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Exploring the dynamics and fate of total phosphorus in the Florida Everglades using a calibrated mass balance model

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Abstract

The Everglades protection area, which encompasses five Water Conservation Areas (WCA), Everglades National Park (ENP), and a network of canals, levees, structures, and pump stations, exhibits elevated nutrient concentrations in the water and sediments, primarily as a result of phosphorus loads in agricultural runoff. A mass balance model was developed to predict phosphorus fate and transport in the Everglades Protection Area that could result from proposed phosphorus reduction strategies. The modeled area is about a 7000 km^2 region that is divided into 642, 3.2×3.2 km cells, plus additional cell areas for canals. Phosphorus is transported between model cells and canals in accordance with output from a regional hydrology model. Simulated water column phosphorus dynamics within each cell and canal is further controlled by a simple, apparent net settling rate coefficient that integrates the effects of chemical, biological, and physical processes, and leads to net deposition of phosphorus in the sediments. After specification of external phosphorus loads (surface water and atmospheric wet and dry deposition) and system boundary conditions, the model was calibrated to available field data. The calibration procedure consisted of varying the apparent net settling rate coefficients in the WCA and the ENP. The goodness of fit of predicted water column total phosphorus concentrations varied temporally and spatially. Sediment phosphorus net deposition rates calculated by the model matched well with in situ observations where available. The model indicates that phosphorus in seasonal rainfall is a dominant influence on water column phosphorus dynamics in remote areas of the Everglades, whereas phosphorus dynamics in cells directly downstream of runoff inputs exhibit well-documented, nutrient gradients in receiving waters and sediments that could not be caused by rainfall alone. The model suggests that reductions of phosphorus concentrations leaving agricultural areas at the north end of the system will lead to lower concentrations entering ENP at the south end of the system. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Water quality modeling; Everglades; Phosphorus transport; Net settling rate

1. Introduction

The Everglades is a valuable natural resource of South Florida, USA, which contains unique plant

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and animal communities for that region. Historically, the Everglades constituted the southern portion (ca. 11 000 km^2) of a large natural freshwater system (ca. 28 000 km^2) that extended from central Florida near Orlando south to Florida Bay. The first development activities in the Everglades began in the 1800's and included canals for draining the region to exploit its natural rich soils and tropical climate for agriculture. Later the canal system was improved for navigational use to transport products to coastal markets. These modifications caused over-drainage of interior wetlands and extensive saltwater intrusion near the coast. The canal system did not provide adequate flood protection during major storm events and, consequently, numerous alterations and improvements have been made periodically since the 1930s to control flood water and salinity intrusion.

The hydrologic characteristics of the natural Everglades were significantly altered by the canals, levees, drainage, water diversion, and loss of area (about 50%) to development (Fig. 1). Historically, water would sheet flow across the Everglades, but now, water flows through canals and structures to and from a series of impoundments (Water Conservation Areas, WCA) and then on to Everglades National Park (ENP). Much of the habitat in these remaining areas of the Everglades has deteriorated because of changes in the timing and amount of water distribution (Davis et al., 1994). Coastal waters adjacent to the Everglades along the Atlantic Ocean, Florida Bay, and in the Ten Thousand Islands areas have also suffered from altered timing, quantity, and frequency of freshwater discharge.

Excess nutrient runoff from agricultural and urban areas has also caused habitat deterioration in the Everglades (McCormick and O'Dell, 1996; McCormick et al., 1996, 1997, 1998). Water pumped through and from the Everglades agricultural area (EAA) via structures S5-A, S6, S7, S8, and S150 (Fig. 1), contributes significant amounts of phosphorus to the WCA. During the base period of 1979–1990, the average total phosphorus load was 2.0×10^5 kg/year and the average concentration was 120 ug/l. The major portion of phosphorus loads to WCA-2A enters through the S10 structures (S10A, S10C, and S10D, Fig. 1). Downstream of these structures, the water column and sediment are phosphorus-enriched and large areas of naturally oligotrophic native sawgrass and slough community vegetation have been replaced by cattail (*Typha* sp., Rutchey and Vilchek, 1994, 1999). Cattail is a native species, previously restricted to isolated areas such as alligator holes where fauna concentrate (Davis, 1994). In controlled experiments, cattails have been shown to have a competitive advantage over sawgrass in nutrient enriched systems (Miao and DeBusk, 1999). Therefore, concern exists that cattail will continue to spread if phosphorus loads are not reduced. Further south, the S12 structures and the S333 structure (not shown) deliver a large fraction of the freshwater that enters ENP (Fig. 1). Walker (1991, 1999) has shown that phosphorus concentrations at the S12 structures have increased steadily between 1978 and 1990. Concern that cattails could eventually spread throughout ENP like they did in WCA-2A led to litigation and subsequent settlements that called for significant reductions in phosphorus loading from agricultural areas.

