VOL. 31, NO. 4 WATER RESOURCES BULLETIN
AMERICAN WATER RESOURCES ASSOCIATION AUGUST 1995

DESIGN BASIS FOR EVERGLADES STORMWATER TREATMENT AREAS[1]

William W. Walker, Jr.[2]

ABSTRACT: The State of Florida (1994) has adopted a plan for addressing Everglades eutrophication problems by reducing anthropogenic phosphorus loads. The plan involves implementation of Best Management Practices in agricultural watersheds and construction of regional treatment marshes (Stormwater Treatment Areas or STA's). This paper describes the development, testing, and application of a mass-balance model for sizing STA's to achieve treatment objectives. The model is calibrated and tested against peat and water-column data collected in Water Conservation Area-2A (WCA-2A), where phosphorus dynamics and eutrophication impacts have been intensively studied. The 26-year-average rate of phosphorus accretion in peat is shown to be proportional to average water-column phosphorus concentration, with a proportionality constant of 10.2 m/yr (90 percent Confidence Interval = 8.9 to 11.6 m/yr). Spatial and temporal variations in marsh water-column data suggest that drought-induced recycling of phosphorus was important during periods of low stage in WCA-2A. Maintaining wet conditions will be important to promote phosphorus removal in STA's. Sensitivity analysis of STA performance is conducted over the range of uncertainty in model parameter estimates to assess the adequacy of the model as a basis for STA design.
(KEY TERMS: wetlands; phosphorus; modeling/statistics; stormwater management; peat; nonpoint source pollution; Everglades; eutrophication; wetland treatment.)

INTRODUCTION

Eutrophication induced by anthropogenic phosphorus loads poses a long-term threat to Everglades ecosystems (Belanger *et al.*, 1989; Davis, 1994). The substantial north-south phosphorus gradient in this region reflects location of oligotrophic marshes downstream from agricultural areas and Lake Okeechobee (Figure 1). Impacted areas are largely within the Everglades Water Conservation Areas (WCA's), a system of shallow, wetland reservoirs which discharge primarily to Everglades National Park (ENP). Eutrophication impacts on Loxahatchee National Wildlife Refuge (WCA-1) and ENP are of particular concern. Total phosphorus concentrations range from 100-250 ppb at WCA inflows from the Everglades Agricultural Area to below 10 ppb at remote marsh stations. Native Everglades plant and microbial communities developed under nutrient-poor conditions and rely upon such conditions for their survival (Belanger *et al.*, 1989; Davis, 1994). Symptoms of eutrophication observed in the WCA's include increasing trends in phosphorus concentration (Walker, 1991) and shifts in microbial, macroinvertebrate, and macrophyte communities (Belanger *et al.*, 1989; Davis, 1991, 1994; Nearhoof, 1992; Grimshaw *et al.*, 1993). The most visually-apparent symptoms have included disappearance of native periphyton mats and conversion of native sawgrass to dense cattail stands in enriched areas with sufficient hydroperiod.

A two-phase program designed to address this eutrophication problem is currently being implemented by the South Florida Water Management District (State of Florida, 1994). The ultimate goal is to eliminate nutrient-induced ecological imbalance throughout the WCA's and ENP. The first phase involves application of available technology to reduce phosphorus concentrations at WCA inflows to a long-term, flow-weighted-mean concentration of 50 ppb or less. This interim target has been selected based upon its technical feasibility using an appropriate mix of Agricultural Best Management Practices (BMP's) and treatment marshes (Stormwater Treatment Areas or STA's) (Figure 1). Successful implementation of the first phase will reduce average phosphorus loads to the WCA's by more than 75 percent while providing secondary benefits related to the magnitude, timing,

[1]Paper No. 94139 of the *Water Resources Bulletin.* **Discussions are open until April 1, 1996.**
[2]Environmental Engineer, 1127 Lowell Road, Concord, Massachusetts 01742.

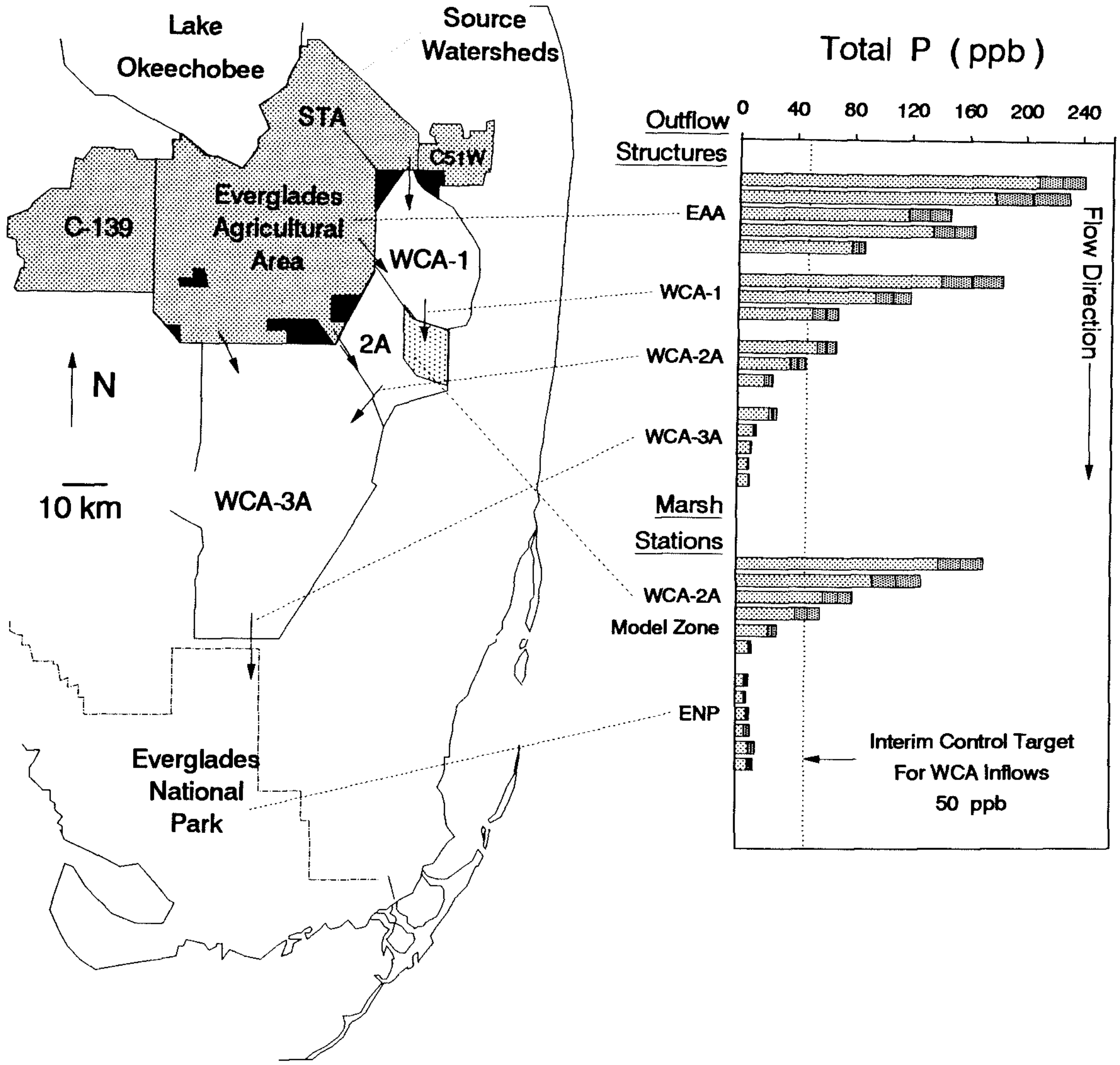

Figure 1. Everglades Phosphorus Gradient. Phosphorus concentrations at WCA inflow/outflow structures and Marsh stations monitored by the South Florida Water Management District between 1973 and 1991 (Germain, 1994). Bars show flow-weighted-mean concentrations ± 1 standard error. Black areas of map show regional Stormwater Treatment Areas (STA's) under design by Burns and McDonnell (1994). Source watersheds for the STA's are in grey. Shaded portion of WCA-2A is used for model development.

and spatial distribution of flow. Because the 50 ppb interim target is more than five times marsh background levels and above concentrations at which ecological impacts have been indicated (Nearhoof, 1992; Grimshaw *et al.*, 1993), a second control phase may be required to achieve ultimate objectives. Treatment levels and technology for the second phase will be determined in future research.

This paper describes the development, testing, and application of a mass-balance model for use in sizing STA's to achieve treatment objectives. The model is calibrated and tested against monitoring data from WCA-2A, where phosphorus distributions in the water column, peat, and plant communities have been intensively studied. Mechanisms controlling phosphorus uptake and recycling are discussed in relation to spatial and temporal patterns identified in the modeling effort and in relation to results of previous field studies. Sensitivity of predicted STA performance to uncertainty in model parameter estimates is examined to assess adequacy as a basis for STA design.

MODEL FORMULATION

The model is developed using data from the 11,550-hectare region of WCA-2A extending 11 km south of the S10 inflow structures along Levee-39 (Figure 2). The S10 structures discharge water from WCA-1 into WCA-2A. Because of their proximity to the EAA and hydraulic characteristics of WCA-1, S10 flows are strongly influenced by agricultural runoff. The substantial north-to-south trophic gradients in this region reflect marsh responses to S10 phosphorus loads. This region of WCA-2A has been used as a model prototype for the following reasons:

1. Availability of historical flow, stage, and water-quality monitoring data collected over a 15-year period.
2. Availability of extensive data on plant communities and on the horizontal and vertical distribution of phosphorus in peat and pore waters.
3. Characteristics similar to STA design conditions (Burns and McDonnell, 1994):

   (a) hydraulic conditions approaching sheet flow (from north to south);
   (b) average phosphorus concentrations ranging from ~150 ppb (north) to < 10 ppb (south); and
   (c) historical periods of continuous inundation at water depths including the STA design range (15 to 122 cm or 0.5 to 4 ft).

