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A Model for Simulating Phosphorus Concentrations in Waters and Soils Downstream of Everglades Stormwater Treatment Areas

prepared for

U.S. Department of the Interior

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ABSTRACT

The model used for Stormwater Treatment Area (STA) design is expanded to include mass balances on marsh waters and surface soils. EPGM (Everglades Phosphorus Gradient Model, Figure 1) simulates variations in water-column P concentration, peat accretion rate, and soil P concentration along a horizontal gradient imposed by an external phosphorus load and sheet-flow conditions. Potential biological responses are expressed in terms of marsh surface areas exceeding threshold criteria for water-column and soil phosphorus concentrations. Areas exceeding water-column P threshold criteria (10 to 30 ppb) are surrogates for impacts on ecosystem components which respond primarily to variations in water-column concentration (e.g., periphyton, algae). Areas exceeding soil P threshold criteria (540 to 990 mg/kg) are surrogates for impacts on ecosystem components which respond primarily to variations in soil P (e.g., rooted vegetation). Cattail densities and total areas are predicted based upon correlations with soil P concentration. EPGM is calibrated to soil and vegetation data from WCA-2 (primarily), WCA-1, and WCA-3A.

The linked water and soil mass balances suggest that there is a linear relationship between water-column and soil P concentrations averaged over long time scales. Times required for soil P levels to reach steady-state following a change in average water-column concentration are derived by mass balance. Steady-state is achieved when the rate of P accretion from above is balanced by the rate of P burial below the simulated depth interval. Soil response times are inversely proportional to average water-column concentration. With.a 50-ppb average concentration, soil response times are 20 and 40 years for soil depths of 10 and 20 cm, respectively.

The model successfully simulates observed horizontal gradients in soil P concentration downstream of the S10 structures in WCA-2A after ~28 years of external P loading (1962 to 1990). The simulated area with 0-20 cm soil P concentration exceeding 720 mg/kg is the best predictor of observed cattail expansion between 1973 and 1991. Model results indicate that soil P concentrations and cattail densities in this region have not reached steady-state in response to historical P loads. The soil impact area would continue to expand at a reduced rate for another 30 years if P loadings were maintained at historical levels.PGM is used to estimate P-related impacts of routing 50 ppb STA discharges through flow-distribution structures designed to improve hydropattern and hydroperiod in the northern Everglades. Impacts likely to occur within 4-8 years after start of discharge (the expected maximum duration of 50 ppb concentrations) are evaluated. Simulations are performed for average hydrologic conditions. Water-column impact areas range from 315 to 12,000 hectares, depending upon STA and P threshold criterion (10 - 30 ppb). Soil impact areas range from 0 to 1755 hectares, depending upon STA, threshold criterion (540 - 990 mg/kg), and simulated soil depth (0-10, 0-20 cm). Because of differences in initial soil conditions, predicted initial rates of soil P increase and cattail growth are much lower below STA's -34, -5, and -6 than below STA-2. Simulations indicate that if the 50 ppb discharges were to continue over longer time frames (> 20-40 years), soil impact areas would be similar in scale to water-column impact areas.

The distinction is made between the gross and net impacts of discharging through the hydropattern-restoration facilities. Discharging to other locations would displace phosphorus impacts of similar magnitude to other WCA locations. This would delay recovery and risk further expansion of existing impacted zones. Other factors to be considered in evaluating discharge alternatives include (1) likelihood that discharges to canals would promote P transport over longer distances; (2) long-term impacts of additional phosphorus loads occurring as a result of delays in STA construction if alternative discharge locations were selected; and (3) possible reversibility of biological impacts caused by short-term increases in water-column P (vs. Soil P) concentrations. Overall, the project is expected to provide substantial long-term reductions in wetland areas exceeding P threshold criteria for soil and water as a result of the substantial (~80%) decrease in P load. Delays in achieving these load reductions using available STA technology would translate into additional cumulative P load to the system and risk further expansion of the existing impacted area before Phase II control technology can be developed and implemented.

The sensitivity of model predictions to input variables (coefficients, initial conditions, driving variables) is explored using several techniques. Considering its structure, calibration, and sensitivities, EPGM is most reliable for predicting long-term-average water-column and soil P levels. Measured initial soil conditions have a strong influence on predicted soil P and cattail responses within a 4-8 year time frame. Refinements to the model structure are needed to improve model performance over short time scales in response to variations in hydrology (flow, hydroperiod, drought), P loading, biomass P storage, and STA startup phenomena.

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Introduction

Interim plans for controlling Everglades eutrophication involve construction of six Stormwater Treatment Areas (STA's) designed to reduce phosphorus concentrations in Water Conservation Area (WCA) inflows to a long-term flow-weighted mean of 50 ppb or less. This will be accomplished under the Everglades Construction Project slated for completion between 1997 and 2005 (Burns & McDonnell, 1994). The long-term solution may involve further treatment to concentrations below 50 ppb, depending upon results of ongoing research to develop a numerical phosphorus standard. A default value of 10 ppb will apply if the standard is not developed and adopted within the required time frame. Depending upon determination of the standard and upon observed STA performance, implementation of additional control measures upstream of or within the STA's may be required to achieve compliance with the long-term standard by the required date (December 31, 2006).

The STA's have been sized to meet the 50 ppb objective using a model which simulates the long-term-average water and phosphorus balances of the treatment marshes (Walker, 1995). Additional calibration and testing of the model would be useful for improving performance over wider ranges of conditions, as defined by phosphorus concentration, hydroperiod, marsh community types, and initial soil conditions. Greater complexity is needed to permit simulation of temporal variations (e.g. month-to-month or year-to-year). These refinements would promote uses of the model for optimizing STA operation to achieve phosphorus concentrations below 50 ppb, for simulating STA startup periods, for interpreting measured performance data, and for predicting spatial and temporal variations in the concentrations of phosphorus in the water column and soils downstream of the treatment wetlands. Appropriate factors for consideration in future versions of the model include phosphorus storage in soil, phosphorus storage in biomass, and drought-induced recycling.

This report describes refinements of the model to include phosphorus balances on both the water column and surface soil. The refined model (EPGM = Everglades Phosphorus Gradient Model, Figure 1) predicts phosphorus concentrations in the water-column and surface soil along a longitudinal gradient established by an external phosphorus source and uniform sheet flow. Relative to the water column and biomass, surface soils store relatively large quantities of phosphorus and integrate conditions over longer time scales. Changes in soil phosphorus levels are important because they may reflect long-term impact and because spatial variations in soil P are correlated with spatial variations in dominant vegetation (i.e. native sawgrass or slough communities vs. cattail and other species characteristic of eutrophic marshes). Marsh areas exceeding threshold criteria for water-column and soil phosphorus concentrations are used as surrogates for ecosystem impacts. The soil model is calibrated and tested against data from WCA-2A (primarily), WCA -1, and WCA-3A.

The model is applied to predict impacts of proposed STA discharges through distribution structures designed to improve hydropattern and hydroperiod in northern Eve les marshes (Figure 2). These simulated regions include (SFWMD, 1996b):

STA	Receiving Area	Completion Date
2	WCA-2A - Northwest	January 1999
34	WCA-3A - Northeast	October 2003
6	WCA-3A - Northwest	January 1999
5	Rotenberger - North	January 1999

Completion dates reflect construction of the STA's and flow distribution structures. Historically, the receiving marsh areas have not been directly exposed to anthropogenic phosphorus loads. Concerns have been raised about impacts in these areas resulting from the fact that treated inflows may have phosphorus concentrations above the long-term standard for the period between completion of the STA's and implementation of Phase 2 control measures.

Determination of the phosphorus standard and implementation of controls for meeting that standard are scheduled to be completed by 2007. Completion dates for the above STA's and associated outflow distribution facilities range from 1999 to 2003. If the standard is determined to be less than 50 ppb and if the STA's perform according to design, the duration of 50 ppb discharge will be 4-8 years. Any impacts resulting from discharge of 50 ppb water would have to occur within this time frame.

The model is applied to predict impacts of the 50 ppb discharges on marsh water-column and soil phosphorus concentrations downstream of each structure. Although results for longer time frames are given to demonstrate sensitivity, the report focuses on impacts potentially occurring with the relevant 4-8 year time frame. STA's 1E and 1W are not evaluated because alternative discharge locations are not being considered for these facilities and because the sheet-flow assumption inherent in the analysis is not valid for the Refuge. Regardless of discharge location and possible localized increases in water-column and soil P concentrations, the interim level of treatment provided by the STA's is expected to provide 3 to 4-fold reductions in existing phosphorus loads and associated impacts on downstream marshes.

Since idealized representations of flow patterns are employed (uniform sheet flow) and simulations are performed for average hydrologic conditions, the model provides general indications of the spatial and temporal scales of impact and is not intended to predict conditions at a particular latitude and longitude or on a particular date. With appropriate modifications to hydraulic elements, more complex flow-distribution patterns could be simulated. The model predicts impacts of external phosphorus loads on P distribution in the soil and water and related potential for expansion of cattail populations. Impacts on vegetation relating to changes in flow or hydroperiod are not evaluated. These applications of the model help to identify sensitive variables, data needs, and appropriate directions for further model development.

Model Development

EPGM consists of coupled differential equations representing a flow balance, water-column mass-balance, and soil-column mass-balance under sheet-flow conditions. Model structure is shown in Figure 1. The flow and water-column mass balances are identical to those used as a basis for STA design (Walker, 1995). The model predicts steady-state flow and phosphorus concentration profiles downstream of the STA. Flow input terms include discharge from the STA and rainfall. Flow output terms include downstream discharge and evapotranspiration. Phosphorus input terms include STA phosphorus loads and atmospheric deposition (uniform over simulated area). Phosphorus output terms include downstream discharge and net deposition to soils. Net phosphorus deposition is represented as a first-order process which is proportional to surface area and water-column concentration. Soil accretion is represented as the only long-term, sustainable mechanism for phosphorus removal from the water column.

The following differential equation describes the flow balance and water-column phosphorus balance under sheet-flow conditions at steady state (Walker, 1995; Kadlec & Knight, 1996):

$$dQ/dA = P - E \tag{1}$$

b. c.: $Q = Q_i$ @ $A = 0$

$$S = K_e F_w C \tag{2}$$

$$d(QC)/dA = P C_p \quad S = P C_p - K_e F_w C \tag{3}$$

b.c.: $C = C_i$ @ $A = 0$

where,

Q	=	Flow (hm^3/yr)
A	=	Accumulated Area (km^2)
Q_i	=	Inflow Volume (hm^3/yr)
C_i	=	Inflow Phosphorus Concentration
E	=	Evapotranspiration Rate (m/yr)
P	=	Precipitation Rate (m/yr)
C	=	Water-Column Phosphorus Concentration (ppb)
S	=	Phosphorus Accretion Rate (mg/m^2-yr)
W	=	Width of Discharge Path (km)
K_e	=	Phosphorus Settling Rate (m/yr)
F_w	=	Hydroperiod (Fraction of Time System is Wet)
C_p	=	Rainfall P Concentration (ppb)

Solutions can be expressed as follows:

$$A = WX \tag{4}$$

$$C_b = P\,C_p / (F_w K_e) \tag{5}$$

$$R = 1 + F_w K_e / (P - E) \tag{6}$$

$$Q = Q_i + (P-E)\,A \tag{7}$$

$$C = C_b + (C_i - C_b)\,[\,Q / Q_i\,]^{-R} \tag{8}$$

where,

X	=	Distance Downstream of Inflow (km)
R	=	a convenient dimensionless variable
C_b	=	marsh background concentration (@ A = ∞) (ppb)

These equations permit prediction of flow and water-column concentration at any point (X km) downstream of the STA discharge assumed to be uniformly distributed over a defined width (W km). The hydroperiod coefficient (F_w) accounts for drought conditions, when no net P accretion is assumed to occur. Drought-induced recycling of soil P is not simulated directly, but is implicit in calibration of the settling rate (K_e).

A fixed depth interval (e.g., 0-10 cm or 0-20 cm) establishes the control volume for the soil mass balance at any point downstream of the STA discharge. EPGM tracks both the total soil mass within the control volume (average bulk density) and the total phosphorus mass. The model simulates the accumulation of new soil on top of the soils present at the time of STA startup. Each soil layer (new soil, initial soil) is assumed to be of constant (but possibly different) bulk density. The only input term for total soil mass is accretion (i.e., creation of new organic soils from the decay of vegetation at the soil surface). The only output term is burial (i.e., downward movement through the bottom of the control volume located a fixed depth from the soil surface). As soil accretion occurs at the surface (typical rates 0.2 - 1.0 cm/yr or 0.1-0.6 kg/m ^{2}-yr), soil exits at the bottom of the control volume. Corresponding accretion and burial terms are considered for soil phosphorus.

Figure 3 plots 10 cm (interpolated) vs. 0-10 cm (average) and 20 cm vs. 0-20 cm soil P concentrations in cores from WCA-2A (Reddy et al., 1991; Duke Wetland Center, 1992) and WCA-3A (Reddy et al., 1994b). For each depth, bottom concentrations are relatively constant for average concentrations between 300 and 1000 mg/kg. The 300 to 1000 mg/kg range is of primary interest for modeling increases in soil P concentrations from background levels to levels associated with vegetation change. At higher average concentrations, bottom concentrations increase, especially for a soil depth of 10 cm. These patterns presumably reflect enrichment from the top of the soil column and eventual penetration of the 10 cm depth with enriched soils in areas with high average soil P concentrations and high accretion rates. This picture is generally consistent with vertical profiles taken along the S10C transect in WCA-2A (Figures 4-6). Soils above the Cesium-137 peaks (as marked) reflect enrichment occurring after the early 1960's, when maximum atmospheric deposition of Cesium-137 occurred and when opening of the S10 structures substantially increased phosphorus loads to the area.

Mass balances on soil and soil phosphorus are constructed for two time intervals:

(1) Initial Phase. New soil accumulates on top of the initial soil at a fixed rate. Output concentrations at the bottom of the control volume (fixed depth) reflect vertical gradients in the initial soil profile.

(2) Final Phase. Steady-State. Starts when the depth of new soil equals the depth of the control volume. Soil properties in control volume equal properties of new soil.

Advective and diffusive transport of phosphorus across the bottom of the soil control volume (in pore waters) are ignored. There is no evidence to suggest that such mechanisms are important. If they do exist, their influences are implicit in the calibration of the settling rate (K_e). If a net downward flux could be quantified and added to the output term of the soil phosphorus balance, the settling rate parameter would also have to be re-calibrated (increased) because the 10.2 m/yr estimate assumes that this transport mechanism is negligible. Considering this mechanism would have little or no influence on the steady-state longitudinal soil phosphorus profile because it would increase both the input and output terms of the soil phosphorus mass balance.

With the above assumptions, the following differential equation describes the soil mass balance at a fixed location downstream of the STA discharge:

$$d\,M/d\,t = T - 10\,V\,D_i = T - T\,D_i/D_s \tag{9}$$

$$\text{b.c.:} \quad M = M_i \;@\; t = 0$$

$$T = 10\,D_s\,V \tag{10}$$

$$M_i = 10\,D_i\,Z \tag{11}$$

where,

M	=	Soil Mass Per Unit Area (kg/m^2)
t	=	Time (years)
T	=	Soil Mass Accretion Rate (kg/m^2-yr)
V	=	Soil Volume Accretion Rate (cm/yr)
D	=	Soil Bulk Density (g/cm^3)
Z	=	Soil Column Depth (cm)
I	=	Subscript Denoting Initial Soil Property

s = Subscript Denoting New or Steady-State Soil Property

The solution is given for two time intervals: before and after the point at which the depth of new soil equals the depth of the control volume:

$$M = M_i + T(1 - D_i / D_s)\,t \qquad , t <= t_e \tag{12}$$

$$M = M_s \qquad , t > t_e \tag{13}$$

$$M_s = 10\,D_s\,Z \tag{14}$$

$$t_s = M_s / T = Z / V \tag{15}$$

where,

t_s = Time to Steady-State Soil Profile (years)

These equations represent a linear decrease (if $D_s < D_i$) or increase (if $D_s > D_i$) in soil mass per unit area until steady state (t_s) is reached, at which point the control volume is filled with new soil and results are independent of initial soil conditions.

The following differential equation describes the soil phosphorus balanc

$$d(MY)/dt = S - 10^4 V X_z \tag{16}$$

$$\text{b.c.:} \quad MY = M_i Y_i \ @ \ t = 0$$

As for the soil mass balance, the solution is given for two time intervals:

$$MY = M_i Y_i + St - 10^4 Z_n (X_i + gZ/2) + 5x10^3 g Z_n^2 \quad t <= t_s \tag{17}$$

$$MY = M_s Y_s = S\,Z / V, \quad t > t_s \tag{18}$$

$$Z_n = V t \tag{19}$$

$$X_z = X_i \quad g(Z_n - Z/2) \tag{20}$$

$$X_i = 10^{-3} Y_i D_i \tag{21}$$

where:

Y = Average Soil P Content over Depth 0 to Z (mg/kg)
Y_s = Steady-State Soil P Content (mg/kg)

X_i = Initial Average Volumetric Soil P Content over Depth 0 to Z (mg/cm ^{3})
X_z = Volumetric Soil P Content at Depth Z (mg/~~kg)~~ cm³
g = Vertical Gradient in X Present in Initial Soil (mg/cm ^{3}/cm)
Z_n = Accumulated Depth of New Soil (cm)

During the initial phase, the output concentration is estimated assuming that the initial (relatively unenriched) soil contains a linear gradient in volumetric soil P concentration (slope = g in mg/cm^3/cm) within the model depth range (0-10 or 0-20 cm). This is supported by soil profiles at relatively unenriched sites in WCA-2A (Figure 5) and by additional data presented below.

An estimate of the soil mass accretion rate (T, kg/m ^{2}-yr) is required in order to solve above equations. This estimate is derived from an empirical model relating the average phosphorus content of soil above the Cesium-137 peak to the average phosphorus accretion rate:

$$Y_s = a + b\,S \tag{22}$$

Combining equations (22) and (18) ,

$$T = S / Y_s = S / (a + b\,S) \tag{23}$$

The model is calibrated to soil accretion data from WCA's-1, 2A and 3A below.

At steady-state ($t > t_s$), soil characteristics within the control volume are constant and independent of the initial soil characteristics. Combining the above equations, this condition is described by:

$$t_s = M_s / T = 10\,D_s\,Z\,(a + b\,S) / S = 10\,D_s\,Z\,(b + a / K_e F_w C) \tag{24}$$

$$Y_s = a + b\,K_e\,F_w\,C \tag{25}$$

Suppose that undesirable changes in Everglades macrophyte communities are associated with average soil phosphorus levels above a hypothetical threshold (Y_t, mg/kg). Equation 25 can be solved for the corresponding threshold concentration (C_t, ppb):

$$C_t = (Y_t - a) / b\,K_e\,F_w \tag{26}$$

This provides a quantitative linkage between soil and water phosphorus criteria for avoiding undesirable shifts in macrophyte communities. For a given soil P threshold, the water-column threshold is inversely proportional to the effective P settling rate (K_e) and wet fraction (F_w).

Model Calibration

Calibration of the water-column flow and phosphorus balances based upon data from WCA-2A (Walker,1995) yields the following settling rate estimate:

$$K_e = 10.2 \pm 0.8 \text{ m/yr} \tag{27}$$

This estimate has been derived from a region with P accretion rates between 100 and 1200 mg/m^2-yr and average water-column phosphorus concentrations between 10 and 120 ppb.

Deviations from the predicted long-term-average concentration and phosphorus accretion profiles may occur during the startup phase of each STA (~1-2 years), as the soils and biota adjust to new loading conditions (Kadlec & Newman, 1992; Kadlec & Knight, 1996). During this period, a portion of the influent phosphorus load will be stored in the form of increased biomass. Net adsorption to soils is another transient phosphorus sink. As a result, settling rates during this period may exceed the long-term average rate (which reflects only net peat accretion).

Simulations are performed using a settling rate sequence of 30 m/yr in the first year, 20 m/yr in the second year, and 10.2 m/yr thereafter. This range is consistent with observed performance of wetland treatment systems during the startup phase (Kadlec & Knight, 1996). During the stabilization phase of the Iron Bridge (Florida) treatment system, for example, the settling rate decreased from ~ 30 m/yr to ~10 m/yr. The higher settling rates in Years 1 and 2 apply to the upstream end of the discharge zone. K_e values revert to 10.2 m/yr at the location where the predicted concentration equals the background concentration (equation 5) calculated with a K_e value of 10.2 m/yr.

The relationship between soil phosphorus content and phosphorus accretion rate (equation 22) has been calibrated to data from WCA-2A (Reddy et al., 1991; Duke Wetland Center (1992); Craft & Richardson (1993)), WCA-3A (Reddy et al., 1994b, Robbins et al., 1996), and WCA-1 (Reddy et al., 1994a, Robbins et al., 1996). Observed and predicted values for soil phosphorus content and mass accretion rate are shown in Figure 7. The calibrated parameters and equations are as follows:

$$a = 463 \pm 27 \tag{28}$$

$$b = 1.467 \pm 0.124 \tag{29}$$

$$Y_s = a + b\,S \qquad (\, r^2 = 0.78,\ SE = 171 \text{ mg/kg}\,) \tag{30}$$

$$T = S\ /\ (\,a + b\,S\,) \qquad (\, r^2 = 0.88,\ SE = 0.05 \text{ kg/m}^2\text{-yr}\,) \tag{31}$$

The calibration reflects the average soil response integrated over 26-29 years of peat accretion. Model parameter values may deviate from these average values during the startup or transition period when the system is responding to a change in phosphorus loading. As described above, the transition period is simulated using elevated settling rates. During this period, the predicted total soil accretion rate (T, kg/m^2- yr) is constrained to the value predicted using the long-term-average settling rate. The P content of new soil (Y_s) is increased accordingly to preserve the phosphorus balance. This injects the excess phosphorus removal associated with transition phenomena into the soil without accreting additional soil. Essentially, this is a worst-case scenario in terms of predicting the net rate of increase in soil phosphorus content (Y). This assumption is implemented by modifying equations (22) & (23) as follows:

$$Y_s = a f + b S \tag{32}$$

$$T = S / Y_s = S / (a f + b S) \tag{33}$$

$$f = K_e / K_{eo} \tag{34}$$

where:

K_{eo}	=	Long-Term-Average Settling Rate (m/yr)
f	=	Settling Rate Enhancement Factor During Transition Period

This assumption increases the net rate of phosphorus buildup in the soil during the transition period, relative to the rate predicted using equations 22 & 23. To the extent that actual soil accretion rates exceed the long-term average during the transition phase, the assumption results in an over-prediction of net phosphorus buildup.

According to equations 24 and 25, the parameter values a = 463 and b = 1.467 influence both the time scale of the soil response (t_s) and the steady-state solution (Y_s). Figure 8 plots t_s and Y_s as a function of water-column concentration for each parameter set and for the following conditions: Z = 10 cm, K_e = 10.2 m/yr, F_w=1.0, and D_s = .08 g/cm^3. For phosphorus concentrations between 10 and 50 ppb, soil response time ranges from 50 to 20 years and soil P levels range from 600 to 1200 ppb. Response times for a 20-cm soil depth would be twice those shown for a 10-cm soil depth. Figure 9 shows that decreasing the average hydroperiod (fraction of time that water levels are above ground surface) increases both the water-column threshold and the soil response time.

Initial soil and water-quality conditions in the discharge zone of each modeled STA are summarized in Table 1. Soil properties required to drive the simulation of each STA include:

D_i	=	Bulk Density of Initial Soil (g/cm ^{3})
Y_i	=	Initial Soil P Content (mg/kg)
D_s	=	Bulk Density of New Soil (g/cm ^{3})
g	=	Vertical P Gradient in Initial Soil (mg/cm ^{3}/cm)

Values for D_i, Y_i and g are derived from soil measurements in relevant portions of WCA-2A, WCA-3A, and Rotenberger (Reddy et al., 1991; Reddy et al, 1994b; SFWMD,1996c). Properties are estimated for 0-10 and 0-20 depth intervals.

Based upon pooled data from least impacted sites in WCA-2A and 3A (Figure 10), a typical gradient estimate is g = -0.0019 mg/cm ^{3}/cm (standard error = 0.000016). In each simulation, the initial soil gradient is estimated from direct measurements. The vertical gradient (g, mg/cm ^{3}/cm) is calculated from the following equation, using measurements typically available for 0-10 and 10-20 cm intervals:

$$g = (Y_{0-10} D_{0-10} - Y_{10-20} D_{10-20}) \times 10^{-4} \tag{30}$$

This estimates the gradient based upon the difference between the 0-10 cm concentration and the 10-20 cm concentration. More precise estimates of g could be developed from detailed vertical profiles at specific sites (if available). Simulations indicate, however, that predictions of soil P response are very insensitive to this parameter (i.e., assuming g=0 or no gradient gives approximately the same results). Like other initial soil properties, values for this parameter do not influence the steady-state soil phosphorus values (equation 25).

The bulk density of new soil, D_s (g/cm^3) is set at 0.08 g/cm^3, based upon measured densities in the NW region of WCA-2A (discharge zone of STA-2). It is assumed that this reflects typical marsh soils generated under hydrologic conditions similar to those expected in the STA discharge zones. Soils at other STA discharge sites (northern WCA-3A and Rotenberger) have higher initial bulk densities (0.18 to .22 g/cm^3). Higher densities probably reflect frequent dryout and mineralization at these locations under historical conditions. It is assumed that new soils formed in these areas under future conditions (~continuously wet) will have bulk densities similar to those currently found in WCA-2A. If new soils formed in these areas actually have higher bulk densities, soil response times would be longer than those predicted (equation 24).

Water-column phosphorus concentration in relevant areas of WCA-2A and WCA-3A are available for two time intervals: 1978-1984 (contains wet and dry years) and 1995-1996 (wet years) (Table 1). Geometric-mean concentrations range from 13 to 20 ppb and from 7 to 8 ppb in each period, respectively. The apparent temporal variations are partially attributed to variations in hydrologic conditions. These concentration values are provided for descriptive purposes, but are not used in modeling.

The following model input variables reflect atmospheric inputs and outputs:

P = 1.23 m/yr	STA Design Basis (Burns & McDonnell,1994)
E = 1.38 m/yr	Abtew & Sculley(1991); SFWMD (1996b)
C_p = 30 ppb	Walker (1995); Davis (1994)

The remaining model input variables reflect boundary conditions or measured soil characteristics specific for each STA simulation:

W	=	Discharge Width (km)
Q_i	=	STA Outflow Volume (hm ^{3}/yr)
C_i	=	STA Outflow Concentration (ppb) = 50 ppb
F_w	=	Hydroperiod (%)

Discharge widths have been derived from the project conceptual design document (Burns & McDonnell, 1994). STA outflow volumes include both treated runoff and BMP replacement water. They include only those portions of the STA discharges which will be released through flow distribution structures. Flows into Rotenberger (from STA-5) and flows into the NW corner of WCA-3A (from STA's 5 & 6) are derived from the South Florida Water Management Model (SFWMM Version 2.9, Neidrauer, 1996) . Flows into the NW region of WCA-2A (from STA-2) and into the NE corner of WCA-3A (from STA-34) are derived from SFWMD(1996b). Estimates of hydroperiod ranging from 61% for STA-6 to 92% for STA-2) are also derived from SFWMM results using model grid cells defined in Table 1.

Biological Response

As illustrated in Figure 2, the last step in the model linkage is to predict biological responses. based upon predicted changes in water-column and soil P concentrations. Biological responses are expressed in the following terms:

1. Marsh areas with long-term-average water-column concentrations exceeding threshold criteria of 10, 20, and 30 ppb.

2. Marsh areas with soil P concentrations exceeding criteria or thresholds for cattail dominance (range 540 to 990 ppb, derived below).

3. Total cattail area, estimated from a logistic equation relating cattail density (% coverage) to soil P concentration.

Item 1 is a surrogate for impacts on ecosystem components which respond to water-column concentrations in the 10-30 ppb range (e.g., periphyton, algae). Items 2 and 3 are surrogates for impacts on ecosystem components which respond to soil P concentrations in the 540-990 ppb range (e.g., cattails & other rooted vegetation). The soil threshold values are calibrated to data from WCA-2A. A range of threshold values is used to reflect the uncertainty involved in applying these values to other regions.

The model estimates changes in cattail areas and densities potentially resulting from changes in external phosphorus loads. Changes resulting from other factors (water depths, fire, etc.) may occur but are not considered here. Although macrophyte changes may be driven by available phosphorus (vs. total), a much more complex model would be required to predict individual phosphorus fractions. Available P (as measured by bicarbonate extractable P) averages less than 2% of Total P but is highly correlated with Total P in WCA-2A soils (Reddy et al., 1991).

