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PHOSPHORUS UPTAKE IN FLORIDA MARSHES

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ABSTRACT

Four Florida wetlands have been studied, by various groups, to provide data on hydrology, biota, and water chemistry. A subset of that data is here further analysed to determine the unifying principles of phosphorus removal. The uptake of this nutrient was found to be first order on an areal basis for long term average performance. Flow-through wetlands exhibit strong gradients in the direction of flow. The first order rate equation was used in conjunction with mass balances on water, soils and biota for water and phosphorus, to determine values of the rate constant ranging from 6.4 to 13 m/yr.

KEYWORDS

Wetlands, Florida, nutrient cycling, modeling, phosphorus, hydrology.

INTRODUCTION

Phosphorus removal from flowing wetland waters is observed in many situations, as evidenced by reductions in the total phosphorus (TP) concentration. The design of several very large stormwater treatment areas in southern Florida necessitated the synthesis of a design model, founded on the performance of regional systems. Four wetland systems provided a large amount of data (Fig. 1). Water Conservation Area 2A (WCA2A) is a natural emergent marsh receiving agricultural runoff. Boney Marsh is a constructed emergent marsh receiving pumped Kissimmee River water. The Iron Bridge treatment marsh was built on former pasture land to provide advance treatment for a portion of the City of Orlando's wastewater. The Orange County Eastern Service Area (OCESA) wetland complex also provides advanced treatment of municipal wastewater. Each system was studied intensively by several agencies. A more detailed analysis of this information may be found in Kadlec and Newman (1992).

The period of record was 14 years for WCA2A, 11 years for Boney Marsh, 4 years for Iron Bridge, and 3 years for OCESA. All four systems had information at interior locations as well as at inlet and outlet points. All were diked systems, and thus isolated from catchment runoff. Detailed water budgets showed little communication with groundwater. Data was available for water and nutrient budgets, and for soils and biota. All four wetlands displayed gradients in water chemistry and vegetation density in the flow direction. Gradients in soil accretion, and in soil phosphorus content, were measured in WCA2A. The two younger systems displayed startup effects, as vegetation became established after the initial planting.

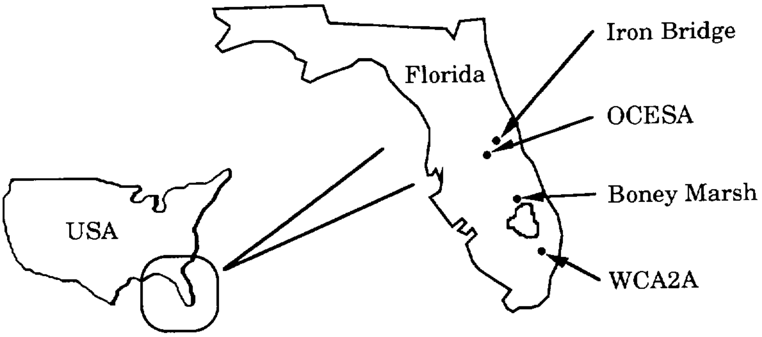

Fig. 1. Site locations.