Given the hydrologic and nutrient issues facing the Everglades, programs were initiated to conduct research and develop predictive models to define hydroperiods and water quality conditions that could ensure the sustainability of desirable Everglades biological communities. Accordingly, the Everglades Water Quality Model (EWQM) was developed to determine external phosphorus loads that would lead to 'no imbalance' phosphorus concentrations for biota in the Everglades. These concentrations are not numerically defined at this time but are the subject of extensive research (Richardson et al., 1992; McCormick and O'Dell, 1996; McCormick et al., 1996, 1997, 1998). In the event that a numeric criterion is not set by 2003, the state of Florida has established a default total phosphorus criterion of 10 ug/l as protective of the Everglades. The EWQM was designed to determine what source load reductions would be needed to achieve the default or other criteria as determined by research.

2. Methods

2.1. Existing studies and models of wetland nutrient removal

A comprehensive overview of processes associated with wetland systems such as the Everglades is provided by Mitsch and Gosslink (1993). Others (Kadlec, 1986; Mitsch and Reeder, 1991; Mitsch et al., 1988; Flanagan et al., 1994; Alvord and Kadlec, 1996; Lung and Light, 1996; Martin and Reddy, 1997; Tsanis et al., 1998; Van der Peijl and Verhoeven, 1999; Wang and Mitsch, 2000) have developed simulation models of wetlands, with particular emphasis on water quality issues (nutrient or contaminant fate, transport and behavior). There is ample evidence for the ability of wetlands to remove nutrients. Moustafa et al. (1996) examined phosphorus transport through the Boney Marsh area of the Kissimmee River basin, and concluded that natural floodplain marshes can sequester up to 75% of annual phosphorus loads when those loads are primarily in dissolved forms. Reddy et al. (1993a) stated that the effectiveness of a wetland system in removing water column phosphorus is dependent on vegetation, sediment chemistry, pH, and redox potential. Craft and Richardson (1993), Reddy et al. (1993b) employed Cs-137 dating techniques to estimate phosphorus accretion rates (PAR) in Everglades peat. Sediment PAR represent the long-term integration of many individual, short-term biogeochemical processes, and as such, provide excellent data for calibration of phosphorus fate and transport models.

Kadlec (1986) reviewed modeling approaches that describe pollutant removal processes in wastewater wetland treatment systems, and Kadlec and Hammer (1982) developed a simple, first-order process for empirically modeling pollu-

