FACTORS CONTROLLING PHOSPHORUS REMOVAL IN LARGE CONSTRUCTED WETLANDS IN SOUTH FLORIDA

By

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To the people and places in this world in need of our mercy

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ALR	Areal loading rate
Ca MR	Calcium mass retention
CDF	Cumulative distribution function
CFW	Central Flow-way
DIP	Dissolved inorganic phosphorus
DOP	Dissolved organic phosphorus
EAA	Everglades Agricultural Area
EAV	Emergent aquatic vegetation
NFW	North Flow-way
P	Phosphorus
PIP	Particulate inorganic phosphorus
POP	Particulate organic phosphorus
POR	Period of record
PP	Particulate phosphorus
RWA	Relative wetted area
SAV	Submerged aquatic vegetation
SFWMD	South Florida Water Management District
SRP	Soluble reactive phosphorus
STA	Stormwater treatment area
TDP	Total dissolved phosphorus
TP	Total phosphorus
TPALR	Total phosphorus areal loading rate
WA	Wetted area

Abstract of Thesis Presented to the Graduate School
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The Florida Everglades is an oligotrophic, subtropical wetland extremely susceptible eutrophication from anthropogenic phosphorus (P) inputs. Six large treatment marshes (total effective treatment area 18,000 ha), called Stormwater Treatment Areas (STAs), have been constructed over the last fifteen years to remove P from agricultural runoff before it enters the Everglades. Because of the massive investment to build and maintain these wetlands, it is important to evaluate the factors that contribute to their performance. Naturally, each STA had a different performance record. This study attempted to account for those differences by investigating 1) the relative wetted area (RWA), 2) the relationship between the total P (TP) areal loading rate (ALR) and the outflow TP concentration and 3) the wetland characteristics co-variant with the outflow TP concentration and the TP areal settling rate.

The RWA was determined by subtracting the elevation distribution function from the average water level (stage). The RWA was less than 1.0 in 230 out of 1044 (22%) of months. The TPALR was not statistically different when calculated with the RWA rather than the nominal area; the nominal area was deemed sufficient for most loading rate calculations. Among months with substantial re-flooding ($n = 39$), the TP areal settling rate was negatively correlated with the magnitude of the re-flooding event ($r = -0.605$, $p < 0.0001$).

In most of the STAs, the monthly outflow TP concentration was uncorrelated to the monthly TPALR. The vegetation type (submerged vs. emergent) and the magnitude of the loading rate were hypothesized to contribute to this uncoupling, but neither played a quantifiable role. The cause of this independence remains unclear. Possibly, the Damköhler number (areal settling rate divided by hydraulic loading rate) was sufficiently high in most STAs such that wetland factors other than the loading rate and settling rate tended to control the outflow TP concentration.

Through multiple linear regression, five variables (inflow TP concentration, change in monthly wetted area, hydraulic residence time, wetland age and inflow Ca concentration) were found to explain 32% of the variability in the monthly outflow TP concentration. Six factors (hydraulic loading rate, inflow dissolved organic P fraction, inflow particulate P fraction, wetland age, outflow water temperature and TPALR) accounted for 51% of the variation in the monthly TP areal settling rate. The proportion of explained variability may be improved in future analyses by including variables not considered herein.

Additional research is needed to confidently identify the factors that control the outflow TP concentration.

CHAPTER 1
INTRODUCTION

Phosphorus (P) is a naturally occurring, abundant element required by all forms of life. In the natural environment, the biosphere obtains P weathered from minerals. Typically, hydrologic flows transport P from uplands to aquatic environments, often via wetland ecotones. Excess P applied to the landscape (often as fertilizer) can join this migration and frequently contributes to eutrophication of downstream water bodies. In the landscape, mediating wetlands can serve as P sinks, dampening the transfer of P into aquatic systems (Richardson, 1999) and natural wetlands have long been used as receiving sites for point discharges of wastewater (Kadlec and Wallace, 2008). From this insight, it followed that wetlands could be employed to reduce P loads to downstream ecosystems, and many wetlands have been restored or constructed for the purpose of water treatment (Kadlec and Wallace, 2008). Treatment wetlands as a technology have progressed from being first a novelty, past trial pilot systems, to a point where optimization and diversity of application has become the focus (e.g. Mitsch et al., 1995; Kadlec and Knight, 1996; Higgins et al., 2000; Braskerud, 2002a; Turner et al., 2006; Vymazal, 2007; Kadlec and Wallace, 2008). Understanding and quantifying the internal P processing mechanisms are essential to maximizing treatment wetland P removal and retention.

Phosphorus Cycling in Wetlands

Phosphorus is found in wide variety of biological molecules beyond the notable examples including DNA and ATP (Turner and Newman, 2005). Phosphorus is also chemically active and may be found in myriad minerals in association with Ca, Mg, Fe, Al (Reddy et al, 1999). It is convenient to classify these many forms of P by their physical, chemical or operational characteristics. Many taxonomic schemes exist, but four broad P pools are commonly conceptualized: dissolved inorganic P (DIP), dissolved organic P (DOP), particulate inorganic P

(PIP) and particulate organic P (POP) (Reddy and DeLaune, 2008). In each of these terms, "dissolved" and "particulate" distinguish particles that do and do not pass through a filter membrane (pore size typically, but not always, 0.45 μm), respectively. For methodological convenience, the following pools are often determined for water-column P: soluble reactive P (SRP), dissolved organic P (DOP) and particulate P (PP). These groups are somewhat operationally defined (i.e. the boundaries of these groups depend more on analytical technique than the chemical or physical properties of the compounds). Soluble reactive P is composed mainly of orthophosphate (PO_4-P) (Reddy and DeLaune, 2008) but may include some readily hydrolysable organic P (Kadlec and Wallace, 2008). Particulate P encompasses all P-containing molecules larger than 0.45 μm.

Commonly, P is not limiting in wetlands, although the Florida Everglades are a well-known exception. Phosphorus enters wetlands through surface water, groundwater, wet and dry atmospheric deposition, and biological transfers (e.g. guano production). Surface water flow dominates the P budget in many treatment wetlands (Kadlec and Wallace, 2008). Within wetlands, P is cycled between various storage compartments at rates which depend on the physical, chemical and biological conditions (Figure 1-1). The net effect of these P transformations determines the status of a given wetland as a source or sink of P. Wetlands have been successful as a P treatment technology because often the P processing results in net storage or P within the system. Four broad processes that contribute to P retention in wetlands: sorption to soil solids, sedimentation, co-precipitation and biological uptake. Various physical, chemical and biological characteristics inhibit or enhance each of these processes in a given wetland.

The movements of P on and off charged sites on the surface of soil solids are called adsorption and desorption, respectively (Reddy and DeLaune, 2008). Froelich (1988) described two steps in the sorption process. First, following changes in pore water P concentration (e.g. in response to novel anthropogenic P loads) adsorption/desorption equilibria are reached within minutes or hours (Froelich, 1988). Reddy and DeLaune (2008) note "The balance between P adsorption and desorption maintains the equilibrium between solid phases and P in soil pore water." Second, absorption, the "solid-state diffusion of adsorbed phosphate from the surface into the interior of particles" occurs over days to months (Froelich, 1988). Generally, sorption is limited to SRP and some reactive components of DOP (Anderson and Magdoff, 2005). The net direction of the flux (on or off the soil) is controlled by the pore water P concentration and the affinity of the soil particles for P ions. In wetlands, the amount of P that can be adsorbed to the soils is often related to the amount of iron and aluminum in the soil (Lijklema, 1977). In South Florida wetlands, soil calcium is an important determinant of soil P sorption capacity (Reddy et al., 1998). Soil adsorption is not considered a sustainable P removal mechanism in treatment wetlands due to the relatively fast reaction time and the finite sorption capacity (Kadlec and Wallace, 2008).

The inflow water to wetlands often contains suspended solids, some of which contain P. The aggregate of suspended solids often includes eroded soil particles, macrophyte detritus, and algae or other plankton cells (Stuck et al., 2001). Wetlands function to remove suspended particles primarily by reducing water velocity (by low elevation gradients and drag caused by dense plant stems) such that gravity allows the particles to settle out. This removal is enhanced by the trapping of particles within benthic litter and on biofilms (Schmid et al., 2005). Sedimentation of suspended solids can account for a significant portion of total phosphorus (TP) removal, and sustainability is constrained only by changes in bottom elevation (due to sediment accretion) that prevent surface water flows (Kadlec and Wallace, 2008).

An additional pathway of removal is the precipitation of P with Ca, Fe, Al or Mg cations (Reddy and DeLaune, 2008). It may be difficult to quantify precipitation separately from adsorption, since the precipitates often form on the surfaces of soil particles. Reddy and DeLaune (2008) provided a thorough discussion of P co-precipitation in wetlands, particularly regarding the conditions that promote P co-precipitation with each of the identified cations. Generally, acidic conditions promote the co-precipitation of P with Fe and Al, and alkaline environments support the formation of P-Ca and P-Mg precipitates. In wetlands, both apatite ($Ca_5(Cl)(PO_4)_3$) and hydroxylapatite ($Ca_5(OH)(PO_4)_3$) are notable precipitates (Reddy and D'Angelo, 1994). Co-precipitation with Ca may be particularly important for P dynamics in the Everglades; Reddy et al. (1993) found a linear correlation between P and Ca accumulation in Everglades soils. Apparently promoted by the consumption of carbonate ions by submerged photosynthesizers, the precise mechanism of the P-Ca interaction may be either adsorption of P onto the surface of $CaCO_3$ precipitates or the formation of mixed crystals during co-precipitation (Otsuki and Wetzel, 1972; Scinto, 1997).

The P requirement of all organisms combined with the high productivity of wetland primary producers makes biological uptake an important mechanism of wetland P removal. Algae and other microorganisms can consume significant amounts of P very rapidly; for example, a diverse algal community reduced mesocosm water column P concentrations from 1,100 μg/L to 50 μg/L in 28 days (Havens et al., 1999). Plants and microorganisms typically can utilize only SRP directly. Other forms of P must first be hydrolyzed before they can be taken up biologically. In wetlands, much of this SRP is promptly transformed into PP (Noe et al., 2003). Many studies have investigated the P uptake potential of wetland plants (e.g. Reddy and DeBusk, 1985; Tanner, 1996). Nearly all of the P incorporated into microbial biomass and most of the macrophyte-P is returned to the P cycle through decomposition (Reddy et al., 1995; Kadlec and Wallace, 2008). However, the anaerobic condition resulting from flooding slows decomposition and promotes organic matter accumulation. The P stored in refractory biomass compounds contributes to the long-term sustainable P removal by burial in accrued sediments.

The conditions supporting and enhancing each of these P removal mechanisms vary from wetland to wetland depending in large part on soil characteristics, vegetation type and density and water column chemistry, including cation availability and the distribution of the TP pool among the various functional P forms. Maximizing P treatment in wetlands requires an understanding and quantification (and manipulation) of the relative contributions of each of these processes to net P removal.

Methods

Site Description

Over the past 15 years, 6 treatment marshes, called Stormwater Treatment Areas (STAs) have been constructed in South Florida to capture P from agricultural runoff before it enters the Florida Everglades, an oligotrophic wetland susceptible to anthropogenic eutrophication (Chimney and Goforth, 2001). Many investigations have demonstrated P enrichment and the associated disruption of the existing ecosystems in the Everglades (see Reddy and DeLaune, 2008, for a comprehensive review of these works). In particular, most notable to the lay observer, is the shift from saw grass (*Cladium jamaicense* Crantz) prairies to dense monotypic cattail (*Typha* spp.) stands. The Everglades Agricultural Area (EAA), comprising 280,000 ha and approximately 27% of the original Everglades expanse, is a rich producer of sugarcane and winter vegetable crops (Reddy and DeLaune, 2008), and the primary source of P to the Everglades and to the STAs (Pietro et al., 2009).

The STAs are strategically located, spatially and hydrologically, between the EAA and the remnants of the Everglades, now broadly defined by the Everglades Protection Area (Figure 1-2). Altogether, the 6 STAs have a total footprint of over 26,000 ha, with more than 18,000 ha of effective treatment area, subdivided into 35 cells (Figure 1-3; Pietro et al., 2009). The balance of the land area is consumed by roads, levees, pump stations and other infrastructure. As of 2009, the STAs had retained over 1,200 metric tons of P since the inception of the Everglades Nutrient Removal Project (the forerunner to the STA project) in 1994 (Pietro et al., 2010). Over the same time period, flow-weighted mean TP concentration was reduced from 0.143 mg/L to 0.040 mg/L (Pietro et al., 2010).

This report took advantage of the water and P mass balance data compiled by Chimney (2009). It was therefore constrained to the cells for which data were reported in Chimney (2009). Excluded cells are indicated in Figure 1-3. Some currently subdivided cells were treated as combined larger units (e.g. Cell 1A and Cell 1B of STA-5 were considered together as the North Flow-way (NFW)). This was necessary to maintain longer records in cells that had been subdivided after startup or in cases where data were not available at the levee between sub-cells.

Data Sources

South Florida Water Management District (SFWMD) staff collect daily flow and weekly or biweekly water quality data for all STA cells. The data were retrieved from the publicly-accessible, online database, DBHYDRO, maintained by SFWMD.

Data from topographic surveys of each STA cell were provided by SFWMD.

Vegetation coverage data, including maps generated from aerial images and field survey results were produced and collected, respectively, by various contractors hired by SFWMD. The data were made available to this project by SFWMD.

Calculations

Several physical and chemical characteristics of the STAs were important to multiple aspects of this study. For convenience, the methods employed to calculate each relevant parameter are described here.

Hydraulic flows

Daily inflow and outflow volumes were summed to determine the total flows for each period of interest:

$$Q1 = \sum_{t_1}^{t_2} Q1_t \tag{1-1}$$

$$Q2 = \sum_{t_1}^{t_2} Q2_t \tag{1-2}$$

where t_1 = starting date of the period of interest, t_2 = end date of the period of interest, $Q1$ = total inflow volume in the period of interest[L^3/T], $Q2$ = total outflow volume in the period of interest[L^3/T], $Q1_t$ = inflow volume on day t [L^3/T] and $Q2_t$ = outflow volume on day t [L^3/T].

The hydraulic loading rate (q) is the rainfall equivalent [L/T] of the inflow volume:

$$q = \frac{Q1}{A} \tag{1-3}$$

where A = wetland area [L^2]. Chapter 2 provides a discussion of methods for calculating A.

The nominal hydraulic residence time (τ) is an estimate of the travel time [T] required for an average packet of water to pass through the wetland:

$$\tau = \frac{Ah}{Q1} = \frac{h}{q} \tag{1-4}$$

where h = mean water depth [L].

Water column chemical and physical properties

Weekly and bi-weekly composite samples were linearly interpolated to estimate daily TP concentrations. Similarly, weekly and bi-weekly grab samples were linearly interpolated to estimate daily SRP, total dissolved P (TDP) and Ca concentrations. These daily values were flow-weighted to calculate average inflow and outflow concentrations for larger time steps. The same method of flow-weighting was employed for all constituents:

$$C1 = \frac{\sum_{t_1}^{t_2} Q1_t C1_t}{\sum_{t_1}^{t_2} Q1_t} \quad (1\text{-}5)$$

$$C2 = \frac{\sum_{t_1}^{t_2} Q2_t C2_t}{\sum_{t_1}^{t_2} Q2_t} \quad (1\text{-}6)$$

where $C1$ = flow-weighted mean inflow concentration in the period of interest [M/L^3], $C2$ = flow-weighted mean outflow concentration in the period of interest [M/L^3], $C1_t$ = estimated inflow concentration on day t [M/L^3] and $C2_t$ = estimated outflow concentration on day t [M/L^3]. In cells with multiple inflow or outflow stations, concentration values were again flow-weighted by station to estimate a single average value for each cell.

Inflow and outflow concentrations of the P forms DOP and PP were calculated by difference using measured TP, TDP and SRP values:

$$C1_{DOP} = C1_{TDP} - C1_{SRP} \quad (1\text{-}7)$$

$$C2_{DOP} = C2_{TDP} - C2_{SRP} \quad (1\text{-}8)$$

$$C1_{PP} = C1_{TP} - C1_{TDP} \quad (1\text{-}9)$$

$$C2_{PP} = C2_{TP} - C2_{TDP} \quad (1\text{-}10)$$

where $C1_{DOP}$ = inflow DOP concentration [M/L^3], $C1_{PP}$ = inflow PP concentration [M/L^3], $C1_{SRP}$ = inflow SRP concentration [M/L^3], $C1_{TDP}$ = inflow TDP concentration [M/L^3], $C1_{TP}$ = inflow TP concentration [M/L^3], $C2_{DOP}$ = outflow DOP concentration [M/L^3], $C2_{PP}$ = outflow PP concentration [M/L^3], $C2_{\mathrm{SRP}}$ = outflow SRP concentration [M/L^3], $C2_{\mathrm{TDP}}$ = outflow TDP concentration [M/L^3] and $C2_{\mathrm{TP}}$ = outflow TP concentration [M/L^3].

The relative proportions of each of these forms within the TP pool were calculated using the inflow and outflow concentrations:

$$\mathrm{SRP1_R} = \frac{C1_{\mathrm{SRP}}}{C1_{\mathrm{TP}}} \qquad (1\text{-}11)$$

$$\mathrm{SRP2_R} = \frac{C2_{\mathrm{SRP}}}{C2_{\mathrm{TP}}} \qquad (1\text{-}12)$$

$$\mathrm{DOP1_R} = \frac{C1_{\mathrm{DOP}}}{C1_{\mathrm{TP}}} \qquad (1\text{-}13)$$

$$\mathrm{DOP2_R} = \frac{C2_{\mathrm{DOP}}}{C2_{\mathrm{TP}}} \qquad (1\text{-}14)$$

$$\mathrm{PP1_R} = \frac{C1_{\mathrm{PP}}}{C1_{\mathrm{TP}}} \qquad (1\text{-}15)$$

$$\mathrm{PP2_R} = \frac{C2_{\mathrm{PP}}}{C2_{\mathrm{TP}}} \qquad (1\text{-}16)$$

where $\mathrm{SRP1_R}$ = inflow SRP fraction, $\mathrm{SRP2_R}$ = outflow SRP fraction, $\mathrm{DOP1_R}$ = inflow DOP fraction, $\mathrm{DOP2_R}$ = outflow DOP fraction, $\mathrm{PP1_R}$ = inflow PP fraction and $\mathrm{PP2_R}$ = outflow PP fraction.

The same procedure was used to calculate areal loading rates (ALR) for both TP and Ca:

$$\mathrm{ALR} = \frac{\sum_{\mathrm{t_1}}^{\mathrm{t_2}} Q1_{\mathrm{t}} C1_{\mathrm{t}}}{A} \qquad (1\text{-}17)$$

Chapter 2 provides a discussion of methods for calculating A.

The mass retention rate of Ca was calculated for each STA cell:

$$\mathrm{CaMR} = \frac{\sum_{\mathrm{t_1}}^{\mathrm{t_2}} Q1_{\mathrm{t}} C1_{\mathrm{t}} - \sum_{\mathrm{t_1}}^{\mathrm{t_2}} Q2_{\mathrm{t}} C2_{\mathrm{t}}}{A} \qquad (1\text{-}18)$$

where CaMR = Ca mass retention rate [M/L^2/T].

Weekly and bi-weekly inflow and outflow temperature and pH readings were linearly interpolated to estimate daily values of each. The daily values were averaged arithmetically (not flow-weighted) to generate monthly figures.

Wetland chemical and physical properties

Wetland age for any given time period was calculated as the number of whole years between the date of the time period of interest and the initiation of operation. That is, the current age of each wetland was not reflected back to the beginning of the period of record (POR), but rather the actual age of the wetland at each time step was used.

Soil TP concentrations from each sampling event were assumed to be spatially representative of each cell, so the values were arithmetically averaged to obtain a single value for each cell for each sampling event. The resulting value was applied to the entire year in which the sampling occurred. Annual values were linearly interpolated across years in which sampling events did not take place. Estimates were not extrapolated to years before the first sampling event or to years after the last sample collection in each cell.

The daily average water depth was estimated by subtracting the elevation cumulative distribution function (CDF) from the daily mean water surface elevation (stage). A detailed description of the process by which the elevation CDF was obtained for each cell is available in Chapter 2. The resulting function describes the continuous cumulative distribution of depths in the wetland and was compartmentalized into 0.5 ft depth increments for convenience. The mean water depth was the area-weighted average of these depth increments.

Wetland performance models

The k-C* model is commonly used to predict the outflow concentration of contaminants from wetlands (Kadlec and Knight, 1996):

$$C_2\text{-}C^{*}=(C_1\text{-}C^{*})\exp\left(\frac{-k\ A}{Q}\right) \qquad (1\text{-}19)$$

where A = wetland area [L^2], C_1 = inflow concentration [M/L^3], C_2 = outflow concentration [M/L^3], C^* = background concentration [M/L^3], k = contaminant areal settling rate [L/T], and Q = flow rate [L^3/T]. Equation (1-19) can be configured to include depth, such that it considers the volume rather than the surface area of the wetland (Kadlec and Knight, 1996):

$$\begin{aligned} C_2\text{-}C^{*}&=(C_1\text{-}C^{*})\exp\left(\frac{-k_v\ hA}{Q}\right) \\ &=(C_1\text{-}C^{*})\exp(k_v\tau) \end{aligned} \qquad (1\text{-}20)$$

where k_v = contaminant volumetric rate constant [T^{-1}].