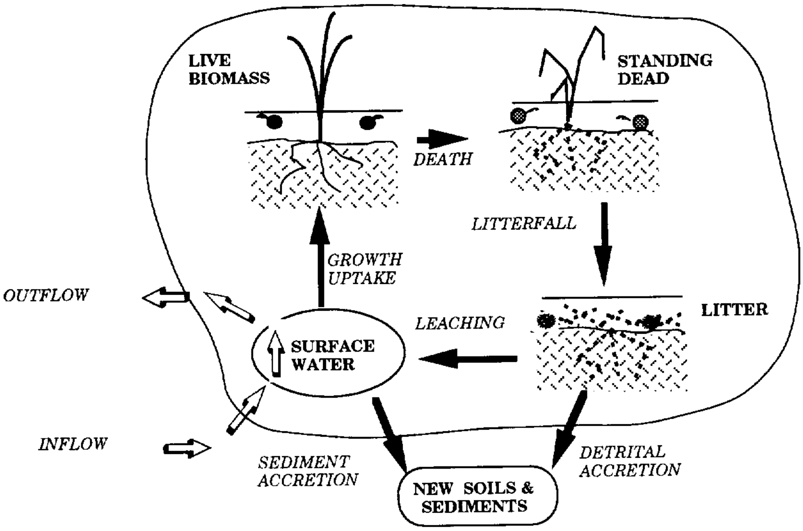

Fig. 2. Compartmentalization of the ecosystem at a specific location.

MODELS

A Two Compartment, Multisection, Dynamic Model

All chemical and biological species, including surface water, are first lumped into one compartment (Fig. 2). The transfers to this compartment are water flows and atmospheric deposition, the transfers from this compartment are water flows and soil/sediment accretion. Accretion builds the second compartment, the soils and sediments.

The wetland is sectioned to account for spatial effects. The number of sections chosen implicitly determines the amount of dispersion and mixing in the wetland cell. The amount of mixing is inversely proportional to the number of sections chosen (Levenspiel, 1972). One section amounts to a well mixed wetland cell, with the maximum amount of mixing. An infinite number of sections corresponds to plug flow, and is characterized by zero mixing. The appropriate mass balances for each section are phosphorus and water budgets for the two compartments:

$$\frac{dV}{dt} = Q_i - Q_o + A(R - ET) \tag{1}$$

$$\frac{d(VC)}{dt} + A\frac{dm}{dt} = QC_i - QC_o + ARC_R - S \tag{2}$$

$$\frac{dB}{dt} = S \tag{3}$$

A = surface area, m^2
B = buried phosphorus in soil/sediment, g
C = concentration of total phosphorus (TP) in water, g/m^3 - mg/l
ET = evapotranspiration, m/yr
m = biomass temporary phosphorus pool, g/m^2
Q = water flow rate, m^3/yr
R = rainfall rate, m/yr
RC_R = rainfall plus dryfall phosphorus deposition, g/m^2yr
S = net phosphorus removal rate, g/yr
t = time, yr
V = water volume, m^3

Dryout, soil oxidation and leaching of pore water phosphorus are known to occur under certain antecedent conditions in wetlands. There are insufficient data for a model of these phenomena to be calibrated. To interpret information from existing wetland sites, it is noted that the net accretion, or removal, rate is:

$$S = S^* - L \tag{4}$$

L = soil/sediment phosphorus loss rate due to oxidation and leaching, gm/yr
S* = gross accretion rate, gm/yr

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 described later. It is also presumed that chemical and biological activity is proportional to land surface area. It is possible that some of the biological activity is proportioned to the volume of water, as more stems become submerged, along with the attached periphyton. However, the macrophytes and sediment-water interface are proportional to land area. The equation which quantifies these statements is:

$$S = kCA \tag{5}$$

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 due to root death and decomposition. The net phosphorus deposition rate, S, has come to be designated as the phosphorus **removal rate**. Great 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 which may form due to chemical reactions.

Water Compartment, Multisection, Dynamic Model

Surface water is the one compartment under consideration (Fig. 2). The transfers to this compartment are water flows, soil leaching, and atmospheric deposition, the transfers from this compartment are water flows, biomass accumulation, and soil/sediment accretion. The wetland is again sectioned to account for spatial effects. The mass balance for water for each section is equation (1). The phosphorus budget is:

$$\frac{d(VC)}{dt} = QC_i - QC_o + ARC_R - U \qquad (6)$$

U = net phosphorus uptake rate, gm/yr

The net uptake is the difference between removals from the water in the section to biological and soil compartments, and additions to the water in the section by releases from biological and soil compartments. These transfers include leaching, sediment accretion, and uptake into growing biomass. Therefore, by comparison to equations (2) and (4), the net uptake is:

$$U = S^* - L + A\frac{dm}{dt} = S + A\frac{dm}{dt} \qquad (7)$$

Data analysis from existing wetlands logically follows from application of equation (6) for determination of the net uptake. In the limit of a stable ecosystem, in which biomass phosphorus is not increasing, dm/dt = 0, and U = S. Therefore, the form of equation (5) is applied to net uptake as well:

$$U = k_u \cdot C \cdot A \qquad (8)$$

k_u = uptake rate constant, m/yr

In a wetland which is leaching phosphorus from the soils due to 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.