Modeling of phosphorus removal in other WCA regions (Figure 1) is complicated by data limitations and hydraulic complexities (mixtures of canal flow, sheet flow, and impounded areas).

A variety of mechanisms regulate phosphorus cycling in Everglades wetlands (Koch and Reddy, 1992; Craft and Richardson,1993a, 1993b; Urban *et al.*, 1993; Davis, 1994). The net rate of phosphorus removal from the water column reflects cycling of phosphorus among important storage compartments, including the water column, plant biomass, surface litter, and soil (Kadlec and Knight, 1995). Accumulation of phosphorus in plant biomass occurs during periods of net vegetation growth. Over long time scales, this accumulation approaches zero as the ecosystem matures and approaches a dynamic equilibrium regulated by hydrologic conditions, nutrient loads, fire, and other environmental factors. Over seasonal and annual time scales, plant communities and phosphorus storage may fluctuate in response to variations in environmental factors such as drought, flood, and fire (Urban *et al.*, 1993).

Achieving net phosphorus removal in the STA's requires burial of phosphorus in accumulating peat as a long-term, sustainable mechanism. Burial of decomposed plant detritus and calcium phosphate precipitation are the two most important mechanisms contributing to phosphorus storage in WCA-2A peat (Koch and Reddy,1992). Rates of peat formation in Everglades marshes tend to be highest in areas which are subject to anthropogenic phosphorus loads and which have extended hydroperiod (Craft and Richardson, 1993). The STA's have been designed and will be operated to avoid dry conditions (Burns and McDonnell, 1994). This strategy is intended to promote peat formation and to avoid drought-induced oxidation and mobilization of stored phosphorus.

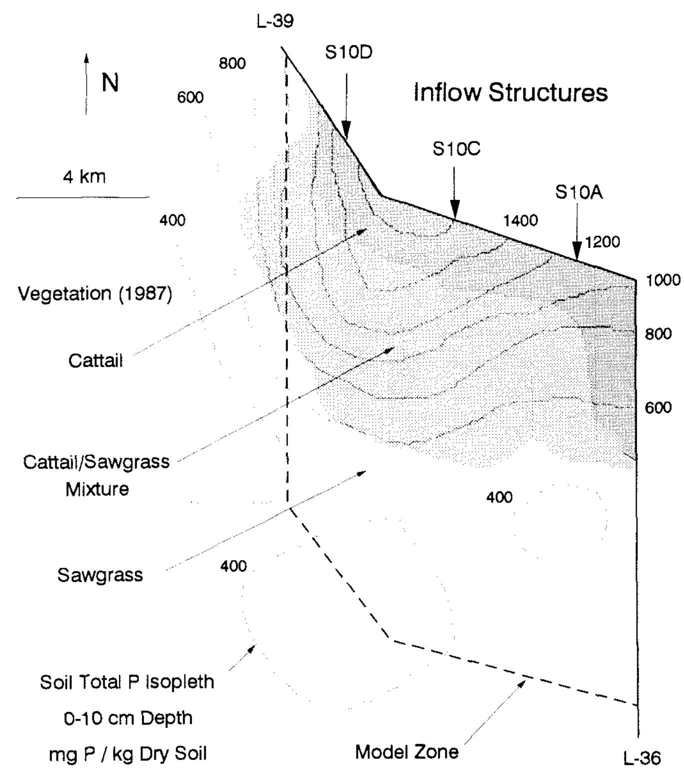

Figure 2. Cattail and Soil Phosphorus Distribution in S-10 Inflow Zone of Water Conservation Area 2A. Figure depicts boundary of model zone, gradients in vegetation (Urban *et al.*, 1993), and gradients in soil phosphorus (Reddy *et al.*, 1993; DeBusk *et al.*, 1994). Regional map is shown in Figure 1.

The model is formulated and calibrated to predict net phosphorus removal resulting from peat accretion. It attempts to predict average phosphorus budgets over a time scale of several years. It is not designed to predict short-term variations attributed to seasonal or hydrologic factors. It is also not designed to reflect initial start-up phases of the STA's, when phosphorus fluxes from stabilization of soils and development of plant communities may be important.

The model consists of coupled water-balance and mass-balance equations representing a steady-state system with sheet-flow hydraulics and first-order phosphorus removal kinetics. Calculations are driven primarily by inflows from the S10 structures and secondarily by atmospheric fluxes (rainfall, evapotranspiration, atmospheric phosphorus loads). Consistent with topographic features and general flow patterns represented by Reddy *et al.* (1991), and Richardson *et al.* (1992), discharges from the S10's are assumed to travel south as sheet flow. The model predicts average water-column concentrations and sediment-phosphorus accretion rates as a function of distance south from Levee-39.

The marsh area upstream from any monitoring location in the model zone is estimated by multiplying the distance south from L-39 by an average width of 10.5 km:

$$A = W\ X \qquad (1)$$

where A = cumulative area downstream from L-39; W = average width of flow path = 10.5 (km); and X = distance south of Levee-39 (km). The 10.5-km width represents the average distance west from Levee-36 to the outer edge of the marsh area affected by the S10ACD discharges (Figure 2). Vegetation maps developed from satellite imagery (Urban *et al.*, 1993) indicate that the western edge of the impact zone in 1987 was between 9.1 km (cattail) and 11.0 km (cattail mixture) west of L-36. Steepest gradients in sediment phosphorus content and sediment pore-water content occur between two North-South transects located 8.5 km and 11.6 km west of L-36 (Reddy *et al.*, 1991,1993; Koch and Reddy, 1992; DeBusk *et al.*, 1993).

Differential equations describing steady-state water and phosphorus balances of a wetland segment with incremental area dA (km^2) are developed below. The following equation describes the water balance under sheet-flow conditions moving South from the S10s:

$$dQ/dA = p - e \qquad (2)$$

Boundary Condition:

$$Q = Q_o \text{ at } X = 0 \text{ (Levee-39)} \qquad (3)$$

where Q = overland flow (hm^3/yr = million cubic meters/yr); Q_o = inflow from S10ACD (hm^3/yr); p = precipitation rate (m/yr); and e = evapotranspiration rate (m/yr). The following differential equation describes the water-column phosphorus balance:

$$d(QC)/dA = p\ C_p - K_e\ F_w\ C \qquad (4)$$

Boundary Condition:

$$C = C_o \text{ at } X = 0 \text{ (Levee-39)} \qquad (5)$$

where C = flow-weighted Total P concentration in surface water (mg/m^3 or ppb); C_p = volume-weighted-mean P concentration in rainfall (mg/m^3); C_o = flow-weighted-mean P concentration in S10 inflows (mg/m^3); K_e = effective settling velocity (m/yr); and F_w = wet period fraction

Based upon observed spatial correlation between water-column P concentrations and P accretion rates in this region (Koch and Reddy, 1992; Craft and Richardson, 1993b), the model represents the net rate of phosphorus removal from the water column per unit area as proportional to the average concentration. The proportionality constant, K_e (m/yr), is designated as an "effective settling velocity." A temporal scale factor, F_w, is applied to reflect the fraction of the time that water exists in the marsh (i.e., to exclude droughts from the periods in which phosphorus removal is assumed to occur). A first-order, settling-rate mechanism was also invoked by Vollenweider (1969) in modeling phosphorus retention in northern lakes. The model makes no attempt to represent specific mechanisms, only their net consequence, as reflected by the long-term-average phosphorus budget of a given wetland segment.

The above differential equations can be integrated analytically to solve for the flow profile, phosphorus concentration profile, and sediment phosphorus accretion profile as functions of cumulative upstream area:

$$Q = Q_o + (p - e)\ A \qquad (6)$$

$$C = (C_o - p\ C_p/g)\ [1 + (p-e)\ A/Q_o]^{-(g/(p-e))} + p\ C_p/g \qquad (7)$$

$$g = K_e\ F_w + p - e \qquad (8)$$

$$S = K_e\ F_w\ C \qquad (9)$$

where S = sediment phosphorus accretion rate (mg/m^2-yr); and g = parameter employed for algebraic convenience (m/yr)

The equations can be used to predict P accretion rate and average water-column concentration at any distance downstream from Levee-39, given measurements or independent estimates of K_e, F_w, p, e, C_p, W, Q_o and C_o.

PARAMETER ESTIMATION

The settling rate, K_e, has been calibrated to predict 26-year-average phosphorus accretion rates measured at 24 locations in the model zone (Figure 3). Accretion rates were measured using the Cesium-137 dating technique at six locations by Reddy *et al.* (1991, 1993) and at 18 locations by Richardson *et al.* (1992) and Craft and Richardson (1993a, 1993b). The sampled peat cores quantify the average rate of accumulation between 1963 (date of Cesium-137 peak) and 1990 (date of core collection). Depth of the Cesium-137 peak ranged from <2 to 30 cm and generally decreased from north to south. Average P accretion rates ranged from 300 to 1200 mg/m^2-yr at northern stations and from <10 to 300 mg/m^2-yr at southern stations. Corresponding phosphorus gradients (reflective of an overall trophic gradient) have been observed in surface waters, plant tissues, surface sediments, and sediment pore waters (Koch and Reddy, 1992; Urban *et al.*, 1993; DeBusk *et al.*, 1993; Craft and Richardson, 1993a, 1993b). The range of P accretion rates is similar to the 70 to 1420 mg/m^2-yr range in net P retention rates resulting from annual plant growth and two years of leaf decomposition measured in this region of WCA-2A by Davis (1991).

