Phosphorus Biogeochemistry *in* SUBTROPICAL ECOSYSTEMS

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27 Management Models to Evaluate Phosphorus Impacts on Wetlands

Robert H. Kadlec and W.W. Walker

27.1 ABSTRACT

Additions of phosphorus (P) and water can alter the status of many types of receiving wetlands. Typical responses involve alterations of sediments and soils, as well as micro and macro flora, and the associated faunal uses. Oligotrophic ecosystems, dominated by sedges (*Cladium* or *Carex*) typically respond to P fertilization by increasing productivity. In the longer term, opportunistic species (such as *Typha*) may replace the original vegetation. Less obvious changes occur sooner in soils, algae and microbes.

Wetland soils in general, and Everglades peats in particular, have sorption capacity for phosphorus. That storage is typically considered to be reversible, and the sorbed P to be available. New additions of P-containing waters may either increase or decrease this temporary P storage on a time scale of weeks. On approximately the same time scale, algal and microbial communities may undergo expansion and shift to a new species composition. Existing wetland flora respond to an increase in P availability by increasing biomass, and by reapportioning that biomass

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from below to above ground parts. This is termed *fertilizer response* and proceeds over several turnover times to a new state characteristic of the new nutrient availability.

If the magnitude of the P load increase is sufficiently large, the macrophyte community (if any) may undergo alteration, as new wetland species are able to assert dominance, and replace some or all of the antecedent species. This change in community species composition is also to some degree dependent on seed banks and vegetative reproduction, and adjacent community structure. Physical processes, such as shading out and the accretion of new rooting media, are long-term influences that contribute to the structure of the replacement ecosystem. The speed of community shifts is typically slower than the fertilizer response.

Under continuously wet conditions, the several large and small components of the wetland biogeochemical cycle produce accretion of new organic sediments. A first-generation model of the carbon and P cycles produces estimates of the alteration of the rhizosphere, which may then be used as an indicator of potential macrophyte colonization. The components of the model include P removal rates linked to surface water concentrations, and the relation between P accretion and soil accretion, as evidenced in soil column P profiles. Calculations of time trends in root zone average P content are then possible, which may then be used as a trigger variable in the prediction of community changes. Stochastic processes are not included in this deterministic model and create the need for probability density overlays.

Calibration of the model to existing Florida wetland data shows reasonable representations of field phenomena.

27.2 INTRODUCTION

Wetlands often change character when subjected to new phosphorus and water loadings. However, wetlands also act to incorporate new phosphorus (P) into the biosphere and soils, and thus protect downstream portions of the ecosystem. Consequently, new P loadings create zonation within the receiving wetland, with stronger effects near the point of discharge, diminishing in the direction of water flow as P is stripped from the water (Fig. 27.1). In general terms, the zone nearest the new discharge may undergo species alteration; zones farther away may retain their species under nutrient enrichment, and at long distances the background ecosystem will continue to prevail (Lowe and Keenan, 1997).

Wetland responses are keyed to P concentrations in the water and to concentrations in the root zone of the soil column (rhizosphere). The aquatic components, such as periphyton, interact directly with dissolved reactive P, which stimulates growth and induces changes in community species composition and relative abundance. These changes appear to occur over a continuum of P concentrations, ranging from essentially zero phosphorus up to moderately high concentrations (McCormick, 1996). Rooted macrophytes respond to increasing soil P concentrations, which are the result of increasing water concentrations. The first response is often biomass increase for the antecedent assemblage of macrophytes, possibly later followed by changes in species composition and abundance. In addition, the magnitude of the

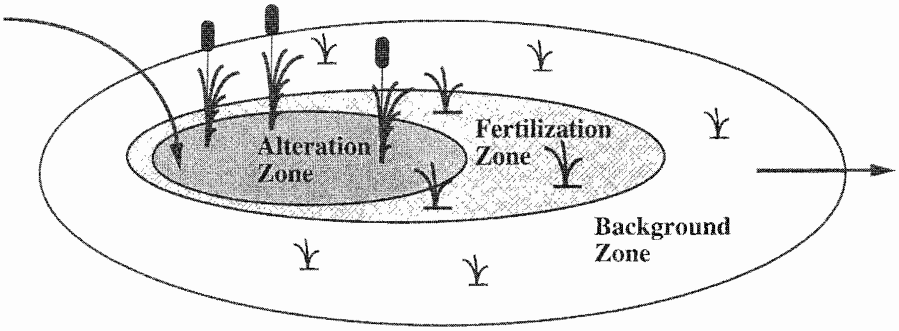

FIGURE 27.1 New phosphorus inputs tend to create zonation in the vicinity of the addition.

biogeochemical cycle increases, with the production of larger amounts of new sediments. Such a sequence of responses is also found along the gradient from the new source (Fig. 27.2). Sudden changes in ecosystem characteristics do not occur along either the spatial or temporal gradients. Rather, these are blurred changes, with new communities gradually interspersing with the old.

It is common for cattails (*Typha* spp.) to invade wetland areas receiving new inputs of water and phosphorus. This phenomenon has been reported for both northern peatlands (Kadlec and Bevis, 1990) and southern peatlands (Davis, 1994).

Phosphorus is not the only factor that may determine wetland changes. In most instances, new P inputs are accompanied by new water inputs, creating a wetter hydrologic regime. Changes in hydrologic regime can cause ecosystem effects in the absence of any additional P. The antecedent soil condition is also of importance, especially if there are prior alterations because of dryout, fire or mechanical disturbance.