Infinite Numbers of Sections

Sectioning a wetland into a very large number of subdivisions in the flow direction is equivalent to presuming "plug" flow through the system (see for example, Levenspiel, 1972). Under steady conditions of flow, concentration and other potential variables, and no atmospheric augmentation, the mass balance equation for phosphorus for such a continuum of sections is:

$$q\,L\frac{dC}{dx} = -\,k_u\,C \qquad (9)$$

q = hydraulic loading rate, m/yr
k_u = uptake rate coefficient, m/yr
C = phosphorus concentration, g/m^3
x = travel distance, m
L = exit travel distance, m

Integrating this equation from inlet to an interior point produces:

$$\ln\frac{C_{out}}{C_{in}} = -\frac{k_u}{q}\frac{x}{L} = -k_u/\left[\frac{qL}{x}\right] \tag{10}$$

The variable grouping [qL/x] is the upstream hydraulic loading rate; and x/L is the fractional distance through the wetland in the direction of flow. The latter is the same as fractional upstream area, Wx/WL, where W is the wetland width.

RESULTS

Iron Bridge

Wetlands provide nutrient removal for the City of Orlando Iron Bridge Regional Water Pollution Control Facility. This wetland treatment system consists of 490 ha of former pasture land which receives approximately 49,000 m^3/day of treated municipal wastewater. The project produces compliance monitoring data, as well as other operational data. The wetlands receive water containing less than 1.0 mg/l of total phosphorus. Data was available from this wetland complex for the time period since startup, September 1987 through December 1991. A series of annual operations reports (PBSJ, 1989-1991) contains operational data. In addition to input-output data, water samples were taken and analyzed at several interior points, at inter-cell transfer points.

The method of internal analysis can be applied, in which the distance dependent phenomena are interpreted according to the spatially variable phosphorus uptake model. The starting point was the spatial, dynamic phosphorus mass balance for the water compartment. Annual averages were used, and it is assumed that changes in storage in water over that period are negligible (for example: -1.6% in 1991 for the whole system). Rainfall phosphorus is a small fraction of the total input: 2.2% in 1990, 5.7% in 1991 at an estimated concentration of .03 mg/l. Thus to that degree of approximation, the annual average phosphorus mass balance (equation 10) may be used.

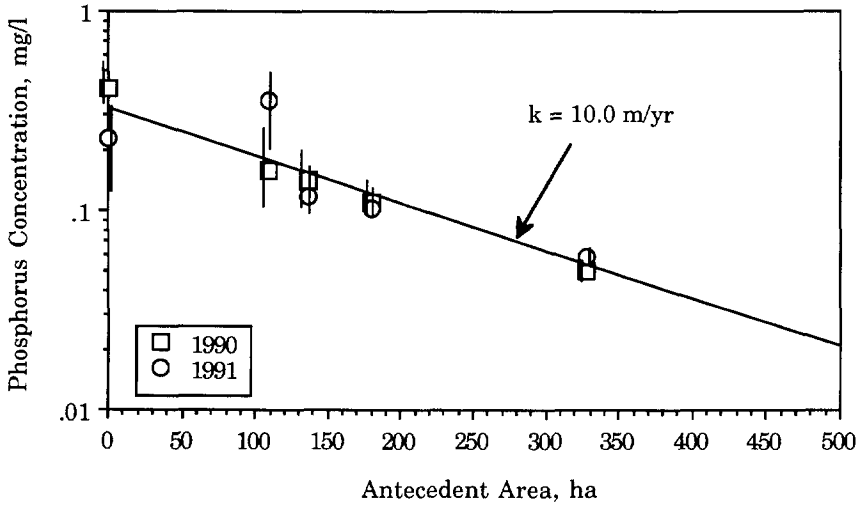

Fig. 3. Decrease of phosphorus in the Iron Bridge system after stabilization. Error bars are monthly standard deviation.