Kadlec and Wallace (2008) noted that most wetland contaminant removal processes are "typically apportioned to wetland area to a greater extent than to wetland water volume." Further, they found that k_v decreased with increasing depth, and advise that the areal settling rate is more appropriate for most situations. Thus, the area-based form of the k-C* model (Equation (1-19)) is considered throughout this document.

The selection of k over k_v has an additional implication. Because of the negative depth dependence of k_v, the increases in τ associated with increases in depth do not result in commiserate improvements in performance. Therefore, only the changes in τ associated with changes in q (Equation (1-4)) effect changes in wetland performance, so q may be considered as a proxy for τ.

Time-Step Selection

With respect to the ultimate purpose of the STAs, to reduce the P load to downstream ecosystems, it is the long-term outflow TP concentration that is justly of interest to regulators on behalf of the Everglades. Practice has shown that the long-term outflow TP concentrations varied among cells over the history of the project. Numerous studies have been undertaken to understand the root of these differences and to explore options for improving treatment effectiveness and decreasing outflow concentrations. In this and other studies comparing the STAs to one another, (POR) averages are valuable, but limiting in that the number of values is restrained by the number of cells (or STAs, depending on the design of the study). Frequently, the characteristics that potentially differentiate STA cells from one another also vary over time within cells (e.g. depth, Ca concentration, hydraulic loading, etc). By increasing the temporal resolution of the data, the number of data values available to explore correlative trends expands. In addition, many of the wetland biogeochemical mechanisms relevant to P processing occur at short time scales (minutes to days), suggesting that shorter periods of time averaging might elucidate valuable process-level information.

Conversely, the non-zero τ observed in all wetlands dictate that at any instant, the outflow water is independent of the inflow water. Also, due to the imperfect hydraulics ubiquitous in wetlands, the outflow water at any instant comprises a mixture of water that entered the wetland a range of τ previously, thereby preventing the simple comparison of inflow waters with waters exiting precisely one mean τ later. These two phenomena necessitate an upper limit on the resolution of the time step. Kadlec and Wallace (2008) suggested an averaging period of at least three nominal τ to ensure that the bulk of the outflow water considered in a given data value entered the wetland during that same period.

For the reasons presented above, many analyses throughout this work aimed to assess the workings of the STAs in the "short-term." Determining the appropriate time step required striking a balance between the aforementioned competing considerations for short- versus long-term averaging, while maintaining data manageability. All of the data included in this study were provided by SFWMD, either directly or through the publicly-accessible, online database, DBHYDRO, which SFWMD populates and maintains. The flow and water quality data were organized by cell at a monthly time step so, given the data at hand, the minimum possible averaging period was 30 d by default. Following the prescription of Kadlec and Wallace (2008), the monthly τ calculated from this data were examined. The average monthly τ was 23 d. In only 44% of the non-screened months was the τ less than 10 d. The τ was less than 30 d in only 77% of months. Together, these findings suggest that the monthly time step was too fine. The additional finding that 95% of months had τ s less than 90 d suggested that a quarterly (90 d) averaging period was more appropriate. However, upon the initial conversion of select data to the quarterly time step, it was found that the correlations between the outflow TP concentration and both the inflow TP concentration and the TPALR were slightly stronger among the monthly data than the quarterly values. Ultimately, it is the physical connection between the inflow and outflow water, as measured by the solutes in that water, which must be maintained by selecting a sufficiently long averaging period. Because the 90 d time step failed to measurably strengthen the inflow-outflow relationship, the 30 d averaging period was selected. Throughout this work, each use of the phrase “short-term” indicates the use of monthly data.

Data Screening

When analyzing data for relationships between known dependent variables and possible independent variables, it is common practice to screen data points generated by unusual operating conditions in the system of interest. For example, within treatment wetland science, convention calls for the exclusion of data from the “start-up period,” the time immediately after initiation of treatment, when temporary nutrient sinks (plant biomass expansion and soil sorption) may exaggerate observed treatment performance (Kadlec and Wallace, 2008). Also, some authors elect to omit periods of internal maintenance (e.g. Pietro et al., 2008; Juston and

DeBusk, 2006). Within this analysis, the former etiquette was observed implicitly; the POR for each cell was selected to correspond with the data range included in Chimney (2009), who omitted start-up years therein.

Extremely low flow events created difficulties for the data analysis required by this study. For example, very low hydraulic loading causes the calculated τ to become very large (exceeding tens of thousands of days in some cases). Likewise, exceptionally low flows (in or out) can generate extreme calculated TP mass removal values. In an effort to suppress such extravagant values (which, being outliers, have unique power to disrupt correlation and regression analyses), while simultaneously maintaining a large number of data points, all months in which neither the inflow nor outflow volume was at least 10% of the respective long-term average were screened. Of the original 1419 data months, 1050 (74%) remained after this criteria was applied.

Some variables required additional special consideration. The appendix lists these variables and the conditions that resulted in the omission of individual values.

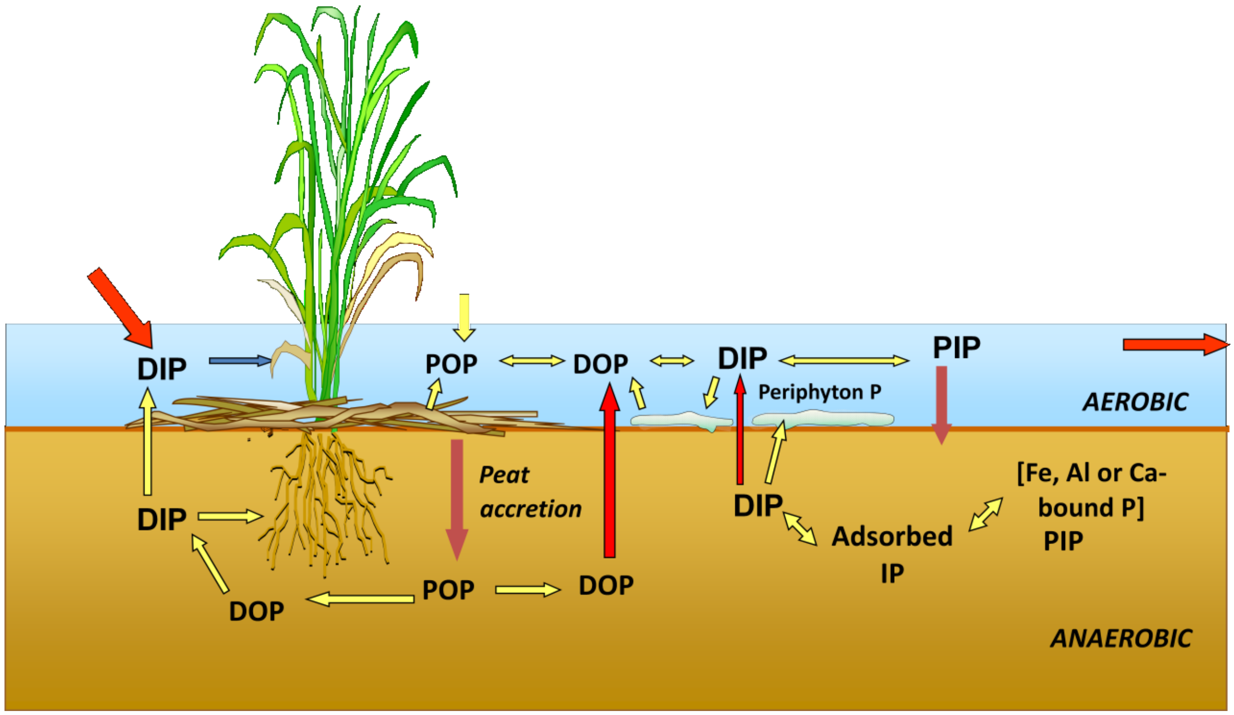


Figure 1-1. Phosphorus (P) cycle in surface flow wetlands. DIP = particulate inorganic P, DOP = dissolved organic P, PIP = particulate inorganic P, POP = particulate organic P. Image: Reddy and DeLaune, 2008.

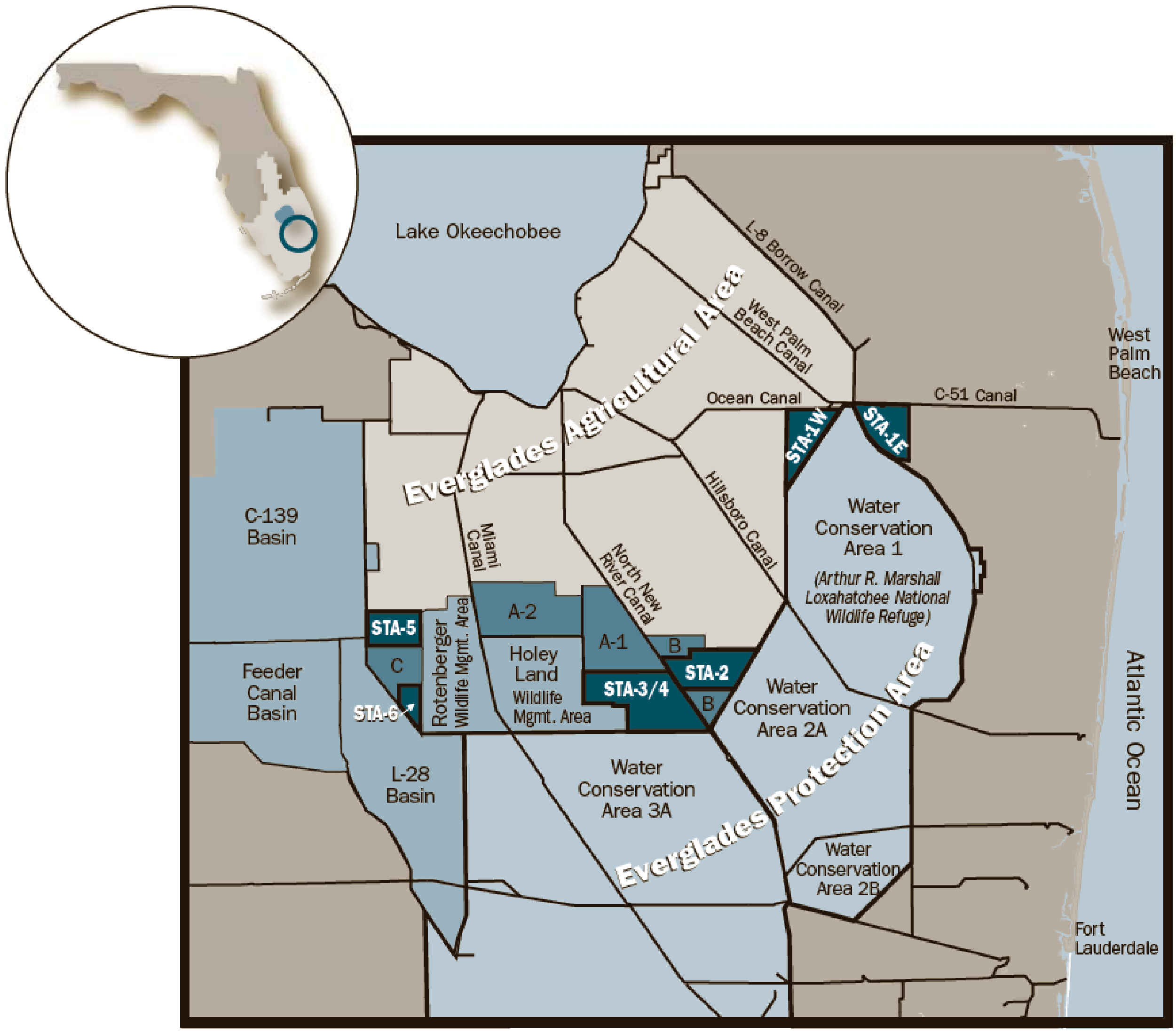


Figure 1-2. Map showing the locations of the six Stormwater Treatment Areas (STAs), the Everglades Agricultural Area and the Everglades Protection Area in South Florida. Image: Pietro et al., 2008.

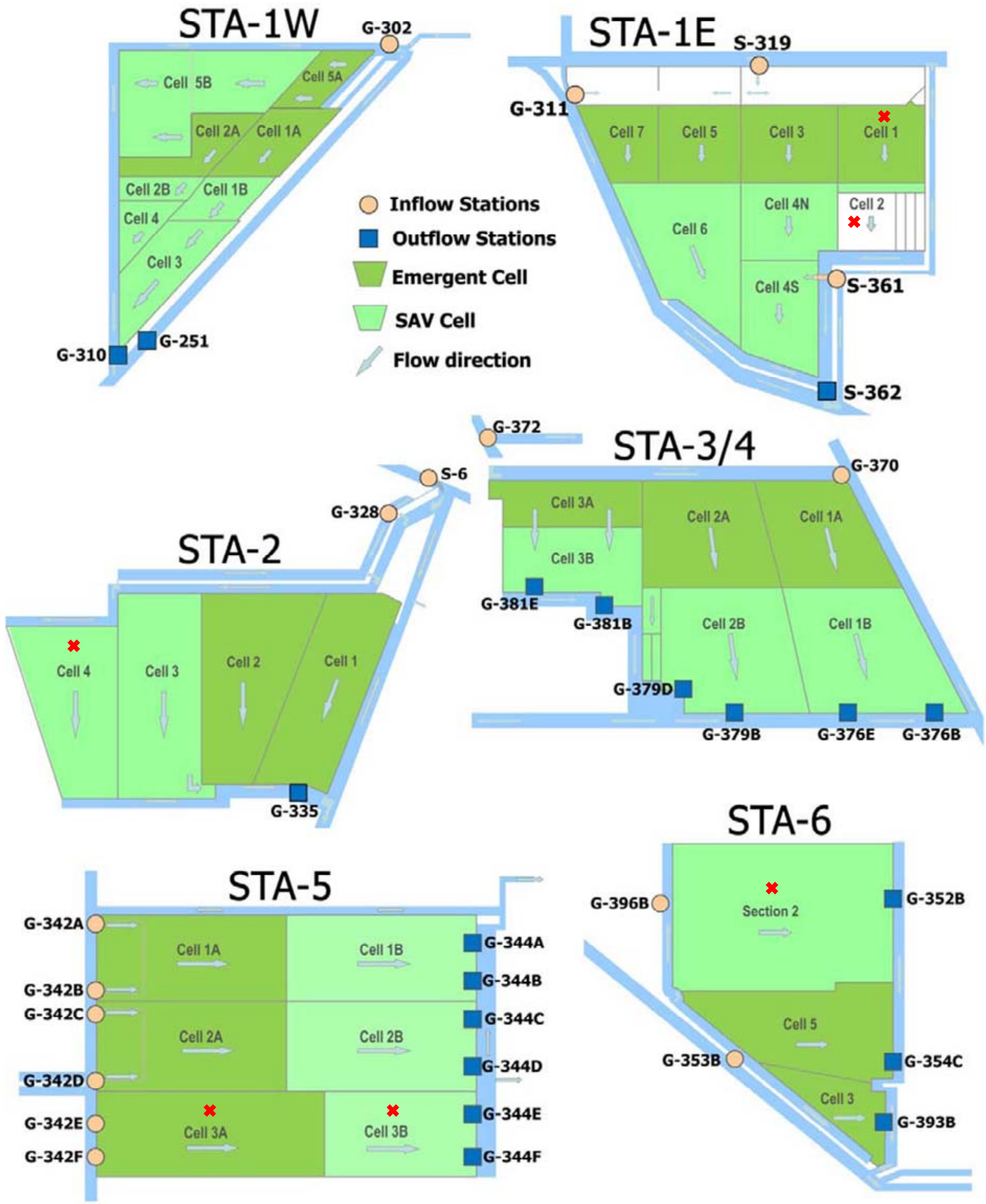


Figure 1-3. Schematics of the configuration of the treatment cells within each Stormwater Treatment Area (STA). The dominant vegetation type in each cell is also indicated. Cells marked with “X” were not included in this study. Image: Pietro et al., 2010.

CHAPTER 2
INFLUENCE OF WETTED AREA ON PHOSPHORUS DYNAMICS IN THE STORMWATER TREATMENT AREAS

Introduction

Performance, measured by any metric (outflow concentration, concentration reduction, or settling rate) varied across the STAs, with some cells and STAs having removed P less effectively than their peers (Pietro et al., 2009). The total expenditures on the STA project are difficult to estimate, but the construction, monitoring and management of treatment wetlands with a combined footprint of over 26,000 ha (Pietro et al., 2009) is an enormous financial undertaking. As such, poor P removal performance by an STA is unaffordable by the SFWMD as well as unacceptable for the preservation of downstream ecosystems. As part of a larger diagnostic exercise to elucidate the controlling factors behind measured performance (and ultimately to advise SFWMD on management strategies to improve performance in trouble STAs), the relationship between TP areal loading rate (TPALR) and outflow TP concentration was explored.

Terms A, C_1, and Q from Equation (1-19) are related by:

$$\mathrm{ALR} = \frac{C_1 * Q}{A} \qquad (2\text{-}1)$$

where ALR = areal loading rate [$M/L^2/T$]. It can easily be seen that in the k-C* model, any change in A, C_1, or Q that would cause ALR to increase, would correspondingly cause the outflow concentration (C_2) to increase. In other words, the outflow concentration of a contaminant is directly proportional to the ALR of that contaminant.

It is common for C_1 and Q to vary over the daily, monthly and even annual operation of a treatment wetland. Less prevalent are changes in the treatment area. As a result, ALR is typically calculated for the nominal area (A_n), that is, the design or built wetland area. However, in certain circumstances, the *actual wetted area* (WA) may not be equal to A_n. All wetlands have a distribution of elevations arising from both macro-scale ground slope and micro-scale topographic heterogeneity. The size of the STAs enhances this variation on both scales, and also precludes grading, which, in many constructed wetlands, minimizes topographic heterogeneity. Most wetlands, including the STAs, experience temporal variability in flow, driven primarily by regional rainfall patterns. During times of low flow, particularly during seasonal or regional drought, insufficient water may be delivered to the wetland to maintain the stage above the maximum ground elevation. When this occurs, WA will be less than A_n. The interaction of the spatial elevation distribution and the temporal stage distribution controls the WA in the STAs.

Often, estimates of k are derived from Equation (1-19), when the other variables are known, so that treatment performance can be compared across wetlands with diverse inputs. Clearly, when WA < A_n, the use of $A = A_n$ in Equation (2-1) would result in suppressed estimates of k.

Some STA cells did experience periodic dry-down conditions in whole or in part (Pietro et al., 2008) due to variability in weather conditions in the tributary basins, therefore previous estimates of k and ALR (of specific relevance to this study, k_{TP} and TPALR) that incorporated A_n may have been inaccurate. It was hypothesized that poor performance (specifically as measured by the outflow TP concentration relative to the inflow TPALR), was, in some circumstances, an artifact of imprecise calculations. For example, hypothetical wetlands A and B have nominal TPALR of 1 g/m^2/yr and observed outflow TP concentrations of 0.075 and 0.10 mg/L, respectively. Investigation reveals that only half of the nominal area of wetland B was actually flooded, due to topographic and stage variability. The revised TPALR in wetland B becomes 2 g/m^2/yr, and it becomes evident that some portion of the "poor performance" (high outflow concentration relative to loading rate) of wetland B was a product of the data used in the ALR calculation. If the hypothesis held true, an extension of that logic would suggest that realized performance (absolute outflow concentration, regardless of inlet loading) could be improved by increasing the flooded area of candidate wetlands (while maintaining historical flow rates) through earthwork to reduce the topographic variability.

Accurate estimation of the changes in WA over time is important beyond assuring correct k and ALR calculations. The drying of portions of cells is of particular concern for submerged aquatic vegetation (SAV) which may die if desiccated (Harwell, 2003). However, White et al. (2006) subjected SAV mesocosms to 1-month periods of dry out (the condition of the vegetative communities upon re-flooding was not reported), and found net treatment of TP (outflow concentration lower than inflow concentration) to resume 0-3 weeks following re-flooding. Nonetheless, it may be difficult to maintain SAV in treatment cells that regularly or intermittently dry out. Additionally, re-flooding of exposed sediments results in a flux of P out of the sediments into the water column (Olila et al., 1997, White et al., 2006; Bostic and White, 2007; Pietro et al., 2008 and 2009). Thus, the changing WA due to stage and topographic interaction would be expected to reduce treatment effectiveness.

Objectives

This chapter attempts to answer three primary questions: 1) Was the RWA, or changes in RWA, significantly correlated to k_{TP}? 2) Did WA < A_n significantly alter the TPALR realized by any cell in the STAs? If so, does the use of $A = WA$, rather than $A = A_n$, in Equations (1-19) and (2-1) usefully improve the correlation between outflow TP concentration and TPALR? 3) Is there significant value added by calculating WA via the elevation distribution, as compared to simpler methods? The following hypotheses were tested to address the questions above:

The long-term TP removal performance will be negatively correlated with variation in elevation within cells.

The short-term TP removal performance will be positively correlated with RWA, and negatively correlated with monthly ΔRWA, in months when ΔRWA was positive.

The STA-wide TPALR calculated by substituting A = WA into Equation (2-1) will be significantly higher than the TPALR calculated using $A = A_n$.

The correlation between the monthly TPALR and the monthly outflow TP concentration will be usefully higher when Equation (2-1) is evaluated using A = WA derived from the stage-area curve, than when Equation (2-1) is solved using either A = WA derived from the mean elevation or $A = A_n$.