Previous studies have correlated spatial variations in dominant vegetation with soil P levels in WCA-2A. Data summarized by Duke Wetland Center (1995) indicate that increases in soil P levels are spatially correlated with declines in native slough macrophyte species (e.g., Eleocharis, Utricularia, Cladium) (Figure 11). These species are replaced by cattail and other macrophytes characteristic of eutrophic Everglades. In discussing these results, Richardson (1996) noted that shifts in dominant vegetation from oligotrophic to eutrophic species generally occurred at surface soil P levels above 500-700 mg/kg. DeBusk et al (1994) reported average soil phosphorus concentrations (0-10 cm) in three WCA-2A plant communities:

Community	Soil P (mg/kg)
Sawgrass	473 ± 134
Mixed	802 ± 444
Cattail	1338 ± 381

Wu et al.(1996) developed a Markovian model of cattail propagation in WCA-2A; the maximum rate of conversion from native vegetation to cattails occurred at a soil P content of 650 mg/kg (0-10 cm). The above three studies all suggest soil P thresholds for spread of cattails in the 500-700 mg/kg range for a depth interval of 0-10 cm. Soil P concentrations in the same range are correlated with reductions in alkaline phosphatase activity in ENP soils (Jones, 1990).

None of the above studies examined sensitivity of soil criteria to the depth interval over which soil P concentrations are averaged. Because of mass-balance constraints, simulations of soil P response to surface-water loads are sensitive to the assumed soil-column depth. If simulated soil P levels are to be used to predict vegetation change, the depth should be set at a value which has the most biological meaning. The surface layer where seed germination occurs and where plant root systems tend to be most concentrated is one possible frame of reference. The entire root zone (typically 0-30 cm, Kadlec & Knight, 1996) is another frame of reference.

Because soil P concentrations used for initializing the model and for calibrating vegetation response are typically measured in 10 cm intervals, there are three practical choices for soil-column depth (0-10, 0-20, or 0-30 cm). Under the assumption that any vegetation change related to soil enrichment would be driven by exposure of plant root systems to enriched soils, the most meaningful measure of soil P content would be vertically averaged over the entire root zone and weighted based upon the surface area of roots in each depth interval. The 0-10 cm interval may be too shallow because it excludes a significant portion of the root zone. On the other hand, the 0-30 cm interval may be too deep because both root density and soil P content tend to decrease with depth. A simple vertical average over 30 cm would place too much weight in the 20-30 cm horizon and too little weight on the 0-10 cm horizon. For typical vertical P gradients and root geometry, the 0-20 cm simple average most closely approximates the 0-30 cm weighted average. Model simulations are performed using depth intervals of 0-10 cm and 0-20 cm. As demonstrated below, the 0-20 cm depth interval provides a sharper contrast of vegetation types and a better simulation of observed cattail expansion below the S10 structures in WCA-2A .

It has been suggested that soil P criteria might be more meaningfully expressed on a volume basis (mg/cm^3), as compared with a mass basis (mg/kg). Two soils with the same soil P content on a mass basis but with different bulk densities would have different volumetric concentrations and different total quantities of soil phosphorus stored within a defined depth interval. If these factors drive vegetation response, expression on a volumetric basis may be appropriate. If, on the other hand, vegetation response is driven by porewater concentrations which are controlled by adsorption isotherms, expression on a mass basis may be appropriate. Both units of expression are available from model simulations, although mass concentrations are found to be more strongly correlated with observed vegetation patterns.

Criteria (or threshold) values for use in simulating areas downstream of STA discharges have been estimated using paired soils and vegetation data from WCA-2A (Reddy et al., 1991) and WCA-1 (Reddy et al., 1994a; Newman, 1996). With sites initially classified into two groups based upon observed vegetation communities, criteria estimates have been optimized by selecting values which result in the least number of mis-classified sites. Goodness-of-fit is characterized by percent classification error. The WCA-2A data cover 74 sites with vegetation classified into three groups (49 sawgrass, 13 mixed, 12 cattail). The WCA-1 data cover 90 sites with vegetation initially classified into four groups based upon cattail occurrence (66 absent, 4 present, 15 significant, 5 cattail dominant). Because of the limited numbers sites in the second and fourth groups, vegetation classes have been collapsed into 2 groups (66 cattail absent vs. 24 cattail present). Results for each soil depth interval, soil P expression, WCA, and vegetation contrast are summarized in Table 2 and Figure 12.

Based upon classification error, mass-based criteria perform better than volume-based criteria for both depth intervals and in both WCA's. Classification errors are similar for the 0-10 cm and 0-20 cm depth intervals, but criteria values are lower for the 0-20 cm depth. Mass-based soil P criteria for WCA-1 (cattail present vs. absent) are similar to criteria for WCA-2A (sawgrass vs. mixed or cattail). The cattail vs. sawgrass contrast in WCA-2A has the lowest classification error (1.4% or 1 misclassified site out of 74) for either depth interval. The following criteria or thresholds are used in model simulations:

		Soil Total P (mg/kg)	
Threshold	Contrast	0-10 cm	0-20 cm
Low	Sawgrass <--> Mixed or Cattail	610	540
Medium	Sawgrass <--> Cattail	870	610
High	Sawgrass or Mixed <--> Cattail	990	720

In addition to having higher classification errors, volumetric criteria do not exhibit the expected increase in criteria moving from the first to the third contrast. For 0-10 cm, volumetric criteria range from 0.060 to 0.062 mg/cm ^{3}, while mass criteria range from 610 to 990 mg/kg. Mass criteria are used in STA simulations because they appear to be more strongly correlated with vegetation types. Sensitivity of results to the assumed criteria units is examined.

The above soil threshold values are used to demonstrate application of the model. Additional data and analyses may suggest other soil criteria. Using equations 24-26, soil thresholds of 540 - 990 mg/kg correspond to steady-state water-column concentrations ranging from 5 to 35 ppb and to soil response times ranging from 22 to 164 years under conditions specified in Figure 8.

To provide a basis for comparing model with results with those reported by SFWMD (1996b), predictions of "total cattail area" are developed by mapping the spatial distribution of soil P levels predicted for a given year onto a logistic function relating cattail density (% of area) to soil P. Separate functions are developed for the 0-10 cm and 0-20 cm soil depths (Figure 13). The model is similar in form to that used by Wu et al. (1996) for predicting annual vegetation transition probabilities as a function of soil P levels.

Logistic parameters are calibrated to the soil P criteria estimated above (Table 2). Threshold soil P values are paired with the following estimates of cattail density at the boundaries of the vegetation categories:

Threshold	Low	Medium	High
Community	<---Sawgrass	<--Mixed-->	Cattail --->
Cattail Density	<---5.0%	<--23.6%-->	42.3% --->

The "Sawgrass" sites are assumed to contain a maximum cattail density of 5%. This density is paired with the "Low" criteria in Table 2 for distinguishing between "Sawgrass" and "Mixed" sites. Based upon reduction of 1991 satellite image data (Jensen et al, 1995), the average density of cattails in regions classified as "Cattail" (sparse, medium, dense) was 60.4%. Similarly, the average cattail density in areas classified as various mixtures of sawgrass and cattail was 24.1%. It is assumed that these densities are applicable to the "Cattail" and "Mixed" sites, respectively, in the data set used above to derive the criteria (Reddy et al, 1991). The spatial density corresponding to the "high" criterion for distinguishing between "Cattail" and "Mixed" site is calculated as the midpoint of the group averages ((60.4% + 24.1%)/2 or 42.3%). The density corresponding to the "medium" threshold for distinguishing between "Sawgrass" and "Cattail" sites is calculated as the midpoint of the densities corresponding to the "Low" and "High" threshold (5% + 42.3%)/2 = 23.6%). Logistic curve calibrations are much more sensitive to the High and Low thresholds than to the Medium thresholds.

Logistic equations are fit to paired criteria/density values for each soil depth in Figure 13. Predicted and observed (low, best, & high) criteria values are shown. Resulting equations are:

$$\text{Cattail Density} = [\ 1 + \exp(-(Y - 1034)/144)\ ]^{-1}, \quad \text{for 10-cm soil depth} \qquad (31)$$

$$\text{Cattail Density} = [\ 1 + \exp(-(Y - 727)/71)\ ]^{-1}, \quad \text{for 20-cm soil depth} \qquad (32)$$

When applied to predicted longitudinal soil P profiles, these equations serve as integrators of soil response. The spread of the logistic distribution is much wider for the 10-cm soil depth than for the 20-cm depth (144 vs. 71 mg/kg, respectively). The latter provides sharper resolution of cattail densities. Although the criteria/density pairs conform to the logistic shape, criteria ranges (as defined in Table 2) are wide in most cases. For soil P levels in the predicted ranges described below for 4-8 year time frames (see Results), predictions of cattail area are insensitive to upper portions (densities > 50%) of the logistic curves, which are essentially extrapolations. Additional data (particularly at high densities) and analyses would be needed to refine the calibrations and to estimate confidence limits. In particular, field surveys designed specifically to gather paired cattail density and soil P values would be most useful.

Logistic curves similar to those shown in Figure 13 could be used to model responses of other ecosystem components to changes in soil phosphorus (or water-column phosphorus). Although the graphs are labeled "cattail density", the curves represent the extent of impact on any organism or community that has similar sensitivity to soil phosphorus. Mirror images of these curves would be appropriate for ecosystem components which decrease with increasing phosphorus levels. The 20-cm cattail density-curve is a surrogate for impacts on any component which responds to soil P in the range of 570 to 880 mg/kg (10% to 90% response range). This range is similar to that indicated for decreases in alkaline phosphatase activity in ENP soils (Jones, 1990). Figure 8 indicates that, for a hydroperiod of 100%, steady-state soil P levels in this range correspond to long-term average water-column P concentrations between 7 and 28 ppb. Thus, long-term average cattail densities predicted by the model are surrogates for impacts on organisms which occur as average water-column concentrations increase from 7 to 28 ppb. Conversely, the water-column impact areas predicted below using thresholds of 10-30 ppb would be similar to long-term cattail responses. The equivalent concentration range increases with a decrease in hydroperiod (Figure 9). The correspondence between water-column and soil impacts does not hold for short time scales following a significant change in P loading, however, because of long soil response times (Figure 8).

Model Testing

EPGM has been applied to simulate increases in WCA-2A soil phosphorus concentrations and cattail expansion following opening of the S10 structures in the early 1960's. Data from this region have been used extensively in calibrating key model components and parameters (P accretion rate vs. water-column concentration (K_e), soil P content vs. P accretion rate (Figure 7)). Therefore, comparing observed and predicted soil phosphorus levels does not constitute a truly independent test of the model. Observed average soil P contents for specific depth intervals (0-10 cm and 0-20 cm) along the dated transects have not been used in calibration, however. The exercise provides a means for testing the overall model linkage (water-column balances, soil phosphorus balances, vegetation change), as driven primarily by historical flows and loads from the S10 structures.

Detailed simulation results for the S10's are given in the Appendix. Figure 14 compares observed and predicted longitudinal gradients in soil phosphorus for soil column depths of 10 and 20 cm. Observed values are from dated cores. The relevant starting point of these simulations (t=0) is approximately 1962, when WCA's 1 and 2A were enclosed (Light & Dineen, 1994). Soil measurements were collected in 1990-1991 (Reddy et al, 1991; Duke Wetland Center, 1992), or approximately at t=28 years into the simulation. Average measured values at a depth of ~24 cm (greatest depth sampled by Duke Wetland Center (1992)) are used to estimate initial soil conditions (D_i = 0.102 mg/cm^3, Y_i = 198 mg/kg); soils at 24 cm are below the ~26 year-old Cesium 137 peak (Figures 4-6). Predicted profiles after 28 years of simulation are insensitive to initial conditions, particularly in the upper end of the model zone. Other model input values are listed in Walker (1995). The average inflow phosphorus concentration from the S10s during this period was 122 ppb.

Agreement between observed and predicted soil P levels after 28 years is good for both depth intervals (Figure 14). The top 10-cm of the soil column reached steady-state with the influent phosphorus loads at t=28 years between 0 and 6 km south of the S10's. At this time, 0-10 cm phosphorus levels south of 6 km and 0-20 cm levels south of 0 km (the whole profile) were still increasing. Results indicate that soils in this area have not responded fully to average S10 loads (as measured between 1976 and 1991), except for the top 10 cm between 0 and 6 km. At historical loading rates, stabilization of the impacted area would occur after 48 years (cy 2009) using the 610 mg/kg / 10 cm soil P criterion and after 66 years (cy 2027) using the 720 mg/kg / 20 cm criterion. Future soil P levels will respond (slowly) to future changes in S10 loads. Reductions in S10 loads are expected to result from implementation of agricultural BMP's, construction of STA-1W and STA-1E, diversion of S6, and a higher regulation schedule in the Refuge.

Figure 15 compares the simulated area exceeding each soil P threshold with the observed area of cattails derived from satellite images in 5 years (1973, 1976, 1982, 1982, & 1991). The "observed" values are estimates of "pure" cattail areas calculated as the sum of values across all vegetation categories, weighted according to the average percent cattail density in each category (SFWMD, 1996b). Weights were estimated from 1991 data (Jensen et al., 1995). The observed cattail areas are for the entire WCA-2A; areas below the S10 structures (relevant to these simulations) would be lower than those shown. Given the extensive numerical manipulations necessary for creating the observed data set, these data are considered useful for testing the model, but not for calibrating it.

Agreement with observed cattail area is best for the following predicted variables:

1. Total Cattail Area , Soil Depth = 0-20 cm (from logistic curve, Figure 13); and
2. Area Exceeding High Threshold (720 mg/kg), Soil Depth = 0-20 cm

These variables over-predict vegetation response in the first 20 years or so. Predictions based on a 10-cm soil depth and/or lower threshold criteria are significantly below the observations, especially in the first 20 years. A lag in vegetation response is expected because (1) the model does not account for phosphorus stored in plant biomass (which would decrease the rate of soil P buildup); and (2) cattail spread may be controlled to some extent by fragmentation, as suggested by (Wu et al., 1996). The cattail response model has been calibrated to a snap shot of vegetation & soil P patterns in 1990-1991, after approximately 28 years of S10 discharge. If fragmentation or other factors controlling the rate of cattail expansion are important, there would be a lag between the observed cattail area in the early years and the area predicted based only on soil total P

Simulated total cattail area and area exceeding 720 mg/kg soil P with a 20-cm soil depth are the primary predictors of cattail response below the hydropattern restoration facilities. Based upon S10 cattail data, these predictors appear to be conservative during the first 20 years. To evaluate sensitivity to the biological component of the model, more conservative results using a 10-cm soil depth and/or lower soil criteria are also presented.

Simulation Results

Simulation of water-column and soil phosphorus concentrations in areas between 0 and 15-km downstream of the flow distribution structures have been performed for a period of 40 years using a 1-year time step and 100-meter distance increment. A Lotus-123 spreadsheet (EPGM.WK4) has been constructed for this purpose. Simulations have been performed for each STA discharging to WCA-3A, WCA-2A, or Rotenberger through flow-distribution structures. Soil depth intervals of 0-10 cm and 0-20 cm have been employed. Table 1 summarizes initial soil and hydrologic conditions in each discharge zone. Table 3 summarizes discharge characteristics and key simulation results for 8 base runs (4 STA's x 2 Depth Intervals). The Appendix contains detailed listings of input values and results.

Model predictions are for average hydrologic conditions, as defined by STA discharge volume, hydroperiod, rainfall, and ET. Actual responses will vary, depending the average hydrologic conditions experienced over the relevant 4-8 year time frames. Base runs use K_e values of 30, 20, and 10.2 m/yr in years 1, 2, and >=3, respectively. Sensitivity to variations in hydrologic variables, setting rates, and other input variables is examined in the next section.

Steady-state phosphorus concentration profiles are plotted in Figure 16; these curves apply to the third and subsequent years of each simulation. Distances and marsh areas exceeding 10, 20, and 30 ppb below each STA are listed in Table 3. Areas range from 135 to 12,000 hectares and are highly correlated with the annual phosphorus load divided by the average hydroperiod (Figure 17). As discussed below, these areas should not be considered measures of the net impacts of discharging through the hydropattern restoration facilities on water-column phosphorus concentrations because moving the discharges to alternative locations would move impacts of similar magnitude to other marsh areas. As shown in the Appendix, concentration declines more rapidly with distance during the first two years of each simulation, when setting rates above 10.2 m/yr are used.

Predictions of soil P profiles and cattail areas at the end of 2006 using a 20-cm soil depth are most relevant for evaluating soil-related impacts of the hydropattern restoration facilities. Results over longer time frames and/or using the 10-cm soil depth are also presented to demonstrate sensitivity. The following figures compare soil P and cattail simulation results across STA's:

18 Soil P Concentrations Immediately Below Structures vs. Year
19 Exceedance of Low Threshold Criteria vs. Year
20 Exceedance of High Threshold Criteria vs. Year
21 Total Cattail Areas vs. Year
22 Soil Phosphorus Profiles in Year 2007
23 Cattail Density Profiles in Year 2007

Based upon simulated increases in area exceeding various soil P criteria between the start of each discharge and the end of 2006, results can be summarized as follows:

Soil P Criterion	Increase In Area at End of 2006 (hectares)			
	STA-2	STA-34	STA-5	STA-6
> Low Threshold	1029-1755	0-355	0-195	0-90
> Medium Threshold	424-182	0-0	0-0	0-0
> High Threshold	0-0	0-0	0-0	0-0
Cattails	236-259	44-93	13-23	12-33
Max Cattail Density %	32-32%	2-6%	4-9%	1-5%

Ranges reflect results for 20-cm and 10-cm soil depths, respectively. Increases in total cattail area occur along the longitudinal density gradients shown in Figure 23. The maximum cattail density values refer to regions immediately below the flow distribution structures. The relatively small increases in total cattail areas for STA's 34, 5, and 6 reflect integration of small density increases over large areas (0-15 km below each structure.

Increases in soil P levels and cattail expansion prior to 2007 occur over much smaller areas than changes in water-column concentrations. This reflects slow soil response times. If the 50 ppb discharges were to continue for 20-40 years (steady-state), soil and cattail impact areas would be similar to water-column impact areas (see Biological Responses).

Soils below the STA-2 discharge respond more rapidly than soils below the other STA's (Figures 18, 21). This reflects the lower initial bulk density of STA-2 soils (0.08 vs. 0.18 to 0.22 g/cm ^{3}). Higher initial densities dampen the time response of the soils, but do not influence steady-state results (equations 24 & 25).

Comparison with SFWMD Results

The estimated spatial scale of cattail impacts can be compared with values estimated by South Florida Water Management District (1996b) using a different methodology. Based upon observed phosphorus loads and cattail areas below the S10's in WCA-2A, conversion factors of 6.3 to 17.3 acres/metric ton were used estimate potential cattail acreage downstream of each hydropattern restoration facility. The range reflects observed rates of cattail expansion from 1976 to 1982 (14 - 20 years after start of S10 discharge) and from 1982 to 1987 (20-27 years), respectively (Figure 15).

On one hand, the SFWMD methodology will tend to over-estimate initial cattail growth because it does not account for the time lag between the start of phosphorus loading and the expansion of cattails. This lag is required for soil P levels to build up to threshold levels (Figure 13). On the other hand, the methodology will tend to under-estimate initial cattail growth below STA-2 because it does not account for the fact that the initial soil P concentrations below the S10's in 1962 were probably lower than the current concentrations in STA-2 discharge region (198 vs. 366 mg/kg). Based upon the slopes of the cattail area vs. time curves in Figure 21, average predicted rates of cattail expansion rates below STA-2 are 5.7 acres/mton in years 0-8 and 16.1 acres/mton in years 8-16. Since these rates are in good agreement with those derived by SFWMD, it appears that the net effects of the above counteracting factors (lag time and initial soil conditions) are close to zero.

Because of differences in initial soil conditions (primarily, bulk density), the above conversion factors are likely to over-estimate cattail expansion rates below the other STA's. Expansion rates estimates derived from Figure 21 (0-20 cm simulations) are:

Cattail Expansion Rates (acres / metric ton)		
Time Frame	0-8 yrs	8-16 yrs
STA-2	5.7	16.1
STA-34	1.4	4.2
STA-5	2.2	4.4
STA-6	1.0	1.8

The 0-8 year values are more appropriate for predicting responses likely to occur before 2007.

Sensitivity Analysis

This section examines sensitivity of results to the following factors:

Model Input Values
Phosphorus Storage in Plant Biomass

Initial Phosphorus Settling Rates
STA Outflow Concentrations
Current Projected Performance of STA-2
Expression of Soil P Threshold Criteria

Additional model runs with alternative coefficient values and/or experimental modifications to the model structure are used to explore the potential effects of these factors.

Sensitivity to Model Input Values

Sensitivity of simulation results for STA-2 to model coefficient values, external driving variables, and initial conditions are summarized in Tables 4 and 5. Results are expressed as sensitivity coefficients (Walker, 1982), which approximately equal the percentage change in an output variable divided by the percentage change in an input variable. A value of 100% indicates a linear or proportionate response. Coefficients have been calculated for a ± 10% perturbation in each input variable. Table 4 lists results for soil P content (mass & volume basis), water-column P concentration, and cattail density for distances ranging from 0 to 12 km. Table 5 lists results for total cattail area as a function of time. Results are particularly useful for estimating uncertainty in model predictions and for guiding future data collection and model refinements in the interest of improving model accuracy and precision.

Sensitivity coefficients are identical for settling rate and hydroperiod; simulations are driven by the product of these values (equation 2). Coefficients for STA outflow volume and discharge width are also equal but reversed in sign; simulations are driven by the ratio of these values (flow per unit width). Rainfall depth and concentration become increasingly important as distance from the STA increases.

Predicted water-column P concentrations become more sensitive to settling rate and hydroperiod as distance from the inflow increases. The settling rate estimate has been derived from an area (WCA-2A) with an average hydroperiod of 91%. The calibration has not been tested in regions with lower hydroperiod (i.e. 61% for STA-6, 69% to STA-5, and 88% for STA-34). The hydroperiod values used in the simulations are estimates derived a hydrologic model (Neidrauer, 1996). Because of these three factors, there is greater uncertainty in the predicted water-column concentration profiles for STA's -34, -5, and -6 than for STA-2. This applies particularly to the predicted areas exceeding 10 ppb.

Predicted soil P concentrations and cattail densities in 2007 are sensitive to more variables, many of which are measured initial soil properties. In contrast to water-column P, soil P sensitivity to settling rate and hydroperiod decreases with distance. The high sensitivity of cattail densities to logistic curve parameters (midpoint, spread) reflects the highly non-linear shape of the logistic curves (Figure 13).

Predicted total cattail area in 2007 is most sensitive to the logistic parameters, initial soil P concentration, STA outflow concentration, and initial bulk density (Table 5). The last three input variables are initial conditions which are specified or directly measured. Results suggest that spatially intensive mapping of soil P levels in regions below may improve the precision of predicted cattail areas, depending upon the actual spatial variability of soil conditions in these regions. Sensitivity to initial conditions and many other coefficients fades with time. Long-term (40-year) cattail area is most sensitive to the logistic midpoint (i.e., threshold soil P), intercept of the soil P vs. accretion rate regression (i.e., P content of new soil), and STA outflow volume and concentration (i.e., STA phosphorus load). Long-term total cattail area are relatively insensitive to settling rate and hydroperiod. Generally, the cattail area sensitivity matrix indicates that predictions of short-term response are more sensitive (and, therefore, more uncertain) than predictions of long-term response. Additional analysis would be required to quantify uncertainty..

Sensitivity to Phosphorus Storage in Plant Biomass

The model assumes that all of phosphorus removed from the water column is added directly to the soil. One of the expected responses to enrichment is an increase in above-ground plant biomass (Craft & Richardson, 1995; Duke Wetland Center, 1995). Predictions of soil P response will be conservative (i.e, over-estimated) to the extent that a net increase in phosphorus stored in biomass occurs during the initial years. Data from WCA-2A (Reeder & Davis, 1983; Davis 1984, 1991) indicate that phosphorus storage in live leaf tissue ranges from about 600-800 mg P/m ^{2} in the northern portion of the S10 inflow zone to above 90-120 mg P/m ^{2} in the southern portion. These values correspond to about 1 year of net P accretion in peat along the P gradient below the S10's (Walker, 1995). Approximately 2-fold higher P storage is indicated by fertilizer experiments conducted in WCA-2B by Craft & Richardson (1995), who measured phosphorus storage in sawgrass (live + dead shoots) ranging from 200 mg P/m ^{2} (unfertilized plots) to 1910 mg P/m ^{2} (fertilized plots).

A relatively simple manipulation of model output can be performed to evaluate potential impacts of P storage in plant biomass. At each point along the gradient, the predicted cumulative increase in soil P mass (relative to start of simulation) is reduced by an amount equal to the potential cumulative increase in biomass P. Steady-state biomass P storage is assumed to equal 1 year of net P accretion. The potential cumulative increase in biomass P resulting from the STA discharge is equal to the predicted biomass P (~accretion rate) at a given location minus the predicted biomass P at 10 km downstream of the discharge (~background conditions).

Potential effects of biomass storage on STA-2 simulations using soil depths of 10 and 20 cm are shown in Figures 24 and 25, respectively. With a 10-cm depth (Figure 25), soil P levels immediately below the STA discharge in 2007 are reduced by 53 mg/kg. The effect decreases with increasing distance from the discharge. The time before exceedance of the low threshold immediately below the STA discharge increases by ~.5 years and the time required to exceed the high threshold increases by ~ 1.5 years. With a 20-cm depth (Figure 25), soil phosphorus levels immediately below the STA discharge in 2007 are reduced by 27 mg/kg (from 675 to 648 mg/kg).

Times before exceedance of low and high threshold criteria immediately below the STA discharge increase by ~1 year. Using the higher biomass P levels reported Craft & Richardson (1995), soil (and cattail) response would be delayed by ~2 years. Refinements to the model and additional calibration data are needed to simulate biomass storage directly.

Sensitivity to Initial P Setting Rates

As discussed above (see **Model Calibration**), higher settling rates may be experienced in the first 1-2 years when the system is initally responding to the change in phosphorus load. Table 5 indicates that predicted cattail area in 2007 is relatively insensitive to the assumed settling rate sequence over the first few years: Simulations using alternative settling rate sequences are shown Figure 26. Three sequences are tested:

	P Settling Rate (m/yr)		
Sequence	Year 1	Year 2	Years >=3
1	10.2	10.2	10.2
2	30.0	20.0	10.2
3	50.0	30.0	10.2

Sequence 2 has been used in the base simulations discussed above. Sensitivity is greatest at the upstream end of the model zone and decreases rapidly moving downstream. Very little sensitivity remains at >1 km. Higher initial K_e values cause more phosphorus retention in the upstream portion of the model zone and less retention in the downstream portion. Applying Sequence 3 (vs. Sequence 2) to simulations of STA-2 increases total predicted cattail area in 2007 by 14% using a soil depth of 10 cm and by 22% using a soil depth of 20 cm. Increases in cattail areas for the other STA's are less than 3%. Actual sensitivity to initially high setting rates would be lower than indicated because a portion of initial P removal would be stored as increased biomass P (see above). When expressed as areas exceeding soil P thresholds and total cattail area (Table 5), long-term impacts are independent of settling rates; they are constrained by mass balance and are primarily determined by phosphorus load.

Sensitivity to STA Outflow Concentrations

Figure 27 illustrates sensitivity to variations in STA-2 outflow concentration over a range of 20 to 150 ppb Water-column and soil P profiles are plotted vs. distance for each outflow concentration. In addition, total cattail areas are plotted as a function of time. As expected, sensitivity to inflow concentration declines with increasing distance from the structure. Reducing the inflow concentration from 150 ppb (~ current conditions) to 50 ppb or below results in a substantial reduction in cattail response. Simulations using outflow concentrations below 30 ppb are hypothetical, since practical technologies for achieving these levels have not yet been identified or demonstrated in this region.

Sensitivity to Current Projected Performance of STA 2

Results indicate that potential impacts on soil P and cattails are higher for STA-2 than for the others. STA outflow volumes and concentration (50 ppb) used in these simulations are derived from initial design calculations (Burns & McDonnell, 1994), as modified to subsequent modifications in delivery patterns (SFWMD, 1996b). A recent report (Brown & Caldwell, 1996) develops STA performance projections using updated information. As a consequence of higher agricultural BMP load reductions (45% observed vs. 25% assumed in design) and potential load reduction benefits associated with seepage (ignored in design), current projections of STA outflow concentrations range from 31 to 40 ppb. The Appendix (cases labeled "STA-2 GDR") shows simulation results for STA-2 using performance projected by Brown & Caldwell (their "Case 9"). Average STA-2 outflow volume is increased from 254 to 305 hm ^{3}/yr and outflow concentration is reduced from 50 ppb to 40 ppb. With these changes, the initial exceedance of the 720 mg/kg / 20-cm threshold is delayed from 2008 to 2014 and the net increase in cattail area by 2007 (as predicted by the logistic model) is reduced from 236 to 166 hectares, or 30%.