Model input values for calibration are listed in Table 1. The model is driven primarily by average flows and phosphorus loads from the S10 structures for the 1976-1991 period. In the absence of phosphorus concentration data prior to 1976, it is assumed for the purpose of calibration that the average phosphorus load for the entire 1963-1991 period was similar to that measured in the 1976-1991 period. Phosphorus load from each structure has been calculated by interpolating phosphorus concentrations (typically measured biweekly) onto the daily flow record. Based upon these input values, discharges from the S10 structures account for 72 percent of the total inflow and 90 percent of the total phosphorus load to the model zone during the 1976-1991 period.

A least-squares estimate of the average setting velocity has been derived by comparing observed and predicted P accretion rates for various values of K_e. The settling rate has been calibrated to minimize the residual sum of squares calculated from the following equation:

$$RSS = \Sigma(S_o^u - S_e^u)^2 \qquad (10)$$

where RSS = residual sum of squares; S_o = observed accretion rate (mg/m^2-yr); S_e = predicted accretion rate (mg/m^2-yr); and u = exponent.

The exponent (u=0.71) has been calibrated to control heteroscedasicity (i.e., to stabilize residual variance as a function of predicted accretion rate). The least-squares estimate of K_e is 10.2 m/yr. Using response-surface methods (Box *et al.*, 1978), the 90 percent confidence range for K_e is 8.9 to 11.6 m/yr and the standard error is 0.79 m/yr. The model explains 89.5 percent of the variance in the observed accretion rates with a residual standard error of 80 mg/m^2-yr.

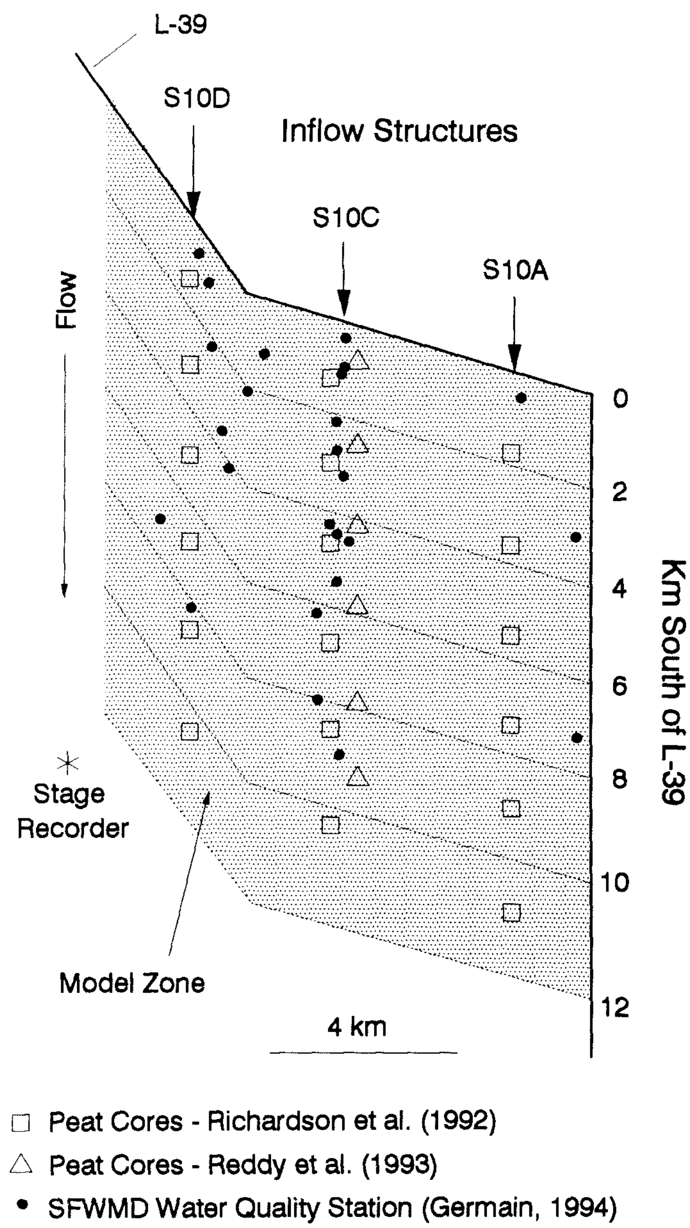

Figure 3. Model Zone and Sampling Stations. Symbols depict locations of peat cores used for model calibration and water-quality monitoring stations used for model testing. Dashed lines depict model coordinate system (distance south of Levee-39). Regional map is shown in Figure 1.

TABLE 1. Input Values for Model Calibration.

Symbol	Description	Units	Value	Comments
p	Rainfall	m/yr	1.16	Average WCA-2A rainfall (SFWMD, 1976-1991).
e	Evapotranspiration	m/yr	1.38	From regional pan-evaporation (Abtew and Sculley, 1991).
F_w	Wet Period Fraction	–	0.914	Fraction of days stage above ground level, 1963-1990.
Q_o	S10A+C+D Flow	hm^3/yr	347.2	Average inflow, May 1976 to April 1991.
C_o	S10A+C+D Inflow Conc.	ppb	122	Flow-weighted-mean, May 1976 to April 1991.
F_W	Width of Flow Path	km	10.5	From soil P, vegetation maps (Figure 2).
C_p	Rainfall P Conc.	ppb	37	Volume-weighted-mean, Station S7 (SFWMD, unpublished).

Sensitivity of the predicted accretion profile to settling rate is demonstrated in Figure 4. The 90 percent confidence interval represents the spatially-averaged accretion rate as a function of distance, as predicted by the probable range for the average K_e value in the entire model zone. Predicted profiles are shown for values of K_e ranging from 6 to 14 m/yr, which is considerably wider than the 90 percent confidence interval for K_e. For K_e = 6 m/yr, the model underpredicts measured accretion rates at the upstream stations and overpredicts rates at downstream stations. When K_e is too low, the water-column load is eliminated too slowly near the inflow structures and the load is transported too far into the marsh. For K_e = 14 m/yr, the reverse pattern is observed. For K_e = 10.2 m/yr, predictions are unbiased over a distance range of 0 to 11 km. Residual scatter is also independent of data source [i.e., Reddy *et al.* (1991, 1993) vs. Richardson *et al.* (1992)].

Sensitivity of the least-squares K_e estimate to input variables has been explored by varying each of the inputs in Table 1 by ± 25 percent from its initial value and re-estimating the settling rate (Walker, 1993). Optimal K_e estimates range from 8.3 to 13.6 m/yr. The most sensitive input variables are wet period fraction (K_e = 9.3 to 13.6 m/yr) and S10 inflow concentration (K_e = 8.3 to 12.4 m/yr). The least sensitive input variables are evapotranspiration (K_e = 10.1 to 10.3 m/yr) and rainfall phosphorus concentration (K_e = 10.0 to 10.4 m/yr). Potential regional variations in settling rate have been explored by calibrating the model separately to different sets of stations, defined by maximum distance south of Levee-39. For maximum distances between 4 and 11 km, the number of stations varies from 9 to 24 and optimal K_e values vary from 9.9 to 10.2 m/yr.

The estimate of average rainfall phosphorus concentration has a high degree of uncertainty relative to the other model input variables listed in Table 1. The estimate of 37 ppb is based upon SFWMD wet-deposition measurements at the S7 pump station in the northwest corner of WCA-2A. At an average rainfall of 1.16 m/yr (Table 1), the 37 ppb concentration corresponds to an atmospheric deposition rate of 43 mg/m^2-yr. Measurements of atmospheric deposition rates are complicated by numerous sources of contamination which can cause positive bias. Sampler invasion by insects and other organisms is a particular problem in this region (SFWMD, unpublished). Hendry *et al.* (1981) reported atmospheric deposition rates at seven South Florida locations ranging from 17 to 96 mg/m^2-yr (sums of wet and dry deposition). Rates were lower at coastal and southern sites and higher at northern interior sites adjacent to Lake Okeechobee. This range brackets the 43 mg/m^2-yr rate assumed for WCA-2A.

For assumed rainfall phosphorus concentrations ranging from 0 to 100 ppb (deposition rates of 0 to 116 mg/m^2-yr), optimal K_e values range from 9.3 to 11.6 m/yr (Walker,1993). The best fit of the accretion profile is obtained for rainfall concentrations between 20 and 40 ppb. Calibration of the model to optimize settling rate and rainfall concentration estimates simultaneously yields 90 percent confidence ranges of 8.4 to 12.2 m/yr for K_e and < 5 to 70 ppb for C_p. Thus, when prior estimates of rainfall concentration are ignored, the 90 percent confidence interval for K_e widens slightly from 8.9-11.6 m/yr to 8.4-12.2 m/yr. Uncertainty in atmospheric phosphorus loads has a small impact on the precision of K_e estimated from peat-accretion measurements.