Methods

Calculation of the Wetted Area

Brown and Caldwell (1996) formalized the calculation of the relative wetted area (RWA):

$$\mathrm{RWA} = \frac{1}{(t_2 - t_1)\, A_n} \int_{t_1}^{t_2} WA(t)\, dt \qquad (\text{2-2})$$

where t_1 = start of time period, and t_2 = end of time period. Note that RWA = WA / A_n. The RWA was calculated for each individual cell, and area-weighted averages were calculated at larger spatial scales. The cell areas reported in Pietro et al. (2009) were used for A_n. Approximations for the integral portion of Equation (2-2) can be made by any one of three methods. The simplest approach, employed by SFWMD (Pietro et al., 2009), uses the operational status of each cell as a proxy for inundation status on any given day, where online cells are fully inundated (WA = A_n) and offline cells are fully dry (WA = 0) and then the values of WA for all days in the period of interest are summed and then substituted for the integral portion of Equation (2-2). Alternatively, WA(t) can be estimated by (Pietro et al., 2010):

$$\text{WA(t)} = \begin{cases} A_{\text{n}} & \text{if } h_{wi} \geq h_{mean} \\ 0 & \text{if } h_{wi} < h_{mean} \end{cases} \qquad (2\text{-}3)$$

where h_{wi} = average elevation of water surface (stage) on day i [L] and h_{mean} = mean elevation of the ground surface [L]. Again, the WA values for all days in the period of interest are summed and applied to Equation (2-2). In some STAs, particularly those with wide elevation ranges or highly pulsed inflows, the methods of SFWMD may not accurately estimate the effective area. Finally, WA(t) may be estimated from a stage-area curve, a function that relates the flooded wetland area to the elevation of the water surface. This final method of WA calculation was selected for this analysis as it quantifies the extent of flooding when $h_{\text{min}} < h_w < h_{\text{max}}$, as opposed to the flooded/dry dichotomy created by the two other methods. To construct the stage-area curve for each cell, topographic data from the most recent, or otherwise most reliable, survey of each STA were interpolated using the kriging method in ArcGIS 9.2 (ESRI, Redlands, CA). Extreme values (e.g. tops of levees, bottoms of ditches) included in the original survey data were excluded from interpolation. From the resulting continuous bathymetric map, ArcGIS returned tabulated frequencies of the elevations in each cell. These frequencies were transformed into cumulative elevation distributions, the vertical axes of which were multiplied by A_n. Sixth-order polynomial curves were fit to the resulting points to estimate the stage-area curve:

$$y = ah^6 + bh^5 + ch^4 + dh^3 + eh^2 + fh + g \qquad (2\text{-}4)$$

where h = elevation, ft NGVD29, y = area of cell with elevation $\leq x$, a-g = constants, unique for each cell. Sixth-order curves generally provided strong fits to the data, though the large number of unique coefficients for each cell was somewhat burdensome. Equation (2-4) was solved for $h = h_{wi}$, returning the WA for each day i. The sum of the resulting values served as an estimate of the integral portion of Equation (2-2).

The nature of these high-order polynomials dictates that they only describe the stage-area relationship over a specified domain, unique to each cell. This range of valid elevations (h-values that produce frequency [y] values between 0 and A_n and lie within the range of surveyed elevations) is bounded by the minimum and maximum elevation within each cell.

The effects of the method of RWA and TPALR calculation were examined. These terms are given the subscript "D" when they were based on the elevation distribution (stage-area curve), the subscript "M" when they were calculated from the mean elevation, and the subscript "N" when they relied on the nominal area. The practice of using operational status to estimate the inundation status was not considered here.

Statistical Analyses

All statistical analyses were conducted with SAS 9.1 (SAS Institute, Cary, NC). Non-parametric tests were applied as necessary when data failed to meet assumptions of normality.

Results and Discussion

Characterization of Elevation Distribution and Wetted Area in the STAs

The CDF (equivalent to the stage-area curve, normalized for area) of ground elevation varied among cells in the STAs (Figure 2-1). Qualitatively, the shape and spread of the distribution of elevation in each cell alone was not correlated with long-term P removal performance. For example, despite similar elevation CDFs, STA-1W Cell 1 and STA-3/4 Cell 1A have shown very different POR P mass removal effectiveness (7.6% and 44.9%, respectively; Chimney, 2009). Quantitatively, the standard deviation of the elevation in each STA was not correlated with the POR P mass removal effectiveness (r^2 = 0.036).

The annual RWA_D was less than 100% for 74/118 cell-years but was lower than 90% for only 28 of 118 cell-years (Table 2-1). The POR average RWA_D for all STAs was 96%. Most of the low RWA_D cell-years are concentrated in water years 2007 and 2008 (Figure 2-2), a documented period of drought in South Florida (Pietro et al., 2009).

Changes in RWA_D were brought on by intra-annual as well as inter-annual precipitation cycles. For most cells, the seasonal low RWA_D occurs in May (Table 2-2), corresponding with the end of the South Florida dry season.

Relative Wetted Area and Total Phosphorus Removal Performance

The TP areal settling rate was poorly but significantly correlated to the RWA_D across all cells and all non-screened months (r=0.162, p<0.0001, n=943). The relative lack of variability in the explanatory term (RWA_D was greater than 95% in 89% of months; Figure 2-3) obscured the influence of RWA_D on k_{TP}. Considering only months where $RWA_D < 1.0$ (that is, months when $h_w < h_{max}$) increased r to 0.308 (p<0.0001, n=247). The relationship between k_{TP} and RWA_D was strongest among all of the months when $RWA_M < 1.0$, though this filter greatly reduced the number of included observations (r=0.412, p=0.0408, n=25). This suggests that, on the whole, the RWA_D influenced the TP settling rate in the STAs (months with high RWA_D were more likely to also have high k_{TP}), but the overall impact across the operating history of the whole project was minimized by the relative infrequency of months with RWA_D substantially less than 1.0.

Likewise, there was a weak but significant relationship between the monthly outflow TP concentration and RWA_D across all cells and all non-screened months (r= -0.181, p<0.0001, n=989). The relationship was only marginally stronger among months where $RWA_D < 1.0$ (r= -0.211, p=0.0003, n=285). Contrary to the findings for k_{TP}, there was no correlation between outflow TP concentration and RWA_D within months with $RWA_M < 1$ (r=0.078, p=0.6775, n=31). Apparently the RWA_D has little effect on the outflow TP concentration, relative to the variation caused by all other wetland processes.

Several conditions may have contributed to the relationship between k_{TP} and RWA_D. First, in those cells where deviation from $RWA_D = 1.0$ was augmented by highly variable topography (e.g. cells in STA-5, Figure 2-1), at any given average depth, the variance on the distribution of depths would have been higher than in more ‘flat-bottomed’ cells (e.g. cells in STA-3/4, Figure 2-1). The effect of extreme depths on short- and long-term performance has not been quantified. Second, dry-out could have caused localized death of SAV or transition of herbaceous emergent aquatic vegetation (EAV) to less desirable woody shrubs, decreasing treatment capacity upon re-flooding. The vegetation records in the STAs did not have sufficient temporal or spatial resolution to test this hypothesis. Finally, the absolute RWA may have had little influence on k_{TP}, with *changes* in RWA primarily affecting the apparent settling rate through oxidation and rewetting of the soil. Non-zero changes in RWA can occur only when the RWA varies from 1.0, thus the relationship observed above may be only a vestige of a connection between changing RWA and settling rate.

Interpretation of these correlation coefficients requires caution however. Although the RWA_D is normalized to the A_n of each cell, the k_{TP} values were not normalized to the cell means. Because the mean k_{TP} was different in each cell, it is dangerous to compare points of equivalent RWA_D if they came from different cells. Within cells, the strength and sign of the correlation between k_{TP} and RWA_D vary widely and the relationship was significant only in STA-5 Central Flow-way (CFW; Cells 2A and 2B) and STA-6 Cell 3. Possibly, perennially high RWA_D lends itself to higher k_{TP} values. Additionally, the subsets of observations resulting from each of the sequential screening criteria were not necessarily representative subsamples of the larger sample of observations. For example, of the 25 months with $RWA_M < 1.0$ and valid k_{TP} values, approximately half came from STA-5, which accounted for only 14% of the original 943 observations.

The relationship between k_{TP} and the change in monthly RWA_D (ΔRWA_D) tells a more interesting story. With all cells and all non-screened months included, r= -0.074 (p=0.0241, n=932). Despite the expected negative coefficient, the strength of the correlation does not strongly support the hypothesis that k_{TP} would decrease during re-flooding months. The coefficient of correlation was slightly greater (as was the level of significance) with ΔRWA_M (r= -0.090, p=0.0059, n=932), likely because the substantial dry-down and re-flooding events required to shift the stage past h_{mean} may have had more of an effect on the settling rate than small events that could cause ΔRWA_D to be different from 0. As discussed above, the RWA_D infrequently varied far from 1.0. As a result, ΔRWA_D did not often vary far from 0. Removing from the correlation those cells that never experienced $RWA_D \neq 1$ improved the strength and significance of the relationship between k_{TP} and ΔRWA_D only slightly (r= -0.088, p=0.0167, n=745). Again, k_{TP} was slightly more closely associated with ΔRWA_M (r = -0.105, p=0.0039, n=745). Of course, the deleterious effects of changing RWA (as explicated in the hypothesis) are expected only in re-flooding months, or months with $\Delta RWA_D > 0$. Screening out all months that do not meet this criterion tripled the strength of the co-variation (r= -0.313, p<0.0001, n=159). This implies that, in months when re-flooding occurred, about 10% of the variability of k_{TP} was explained by variability in the extent of the re-flooding event. Finally, in the few months of substantial re-flooding ($\Delta RWA_D > 0.1$), the k_{TP} and ΔRWA_D were remarkably co-variant (r= -0.605, p<0.0001, n=39). The large amount of variability in k_{TP} explained by ΔRWA_D in these large re-flood months, suggests that ΔRWA_D may be a useful variable to include in a multiple linear regression analysis to determine the factors controlling k_{TP} (Chapter 4). The previous discussion on the caution that must be applied when interpreting data of this nature applies to these results as well.

Relative Wetted Area and Total Phosphorus Mass Loading Rate

Determining the importance of WA < A_n on the TPALR in the STAs was a surprisingly complex task. In absolute terms, the $TPALR_D$ and $TPALR_M$ must be greater than $TPALR_n$ for a cell in any given month, year, or other period of interest where the $WA_D < A_n$ and $WA_M < A_n$, respectively. It is the size of these differences and their implications for other assessments that require an accurate measure of the TPALR that are of interest.

When the three methods of TPALR calculation were treated as repeated measures on each unique cell-month (n=1000) the means were statistically, though not substantially, different (0.275 g/m^2/mo, 0.273 g/m^2/mo and 0.272 g/m^2/mo for $TPALR_D$, $TPALR_M$ and $TPALR_n$, respectively. All pairs of means significantly different at p=0.05). The large number of observations boosted the significance of these trivial differences. This finding imparts nothing except the fact that the adjustment for WA makes very little impact on the long-term mean TPALR; the precision of flow (Q in Equation (2-1)) measurements does not support the estimation of the loading rate to thousandths of a gram per m^2 per month. Accordingly, when the repeated measure design was removed from the analysis and the means compared directly, the calculated TPALR was not significantly influenced by the method of WA calculation when all STA cells and all months with valid TPALR data (n=1000) were included (Kurskal-Wallis χ^2=0.1261, df=2, p=0.9389). In fact, the TPALR adjusted for the WA (regardless of calculation method) was not statistically different from the $TPALR_n$. The general tendency toward complete or nearly complete flooding, again, obscured statistical differences between the adjusted TPALR and the $TPALR_n$ because the WA-correction has no effect in months when $RWA_D = RWA_M$ = 1.0. To isolate the true effects of the WA calculation on the TPALR, the three TPALR rank-sums were again compared including only months where $RWA_D < 1.0$ (n=280). The Kurskal-Wallis χ^2=0.1264 (df=2, p=0.9388) which failed to allow rejection of the null hypothesis that there is no effect of WA calculation on TPALR. Even considering only the months where $RWA_M < 1.0$ (n=38) there was no effect of the method of WA calculation (χ^2=2.4048, df=2, p=0.3005). Finally, the TPALR rank-sums were compared considering all months (regardless of WA value) only in those cells with POR mean $WA_D \leq 0.95$ (n=209; χ^2=0.1985, df=2, p=0.9055). In none of these cases was there a significant difference between any pair of the TPALR rank-sums. Apparently, the variation in monthly TPALR due to fluctuations in flow rate and inflow TP concentration overwhelmed the slight variance contributed by the shifting RWA. This suggests, that no correction for WA < A_n was necessary for a sufficiently accurate accounting of the monthly TPALR in the STAs.

Months with low RWA_D tended to coincide with months of low flow (Figure 2-4). Possibly, the adjustment of TPALR for WA < A_n was ineffectual in the monthly data because relatively low loading rates tended to dampen the impact of the adjustment in low-RWA_D months. To estimate the annual TPALR, the sum of the 12 monthly loads is divided by the average of the 12 monthly WA values. (In adopting this calculation method, the dubious assumption that the water delivered to a cell in any given month was available for delivery in any other month, as would be the case if the water was metered out of a reservoir, was accepted). In this way, a low-RWA month contributes to the calculation (increasing the calculated TPALR) even if the mass load in that month was low or negligible. However, despite these considerations, the different methods of TPALR calculation did not lead to significant differences between the rank-sums.

Despite the lack of significant effect on the mean TPALR, adjustment for the calculated WA would still be warranted if the correction improved the strength of the correlation between the TPALR and the outflow TP concentration. The coefficients of correlation (and p-values) between outflow TP concentration and TPALR are shown for each method of TPALR calculation over various subsets of the data in Table 2-3. When all months for all cells were included, the increases in the coefficient of correlation due to WA-correction were trivial. The largest improvements in *r* were found among months with $RWA_D < 1.0$ (in all cells) and among all months in cells with POR mean $RWA_D < 95\%$ (STA-2 Cell 2, STA-5 NFW, STA-5 CFW), though in both of these cases the relationship was so weak, regardless of TPALR calculation method, as to render the slight co-variation valueless. Interestingly, within every subset of observations, $TPALR_M$ was a better co-variable with outflow TP concentration than was $TPALR_D$. Of course, the relationship between TPALR and outflow TP concentration was not uniform within each cell. The results and implications of the cell-by-cell analysis are presented in Chapter 3.

Wetlands integrate, and thus dampen, short-term loading effects through dynamic soil and macrophyte processes. For example, the vegetation in a healthy wetland may be able to assimilate a pulse of incoming P through biomass expansion. The excess P may be released over many more τ than the mass of water that carried the initial pulse, as the plants die and decompose, and a short-term time step (e.g. month) may fail to capture the effect of TPALR on outflow TP concentration. To that end, annual outflow TP concentration was compared to annual $TPALR_n$, $TPALR_M$ and $TPALR_D$. The value of examining these variables over a longer time step was immediately apparent from the improvement in *r*-values compared to the whole population of cell-months. Once again, the method of WA determination was insignificant: annual outflow

TP concentration was more closely related to $TPALR_D$ (r=0.476, p<0.0001, n=111) than it was to either $TPALR_M$ (r=.475, p<0.0001, n=111) or $TPALR_n$ (r=0.466, p<0.0001, n=111), though only trivially.

Conclusions

In the STAs, the interaction of intra-cell topography and time-variable stage occasionally resulted in the incomplete inundation of some cells, as revealed by the characterization study. When the actual WA is less than the nominal area, exposed soils and vegetation are subject to oxidation and desiccation. In addition, the value of the ALR calculated with A_n will not reflect the realized ALR of the system, potentially affecting expected relationships between ALR and wetland treatment performance indices. There existed a weak positive linear relationship between k_{TP} and RWA_D and a weak negative linear relationship between k_{TP} and ΔRWA_D. Both correlations increased in strength with sequential screening of "unimportant" months, e.g. months with RWA_D = 1.0 or ΔRWA_D = 0. However, the number of months among which these relationships were important was very limited. Neither the TPALR nor the strength of the correlation between TPALR and outflow TP concentration was meaningfully altered by adjusting the calculated TPALR for WA < A_n.

These non-dramatic results support important conclusions nonetheless. First, the expected biogeochemical consequences of dry-out and rewetting appear to have been at work in the STAs. Fortunately, from a treatment point of view, RWA infrequently varied far from 1.0, so the bulk of the TP processing in the STAs was unaffected by dry-out/re-flooding events. Second, A_n was a satisfactory approximation of WA since neither the monthly nor annual TPALR was significantly different under either alternative calculation scheme. Finally, poor performance in certain cells (elevated outflow TP concentrations relative to inflow TPALR) was shown not to be an artifact of the TPALR calculation, validating the need for additional work to diagnose those factors contributing to performance in the STAs, as presented in the following chapters.

Table 2-1. Average annual relative wetted area by water year for each cell in the Stormwater Treatment Areas.

	Area (ha)	2000	2001	2002	2003	2004	2005	2006	2007	2008	Average
STA-1E	1628								99%	98	98
Cell 3	238								97	93	95
Cell 4N	261								99	99	99
Cell 4S	304								99	100	99
Cell 5	231								96	92	94
Cell 6	425								100	100	100
Cell 7	169								100	100	100
STA-1W	2699	100	100	100	100	100	99	77	69	95	96
Cell 1	603	100	100	100	100	100	100	100	69	90	95
Cell 2	381	100	100	100	100	100	100			98	100
Cell 3	415	100	100	100	100	100	100	100	55	85	93
Cell 4	145	100	100	100	100	100	87	100	73	100	96
Cell 5	1155		100	100	100	100	100	80	95	100	97
STA-2	2565				92	100	98	97	96	94	96
Cell 1	728				79	100	100	100	100	97	96
Cell 2	919				94	99	94	93	89	87	92
Cell 3	919				100	100	100	100	100	100	100
STA-3/4	6695							99	99	97	98
Cell 1A	1230							99	98	90	96
Cell 1B	1412							99	100	100	100
Cell 2A	1029							100	99	99	99
Cell 2B	1171							99	100	100	100
Cell 3A	871							97	93	99	96
Cell 3B	982							99	99	98	98
STA-5	1663		84	91	95	97	91	73	69	72	84
CFW	832		79	88	93	95	94	65	63	75	81
NFW	832		89	93	97	99	87	82	76	69	87
STA-6	352				93	97	94	93	70	74	87
Cell 3	99				87	94	88	88	51	51	77
Cell 5	253				96	99	96	95	78	83	91

Table 2-2. Intra-annual trends in relative wetted area.

	No. Yr.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
STA-1E		**100%**	**100**	**99**	**95**	**88**	**96**	**100**	**100**	**100**	**100**	**100**	**100**
Cell 3	2	100	100	99	82	62	94	100	100	100	100	100	100
Cell 4N	2	100	100	100	100	95	95	99	100	100	100	100	100
Cell 4S	2	100	99	99	100	98	99	100	100	100	100	100	100
Cell 5	2	100	100	97	81	65	85	100	100	100	100	100	100
Cell 6	2	100	100	100	100	100	100	100	100	100	100	100	100
Cell 7	2	100	100	100	100	100	100	100	100	100	100	100	100
STA-W		**97**	**94**	**91**	**89**	**91**	**98**	**100**	**100**	**100**	**100**	**99**	**98**
Cell 1	9	93	91	89	89	89	98	99	100	100	100	99	97
Cell 2	7	100	100	100	100	96	100	100	100	100	100	100	100
Cell 3	9	89	89	89	89	89	91	100	100	100	100	94	91
Cell 4	9	100	100	93	80	84	91	100	100	100	100	100	100
Cell 5	8	100	95	88	87	92	100	100	100	100	100	100	100
STA-2		**97**	**97**	**98**	**96**	**87**	**92**	**96**	**98**	**99**	**98**	**98**	**98**
Cell 1	6	100	98	100	100	81	85	90	98	100	100	100	100
Cell 2	6	91	94	95	90	78	88	97	96	97	94	94	95
Cell 3	6	100	100	100	100	100	100	100	100	100	100	100	100
STA-3/4		**100**	**100**	**99**	**97**	**91**	**96**	**100**	**100**	**100**	**99**	**98**	**100**
Cell 1A	3	100	100	100	93	73	87	100	100	100	99	97	100
Cell 1B	3	100	100	100	100	100	100	100	100	100	99	97	100
Cell 2A	3	100	100	100	97	97	100	100	100	100	99	100	100
Cell 2B	3	100	100	100	100	100	100	100	100	100	99	98	100
Cell 3	3	100	99	97	95	89	95	100	100	100	99	99	100
STA-5		**81**	**76**	**76**	**70**	**65**	**80**	**92**	**94**	**96**	**96**	**93**	**90**
CFW	8	76	68	73	64	60	77	91	95	96	96	94	89
NFW	8	87	83	80	76	69	83	92	93	96	96	93	90
STA-6		**84**	**82**	**86**	**79**	**56**	**75**	**94**	**100**	**100**	**100**	**98**	**93**
Cell 3	6	70	69	75	64	23	50	84	100	100	100	97	88
Cell 5	6	89	87	90	85	68	85	97	100	100	100	99	94
Grand Total		**97**	**95**	**95**	**92**	**87**	**93**	**98**	**99**	**99**	**99**	**98**	**98**

Table 2-3. Changes in the coefficients of correlation for different subsets of data.