A first step toward prediction of possible ecosystem effects is a prediction of the altered surface water total P concentrations, and the spatial and temporal allocation of the new cumulative P load. In the following sections, a P removal model

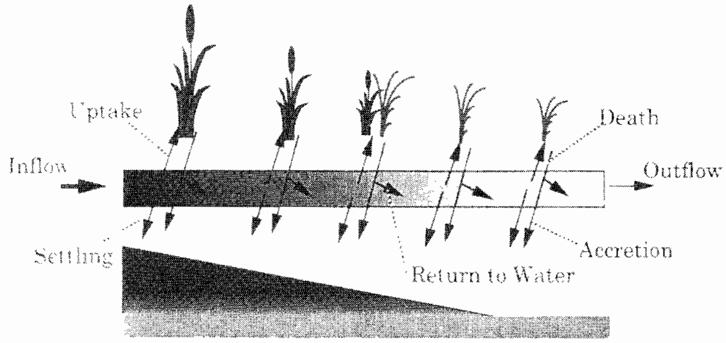

FIGURE 27.2 Gradients in surface water P lead to enhanced biomass, a larger biogeochemical cycle, and larger accretion rates for recalcitrant residuals. Arrows indicate the movement of phosphorus.

for the water is combined with a P mass balance on the soil to determine those allocations. A second step to improving the predictive tools is including the mass balance on the biomass in the wetland. When combined with estimates of wetland change criteria, potential wetland biological responses may be evaluated.

This chapter is based on three precursor publications: Walker (1995), Walker and Kadlec (1996), and Kadlec (1997). Walker (1995) describes a first-order P removal model that reproduces stationary soil and water P concentrations along the gradient in Water Conservation Area 2A (WCA-2A). Walker and Kadlec (1996) predicts the accretion of soil P with time in several wetlands. Kadlec (1997) shows that the first-order model is a close approximation to the response of the wetland biogeochemical cycle and its development.

This suite of models embodies water and phosphorus mass conservation and contains only a few relevant features of the wetland. It is intended to provide a tool for design and management of P in wetlands. A flowchart of the calculation strategy shows the integration of the several mass balances, and the input information needs (Fig. 27.3).

27.3 SURFACE WATER REMOVAL MODEL: ONE PARAMETER

27.3.1 Model Development

Under conditions of increased P inputs, concentrations typically decline within a wetland, along the flow direction (Fig. 27.4). The simplest fit to these observed

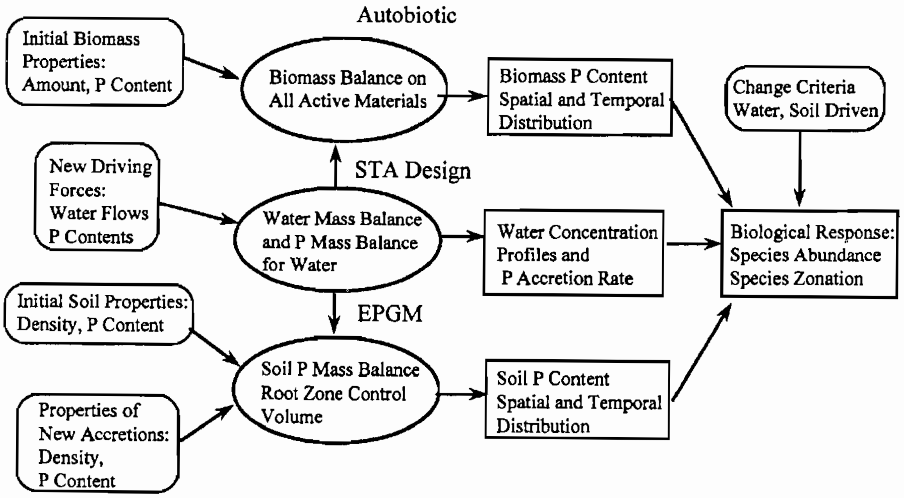

FIGURE 27.3 Interactions and data needs for the impact model network. The Stormwater Treatment Area (STA) design model (Walker, 1995) is represented by the center oval. The bottom two ovals are the Everglades Phosphorus Gradient Model (EPGM) (Walker and Kadlec, 1996). The top two ovals are the biomachine model (Kadlec, 1997).

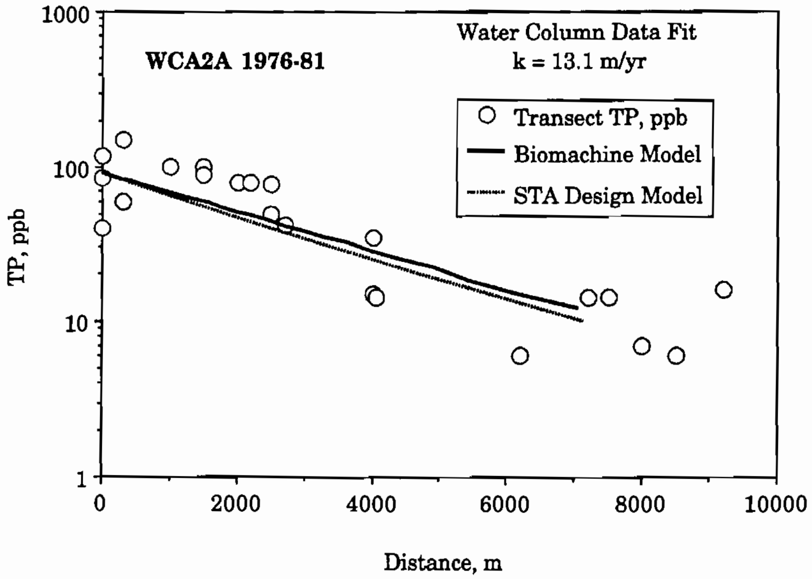

FIGURE 27.4 STA design and biomachine models fit the transect data for WCA-2A.

concentration gradients is a global, one parameter model. Several studies have shown that a first-order areal model provides a reasonable description (i.e., $R^2 \approx 0.8$) of the long-term sustainable phosphorus removal in emergent marshes (Kadlec, 1993, Walker, 1995, Mitsch et al., 1995). This model is an extension of the traditional lake model for phosphorus (Vollenweider, 1975; Kirchner and Dillon, 1975).