MODEL TESTING

Water-column P concentrations and sediment P accretion rates are coupled by mass-balance (Equations 6-9). Water-column data provide a basis for testing the settling rate calibrated above to peat-accretion measurements. Spatial and temporal variations in settling rate can be assessed by applying the model to

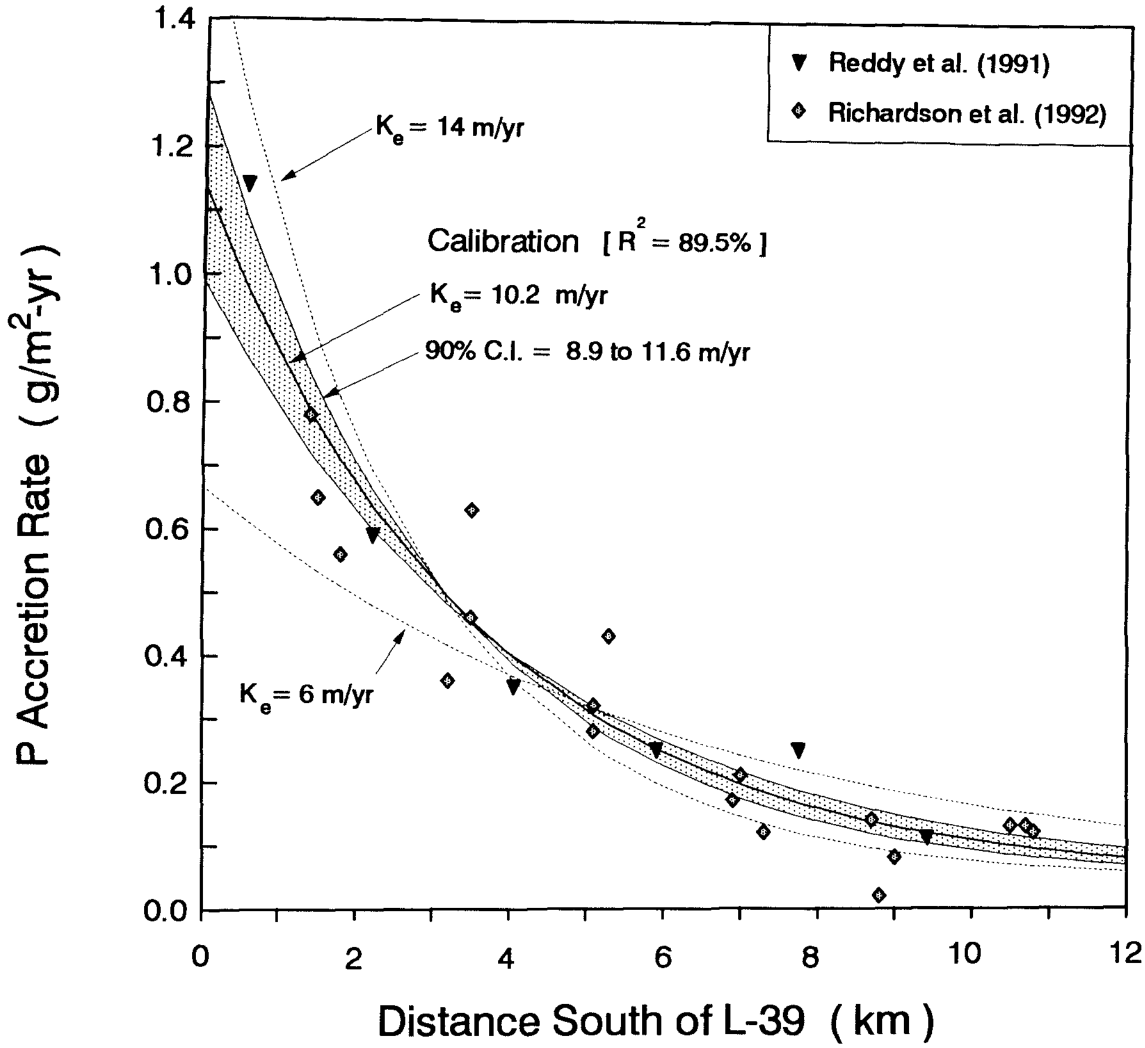

Figure 4. Observed and Predicted Phosphorus Accretion Rates. Symbols depict measured, 26-year-average accretion rates. Solid line depicts model prediction with the calibrated setting rate (10.2 m/yr). Shaded area depicts model prediction for the 90 percent confidence interval in settling rate (8.9 to 11.6 m/yr). Dotted lines depict model predictions for setting rates of 6 and 14 m/yr.

different zones and monitoring periods. Water-column chloride data provide bases for discerning flow paths and testing water budgets. Figure 3 locates 25 SFWMD water-quality monitoring stations used for model testing. Stations reflect routine monitoring (Germain, 1994; Millar, 1981a, 1981b), as well as special field studies (Davis, 1991; Swift, 1984; Swift and Nicholas, 1987; Koch and Reddy, 1992; Urban *et al.*, 1993). Sampling intervals and frequencies vary from station to station. Phosphorus and chloride analyses have been performed by SFWMD using methods documented by the above authors.

Monthly-mean water level at Gauge 217 in the center of WCA-2A is shown in Figure 5. Based upon comparisons with water depths measured at water-quality stations on dates of sampling, water depth at this location is a good indicator of water depths in the model zone, particularly during periods of low inflow. Urban *et al.* (1993) reported no significant difference in average water levels at the 217 gauge compared with stations monitored between 1986 and 1991 along a transect south of S10C. Because of hydraulic affects, water depths are slightly higher in northern portions of the model zone during periods when the S10's are discharging. Because of a slight slope in the soil surface, the maximum soil elevation in the northern region is approximately 10 cm above the soil elevation at Gauge 217. Northern regions may dry out more frequently than the central and southern regions of WCA-2A because of higher soil elevations and effects of downstream elevation control at the S11 structures which release water from WCA-2A into WCA-3A (Figure 1) (Worth, 1988; Craft and Richardson,1993a).

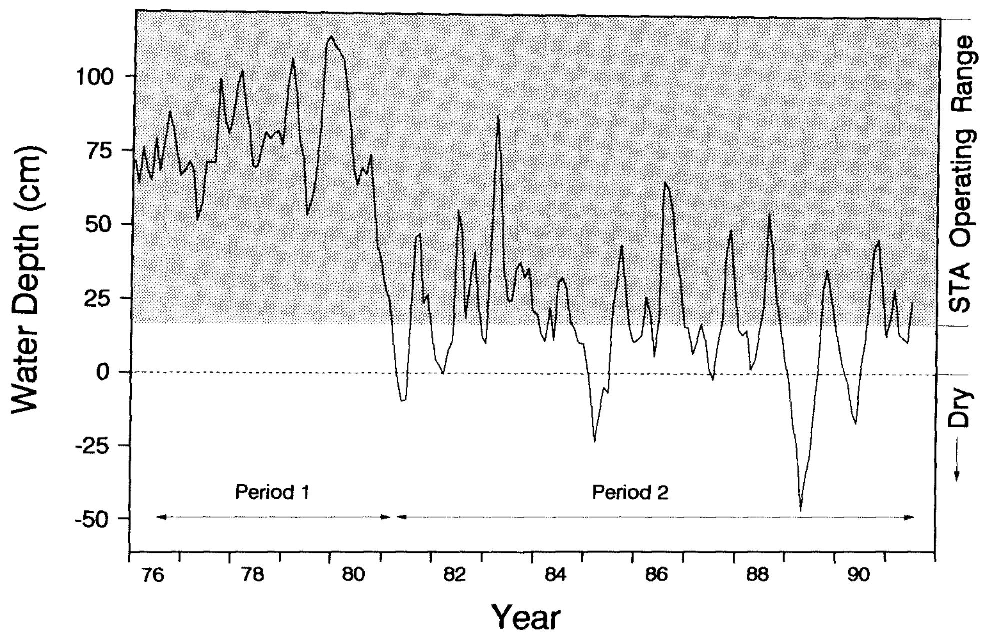

Figure 5. Mean Monthly Water Depth at WCA-2A Gauge 217. Values measured by U.S. Army Corps of Engineers (unpublished). Shaded area depicts STA design range. Gauge location is shown in Figure 3.

Phosphorus settling rates have been estimated using water-column data from two time periods which reflect data availability and modification of the WCA-2A stage regulation schedule in March 1981 (Worth, 1988):

1. Period 1 – June 1976 through February 1981.
2. Period 2 – March 1981 through August 1991.

In Period 1, water levels were relatively high and typical of STA design conditions (design depth range = 15 to 122 cm or 0.5 to 4 feet) (Burns & McDonnell, 1994). Stage dropped below ground level on several occasions in Period 2, which included three severe droughts (1981, 1987, and 1989-1990).

Effective settling velocities for phosphorus and chloride have been calibrated for each time period by using the same nonlinear regression algorithm applied to the peat-accretion data. In calculating the least-squares objective function, a logarithmic transformation has been applied to the observed and predicted concentrations to stabilize variance as a function of predicted concentration. Longitudinal variations in settling rate have been characterized by calibrating separate values for 0-5 km and 0-10 km distance intervals.

Because the model reflects water-column mass balances, comparison of model predictions with flow-weighted-mean concentrations at marsh stations is appropriate. In the absence of direct flow measurements at the marsh stations, flow-weighted-means have been calculated by weighting each concentration measurement using the 14-day antecedent inflow from the S10 structures. Results are insensitive to flow-averaging periods between 1 and 30 days. Flow-weighted-means calculated for various periods are based upon 3 to 88 samples per station. Similar settling-rate estimates are obtained when the model is calibrated to individual marsh samples collected during S10 discharge periods (as compared with calibration to flow-weighted-means at each marsh station). Parameter estimates and inflow conditions for each period, constituent, and distance interval are summarized in Table 2.