1	2	3	4	5
	All cells	Months when $RWA_D < 1.0$	Months when $RWA_M < 1.0$	All months in cells with mean $RWA_D < 0.95$
No. data months	945	248	25	187
$TPALR_n$	0.266 (<0.0001)	0.099 (0.1214)	0.493 (0.0122)	0.048 (0.5154)
$TPALR_D$	0.271 (<0.0001)	0.119 (0.0614)	0.486 (0.0137)	0.067 (0.3589)
$TPALR_M$	0.273 (<0.0001)	0.133 (0.0370)	0.516 (0.0083)	0.083 (0.2567)

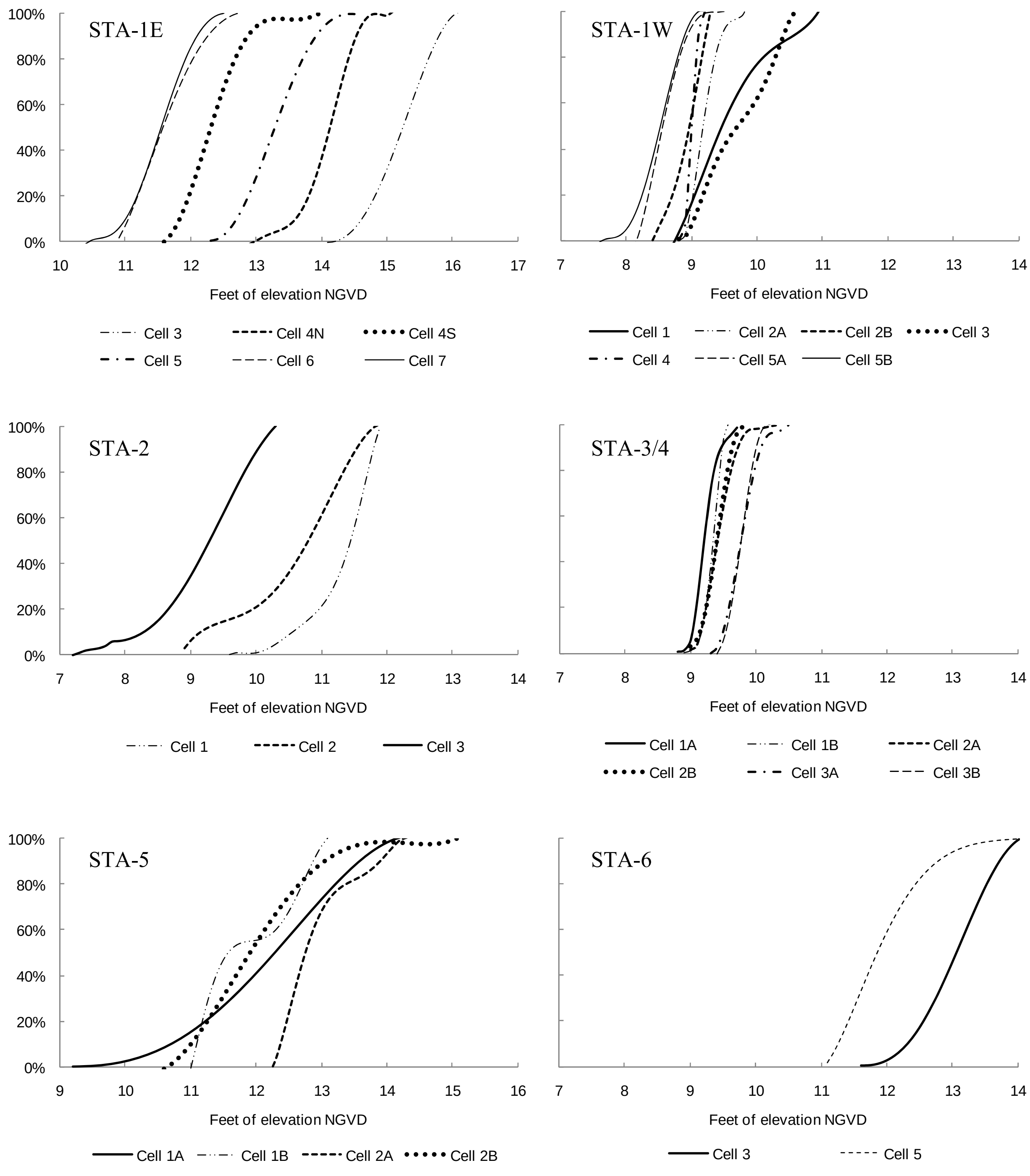


Figure 2-1. Cumulative elevation distribution for each cell in the Stormwater Treatment Areas. Note that the range of each horizontal axis is the same.

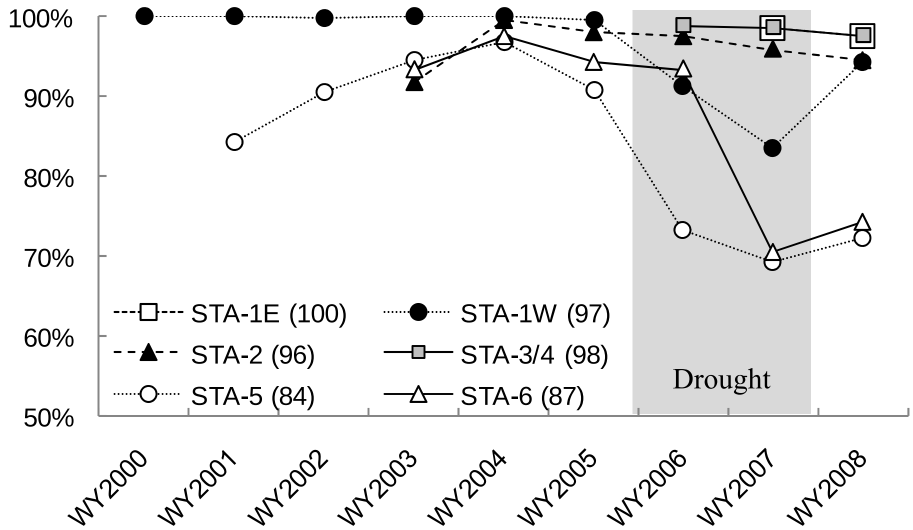


Figure 2-2. Relative wetted area in each of the Stormwater Treatment Areas. Note that the vertical axis does not extend to 0. Error bars have been omitted to increase clarity.

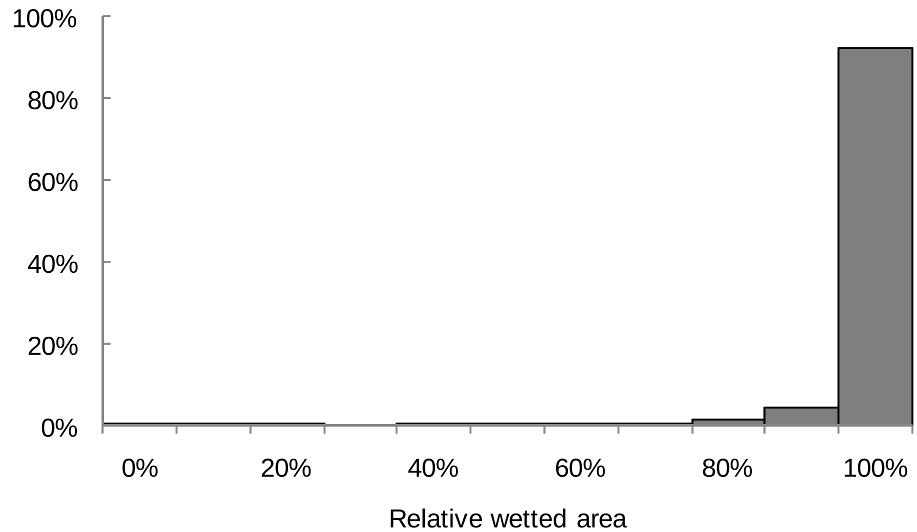


Figure 2-3. Histogram of monthly relative wetted area (determined by the elevation distribution) values across all non-screened months and all included cells.

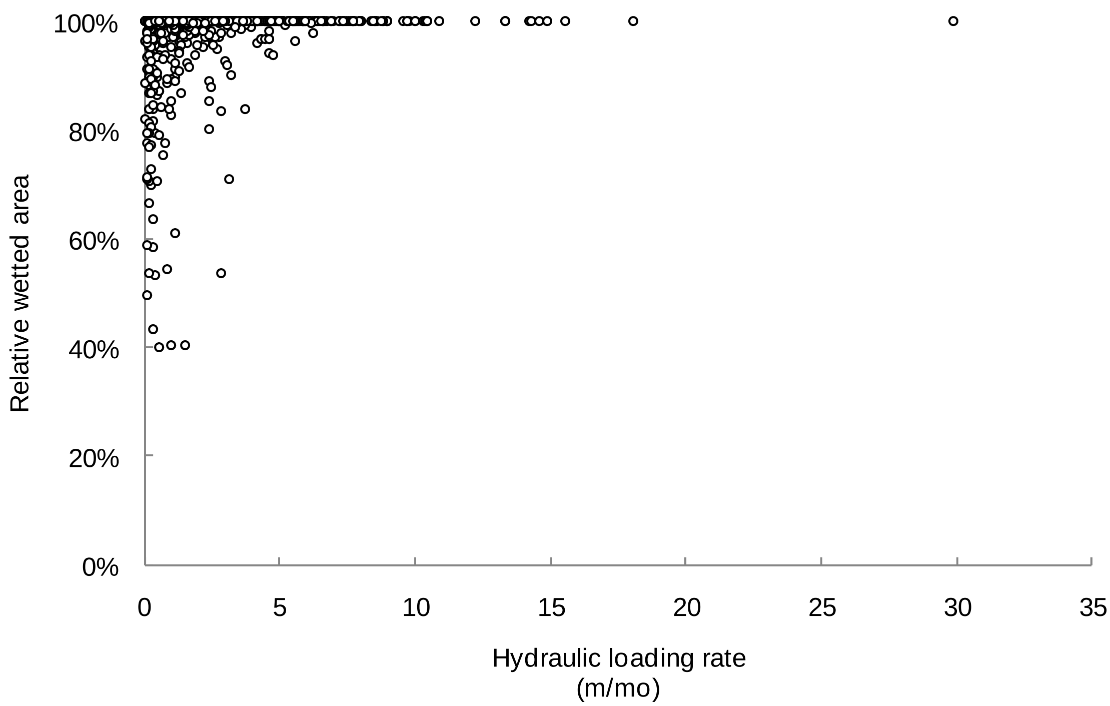


Figure 2-4. Monthly relative wetted area (determined by the elevation distribution) with respect to monthly hydraulic loading for all non-screened months and all included cells.

CHAPTER 3
ASSOCIATION BETWEEN LOADING RATE AND OUTFLOW CONCENTRATION IN THE STORMWATER TREATMENT AREAS

Introduction

Several species of SAV, macrophytes with the bulk of their biomass suspended in the water column, are common in wetlands and other water bodies in South Florida (Dierberg et al., 2002). Because of their growth habit, the mechanisms of P removal in SAV systems include two distinct differences from those in EAV wetlands. First, roots of emergent plants can access only porewater nutrients (with diffusion or mass transfer of nutrients to the sediment mediating uptake from the water column), whereas SAV obtains nutrients directly from the water column through the shoots and leaves (Granéli and Solander, 1988). This means that SAV can uptake SRP very quickly, particularly in the short-term (Pietro et al., 2006). Second, during photosynthesis, SAV removes carbon dioxide and bicarbonate from the water column, which raises the system pH, and drives the system towards calcium carbonate ($CaCO_3$) supersaturation, promoting $CaCO_3$ precipitation (McConnaughey et al., 1994). Several studies have proposed co-precipitation with $CaCO_3$ as a mechanism of P removal in a variety of systems (Scinto, 1997 reviews some of these works). It has been reasoned that SAV is more suited for P removal in treatment wetlands than EAV, a hypothesis supported by studies at mesocosm- (Dierberg et al., 2002) prototype- (Nungesser and Chimney, 2001) and field-scales (Juston and DeBusk, 2006).

SAV systems have generally been successful within the STAs, and now comprise over half (ca. 10,000 ha) of the STA treatment area, often in downstream positions within serial flow-trains (Pietro et al., 2010). Most of the cells with the lowest long-term outflow concentrations are dominated by SAV; of the nine cells with long-term flow-weighted average outflow TP concentrations below 0.030 mg/L, six are designated SAV.

Though elevated relative to the levels in the historical, unimpacted Everglades, it has been suggested by way of internal profile studies that these low outflow concentrations approach C* in some SAV cells (i.e. the concentration profile reaches a plateau some fraction of the way through the cell, beyond which no additional treatment is observed; Pietro et al., 2010). The alternative P treatment mechanisms at work in SAV may be responsible for the reduction of TP to C*, possibly because, given non-limiting calcium and light for photosynthesis, the co-precipitation process is not subject to 'saturation', as soils (via sorption) and microbial and plant biomass may be, nor is it rate-limited by biotic uptake.

Excessively loading a wetland with a high settling rate conceptually results in poor performance (e.g. elevated outflow concentrations, lowered percent removal). Conversely, even wetlands with low settling rates can conceptually perform well at sufficiently low loading rates. The interaction of the settling rate and loading rate determines the realized treatment performance for a wetland (assuming the inflow concentration is well above C*). It is convenient to employ the Damköhler number, which captures the "treatment potential" of a wetland by combining the settling rate with the loading rate (Kadlec and Wallace, 1996):

$$\mathrm{Da} = \frac{k}{q} \tag{3-1}$$

where Da = Damköhler number. By inserting Equation (3-1) into Equation (1-19), the k-C* model suggests that at very high Da, C* controls the outflow concentration:

$$C_2 - C^* = (C_1 - C^*) \exp(-\mathrm{Da}) \tag{3-2}$$

Internal profile studies are reliable for determining whether a wetland is treating to C*. They are however, laborious and expensive both in the field and the laboratory. Potentially, the strength of the correlation between the outflow concentration and the TPALR may be used as a proxy to estimate if wetland effluent is at C*. Since C* is independent of the short-term TPALR

(Equations (1-19) and (2-1)), in situations where the outflow TP concentration approaches C*, the correlation between the outflow TP concentration and the TPALR will be weak or absent. For example, internal profiles were estimated for a hypothetical wetland with a very high Da under four different loading scenarios, each with a different ALR (Figure 3-1). In each scenario, the outflow concentration was equal to C* and outflow concentration and ALR were uncorrelated. The term 'apparent background concentration' is adapted from Kadlec and Knight (1996) to describe the outflow TP concentrations from those cells with weak short-term outflow concentration-TPALR interactions, even when those concentrations were above the range of commonly described background TP concentrations for South Florida systems of 6-16 µg/L (Juston and DeBusk, 2006; Kadlec and Wallace, 2008). The hypothesis that alternative P removal mechanisms elevate Da such that SAV cells tend to produce apparent TP background concentrations (while EAV cells are less likely to do so) may be tested by comparing the correlations between outflow TP concentration and TPALR within SAV cells to those in EAV cells.

It should be noted, however, that even for well performing cells, the outflow concentration varied, both from cell to cell and over time. In conjunction with the previous discussion, this implies that the apparent background concentration was not fixed. In a plug-flow wetland, the real P background concentration is the point of equilibrium between P availability and biogeochemical P demand. Atmospheric deposition, internal hydraulics (the degree of mixing within a wetland), TP fractionation, and the internal loading (particularly of PP and DOP) are known to contribute to the apparent background concentration (Kadlec and Wallace, 2008). Some of these factors can be easily measured (TP fractionation) and others can be inferred from easily quantifiable factors (e.g. temperature can be a proxy for seasonal changes in biomass production and senescence, both of which contribute to autochthonous P loads). In STA cells that produce outflow TP concentrations independent of the TPALR, understanding and quantifying the factors that control the apparent background concentration are important for increasing both realized performance and predictions of that performance.

Objectives

This chapter addresses four primary questions: 1) Were SAV cells in the STAs operating at apparent background concentrations, as determined by independence of outflow TP concentration from the TPALR? 2) Were the outflow TP concentration data uncorrelated to the TPALR in all SAV cells, or only a specific subset? 3) In the case that only certain cells are exempt from this correlation, what was the underlying cause if not the dominant vegetation? 4) What determined the outflow TP concentration in cells operating at an apparent background concentration? The above questions were answered by testing the following hypotheses:

The outflow TP concentration data will be more poorly correlated to the TPALR data in SAV cells relative to EAV cells.

The outflow TP concentration data will co-vary weakly with TPALR data in most SAV cells, and will not co-vary at all with TPALR in some SAV cells.

The strength of the co-variation will be negatively correlated to the percent cover of SAV within cells.

In those cells operating at an apparent C*, the outflow concentration will be a function of one or more of the variables: TP fractionation, long-term TPALR and temperature.

Methods

Methods regarding the calculation or preparation of TPALR, τ, TP fraction, and temperature data may be found in Chapter 1.

Vegetation

Each STA cell has been classified by dominant vegetation type (SAV/EAV) by SFWMD (Pietro et al. 2008). While the classifications generally capture the dominant vegetation types, and reflect the plant communities targeted by SFWMD for each cell, they do not imply 100% coverage by the indicated vegetation class. The term 'Mixed' was applied to those units composed of cells of different designations, but for which water quality data was only examined at the larger scale (e.g. the North Flow-way of STA-5 consists of an EAV- (Cell 1A) and a SAV- (Cell 1B) designated cell, but flow data were only available at the inflow and outflow of the flow-way).

To enhance the precision of the vegetation classification, the percent SAV cover was estimated for each cell in this study using tabulations of vegetation cover based on aerial imagery and vegetation field survey data provided by the SFWMD. The detailed (often species-level) designations from the map tabulations were combined into three distinct groups: EAV, SAV and open water. For this study, the SAV and open water coverages tabulated from vegetation maps were combined and assumed to approximately represent total SAV cover. The field survey data available to this project were collected by several different contractors and each employed a unique reporting system. Briefly, the coverage or abundance data at each survey point, plot or transect were normalized to a 0 to 1 scale (1 representing 100% cover). The relative coverages of each SAV species (including algae, when reported) were summed at each survey location. The nature of field surveys allowed for the distinction of SAV from open water, so open water did not contribute to the total SAV cover at each site. The values of percent SAV cover were averaged over all survey locations to estimate the total relative SAV cover for each cell. The spatial distributions of the survey points were checked to verify representative sampling within each cell. This study did not attempt to address changes in SAV cover over time. In cells where more than one estimate of SAV cover was available, the values were simply averaged, with equal weight given to survey and map data.

Outflow Concentration and Total Phosphorus Areal Loading Rate

The Pearson product-moment correlation coefficient (r) between monthly outflow TP concentration and monthly $TPALR_M$ (the best regressor of the three possible TPALR calculations; see Chapter 2) was determined for the POR for each cell. As r describes only the strength of the linear relationship between two variables, scatter plots were produced for each cell and visually inspected for non-linearity. It was noted that the significant (p = 0.05) positive r-values in several cells resulted entirely from the presence of outliers in the upper-right quadrant (high outflow concentrations corresponding to high loading events). The practical significance of these relationships defined by outliers is discussed below. However, in an effort to capture the "typical" behavior of each cell, r was recalculated after excluding the month with the largest TPALR value in each cell, and termed r' for convenience. The bulk of this study relies on r' because approximately one-half of the significant r values were artifacts of single outliers (Table 3-1).

Results and Discussion

Outflow Concentration- Areal Loading Relationship

Effect of vegetation type and cover

The magnitude and significance of r' was not clearly determined by the vegetation designation reported for each cell in Pietro et al. (2008) (Table 3-1). Of the 7 SAV-classified cells examined, r' was non-significant in 6 (86%). Similarly, 9 (75%) of the included 12 EAV cells had non-significant r'. Unexpectedly, one EAV cell (STA-2 Cell 1) reported a weak but significant *negative* co-variance between outflow TP concentration and TPALR. Possible causes for this counter-intuitive relationship were unclear. As a result, data from Cell 1 of STA-2 were excluded from further analyses in this chapter. Three of the four (75%) 'mixed' units had non-significant r'. Broadly, EAV and SAV cells were not overwhelmingly differentiated by the strength of *r'* (Table 3-1), though the caveats associated with the vegetation designations (see Methods of this chapter) depreciate the power of this assessment.

To avoid the difficulties and inaccuracies associated with using the SFWMD-assigned vegetation classifications, *r*' was plotted against estimates of the actual percent cover of SAV. The cells clustered into three distinct groups, (Figure 3-2). Group 1 contains cells with low to moderate SAV coverage and low *r*'-values. The low- to mid-SAV coverage cells, with relatively high *r*'-values comprise Group 2. Group 3 consists of high-SAV cells with non-significant *r*'. Immediately apparent from Figure 3-2 are the strictly non-significant *r*'-values in all high-SAV cells. Secondly, the unexpected tendency for non-significant *r*'-values in low- and moderate-SAV cells is noteworthy. Together these observations do not support any conclusions about the influence of SAV P processing mechanisms on the uncoupling the short-term outflow TP concentration from the TPALR in SAV cells, but do suggest that this method may be inappropriate for testing that hypothesis. Also, importantly, they make clear that some other factor (or factors) contributed to the disassociation of the outflow TP concentration from the monthly TPALR.