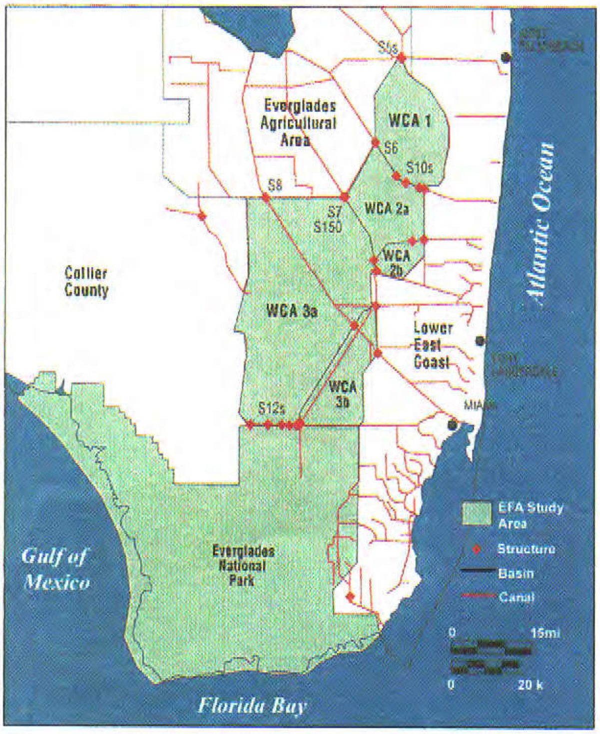


Fig. 1

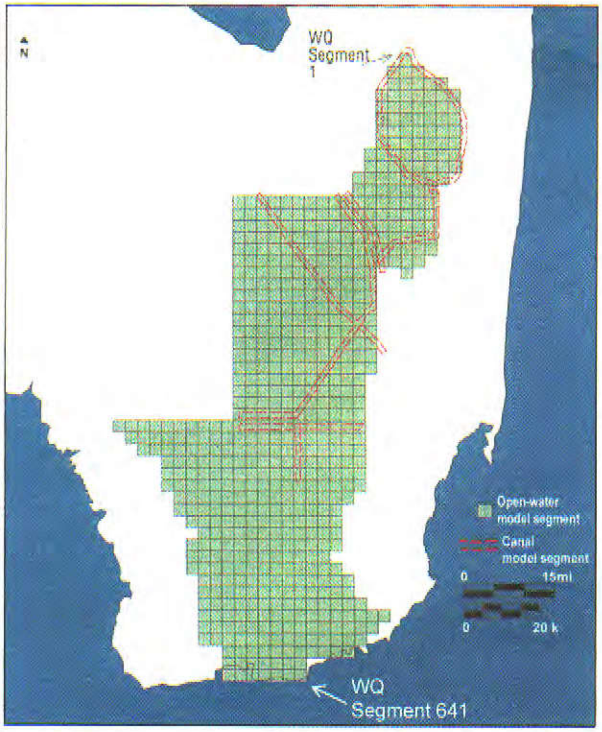


Fig. 2

Fig. 1. EWQM study area.
Fig. 2. Spatial discretization of modeled area.

tant removal in wetland treatment systems. The authors concluded that the relatively fast first-order removal rates observed in these systems are primarily controlled by adsorption processes. Later, Alvord and Kadlec (1996) concluded that removal rates of different types of pollutants may be similar and could reflect similar underlying mass transfer rate limitations. Mitsch et al. (1995) employed similar first-order models to describe phosphorus dynamics in freshwater, riparian marshes, and tested the usefulness of modifying such models to account for temperature and hydrologic loading effects on phosphorus retention. Recent water quality modeling conducted on the Everglades system (Walker, 1995) has focused on developing and evaluating a design basis for constructed wetlands known as Stormwater Treatment Areas (STAs) that will reduce phosphorus runoff from the EAA. This modeling effort is based on analysis of PAR in an intensively monitored area of WCA-2A immediately downstream of the S10 structures (SFWMD, 1992; Craft and Richardson, 1993; Reddy et al., 1993b; Walker, 1995). This area is especially suitable for calculating PAR because its hydraulic conditions approach sheet flow, its soil and water column chemistry has been extensively monitored over a long period, and its vegetation communities have been well-documented (Rutchey and Vilchek, 1994, 1999; Walker, 1995). Based on these data, Walker (1995) suggested that the apparent net settling rate for phosphorus removal at WCA-2A was about 10.2 m/year.

2.2. Conceptual basis of the Everglades Water Quality Model (EWQM)

The EWQM was developed by constructing a detailed description of the processes that affect nutrient dynamics in the Everglades, and then simplifying this description to the point where it could be supported by available data. The state variables of a complex Everglades nutrient model would include the dissolved and particulate nutrient fractions that comprise the total nutrient pool in sediments and water, nutrients associated with periphyton and macrophytes, and the many processes that link these state variables. Although the existence of these many state variables and associated processes is known, accurate simulation of them requires quantitative information that is not yet available for the Everglades. Therefore, our modeling approach uses a more empirical approach (in contrast to mechanistic approaches such as used by Van der Peijl and Verhoeven, 1999; Wang and Mitsch, 2000) by employing an apparent net settling rate coefficient (see Walker, 1995) which aggregates multiple biogeochemical processes in one term. The mass balance differential equation corresponding to such a conceptualization is based on the theory and mathematics described in Thomann and Mueller (1987).

For any segment i

$$V\frac{\mathrm{d}Ci}{\mathrm{d}t} = Wi - Ci\sum_{\substack{j=1\\ j\neq i}}^{n} Qij + \sum_{\substack{j=1\\ j\neq i}}^{n} QjiCj - v_{\mathrm{net}}\,ACi$$

where C is the total phosphorus concentration (kg/m^3), Q the flow (m^3/day), v_{net} the apparent net settling rate (m/day), W the phosphorus loading (kg/day), A the area (m^2), V the volume (m^3), and i, j are water quality model segment numbers. Note that i and j range from 1 to 661 in the current EWQM.

The first-order net loss term in the equation represents the sum of all physical, biological, and chemical processes that act to change the concentration of phosphorus during its residence in a model segment. Phosphorus inputs to segments are from adjoining segments, rainfall, and at model boundaries, forcing functions. Phosphorus outputs are to other segments and include overland flows, structure flows, transfer between canals and surface waters, transfer between surface waters and groundwater, and seepage through levees. The hydrologic underpinning of the EWQM is output from the cell-based South Florida Water Management Model (SFWMD, 1984, 1997a). The EWQM computes nutrient concentrations in the surface water compartment only, but also tracks nutrient flux to the sediments for comparison with phosphorus accretion measurements taken in the field.