Figure 6 shows observed and predicted concentration profiles for the June 1976 through February 1981 period, when the marsh was continuously flooded and depths were similar to the STA operating range. The 90 percent confidence interval for the phosphorus settling rate calibrated to marsh water-column data (11.3 to 14.8 m/yr) slightly exceeds the 10.2 m/yr value calibrated to peat-accretion data. The chloride settling rate is not significantly different from zero. This is consistent with expected conservative behavior. For both phosphorus and chloride, spatial variations in settling rate are not indicated for this period; estimates for the 0-5 km zone are similar to estimates for the 0-10 km zone (Table 2).

Chloride concentrations along each marsh transect mimic the average inflow concentrations at the respective S10 inflow structures (D > C > A). This is consistent with a general southerly flow path and

TABLE 2. Parameter Estimates Based Upon Marsh Water-Column Data.

Variable	TP	TP	TP	TP*	TP*	Cl	Cl	Cl
Sampling Dates (Year-Month)								
First	7606	8103	7606	8103	7606	7606	8103	7606
Last	8102	9108	9108	9108	9108	8102	9108	9108
S10 Inflows and Atmospheric Fluxes								
Q_o	384.6	337.9	352.4	337.9	352.4	384.6	337.9	352.4
C_o	90.7	136.7	121.1	136.7	121.1	176.5	136.6	150.1
F_w	1.000	0.840	0.890	1.000	1.000	1.000	0.840	0.890
p	1.14	1.19	1.17	1.19	1.17	1.14	1.19	1.17
e	1.37	1.40	1.39	1.40	1.39	1.37	1.40	1.39
C_p	37	37	37	37	37	1.7	1.7	1.7
Parameter Estimates for 0-10 km Zone								
Stations	19	24	25	13	22	19	14	19
Samples	201	363	564	81	293	214	107	321
R^2	0.823	0.543	0.641	0.831	0.835	–0.071	0.043	–0.087
SE	0.471	0.821	0.665	0.410	0.412	0.106	0.335	0.247
K_e	13.0	9.5	9.9	10.6	12.2	0.2	0.8	0.1
K_e – 5 percent	11.3	7.0	7.9	9.2	11.0	–0.1	–0.4	–0.7
K_e – 95%	14.8	12.1	12.0	12.1	13.5	0.5	2.0	0.8
Parameter Estimates for 0-5 km Zone								
Stations	13	17	18	8	15	13	9	13
Samples	143	229	372	49	201	158	73	231
R^2	0.643	–0.007	0.176	0.617	0.698	–0.027	0.040	–0.020
SE	0.473	0.545	0.500	0.497	0.362	0.087	0.308	0.205
K_e	12.1	1.2	4.1	10.6	11.6	–0.3	–0.8	–1.3
K_e –5%	8.8	–2.0	1.2	7.1	9.6	–0.9	–3.4	–2.7
K_e – 95%	15.5	4.4	7.0	14.1	13.7	0.3	1.9	0.1

SE = Standard Error of Estimate, ln (Marsh TP Concentration).
K_e = 5%, 95% = lower and upper end of 90% confidence interval for K_e (m/yr).
C_o, C_p units ppb for phosphorus and ppm for chloride.
*Wet periods only; samples collected on days when water depth exceeded 7.6 cm for at least 120 days prior to sampling.

relatively little east-to-west transport within the marsh. Transect differences are also evident in the phosphorus data at stations close to the S10's, but not at southern marsh stations, where concentrations are reduced ~ 10-fold relative to the S10 inflows. Random variations in phosphorus uptake rates and mechanisms along the southerly flow path from the S10's may explain the disappearance of east-west phosphorus gradients despite the persistence of chloride gradients at the south end of the model zone.

Chloride concentrations at marsh stations south of S10A and S10C are slightly higher than the inflow concentrations at S10A and S10C. This may reflect initial diversion of high-chloride S10D inflows towards the east prior to entering the marsh, an observed phenomenon caused by topographic variations in the vicinity of L-39. Data from marsh stations closer to the inflows are more sensitive to the particular spatial distribution of inflows. These stations have little impact on the calibrated settling rates, since the left end of the model prediction is anchored at the average inflow concentration for the combined S10's.

Figure 7 shows observed and predicted concentration profiles for the February 1981 through August 1991 period, when several droughts were experienced (Figure 5). Consistent with results from 1976-1981, chloride setting rates are not significantly different from zero. Confidence intervals for phosphorus settling rate are 7.0 to 12.0 m/yr for the 0-10 km zone and –2.0 to 4.4 m/yr in the 0-5 km zone. Very little phosphorus retention is indicated in the first 5 km, where concentrations exceed model predictions for K_e = 10.2 m/yr at 16 out of 17 marsh stations. Essentially no retention is indicated along the western (D) transect. Phosphorus concentrations along the central transect (C) drop sharply from ~ 80 ppb at 5 km to ~ 20 ppb at 7 km. The calibrated settling rate for the entire 0-10 km zone is determined primarily by stations between 6 and 10 km and does not reflect a much lower apparent settling rate in the northern 5 km during this period.

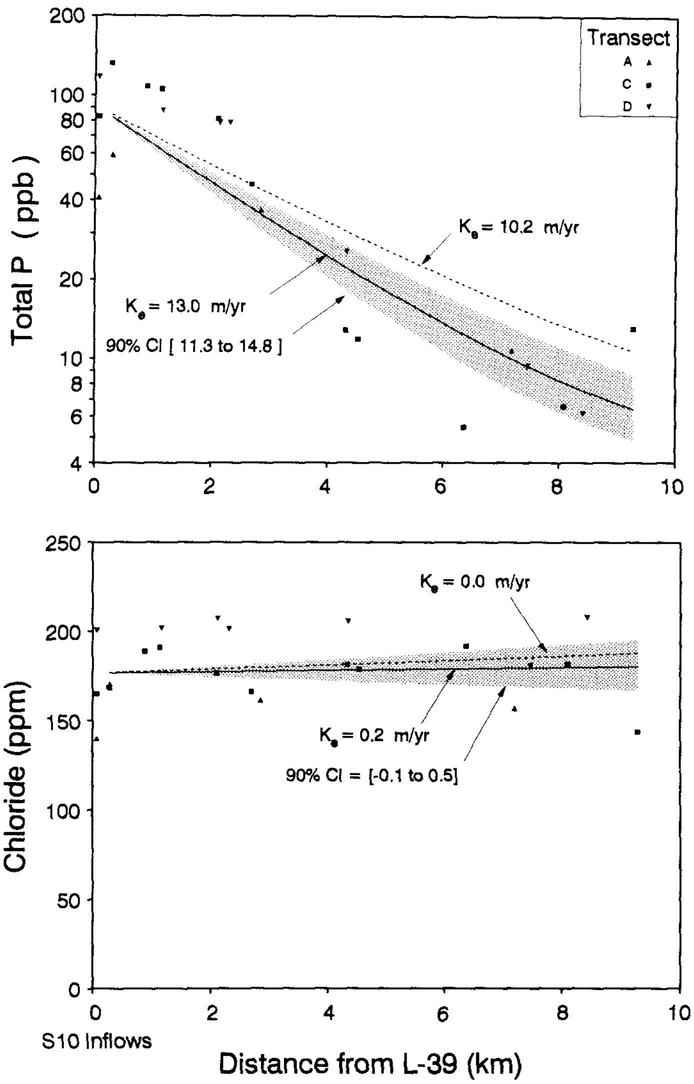

Figure 6. Observed and Predicted Concentrations, June 1976-February 1981. Symbols depict flow-weighted-mean concentrations of TP and chloride at marsh stations for the June 1976-Feb 1981 period of high stage. Symbols at Distance = 0 km indicate flow-weighted-mean concentrations in discharges from each S10 structure. Dotted lines depict model predictions for phosphorus settling rate of 10.2 m/yr (calibrated to sediment P accretion rates) and chloride settling rate of 0.0 m/yr. Shaded areas depict model predictions for 90 percent confidence intervals of settling rates calibrated to water-column data from this period.

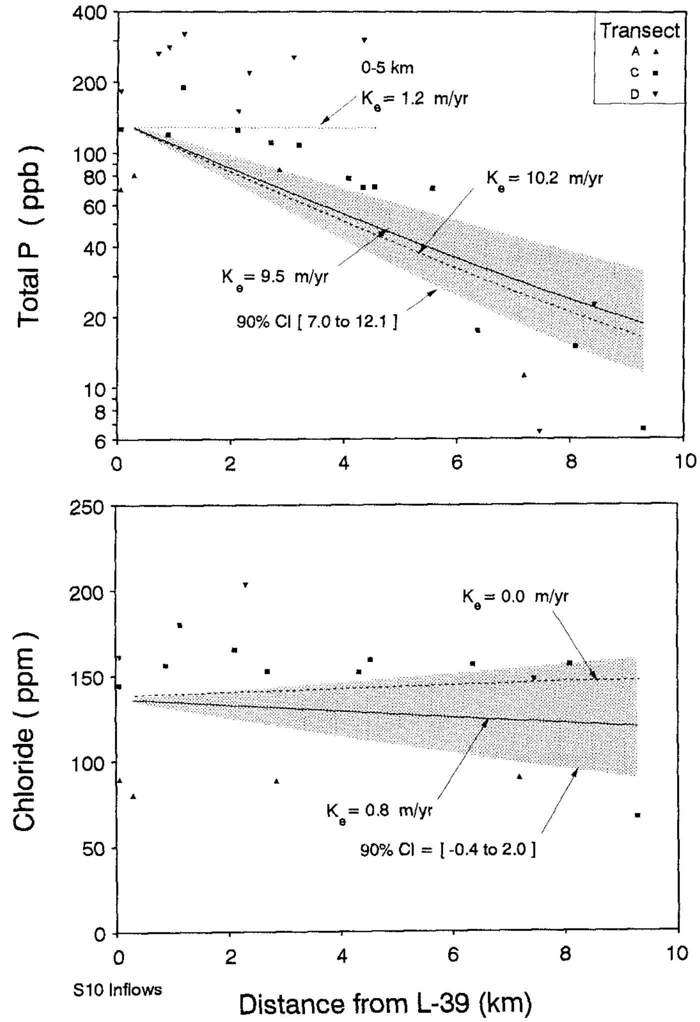

Figure 7. Observed & Predicted Concentrations, March 1981-August 1991 (see Figure 6 legend for explanation).