Sensitivity to Expression of Soil P Threshold Criteria

If cattail communities actually respond to changes in volumetric soil P content (mg/cm ^{3}) instead of mass content (mg/kg), considerably different results would be obtained. Figure 28 shows predicted volumetric soil P profiles in 2007 for each STA. Observed soil phosphorus and vegetation patterns in WCA-2A suggest a volumetric threshold criterion of ~0.062 mg/cm ^{3} for a 10-cm soil depth and 0.053 mg/m ^{3} for a 20-cm depth (Table 2). Because of high bulk densities (0.18 to 0.23 g/cm^3), soils in the discharge zones of STA's- 34,5,& 6 have initial volumetric P concentrations (.08 - .10 mg/cm^3) which exceed both criteria. Simulations indicate that significant changes in volumetric P content in these areas are not expected to result from discharge of 50 ppb water. If a volumetric criterion is appropriate, these areas would be at risk for cattail expansion at any time, regardless of phosphorus concentrations in the inflowing waters.

Additional research is needed to determine whether expression of soil P criteria on a volume basis is more appropriate than expression on mass basis. The following factors suggest, however, that mass-based criteria are more appropriate:

1. Based upon classification errors, observed vegetation patterns in WCA-2A and WCA-1 are more strongly correlated with soil P content expressed on a mass basis (Table 2).

2. Threshold criteria estimated from WCA-1 data are more consistent with criteria estimated from WCA-2A data when they are expressed on a mass basis than when they are expressed on a volumetric basis.

3. As reflected in typical soil P adsorption isotherms (Richardson & Vaithiyanathan, 1995), phosphorus concentrations in soil porewater are more directly related to soil P concentrations expressed on a mass basis than to concentrations expressed on a volumetric basis.

4. If volumetric criteria were important, observed vegetation communities in relevant regions of the WCA-3A and Rotenberger (predominately sawgrass) would be inconsistent with the fact that volumetric soil P concentrations in these areas (0.08 - 0.10 mg/cm^3) already exceed the 0.06 mg/cm^3 criterion. Variations in hydroperiod may complicate this perspective, however.

Even if mass criteria are more relevant for cattail expansion, the applicability of threshold criteria estimated from WCA-2A data to denser soils in Rotenberger and WCA-3A has not been demonstrated. For this reason, there is greater uncertainty in predictions of cattail response downstream of STA's 34, 5, & 6 than in predictions of cattail response below STA-2.

Discussion

EPGM has been used to estimate the spatial and temporal scales of phosphorus impact on marsh areas downstream of the hydropattern restoration facilities. These impacts should be considered relative to those which would occur if the STA outflows were diverted to canals or other locations. Gross impacts have been described in terms of (a) areas exceeding water-column threshold criteria, (b) areas exceeding soil threshold criteria, and © cattail density & total cattail area. Net impacts are defined as the difference between the gross impacts of one discharge location vs. another.

Moving the discharges to other locations (canals) would displace predicted increases in soil and water-column P concentration to other WCA regions. The notion that canal alternatives would affect only areas that have already been impacted is incorrect. The canal alternatives would delay recovery and risk further expansion of existing impacted areas, including portions of WCA-1, the S10 inflow zone of WCA-2A, and WCA-3A regions adjacent to the Miami Canal and L-67. Biological responses to phosphorus loads at the edges of the existing impacted areas would tend to be high because soil P levels in these regions (by definition) are close to threshold levels.

The Everglades Construction Project is expected to achieve substantial long-term reductions in wetland area exceeding P criteria for water and soil as result of the substantial (~80%) reduction in phosphorus load. Simulations of the S10 inflow zone of WCA-2A (see Model Testing) indicate that the existing soil impact area and total cattail area would continue to expand (for another 30 years or so) if future phosphorus loads were maintained at historical levels. Delays in achieving planned load reductions using available STA technology would translate into additional cumulative P loads to the system and risk further expansion of the existing impacted area. Selecting canal discharge alternatives is expected to cause 18-24 month delays in STA completion (SFWMD, 1986b). The additional untreated phosphorus loads occurring during such delays should be considered net negative impacts of these alternatives. These increased loads could have long-term consequences, given the predicted long time scales of soil P recovery (Figure 9).

Gross impacts of discharging through the hydropattern restoration facilities would include temporary increases in water-column phosphorus concentrations in relatively unimpacted marsh regions over the spatial scales described above. Impacts on various ecological components (e.g., bacteria, algae, periphyton) may result from these increases in water-column P concentrations. A key issue in evaluating these alternatives is the extent to which impacts caused by short-term increases in water-column concentration are reversible. Compared with impacts on organisms sensitive to soil P concentration, impacts on organisms sensitive to water-column P concentration may be more reversible because water-column P concentrations would be expected to respond faster than soil P concentrations to reductions in external load. More information is needed, however, on the time scales of biological recovery following decreases in water-column P concentration.

With regard to selecting discharge locations, specific considerations for the Department if Interior would include:

1. Bypassing STA-2 outflows to S-6 (STA-2 Bypass Option 1, SFWMD, 1996b) would substantially increase P loads to Loxahatchee National Wildlife Refuge, relative to those contemplated either in the State/Federal Settlement Agreement or in the Mediated Technical Plan (basis for Everglades Construction Project).

2. Bypassing STA's 34, 5, and/or 6 outflows directly to the Miami Canal would promote phosphorus transport through WCA-3A and into Everglades National Park, especially under low stage conditions.

3 There would be a potential impact on Miccosukee lands resulting from discharge of STA-6 through flow distribution structures in northwestern WCA-3A. Simulations indicate, however, that average total phosphorus concentrations will be reduced to <10 ppb within the first 5 kilometers downstream of the structures. The northern boundary of Miccosukee lands is approximately 8 km south of L-4. Potentials for water and soil-related impacts on Miccosukee lands appear to be low. More detailed simulations considering land topography and the specific geometry of the discharge structure would be needed for a more precise evaluation.

Delays in STA completion associated with moving the discharge locations would have negative impacts on any of the above regions.

The predicted time scales of soil P and cattail response to 50 ppb discharges are consistent with observed marsh responses following opening of the S10's in the early 1960's. Cattail populations did not start expanding in WCA-2A until ~8-10 years later (Figure 15), despite the fact that S10 phosphorus concentrations (averaging 122 ppb) were well above 50 ppb. If the S10 experience were extrapolated directly to STA-2 hydropattern restoration facilities, the predicted time scale would be 13-16 years (adjusting for differences in inflow concentration and initial soil concentration).

Between 1983 and 1984, an experimental dosing study was conducted in ENP Shark River Slough to evaluate effects of nutrient enrichment (Flora et al., 1988). Impacts on periphyton and vegetation were observed in the dosed channels within the first year of the study. Cattails first appeared in the dosed channels in 1989-1990. Visible changes in the plant community are currently apparent in areas downstream of channels. An average ortho-P dose of 29 ppb was applied to natural flows in two channels, each 5 meters wide and 100 meters long. At the reported flow rates, the ortho P dose to each channel over the study period (~23 kg) was sufficient to increase the average soil P content in the top 10 cm of each channel by more than 4000 mg/kg. Average 0-10 cm soil P concentrations measured in 1988 (Jones, 1988) were 258 mg/kg in the control channel and 593 mg/kg in the dosed channels. Soil P concentrations in the dosed channels exceeded 850 mg/kg at several locations. It is apparent that an appreciable portion of the phosphorus applied was discharged downstream of the channels. Despite the small spatial scale of the experiment and the approximate nature of the dose estimates (attributed to complexities in measuring flow), the appearance of cattails and the current persistence of visible vegetation impacts downstream of the facility are consistent with potential and measured increases in soil P. Effective settling rates for ortho phosphorus applied to unimpacted marsh would be much higher than settling rates for total phosphorus in STA outflows, which would be stabilized to some extent by contact with vegetation and soils within the STA's.

Soil P criteria for cattail growth have been estimated using data primarily from WCA-2A (Table 2, Figure 13). These values have not been tested for applicability to denser soils with historically shorter hydroperiod found in northern WCA-3A and Rotenberger. Newman et al. (1996) correlated observed cattail distributions in Rotenberger and Holeyland with soil properties and hydrologic variables. Existing soil P concentrations in the STA-5 discharge zone of Rotenberger (averaging 508 mg/kg, Table 1) are lower than those found in central and southern portions of Rotenberger where cattails are found (averaging 619 mg/kg). Spatial distribution of cattail in Rotenberger is correlated best with historical fires. Cattail growth rates following rehydration of the Holeyland were higher than those observed in WCA-2A. The spatial distribution of cattail is correlated primarily with water depths. Elevated soil P levels in the Holeyland appear to be related to historical fires and soil oxidation, not to external P loads. Soil total P concentrations in Holeyland cattail areas are the range of 600 to 1200 mg/kg (Reddy et al, 1991b).

Between January 1991 and April 1996, flow containing 39 metric tons of P at an average concentration of 78 ppb was pumped into the Holeyland through structure G200.. Newman et al. (1996) report that 1993 cattail densities were < 2% in the vicinity of this inflow, where soil P levels averaged less than 500 mg/kg in 1991 (Reddy et al, 1991b). The observed growth of cattail since 1993 is not spatially correlated with the G200 inflow location. This can be taken as further indication that rapid response of cattail populations to external phosphorus loads at concentrations of 50 ppb is not expected for soils in this region.

Generally, observations from the Holeyland and Rotenberger indicate that factors other than external P loads (fire, soil oxidation) can cause elevated soil P levels and that factors other than phosphorus (fires, water depth) can control cattail distribution. There does not appear an indication in these data, however, that cattails dominate in undisturbed soils with P concentrations substantially below threshold values estimated from WCA-2A data (Figure 13). Threshold values may be lower, however, in locations with water depths greater than those typically found in WCA-2A. Based upon preliminary review of data from the Everglades Nutrient Removal Project (Chimney, 1996), lower thresholds may also be appropriate for disturbed (e.g., previously farmed) soils.

The time scales over which the model parameters have been calibrated should be considered in interpreting simulation results. Key model coefficients (K_e, a, b) have been calibrated to 26-year average soil P accretion rates and therefore reflect long-term-average conditions. The model is therefore most reliable for predicting long-term-average water-column and soil phosphorus concentrations along gradients induced by external phosphorus loads. This is also reflected in the sensitivity coefficient matrices (Tables 4 & 5). Refinements to the model structure are needed to improve performance over short time scales in response to variations in hydrology (flow, hydroperiod, drought), phosphorus loading, biomass P storage, and startup phenomena. Compilation of other data sets is suggested to support future refinement, calibration, and testing of the model.

Additional data and model testing are needed on the extent to which short-term variations in model coefficients may occur during the initial transition period as the system is responding to a change in phosphorus load. Settling rates substantially above the long-term average may be experienced during transition periods owing to net uptake by biological and physical/chemical mechanisms. The assumptions made in simulating this transition period are thought to be conservative for predicting the rate of soil P buildup. Sensitivity analyses indicate that higher initial rates could result in exceedance of soil P criteria within the relevant time frame for short distances downstream of the STA's (< 1 km). Long-term, area-wide impacts on soil P levels are constrained by mass balance, however, and are insensitive to short-term (or long-term) variations in phosphorus settling rate.

The model is thought to generate conservative estimates of soil and cattail response for the following reasons:

a. In the early years of the project, a portion of the P removed from the water column will not reach the soil, but will be stored as increased plant biomass. As a result, soil P responses may be slower than predicted

b. To the extent that spread of cattails is controlled by fragmentation of existing populations (Wu et al., 1996), the rate of cattail expansion would be lower than that predicted based only upon soil P levels.

c. Soil threshold criteria for invasion of cattails into well-established sawgrass communities (e.g., discharge zone for STA-2) may be higher than criteria estimated from historical WCA-2A and WCA-1 data, which primarily reflect invasion into slough communities.

d. The 20-cm simulations of cattail area in WCA-2A over-estimate the rate of cattail expansion below the S10's in the first 20 years.

e. Recent projections of STA performance accounting for revised BMP load reductions and seepage (Brown & Caldwell, 1996) indicate average outflow concentrations in the range of 31 to 44 ppb. If this performance is realized, impacts on soil P levels would be lower than those predicted assuming a 50 ppb discharge concentration.

The model has been used to predict impacts related to discharge of phosphorus from the STA's. Cattail expansion may be caused by variations in other factors (e.g., hydroperiod, disturbance, fire). These mechanisms may be important, but have not been considered in this analysis.

Conclusions

1. The model used as a basis for STA design has been modified to include mass balances on the water-column and surface soils in marsh areas downstream of STA discharges. The revised model (labeled EPGM = Everglades Phosphorus Gradient Model) has been used to project impacts of discharges from STA's 2, 34, 5, and 6 through flow distribution structures into the northern areas of WCA-2A, WCA-3A, and Rotenberger. Impacts likely to occur prior to 2007, when Phase II controls will be implemented, have been evaluated. Impacts are expressed in terms of areas exceeding threshold criteria for water-column and soil phosphorus concentrations. Estimates of total cattail area are also derived from an empirical model relating soil P concentration to cattail density. Predicted increases in cattail density and area are surrogates for impacts on any ecosystem components which respond to soil P levels in similar concentration ranges.

2. Soil P thresholds for cattail expansion estimated from WCA-2A and WCA-1 data range from 610 to 990 mg/kg for a 10 cm soil depth and from 540 to 720 mg/kg for a 20 cm soil depth. Errors in predicting vegetation types based upon observed soil P levels range from 1% to 19%. Site classification errors are higher when soil P criteria are expressed on a volumetric basis.

3. The model successfully predicts observed spatial variations in soil phosphorus below the S10's, averaged over depths of 10 and 20 cm after ~28 years of loading (1962 - 1990). Observed cattail expansion during the first 20 years of S10 discharge is best simulated with a soil depth of 20 cm and threshold soil P value of 720 mg/kg. Simulations a 10-cm depth or lower threshold criteria substantially over-predict observed cattail response. Results indicate that the size of the S10 soil impact zone (>720 mg/kg over 20 cm) and total cattail area would continue to increase at a reduced rate for another 30 years or so if historical P loads were maintained in the future.

4. The model predicts that there is a linear relationship between long-term average, flow-weighted-mean, water-column concentration and steady-state or long-term-average soil phosphorus concentration. Under continuously wet conditions, water column concentrations ranging from 10 to 50 ppb correspond to steady-state soil P levels ranging from 612 to 1211 mg/kg. For the same concentration range, times required to achieve steady-state soil P levels range from 48 to 19 years, respectively, for a 10-cm soil depth and from 96 to 38 years for a 20-cm soil depth. Steady-state soil P levels decrease and response times increase as hydroperiod decreases.

5. Simulations are for <u>average</u> hydrologic conditions. Actual responses will deviate from the predictions, depending actual hydrologic conditions and system

sensitivity. Since an idealized representation of flow distribution is employed (uniform sheet flow), simulations provide approximate estimates of the spatial scales of impact, not estimates of impact at particular locations or dates.

6. When the STA's are operating, water-column concentrations in marsh areas immediately below the STA discharges will increase from background levels (< 10 ppb) to ~50 ppb. Soil P levels will increase over time scales which are long in relation to expected 4-8 year duration of 50 ppb discharges. With a water-column P concentration of 50 ppb, times required to reach steady-state soil P levels are ~20 and ~40 years for soil column depths of 10 and 20 cm, respectively.

7. Gross water-column impacts are expressed as areas and distances exceeding threshold criteria of 10, 20, and 30 ppb. Predicted areas exceeding 10 ppb range from 1215 to 12,000 hectares and are highly correlated with the ratio of the annual phosphorus load to the average hydroperiod. Distances exceeding 10 ppb range from 4.1 to 8.5 kilometers.

8. Gross impacts on soils are characterized by areas exceeding soil P thresholds, total cattail area, and cattail density. Based upon the most conservative soil P criterion (610 mg/kg & 10 cm soil depth), soil P impact areas would range from 75 to 1755 hectares. Based upon the threshold criterion which results in the most accurate simulation of cattail expansion below the S10's, impact areas would be 0 hectares for all STA's. Increases in total cattail area prior to 2007 range from 12 to 236 hectares. Simulated cattail densities immediately below the discharge structures at the end of 2006 are 32% for STA-2, and 1-4% for the other STA's.

9. Predicted cattail response rates, expressed in acres per metric ton, for areas below STA-2 are similar to those derived by SFWMD (1996b). Primarily because of higher initial bulk densities (reflecting historically drier conditions), soil P levels downstream of STA-23, 5, & 6 will respond slower than soil P levels downstream of the STA-2. Lower cattail response rates are estimated for these areas within the relevant 4-8 year time frames. There is greater uncertainty in predictions of cattail response in northern WCA-3A and Rotenberger, because the model has been calibrated to data primarily from WCA-2A. Cattail distributions in Holeyland and Rotenberger do not appear to be inconsistent with the model calibration, however.

10. If cattail communities actually respond to changes in volumetric soil P content instead of mass P content, considerably different results would be obtained. Because of high bulk densities, soils in the discharge zones of STA's- 34,5,& 6 have initial volumetric P concentrations which exceed volumetric criteria estimated from WCA-2A data. Significant changes in volumetric P content in these areas are not expected to result from discharge of 50 ppb water. If volumetric criteria

are appropriate, these areas would be at risk for cattail expansion at any time, regardless of phosphorus concentrations in the inflowing waters. While various factors indicate that mass-based criteria are more relevant, this is an important area for future research.

11. The simulations quantify the spatial and temporal scales of gross impact on water-column and soil P levels downstream of the hydropattern restoration facilities. The distinction is made between the gross and net impacts of discharging through these facilities. Discharging to other locations would displace phosphorus impacts of similar magnitude to other WCA regions. This would delay recovery and risk further expansion of existing impacted zones. Other factors to be considered in evaluating discharge alternatives include (1) likelihood that discharges to canals would promote P transport over longer distances; (2) long-term impacts of additional phosphorus loads occurring as a result of delays in STA construction if alternative discharge locations were selected; and (3) possible reversibility of biological impacts caused by short-term increases in water-column P (vs. Soil P) concentrations.

12. Overall, the project is expected to provide substantial long-term reductions in wetland areas exceeding P threshold criteria for soil and water as a result of the substantial (~80%) decrease in P load. Delays in achieving these load reductions using available STA technology would translate into additional in cumulative P load to the system and risk further expansion of the existing impacted area before Phase II controls can be developed and implemented.

13. Considering its structure, calibration, and sensitivities, EPGM is most reliable for predicting long-term-average water-column and soil P concentrations along gradients induced by external P loads. Measured initial soil conditions have strong influences on predicted soil P and cattail responses within 4-8 year time frames. Refinements to the model structure are needed to improve model performance over short time scales in response to variations in hydrology (flow, hydroperiod, drought), P loading, biomass P storage, and startup phenomena. Compilation of other data sets will support future refinement, calibration, and testing of the model. Sensitivity analyses (Tables 4 & 5) can guide such efforts.

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Everglades Phosphorus Gradient Model

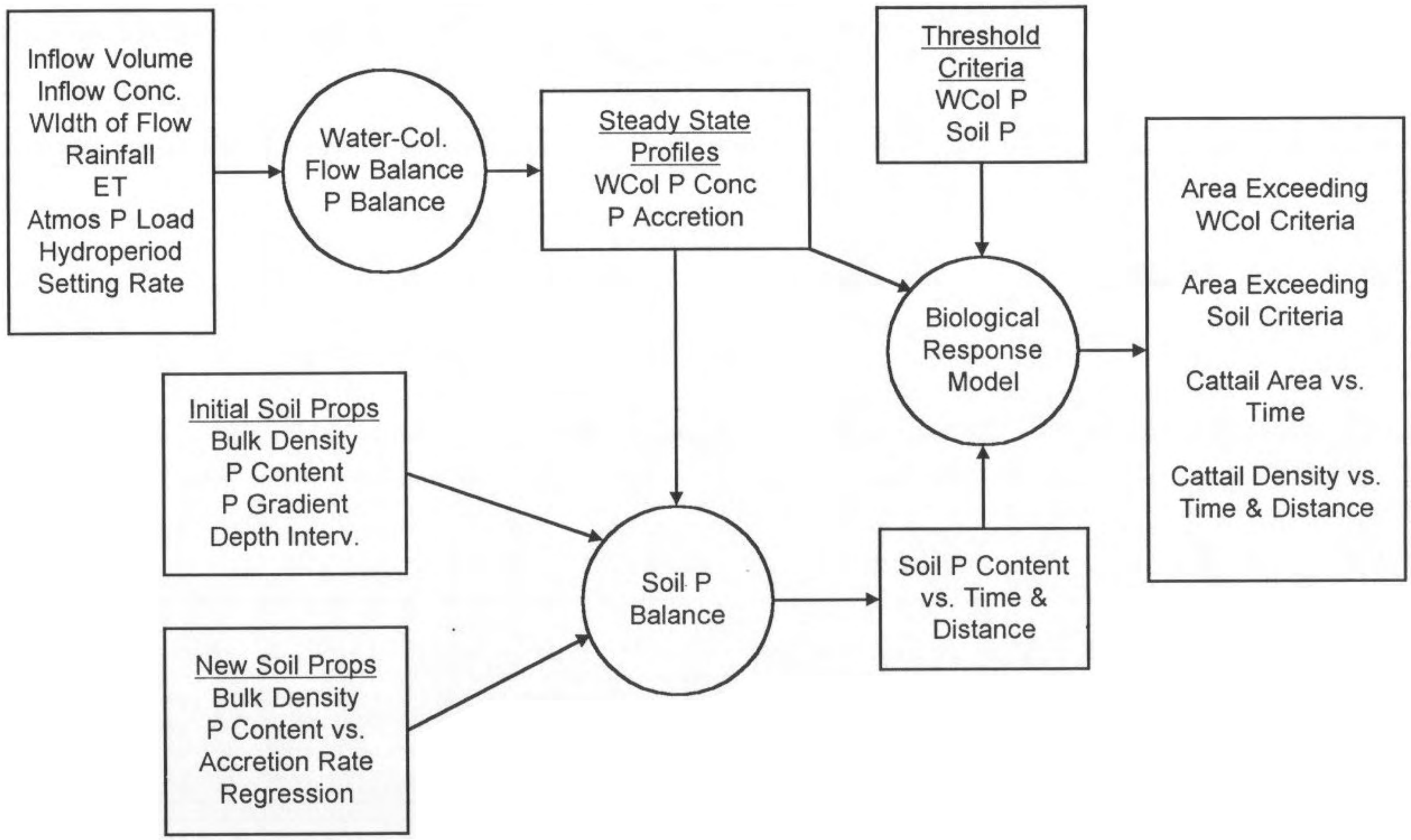
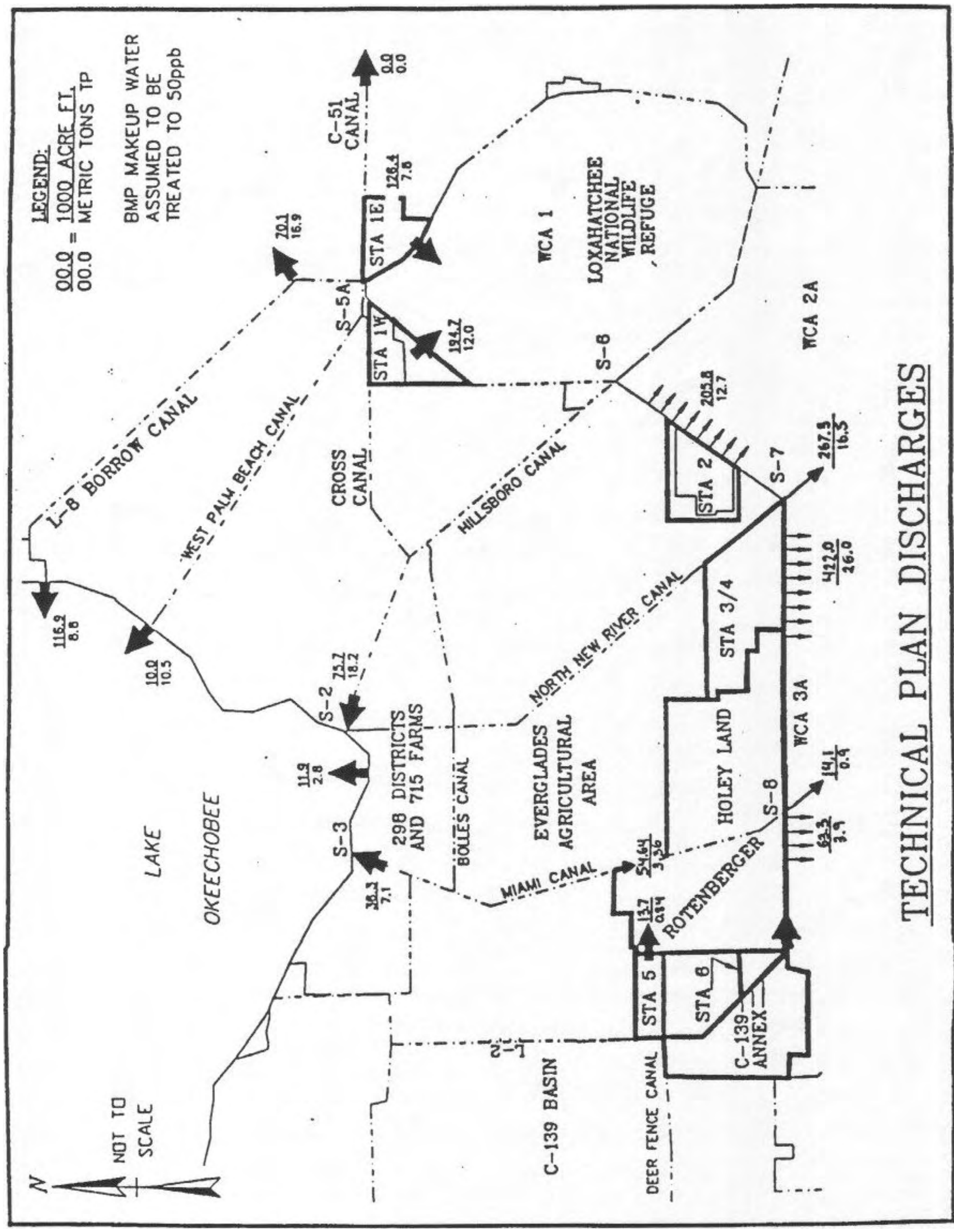