2.3. EWQM spatial and temporal scales

The model simulation is limited to a 129-month period (January 1979–September 1989) for which the SFWMM results were available. The hydrologic and phosphorus loads to the EWQM are input on a monthly basis; model outputs of EWQM are also computed on a monthly basis.

The spatial resolution of the EWQM is dictated by the SFWMM, which divides the modeled area into 3.2×3.2 km squares, except for canals which are handled differently (Fig. 2). The spatial segmentation of both models is identical and consists of 642 segments and 19 canals for a total of 661 segments. Bottom elevations for canals in the modeling area are not currently available. Currently, the EWQM assumes a constant water depth of 3 m in all canals. Thus, canals are always considered wet, with constant volumes computed as the product of a fixed length, width, and depth.

The EWQM treats each segment and canal as completely mixed. During certain dry months the SFWMM predicts that water depths in some cells drop to zero or a very low value. Under these conditions the EWQM simulation skips the cell in question in order to retain mathematical stability. When a 'dry' segment becomes 'wet' during subsequent months, the initial conditions are updated to the mass of total phosphorus that existed in the segment during the last 'wet' month.

2.4. EWQM data and model inputs

The water quality monitoring data used to initialize or calibrate the model was organized in a database (Limno-Tech, Inc., 1995). Monthly average, segment-specific concentration records were developed for all EWQM segments that had at least one associated water quality monitoring station. This was necessary to make the calibration data consistent with the monthly temporal scale of the model application. Calibration data time series were developed for a total of 112 open-water segments and six canal segments by this process.

The external loads of nutrients to the EWQM grid were input as surface water, ground water, and atmospheric loads. Surface water loads were those principally entering through flow control structures located along the periphery of the model domain; groundwater loads were those which entered via seepage; atmospheric loads included wet and dry deposition. Surface water loads were calculated as the product of a monthly average flow and a monthly median concentration. All surface flows at structures and boundaries, as well as ground water flows, were extracted from SFWMM results. There were adequate water quality data to compute a monthly median phosphorus concentration at all major inflow structures. However, at other surface water boundary locations the data were relatively sparse and a constant boundary condition of 10 ug/l TP was assigned. Similarly, boundary conditions for groundwater quality were assigned with the following values, 100 ug/l in WCA-1 and WCA-3A, 10 ug/l in WCA-2A, and 30 ug/l in WCA-2B, WCA-3B, and ENP. These values are within the range of available groundwater quality data in South Florida (SFWMD, 1989).

An average atmospheric phosphorus load of 3.17×10^5 kg/year (approximately 47 mg/m^2 per year) was assigned to the entire modeled system for the period of historical simulation and is input proportional with monthly SFWMM rainfall. This loading estimate is close to recent estimates of atmospheric loads that range between 20 and 40 mg/m^2 per year (SFWMD, 1997b). Initial parameterization of the apparent net settling rate for phosphorus removal was based on Walker (1995).

3. Results

3.1. Model calibration

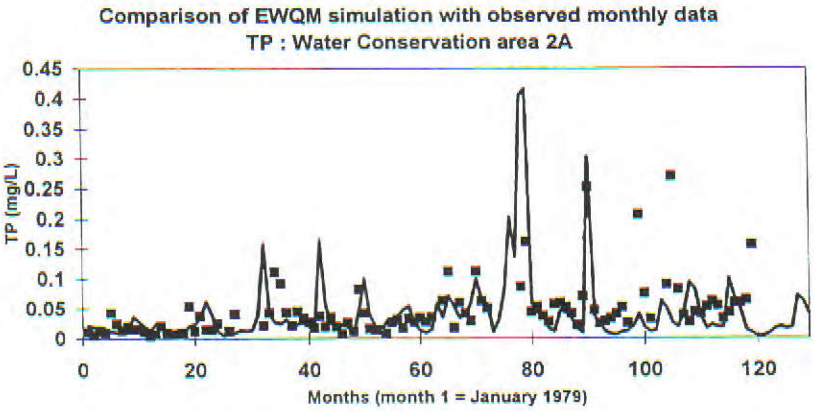
The intent of the calibration process was to find a realistic value (or set of values) for the apparent net settling rate coefficient that would give the best match of simulated average and measured aqueous total phosphorus concentrations and PAR in sediments. Because the system is separated into distinct hydrologic basins (i.e. the WCA), a constant apparent net settling rate coefficient was determined for each basin.