Effect of areal total phosphorus loading rate

Equation (1-19) indicates that, at sufficiently light loads, the outflow concentration from a wetland will converge on the background concentration, C*, and thus approach independence from the loading rate. This was supported by the findings of Qian and Richardson (1997) (and reinforced by Richardson and Qualls, 1999) that showed that below POR TPALR of about 1.0 g/m^2/yr, the long-term average outflow concentrations from a large number of North American wetlands were fairly invariant with respect to changes in TPALR. Likewise, among SAV and select EAV cells with annual TPALR at or below 2.0 g/m^2/yr, Juston and DeBusk (2006) noted "no significant relationships (*p*>0.05) were identified in the slopes of P-ALR relationships using either 1 or 2 year average ALRs, thus suggesting no evidence of association of ALR with TP concentrations in this range." It follows that the areal loads in cells in Groups 1 and 3 were possibly too low to force the outflow TP concentration above the apparent background concentration. A one-way analysis of variance was performed on the monthly TPALR to compare each of the three groups. The F-value was 17.19 (df=2, p<0.0001). A Student-Newman-Keuls test (p=0.05) found that the mean monthly TPALR was significantly higher in Group 2 (0.42 g/m^2/mo) than in either Group 1 or Group 3. The mean monthly TPALR were similar in Groups 1 and 3 (0.21 and 0.22 g/m^2/mo, respectively). The implication, in the spirit of Richardson and Qualls (1999), is that the TPALR became influential on the outflow TP concentration once it exceeded some threshold. All cells with average annual $TPALR_M$ less than about 2.0 g/m^2/yr showed no significant relationship between short-term outflow TP concentration and the $TPALR_M$ (Figure 3-3), as expected from the work of Juston and DeBusk (2006). The presence of significant, positive r'-values only in cells loaded with greater than 2.0 g/m^2/yr does suggest that the magnitude of the loading rate contributed to the strength of the TPALR-outflow TP concentration relationship. The fact that some cells also loaded above 2.0 g/m^2/yr had non-significant correlations between outflow TP concentration and $TPALR_M$ indicates the action of an additional factor (or factors) restraining r' even under large loads. Moreover, this additional factor was very likely *not* the alternative mechanisms of SAV systems, as the high-$TPALR_M$, low-r' group contained both EAV and SAV cells.

A mention must be made of the substantial difference between r and r' in a few cells (Table 3-1). The extreme influence that the outliers had on the correlation between the outflow TP concentration and the TPALR justifies their exclusion for analytical purposes. Nonetheless, these data imply that, had these cells experienced higher and more variable loading rates on a monthly basis, than was observed during their recorded operation, the outflow TP concentration may have actually been influenced by the TPALR. The near-universal tendency for the month of maximum load to increase the strength and significance of *r* suggests that, regardless of the vegetation type or the short-term outflow concentration-TPALR relationship under 'typical' operating conditions, extreme pulses of P were very likely to produce above-average outflow concentrations.

Factors Controlling the Apparent Background Concentration

Having established that, in most cells of the STAs, the short-term outflow TP concentration did not depend strongly on the monthly TPALR, the challenge of identifying the factors that did determine the short-term outflow concentration arises. Curiously, the POR FWM outflow TP concentrations from those cells with non-significant *r*'-values showed the same range and variability as those cells with moderate to strong TPALR-outflow TP concentration relationships (Figure 3-4). This chapter considers two possible controls on the long-term mean outflow TP concentration and one possible regulator of the short-term outflow concentration. A more thorough exploration of potential factors controlling monthly outflow TP concentrations is presented in Chapter 4.

Inflow phosphorus fractions

The most chemo- and bioavailable P forms comprise the SRP fraction of the TP pool (Kadlec and Wallace, 2008; Reddy and DeLaune, 2008). In treatment wetlands, this often leads to preferential removal of SRP relative to the TP aggregate (Dierberg et al., 2002; Chimney, 2007). Conversely, DOP is thought to be generally less bioavailable and has been found to be less effectively removed than the bulk TP in treatment wetlands (Reddy and DeLaune, 2008; Chimney, 2007), though this may be due as much to internal production of DOP as to non-treatment of influent DOP (Pinney et al., 2000). Therefore, it is proposed that the composition of the inflow TP potentially contributed to the apparent background concentration in the STAs, with relative increases in SRP lowering C* and relative increases in DOP elevating C*.

Although the monthly outflow TP concentration from the set of cells of interest was not correlated to the TPALR, it was weakly but measurably influenced by the inflow TP concentration: $r = 0.353$ ($p < 0.0001$, $n = 597$ considering monthly data among all the cells of interest). The positive relationship also existed within the monthly data for 4 of the 18 included individual cells (STA-1E Cell 7, STA-2 Cell 3, STA-3/4 Cell 1B, STA-6 Cell 5). The presence of this co-variance required that the effects of the TP fractionation on the outflow concentration be assessed within the effects of the inflow TP concentration. After the variability due to the inflow TP concentration was removed, neither the relative size of the SRP fraction nor the DOP fraction had any significant effect on the outflow TP concentration (SRP: F-value = 0.12, p = 0.7298, df = 1; DOP: F-value = 0.03, p = 0.8722, df=1). The effect of the inflow DOP concentration was significant (F-value = 6.89, p = 0.0089, df = 1), but the additional variability explained was minor (approx. 1%). The three variables, inflow DOP concentration, inflow DOP fraction and inflow SRP fraction, had a significant effect on the monthly outflow TP concentration after accounting for the inflow TP concentration in only 2, 3, and 4 cells, respectively. In addition, there was no relationship found between the outflow TP concentration and any of these three variables at either annual or POR averaging periods. In summary, both across cells and within cells, the composition of the inflow TP played a minor role, at best, in the determination of the outflow concentration from the cells where the outflow TP concentration was not related to the TPALR.

Long-term areal loading

Sustained high annual areal P loading is known to increase the soil P concentration. In South Florida, a well-studied example of this phenomenon is Water Conservation Area 2A

(WCA-2A), where decades of P loading have resulted in elevated soil P concentrations immediately downstream from the inflows. Reddy and DeLaune (2008) provide an excellent review of the literature on WAC-2A. As part of a positive feedback cycle with increasing soil P, primary productivity of wetlands tends to increase with sustained P loads (Lowe and Keenan, 1997; Kadlec and Knight, 1996). As a result, the P-processing "biomachine" grows in response to increased P loads. The P-sequestering power (in terms of g P/m^2/yr) grows as well, until biomass expansion becomes limited by space-, light- or nutrient-(e.g. N) availability. Biomass production, senescence and decomposition are known to export dissolved nutrients to the water column (Pinney et al., 2000; Qualls and Richardson, 2002, Reddy and DeLaune, 2008). It is conceivable that increasing the size of the "biomachine" would increase the autochthonous P production and export. Thus, STA cells with high long-term TPALR may be expected to operate with relatively higher apparent background concentrations, even if in the short term, the outflow TP concentration is independent of the TPALR.

It has been previously established that the expected positive relationship between outflow TP concentration and TPALR exists in the STAs when long-term (POR) averaging periods are considered; among all STA cells, the POR outflow TP concentration was positively, non-linearly correlated to the POR TPALR through a power function (Pietro et al., 2009). The objective here is to assess if that relationship holds when considering only those cells in which the short-term TPALR did not directly control the monthly outflow TP concentration.

Among all the cells operating with non-significant r', the POR FWM outflow TP concentration was significantly linearly correlated to the average annual TPALR (r = 0.703, p=0.0011, n = 18; Figure 3-5). A power function (Pietro et al. 2009) described the data only slightly more accurately (r^2 = 0.508; Figure 3-5). The shape of the data cloud in Figure 3-5 was remarkably similar to the distribution of the wide variety of wetlands studied by Richardson and Qualls (1999), including an apparent breakpoint near 1.0 g P/m^2/yr. Unclear, for both the STA cells and the wetlands documented by Richardson and Qualls (1999), is why some wetlands are able to produce low outflow concentrations even under high areal loads (e.g. STA-1E Cell 4N).

At an annual scale, the data demonstrated a similar relationship, although the non-linearity observed in the POR data was absent (Figure 3-6). Even among cells where the monthly outflow concentration was independent of the monthly TPALR, years with higher areal loads tended to also have higher outflow TP concentrations. This may be attributable to the aforementioned effect of the size of the "biomachine." The non-linearity in the POR data may develop as the effects of consistent light or heavy loading compound over years of operation.

Seasonality

The bulk of the long-term sustainable P removal in wetland is biologically mediated by microorganisms, algae and submerged and emergent macrophytes (Kadlec and Knight, 1996; Kadlec, 1997; Dierberg at al., 2002). The P demand and production from these biomass compartments varies as their size and activity fluctuate in response to environmental factors (e.g. temperature and insolation) (Kadlec and Wallace, 2008). Seasonal cycles are common in treatment wetlands, but are minimized, particularly for P, in subtropical wetlands with a year-round growing season (Kadlec and Wallace, 2008). Nonetheless, a distinct intra-annual temperature cycle is observed in South Florida (Figure 3-6) that may lend itself to seasonal fluctuations in biological processing sufficient to alter treatment performance. If so, the impacts ought to be seen as an annual cyclical variation in the outflow concentration, particularly in those cells producing effluent at an apparent background concentration. Water temperature is known to control microbial activity (Reddy and DeLaune, 2008) and serves as a good proxy for the average insolation, a driver of primary productivity (Best and Visser, 1987), so any annual cyclical variation in outflow TP concentration may be a reflection of the annual water temperature cycle (Figure 3-6).

Considering only the cells with non-significant *r*'-values, the monthly outflow TP concentration did not significantly vary with either the monthly inflow or outflow water temperature ($r \leq 0.064$, $n = 578$). Likely, the cell-to-cell variation in outflow TP concentration devalued this assessment. The monthly outflow TP concentration was significantly ($p = 0.05$) correlated to the monthly inflow water temperature in only 3 cells (positively in STA-3/4 Cell 3 and STA-5 CFW and negatively in STA-5 NFW), and to the outflow water temperature in only 2 cells (positively in STA-6 Cell 3 and negatively in STA-3/4 Cell 2B). No non-linearity was found between outflow TP concentration and water temperature in a visual inspection of scatter plots within each cell.

That the relationship was significant in relatively few cells and that the conditions of the co-variances were inconsistent (some positively and some negatively correlated), suggest that the water temperature in the STAs did not play a critical role in determining the apparent background TP concentration in the STAs. Water temperature was thought to be a satisfactory surrogate for seasonality because many other variables are expected to be strongly correlated to it (e.g. insolation, seasonal biomass changes). However, a flaw is recognized in this approach: because of the sinusoidal nature of temperature over time, each average monthly temperature occurs twice per year (except for the annual maximum and minimum temperature). The environmental conditions may be quite different at the two manifestations of a given temperature. For example, the average water temperature tended to be about 25 °C in both April and October in STA-1W Cell 4 (Figure 3-6), but this fails to capture the obvious biological differences between the two months (e.g. spring flush vs. fall senescence). In none of the 18 cells with low *r*'-values was the outflow TP concentration significantly correlated to the ordinal month value (e.g. January = 1, February = 2…). Additionally, no regular non-linear patterns were observed in scatter plots of outflow TP concentration vs. time in months. A more powerful signal-processing method (e.g. Fourier transform) might be applied to the monthly outflow TP concentration data to better effect.

Conclusions

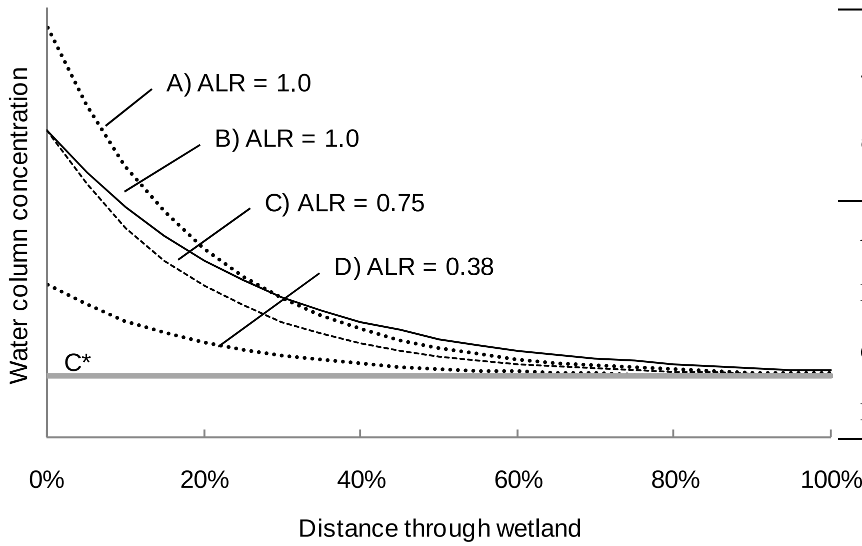
Although the POR outflow TP concentration was generally a function of the long-term average annual TPALR among all cells of the STAs (Pietro et al., 2009), as is common in treatment wetlands (Qian and Richardson, 1997), in a majority of cells the monthly outflow TP concentration was statistically independent of the monthly TPALR. Cell-to-cell variability in the strength of the short-term outflow concentration-TPALR relationship was not explained by the dominant vegetation type, and unsatisfactorily justified by the long-term TPALR. In the short-term, the outflow TP concentration from those cells operating at an apparent background concentration was not determined by the relative fractionation of the inflow TP pool nor did it vary with season, as approximated by the water temperature. Among these cells in the long-term, the annual average TPALR accounted for approximately 51% variation in the POR FWM outflow TP concentration.

Two useful implications arise from this study. First, the apparent uncoupling of the monthly outflow TP concentration from the TPALR suggests large Da in most STA cells, independent of the vegetation type. Equation (3-2) demonstrates that in wetlands with high Da, the realized outflow TP concentration will be controlled primarily by the apparent background concentration. Therefore, the ability for k-C* to accurately model outflow TP concentrations in the STAs may depend heavily on accurate estimates of C*.

Second, the notable lack of powerful descriptive variables for the short-term outflow TP concentration resulting from this work highlights the limits of both the currently available data and the body of knowledge of wetland P processing at this time. If minimizing the outflow concentrations from the STAs remains a political and managerial priority in South Florida, small-scale (e.g. mesocosm) research ought to be applied to identify additional potential controllers of the short-term outflow TP concentration, and large-scale (e.g. field) studies will be needed to define the interactions of these variables under operational conditions.

Table 3-1. Coefficients of correlation between monthly outflow total phosphorus (TP) concentration and monthly TP areal loading rate (ALR) within each cell before (*r*) and after (*r*') exclusion of the month of maximum TPALR. Non-significant ($p = 0.05$) coefficients are reported as 0.0.

Cell	Vegetation Designation	*r*	*r*'
STA-2 Cell 1	EAV	-0.284	-0.293
STA-1E Cell 4N	SAV	0.0	0.0
STA-1E Cell 4S	SAV	0.0	0.0
STA-1E Cell 3	EAV	0.0	0.0
STA-1E Cell 5	EAV	0.0	0.0
STA-1E Cell 6	SAV	0.859	0.0
STA-1E Cell 7	EAV	0.648	0.0
STA-1W Cell 5	SAV	0.085	0.0
STA-3/4 Cell 1A	EAV	0.0	0.0
STA-3/4 Cell 1B	EAV	0.0	0.0
STA-3/4 Cell 2A	EAV	0.433	0.0
STA-3/4 Cell 2B	SAV	0.0	0.0
STA-3/4 Cell 3	Mixed	0.0	0.0
STA-5 CFW	Mixed	0.0	0.0
STA-5 NFW	Mixed	0.0	0.0
STA-2 Cell 2	EAV	0.0	0.0
STA-2 Cell 3	SAV	0.0	0.0
STA-6 Cell 3	EAV	0.0	0.0
STA-6 Cell 5	EAV	0.622	0.0
STA-1W Cell 4	SAV	0.433	0.292
STA-1W Cell 1	EAV	0.524	0.422
STA-1W Cell 2	Mixed	0.742	0.591
STA-1W Cell 3	EAV	0.692	0.707



Scenario	HLR	Inflow conc.	ALR
	m/yr	mg/L	$g/m^2/yr$
A	15	0.067	1.00
B	20	0.050	1.00
C	15	0.050	0.75
D	15	0.025	0.38

Figure 3-1. When a wetland treats to background concentration (C*), the areal loading rate (ALR) does not affect the outflow concentration.

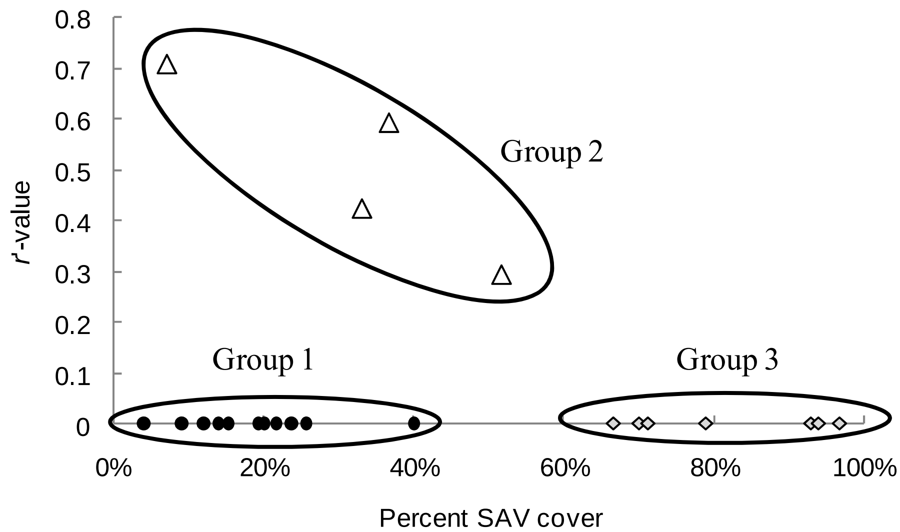


Figure 3-2. Correlation between outflow total phosphorus (TP) concentration and TP mass loading rate with respect to submerged aquatic vegetation (SAV) coverage. Non-significant correlations were assigned an *r*'-value of 0.

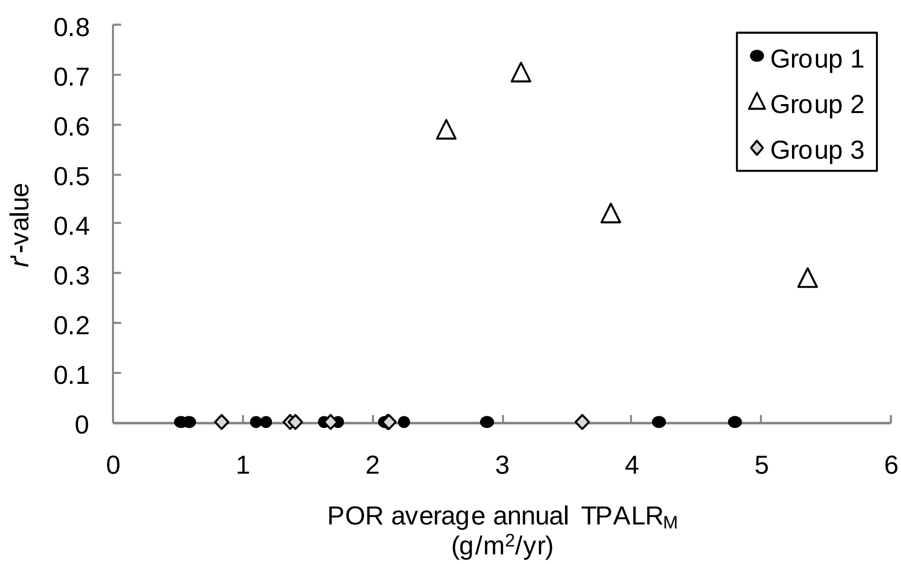


Figure 3-3. Correlation between outflow total phosphorus (TP) concentration and TP areal loading rate (ALR) as a function of the average annual TPALR. Non-significant correlations were assigned an *r*'-value of 0.

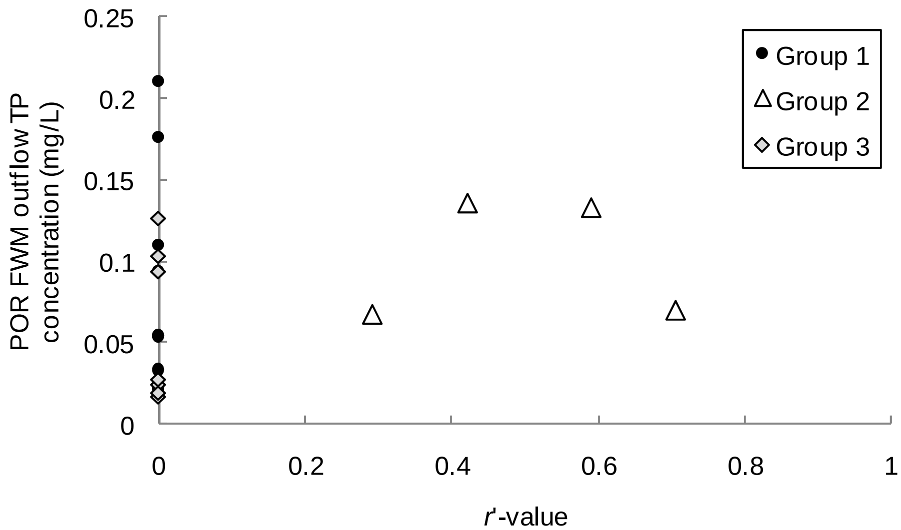


Figure 3-4. Outflow total phosphorus (TP) concentration with respect to the correlation coefficient between the TP areal loading rate (TPALR) and the outflow TP concentrations.