VARIATIONS IN SETTLING RATE

Figure 8 compares 90 percent confidence intervals for settling rates estimated from peat-accretion and water-column data from various distance intervals and periods. Compared with the 8.9-11.2 m/yr estimate derived from peat accretion data, water-column data suggest a higher K_e (11.3 to 14.8 m/yr) during the earlier period of continuous inundation and a lower K_e (–2.0 to 4.4 m/yr) in the northern 5 km during the later period with intermittent droughts. Settling rates inferred from water-column data reflect the combined effects of peat accretion and transient phosphorus fluxes to and from biomass, litter, and peat compartments. Two possible mechanisms accounting for these differences in settling rates, drought-induced recycling, and vegetation changes are discussed below.

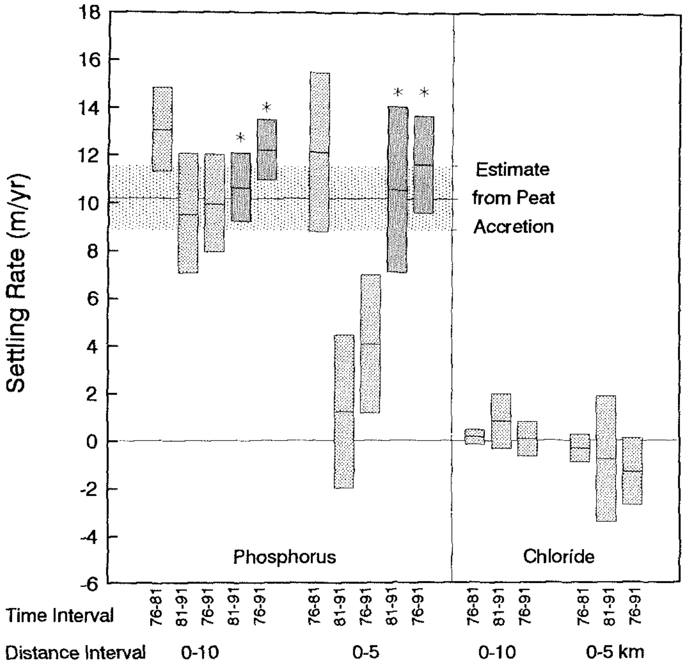

Figure 8. Settling Rates vs. Time and Distance Intervals. Shaded bars depict 90 percent confidence intervals for setting rates calibrated to peat-accretion and water column measurements from various periods and distance intervals. Asterisks (*) indicate calibrations to water-column samples collected under wet conditions (water depth >=7.6 cm for a period >=120 days prior to sampling).

Drought-induced oxidation of peat and subsequent dissolution are important phenomena promoting phosphorus recycling from Everglades peats enriched by anthropogenic phosphorus inputs (Davis, 1994; Urban *et al.*, 1993). Examination of time-series data from individual marsh stations in the northern model zone reveals a tendency for water-column phosphorus concentrations to increase shortly after reflooding of the marsh following droughts. To test the hypothesis that the low settling average rate in the northern region between 1981 and 1991 was related to drought-induced recycling, phosphorus concentration data from all marsh stations have been classified based upon antecedent hydrologic conditions, defined by minimum depth and duration of water level at the 2A-217 gauge prior to sampling. Calibration of the model to all water-column data collected between 1981 and 1991 yields a K_e estimate of -2.0 to 4.4 m/yr for the 0-5 km zone. For this same time period and distance interval, calibration to samples collected on dates when water depth exceeded 7.6 cm (3 inches) for at least 120 days prior to sampling yields a K_e estimate of 7.1 to 14.1 m/yr (Table 2). This screening procedure eliminates samples collected during and immediately following periods of low stage, when phosphorus recycling attributed to peat oxidation and/or plant die-off would be most apparent.

Sensitivity of calibrated settling rates to minimum depth and minimum duration of inundation criteria is shown in Figure 9. In the 0-5 km zone, K_e increases with duration of inundation between 0 and 120 days and stabilizes thereafter. For wet durations exceeding 120 days, results stabilize at values ranging from 10 to 14 m/yr. The 0-10 km settling rates are less sensitive to water depth and duration. Spatial variations in K_e are not significant when drought/reflood periods are excluded.

Figure 10 shows the predicted concentration profile for K_e = 10.2 m/yr in relation to marsh water-column concentrations classified according to antecedent water depth and duration. Results suggest that phosphorus uptake and recycling mechanisms are more sensitive to water levels and drought in the northern zone, as compared with the southern zone. This greater sensitivity may reflect higher concentrations of phosphorus in surface peats. Koch and Reddy (1992) measured 0-10 cm peat phosphorus concentrations ranging from 1200-1600 mg/kg in the northern model zone to 400 mg/kg in the southern model zone (Figure 2).

The observed spatial and temporal variations in K_e may also be related to changes in vegetation. Cattails have dominated the northern end of model zone since the late 1970s but have expanded in surface area. Relatively rapid growth rates give cattails a competitive advantage over native sawgrass in enriched areas with long hydroperiod (Reeder and Davis, 1983; Davis, 1984, 1994). Fluctuations in cattail density and area have been observed in response to nutrient regime, drought, and fire (Urban *et al.*, 1993).

Based upon leaf biomass and composition measurements reported by Reeder and Davis (1983) and by Davis (1984, 1991), phosphorus stored in live leaf tissue ranges from about 600-800 mg P/m^2 in the northern portion of the model zone to about 90-120 mg P/m^2 in the southern portion. These ranges correspond to about one year of phosphorus storage ir peat, based upon the accretion profile (Figure 4). Th slightly higher K_e values inferred from the water column data during the 1976-1981 period (vs. 1981-1991) may reflect net growth of the cattail communit and net increase in phosphorus storage in biomas and litter compartments. Such an increase would b reflected in the water-column phosphorus balance bu not in the peat-accretion measurements.

Urban *et al.* (1993), reported that sawgrass is mor stable than cattail under stress induced by drought o fire. Sawgrass plants normally survive drought an burning (Gunderson, 1994). Both peat oxidation an cattail die-off may have contributed to the low settlin rate in the 0-5 km zone between 1981 and 1991. Th

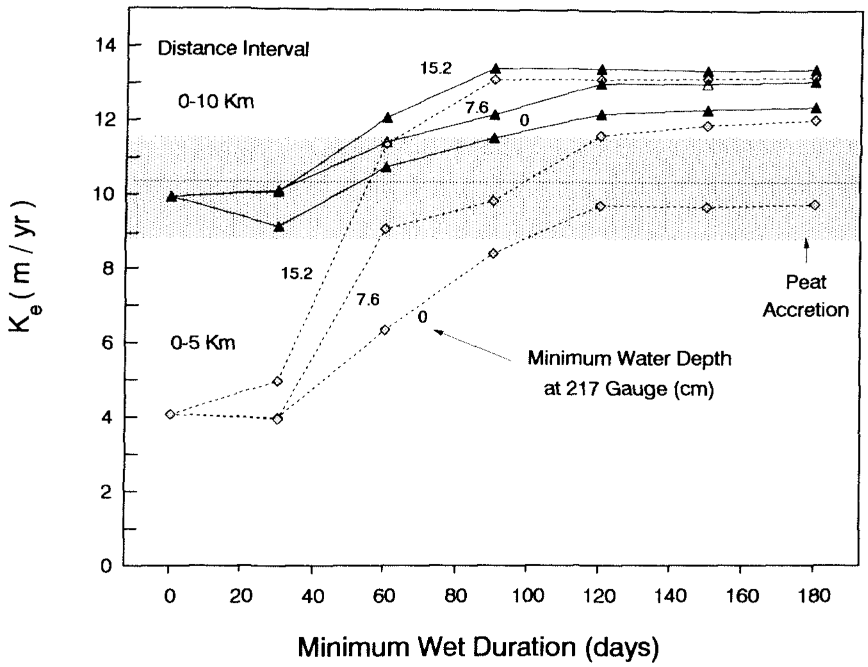

Figure 9. Settling Rate vs. Minimum Water Depth & Duration. Shaded area depicts 90 percent confidence interval for P settling rates calibrated to peat accretion data. Solid lines depict settling rates calibrated to water-column data from the entire model zone (0-10 km) as a function of minimum water depth and minimum duration of inundation. Dotted lines depict same information for the northern half of the model zone (0-5 km). Samples were collected between June 1976 and August 1991.