Phosphorus is presumed to be removed from water at an areal rate that is proportional to the P concentration in the water at the location in question. This removal rate is incorporated into a nondispersive (plug flow) mass balance. This model is here written for a one-dimensional, time averaged situation. The component parts are shown below.

- Dynamic, spatial water mass balance:

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial \mathcal{A}} = P - ET \qquad (1)$$

- Dynamic, spatial P mass balance on water plus biomass and active soils:

$$\frac{\partial (hC)}{\partial t} + \frac{\partial M}{\partial t} + \frac{\partial A}{\partial t} + \frac{\partial (QC)}{\partial \mathcal{A}} = PC_p - S \qquad (2)$$

- Dynamic, spatial P mass balance on inactive soils:

$$\frac{\partial B}{\partial t} = S \qquad (3)$$

where

A = adsorbed plus porewater mobile phosphorus, g P/m^2
$\mathcal{A}$ = $W \bullet x$ = accumulated wetland area downstream, m^2
B = buried refractory phosphorus in soil/sediment, g P/m^2
C = concentration of total phosphorus (TP) in water, g/m^3 = mg/L
ET = evapotranspiration, m/yr
h = water depth, m
M = biomass temporary phosphorus content, g P/m^2
P = rainfall rate, m/yr
PC_p = rainfall plus dryfall phosphorus deposition, g P/m^2/yr
Q = water flow rate, m3/yr
S = net phosphorus removal rate, g P/m^2/yr
t = time, yr
W = wetland width, m
x = distance downstream of P addition point, m

It is assumed that surface water concentration is an indicator of the general chemical and biological activity at any given location, and that phosphorus deposition to the sediment follows in direct proportion to that activity. Justification is found in the transect profiles of TP concentrations in several studies (Kadlec and Knight, 1996). It is also presumed that chemical and biological activity, the macrophyte biomass and sediment-water interface are locally proportional to land surface area. The equation that quantifies these statements is:

$$S = kC \tag{4}$$

where k = removal rate constant, m/yr.

Terminology has evolved to designate the constant of proportionality k, which is a first-order areal rate constant, as the net apparent removal rate constant. There is a fraction of the phosphorus entering a wetland that is particulate and physically settles to the bottom, but the removal rate also includes the particulates generated within the wetland, including those formed underground because of root death and decomposition. The net phosphorus deposition rate, S, has come to be designated as the phosphorus removal rate. Care must be taken to properly interpret these terms. The removal rate is for all undecomposed particulate matter, which includes incoming suspended particulate matter and the detritus from carbon cycling in the wetland, and any precipitates that may form because of chemical reactions.

Surface water may also be considered as the control volume, or enclosed system for the mass balance. The transfers to this compartment are water flows, soil leaching, and atmospheric deposition. The transfers from this compartment are water flows, biomass accumulation, sorption and soil/sediment accretion. The dynamic, spatially distributed phosphorus budget is:

$$\frac{\partial(hC)}{\partial t} + \frac{\partial(QC)}{\partial \mathcal{A}} = PC_p - U \tag{5}$$

where U = net phosphorus uptake rate, g/m^2/yr.

The net uptake is the difference between removals from the water to biological and soil compartments, and additions to the water by releases from biological and soil compartments. These transfers include leaching, sediment accretion, and uptake into growing biomass. Therefore, by comparison to Eqs. (2) and (5), the net uptake is:

$$U = S + \frac{\partial M}{\partial t} + \frac{\partial A}{\partial t} \tag{6}$$

Analysis of data from existing wetlands logically follows from application of Eq. (6) for determination of the net uptake. In the limit of a stable ecosystem, in which biomass phosphorus is not increasing and sorption sites are saturated, $dM/\partial t = 0$, $dA/\partial t = 0$, and $U = S$. Therefore, the form of Eq. (4) may also be applied to net uptake:

$$U = k_u C \tag{7}$$

where k_u = uptake rate constant, m/yr.

In a wetland that is leaching phosphorus from the soils because of antecedent conditions, U, and therefore k_u, may be small or even negative. In the limit of a stable ecosystem, $k_u = k$, the removal rate constant. In a developing wetland, large amounts of biomass are accumulating and dM/dt is large, leading to values of k_u that are larger than k. U is much larger than S in that situation. If hydroperiod (percentage of days wet) is less than 100%, then, as an ad hoc procedure, the value of k_u should be reduced by a factor not less than the hydroperiod, because P removal from water cannot occur when there is not water present.

Solution

Equations (5) and (7) may be solved under the assumption of negligible storage change. It will also be assumed that there is no groundwater recharge or discharge. Averaging over several water displacements, or over several flow events, is also assumed. Solution yields:

$$C = C_\infty + (C_i - C_\infty)\left(\frac{Q_i + a\alpha}{Q_i}\right)^{-(1 + k/a)} \qquad a \neq 0 \tag{8a}$$

$$C = C_\infty + (C_i - C_\infty)\exp\left[-\frac{k\alpha}{Q_i}\right] \qquad a = 0 \tag{8b}$$

where C_i = inlet concentration, mg/L; C_∞ = background concentration, mg/L; and Q_i = inlet volumetric flow rate, m^3/yr; and where

$$a = P - ET \tag{9}$$

$$C_\infty = \frac{PC_p}{(P - ET + k)} \tag{10}$$

The wetland background concentration c_∞ is that which would exist very far from a P addition point, where the only source of phosphorus would be from the atmosphere. Because k is an order of magnitude greater than P or ET, Eq. (10) predicts a very low limiting value of c_∞, about a factor of ten lower than rainfall phosphorus.