Table 1
Calibrated settling rates used in the EWQM

Basin	Location	Apparent net settling rate (m/year)
1	WCA-1	6.30
2	WCA-2A	9.13
3	WCA-3A	7.30
4	WCA-2B	10.95
5	WCA-3B	9.13
6+44	ENP	7.30
Canals	Various	14.60

During calibration exercises, apparent net settling rate coefficients in each basin were varied until the best fit of model and data was achieved. The coefficient values that provided the best calibration for the WCA ranged from 7 to 11 m/year (Table 1), which are reasonable when compared with rates reported for wetlands and other calibrated models of nutrient fate and transport (Walker, 1995). Sample calibration results for model segments in WCA-2A and ENP show reasonable agreement with long-term average water column total phosphorus concentration data (Fig. 3). Because the model output represents the average of daily concentration values within a given month and the measured data represent concentrations on specific days of the month, the model output may not track occasional data spikes of the measured data. The details of the calibration exercise and the comprehensive results and figures can be found elsewhere (Limno-Tech, Inc., 1997).

Sediment phosphorus is not explicitly modeled in the EWQM, but simulated settling losses can be mathematically accumulated to predict long-term sediment PAR. Sediment total PAR (in g/m^2 per year) for each segment was computed using the equation:



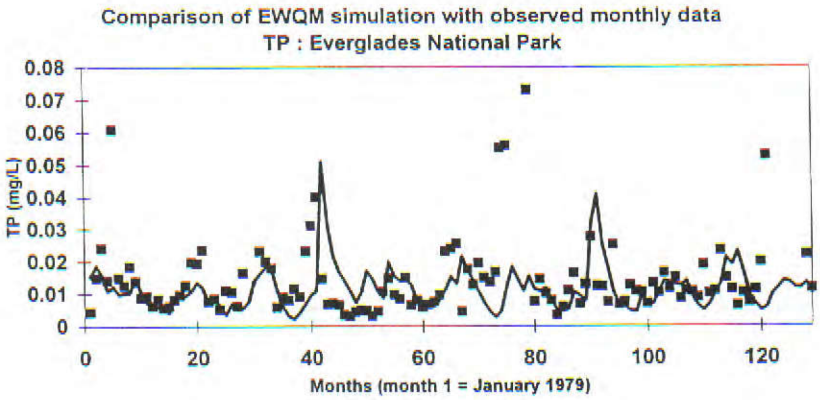


Fig. 3. EWQM calibration for selected model segments in WCA-2A and ENP.