This form of the phosphorus mass balance can serve to interpret the interior sampling points at Iron Bridge. The graph of concentration fraction remaining versus upstream area (Fig. 3) is well represented by equation (10). These two years are past the initial plant growth surge, and probably past antecedent pore water leaching. Therefore the uptake rate coefficient is close to settling rate constant. Application of equation (10) to Fig. 3 yields $k_u = k = 10.0$ m/yr.

OCESA

The Orange County Eastern Service Area (OCESA) provides nutrient removal for wastewater treatment plants in Orange County. The entire system consists of 120 ha; 60 ha of natural wetlands and 60 ha of former pine flatwoods. The OCESA is designed to treat 23,500 m^3/d but is currently permitted for 13,000 m^3/d. Water quality and other environmental parameters are monitored by Camp, Dresser and McKee (1989-92). Water exits the wetlands to a nameless tributary which ultimately reaches the Big Econlockhatchee River.

For this document, emphasis is placed on compartments 1 ,2 and 3, in which most of the TP reduction occurs. Compartment 1 is dominated by herbaceous vegetation, and is in very shallow, overland flow. Compartment 2, the treatment wetland, is a natural cypress-mixed hardwood swamp. Monitoring results from April 1988 through February 1991 are presented in several volumes (Camp, Dresser and McKee, 1989-92). Compartment 3, the redistribution wetland, contains emergent non-woody vegetation.

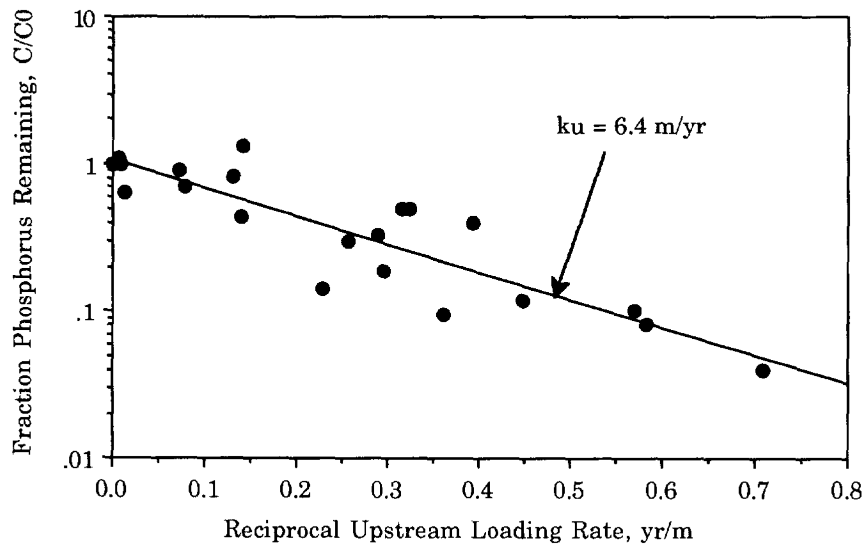

Fig. 4. Decrease of phosphorus in the OCESA system during the first three years of operation. Each point represents an average over one year over several stations equidistant from the inlet.