27.3.2 CALIBRATION

The flow and water-column mass balances have been calibrated to data from WCA-2A (Walker, 1995). Long-term average, steady-state flow, and phosphorus concentration profiles downstream of the S10 structures are predicted. Flow input terms include entering flows and rainfall. Flow output terms include downstream discharge and evapotranspiration. Phosphorus input terms include incoming phosphorus loads and atmospheric deposition (uniform over simulated area). Phosphorus output terms include downstream discharge and net deposition to soils. That calibration produced k =10.2 m/yr for WCA-2A. Similar values have been determined for many other wetlands, including other Florida wetlands (Kadlec, 1994).

27.4 SURFACE WATER REMOVAL MODEL: THE BIOMACHINE MODEL

An alternate approach for modeling the removal of P from surface water involves calculation of the total biomass at a point within the wetland. Growth is driven by the surface water concentration, and thus this approach acknowledges the presence of the biological mediation of the transfer of P from the water to accreting solids. As a premium, this model describes the spatial and temporal variations in total biomass; as a penalty, it requires input parameters that increase the tasks of calibration. This model has been presented and calibrated to extensive data from a wastewater impacted wetland (Kadlec, 1997), and here for WCA-2A. The model is autobiotic, because more P stimulates more cycling and more P removal.

27.4.1 MODEL DEVELOPMENT

The biomass cycle is the prime driving force for the creation of refractory, P-containing residuals that add to the sediments. The size of the return flux from the various biomass compartments is clearly most directly related to the size of the biomass pool, here termed the biomachine. It is indirectly related to the concentration of P in the water, because more nutrients stimulate more growth and higher standing crops. In this section, the local accretion flux is presumed to be proportional to the lumped biomass at that given location in the wetland. This approach has been described for rivers, in which the attached plant biomass is assumed to be the primary determinant of P uptake (Thomann and Mueller, 1987).

The rate of P burial is therefore written as:

$$S = k_N N = [x_N m(1-\beta)]N \qquad (11)$$

where k_N = burial rate constant, g P/g/yr; N = total biomass, g/m^2; m = biomass loss rate constant, yr^{-1}; x_N = P concentration in biomass, g P/g; and β = fraction of biomass P returned to the water.

This redefinition of the accretion rate has the advantage of tying the P removal calculation directly to the size and speed of the removal "engine" or "biomachine." It suffers from a disadvantage in that biomass is not frequently measured in wetland nutrient studies.

The size of the total, lumped biomass pool may be calculated from a growth-death model:

$$\frac{\partial N}{\partial t} = \frac{m}{N_{max}}(L - N)N \tag{12}$$

Equation (12) is the inhibited form of Malthus' law, long used to describe population growth (Bailey and Ollis, 1986). It postulates that growth will occur in proportion to the biomass present, but only up to a limiting density determined by the local surface water P concentration and physical space limitations. The form of the relation for the growth limit is presumed to be:

$$L = N_{max}\left(\frac{C}{C + s}\right) \tag{13}$$

where L = upper limit of biomass that can exist at a given C, g/m^2; N_{max} = maximum biomass that can exist per unit area, g/m^2; and s = biomass half saturation concentration, g/m^3.

27.4.2 CALIBRATION

The biomachine model was calibrated to data from WCA-2A. The parameters required are β, s, N_{max}, m, and x_N. The following requirements were imposed as objectives of model calibration: reasonable descriptions of (1) P concentration profiles in surface waters under long-term stationary conditions, both in the shape of the concentration gradient and in the global removal as characterized by the predicted first-order areal removal rate constant (k), (2) the increase in areal extent with time of the affected biomass zone, (3) the gradient in biomass from the discharge out to the background area, and (4) the amount of solids accretion in the wetland. The selected values were required to meet these conditions simultaneously. Both k and N are quite sensitive to the fit parameters, which implies that the optimal set occurs within a narrow range of acceptably close values. In other words, there is not much leeway in selecting β, N_{max}, m, and x_N to provide the observed uptake rates and biomass (Kadlec, 1997).

Data for calibration was available from the sources used by Walker (1995), for accretion and water phase P concentrations along the gradient. Information on standing crop along the gradient, and for implied turnover times was from Davis (1989); for tissue P concentrations in live and dead leaves, along the WCA-2A gradient from Davis (1991); and for P concentrations in a variety of plant parts in north and south WCA-2A from Toth (1988). Numerical values for the combined biomass pool were:

- $x_N = 0.0012$ g P/gm
- m = 5 turnovers per year
- $\beta = 93\%$ biomass P returned to the water
- $N_{max} = 12{,}200$ g/m^2, corresponding to an inlet aboveground crop of 584 g/m^2
- s = 320 μgP/L, which limits the inlet total crop to 2694 g/m^2 for the sum of above and below ground macrophytes, litter, and live and dead periphyton

The fit of this model to water P concentrations and P accretion is comparable to that of the one parameter settling rate model (Fig. 27.4).

27.5 BENTHIC AND ROOT ZONE PROCESSES

A number of processes typically occur in and on the wetland rhizosphere. The simple first-order removal model presumes that P is accreted directly into new sediments and soils. The contributing processes layer some new material on top of older, but add accretions to lower horizons as well (Fig. 27.5). The overall biogeochemical