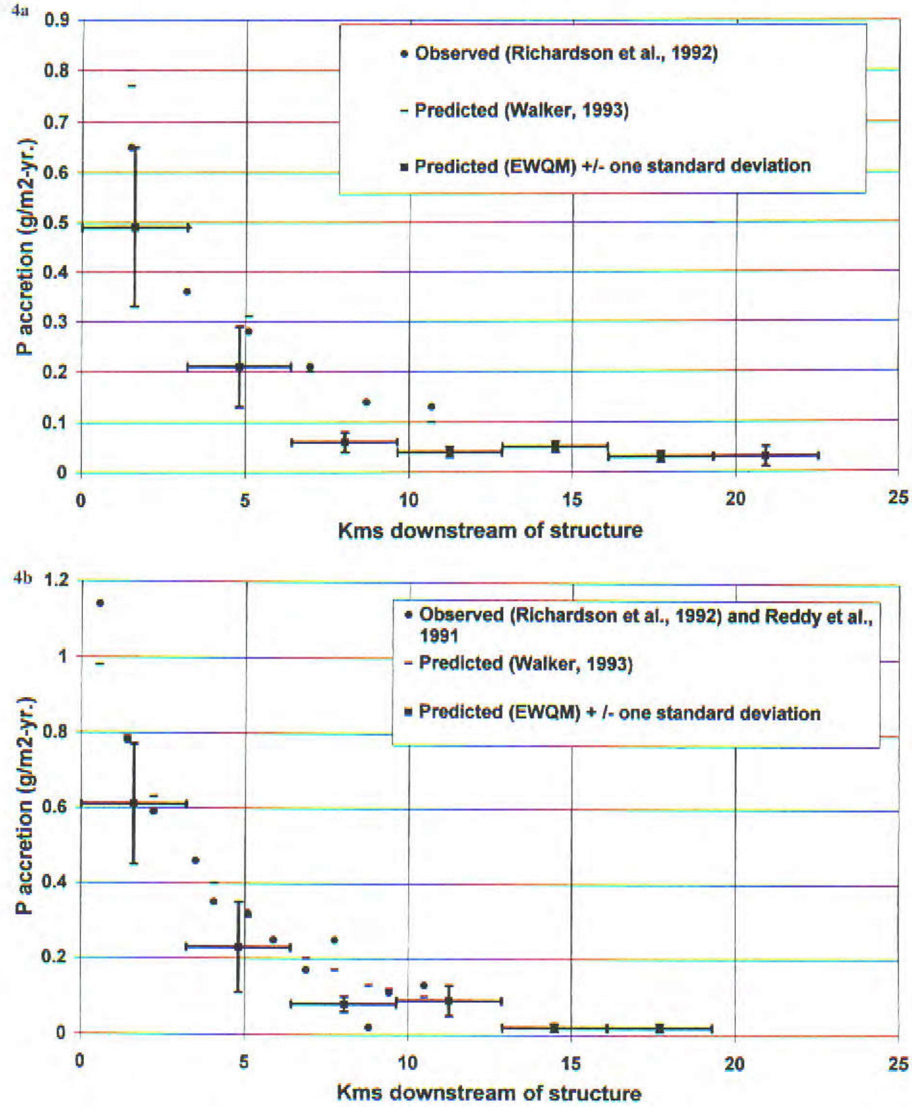


Fig. 4. (a) Sediment PAR downstream of structure S-10D. (b) Sediment PAR downstream of structure S10C. (c) Sediment PAR downstream of structure S10A. Vertical bar denotes variation around the mean value of simulation years. Horizontal bar represents the length of the model segment over which the EWQM prediction applies.

$$\mathrm{PAR}_i = K \frac{\sum_{n=1}^{129} (\mathrm{SetFlux})i,n}{Ai}$$

where K is the unit conversion constant, equals 93.023 (converting the sum of 129-month data in kg/m^2 to g/m^2 per year), $(\mathrm{SetFlux})_{i,n}$ the total settling flux (kg/month) for month n and segment i, and A_i is the surface area of the segment in m^2.

The PARs computed from the EWQM were compared with in situ field measurements of accretion rates (Fig. 4a–c). Modeled and measured PARs downstream of the S10 discharge structures ranged between about 0.1 and 1.2 g/m^2 per year and compared well with each other.

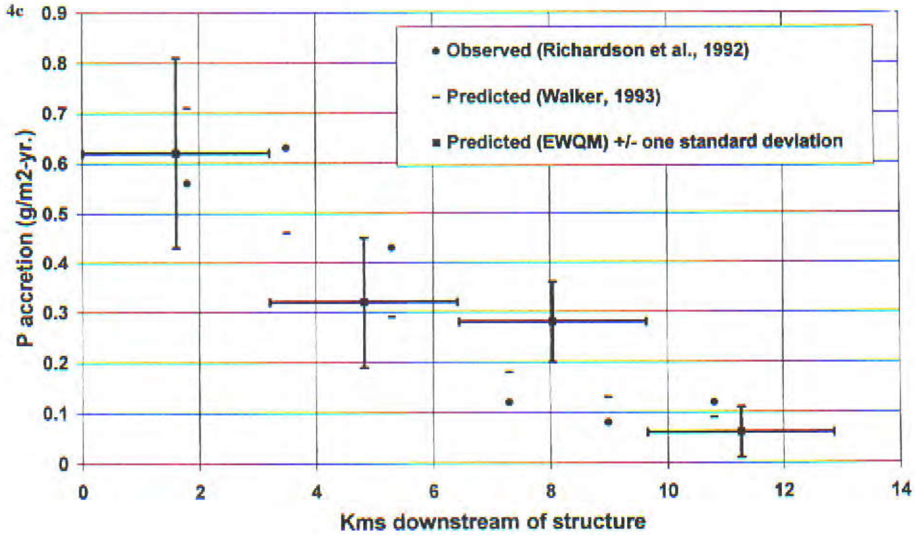


Fig. 4. (*Continued*)

3.2. Simulated characteristics of regional phosphorus dynamics in the Everglades

The 129-month average of simulated total phosphorus concentrations in the Everglades on a segment-specific basis show clear spatial differences (Fig. 5). The interior area of WCA-1 exhibits much lower concentrations than the area near the surrounding canal (rim canal). The rim canal receives all the loads from structures S-5A and S6 and exhibits concentrations in excess of 100 ug/l in all years except during 1980 and 1989 (data not shown). This canal shunts the loads from these structures rapidly, with little penetration to the interior of WCA-1, to the vicinity of the S10 structures located on the boundary of WCA-1 and WCA-2A. The entire 54-mile stretch of the rim canal is presently modeled as a single water quality segment because of the structure of the underlying hydrology model (SFWMM). Therefore, nutrient concentration gradients in this canal, although possible, cannot be simulated at this time.