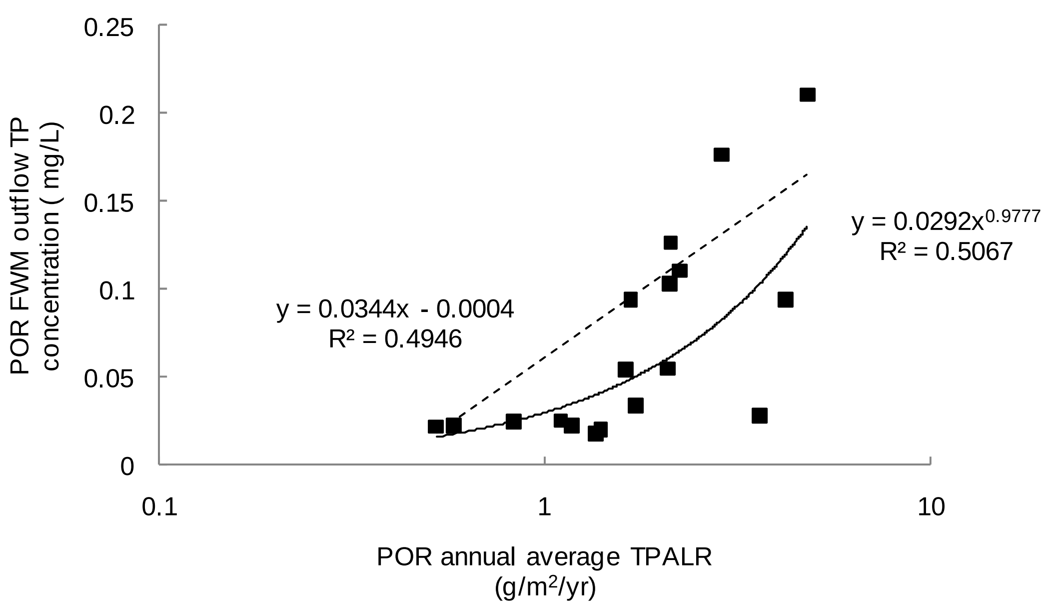


Figure 3-5. Period-of-record (POR) flow-weighted mean outflow total phosphorus (TP) concentration as a function of the POR average annual TP areal loading rate.

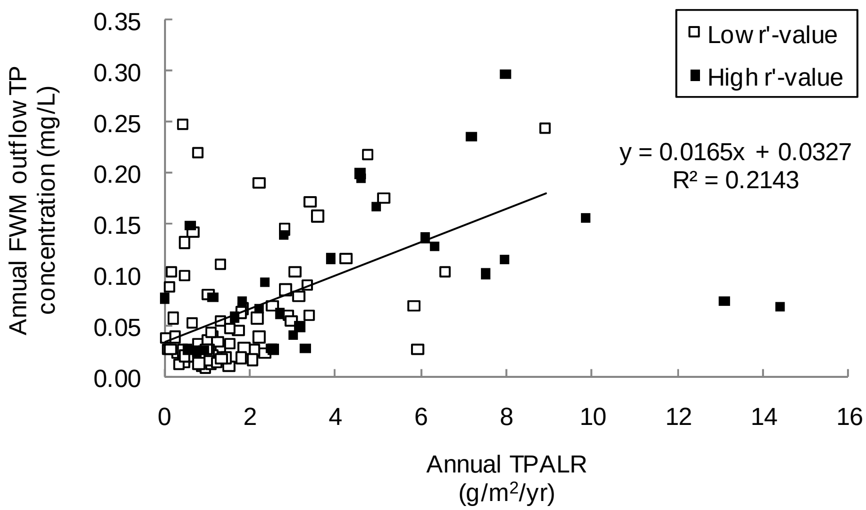


Figure 3-6. Annual flow-weighted mean (FWM) outflow total phosphorus (TP) concentration as a function of the annual TP areal loading rate (ALR). Data from cells with high *r*'-values are differentiated. The regression line considers data from low *r*'-value cells only.

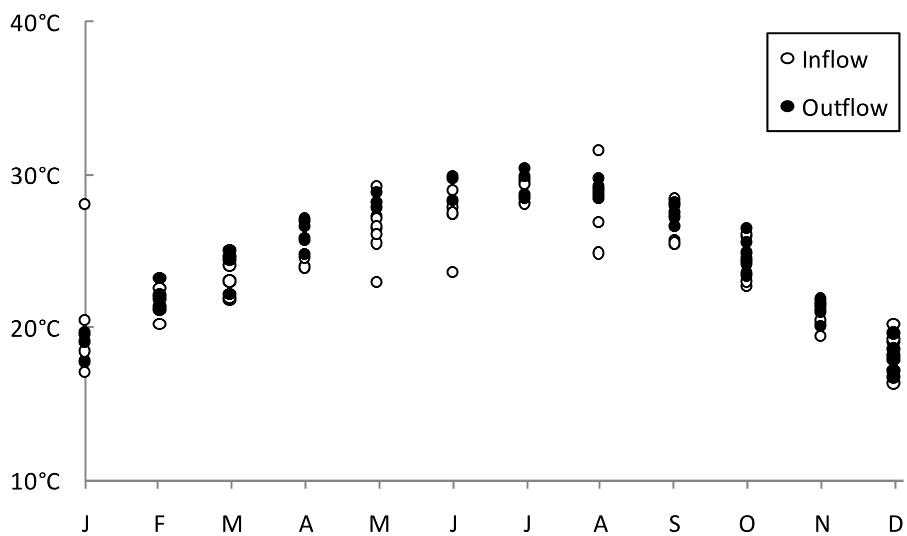


Figure 3-7. Monthly average temperature (°C) of inflow and outflow water in STA-1W Cell 4.

CHAPTER 4
MULTIPLE LINEAR REGRESSION TO DETERMINE FACTORS CONTROLLING PHOSPHORUS CONCENTRATION AND SETTLING RATE IN THE STORMWATER TREATMENT AREAS

Introduction

The cardinal performance metric for the STAs is outflow TP concentration. Many studies evaluating the STAs have investigated the outflow TP concentration with respect to various wetland characteristics, such as TPALR or vegetation type (e.g. Dierberg et al., 2002; Juston and DeBusk, 2006; Pietro et al., 2009). Importantly, the enforced and proposed regulations on the STAs also consider, primarily, the effluent concentration (Pietro et al, 2008). These regulations obligate STA managers to minimize the outflow TP concentrations. Ensuring the conditions for high Da-values (high settling rates and low loading rates) is critical to that effort. Chapter 3 of this work showed that the short-term outflow TP concentration was controlled more by C* than by TPALR or Da in most STA cells. Therefore, it is important to understand the wetland factors that contribute to the C*.

Inter-wetland and temporal variations in outflow TP concentration have been well studied (Kadlec and Wallace, 2008). Likewise, fluctuations in outflow TP concentration have been documented in the STAs (e.g. Pietro et al., 2008). A stated or implied assumption in almost all treatment wetland work, and adopted here as well, is that the outflow TP concentration is a function of various wetland characteristics. That is, the difference in the outflow TP concentration observed for two different wetlands ought to be due to the variation of some feature(s) between those wetlands. Similarly, the fluctuations of outflow concentration with time within a wetland are assumed to have resulted from changes in attributes of that wetland. For example, holding everything else constant, a wetland with a TP load comprised primarily of SRP may be expected to demonstrate a lower outflow concentration than an identical wetland receiving mainly DOP.

In wetland science of course, it is impossible to “hold everything else constant,” and so the effects of a single wetland characteristic are easily confounded. Even wetlands in side-by-side studies show some disparities in outflow concentrations (Kadlec and Wallace, 2008). Such differences are often ascribed to “stochastic variability,” a lumped error term containing all of the variance due to unaccounted-for wetland properties (Kadlec and Wallace, 2008). The objective of this study was to partition the variability in the short-term outflow TP concentration, to the maximum extent possible, to quantifiable wetland characteristics. In addition, the outflow concentration was correlated to TPALR in a few STA cells (Chapter 3), implying that Da was limiting performance. Therefore, the factors controlling the TP areal settling rate were also explored here. Being unable to isolate the effects of single variables in the field, this study attempts to do so via multiple regression using the vast datasets available for the STAs.

Considering the entire pool of non-screened months from all STA cells, the differences in means from cell to cell accounted for approximately 30% and 20% of the variation in monthly outflow TP concentrations and TP settling rates, respectively. From a managerial perspective, identifying the combination of variables responsible for these cell-to-cell differences (as well as the factors responsible for the substantial intra-cell variability) may possibly allow managers to better regulate the performance of the STAs by manipulating key attributes in all or some wetland cells. In addition, understanding which macro-scale wetland characteristics control the outflow concentration and the k-value in the STAs would provide guidance for future work on the illumination of poorly-understood process-level P dynamics in all subtropical surface-flow treatment wetlands.

Objectives

The objective of this chapter was to assess the relative influence of a wide variety of factors on the outflow TP concentration and the TP areal settling rate in the STAs. Multiple regression methods were implemented as an initial evaluation. It is recognized that the methods employed herein were relatively elementary, but were necessary to provide guidance for future exercises in this vein.

This chapter specifically addresses the question: can variation in STA performance be adequately explained by variations in the characteristics of the wetlands that comprise the STAs? Of course, the wetland properties open to investigation were limited to those for which appropriately spatially- and temporally-resolved, quantitative data were available. After the first inquiry, a second question naturally follows: which factors *did* contribute to variation in STA performance, and are they subject to manipulation by STA managers?

This chapter tested the following hypothesis: variability in the monthly outflow TP concentration and TP areal settling can be significantly explained by a subset of these factors: inflow TP concentration, inflow TP composition (fractionation), TPALR, τ, soil TP concentration, mean water depth, wetland age, inflow Ca concentration, Ca ALR, Ca areal retention, water column pH, and water temperature.

Methods

Multiple Linear Regression

Multiple regression considers linear models of the form:

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i} + \ldots + \beta_n x_{ni} + \varepsilon_i \qquad (4\text{-}1)$$

where y_i = the ith observation of the dependent variable of interest, x_{1i}-x_{ni} = ith values of independent variables related to y, β_0 = estimated value of y when x_1 through x_n = 0, β_1-β_n = parameters (coefficients) estimating the effect of each x_1-x_n on y, and ε_i = ith residual. Multiple regression procedures seek to select values of β_0-β_n which minimize the sum of the squares of the residuals.

Multiple regression analyses were used to determine the most influential independent variables (x_1-x_n in Equation (4-1)) on the dependent variables monthly outflow TP concentration and monthly TP areal settling rate (k_{TP}). Because the absolute value of k_{TP} was not considered here, but rather the relative differences from cell to cell and month to month (Pietro et al., 2009), for simplicity, it was calculated with C* = 0:

$$k_{\mathrm{TP}} = -\left(\frac{\left(\frac{Q_1+Q_2}{2}\right)}{\mathrm{WA_D}}\right)\ln\left(\frac{C_2}{C_1}\right) \tag{4-2}$$

where C_1 = inflow concentration [M/L^3], C_2 = outflow concentration [M/L^3], and Q_1 = flow rate in [L^3/T], Q_2 = flow rate out [L^3/T], and $\mathrm{WA_D}$ = wetted area, determined by elevation distribution [L^2]. The assumption of a constant C*-value for all STA cells (in this case C*=0) presents a special difficulty. This and previous chapters function on the recognition of spatially and temporally variable C*, meaning that the use of any constant C* is inappropriate. Unfortunately, the value (or function) that should be used for C* for each STA cell is yet unclear, though this chapter attempts to clarify the matter.

The multiple regressions were performed using SAS 9.1 (SAS Institute, Cary, NC). Built-in variable-selection procedures were not viable for this dataset; these routines include only observations (months) for which a value was present for every possible factor. For example, the missing inflow Ca concentration value in STA-1W Cell 5 in March 2005 would remove all the data for that month from consideration even if the inflow Ca concentration was not selected for the final model. After the extensive screening process (see Methods, Chapter 1), only about 15% of months had values for each variable. Since it was unlikely that all of the variables would prove to be useful in the final model, manual incremental construction of the model was deemed more appropriate. The regression model building approach was similar for both the outflow TP concentration and the TP areal settling rate. In all instances throughout this chapter, the adjusted coefficient of determination (r^2) is reported, to enforce parsimony and appropriately penalize the measure of fit for the number of dependent variables included in each model.

The manual variable selection procedure was intended to be straightforward. The r^2 was determined for each univariate model. Next, bivariate models were tested using the top regressor (variable producing the highest r^2) from the single-variable models and iteratively inserting each other variable. Trivariate models were tested by iteratively introducing each remaining variable into the best (highest r^2) bivariate model. This process was repeated until the marginal gains in explanatory power (increase in r^2 due to each additional variable) were deemed trivial.

Each cell had a different POR mean outflow TP concentration (Figure 3-4) and settling rate (not shown). The mean value for each cell may be thought of as an estimate of each monthly value in each cell. The variability in the cell means explained a portion of the overall variability in the monthly values. It was possible to model the effects of each cell on the dependent parameters. At each level of complexity, the model was also tested with the cell effects to assess the extent that each additional variable accounted for cell-to-cell differences in outflow concentration and settling rate.

Variables Considered

The inclusion of specific variables for consideration was based primarily on data availability with a focus on wetland attributes commonly thought to influence P processing. Some wetland characteristics that may be commonly expected to influence wetland P processing were necessarily omitted for lack of quantitative data in the monthly timescale (e.g. plant biomass). Altogether, 21 quantitative variables were tested in each regression model.

k-C* model terms

A great deal of research has supported the validity of the k-C* model for application to a variety of wetlands (Kadlec and Knight, 1996; Kadlec and Wallace, 2008). As discussed previously (see Chapters 1 and 2), the model captures some intrinsic relationships between several wetland parameters. For example, as described by the model, increases in the inflow TP concentration result in elevated outflow TP concentrations. The critical model variables inflow TP concentration and *q* were included in the set of variables for regression. The inflow TP concentration multiplied by *q* yields of course the TPALR. The intuitive notion that the outflow TP concentration ought to be correlated to the TPALR has been confirmed by many studies of long-term data (e.g. Qian and Richardson, 1997; Pietro et al., 2009; Kadlec and Wallace, 2008), so the nominal (based on the findings of Chapter 2) TPALR was also included in the regression analysis. Wetlands integrate continuous loads and so outflow concentrations may reflect past operating conditions as well as recent inflow events (Juston and DeBusk, 2006; Reddy and DeLaune, 2008), so both the 1-year and 2-year rolling average $TPALR_N$ were incorporated in the variable set.

Inflow phosphorus fractions

Within wetlands, not all P-containing compounds are treated equally. Soluble reactive P is typically preferentially removed because it is highly bioavailable (Havens et al., 1999, Dierberg et al., 2002, Pietro et al,. 2006). Particulate P removal may be high if the wetland conditions promote settling and retention of the suspended solids (e.g Braskerud, 2002a,b). When water velocities or other turbations inhibit settling, the P associated with particles has to be enzymatically cleaved before biota can access it, so a portion of the PP may progress through the wetland, escaping removal (Dierberg and DeBusk, 2008). Finally, DOP may contain molecules that resist uptake or transformation in the wetland environment. In fact, previous studies of the

Everglades and the STAs have demonstrated poor sequestration of DOP (Proctor et al., 1999; Chimney, 2007). For these reasons, the nature of the inflow TP pool was expected to affect the treatment of that TP, and so the relative proportions of each fraction were included in the regression variable set.

Wetland age and soil phosphorus

A small but growing number of treatment wetlands have been operated for P removal for time periods longer than a decade (Kadlec and Wallace, 2008), so the longevity of wetlands for sustained, effective P removal remains a matter of investigation. Two well known examples of treatment wetlands with long-term performance data, Houghton Lake in Michigan and the Orlando Easterly Wetland in Florida, provide some insight. Following mesocosm and pilot studies, full scale discharge of wastewater into the Houghton Lake wetland began in 1978 (Kadlec, 1993). Nearly 30 years later, the former sedge meadow was transformed into *Typha* marsh and was still providing positive P removal (Kadlec and Wallace, 2008). Kadlec and Wallace (2008) note that although Richardson and Marshall (1986) predicted P “saturation” of the wetland following a total loading of 1.0-1.5 g/m^2, the wetland still provided P mass removal exceeding 80% after cumulative loading of 63 g/m^2. However, the percent removal was slightly lower and much more variable in the most recent 10 years of operation than in the previous 20 years. This variation was attributed to changes in site hydrology and hydraulics (Kadlec and Wallace, 2008).

Similarly, the Orlando Easterly Wetland successfully polished tertiary wastewater from the city of Orlando, Florida, from 1988 until 2003 (Sees and Jackson, 2001; Kadlec and Wallace, 2008). After 10 years of operation, a strong seasonal trend developed in the outflow TP concentration, resulting in unacceptably poor P removal effectiveness in some winter months (Wang et al., 2006). A series of studies identified that both sediment P recycling (White et al.,

2002) and hydraulic inefficiencies (Martinez and Wise, 2003) contributed to the observed reduction in P removal performance. A rejuvenation project in 2002-2003 that included sediment removal and earthwork to increase hydraulic efficiency immediately boosted P removal performance (Wang et al., 2006).

The changes in performance after long-term operation observed in the two preceding examples justify the inclusion of wetland age in the multiple regression exercises. As Wang et al. (2006) alluded to by their consideration of a host of studies to diagnose the problems experienced by the Orlando Easterly Wetland, wetland age is a “lumped” parameter, integrating the effects of many wetland characteristics that change with time (e.g. soil P, internal hydraulics and vegetation characteristics). Because soil P, in particular, is known to influence the P concentration of the overlying water (White et al., 2003; Reddy and DeLaune, 2008), it was included in the regression analyses in an effort to isolate the integrated effects of age. Data for internal hydraulics and vegetation in the STAs were not available at a temporal scale useful for this analysis.

Calcium and pH

Phosphorus is well known to co-precipitate with Ca in aquatic systems and wetlands (e.g. House and Donaldson, 1986; Diaz et al., 1994; Hartley et al., 1997; Scinto, 1997). In their review of the literature on the topic, Reddy and DeLaune (2008) state “retention of inorganic phosphorus by precipitation will be significant in waters with high Ca^{2+} and alkalinity.” Indeed, in Everglades marsh soils, the accumulation of P was correlated with the accumulation of Ca, providing possible evidence of Ca-P interactions (Reddy et al., 1993). Therefore, inflow Ca concentration, Ca ALR, and Ca mass removal ($M/L^2/T$) were added to regression analysis to investigate the effects of possible differences in Ca supply and processing among the STAs. In addition, inflow and outflow pH were included in recognition of the pH dependency of Ca precipitates (Diaz et al., 1994).

Water temperature

The rates of many microbial processes relevant to the wetland P processing are temperature dependent. For example, rates of decomposition of Everglades histosols increased dramatically with increasing temperatures (Volk, 1973). Indeed, the release of soluble P from an organic wetland soil was strongly dependent on temperature (Kadlec and Reddy, 2001). By these bases it may be expected that P removal in the STAs would also show some temperature dependence, but previous studies have suggested relatively little influence of temperature on measured P removal in wetlands (Kadlec and Reddy, 2001; Kadlec and Wallace, 2008). Nonetheless, inflow and outflow water temperature were incorporated in the multiple regression to increase the comprehensiveness of this study.

Relative wetted area and water depth

The biogeochemical influences of RWA_D are discussed in Chapter 2. In that chapter it was found that the RWA_D was very nearly 1.0 in the STAs, and therefore no significant biogeochemical impacts of the wetted area were detected. However, RWA_D was included in the regression exercise in the event that it offered some explanatory power when combined with other wetland characteristics. The findings of Chapter 2 also indicated that, though infrequent, draw-down/re-flood events were important determinants of the outflow TP concentration. They were therefore also included in the multiple regression analysis.

Water depth influences the wetland characteristics and processes such as vegetation types, internal hydraulics and oxygen diffusion (Kadlec and Wallace, 2008). Studies on the integrated effect of water depth on P removal in wetlands associated with the STA project have produced unclear results; at high P concentrations, depth inhibited removal for cattails (Chimney et al.,

2004) and SAV (Jorge et al., 2002), but did not produce a pronounced deleterious effect at low P concentrations. Despite this, the individual biogeochemical effects of water depth in wetlands call for its inclusion in the multiple regression investigation.

Results and Discussion

Outflow Total Phosphorus Concentration: All Cells

The results of the variable-selection procedure are presented in Table 4-1 and Figure 4-1. Altogether, only about 32% of the total variability in the monthly outflow TP concentration was explained by the final 5-variable model. The relatively poor explanatory power of this model was unexpected since factors known to influence treatment wetland outflow concentration (e.g. inflow TP concentration) (Kadlec and Wallace, 2008) were included in the selection process. However, this finding was congruent with the very weak connection found between the TPALR and the outflow TP concentration in most cells (demonstrated in Chapter 3).