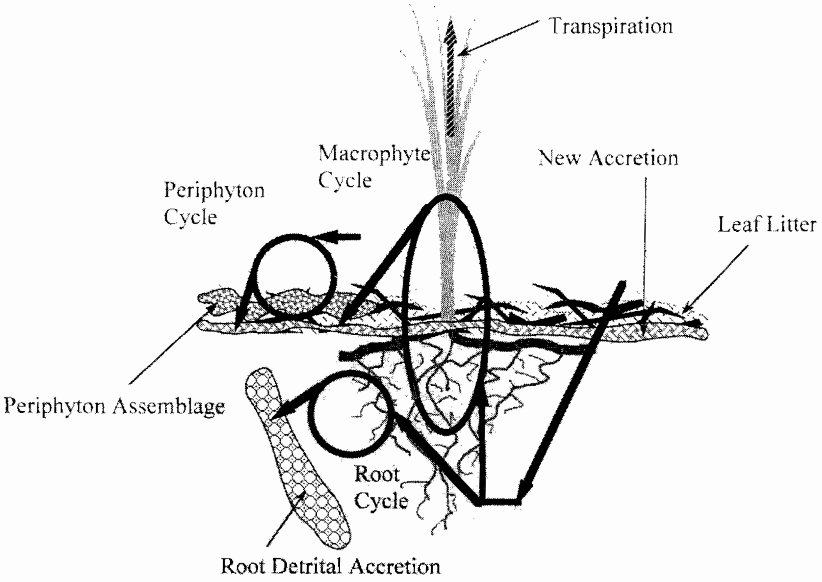

FIGURE 27.5 The total biogeochemical cycle may be broken into loops representing roots, shoots, and periphyton. The two macrophyte cycles interact via translocation and transpiration flows. The periphyton cycle draws phosphorus directly from the water column.

cycle can be broken down into three distinct loops, based on location. The aboveground macrophyte parts draw nutrients and water from the root zone, and return a large proportion of the nutrients back to the water, as a result of litter decomposition. In addition, nutrients can be translocated from aboveground tissues to rhizomes. The residuals of aboveground tissue decay are incorporated into the top layer of the soil column. At the top of the soil column, there is often a periphyton benthic assemblage that also undergoes a growth/death/decomposition cycle. That assemblage can obtain nutrients directly from the water, and also deposits its detrital residue on the top of the soil column. The plant roots grow and die, with an undecomposing residual that becomes an inert part of the rhizosphere. The roots draw and use nutrients from adjacent porewaters, and supply aboveground plant parts.

Shoot turnover times in the Everglades may be as short as two to three months (Davis, 1994). Root turnover times are largely unstudied, but have been reported to be on the order of 1.5 to 3.0 years (Prentki, 1978). Periphyton growth is fast, and lifespan relatively short, with 2 to 10 turnovers per year. In an emergent macrophyte stand, root and shoot biomass often dominate the biomass standing crop.

Diffusion, infiltration, and transpiration pumping carry phosphorus into the root zone. In a "sealed" wetland, infiltration is blocked, and the other two mechanisms must transport the required P. Calculations show that diffusion alone cannot supply the needs of the macrophytes, rates are an order of magnitude too slow. However, vertical water flow from the litter benthic zone can carry sufficient P to meet growth needs. For conditions of nearly equal periphyton and macrophyte cycling, most of the accretion (90%) is into a top soil layer (Table 27.1). This is caused by the presumed low turnover rate of root biomass compared to aboveground plant parts and periphyton.

TABLE 27.1
Hypothetical Multicycle Apportionment of Phosphorus Removal

	Standing crop, gmDW/m^2	Turnover time, 1/yr	P content, g P/gmDW	Gross P req'd, g P/m^2 • yr	Cycle burial efficiency, %	Net P req'd., g P/m^2 • yr	P standing crop, g P/m^2
Below-ground macrophytes	500	1.0	0.0010	0.50	10	0.05	0.50
Above-ground macrophytes	500	4.0	0.0010	2.00	10	0.20	0.50
Periphyton mat	250	8.0	0.0015	3.00	10	0.30	0.38
Total above ground	750	5.7		5.00		0.50	0.88
Total or avg.	1250	4.0		5.50		0.55	1.38

At 50 μg/L TP in the water, the settling rate constant for the example in Table 27.1 would be 0.55 ÷ 0.050 = 11 m/yr. If the plant transpired 0.5 cm/d [75th percentile for the monthly ET means for the Everglades Nutrient Removal (ENR) project

(Abtew, 1996)], the infiltrating concentration would be (2.00 + 0.05) g P/m2 • yr ÷ (0.005 • 365) m/yr = 1.12 g P/m3 (1,123 µg/L). This is typical of the top layer porewater P measured by Richardson et al (1992) and Reddy et al (1991).

27.6 INTEGRATION OF PHOSPHORUS LOADS

27.6.1 Model Development

Phosphorus removed from the water column is deposited in the soil sediment compartment, primarily in new top layers. A control volume is selected that occupies a fixed vertical distance from the sediment-water interface. That control volume moves slowly upward as material accretes, with older solids passing out through the bottom surface (Fig. 27.6). Rates of accretion in WCA-2A were measured to be 0.27 to 1.13 cm/yr (Reddy et al, 1991) and 0.003 to 0.66 cm/yr (Craft and Richardson, 1993), depending on position along the nutrient gradient. These accretions are predicted by the water phase mass balance on phosphorus [Eqs. (4) and (8)], coupled with information on soil P content and bulk density.

The upward movement of the soil surface varies along the gradient in WCA-2A so that predischarge vertical soil P profiles are covered to different depths along the gradient, ranging from about 30 cm near the S10s to about 5 cm toward the center of WCA-2A, as a result of accretion over 30 years. Therefore, when results are presented in terms of the vertical depth below the current soil surface, there exists a variable vertical displacement along the WCA-2A gradient. These P profiles can be adjusted to a common datum by use of the depth of the Cesium-137 peak at each station along the gradient. When this is done, there is good conformity of all vertical profiles below the Cesium-137 datum (Fig. 27.7).