Figure 1

Figure 2


TECHNICAL PLAN DISCHARGES
LEGEND:
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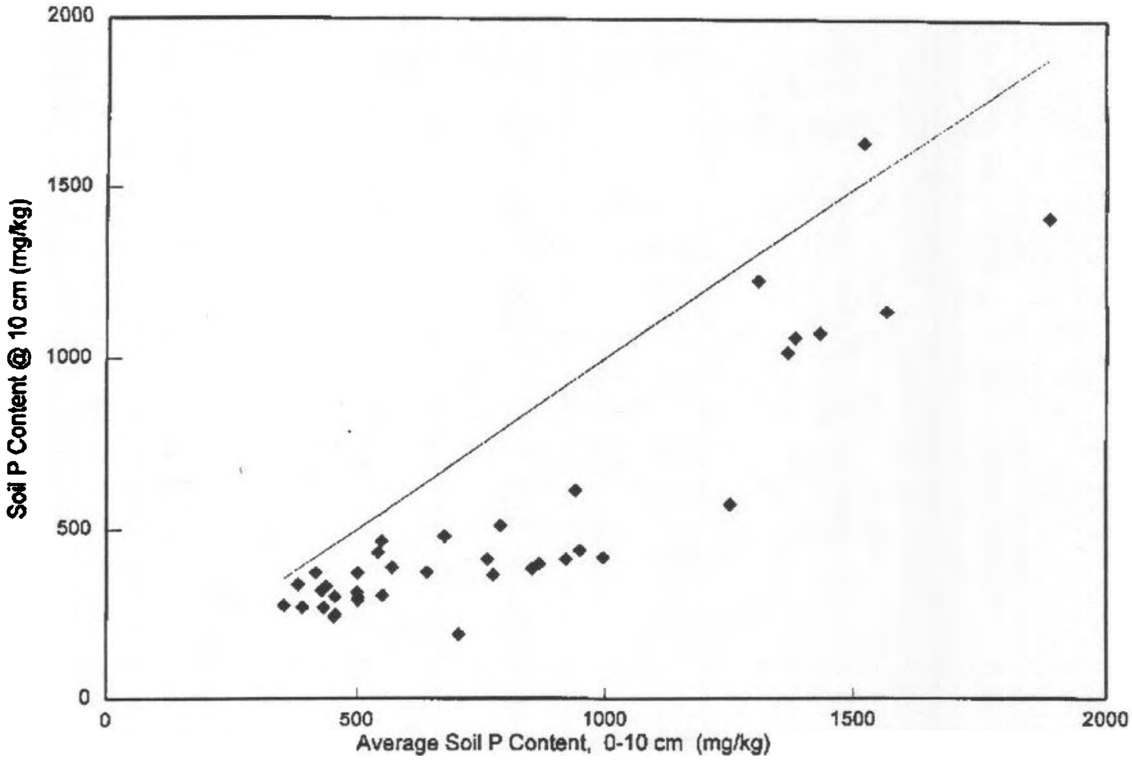
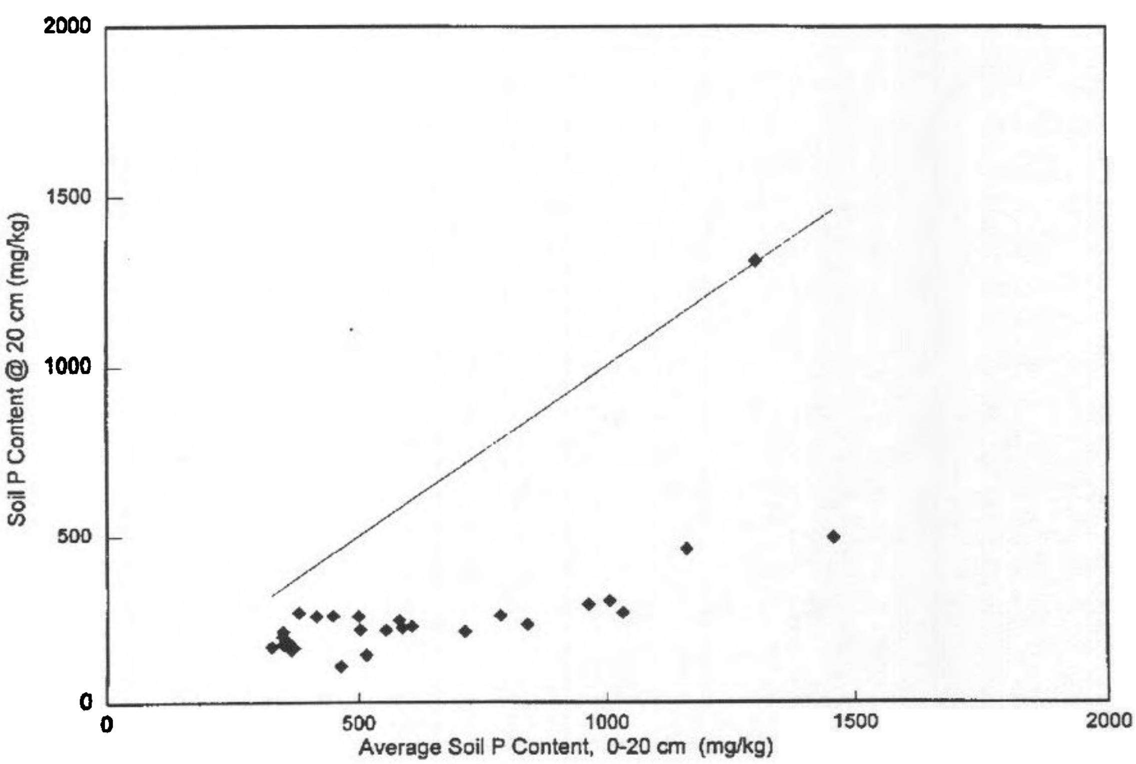
00.0 = METRIC TONS TP
BMP MAKEUP WATER ASSUMED TO BE TREATED TO 50ppb
NOT TO SCALE
N
LAKE OKEECHOBEE
L-8 BORROW CANAL
WEST PALM BEACH CANAL
CROSS CANAL
HILLSBORO CANAL
NORTH NEW RIVER CANAL
MIAMI CANAL
BOLLES CANAL
C-51 CANAL
298 DISTRICTS AND 715 FARMS
EVERGLADES AGRICULTURAL AREA
HOLEY LAND
ROTENBERGER
WCA 1
LOXAHATCHEE NATIONAL WILDLIFE REFUGE
WCA 2A
WCA 3A
STA 1E
STA 1W
STA 2
STA 3/4
STA 5
STA 6
C-139 ANNEX
C-139 BASIN
DEER FENCE CANAL
L-2
S-2
S-3
S-5A
S-6
S-7
S-8
116.9
8.8
10.0
10.5
73.7
18.2
11.9
2.8
38.3
7.1
70.1
16.9
0.0
0.0
126.4
7.8
194.7
12.0
205.8
12.7
267.5
16.5
412.0
26.0
14.1
0.4
63.5
3.9
13.7
0.94

Figure 3

Vertical Variations in Soil Phosphorus Content

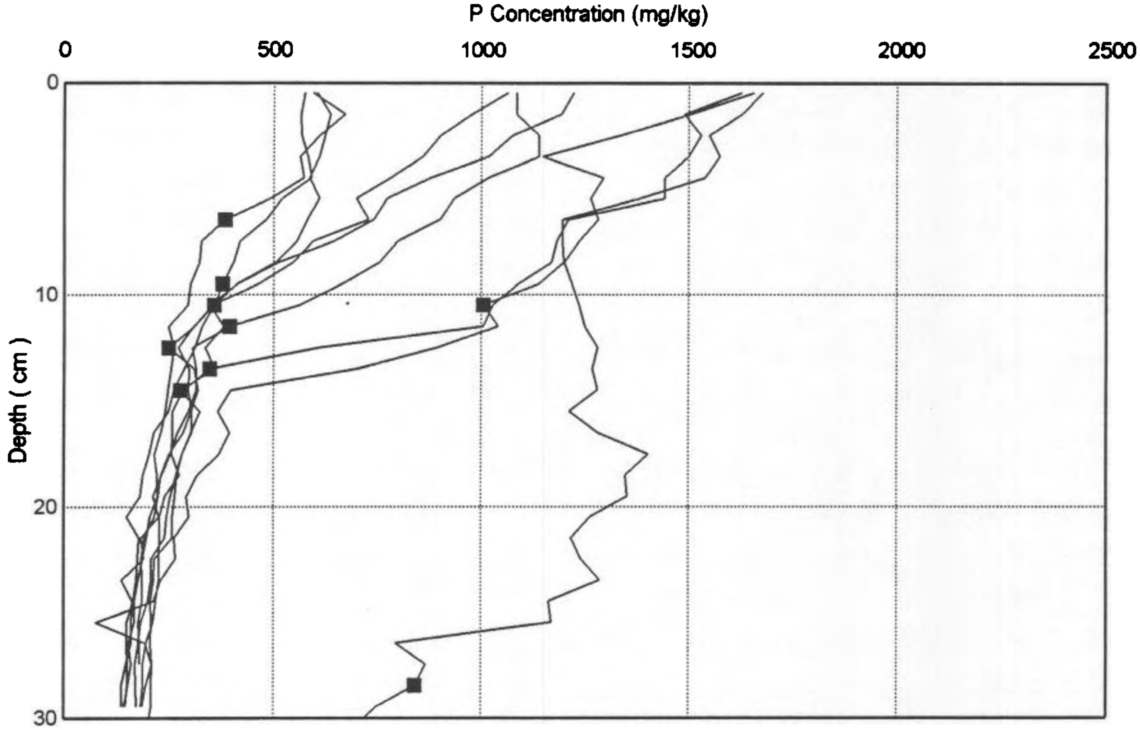




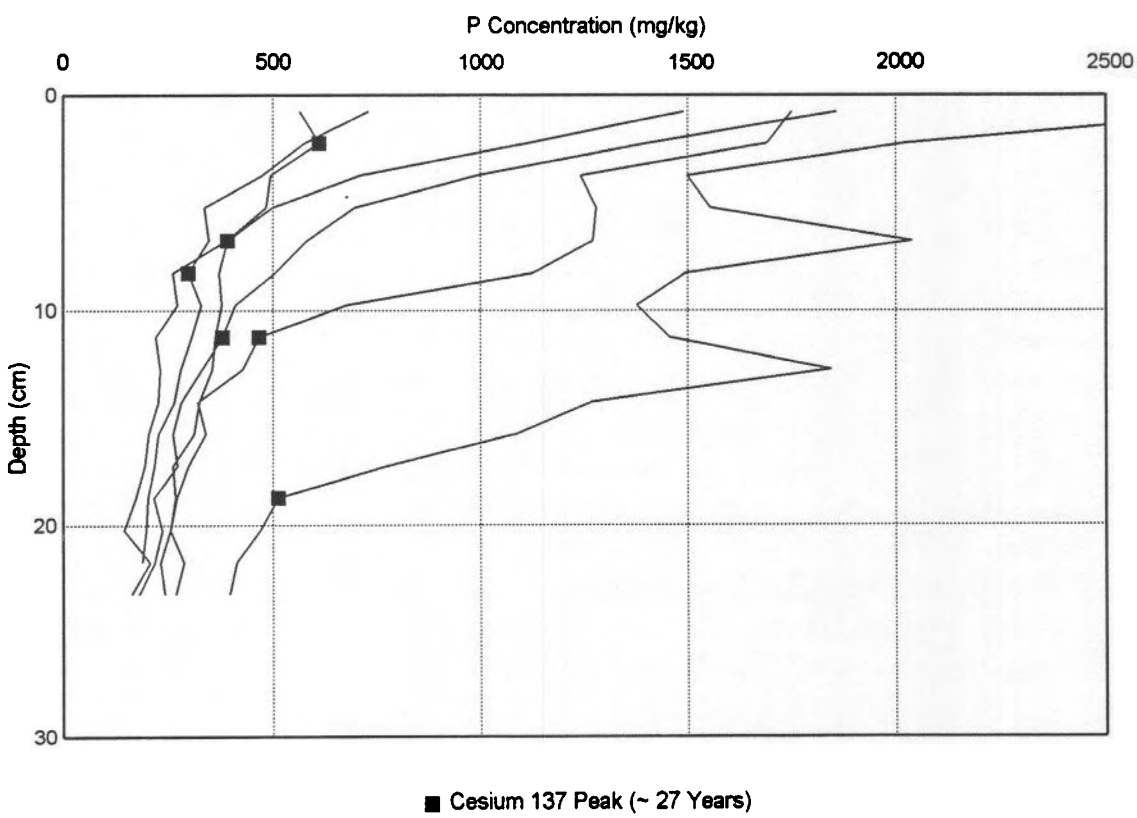
Data: WCA-2A & WCA-3A

Figure 4

WCA-2A Soil Profiles - P Concentration

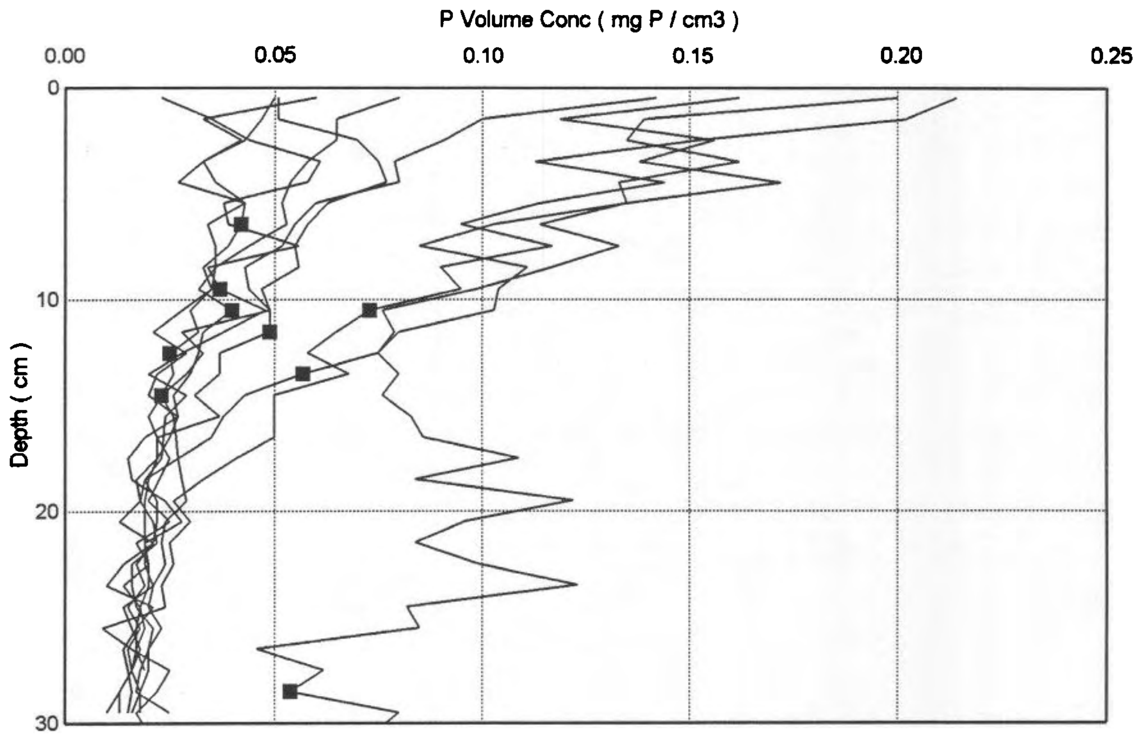


Reddy et al (1991)

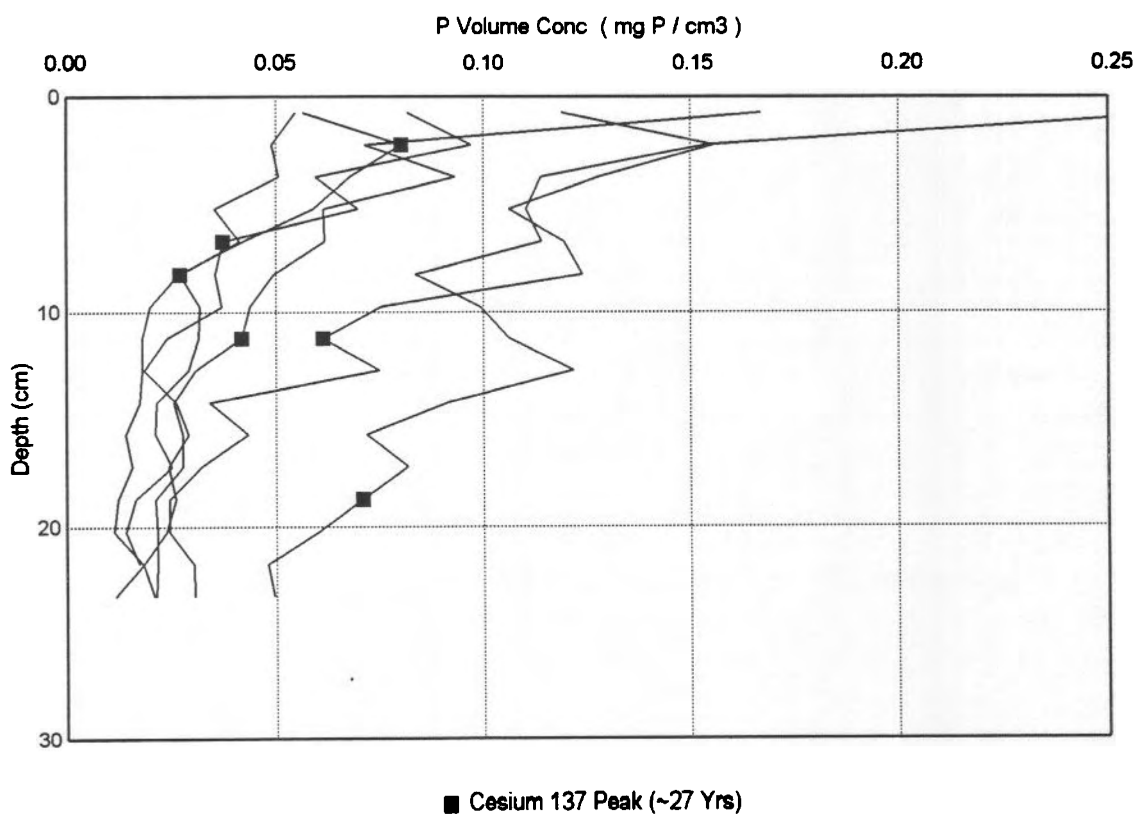


Duke Wetland Center (1992), C Transect

WCA-2A Soil Profiles - Volumetric P Concentration

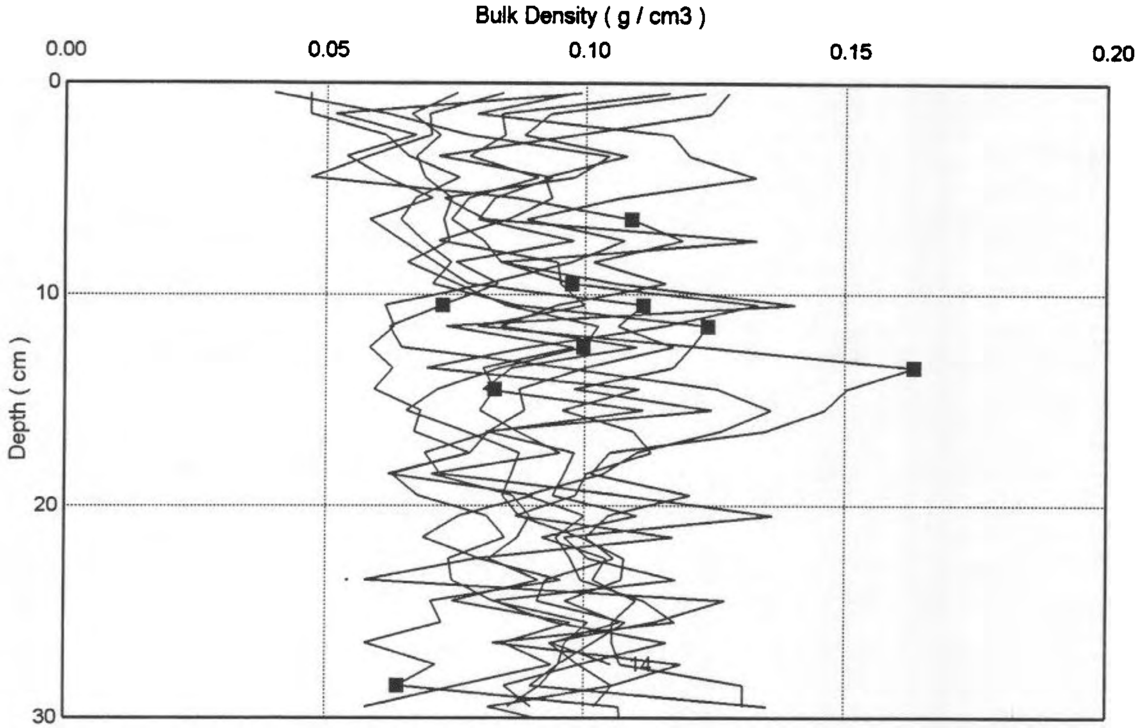


Reddy et al (1991)

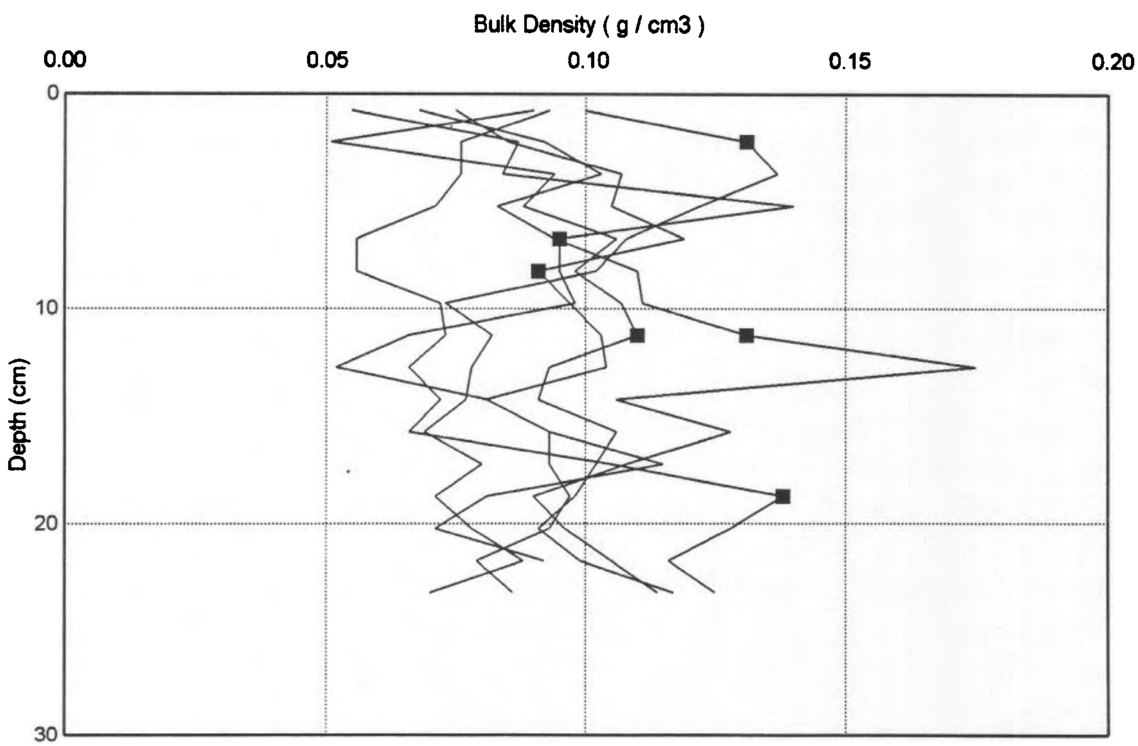


Duke Wetland Center (1992), C Transect

WCA-2A Soil Profiles - Bulk Density



Reddy et al (1991)

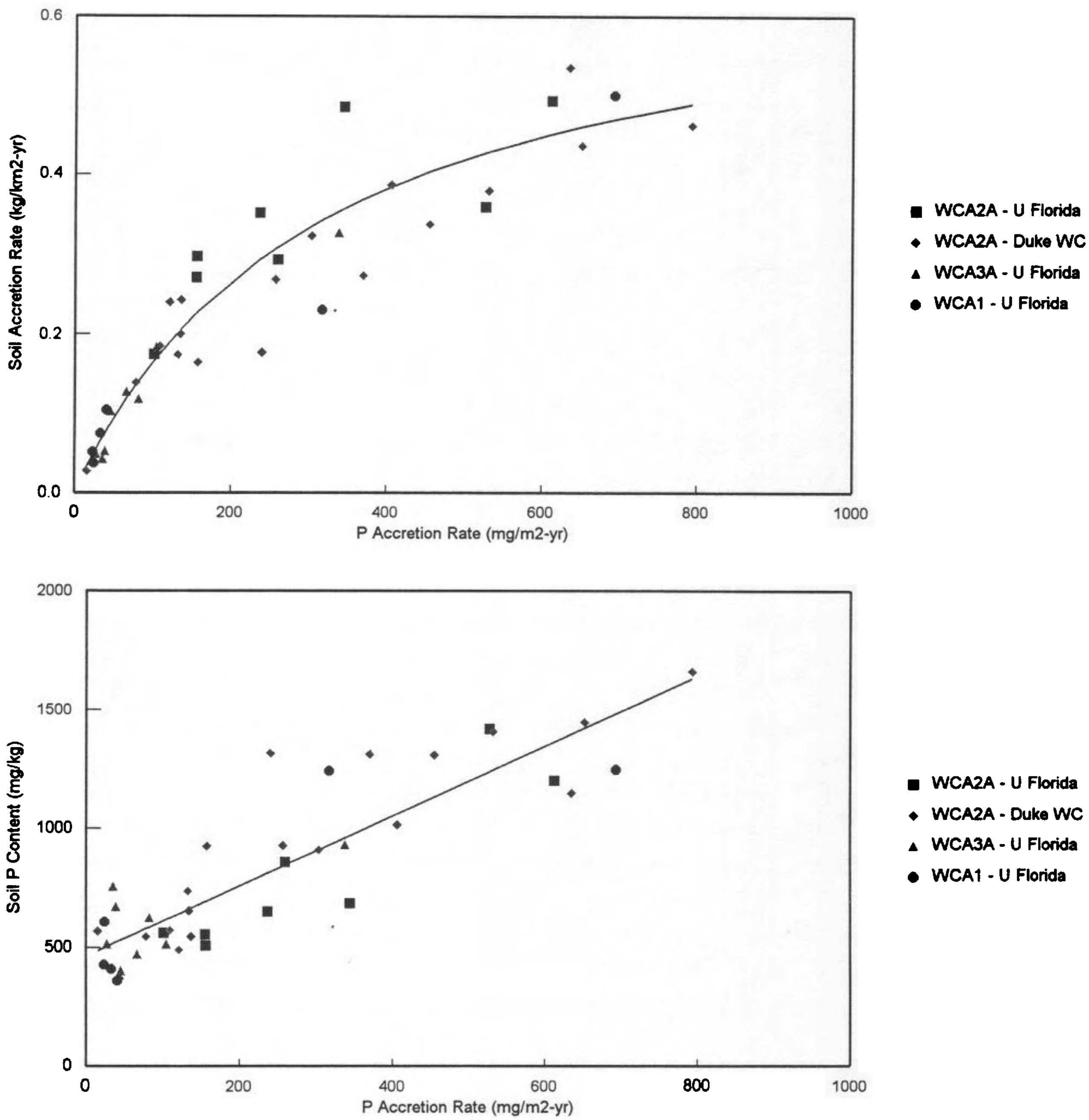


■ Cesium 137 Peak (~27 Years)

Duke Wetland Center (1992), C Transect

Figure 7

Calibration of Soil Accretion Model



Parameter Estimation

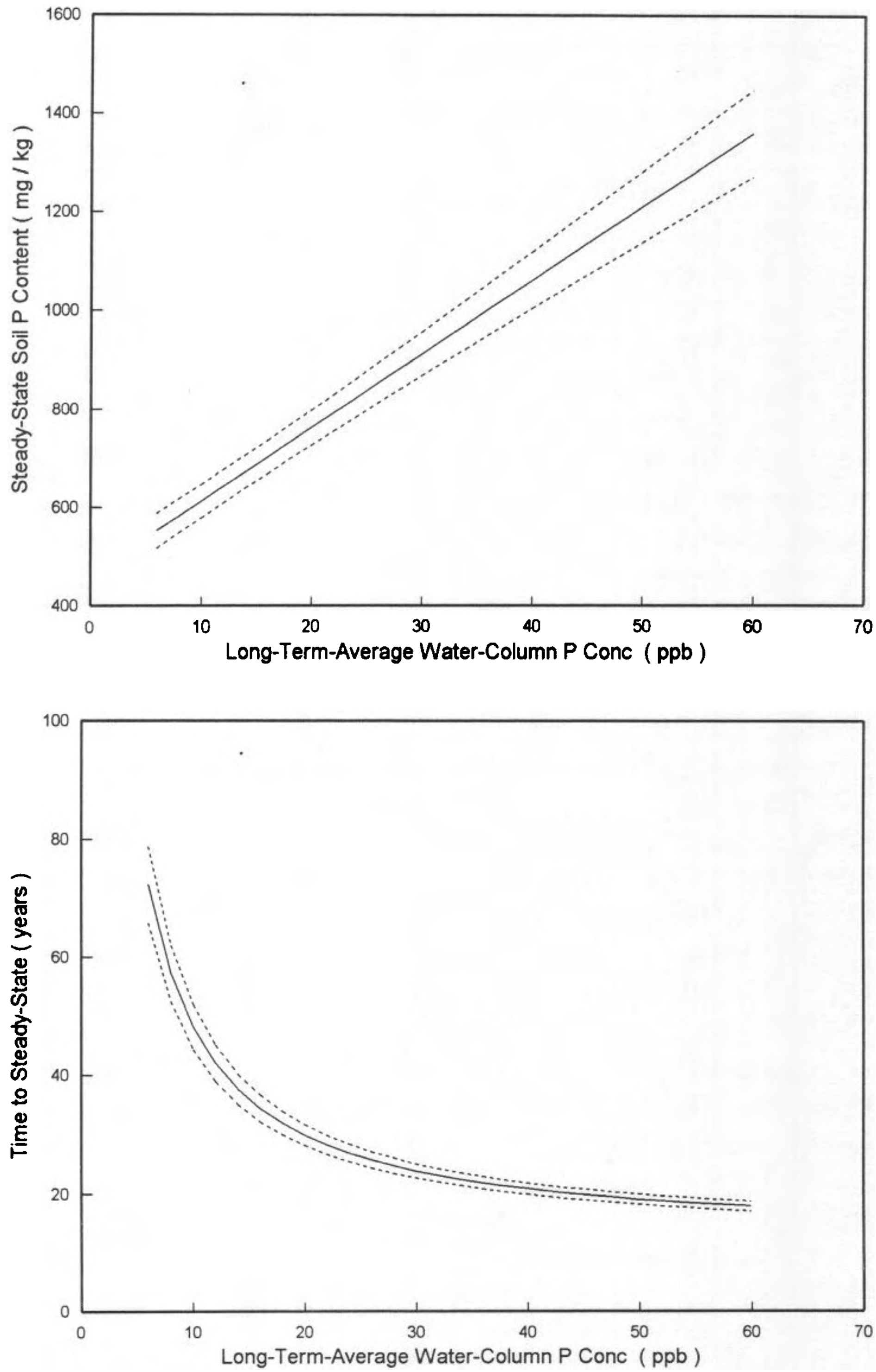
T = Soil Accretion Rate, kg/m2-yr
S = Phosphorus Accretion Rate, mg/m2-yr
Y = Soil Phosphorus Content above Cesium 137 Peak, mg/kg