WCA-2A shows some of the highest water column total phosphorus concentrations in the entire Everglades, especially in the vicinity of the S-10 structures (Fig. 5). The gradients downstream of structures S10A, S10B, and S10C are well-documented (Walker, 1995). WCA-3A has simulated nutrient gradients downstream of its input structures. WCA-2B and 3-B also show elevated total phosphorus concentrations near canals where interactions between the rim canals and the open-water segments occur. The ENP shows lower concentrations, in general, than the WCA.

3.3. Sensitivity analyses

The sensitivity of water column total *P* concentrations to the apparent net settling rate coefficient value is demonstrated by a conservative simulation where the coefficient is set to zero everywhere at all times (Fig. 6). Under these conditions, water column total phosphorus concentrations in all WCA exceed 100 ug/l and reach as high as 50–100 ug/l in the ENP as compared with the base calibration result (Fig. 5). This analysis shows that losses of total phosphorus to sediments are an important fate mechanism throughout the modeled area. Similar conclusions can be drawn from the simulation results of Wang and Mitsch (2000; Fig. 9) where four wetlands retained between 80 and 97% of their inflow phosphorus.

Atmospheric phosphorus deposition rate in the base model calibration was set at a temporally and spatially constant value of 47 mg/m^2 per year. However, estimates have ranged from near zero to

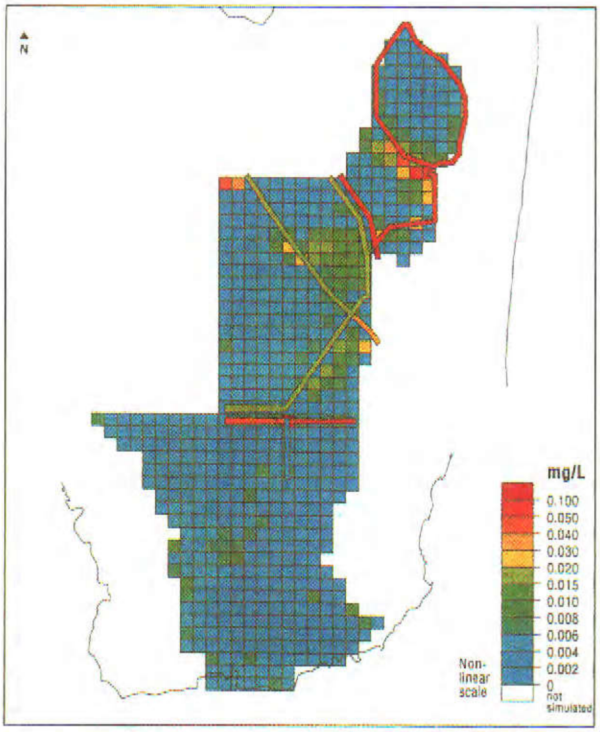


Fig. 5

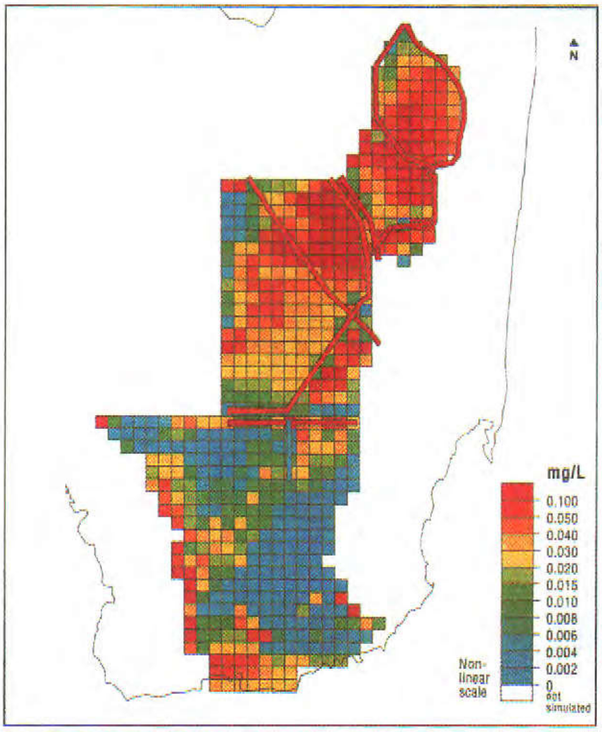


Fig. 6

Fig. 5. Total phosphorus concentration, 129-month average, base model calibration.
Fig. 6. Total phosphorus concentration, 129-month average, conservative simulation (zero net loss).

more than 127 mg/m^2 per year (Davis et al., 1994; Walker, 1995). Therefore, a sensitivity analysis on atmospheric deposition was conducted using these two extremes (Figs. 7 and 8). A deposition rate of 127 mg/m^2 per year relative to zero deposition can elevate concentrations in vast areas of the Everglades surface waters by nearly 20–30 ug/l. The effect of atmospheric deposition is most obvious in the areas remote from discharge structures (e.g. the interiors of WCA-1 and ENP) but is virtually unnoticeable in areas receiving high phosphorus loads.