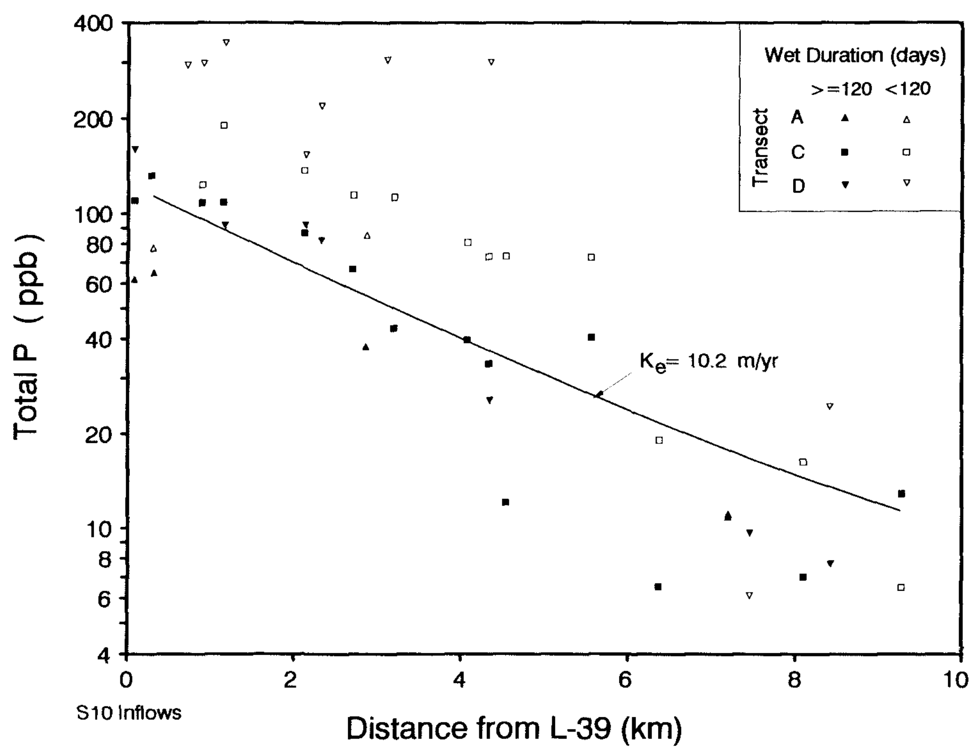

Figure 10. Observed and Predicted Phosphorus Concentrations for Wet and Dry Conditions. Symbols depict observed low-weighted-mean phosphorus concentrations at stations along each transect for wet conditions (solid symbols, wet duration >= 120 days) and dry conditions (open symbols, wet duration < 120 days). Solid line depicts model prediction for K_e calibrated to peat accretion data.

relative stability of the settling rate in the southern model zone during this period is consistent with resilience of sawgrass communities subjected to fire or drought. Studies of leaf decomposition indicate that retention of phosphorus in dead sawgrass leaves is on the order of 50 percent, as compared with 25 percent for cattail (Davis, 1984; Toth, 1987). These factors suggest that higher rates of phosphorus recycling from plant tissue associated with drought or fire in the northern zone may have contributed to the observed spatial variations in settling rate during the 1981-1991 period.

Higher settling rates in the southern model zone in 1981-1991 may also reflect greater importance of calcium phosphate precipitation induced by periphyton as a phosphorus removal mechanism (Koch and Reddy, 1992). Phosphorus stored in the peat as inorganic calcium phosphate may be less susceptible to recycling, as compared with phosphorus stored in organic forms which can be oxidized and mobilized by drought or fire.

Calibration of the model to water-column data from the most recent period of continuous inundation (November 1990 through August 1991) yields a settling rate of 10.2 to 17.7 m/yr, similar to the 11.3 to 14.8 m/yr estimate developed from the 1976-1981 period of continuous inundation. Spatial variations in settling rate are not detectable in either of these periods, when depth regimes closely approximated STA design conditions. Observed regrowth of cattail communities following the 1989-1990 drought (Urban *et al.,* 1993) may account for the fact that the settling rate in 1990-1991 was higher than the 10.2 m/yr long-term average.

Results do not suggest a long-term decline in phosphorus retention capacity associated with vegetative changes. Variations in settling rate appear to be associated primarily with drought/flood cycles and consistent with observed spatial and temporal variations in plant communities. Drought-induced recycling of phosphorus is not expected to occur in the Stormwater Treatment Areas, which have been designed to maintain water depths exceeding 15 cm for the 1979-1988 hydrologic record used as a basis for design (Burns and McDonnell, 1994).

MODEL APPLICATION

In a design mode, Equation (7) can be solved for the surface area required to achieve the target outflow concentration (50 ppb), given an assumed value for the settling rate and independent estimates of the other model input variables. Burns & McDonnell (1994) have applied the model in sizing six regional STA's to accomplish treatment objectives; footprints are shown in Figure 1. For design purposes, STA inflows have been characterized using historical monitoring data for a 10-year period (1979-1988), adjusted to account for future implementation of BMP's. Treatment areas range from 330 to 3370 hectares (total = 16,300 hectares). Hydraulic loads range from 6 to 11 m/yr and inflow phosphorus concentrations, from 120 to 260 ppb.

The 10.2 m/yr settling rate derived from peat accretion data has been selected as a design basis. This is preferred to estimates derived from water-column data for the following reasons:

1. Peat data provide integrated measures of long-term-average accretion rates, whereas water-column data reflect transient conditions for specific sampling periods and are more variable.
2. Given sufficient hydroperiod, peat accretion is a sustainable mechanism for phosphorus removal, whereas water-column data also reflect transient fluxes to/from vegetation and litter compartments. The slightly higher settling rates calibrated to marsh water-column data during periods of continuous flooding may reflect net storage of phosphorus in vegetation and litter. Conversely, lower settling rates observed in the northern enriched zone during drought/reflood periods may reflect net release of phosphorus from peat and other storage compartments induced by oxidation and plant die-off.
3. The spatial array of peat sampling stations is more uniform than the array of water-quality stations (Figure 5) and is thus more likely to reflect the average fluxes simulated by the model.

Uncertainty in STA performance primarily reflects uncertainty in settling rate; other model inputs are directly measured or reflect insensitive model terms.

Consequences of uncertainty in the settling rate can be assessed by predicting STA outflow concentrations for a range of settling rates corresponding to the 90 percent confidence interval derived from peat-accretion data (8.9 to 11.6 m/yr).

Figure 11 shows predicted long-term-average outflow phosphorus concentrations from a typical STA with specifications derived from conceptual design efforts (Burns and McDonnell, 1994). In this example, an STA of 2625 hectares is sized to meet the 50-ppb outflow concentration objective, given an inflow volume of 206 hm^3/yr and inflow phosphorus concentration of 168 ppb.

For settling rates ranging from 8.9 to 11.6 m/yr, predicted outflow concentrations range from 59 ppb to 42 ppb, as compared with the average inflow concentration of 168 ppb. Predicted load reductions for the entire control program (25 percent attributed to

BMP's and the remainder to STA's) range from 75 percent to 82 percent relative to the loads experienced in the 1979-1988 period. For an optimistic settling rate of 13.0 m/yr (K_e derived from marsh water-column data between 1976 and 1981, when marsh water levels were within the STA design range), the predicted outflow concentration is 36 ppb and the overall load reduction is 85 percent.

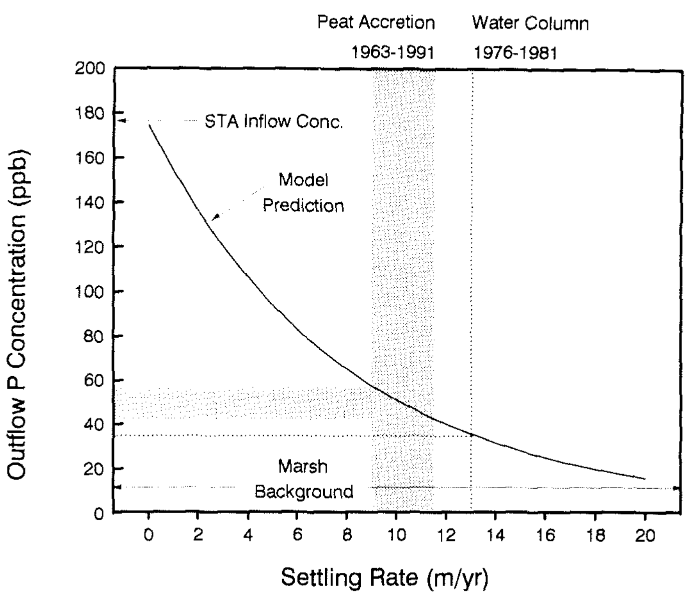

Figure 11. STA Performance vs. Settling Rate. Shaded areas depict predicted STA performance with K_e calibrated to WCA-2A peat-accretion data. Dashed lines depict performance with K_e calibrated to WCA-2A water-column data from 1976-1981, when water column depths were consistently within the STA operating range.

Confidence ranges for K_e do not account for uncertainty associated with translating results from WCA-2A to the STA's. This type of uncertainty would be diminished by geographic proximity and similarities in water chemistry. Settling rates derived from WCA-2A are consistent with settling rates derived from observed performance data from emergent wetland treatment systems in Florida and elsewhere operating over a wide range of concentrations and hydraulic loading rates (Kadlec and Newman, 1992; Kadlec, 1993, 1994; Kadlec and Knight, 1995).