$Y = 463 + 1.466\ S$ (r 2 = 0.78, SE = 171 mg/kg)

$T = S / Y = S / (463 + 1.466\ S)$ (r 2 = 0.88, SE = 0.05 kg/m2-yr)

Figure 8

Steady-State Soil P & Response Time vs. Water-Column Concentration

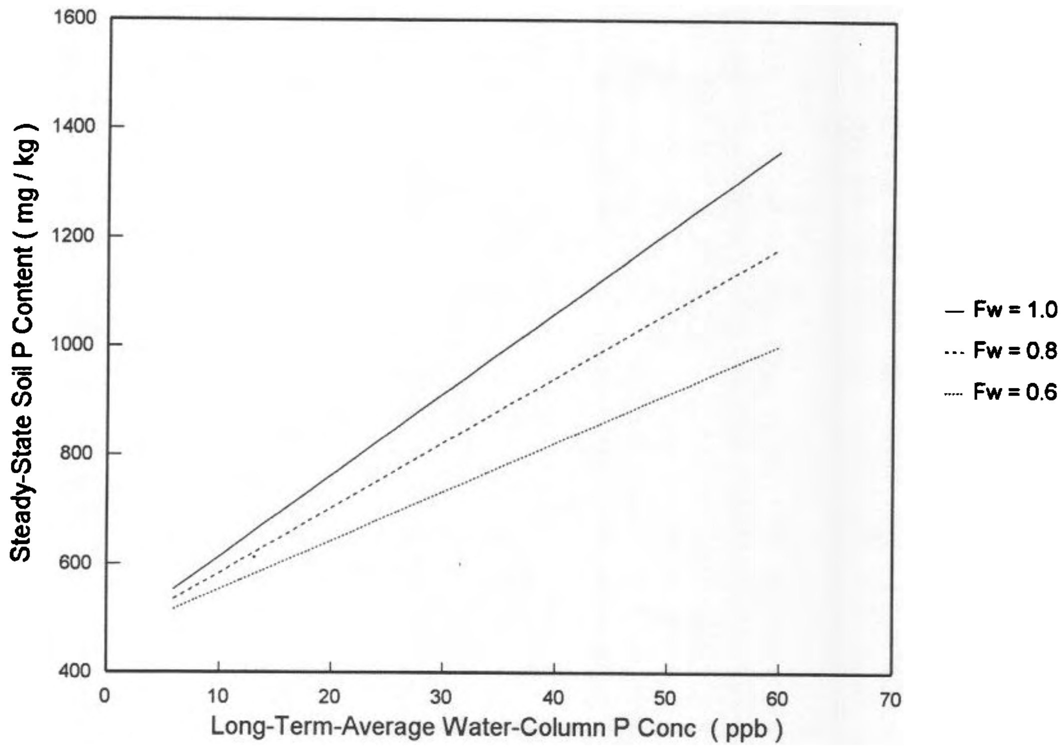


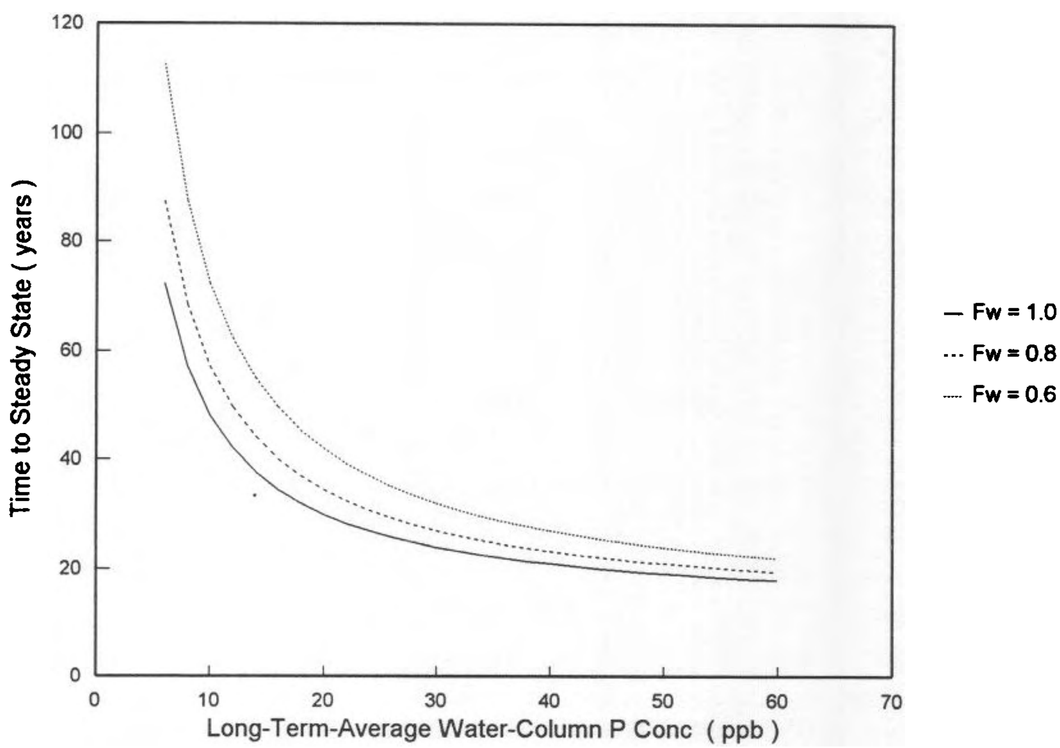
Conditions: Bulk Density = 0.08 g/cm3, Ke = 10.2 m/yr, Fw = 1.0, Depth = 10 cm

Mean +/- 1 Standard Error of Mean, Reflects Uncertainty in Following Parameters:

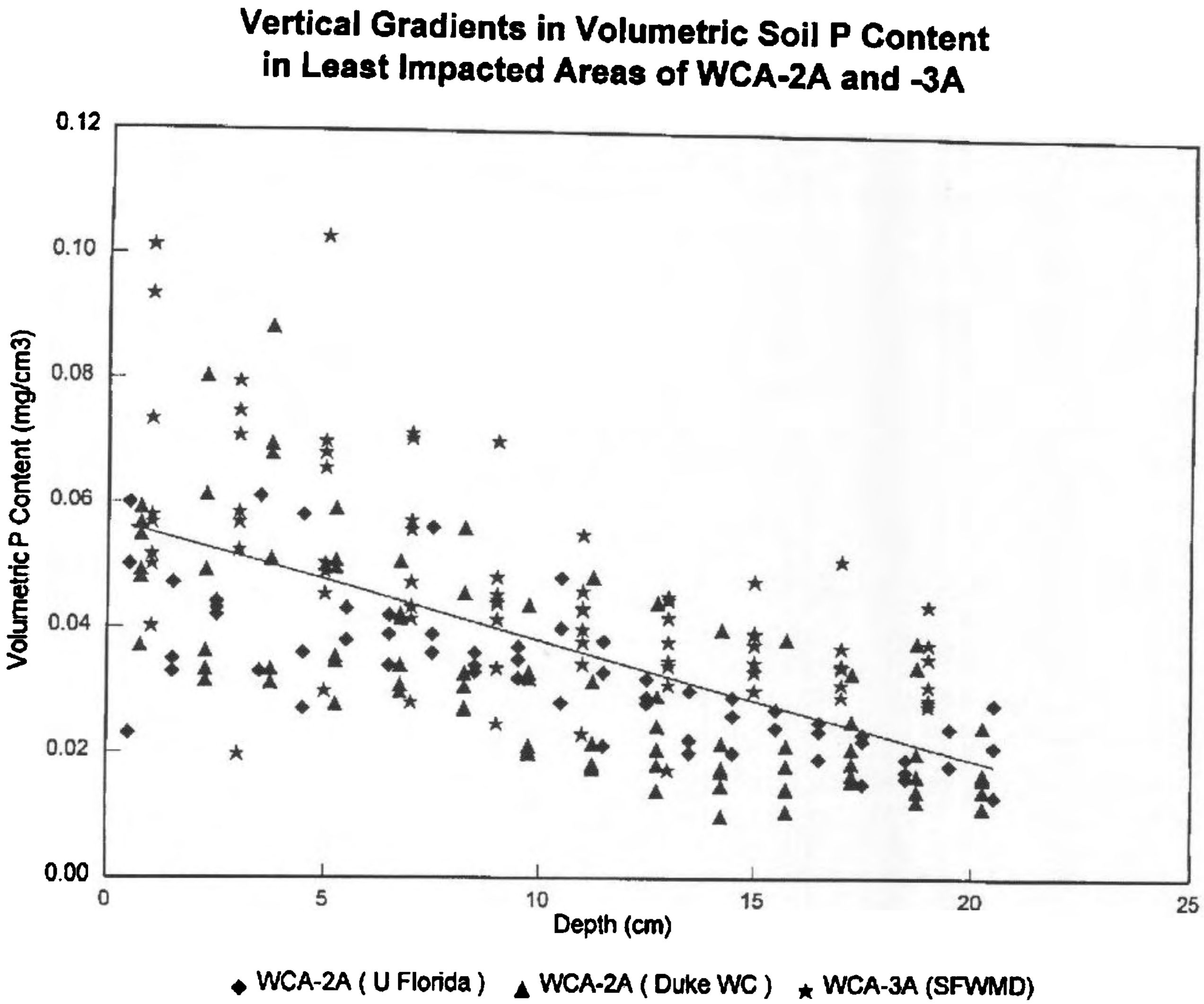
Parameter	Mean	Std Error
b	1.467	0.124
a	463	26.7
Ke	10.2	0.79

Sensitivity of Equilibrium Soil P Content & Response Time to Hydroperiod





Conditions: Bulk Density = 0.08 g/cm3, Ke = 10.2 m/yr, Depth = 10 cm



Regression:

$Y = 0.057 - 0.0019\,X$

$r2 = .39$, see = .014

Standard Error of Slope = 0.00016

Stations in Least Impacted Areas (~Representative of STA Discharge Zones)

WCA-2A (Reddy et al, 1991) - Stations 15, 16, & 17
WCA-2A (Duke Wetland Center, 1992) - Stations A5, A6, C5, C6, D5, D6
WCA-3A (SFWMD,1996) - Stations E3, E6, E7, E11, G1, G2, G4, G6

Macrophyte Frequencies vs. Soil Phosphorus Levels in WCA-2A
Duke Wetland Center (1995)

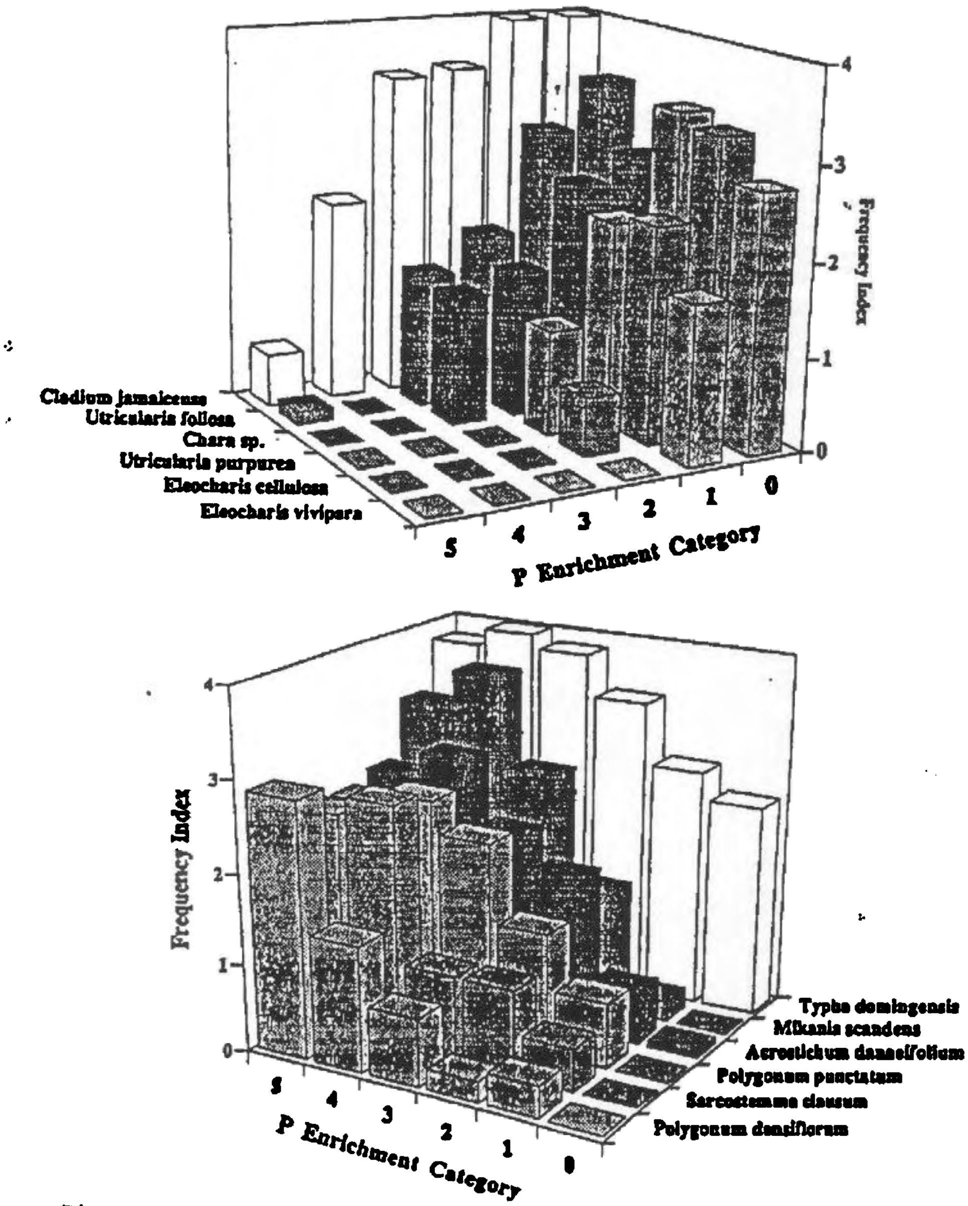
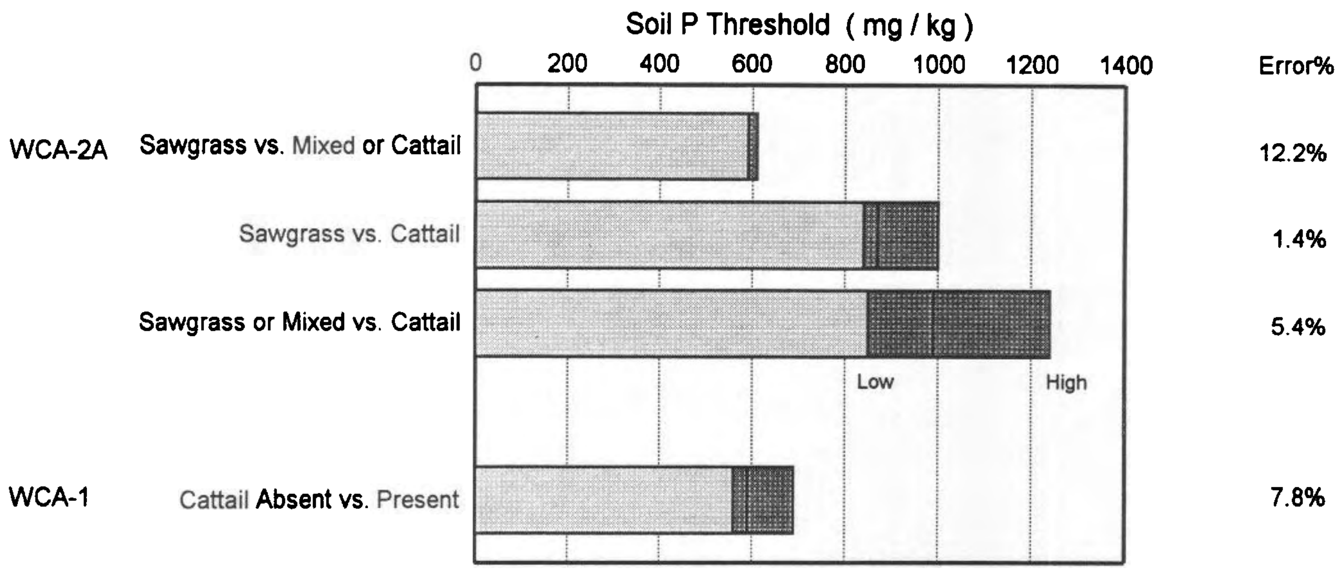


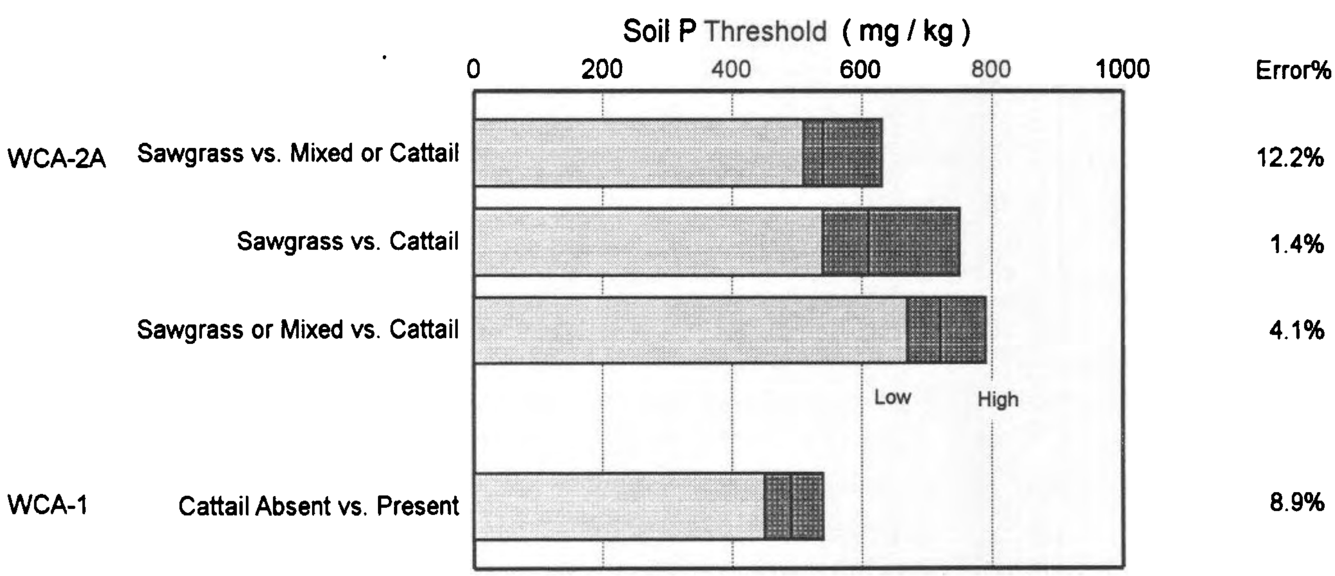
Fig. 10-9. Changes in the frequency index of the macrophyte species. (A) typical slough macrophytes and sawgrass, (B) cattail and other characteristic macrophyte species of the eutrophic Everglades.

P Enrichment Category	5	4	3	2	1	0
Soil P (mg/kg)	>1300	1100-1300	900-1100	700-900	500-700	<500

Soil P Thresholds Estimated from WCA-2A and WCA-1 Data

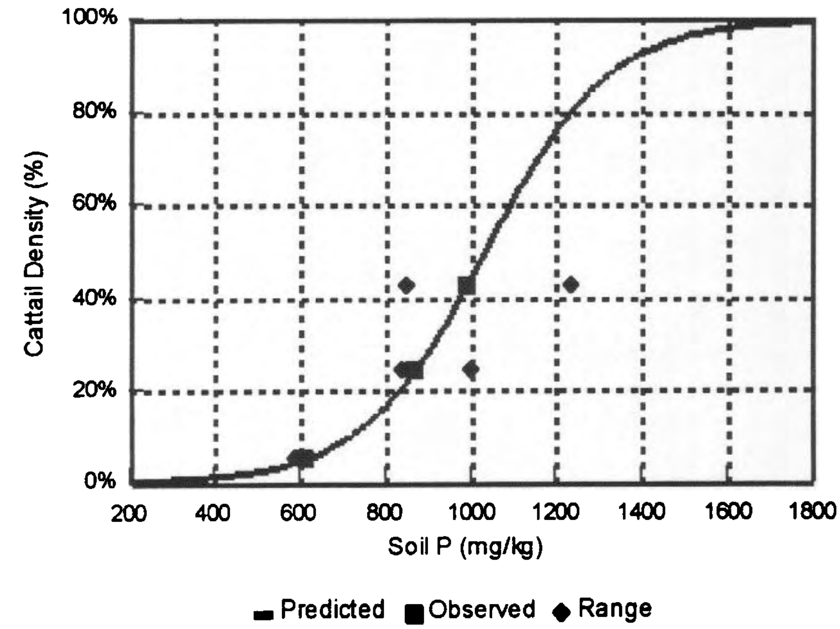


Soil Depth = 10 cm

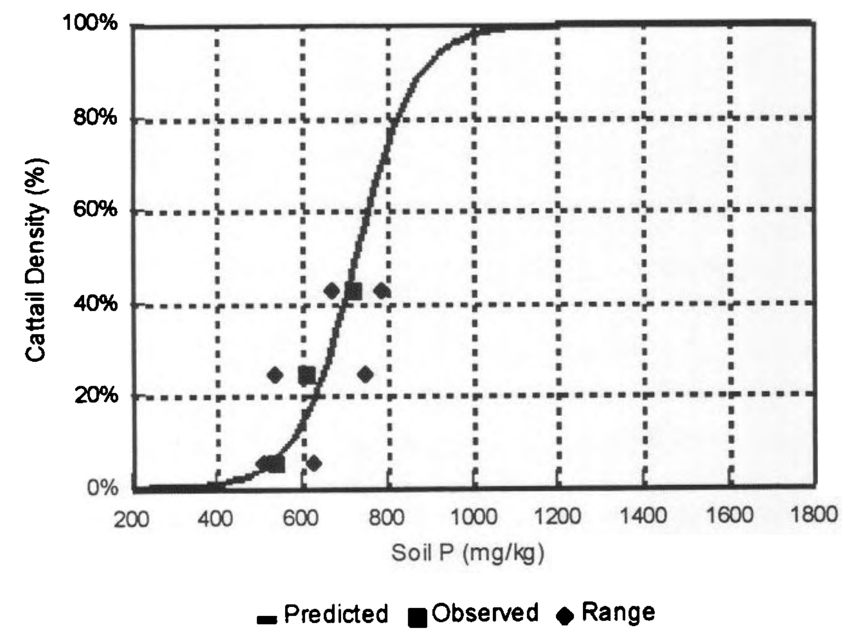


Soil Depth = 20 cm

Logistic Curves for Cattail Density As a Function of Soil Phoshorus Concentration



Soil Depth = 0-10 cm



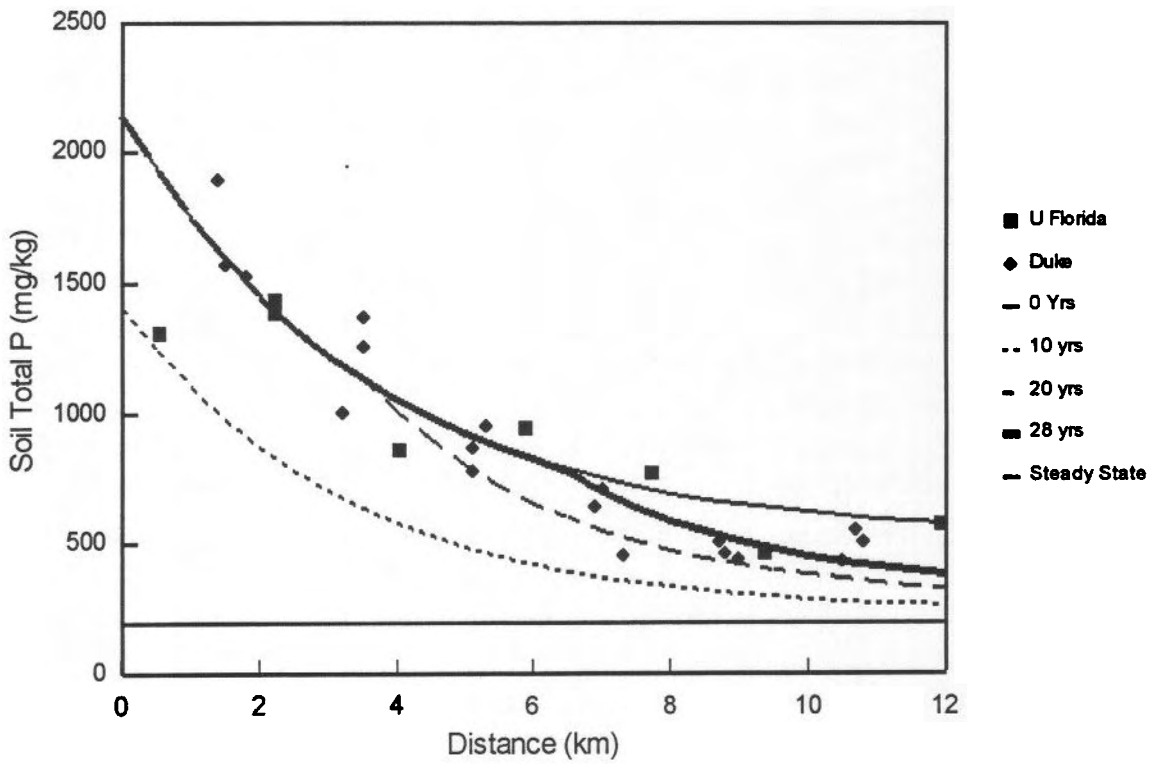
Soil Depth = 0-20 cm

Logistic Curve Parameters:

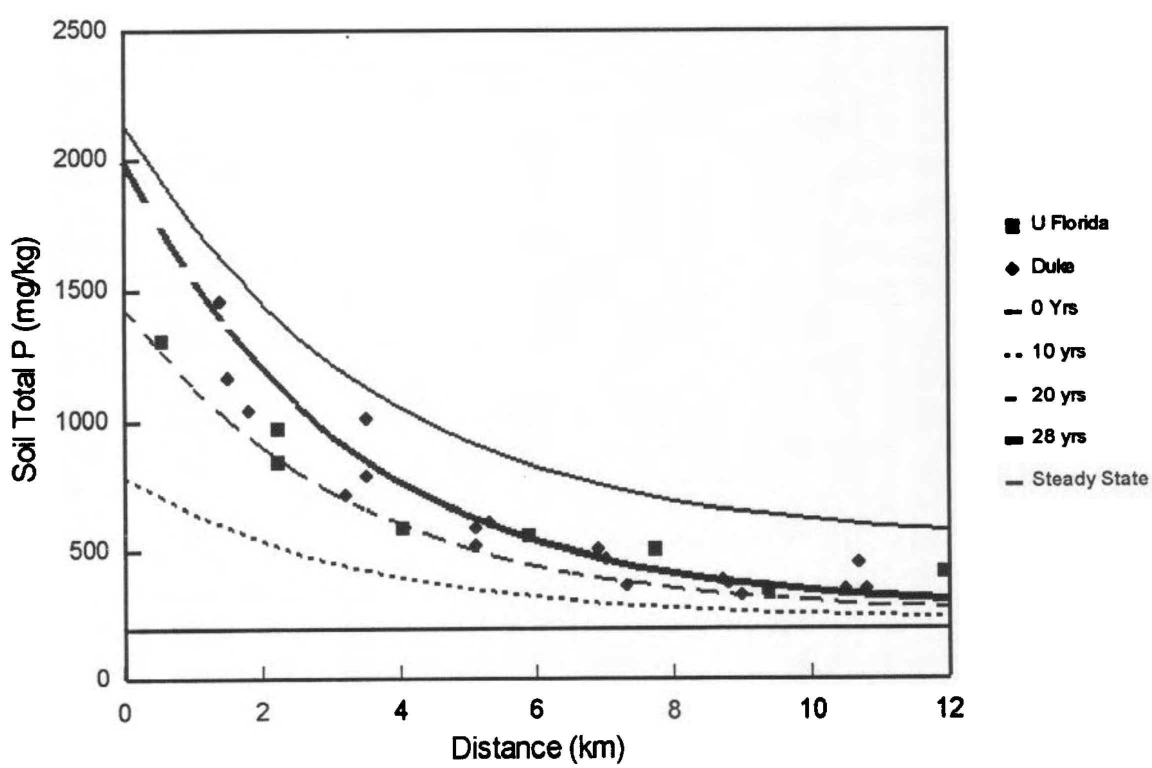
Depth (cm)	MidPoint	Spread	r2
cm	mg/kg	mg/kg	%
10	1034.4	144.1	99%
20	727.7	71.2	89%

Figure 14

Observed & Predicted Soil P Concentrations below S10 Structures



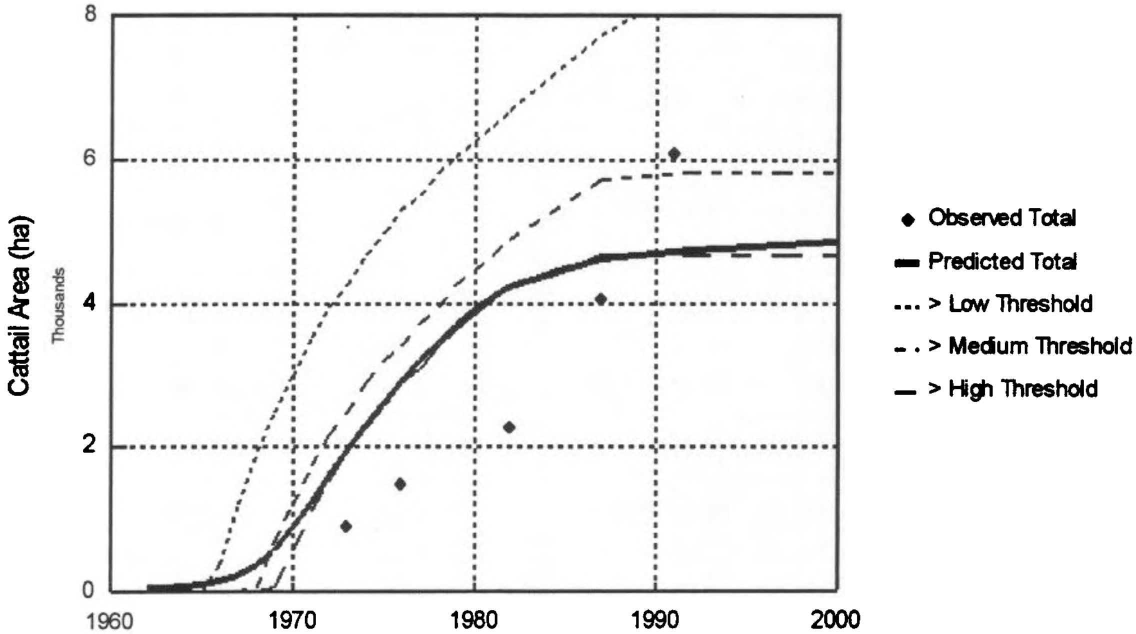
Depth Interval = 0 - 10 cm



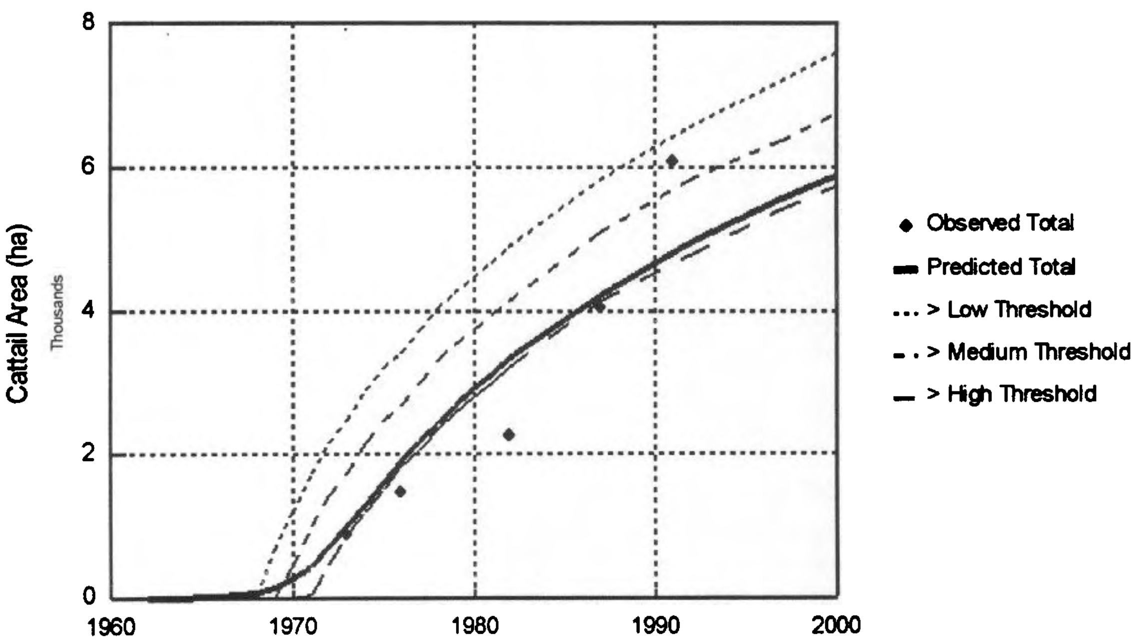
Depth Interval = 0 - 20 cm

Figure 15

Observed & Predicted Cattail Expansion Below S10's



Depth Interval = 0 - 10 cm



Depth Interval = 0 - 20 cm

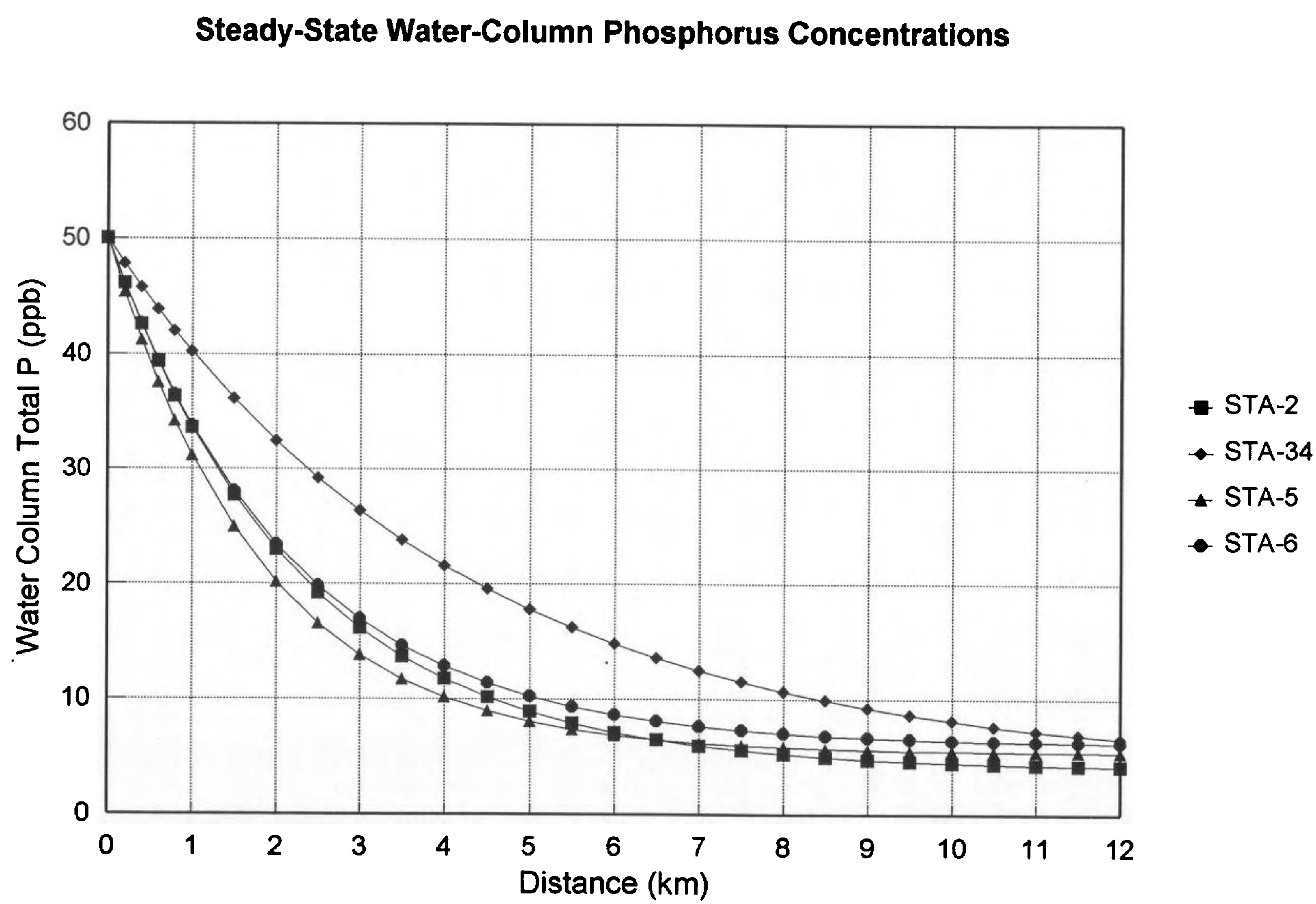
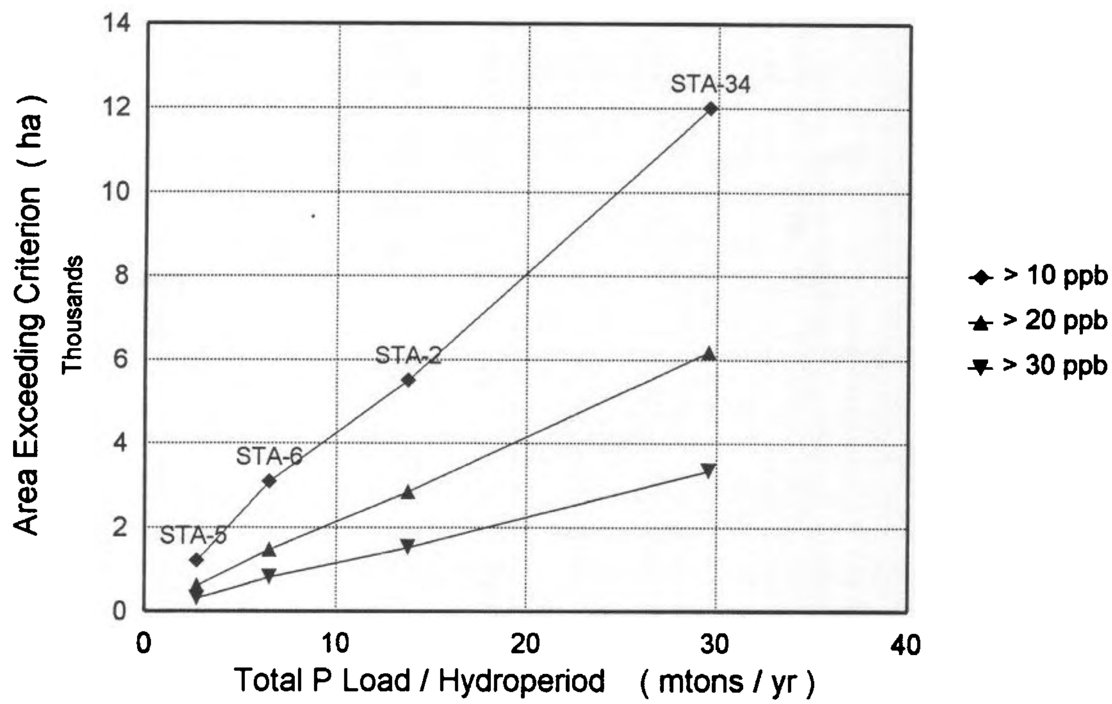

Steady-State Water-Column Phosphorus Concentrations
Water Column Total P (ppb)
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
12
Distance (km)
STA-2
STA-34
STA-5
STA-6

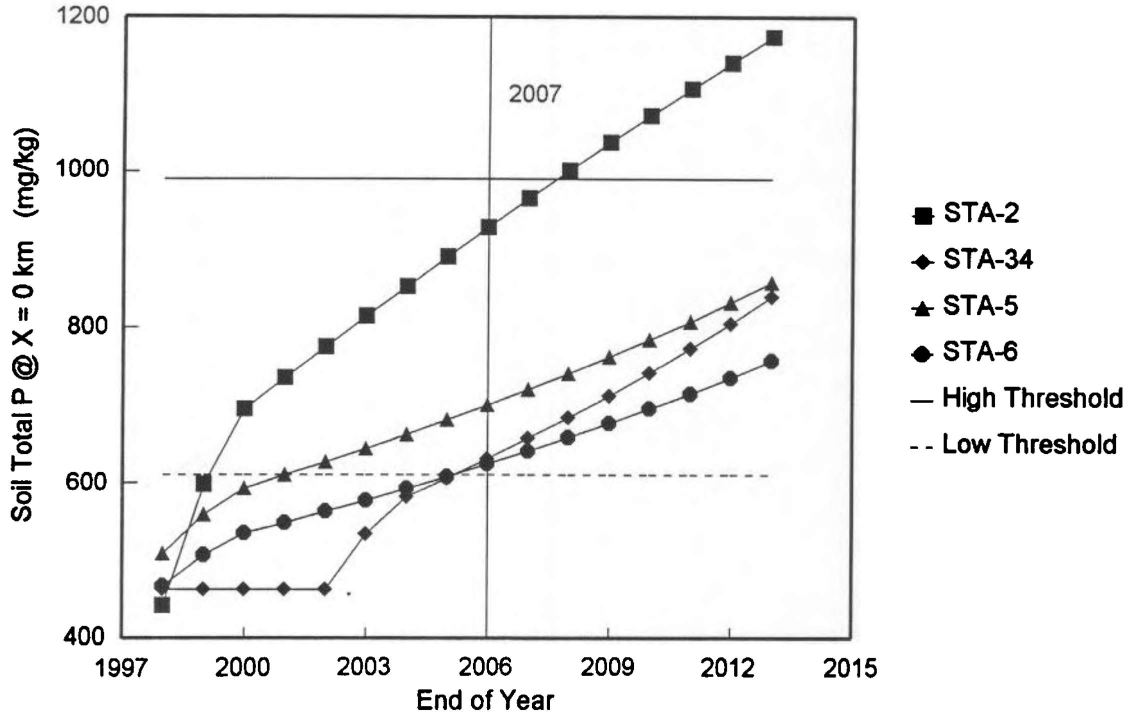
Figure 16

Figure 17

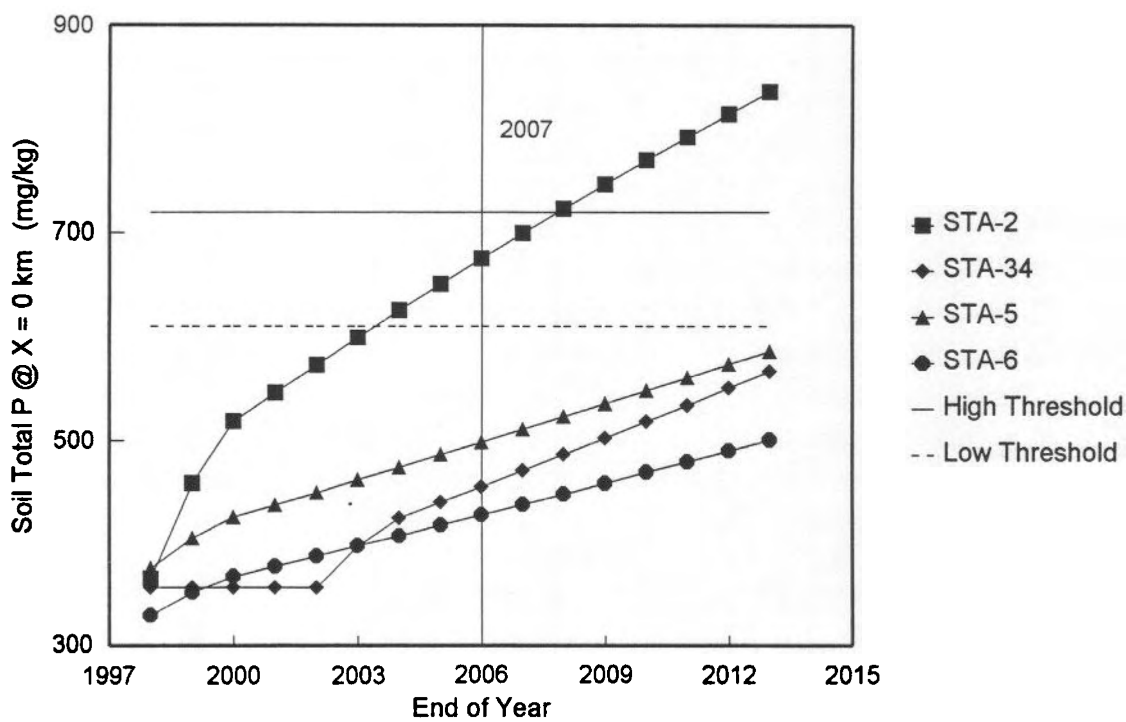
Water-Column Impact Areas vs. STA Phosphorus Load



Soil P Concentrations Immediately Below Structures vs. Year



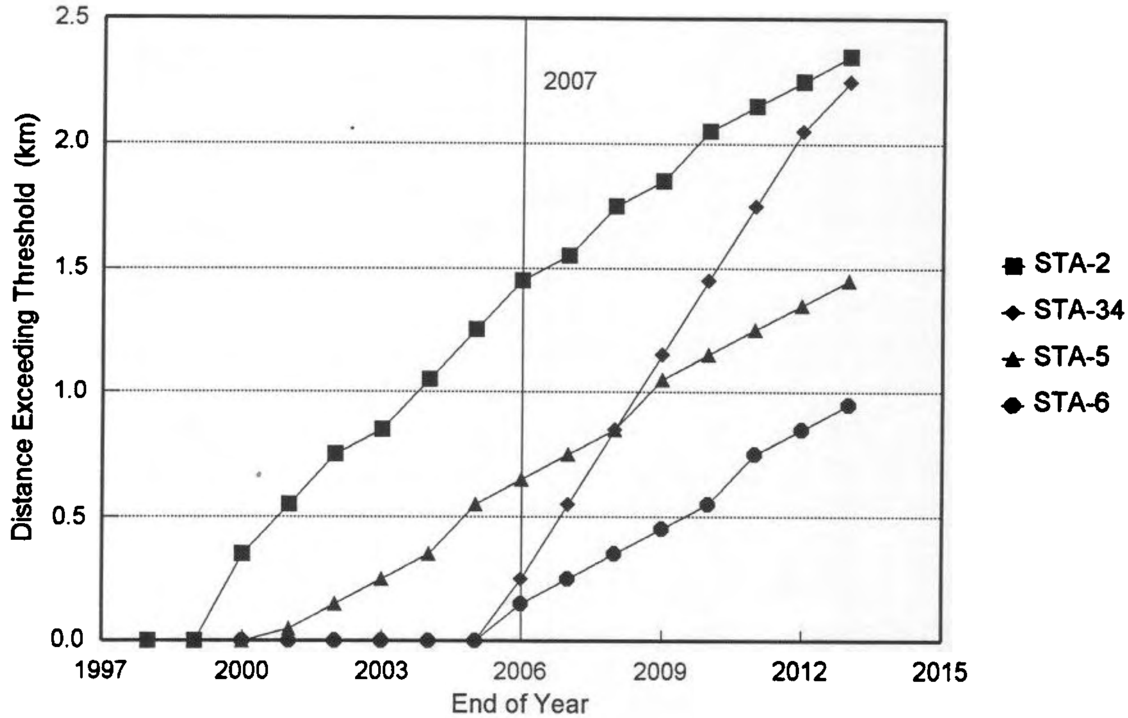
Soil Depth = 10 cm



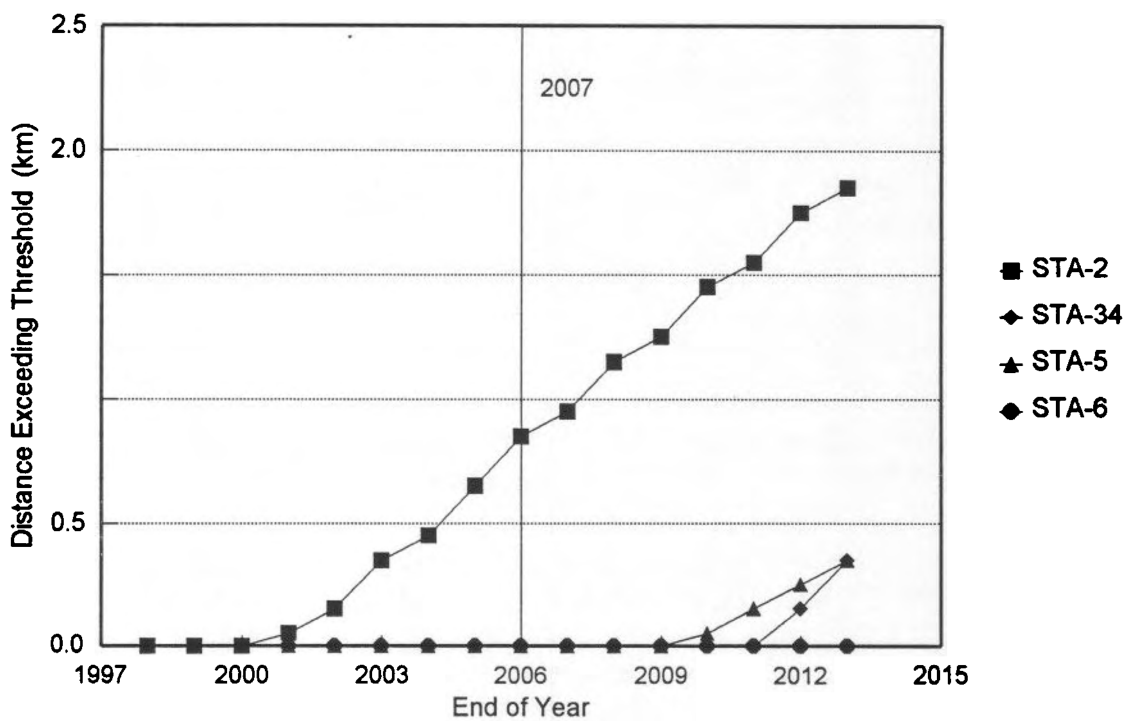
Soil Depth = 20 cm

Figure 19

Exceedence of Low Threshold Criteria vs. Time



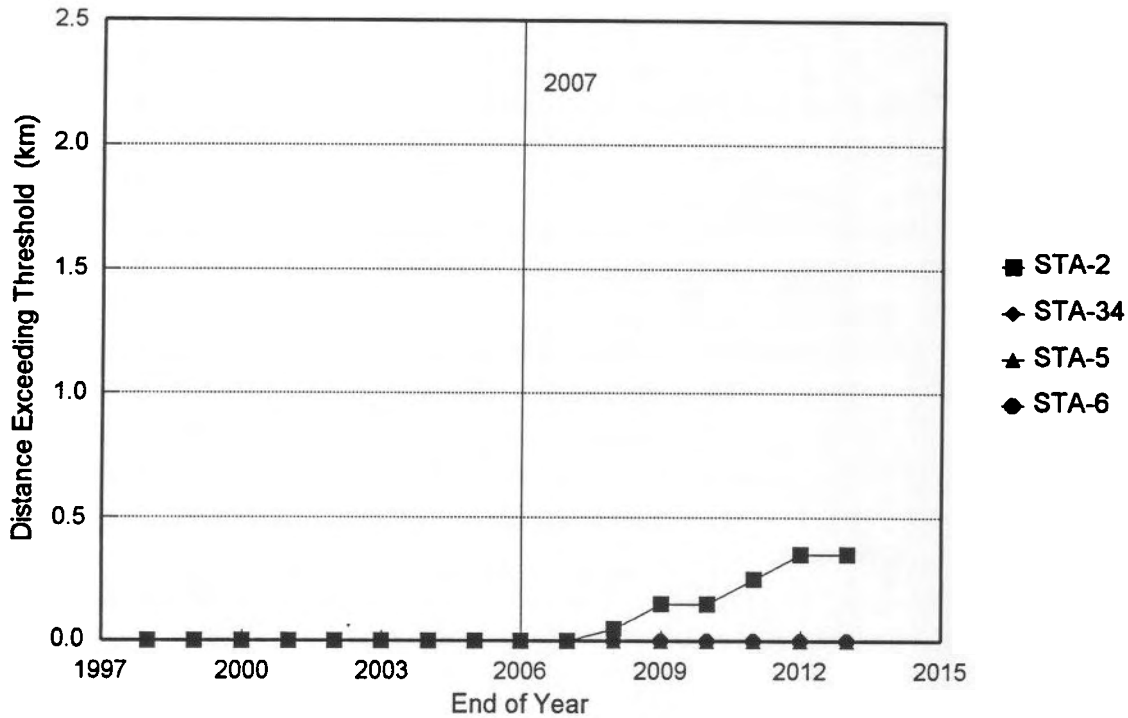
Soil Depth = 10 cm, Threshold = 610 mg/kg



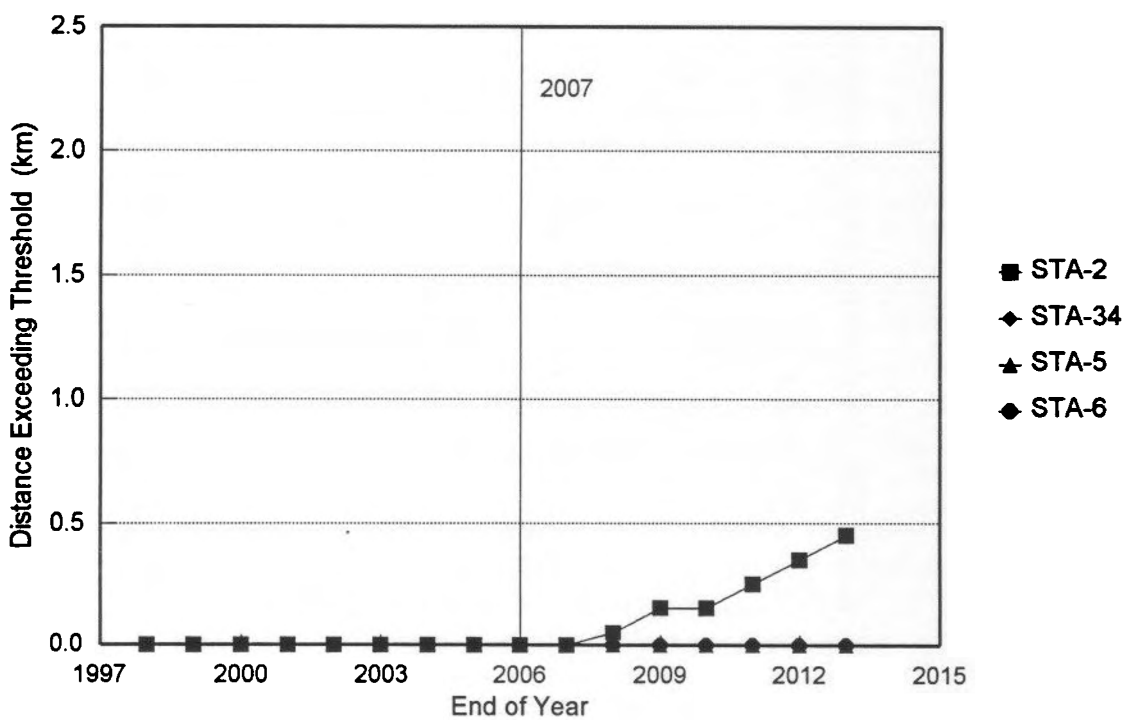
Soil Depth = 20 cm, Threshold = 540 mg/kg