The independent variables included in the final model were (in order of selection) inflow TP concentration, ΔWA_D, τ, wetland age and inflow Ca concentration. When added to these five, one other variable, inflow pH, showed a significant effect on the outflow TP concentration. However, it did not increase the strength of the model fit to the data, and was excluded for parsimony. Estimates of the parameters (coefficients) for each explanatory factor in the final five-variable model are shown in Table 4-2. These values may be interpreted as the number of units of change in the outflow TP concentration reflecting one unit of change in the subject variable, holding the other wetland characteristics constant. The precise values of these estimates are somewhat sample-dependent (i.e. they would change with the inclusion of an additional data year) and change with the introduction or removal of other variables in the model. The relative magnitudes (within parameters of similar units) and signs (positive or negative) are of more value for interpretation.

At every level of complexity, the inclusion of the cell effects contributed a significant portion of explanatory power to the model. In fact, this additional variability explained in the outflow TP concentration appeared to be additive with the variance accounted for by the included wetland attributes. Therefore, the wetland characteristics accounting for observed differences in outflow concentration across cells were evidently not considered in this study. The reduction in r^2 after the inclusion of the fifth variable was a result of marked co-linearity between the cell effects and the wetland characteristics, penalized by the adjusted r^2.

Among the five variables in the outflow TP concentration model, several findings were of interest. First, the relationship between inflow concentration and outflow concentration was positive, as expected from Equation (1-19). However, the inflow concentration accounted for only 20% of the variability in the outflow concentration, in agreement with the poor outflow TP concentration-TPALR correlations found in Chapter 3, and exposing the relative influence of other wetland attributes. Second, as suggested in Chapter 2, the positive coefficient associated with changes in WA confirmed that months of re-flooding tended to have higher outflow concentrations. Third, increases in inflow Ca concentration slightly decreased the outflow TP concentration, an expected relationship based on many studies of the Ca-P interactions in South Florida wetlands (e.g. Reddy et al., 1993; Dierberg et al., 2002). However, within this dataset, the effect of the varying inflow Ca concentrations was minor relative to the influence of the inflow TP concentration; the relative impact of increasing the inflow Ca concentration 1.0 mg/L was 3 orders of magnitude less than the effect of a 1.0 mg/L increase in the inflow TP concentration.

Fourth, outflow concentrations tended to increase with wetland age. This finding, if it can be satisfactorily corroborated, has undesirable implications for the ability of the STAs to produce low outflow concentrations over time. For example, P removal in a large municipal treatment wetland in Orlando, Florida started to flag after 13 years of operation resulting in a massive rejuvenation project including muck removal and other significant earthworks (Wang et al., 2006). Indeed, sediment removal projects have also been undertaken in STA-1W, the longest running STA, though not directly in response to declining P removal (Pietro et al., 2008). If ultimately necessary in additional STAs as they age, maintenance requirements of this nature will undoubtedly reduce the cost effectiveness of the STA project. However, wetland age is likely a lumped term, containing simultaneously the effects soil P concentration and other soil characteristics, plant biomass P concentration and possibly unknown others. Effectively combating any deleterious effects associated with aging STAs will require the evaluation of the isolated effects of each of these factors.

Finally, the positive correlation between τ and outflow TP concentration was surprising. This suggested that months with longer residence times produced relatively higher outflow concentrations. While contrary to the logic of rate-based reaction models of P reduction (e.g. the k-C* model), an explanation may lie in the findings of Chapter 3. It was determined that, in the majority of STA cells, the outflow TP concentration was independent of the TPALR and therefore, it was proposed, expressed the apparent background concentration. In this case then, residence times were generally sufficient to accommodate all potential P removal. Thus, it is hypothesized that any extension of the τ beyond that needed to achieve maximum treatment of inflow P simply expanded the opportunity for autochthonous P production, resulting in the slight positive relationship between the outflow TP concentration and τ.

Outflow Total Phosphorus Concentration: Cells with Non-significant *r*'-values

The variable selection procedure resulted in a trivariate model that explained about 54% of the variability in the monthly outflow TP concentration from cells with non-significant *r*'-values.

The final model included the following factors: change in RWA_D, 1-year rolling average TPALR, and wetland age. The number of variables included was limited to three because no additional factor explained a significant (p=0.05) portion of the variability in the dependent term.

The regression model considering only the cells with non-significant r'-values was different from the model for all STA cells in one considerable way. As expected, the inflow TP concentration was no longer included in the model. The presence of this term in the model for all cells was due only to the inclusion of those four cells (Cells 1-4 of STA-1W) that had previously demonstrated a correlation between inflow and outflow TP concentration.

Two important interpretations may be drawn from the three variables selected for this model. First, the movement of ΔRWA_D to the forefront reinforces earlier findings of its significance in the STAs. Though infrequent, large re-flood events appear to be one of the most powerful and predictable biogeochemical processes in the STAs. Second, the inclusion of both the 1-year rolling average TPALR and wetland age indicates that the long-term operation of these STAs plays a measurable role in their short-term performance. Both of these terms had positive coefficients meaning that the monthly outflow TP concentration tended to increase both in response to large loads throughout the preceding year and as the wetlands aged. Evidently, even though these wetlands assimilate P quickly enough to disassociate the monthly outflow from the monthly inflow concentration, the apparent background concentration is still subject to the influence of longer-term loading. A wetland achieving apparent background concentrations could presumably receive additional loads without experiencing reciprocal elevations in outflow concentration. That notion is countered by the apparent dependence of the background concentration on long-term loads. Therefore, additional loads may be expected to *eventually* increase the outflow concentration, even if inflow and outflow concentrations remained independent.

Outflow Total Phosphorus Concentration: Single Cell

This and other works have clearly established the cell-to-cell variability in performance in the STAs (e.g. Juston and DeBusk, 2006; Pietro et al., 2008). The multiple regression exercises in this chapter presumed that variation in a particular wetland characteristic would have the same relative effect on treatment performance regardless of whether the change was observed between two different cells, or across time in a single cell. Because the results of the multi-cell regressions for outflow TP concentration were not wholly satisfying (i.e. the final adjusted r^2-values were not above 0.54 and most included variables explained trivial proportions of the variance), it was hoped that additional clarity would be gained by regressing the data from a single cell.

Cell 1 from STA-1W was selected for this exercise because it had the largest number of data months (n=70) that had observations for each of the 21 tested variables. The final model had an adjusted r^2 of about 0.54 and included only two independent variables, inflow TP concentration and wetland age (Table 4-5). When added to these two factors, no additional variable explained a significant portion of the variability in outflow TP concentration.

This single-cell regression provided little additional information. A significant correlation between inflow and outflow TP concentrations in STA-1W Cell 1 was established in Chapter 3, so the inclusion of inflow TP concentration was expected in the final model. Not surprisingly, the inflow TP concentration term contributed much more to this single-cell regression than it did in the previous exercise that included cells with both significant and non-significant *r*’-values; the univariate regression model including only inflow TP concentration had an adjusted r^2 of 0.38 for STA-1W Cell 1 data only and an adjusted r^2 of 0.20 for data from all cells. Serious management implications arise when wetland age appears in the regression model with a positive coefficient, but these are discussed previously in this chapter, as well as Chapter 5.

Total Phosphorus Areal Settling Rate: All Cells

The results of the variable selection procedure are presented in Table 4-3 and Figure 4-2. Altogether, the final six-variable model explained about 51% of the variability in the monthly TP areal settling rate. The first variable added to the model, q_N, accounted for the first 40% while, in total, the next five variables, inflow DOP fraction, inflow PP fraction, outflow temperature and $TPALR_N$, increased the r^2 of the model only about 0.10. The importance and influence of q_N was reflected in the relatively high r^2 of the single-variable models with $TPALR_N$ and Ca ALR_N. Variable-inclusion was stopped after six factors because the addition of the last term, $TPALR_N$, increased the explanatory power of the model by less than 1%. The r^2 of the final model (0.512) was unsatisfactory, considering the effort invested in collection and compilation of the extensive dataset. The declining disparity with increasing model complexity between the r^2-values of the models with and without the inclusion of the cell effects suggests that the six wetland attributes in the final model explained a portion of the variability due to cell-to-cell differences. Each additional factor accounted for a small portion of this variance, and the settling rate differences across cells were apparently not due to a single wetland characteristic.

Estimates of the parameters (coefficients) for each explanatory factor in the final six-variable model are shown in Table 4-4. As with the outflow concentration model, these values may be interpreted as the number of units of change in the TP areal settling rate reflecting one unit of change in the subject variable, holding the other wetland characteristics constant. As before, the relative magnitudes (within parameters of similar units) and signs (positive or negative) are of primary interest for interpretation.

The set of variables selected for the final model was noteworthy for several reasons. First, as noted earlier, q_N was the primary determinant of the monthly settling rate. Months with high hydraulic loading tended to have higher k_{TP}-values, holding all else constant. As with the relatively *poor* relationship between inflow and outflow TP concentration, this is likely a result of the Chapter 3 finding that the outflow TP concentration was independent of the TPALR in most cells. The implication that follows from that independence, that the outflow concentration reflected an apparent background concentration, and thus that maximum potential removal occurred in most months, means that the magnitude of the areal mass removal ought to have been based more or less strictly on the loading rate. This was evidenced by the inclusion of both q_N and $TPALR_N$ in the final model.

Second, the negative coefficients associated with both the inflow DOP and PP fractions confirm, primarily, that of the three P fractions, the STAs most effectively remove SRP. Possibly the independent effects of DOP and PP were such that the information contributed to the model by these two fractions was more useful than simply providing the SRP fraction (SRP = TP – PP – DOP).

Third, Pietro et al. (2009) found a negative relationship between POR outflow TP concentration and POR k_{TP}-value, with lower concentrations generally produced from cells with higher settling rates. That interaction may have been expressed in these data through the age term. While increasing wetland age tended to increase the outflow TP concentration, older cells had a greater likelihood of having lower k_{TP}-values. As with the outflow concentration model, age likely contains the combined effects of a variety of wetland features that must be separated for a thorough interpretation and assessment of the implications for the STAs.

Finally, that the TP settling rate was positively related to the outflow water temperature was expected. Kadlec and Wallace (2008) reviewed the matter and their conclusion closely matched the result of this study; the TP settling rate tends to be slightly dependent on temperature, but temperature explains very little variance in the short-term k_{TP}-value.

Total Phosphorus Areal Settling Rate: Single Cell

As was done for outflow TP concentration, a multiple regression model of k_{TP} was assembled for the monthly data from STA-1W Cell 1. The final model included only the terms water depth and wetland age and had an adjusted r^2 of only 0.18 (Table 4-8). The selection of depth as the first factor in the model was not expected; this was the only final model in this study in which it appeared. Apparently, however, this was another expression of the dependence of k_{TP} on q that was observed in the exercise that included all cells. In STA-1W Cell 1, water depth and q were highly collinear (r=0.686, p<0.0001, n=94). It is unclear why depth proved to be a better regressor than q. Once again wetland age was a significant contributor of explained variance. The negative coefficient indicated that the monthly calculated settling rate declined as this cell aged, though the poor fit of this model (low r^2) undermines the strength of any conclusions drawn from it. Note the discussion above in this chapter, as well as in Chapter 5 on the management implications of aging wetlands.

Limitations and Future Application of the Multiple Regression Technique

Multiple regression is attractive for analysis of the deterministic factors in wetlands because it partitions explanatory power among many variables, allowing the isolation of the effects of particular wetland characteristics. The STAs are exceptionally well suited for this technique because of the breadth and quality of the data available. However, the ability to assess a large number of factors simultaneously introduces a significant limitation to the technique. Multiple regression can only consider observations for which valid data are available for every variable included in the model being tested. This can (and in the case of the dataset considered here, did) result in loss of potentially valuable information. As model complexity increased, so did the likelihood of encountering a variable, within a given observation, for which the value had been screened.

Also, the regression techniques as applied here were limited to assessing linear relationships between the dependent and independent variables. Non-linear relationships commonly exist among wetland data at different time scales (e.g. between POR outflow TP concentration and TPALR in Pietro et al., 2009). Potentially this study failed to capture non-linear, but important, relationships within this dataset.

As mentioned previously, this investigation was intended to serve as a first step toward identifying wetland characteristics important to P treatment. Future researchers may contemplate several considerations to advance this technique.

The inclusion of additional wetland attributes as model variables not considered in this study should be a first priority. The “low-hanging fruit” consist of both unique additional variables (e.g. herbicide application or dissolved oxygen) and further permutations of the data included here (e.g. cumulative PP areal loading). Quite possibly though, data for key variables are not currently being collected altogether or at useful spatial and temporal resolutions. Undoubtedly, any call for additional data collection at the massive scale of the STAs would need to be well defended by findings in the literature and potentially even lab- or mesocosm-level studies.

Second, new and existing data should be investigated at additional time scales. Some factors (e.g. soil P or plant biomass) may not vary sufficiently over short (monthly) time scales for their effects on P treatment to be captured by regression techniques. Quarterly, annual and

POR averaging periods are suggested, acknowledging that each reduction in temporal resolution will reduce the available number of observations.

Finally, it is recommended to use multiple regression to investigate possible interactions between wetland characteristics. For example, hypothetically, the effect of depth on P treatment could differ between vegetation types. Including interaction terms complicates regression efforts, and it is suggested that such an investigation be initiated with expected interactions (e.g. Ca concentration and pH), and expanded to include unforeseen interactions if necessary.

Conclusions

Within the data available for this analysis, fluctuations in the monthly outflow TP concentration and the monthly TP areal settling rate were relatively poorly explained by any of the 21 wetland characteristics tested. In combination, the five variables inflow TP concentration, ΔWA_D, τ, wetland age and inflow Ca concentration accounted for about 32% of the variability in the monthly outflow TP concentration. About 51% of the variability in the monthly TP areal settling rate was explained by the linear model containing the six parameters q_N, inflow DOP fraction, inflow PP fraction, wetland age, outflow water temperature and $TPALR_N$. In both cases, the bulk of the explained variability was accounted for by single wetland characteristics; inflow TP concentration most strongly controlled outflow TP concentration and the settling rate was most closely related to the q_N. In both models, each of the remaining variables contributed meagerly to the r^2. The guiding hypothesis, that the tested variables would *significantly* explain the variance in the outflow TP concentration and the TP areal settling rate was rejected, in spirit if not in letter, by the findings of this chapter.

The relatively large amounts of unexplained variance and the distributions of the resolved variability in both tested dependent variables support several important conclusions. First, while

Chapter 3 demonstrated the importance of identifying appropriate values or functions for C* for each STA cell, this chapter revealed the challenge of doing so. Second, it is likely that additional wetland characteristics not quantified in this study were and are influential on the short-term outflow TP concentration and the TP settling rate. Although fully accounting for all the wetland attributes that cause these performance indices to vary (e.g. $r^2 = 1.0$) is the conceptual goal, all the error accumulating from measurement, inflow-outflow lag due to positive τ, and the limitations of multiple linear regression will manifest as unexplained variance. The relative proportions of the unresolved variability in this study contributed by missing variables and other sources of error remain undetermined. Third, the short-term measured outcomes of wetland P processing, which are known to be quite complex, may in fact depend on such an array of wetland attributes that even a majority of the variability may not be explained by only a handful of measured traits. The small individual contributions of most of the variables examined herein attests to this conclusion. In this case, the data collection and processing required to substantially or fully explain the variability in, say, outflow TP concentration, would almost certainly surpass the usefulness of this information.

Readers interested in practical applications of the interpretations in this chapter regarding the potential to improve TP removal performance may find the conclusions of this chapter unsatisfying, particularly with respect to the short-term outflow TP concentration. First, the factor that explained the majority of the variance in the monthly outflow concentration (inflow TP concentration) is not reasonably subject to manipulation by STA managers. Conceivably, inflow concentrations could be lowered by reducing P losses from upstream sources, but this approach falls outside the realm of improving wetland *treatment* effectiveness. Second, though the long-term outflow TP concentration and k_{TP}-value were negatively associated (Pietro et al., 2009), attempts to increase the settling rate by increasing *q* (the primary driver of the settling rate) should not be expected to depress the outflow concentration. Finally, the relative lack of influence (with regard to improvements in r^2) of each of the additional variables that contributed to the outflow TP concentration and the settling rate suggests that modifying any of them would be unlikely to result in cost-effective reductions in outflow concentrations.

Table 4-1. Coefficients of determination (r^2) of multiple linear regression models explaining the monthly outflow total phosphorus concentration in all cells. The column heading indicates the complexity (number of variables included) in the model. For a particular level of complexity, a given value is the r^2 for the model containing that variable and all the variables indicated by "X". The highest r^2-value in each column is boldfaced.

Variable	Number of variables included in model: 1	2	3	4	5	6
Inflow TP concentration	**0.198**	X	X	X	X	X
TPALR[A]-nominal	0.070	--	--	0.287	0.304	--
1-yr rolling average TPALR	0.014	--	0.279	0.301	--	--
2-yr rolling average TPALR	--	--	--	0.260	--	--
Inflow SRP[A] fraction	0.004	--	--	--	--	--
Inflow DOP[A] fraction	--	--	--	--	--	--
Inflow PP[A] fraction	0.010	0.225	0.268	0.276	--	--
Inflow Ca[A] concentration	0.021	0.215	0.266	0.290	**0.323**	X
Ca ALR - nominal	--	--	--	--	--	--
Ca areal mass removal rate	--	--	--	--	--	--
Wetland age	0.032	0.212	0.258	**0.301**	X	X
q[A] - nominal	--	--	--	--	--	--
τ[A]	--	0.224	**0.281**	X	X	X
Mean water depth	0.003	--	--	--	--	--
Soil TP concentration	--	--	--	--	--	--
Inflow pH	0.004	0.212	0.258	0.289	0.303	**0.323**
Outflow pH	--	--	0.245	--	--	--
Inflow water temperature	--	--	0.250	--	--	--
Outflow water temperature	--	--	0.243	--	--	--
WA_D[A]	0.004	0.205	0.253	0.289	--	--
Change in WA_D	0.028	**0.247**	X	X	X	X

[A]TPALR = TP areal loading rate; SRP = soluble reactive P; DOP = dissolved organic P; PP = particulate P; Ca = calcium; q = hydraulic loading rate; τ = hydraulic residence time; WA_D = wetted area, determined by the elevation distribution

Table 4-2. Estimates of parameters for the model explaining monthly outflow total phosphorus (TP) concentration in all cells.

Variable	Units	Parameter estimate (β)	Probability (*p*) that β = 0
Outflow TP concentration	mg/L	--	--
Inflow TP concentration	mg/L	0.4387	<0.0001
Change in wetted area	%	0.2443	<0.0001
Hydraulic residence time	d	0.0004	<0.0001
Wetland age	yr	0.0051	<0.0001
Inflow Ca concentration	mg/L	-0.0004	<0.0001

Table 4-3. Coefficients of determination (r^2) of multiple linear regression models explaining the monthly outflow total phosphorus (TP) concentration in all cells with non-significant r'-values. The column heading indicates the complexity (number of variables included) in the model. For a particular level of complexity, a given value is the r^2 for the model containing that variable and all the variables indicated by "X". The highest r^2-value in each column is boldfaced.

	Number of variables included in model		
Variable	1	2	3
Inflow TP concentration	0.056	0.477	--
TPALR[A]- nominal	0.014	0.445	--
1-yr rolling average TPALR	--	**0.523**	X
2-yr rolling average TPALR	--	--	--
Inflow SRP[A] fraction	0.032	--	--
Inflow DOP[A] fraction	0.019	--	--
Inflow PP[A] fraction	0.042	--	--
Inflow Ca[A] concentration	--	--	--
Ca ALR - nominal	--	--	--
Ca areal mass removal rate	0.016	--	--
Wetland age	0.093	0.470	**0.537**
q[A] - nominal	--	0.443	--
τ[A]	--	--	--
Mean water depth	0.116	0.490	--
Soil TP concentration	0.133	--	--
Inflow pH	0.032	0.425	0.459
Outflow pH	0.026	--	--
Inflow water temperature	0.028	--	--
Outflow water temperature	0.024	--	--
WA_D[A]	0.014	--	--
Change in WA_D	**0.437**	X	X

[A]TPALR = TP areal loading rate; SRP = soluble reactive P; DOP = dissolved organic P; PP = particulate P; Ca = calcium; q = hydraulic loading rate; τ = hydraulic residence time; WA_D = wetted area, determined by the elevation distribution

Table 4-4. Estimates of parameters for the model explaining outflow total phosphorus (TP) concentration in all cells with non-significant *r*'-values.

Variable	Units	Parameter estimate (β)	Probability (*p*) that β = 0
Outflow TP concentration	mg/L	--	--
Change in wetted area	%	0.2080	<0.0001
1-yr rolling average TPALR	$g/m^2/yr$	0.0365	0.0378
Wetland age	yr	0.0018	0.0068

Table 4-5. Estimates of parameters for the model explaining outflow total phosphorus (TP) concentration in STA-1W Cell 1.

Variable	Units	Parameter estimate (β)	Probability (*p*) that β = 0
Outflow TP concentration	mg/L	--	--
Inflow TP concentration	mg/L	0.4254	<0.0001
Wetland age	yr	0.0149	<0.0001

Table 4-6. Coefficients of determination (r^2) of multiple linear regression models explaining the monthly total phosphorus (TP) areal settling rate in all cells. The column heading indicates the complexity (number of variables included) in the model. For a particular level of complexity, a given value is the r^2 for the model containing that variable and all the variables indicated by "X". The highest r^2-value in each column is boldfaced.