Flow enters via pipeline (measurement point IF), and leaves via a structure at the end of a canal (measurement point TC2). Complete water budgets have been determined for three years for compartment one (Camp, Dresser and McKee, 1989-92). Phosphorus concentrations were measured at IF and TC2, as well as at 21 interior locations. The method of internal analysis can be applied, in which the distance dependent phenomena are interpreted according to the spatially variable phosphorus uptake model. Equation 10 was used to analyze information from compartment one and the redistribution wetland, which comprises 21 + 12 = 33 interior measurement points. The annual average of inlet and outlet water flow rates for compartment one was used with upstream areas to calculate the average annual upstream hydraulic loadings. The graph of concentration fraction remaining versus reciprocal upstream hydraulic loading rate [x/Lq] is well represented by equation (10) as shown in Fig. 4. The slope of the line yields $k_u = 6.4$ m/yr.

Boney Marsh

Boney Marsh is a 142 ha two cell system; of which 48.6 ha is in a flow-through configuration: 1.61 km long and 0.3 km wide. The marsh is located in the floodplain of the Kissimmee River, Florida. The marsh was originally diked and drained in 1963, for use as pasture, and was reflooded in 1966 following acquisition of the land by the South Florida Water Management District. The experimental area was constructed in 1975, during this time water levels were kept well below ground surface. The marsh was reflooded in November 1975, following completion of construction. Water was pumped to this wetland from the Kissimmee River, and many ecosystem and water quality parameters were measured from start-up in 1976 through early 1987.

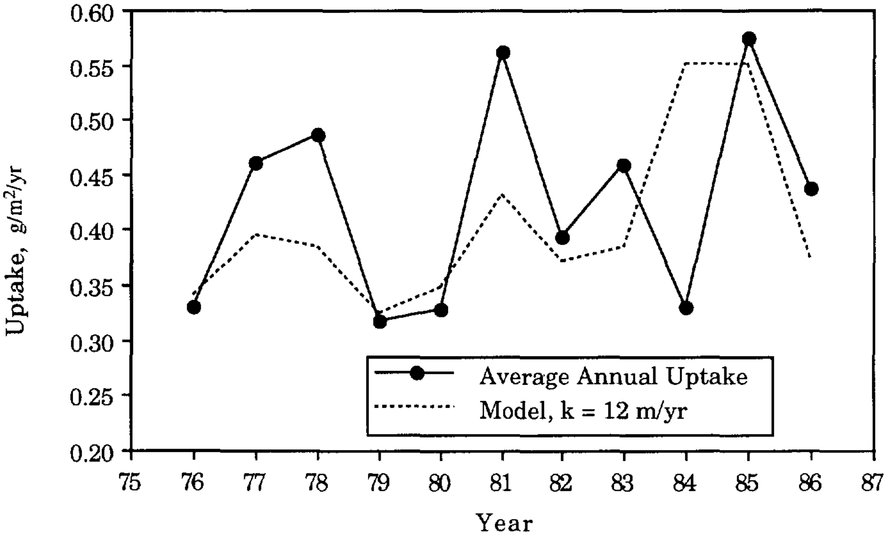

Fig. 5. Decrease of phosphorus in the Boney Marsh system during the eleven years of operation.

Data was collected five days per week and composited weekly. The hydraulic loading averaged 3.1 cm/day. The average incoming TP was 50 ± 11 μg/l and the average outflow was 21 ± 5 μg/l. Water budgets have been reported by Mierau and Trimble (1988); and early water quality trends were reported by Davis (1981). Phosphorus uptake coefficients were calculated from weekly data over the 11 yr period (Fig. 5), together with the prediction based on an uptake coefficient of 12 m/yr. The 11 yr average of weekly uptake coefficients is higher, 13 ± 3 m/yr.

WCA2A

Water Conservation Area 2A is a 44,684 ha wetland located in the Florida Everglades. The area was created in the early 1960's as an area for flood protection, water supply and environmental benefits. The annual average phosphorus load for WCA-2A for the period 1979-1988 was 112 metric tons Forty-one percent of this input is through rainfall, the remaining inflows are from pump stations. Much of the water entering the wetland is agricultural runoff from the Everglades Agricultural Area. The natural, pristine Everglades were developed under low nutrient conditions, with rainfall providing the main source of water and nutrients; increased nutrient loading has resulted in the development of a nutrient gradient, an estimated 8000 ha zone of altered vegetation, in the Northeast portion of the wetland.