Consequences of performance uncertainty can be assessed considering that 50 ppb is an interim technology-based target; a second phase of the control program is anticipated. For scenarios considered above, the predicted range of STA outflow concentration consistently exceeds marsh background levels (<10 ppb) and the 10-30 ppb range at which phosphorus impacts on native Everglades communities have been indicated (Nearhoof, 1992; Grimshaw *et al.,* 1993). Risk of overinvestment in this first phase of the control program resulting from underestimation of the settling rate (producing cleaner water than is necessary to protect the ecosystem) is minimal. Performance deviations of the above magnitudes attributed to uncertainty in the settling rate are not expected to detract significantly from the overall benefits of the program, as derived from substantial phosphorus load reductions and hydrologic improvements. Future steps will be driven by research to define threshold phosphorus concentrations necessary for protection of native Everglades communities (Lean *et al.,* 1992) and by observed performance of controls implemented in this first phase.

CONCLUSION

The mass-balance model developed above predicts long-term-average phosphorus removal in a wetland segment based upon inflow volumes, phosphorus load, atmospheric fluxes, and a regionally-calibrated, first-order settling rate. A settling rate of 8.9 to 11.6 m/yr is supported by peat-accretion and water-column data from WCA-2A and by performance data from wetland treatment systems in Florida and elsewhere. Spatial and temporal variations in settling rate inferred from water-column data appear to be related primarily drought-induced recycling. These variations are consistent with mechanisms previously identified and evaluated in field studies. Refinements in model structure are needed to account for these phenomena if predictions of performance over annual or shorter time steps are desired. Maintaining wet conditions in the STA's will be important for promoting phosphorus removal. Uncertainty in STA performance derived from uncertainty in the settling rate derived from WCA-2A data does not pose a significant risk to achieving substantial phosphorus load reductions under the planned control program.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Justice and the U.S. Department of Interior. Dr. Robert Kadlec of the University of Michigan contributed substantially to the conception, development, and testing of the model framework. Dr. Thomas Fontaine, Dr. Nicholas Aumen, Dr. Garth Redfield, and the Everglades Research Staff of South Florida Water Management District provided valuable insights, data, and reviews.

LITERATURE CITED

Abtew, W. and S. P. Sculley, 1991. Evapotranspiration Estimation Method for South Florida. Presented at the 51st Annual Meeting of Soil and Crop Science Society of Florida, Orlando, September 25-27.

Belanger, T. V., D. J. Scheidt, and J. R. Platko, 1989. Effects of Nutrient Enrichment on the Florida Everglades. Lake and Reservoir Management 5:101-111.

Box, G. E. P., W. G. Hunter, and J. S. Hunter, 1878. Statistics for Experimenters. John Wiley and Sons, New York, New York.

Burns & McDonnell, Inc., 1994. Everglades Protection Project, Conceptual Design. Report to South Florida Water Management District, West Palm Beach, Florida.

Craft, C. B. and C. J. Richardson, 1993a. Peat Accretion and N, P, and Organic C Accumulation in Nutrient-Enriched and Unenriched Everglades Peatlands. Ecological Applications 3(3):446-458.

Craft, C. B. and C. J. Richardson, 1993b. Peat Accretion and Phosphorus Accumulation Along a Eutrophication Gradient in the Northern Everglades. Biogeochemistry 22:133-156.

Davis, S. M., 1984. Cattail Leaf Production, Mortality, and Nutrient Flux in Water Conservation Area 2A. South Florida Water Management District, Technical Report 84-8.

Davis, S. M., 1991. Growth, Decomposition, and Nutrient Retention of *Cladium jamaicense* Crantz and *Typha dominensis* Pers. in Florida Everglades. Aquatic Botany 40:203-224.

Davis, S. M., 1994. Phosphorus Inputs and Vegetation Sensitivity in the Everglades. *In:* Everglades – The Ecosystem and Its Restoration, S. M. Davis and J. C. Ogden (Editors). St. Lucie Press, Florida, pp. 357-378.

DeBusk, W. F., K. R. Reddy, M. S. Koch, and Y. Wang, 1994. Spatial Distribution of Soil Nutrients in a Northern Everglades Marsh: Water Conservation Area 2A. Soil Sci. Soc. Am. J. 58:543-552.

Germain, G. J., 1994. Surface Water Quality Monitoring Network, South Florida Water Management District, South Florida Water Management District. Technical Memorandum DRE 317.

Grimshaw, H. J., M. Rosen, D. R. Swift, K. Rodberg, and J. M. Noel, 1993. Marsh Phosphorus Concentrations, Phosphorus Content and Species Composition of Everglades Periphyton Communities. Arch. Hydrobiol. 128(3):257-276.

Gunderson, L. H., 1994. Vegetation of the Everglades: Determinants of Community Composition. *In:* Everglades – The Ecosystem and Its Restoration, S. M. Davis and J. C. Ogden (Editors). St. Lucie Press, Florida, pp. 323-340.

Hendry, C. D., P. L. Brezonik, and E. S. Edgerton, 1981. Atmospheric Deposition of Nitrogen and Phosphorus in Florida. Atmospheric Pollutants in Natural Waters, Ann Arbor Science, Ann Arbor, Michigan, pp. 199-215.

Kadlec, R. H. and S. Newman, 1992. Phosphorus Removal in Wetland Treatment Areas. Report to South Florida Water Management District, No. DRE 321, West Palm Beach, Florida.

Kadlec, R. H., 1993. Natural Wetland Treatment a Houghton Lake Michigan: The First Fifteen Years. Proc. 66th Annual Conference and Exposition, Water Environment Federation, Anaheim, California.

Kadlec, R. H., 1994. Phosphorus Uptake in Florida Marshes. Water Science and Technology (in press).

Kadlec, R. H. and R. L. Knight, 1995. Treatment Wetlands. Lewis Publishers, Chelsea, Michigan (in press).

Koch, M. S. and K. R. Reddy, 1992. Distribution of Soil and Plant Nutrients Along a Trophic Gradient in the Florida Everglades. Soil Sci. Soc. Am. J. 56:1492-1499.

Lean, D., K. H. Reckhow, W. W. Walker, and R. G. Wetzel, 1992. Everglades Nutrient Threshold Research Plan. Research and Monitoring Subcommittee, Everglades Technical Oversight Committee.

Millar, P. S., 1981a. Water Quality Analysis in the Water Conservation Areas 1978 and 1979. South Florida Water Management District, Technical Memorandum, Interim Progress Report.

Millar, P. S., 1981b. Nutrient Budgets in the Water Conservation Areas of South Florida, 1978-1980. *In:* Progress in Wetlands Utilization and Management, P. M. McCaffrey, T. Beemer, S. E. Gatewood (Editors). Symposium Proceedings, Coordinating Council on the Restoration of the Kissimmee River Valley and Taylor Creek-Nubbin Slough Basin, Orlando, Florida.

Nearhoof, F. L., 1992. Nutrient-Induced Impacts and Water Quality Violations in the Florida Everglades. Florida Department of Environmental Protection, Water Quality Technical Series, Volume 3, Number 4.

Reddy, K. R., W. F. DeBusk, Y. Wany, R. DeLaune, and M. Koch, 1991. Physico-Chemical Properties of Soils in the Water Conservation Area 2 of the Everglades. Report to South Florida Water Management District, West Palm Beach, Florida.

Reddy, K. R., R. D. DeLaune, W. F. Debusk, and M. S. Koch, 1993. Long-Term Nutrient Accumulation Rates in the Everglades. Soil Sci. Soc. Am .J. 57:1147-1159.

Reeder, P. B. and S. M. Davis, 1983. Decomposition, Nutrient Uptake and Microbial Colonization of Sawgrass and Cattail Leaves in Water Conservation Area 2A. South Florida Water Management District, Technical Report 83-4.

Richardson, C. J., C. B. Craft, R. R. Johnson, R. G. Qualls, R. B. Rader, L. Sutter, and J. Vymazal, 1992. Effects of Nutrient Loadings and Hydroperiod Alterations on Control of Cattail Expansion, Community Structure and Nutrient Retention in the Water Conservation Areas of South Florida. Annual Report to Everglades Agricultural Area Environmental Protection District, Duke Wetland Center Publication 92-11.

State of Florida, 1994. Everglades Forever Act.

Swift, D. R., 1984. Periphyton and Water Quality Relationships in the Everglades Water Conservation Areas. *In:* Environment of South Florida, Present and Past II, P. J. Gleason, (Editor). Miami Geological Society, Coral Gables, Florida.

Swift, D. R. and R. B. Nicholas, 1987. Periphyton and Water Quality Relationships in the Everglades Water Conservation Areas. South Florida Water Management District, Technical Report 87-2.

Toth, L. A., 1987. Effects of Hydrologic Regimes on Lifetime Production and Nutrient Dynamics of Sawgrass. South Florida Water Management District, Technical Report 87-6.

Urban, N. H., S. M. Davis, and N. G. Aumen, 1993. Fluctuations in Sawgrass and Cattail Densities in the Everglades Water Conservation Area 2A Under Varying Nutrient, Hydrologic, and Fire Regimes. Aquatic Botany 46:203-223.

Vollenweider, R. A., 1969. Possibilities and Limits of Elementary Models Concerning the Budget of Substances in Lakes. Arch. Hydrobiol. 66(1):1-36.

Walker, W. W., 1991. Water Quality Trends at Inflows to Everglades National Park. Water Resources Bulletin 27(1):59-72.

Walker, W. W., 1993. A Mass-Balance Model for Estimating Phosphorus Settling Rate in Everglades Water-Conservation Area 2A. Report to U.S. Department of Justice, Environment and Natural Resources Division.

Worth, D., 1988. Environmental Response of WCA-2A to Reduction in Regulation Schedule and Marsh Drawdown. South Florida Water Management District, Technical Publication 88-2.