	Number of variables included in model					
Variable	1	2	3	4	5	6
Inflow TP concentration	0.030	0.397	0.446	--	--	0.506
TPALR[A]-nominal	0.277	0.395	0.448	0.474	0.489	**0.512**
1-yr rolling average TPALR	0.041	0.416	0.447	0.478	0.484	--
2-yr rolling average TPALR	0.044	0.393	--	--	--	--
Inflow SRP[A] fraction	0.028	0.422	0.461	--	--	--
Inflow DOP[A] fraction	0.017	**0.432**	X	X	X	X
Inflow PP[A] fraction	0.026	0.401	**0.469**	X	X	X
Inflow Ca[A] concentration	0.008	0.411	--	--	--	--
Ca ALR - nominal	0.346	--	--	--	--	--
Ca areal mass removal rate	--	0.401	0.462	--	--	--
Wetland age	--	0.421	0.458	0.481	**0.503**	X
q[A] - nominal	**0.391**	X	X	X	X	X
τ[A]	0.117	0.387	0.437	--	--	--
Mean water depth	0.036	--	0.439	--	--	--
Soil TP concentration	--	0.389	0.443	--	--	--
Inflow pH	0.026	0.393	0.448	0.476	0.490	--
Outflow pH	--	--	--	--	--	--
Inflow water temperature	0.038	0.396	0.445	--	0.489	0.504
Outflow water temperature	0.058	0.416	0.456	**0.486**	X	X
WA_D[A]	--	0.402	0.447	--	0.488	--
Change in WA_D	0.003	0.395	0.446	0.478	0.495	0.511

[A]TPALR = TP areal loading rate; SRP = soluble reactive P; DOP = dissolved organic P; PP = particulate P; Ca = calcium; q = hydraulic loading rate; τ = hydraulic residence time; WA_D = wetted area, determined by the elevation distribution

Table 4-7. Estimates of parameters for the model explaining total phosphorus areal settling rate in all cells.

Variable	Units	Parameter estimate (β)	Probability (p) that β = 0
TP areal settling rate	m/yr	--	--
Hydraulic loading rate - nominal	m/mo	6.6940	<0.0001
Inflow DOP fraction	%	-33.7914	<0.0001
Inflow PP fraction	%	-13.2197	0.0012
Wetland age	yr	-1.8512	<0.0001
Outflow water temperature	°C	0.6224	0.0064
TP areal loading rate - nominal	$g/m^2/yr$	11.0970	0.0002

[A]TP = total phosphrous; DOP = dissolved organic P; PP = particulate P

Table 4-8. Estimates of parameters for the model explaining monthly total phosphorus (TP) areal settling rate in STA-1W Cell 1.

Variable	Units	Parameter estimate (β)	Probability (*p*) that β = 0
TP areal settling rate	m/yr	--	--
Water depth	m	50.5583	0.0001
Wetland age	yr	-1.7433	0.0221

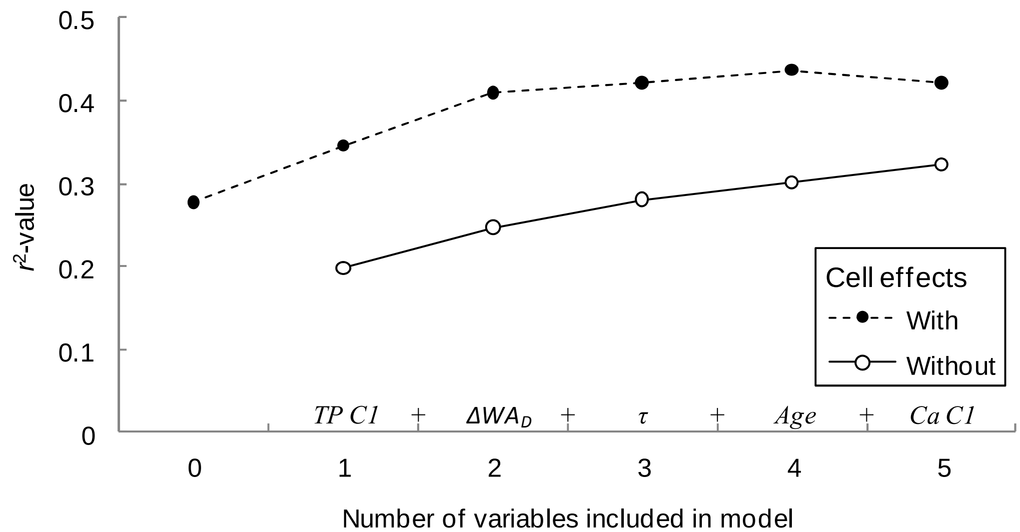


Figure 4-1. Changes in the coefficient of determination (r^2) with increasing complexity of the model explaining monthly outflow TP concentration in all cells. The models are shown with and without the effects of the period-of-record cell means. TP $C1$ = inflow TP concentration, ΔWA_D = change in monthly wetted area, τ = nominal hydraulic residence time, Age = wetland age, Ca $C1$ = inflow calcium concentration.

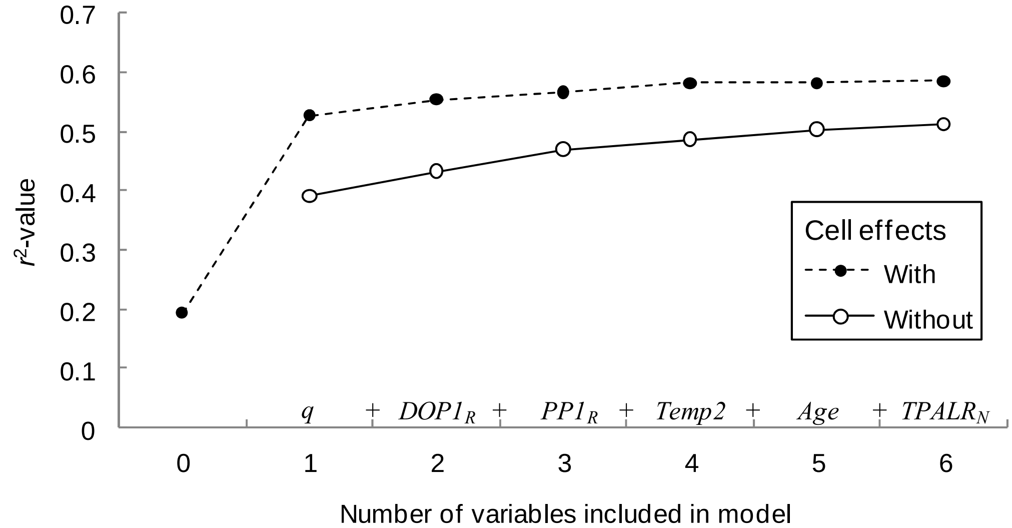


Figure 4-2. Changes in the coefficient of determination (r^2) with increasing model complexity of the model explaining the monthly total phosphorus areal settling rate in all cells. The models are shown with and without the effects of the period-of-record cell means. q = hydraulic loading rate, $DOP1_R$ = inflow dissolved organic P fraction, $PP1_R$ = inflow particulate P fraction, Temp2 = inflow water temperature, Age = wetland age, $TPALR_N$ = nominal total phosphorus areal loading rate.

CHAPTER 5
CONCLUSIONS

This work attempted to address several important questions regarding the operation and performance of the Stormwater Treatment Areas in South Florida. The management of these extensive constructed wetlands is a massive expenditure for the SFWMD and is a major contributor to the reduction of P loads to the Florida Everglades.

The presence of marked elevation gradients and time-variable water levels in some STA cells raised concern that estimates of the hydraulic and TP areal loading rates were inaccurate due to incomplete flooding of the nominal treatment areas. It was demonstrated that the occasions when the relative wetted area was substantially less than 100% were infrequent, and did not significantly increase the TPALR in any of the STAs, suggesting that the nominal treatment area was satisfactory for loading rate calculations. The outflow TP concentration did show a positive correlation to the magnitude of re-flooding, within the months with large re-flood events, an effect confirmed to be significant by multiple regression modeling. Maintaining flooding as to reduce re-wetting events would prevent these occasional pulses of outflow P but this phenomenon was important in less than 5% of non-screened months. It was also shown that poor performance in certain cells (elevated outflow TP concentrations relative to inflow TPALR) was shown not to be an artifact of the TPALR calculation, validating the need for additional work to diagnose those factors contributing to performance in the STAs.

The monthly outflow TP concentration was shown to be uncorrelated to the monthly TPALR (r') in most cells. This independence was not a function of vegetation type or the magnitude of the TPALR. It was hypothesized that the Damköhler number (Da = k/q) was sufficiently high as to remove this correlation, implying that the outflow concentration was controlled primarily by the background concentration. The monthly outflow TP concentration from the cells with non-significant *r*' was not determined by the composition of the inflow TP pool nor by the outflow water temperature. More extensive efforts to isolate the factors controlling the apparent background concentrations were justified because accurate estimates of C* appeared necessary for the successful employment of the k-C* model in wetlands (i.e. most STA cells) with high Da-values.

Regression Variables

Each of the 21 factors was specifically included because either mathematical reasoning (in the case of those terms related by the k-C* model) or previously documented studies suggested their relevance to wetland P cycling (e.g. Ca, pH and temperature). Therefore, it is important to consider the conditions that led to inclusion or rejection of each in the models assembled in this work.

Inflow Total Phosphorus Concentration

The k-C* model (Kadlec and Knight, 1996), introduced in Chapter 2, has been found by many investigators to satisfactorily describe pollutant reduction in wetlands. When using that model to consider the outflow TP concentration, the inflow TP concentration is an important input term (which makes sound intuitive sense). Chapter 3 showed that in the majority of the cells in the STAs, the outflow TP concentration in any given month was unrelated to the conditions of the inflow water in that month. This situation suggests that P removal in the most of the STAs is not limited by residence time (discussed further in Chapter 3), but does imply that the inflow TP concentration ought not to be useful in describing the short-term outflow TP concentration. Indeed, the inflow TP concentration was only important to the regression model that considered outflow TP concentration data from cells that were known to have positive correlations between inflow and outflow TP concentrations. Clearly, the short-term inflow TP concentration will not be an important determinant of the outflow TP concentration in any wetland system whose P reduction is not limited by residence time.

Hydraulic and Total Phosphorus Loading Rates

The hydraulic (q) and total phosphorus loading rates came to bear in interesting ways in the final regression models established in Chapter 4. First, both the monthly q and $TPALR_N$ contributed positively to the monthly areal settling rate when all cells of the STAs were considered together, suggesting that k_{TP} is, in the STAs, a measure of P removal power rather than efficiency. This idea is in line with the previously discussed notion that the observed outflow TP concentrations are limited more by the apparent background concentration than by insufficient contact time. In this case, a hypothetical additional packet of water (thus additional P) does not increase the outflow concentration, but does lead to increased P mass removed. Second, the 1-year rolling average TPALR was the second most important factor in determining the monthly outflow TP concentration from those cells with non-significant r'-values. That is, even when the short-term outflow concentration was apparently independent of the short-term inputs, the long-term loading still influenced the short-term outflow concentration. This is simply a different perspective on the well-understood connection between long-term loading and performance (e.g. Qian and Richardson, 1997; Pietro et al. 2009), but deserves consideration by treatment wetland managers. Increasing loading rates to maximize mass removal in response to the independence of short-term inflow and outflow concentrations may result in a long-term increase in outflow concentrations, visible even in short-term data.

Inflow Phosphorus Fractions

Despite appearing in the final regression model for k_{TP} (data from all cells) the composition of the inflow TP pool did little to affect the measured performance of the STAs. Possibly, the internal transformation and production of the various forms was so substantial as to make the initial P composition irrelevant. This hypothesis gains some support from the finding that residence time did not limit P reduction in most STAs. Regardless of the inflow P composition, additional contact time would not support additional removal of the less-bioavailable DOP and PP. Therefore, the outflow DOP pool, for example, is likely not composed primarily of the same DOP particles that entered the wetland.

Wetland Age and Soil Phosphorus

Wetland age was the only term included in all the final regression models for both outflow TP concentration and k_{TP}. In all cases, the sign on the coefficient indicated decreasing performance (i.e. increasing outflow TP concentrations and decreasing k_{TP}-values) with increasing age. Of course, there are precedents for such a scenario including the Orlando Easterly Wetland in central Florida (Wang et al., 2006) and the impacted zones of WAC-2A in south Florida (DeBusk et al., 2004). Wetland age was such a prominent factor in determining STA performance probably because it is a lumped term, containing simultaneously multiple wetland characteristics that change over time, such as soil P and plant biomass and tissue P. Though wetland managers should anticipate changes in performance as treatment wetlands age, this information is only of real value if the individual variables pooled in the age term can be extracted and evaluated individually. For example, soil P, a wetland parameter expected to change as the wetland ages, was included in the regression analyses, but was not selected for any of the final models. (This analysis should not be taken as conclusive, as the soil P data were ill-suited for evaluation at a monthly time-step.) Therefore, some other characteristic of the STAs was changing with time and caused the broad age term to contribute more information to the regression than the soil P term.

Calcium and pH

Generally, none of the calcium terms included in the multiple regression exercises (inflow Ca concentration, Ca ALR, and Ca mass removal) contributed any explanatory power regarding either outflow TP concentration or TP areal settling rate. The sole exception was the selection of inflow Ca concentration as the fifth variable in the regression model for outflow TP concentration among all cells. Likewise, neither inflow nor outflow pH was selected for inclusion in any model. The chemistry of Ca and P interactions (and the influence of pH) is moderately well understood (e.g. Diaz et al., 2004; Scinto, 1997) and associations between Ca and P have been demonstrated in the field (Reddy et al., 1993). Connecting the process-level dynamics to the field-scale effects has been challenging. Two factors may have contributed to the relative lack of influence of Ca on P observed in this study. First, the amount of P removed from the water column due to interaction with Ca actually may be minimal relative to biological and physical processes. The probability of this being the case is unclear; Ca-P interaction is apparently important in some wetlands (Reddy et al., 1993) but has not been quantified in the STAs. Second, the data possibly failed to capture the Ca-P association. The relatively small proportions of variance explained by most of the considered factors suggest that some of the tested datasets were not suited to analysis at a monthly time-step.

Water Temperature

Kadlec and Wallace (2008) suggest an Arrhenius temperature coefficient of about 1.005 for total P in warm climate wetlands. (Arrehenius coefficients greater than 1.0 indicate improvement in removal performance with increases in temperature and values less than 1.0 denote loss of performance with temperature increases. Values very close to 1.0 imply relatively little temperature dependence.) This value for TP indicates that P removal tends to improve very slightly with increases in water temperature. A temperature term (both inflow and outflow water temperature were considered) was included in the final regression model only for the monthly TP areal settling rate that included all cells. Most likely, the weak temperature dependence of P processing expected for the STAs was obscured by other wetland characteristics.

Relative Wetted Area and Water Depth

The RWA_D was expected to influence P processing primarily by altering the realized loading rates applied to the STAs. Chapter 2 established that the nominal wetted area provided a satisfactory estimate of the actual wetted area for most applications in the STAs. Therefore, the relative unimportance of RWA_D in the regression analyses was anticipated; RWA_D was not selected for any of the final models assembled in this study. Of much more interest from the outset was ΔRWA_D, since great biogeochemical action was expected to associate with dry-down and re-flood events. Indeed, ΔRWA_D was the second variable included in the regression model for outflow TP concentration from all cells and was the factor of primary importance in the explaining variance in the outflow TP concentration from cells with non-significant *r*'-values. Because large re-flood events were fairly infrequent in the STAs (see Chapter 2), these findings indicate that the flushing of P associated with re-flood events is one of the most powerful and predictable biogeochemical processes active in the STAs.

Depth affects the biogeochemistry (and thus P processing) of surface-flow wetlands by regulating oxygen diffusion and changing the hydraulics. However, it was selected for only one regression model developed in this study, where it explained about 14% of the variability in the monthly k_{TP}-value of STA-1W Cell 1. A correlation between q and depth aligned that model with the dependence of the settling rate on the hydraulic loading rate found among all cells. It appears that the other biogeochemical effects of water depth were apparently relatively unimportant to

STA performance, based on the monthly data. The longer-term role of influencing vegetation communities played by water depth was likely not captured by the monthly data.

Future Work

Following the results presented in this work, two major avenues of investigation remain. First, C* needs further elucidation in the STAs. Chapter 3 suggests that the monthly outflow TP concentration from the STAs was more strongly controlled by C* than k_{TP}. This implies the need for accurate estimates of C* when modeling P removal performance in the STAs. Although the outflow concentrations from those cells operating at apparent background concentrations did very with time, it remains unclear whether a function or value will best predict C*.

Second, multiple linear regression was successful in identifying some wetland characteristics that were uniquely important to P processing in the STAs. However, the overall proportions of variance in the dependent variables (monthly outflow TP concentration and monthly TP areal settling rate) that were explained by the regression efforts were unsatisfactory. It is recommended that future multiple regression efforts for the STAs consider non-linearity among the data, as well include additional variables not tested in this study. In particular, 12 of the 21 tested variables concerned water chemistry and hydrology and hydraulics accounted for another five terms. Only one term (soil P) was related to the soil properties and no vegetation data was incorporated. Owing to the relative importance of plants and soil to wetland functions, it is likely that variables regarding these characteristics would be particularly helpful in explaining observed STA performance.

APPENDIX
DATA SCREENING CRITERIA

Variable	Not reported if:
Inflow TP concentration	Inflow volume = 0
Outflow TP concentration	Outflow volume = 0
Inflow SRP concentration	Inflow volume = 0
Outflow SRP concentration	Outflow volume = 0
Inflow DOP concentration	-Inflow SRP concentration or inflow TDP concentration blank -Inflow volume ≤ 0 -Inflow SRP concentration > inflow TPD concentration
Outflow DOP concentration	-Outflow SRP concentration or outflow TDP concentration blank -Outflow volume ≤ 0 -Outflow SRP concentration > outflow TDP concentration
Inflow PP concentration	-Inflow TP concentration or inflow TDP concentration blank -Inflow volume ≤ 0 -Inflow TP concentration > inflow TPD concentration
Outflow PP concentration	-Outflow TP concentration or outflow TDP concentration blank -Outflow volume ≤ 0 -Outflow TP concentration > outflow TDP concentration
Inflow SRP fraction	-Inflow SRP concentration or inflow TP concentration blank or ≤ 0 -Inflow SRP concentration > inflow TP concentration
Outflow SRP fraction	-Outflow SRP concentration or outflow TP concentration blank or ≤ 0 -Outflow SRP concentration > outflow TP concentration
Inflow DOP fraction	-Inflow SRP concentration or inflow TDP concentration blank or ≤ 0 -Inflow SRP concentration > inflow TDP concentration
Outflow DOP fraction	-Outflow SRP concentration or outflow TDP concentration blank or ≤ 0 -Outflow SRP concentration > outflow TDP concentration
Inflow PP fraction	-Inflow TP concentration or inflow TDP concentration blank or ≤ 0 -Inflow TP concentration < inflow TDP concentration
Outflow PP fraction	-Outflow TP concentration or outflow TDP concentration blank or ≤ 0 -Outflow TP concentration < outflow TDP concentration
Areal TP settling rate (k)	Inflow volume, inflow TP concentration, outflow TP concentration or WA_D blank or ≤ 0
TP areal loading rate – nominal	-Inflow TP mass blank -Inflow volume ≤ 0
TP areal loading rate – distribution adjusted	-Inflow TP mass blank -Inflow volume or WA_D ≤ 0
TP areal loading rate – mean adjusted	-Inflow TP mass blank -Inflow volume or WA_N ≤ 0
Inflow Ca concentration	-Inflow Ca mass or inflow volume blank or ≤ 0 -Inflow Ca concentration <= 1

Outflow Ca concentration	-Outflow Ca mass or outflow volume blank or ≤ 0 -Outflow Ca concentration <= 1
Ca areal loading rate – nominal	-Inflow Ca mass blank -Inflow volume ≤ 0
Ca areal loading rate – distribution adjusted	-Inflow Ca mass blank -Inflow volume or $WA_D \leq 0$
Ca areal mass removal rate	Inflow Ca mass, outflow Ca mass or WA_D blank or ≤ 0
Hydraulic loading rate – nominal	Inflow volume blank or ≤ 0
Hydraulic loading rate – distribution adjusted	Inflow volume or WA_D blank or ≤ 0
Hydraulic residence time	-Inflow volume or outflow volume ≤ 0 -Hydraulic residence time ≤ 0 -Hydraulic residence time ≥ 150

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BIOGRAPHICAL SKETCH

Mike Jerauld's passion for the environment, which inspired the undertaking of this advanced degree, was fostered by his experiences fishing, camping and traveling as a child with his parents. His formal education in the field began with the Jupiter Environmental Research and Field Studies Academy at Jupiter High School, in South Florida. Impressed with the urgency of the need to respond to the ever-declining condition of the natural world, Mike earned his Bachelor's degree in Environmental Science from the University of Florida in 2004. His undergraduate studies introduced and developed his awareness of the intimate connection between human and environmental well-being. In 2008, he enrolled in the Soil and Water Science Department at the University of Florida to pursue a Master of Science that would enable him to employ wetlands for the treatment of wastewater. The quality of all aspects of Mike's term in Gainesville was marked best, perhaps, by the four national titles won by the University of Florida football and men's basketball teams, collectively, during his tenure there. In 2009, he married his extraordinary wife, Sarah. After 19 years of education, he now plans to leave academia and try his hand in "the real world."