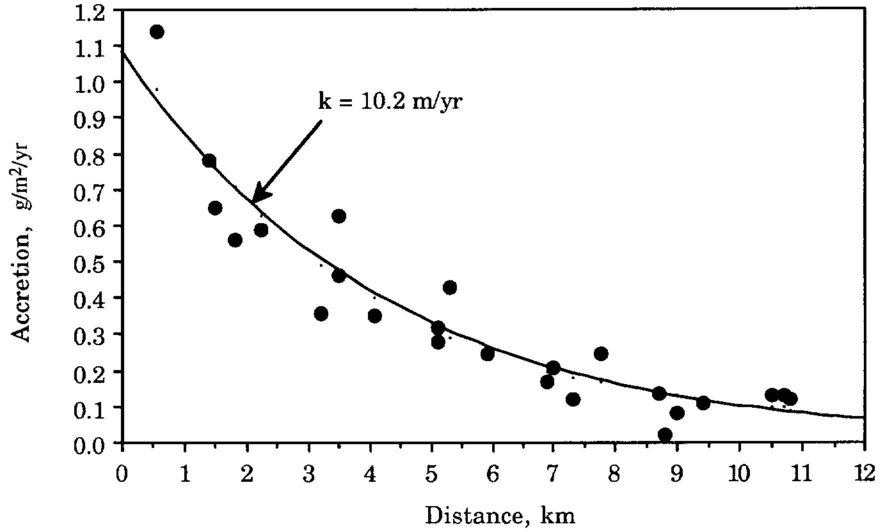

Fig. 6. Accretion of phosphorus in the WCA2A system during the 26 year period since the radiotracer marking.

Phosphorus accumulation and uptake coefficients were determined using transect data (Walker, 1993). Data was obtained by several research groups: the University of Florida (Reddy, et al., 1991), Duke University (Craft and Richardson, 1991) and the South Florida Water Management District (SFWMD). Walker's analysis was based on both water chemistry and hydrology, and upon measured soil accretion. Fig. 6 shows the relationship between phosphorus accretion and distance, based upon data from 1976 - 1990. The removal rate coefficient for this wetland was found to be 10.2 m/yr. This value represents the best fit over the period of record, but there were significant year-to-year variations, resulting in a 90% confidence interval of 8.4 to 12.2 m/yr. There were no time trends in the data, because the period of record begins long after the initiation of TP loading.

DISCUSSION

Phosphorus may be removed from wetland waters to soil sorption, biomass, and accreting sediments. Wetlands undergoing changes in soil status may either leach phosphorus back to the water, or remove it to saturate sorption sites. Wetlands which begin to receive phosphorus in excess of that needed for the initial standing crop of macrophytes and microbiota will utilize phosphorus to build a larger standing crop. These mechanisms are temporary, and to some extent reversible. The wetland biogeochemical cycle can operate to accrete new soils and sediments which contain phosphorus. These soil building processes can provide a more permanent storage of phosphorus.

Information from four Florida wetlands, encompassing many years of operational data, indicate that the lumped processes of removal are globally first order. This means that the removal of phosphorus to new soils is proportional to the concentration in the surface waters, and to the surface area of wetted soils. The range of the first order rate constants is 6.4 - 13 m/yr. The growing season in Florida's subtropical climate is basically 12 months long, so these results will not transfer on an annual basis to colder climates.

