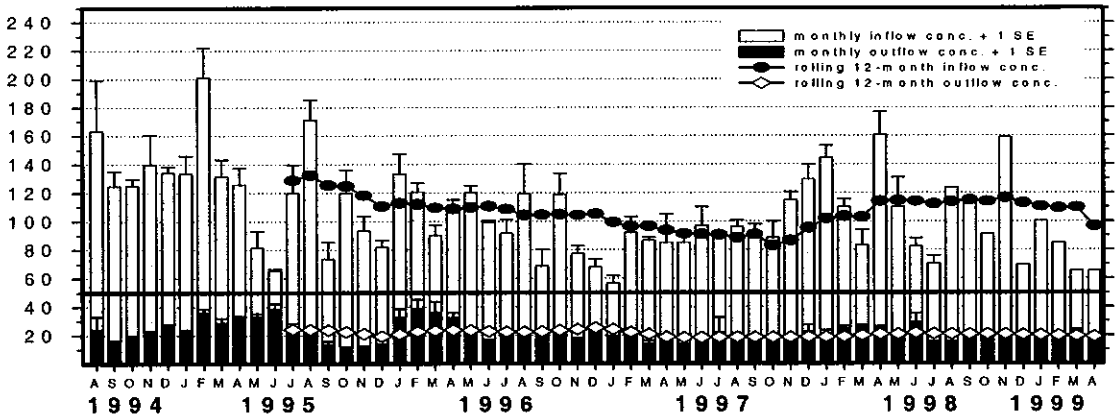


Figure 5. Initial phosphorus removal performance for STA-1 West Cells 1-4, in ppb (from Chimney et al., 2000)

FUTURE CHALLENGES

Optimizing the performance of the STAs. While the performance of the STAs has exceeded design phosphorus removal expectations, much remains to be learned about how to optimize their long-term performance. One aspect receiving attention is the initial start-up period, which has varied from a couple of weeks to over a year. Investigations are underway to determine the most efficient and effective way to bring these large biological systems on-line. Factors such as prior land use, soil preparation, and initial inundation depth and duration are influential in determining the time for these systems to achieve a net improvement in phosphorus concentrations, and subsequently to achieve the design performance goal. The use of submersed aquatic vegetation (as opposed to cattails and other emergent plants) and the incorporation of periphyton-based treatment cells appears to holds promise for optimizing STA performance. In fact, the vegetation management strategy for the 930-ha Cell 5b was modified from emergent cattail vegetation to submerged vegetation (the area was inoculated with material harvested from Cells 3 and 4, and grow-in rates are being monitored). The District and other stakeholders are actively investigating these and other performance factors. In addition, a dye tracer study was conducted to identify hydraulic short circuiting in one treatment cell of STA-1 West, and corrective measures included placing earthen plugs in perimeter canals and gaps in berms adjacent to distribution canals.

Achieving long-term water quality goals. Since their inception, the STAs have been considered an interim step in achieving the long-term water quality goals of Everglades restoration. While phosphorus concentrations of 25-35 ppb may be sustainable in the STAs, discharge levels as low as 10-20 ppb may be required to halt the degradation of the Everglades ecosystem. The District and other stakeholders are evaluating the technical, environmental and economic feasibility of other technologies for achieving these long-term water quality goals. Some of the more promising systems include submersed aquatic vegetation and periphyton-based STAs, as well as chemical treatment and hybrid systems of chemical and biological systems.

CONCLUSIONS

An effective measure of the success of an engineering design is the degree to which the finished product achieves the project objectives. For the Everglades STAs, the early phosphorus removal performance has exceeded design expectations. While it is still too soon to know if the long-term performance of the STAs will replicate this early success, the lessons learned during the collaborative and open design process, in conjunction with timely integration of relevant research results, provide a solid foundation for resolving future restoration challenges, in the Everglades and elsewhere.

ACKNOWLEDGEMENTS

One objective of this paper was to adequately describe the importance of the collective contributions of numerous engineering firms and individuals to the design of the Everglades STAs. Special recognition is given to Bill Walker, Bob Kadlec and Bob Knight for their invaluable contributions to the science and engineering of both the Everglades Construction Project and the body of knowledge of treatment wetlands. Appreciation for effective peer review of this manuscript is extended to Joe Schweigart, Tracey Piccone, Laura Reilly, Jim Kunard, Randy Bushey, Jennifer Jorge and Michael Chimney of the Everglades Construction Project.

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