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

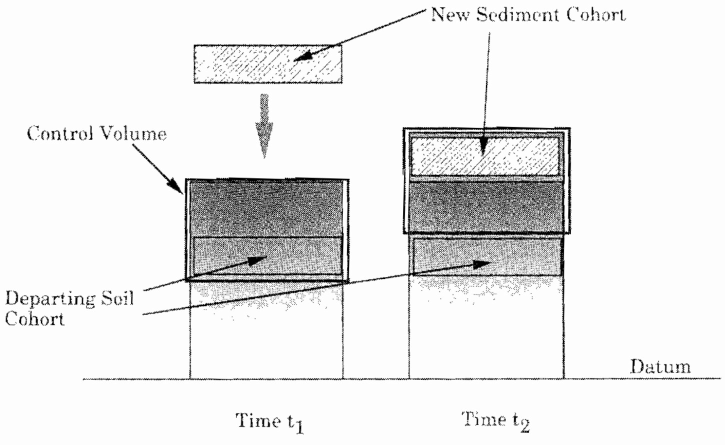

FIGURE 27.6 Soil phase mass balances use a control volume that moves upward with the soil surface.

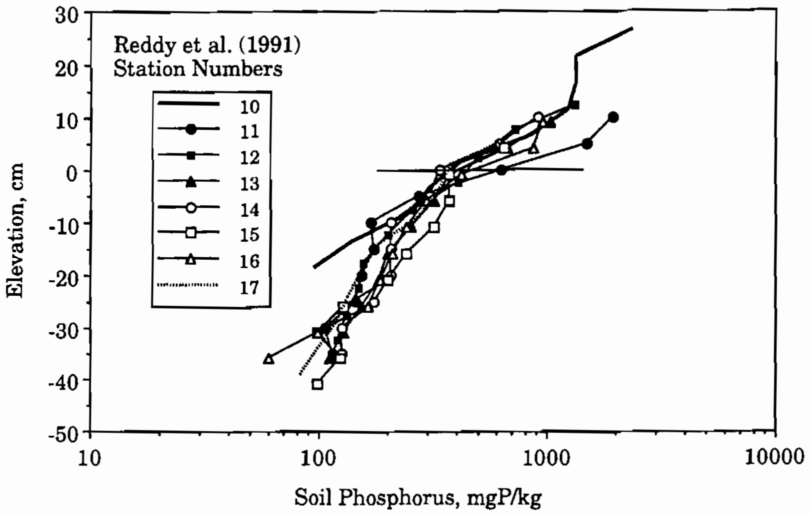

FIGURE 27.7 Soil phosphorus profiles in WCA-2A adjusted to the Cesium-137 datum.

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.

The following differential equation describes the soil mass balance on the control volume:

$$\frac{\partial M}{\partial t} = T - \rho_z V \qquad (14)$$

$$M(0) = M_i = \rho_i Z$$

where

M = soil mass in control volume, kg/m^2
M_i = initial soil mass in control volume, kg/m^2
ρ_i = initial soil mean density, kg/m^3
ρ_z = soil density at depth Z, kg/m^3
t = time, yr
T = new soil accretion rate, kg/m^2/yr

V = soil volume accretion rate, m/yr
Z = control volume depth, m

The time derivative is written as a partial derivative, because the soil mass varies along the gradient as well as with time. The soil phosphorus mass balance on the control volume is:

$$\frac{\partial(MY)}{\partial t} = S - p_z V Y_z \qquad (15)$$

$$M(0) = M_i Y_i$$

where
S = net phosphorus removal rate, g P/m^2/yr
Y = mean soil P content in control volume, g P/kg
Y_i = initial soil P content in control volume, g P/kg
Y_z = bottom layer soil P content in control volume, g P/kg

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:

$$Y_s = a + bS \qquad (16)$$

where Y_s = mean soil P content in control volume at steady state, g P/kg.

From the definition of soil P content and Eq. (16), the required elation is:

$$T = \frac{S}{Y_s} = \frac{S}{a + bS} \qquad (17)$$

27.6.2 CALIBRATION

Data are available on the mean soil P content (Y_s) and settling rate (S), from Cesium-137 studies in WCA-1, WCA-2A, and WCA-3. The relationship between soil phosphorus content and phosphorus accretion rate [Eq. (16)] has been calibrated by Walker and Kadlec (1996) to data from WCA-2A (Reddy et al., 1991, Richardson et al., 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 Fig. 27.8. The calibrated parameters and equations are as follows:

$$Y_s = a + bS \quad (R^2 = 0.78,\ SE = 171\ \text{mgP/kg})$$

$$T = \frac{S}{a + bS} \quad (R^2 = 0.88,\ SE = 0.05\ \text{kg/m}^2 \bullet \text{yr})$$

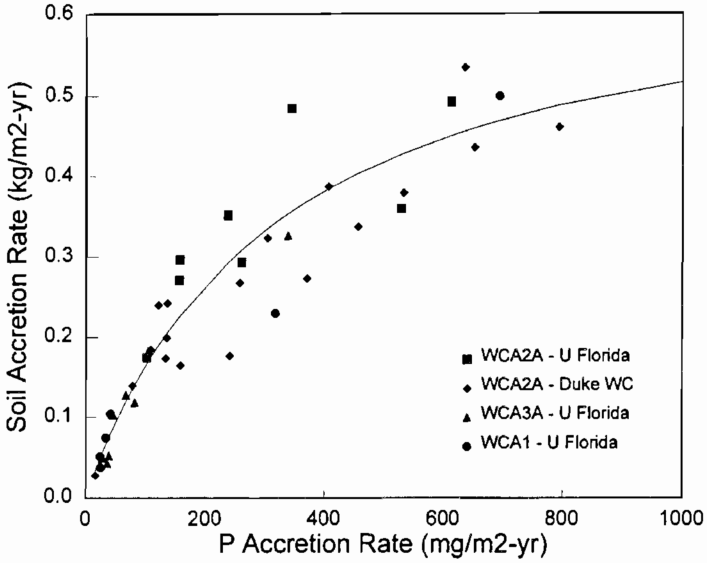

FIGURE 27.8 The fit of the regression for soil accretion and P accretion.

$$a = 463 \pm 27$$

$$b = 1.467 \pm 0.124$$

The calibration reflects the average soil response integrated over 26 to 29 years of peat accretion. Model parameter values may deviate from these average values during the start-up or transition period when the system is responding to a change in phosphorus loading. A measure of the goodness of fit is provided by comparing the data on soil phosphorus in the top 20 cm along the gradient in WCA-2A with the model calculations based on Eqs. (8), (14), and (15) (Fig. 27.9).