Figure 20

Exceedence of High Threshold Criteria vs. Time



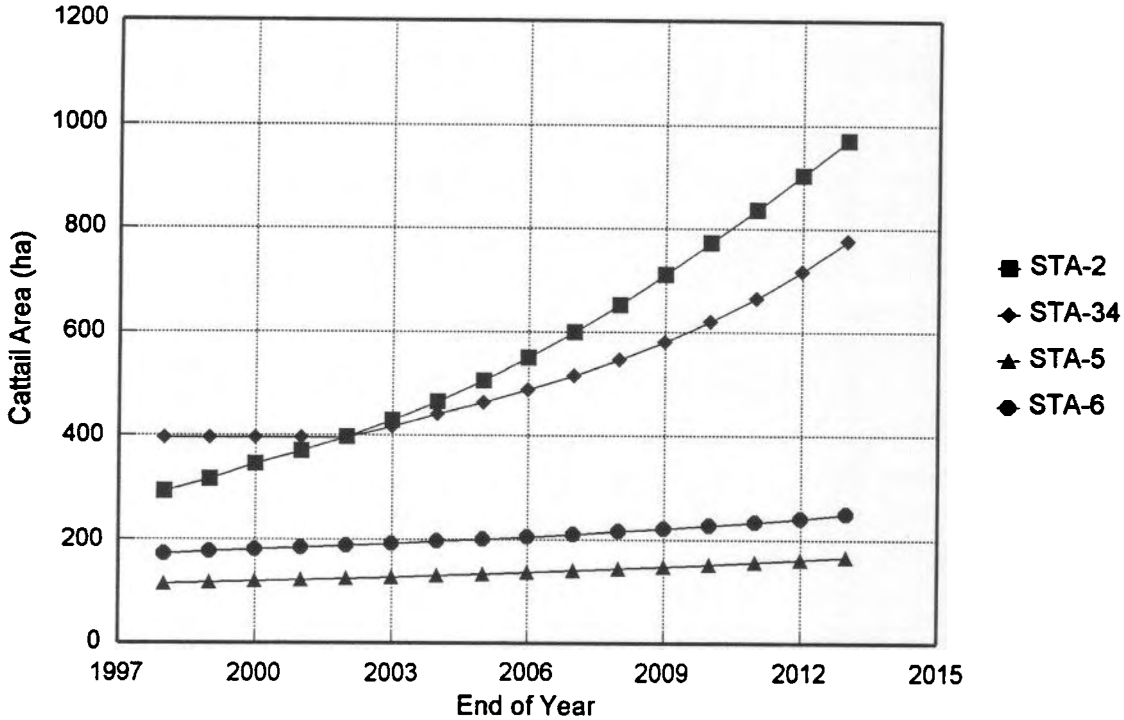
Soil Depth = 10 cm, Threshold = 990 mg/kg



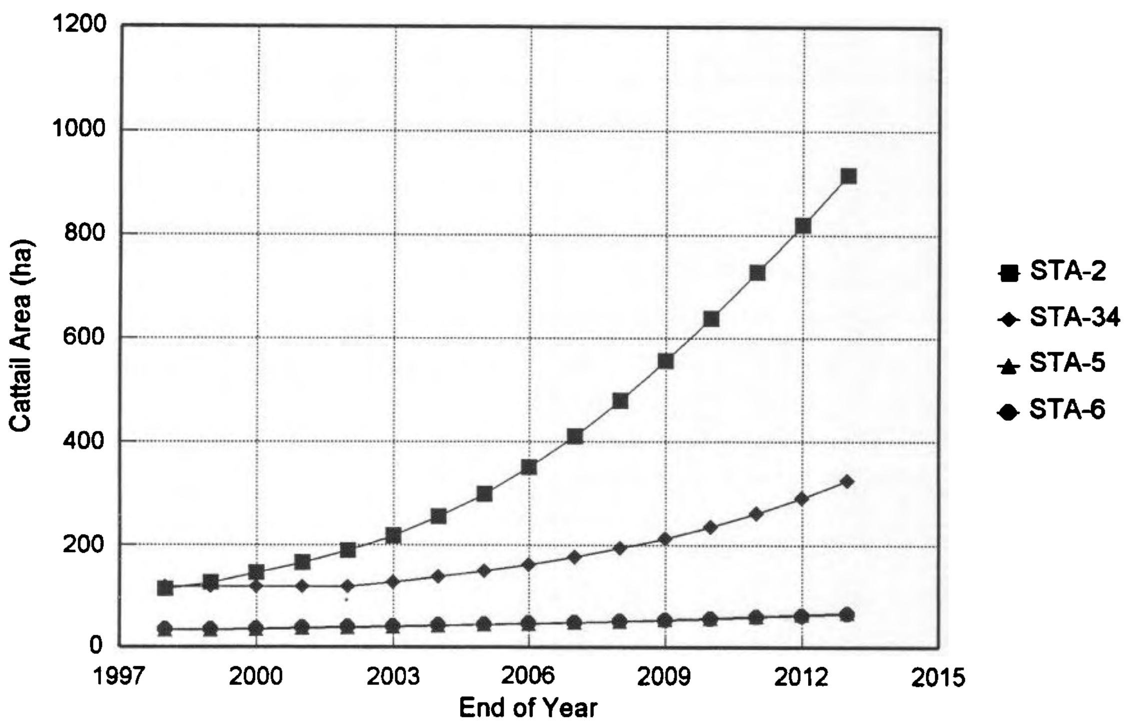
Soil Depth = 20 cm, Threshold = 720 mg/kg

Figure 21

Total Cattail Area vs. Time

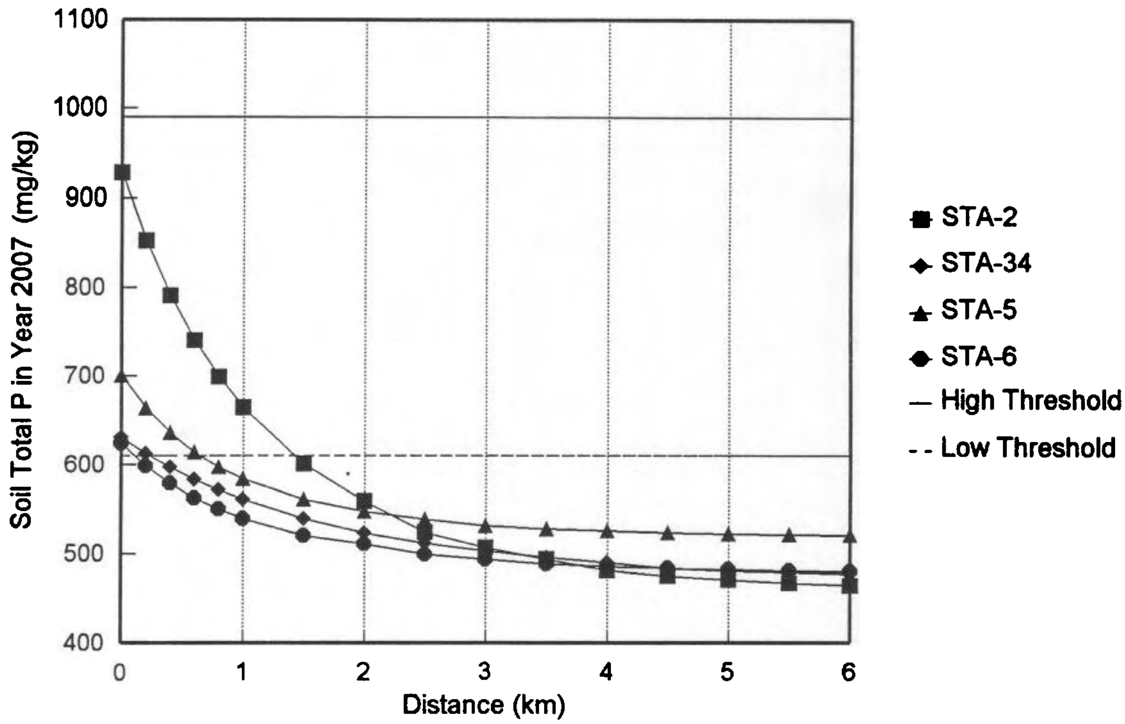


Soil Depth = 10 cm

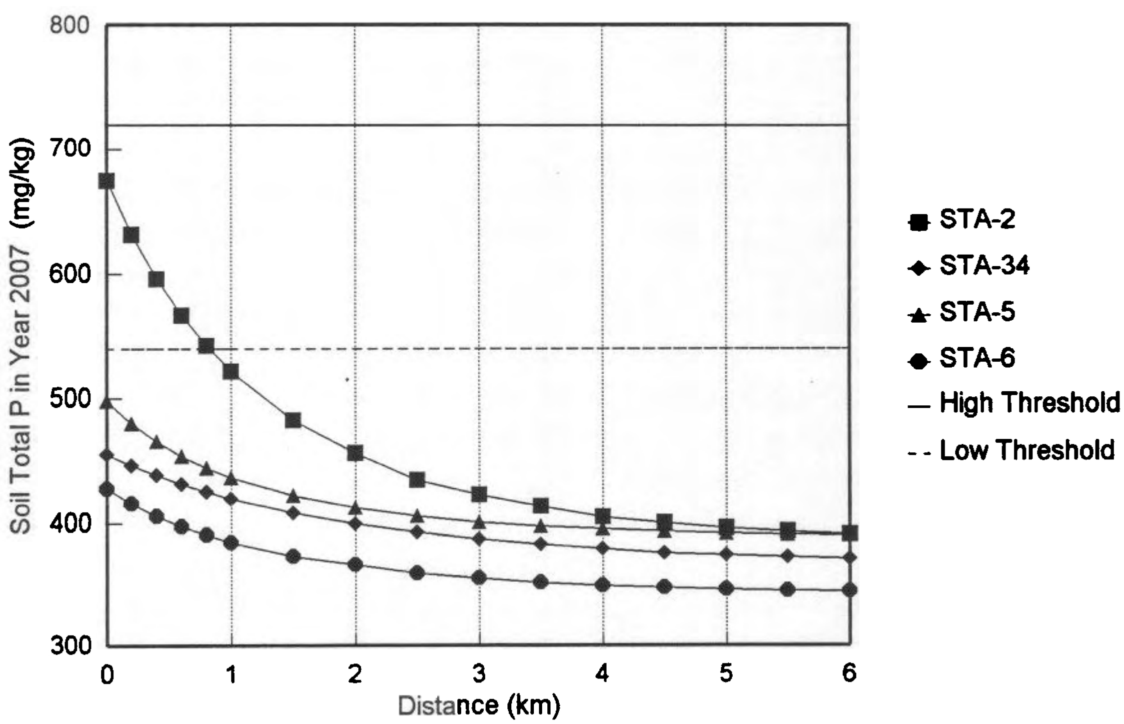


Soil Depth = 20 cm

Soil P Profiles in Year 2007

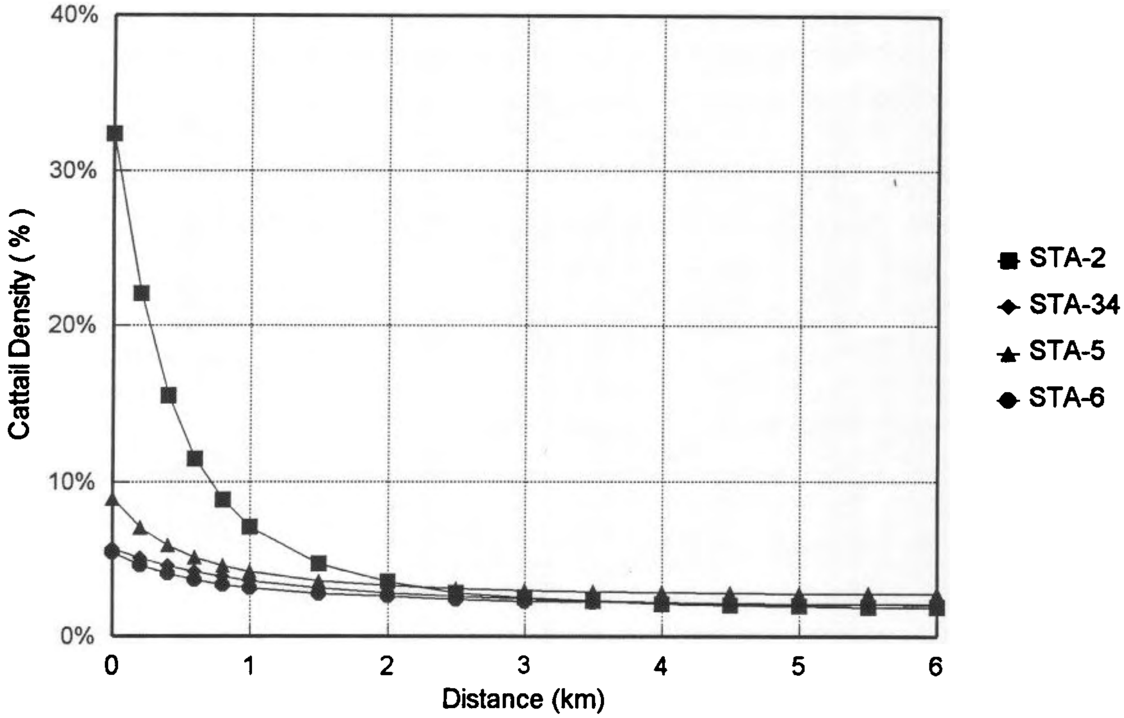


Soil Depth = 10 cm

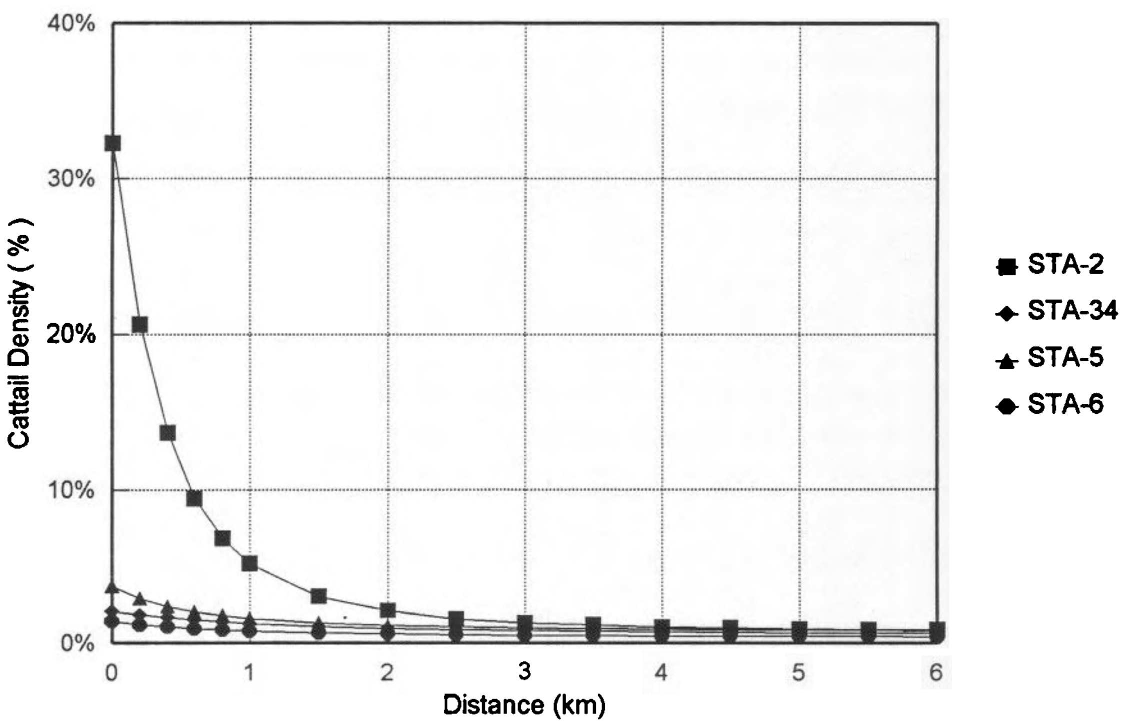


Soil Depth = 20 cm

Cattail Density Profiles in Year 2007

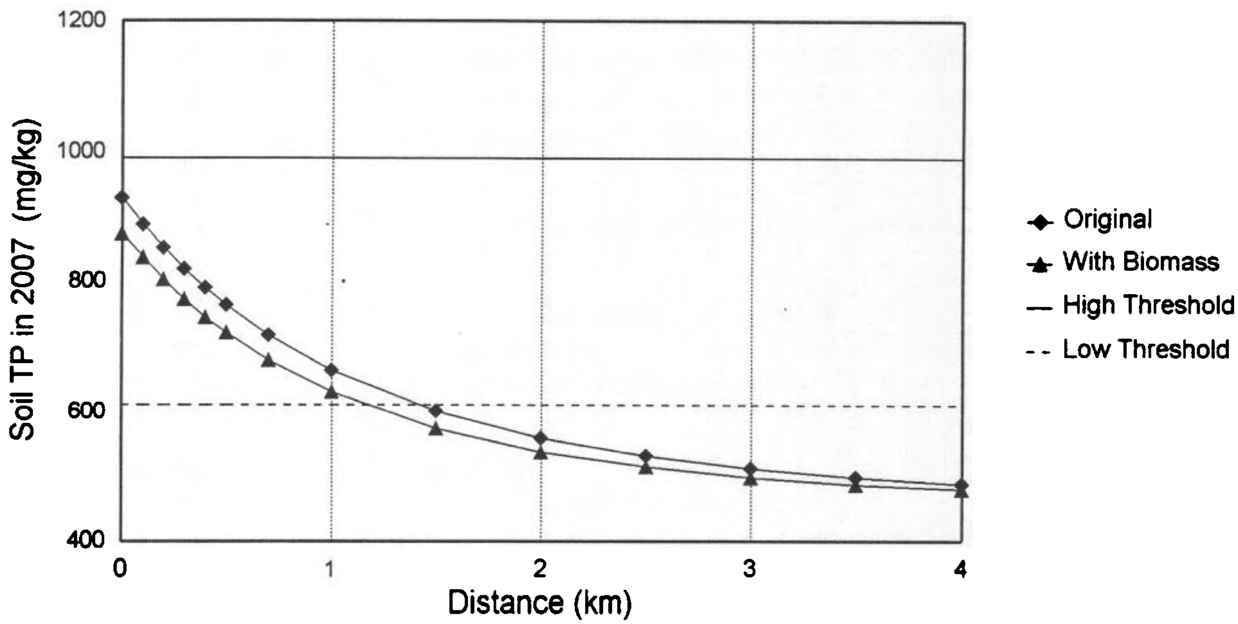


Soil Depth = 10 cm

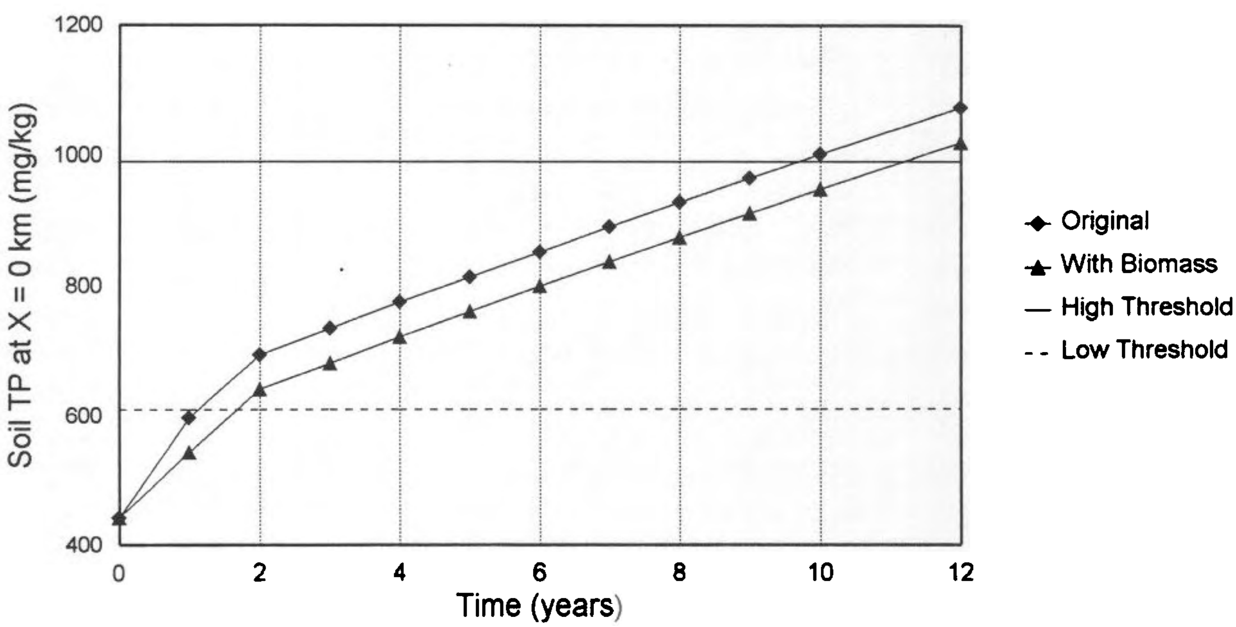


Soil Depth = 20 cm

Impact of Phosphorus Storage in Biomass on STA-2 Simulation
Depth Interval = 0 - 10 cm

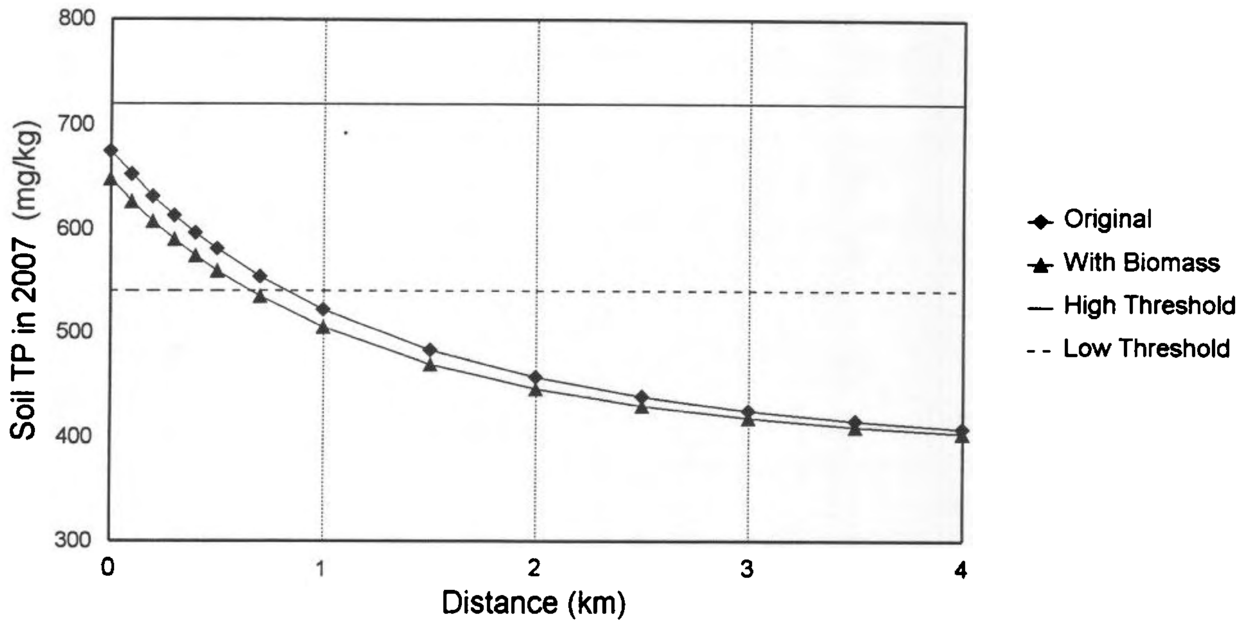


Depth Interval = 0 - 10 cm

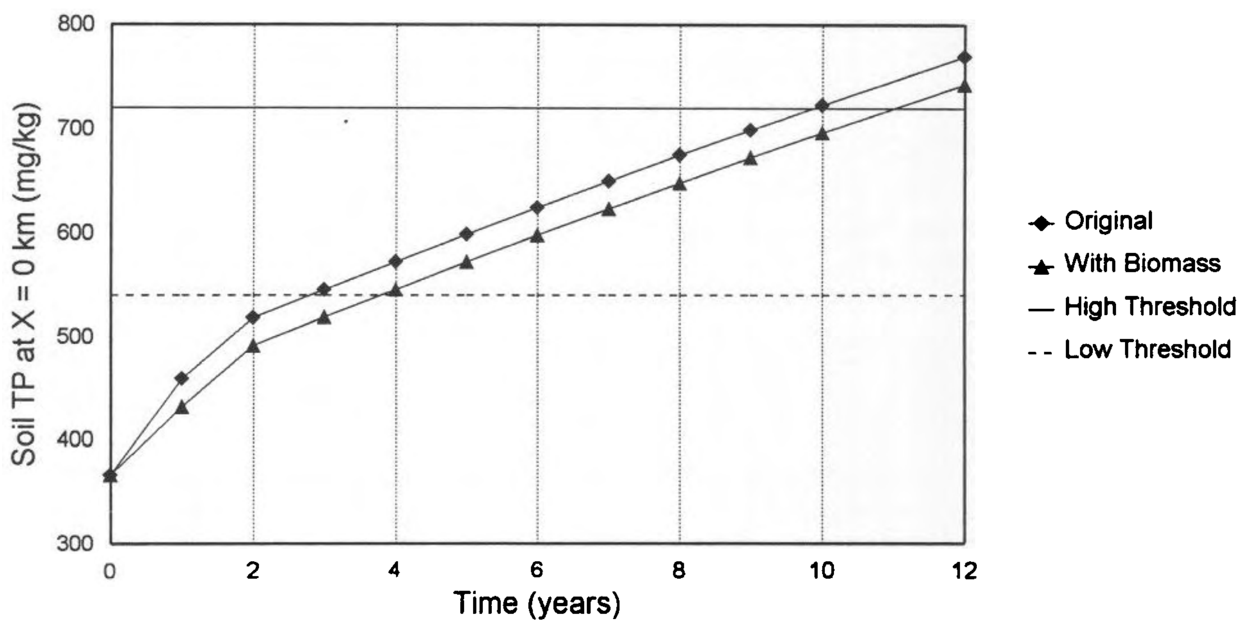


Depth Interval = 0 - 10 cm

Impact of Phosphorus Storage in Biomass on STA-2 Simulation
Depth Interval = 0 - 20 cm