The actual mixing pattern in these four Florida wetlands is not known, because their large scale precludes experimental tracer testing. It is likely that each has some areas which are not flushed by the flowing water, and each has some preferential channels. It is possible to utilize other mixing models, which include dead zones and short-circuiting of water (Kadlec, 1994). Tracer tests in other marshes indicate that mixing may be approximated by two to four well mixed sections. If it is assumed that some dispersion or mixing does occur, the value of the rate constant derived by parameter estimation will be larger than that given by the plug flow (infinite well mixed sections). For instance, the WCA2A data would yield a rate constant $k = 12.7$ m/yr (versus 10.2 m/yr from the plug flow assumption), if three well mixed sections are presumed. Therefore, the presumption of plug flow has been used in the above analyses, not because it is exactly correct, but because it represents the conservative choice. Designs with better hydraulic control, i.e. closer to plug flow than the four systems analysed here, will perform better.

A survey of data from 53 other marshes demonstrates that the first order areal model is applicable to higher concentrations (Table 1). The rate constant displays a site average value of 11.6 ± 5.9 m/yr, corresponding to hydraulic loading rates in the range 0.44 - 20.2 cm/d and inlet TP concentrations in the range 0.1 - 11.1 mg/l. In some of these systems, the first-order, exponential decrease of TP concentrations along transects in the direction of flow has been documented. For example, the distance profiles at Houghton Lake have all been exponential (16 years), with an average R^2 of approximately 0.80 (Kadlec, 1993).

TABLE 1 TP RATE CONSTANTS FOR NON-FLORIDIAN MARSHES

Site	**No. of Wetlands**	**Years of Operation**	**Data Years**	**HLR** cm/day	**TP In** mg/l	**TP Out** mg/l	**K Value** m/yr
Des Plaines, IL	4	6	6	4.77	0.10	0.02	23.7
Jackson Bottoms, OR	17	3	2	6.34	7.51	4.14	14.2
Pembroke, KY	2	6	2	0.77	3.01	0.11	9.3
Great Meadows, MA	1	ca. 70	1	0.95	2.00	0.51	5.7
Fontanges, QUE	1	2	2	5.60	4.15	2.40	11.2
Houghton Lake, MI	1	16	16	0.44	2.98	0.10	11.0
Cobalt, ONT	1	2	2	7.71	1.68	0.77	20.9
Brookhaven, NY	1	3	3	1.50	11.08	2.33	8.9
Leaf River, MS	3	5	5	11.68	5.17	3.96	11.2
Sea Pines, SC	1	9	8	20.20	3.94	3.36	11.7
Benton, KY	2	6	2	4.72	4.54	4.10	2.4
Listowel, ONT	5	4	4	2.41	1.91	0.72	8.2
Humboldt, SAS	5	3	3	3.04	10.16	3.24	12.8
Tarrant County, TX	9	1	1	9.44	0.29	0.16	20.1
Total	53					Average	**11.6**

These rate constants apply only to the case of long term average behavior, since they were derived from long term average concentrations and flows, and from historical deposition data. They may not be used to predict short term transients, which involve temporary transfers to and from the soils and biomass compartments. The effects of average annual hydrology are included, but not the daily or weekly events that move phosphorus among compartments and through the marsh. This is reflected in large short-term variations in TP leaving a marsh. For example, the coefficient of variation for effluent TP, measured every three days, for Boney Marsh was 100%. Burns and McDonnell (1992) showed that rate constants for WCA2A had to be adjusted by a factor of four to describe short term phenomena.

The length of time to reach a stable water quality performance is on the order of two years for the Florida climate. Vegetative species composition and other biotic components of the ecosystem may continue to adapt for longer periods of time. During water quality startup, removal may be greater or less, depending upon antecedent conditions. For instance, Iron Bridge was originally a cow pasture, and the basins were sparsely planted in construction. Some phosphorus leached from the soils for a few weeks, causing a negative uptake constant. Thereafter, phosphorus was utilized in creating the large biomass of macrophytes which filled in the basins, causing a high uptake. Only after two years did these processes stabilize, with a fully developed macrophyte community and an intermediate uptake as described above.

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