Solution

The soil phosphorus mass balance equations may be solved analytically for any specified settling rate (S), provided that the initial soil P content vertical profile is known. In the case of data from WCA-2A, those profiles are approximately linear. The soil bulk density for any specific wetland is nearly independent of depth, and may be considered constant (Walker and Kadlec, 1996).

The appropriate control volume depth (Z) is arbitrary but should contain the majority of the root zone if influences on vegetation are to be inferred. Roots are typically located in the upper 30 cm of the soil column, and are distributed approximately linearly decreasing with depth (Tanner, 1996)

The model returns the mean soil P content for the control volume as a function of time and surface water P concentration. The water P mass balance provides values of surface water P. Consequently, in combination these mass balances allocate historic P loads along a gradient from the source. Impacts to the ecosystem may

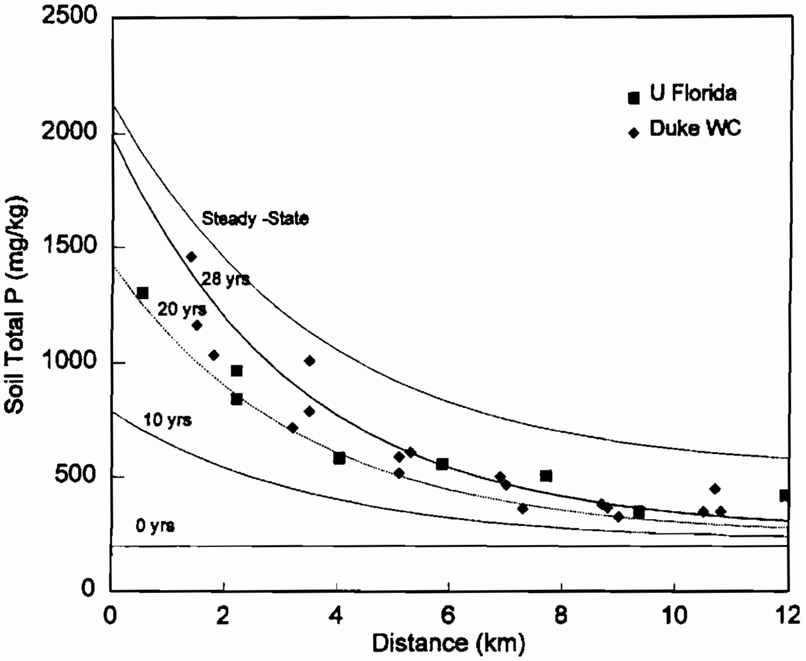

FIGURE 27.9 The time progression of soil P in the top 30 cm for WCA-2A.

then be inferred, as occurring in response to either the new surface water concentrations or the new soil P concentrations.

27.7 TRANSITION TRIGGERS

As illustrated in Fig. 27.3, the last step in model linkage is to predict biological responses, based on predicted changes in vegetation, and in water-column and soil P concentrations. Biological responses may be expressed in the following terms:

1. Marsh areas with long-term average water-column concentrations exceeding a specified threshold criterion
2. Marsh areas with soil P concentrations exceeding criteria or thresholds for changes in species composition or relative abundance
3. Total cattail area, estimated from a logistic equation relating cattail density (% coverage) to soil P concentration
4. Marsh areas exhibiting a growth response above a specified criterion

Item 1 is a surrogate for impacts on ecosystem components that respond to water-column concentrations (e.g., periphyton, algae). Items 2 and 3 are surrogates for impacts on ecosystem components that respond to soil P concentrations (e.g., cattails and other rooted vegetation). Item 4 is a direct indication of a more productive suite of biota (e.g., bigger plants and more algae).

Soil threshold values were calibrated to data from WCA-2A. 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 Richardson, et al. (1995) indicate that increases in soil P levels are spatially correlated with declines in native slough macrophyte species (e.g., *Eleocharis, Utricularia, Cladium*). 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 to 700 mg/kg. DeBusk et al. (1994) reported average soil phosphorus concentrations (0 to 10 cm) in three WCA-2A plant communities: saw grass 473 ± 134; mixed 802 ± 444; cattail 1338 ± 381 mgP/kg.

To provide a basis for comparing model with results with those reported by SFWMD (1996), 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 (Fig. 27.10). 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. Details may be found in Walker and Kadlec (1996).

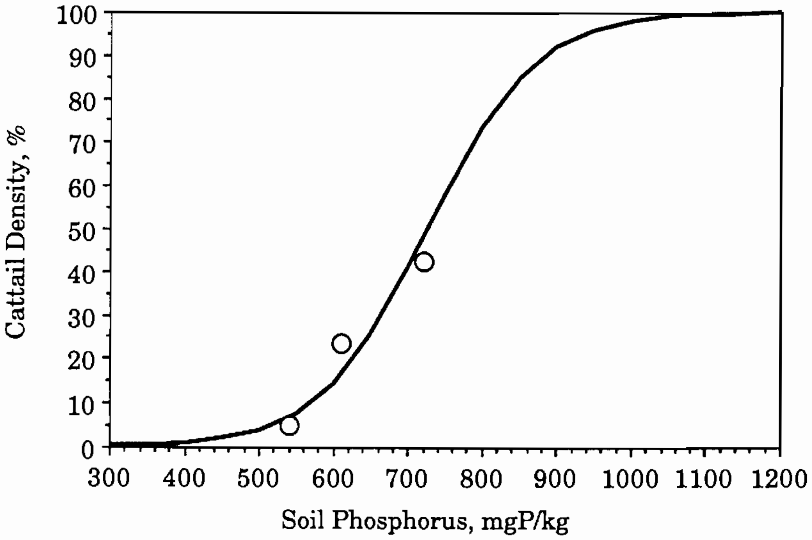

FIGURE 27.10 A logistic curve fit to data on cattail density and soil phosphorus.