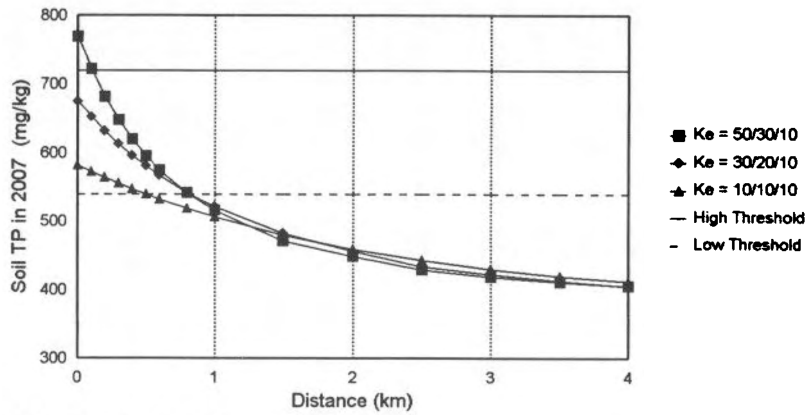


Depth Interval = 0 - 20 cm

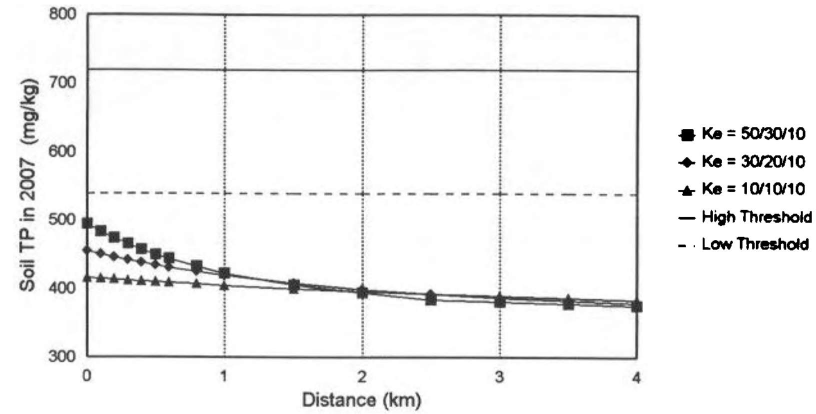


Depth Interval = 0 - 20 cm

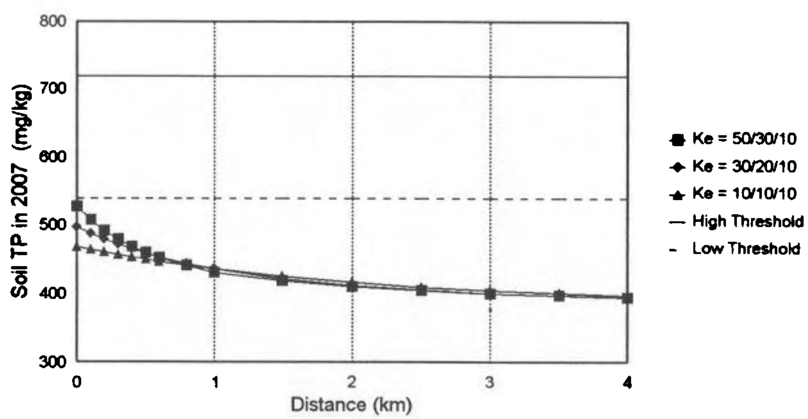
Sensitivity of Soil P Profiles in 2007 to Settling Rates in First 3 Years
Soil Depth = 20 cm



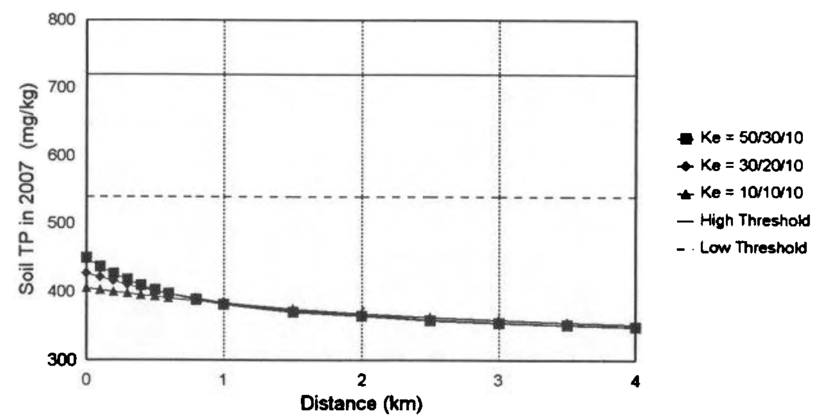
STA-2, Soil Depth = 20 cm



STA-34, Soil Depth = 20 cm



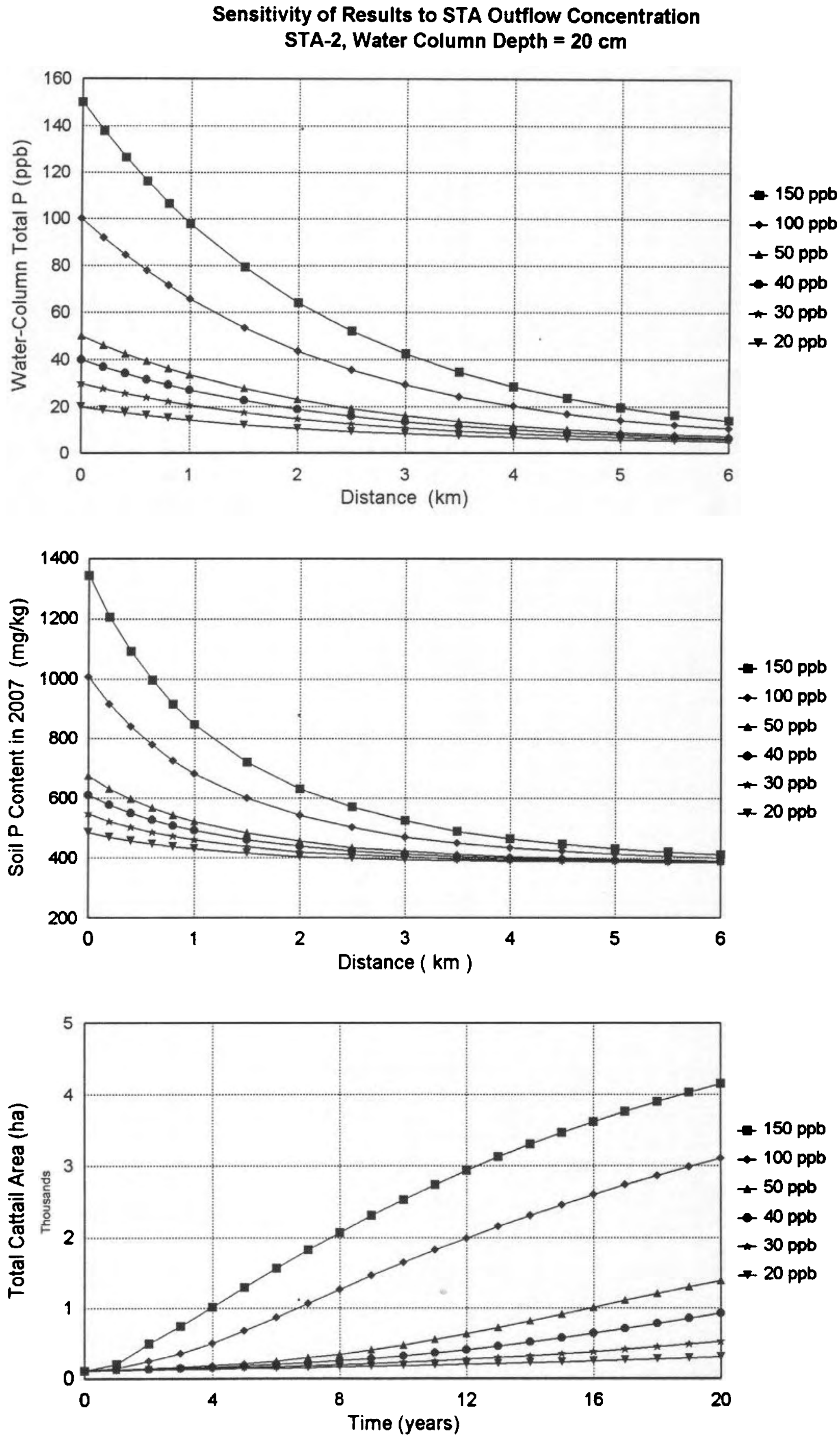
STA-5, Soil Depth = 20 cm



STA-6, Soil Depth = 20 cm

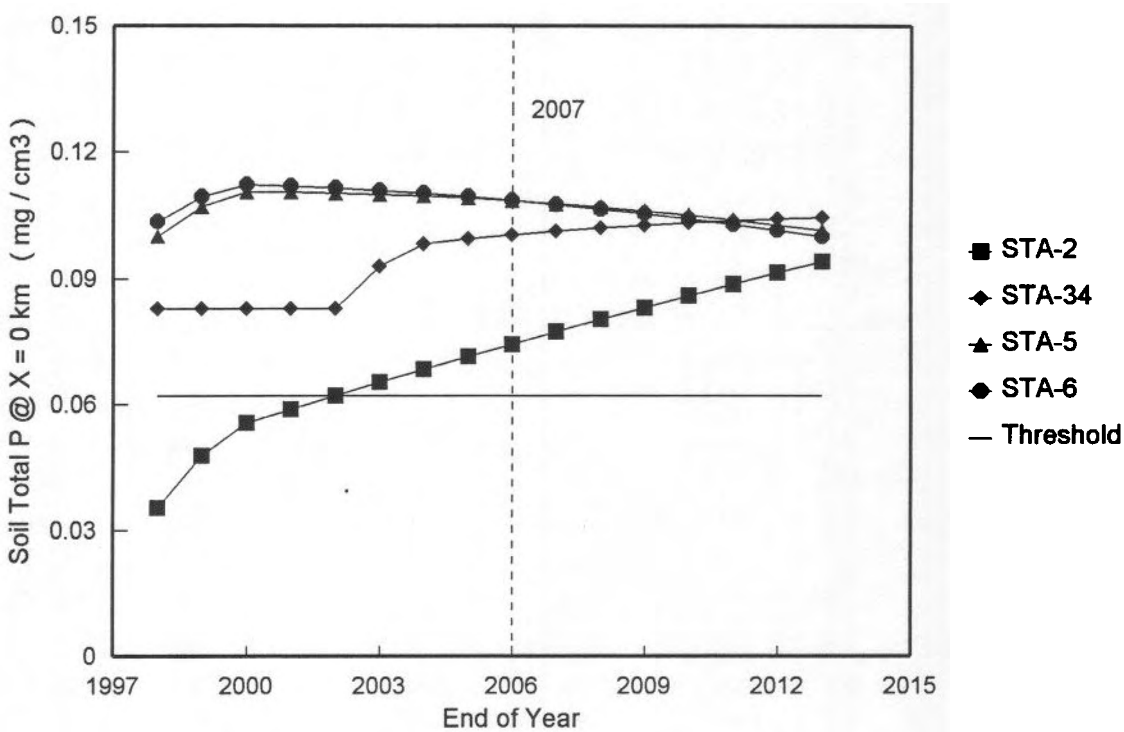
Figure 26

Figure 27

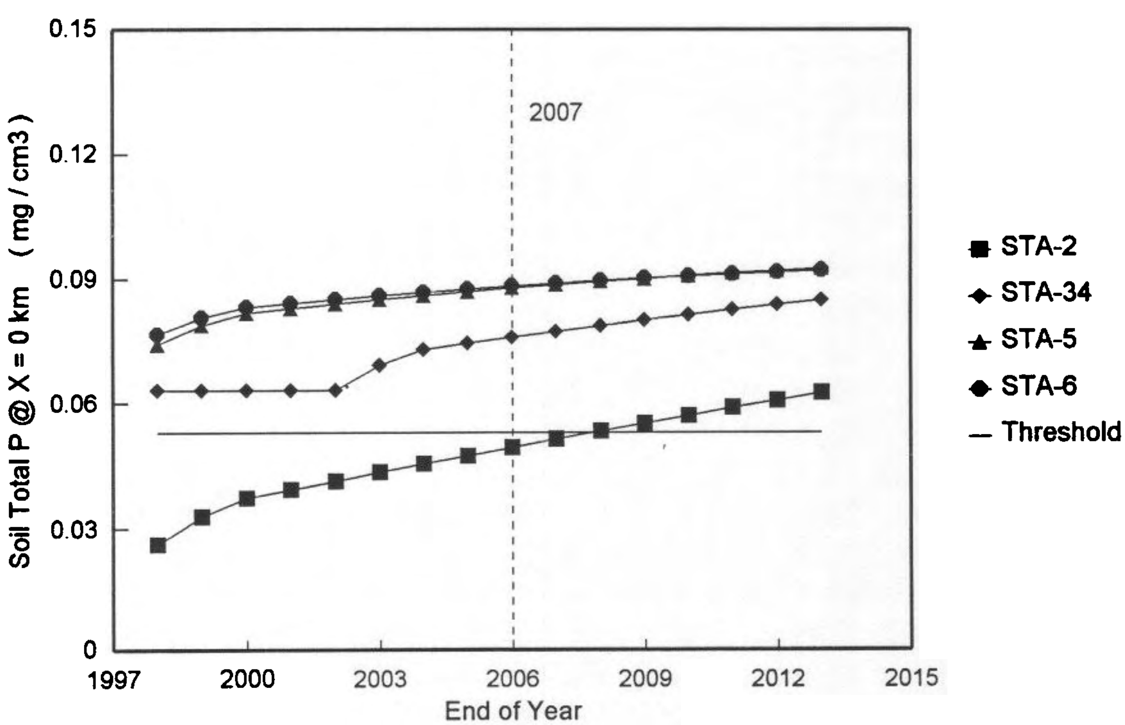


Sensitivity of Results to STA Outflow Concentration
STA-2, Water Column Depth = 20 cm
Water-Column Total P (ppb)
Distance (km)
150 ppb
100 ppb
50 ppb
40 ppb
30 ppb
20 ppb
Soil P Content in 2007 (mg/kg)
Distance (km)
Total Cattail Area (ha)
Thousands
Time (years)

Volumetric Soil P Concentrations At STA Discharges vs. Year



Soil Depth = 10 cm



Soil Depth = 10 cm

List of Tables

1 Initial Soil & Water Conditions in STA Discharge Zones

2 Summary of Soil P Criteria Extracted from WCA-1 & WCA-2A Data Sets

3 Summary of Results

4 Sensitivity Analysis of STA-2 Simulations to Model Parameters & Initial Conditions Phosphorus & Cattail Profiles in 2007

5 Sensitivity Analysis of STA-2 Simulations to Model Parameters & Initial Conditions - Total Cattail Area vs. Time

Initial Soil & Water Conditions in STA Discharge Zones

STA Discharge Zone	STA-2 NW 2A	STA-34 NE 3A	STA-5 Rotenb.	STA-6 NW 3A
Data Source	Reddy et al, 91	Reddy et al., 94b	SFWMD, 96	Reddy et al,94b
Stations	46-51, 61-63, 69	Columns C - J Rows 1-2	1 thru 7	Columns A & B Rows 1-2
Bulk Density (g/cm3)				
0-10 cm	0.080	0.179	0.197	0.222
10-20 cm	0.063	0.174	0.197	0.242
0-20 cm *	0.071	0.176	0.197	0.232
Soil P Content (mg/kg)				
0-10 cm	442	463	508	467
10-20 cm	271	250	245	205
0-20 cm **	366	358	376	330
Volumetric Soil P Content (mg/cm3)				
0-10 cm	0.035	0.083	0.100	0.104
10-20 cm	0.017	0.044	0.048	0.049
0-20 cm	0.026	0.063	0.074	0.077
Vertical Gradient (mg/cm3/cm)	-0.0018	-0.0039	-0.0052	-0.0054
Water Column Phosphorus Concentrations				
Stations	CA2-2,6,7,9	CA3-2,3,4	NA	CA3-5,7,8
Dates	1978-1984	1978-1984		1978-1984
Samples	95	40		36
Geometric Mean (ppb)	13.2	16.8		20.0
Standard Error (ppb)	1.2	2.2		3.1
Dates	1995-1996	1995-1996		1995-1996
Samples	30	40		11
Geometric Mean (ppb)	7.3	6.8		7.8
Standard Error (ppb)	0.8	0.4		1.0
SF Water Management Model Simulation Results (Neidrauer, 1996)				
WMM Cells	C27, R43-44 C28, R43-45 C26, R43	C21-25,R39-41	C15-16, R46	C17, R39-41
Average Hydroperiod**				
1979-1988 Base Period	77%	71%	51%	64%
1965-1990 Without ECP	85%	72%	13%	72%
1965-1990 With ECP	92%	88%	69%	61%

* Rotenberger Value Assumed Equal to 0-10 cm value
** Rotenberger Value Estimated from Average Ratio of 0-20 to 0-10 cm P Content for WCA-3A NE & NW Soi
*** Percent of Month-End Water Surface Elevations above Mean Ground Surface

Summary of Soil P Criteria Extracted from WCA-2A & WCA-1 Data Sets

Location	Vegetation Contrast	Depth = 0-10 cm Low	High	Best	Error %	Depth = 0-20 cm Low	High	Best	Error %
Mass Concentration (mg P / kg)									
WCA-2A	Sawgrass vs. Mixed or Cattail	590	610	610	12.2%	510	630	540	12.2%
	Sawgrass vs. Cattail	840	1000	870	1.4%	540	750	610	1.4%
	Sawgrass or Mixed vs. Cattail	850	1240	990	5.4%	670	790	720	4.1%
WCA-1	Cattail Absent vs. Present	560	690	590	7.8%	450	540	490	8.9%
Volumetric Concentration (mg P / cm3)									
WCA-2A	Sawgrass vs. Mixed or Cattail	0.059	0.064	0.060	18.9%	0.033	0.035	0.034	18.9%
	Sawgrass vs. Cattail	0.059	0.064	0.062	5.4%	0.048	0.063	0.053	5.4%
	Sawgrass or Mixed vs. Cattail	0.061	0.064	0.062	8.1%	0.049	0.063	0.054	6.8%
WCA-1	Cattail Absent vs. Present	0.042	0.046	0.044	11.1%	0.032	0.038	0.036	10.0%

Best	Yields Least Number of Misclassified Sites
Low,High	Range Yielding Least Number of Misclassified Sites + 1
Error%	Total Misclassified Sites / Total Number of Sites
WCA-2A	Reddy et al., 1991; 74 Sites (49 Sawgrass, 13 mixed, 12 cattail)
WCA-1	Reddy et al., 1994a; Newman, 1996; 90 Sites (66 Cattail Absent, 24 Cattail Present)

Table 2

Summary of Results

Stormwater Treatment Area		STA-2	STA-34	STA-5	STA-6
Discharge Zone		NW 2A	NE 3A	Rotenb.	NW 3A
Project Completion Date (Assumed Jan 1)		1999	2003	1999	1999
Duration of 50 ppb Discharge (yrs)		8	4	8	8
STA Outflow (10^6 m3/yr)		254.0	520.9	37.9	79.5
STA Outflow (1000 acre-ft/yr)		205.8	422.0	30.7	64.4
Outflow Conc (ppb)		50	50	50	50
STA Outflow Load (mtons/yr)		12.7	26.0	1.9	4.0
Flow Path Width (km)		12.1	14.2	3.0	6.0
Average Hydroperiod (%)		92%	88%	69%	61%
Spatial Resolution of Model (hectares)		121	142	30	60
Steady-State Water-Column P Concentrations					
Distance Exceeded (km)					
	> 10 ppb	4.6	8.5	4.1	5.2
	> 20 ppb	2.4	4.4	2.1	2.5
	> 30 ppb	1.3	2.4	1.1	1.4
Area Exceeded (hectares)					
	> 10 ppb	5506	11999	1215	3090
	> 20 ppb	2844	6177	615	1470
	> 30 ppb	1513	3337	315	810
Soil P & Cattail Simulations Using 0-10 cm Soil Depth - Areas in Hectares					
Areas Exceeding Soil P Criteria at End of 2006					
Low	> 610 mg/kg	1755	355	195	90
Medium	> 870 mg/kg	182	0	0	0
High	> 990 mg/kg	0	0	0	0
Total Cattail Area					
	Initial Condition	291	395	114	171
	End of 2004	465	441	130	195
	End of 2006	550	488	136	205
	End of 2008	653	546	143	215
	Steady-State	1634	2785	262	505
Net Area Increases - End of 2006					
	Maximum Cattail Density (%)	32%	6%	9%	5%
	Total Cattail Area	259	93	23	33
	Cattail Density > 5%	1755	355	195	90
	Cattail Density > 10%	908	0	0	0
	Cattail Density > 50%	0	0	0	0
Soil P & Cattail Simulations Using 0-20 cm Soil Depth - Areas in Hectares					
Areas Exceeding Soil P Criteria at End of 2006					
Low	> 540 mg/kg	1029	0	0	0
Medium	> 610 mg/kg	424	0	0	0
High *	> 720 mg/kg	0	0	0	0
Total Cattail Area *					
	Initial Condition	113	118	32	34
	End of 2004	254	138	41	42
	End of 2006	349	162	46	46
	End of 2008	479	194	51	51
	Steady-State	4139	7640	754	1545
Net Area Increases - End of 2006					
	Maximum Cattail Density (%)	32%	2%	4%	1%
	Total Cattail Area	236	44	13	12
	Cattail Density > 5%	1271	0	0	0
	Cattail Density > 10%	666	0	0	0
	Cattail Density > 50%	0	0	0	0

* Provide Best Simulations of Cattail Expansion in WCA-2A for First 20 Years

Sensitivity of STA-2 Simulations to Model Input Variables
Phosphorus & Cattail Profiles in 2007

Variable	Units	Value	Distance from Inflow (km) 0.0	0.4	1.0	2.0	4.0	8.0	12.0
Soil Total P Conc in 2007	mg/kg		675	596	522	456	405	385	382
Sensitivity Coefficients									
STA Outflow Conc	ppb	50	48%	40%	30%	18%	6%	1%	0%
STA Outflow Volume	hm3/yr	254	0%	11%	18%	20%	13%	3%	1%
Width	km	12.1	0%	-11%	-18%	-20%	-13%	-3%	-1%
Soil Depth	cm	20	-37%	-30%	-22%	-13%	-5%	-2%	-2%
Initial Gradient	mg/cm3/cm	-0.0018	6%	6%	6%	6%	4%	3%	2%
Initial Bulk Density	g/cm3	0.071	-36%	-31%	-25%	-17%	-9%	-5%	-4%
Final Bulk Density	g/cm3	0.080	-14%	-12%	-10%	-7%	-5%	-3%	-2%
Initial P Content	mg/kg	366	42%	49%	58%	70%	83%	91%	92%
Settling Rate Years 1-3	m/yr	10.2 - 30	48%	29%	12%	-1%	-6%	-2%	-1%
Settling Rate Year 1	m/yr	30	14%	5%	-1%	-2%	1%	1%	1%
Settling Rate Year 2	m/yr	20	9%	5%	1%	-1%	-3%	-0%	-0%
Settling Rate Year 3	m/yr	10.2	25%	19%	11%	2%	-3%	-2%	-1%
Average Hydroperiod	%	0.92	48%	29%	12%	-1%	-6%	-2%	-1%
Rainfall P Conc	ppb	30	0%	1%	2%	2%	3%	4%	4%
Rainfall	m/yr	1.23	0%	-0%	0%	1%	3%	4%	4%
ET	m/yr	1.38	0%	1%	1%	1%	1%	0%	0%
Soil P Slope	yr-m2/kg	1.467	3%	2%	1%	-1%	-1%	-1%	-1%
Soil P Intercept	mg/kg	815.7	6%	7%	7%	6%	5%	3%	3%
Water Column P Conc	ppb		50.0	42.6	33.6	23.0	11.7	5.2	4.2
Sensitivity Coefficients									
STA Outflow Conc	ppb	50	100%	98%	96%	90%	72%	26%	5%
STA Outflow Volume	hm3/yr	254.046	0%	16%	39%	74%	119%	87%	26%
Width	km	12.1	0%	-16%	-39%	-74%	-119%	-87%	-26%
Settling Rate Years 1-3	m/yr	10.2 - 30	0%	-18%	-44%	-85%	-148%	-162%	-122%
Average Hydroperiod	%	0.92	0%	-18%	-44%	-85%	-148%	-162%	-122%
Rainfall P Conc	ppb	30	0%	2%	4%	10%	28%	74%	95%
Rainfall	m/yr	1.2319	0%	-1%	-0%	3%	23%	74%	88%
ET	m/yr	1.38	0%	2%	5%	8%	6%	0%	8%
Cattail Density in 2007	%		32%	14%	5%	2%	1%	1%	1%
Sensitivity Coefficients									
STA Outflow Conc	ppb	50	307%	290%	209%	116%	37%	5%	1%
STA Outflow Volume	hm3/yr	254	0%	78%	126%	123%	75%	19%	4%
Width	km	12.1	0%	-78%	-126%	-123%	-75%	-19%	-4%
Soil Depth	cm	20	-236%	-216%	-150%	-80%	-26%	-10%	-8%
Initial Gradient	mg/cm3/cm	-0.0018	39%	46%	45%	37%	25%	15%	13%
Initial Bulk Density	g/cm3	0.071	-227%	-222%	-171%	-107%	-49%	-25%	-21%
Final Bulk Density	g/cm3	0.080	-87%	-86%	-68%	-46%	-27%	-15%	-13%
Initial P Content	mg/kg	366	269%	353%	403%	437%	467%	486%	490%
Settling Rate Years 1-3	m/yr	10.2 - 30	307%	211%	81%	-8%	-34%	-13%	-4%
Settling Rate Year 1	m/yr	30	90%	35%	-6%	-16%	3%	4%	4%
Settling Rate Year 2	m/yr	20	60%	37%	8%	-7%	-14%	-0%	-0%
Settling Rate Year 3	m/yr	10.2	160%	140%	79%	13%	-16%	-13%	-4%
Average Hydroperiod	%	0.92	307%	211%	81%	-8%	-34%	-13%	-4%
Rainfall P Conc	ppb	30	0%	5%	11%	15%	18%	21%	21%
Rainfall	m/yr	1.23	0%	-1%	2%	8%	16%	20%	19%
ET	m/yr	1.38	0%	7%	10%	8%	4%	1%	2%
Soil P Slope	yr-m2/kg	1.467	16%	12%	4%	-3%	-7%	-6%	-5%
Soil P Intercept	mg/kg	815.7	40%	49%	48%	40%	27%	17%	14%
Threshold Spread	mg/kg	71.2	50%	160%	275%	374%	450%	478%	482%
Threshold MidPoint	mg/kg	727.7	-691%	-876%	-965%	-999%	-1011%	-1014%	-1015%

Sensitivity Coefficient ~ % Change in Output Variable / % Change in Input Variable, Inputs Perturbed +/- 10%

Sensitivity of STA-2 Simulations to Model Input Variables
Total Cattail Area vs. Time

			Years from Start of Discharge										
Variable	Units	Value	0	2	4	6	8	10	12	16	20	30	40
End of Year			1998	2000	2002	2004	2006	2008	2010	2014	2018	2028	2038
Total Cattail Area	ha		113	146	189	254	349	479	639	1010	1390	2198	2802
Average Density	%		1%	1%	1%	1%	2%	3%	3%	6%	8%	12%	15%
Sensitivity Coefficients													
STA Outflow Conc	ppb	50	0%	34%	74%	121%	165%	194%	205%	191%	164%	119%	97%
STA Outflow Volume	hm3/yr	254	0%	18%	33%	47%	60%	69%	75%	83%	86%	89%	90%
Width	km	12.1	100%	82%	67%	53%	40%	31%	25%	17%	14%	11%	10%
Soil Depth	cm	20	0%	-31%	-61%	-95%	-124%	-142%	-146%	-129%	-106%	-70%	-52%
Initial Gradient	mg/cm3/cm	-0.00184	0%	6%	15%	25%	33%	39%	41%	39%	34%	27%	23%
Initial Bulk Density	g/cm3	0.071	-0%	-35%	-71%	-107%	-136%	-149%	-148%	-124%	-98%	-59%	-41%
Final Bulk Density	g/cm3	0.080	0%	-7%	-20%	-37%	-55%	-70%	-79%	-83%	-78%	-65%	-57%
Initial P Content	mg/kg	366	512%	500%	477%	446%	404%	355%	304%	221%	167%	104%	77%
Settling Rate Years 1-3	m/yr	10.2 - 30	0%	16%	40%	73%	105%	125%	129%	107%	77%	29%	7%
Settling Rate Year 1	m/yr	30	0%	11%	15%	19%	21%	20%	16%	7%	2%	-1%	-0%
Settling Rate Year 2	m/yr	20	0%	8%	12%	16%	18%	18%	15%	9%	4%	0%	-0%
Settling Rate Year 3	m/yr	10.2	0%	-1%	15%	40%	68%	90%	100%	92%	71%	31%	9%
Average Hydroperiod	%	0.92	0%	16%	40%	73%	105%	125%	129%	107%	77%	29%	7%
Rainfall P Conc	ppb	30	0%	4%	8%	10%	11%	12%	13%	13%	14%	17%	19%
Rainfall	m/yr	1.23	0%	3%	6%	7%	7%	7%	7%	7%	7%	10%	13%
ET	m/yr	1.38	0%	1%	2%	3%	5%	6%	6%	7%	8%	8%	7%
Soil P Slope	yr-m2/kg	1.467	0%	-1%	-0%	1%	4%	6%	7%	7%	4%	-3%	-10%
Soil P Intercept	mg/kg	815.7	0%	5%	13%	24%	36%	48%	57%	70%	77%	96%	120%
Threshold Spread	mg/kg	71.2	505%	465%	419%	359%	292%	229%	177%	112%	81%	54%	46%
Threshold MidPoint	mg/kg	727.7	-1016%	-1011%	-999%	-973%	-927%	-861%	-782%	-626%	-513%	-378%	-329%

Sensitivity Coefficient ~ % Change in Output Variable / % Change in Input Variable, Inputs Perturbed +/- 10%

Table 5