27.8 RESULTS AND DISCUSSION

The methods above have been applied to the several water conservation areas and the projected Stormwater Treatment Areas (STAs) (Walker and Kadlec, 1996). Some results for WCA-2A are presented here.

The average P loading to WCA-2A was 42.36 metric tons per year, at an incoming concentration of 122 μgP/L. The areas required to reduce surface water TP concentrations to various levels were projected (and calibrated) to be:

- 5,723 ha to 30 μgP/L
- 7,613 ha to 20 μgP/L
- 13,393 ha to 10 μgP/L

The area requirement to reach 30 μgP/L was thus 135 ha/mt. This area requirement varies with the inlet P concentration as well as the inlet P load.

The cattail area, determined as the areal total over a spectrum of densities predicted by the logistic criterion, was found to increase with time (Fig. 27.11). Model predictions are in generally good agreement with measurements by SFWMD, although that data was based on total area with more than a fixed low percentage of cattail cover.

The biomachine model forecasts increases in total biomass, including roots, shoots, litter and periphyton, over a time period of about 15 years (Fig. 27.12). This period is shorter than that predicted for responses of the soil P content, and the resultant changes in species composition. A 20-cm soil column takes 20 years to "flush" to a new steady state for a high-end accretion rate of one centimeter per year, that represents the high end of the WCA-2A gradient. Further downgradient, those rates diminish to 10 to 20% of those near the inlet, and consequently the 20

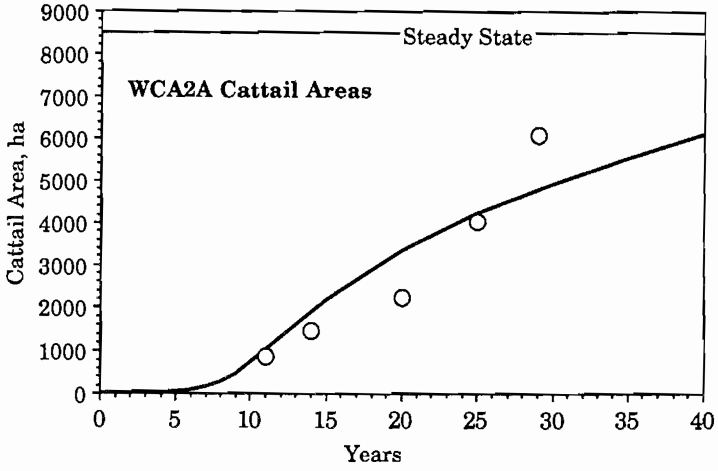

FIGURE 27.11 EPGM model prediction and SFWMD data on cattail expansion in WCA-2A.

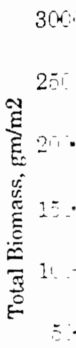

FIGURE 27.1

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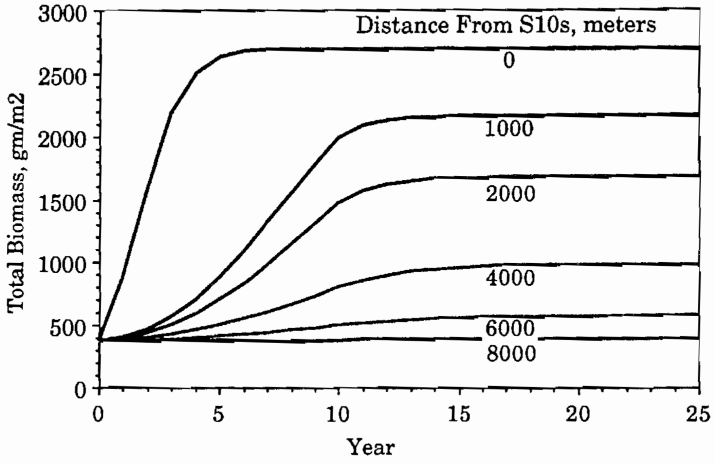

FIGURE 27.12 Autobiotic model predictions for active biomass in WCA-2A.

cm control volume takes many decades to replace. The growth response is greatest in the inlet region, where both soil P and water P are highest.

27.9 CONCLUSIONS

The surface water quality model used as a basis for STA design has been extended 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 into Everglades ecosystems. Impacts are expressed in terms of areas exceeding threshold criteria for water-column and soil phosphorus concentrations, increases in total cattail area, and increases in cattail density.

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 into Everglades ecosystems. Impacts are expressed in terms of areas exceeding threshold criteria for water-column and soil phosphorus concentrations, increases in total cattail area, and increases in cattail density.

A further model extension replaces the first-order removal rule, based on water concentration, with a first-order removal rule based on total lumped biomass. This autobiotic model requires a model for biomass growth in response to phosphorus concentration, and hence increases both the input data requirements and the number of predicted attributes of the ecosystem. Impact assessment may then be extended to include the spatial and temporal distributions of total active biomass.

The EPGM model successfully predicts observed spatial variations in water concentrations and soil phosphorus below the S10s, averaged over a depth 20 cm after 28 years of loading (1962 to 1990). The autobiotic model successfully predicts observed spatial variations in water concentrations, accretion rates, and total biomass.

Soil P thresholds for cattail expansion estimated from WCA-2A and WCA-1 data range from 540 to 720 mg/kg for a 20 cm soil depth. Predicted increases in cattail density and area are surrogates for impacts on any ecosystem components that respond to soil P levels in these ranges.

Simulations are for *average* hydrologic conditions. Actual responses will deviate from the predictions, depending on 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.

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 four- to eight-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 start-up phenomena. Compilation of other data sets will support future refinement, calibration, and testing of the model.

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