The sensitivity of water column total phosphorus concentrations to doubling and halving of all surface water loads from the EAA is most notable in the vicinity immediately downstream of structures S5A, S6, S7, S8, and S150 (Figs. 9 and 10). Interior areas located farther away from these input structures are less affected by changes in the phosphorus loads at these structures. The only areas remote from the structures which are sensitive to structure loads are those which lie beside or at the end of a canal. Thus, the canal segment between WCA-3A and ENP shows higher concentrations when loads are doubled (Fig. 9) as compared with halved (Fig. 10).

3.4. Application to management issues

An important water quality compliance issue concerns the concentration of phosphorus delivered to ENP. Accordingly, the EWQM was used to determine the influence of phosphorus loads from structures S5-A, S6, S7, S8, and S150 on the delivery of total phosphorus to the ENP via the S-12 structures. For the base period (during which settlement agreement mandated on-farm best management practices, BMP, or STAs are not operational), the mean simulated flow-weighted concentration at the S-12 structures was 14.5 ug/l,

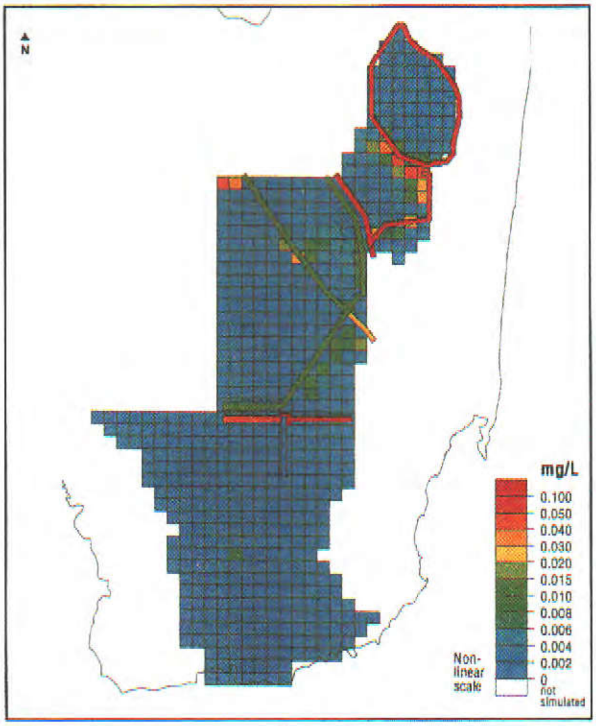


Fig. 7

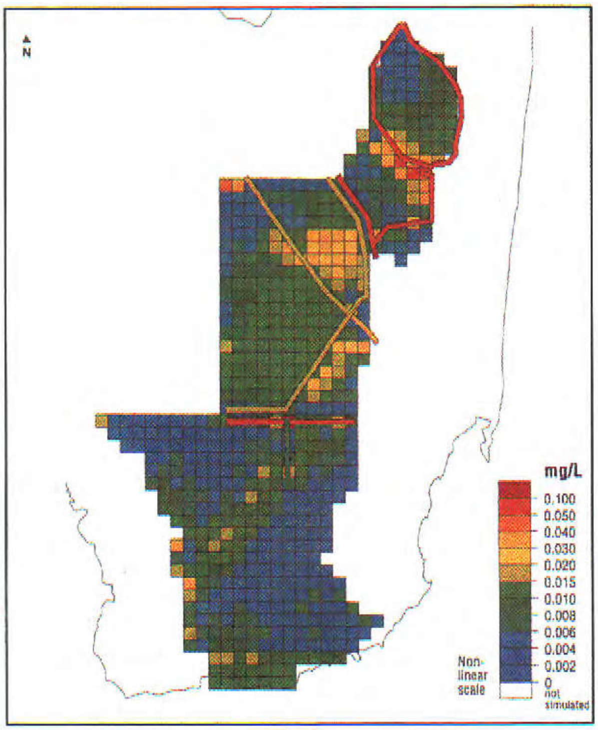


Fig. 8

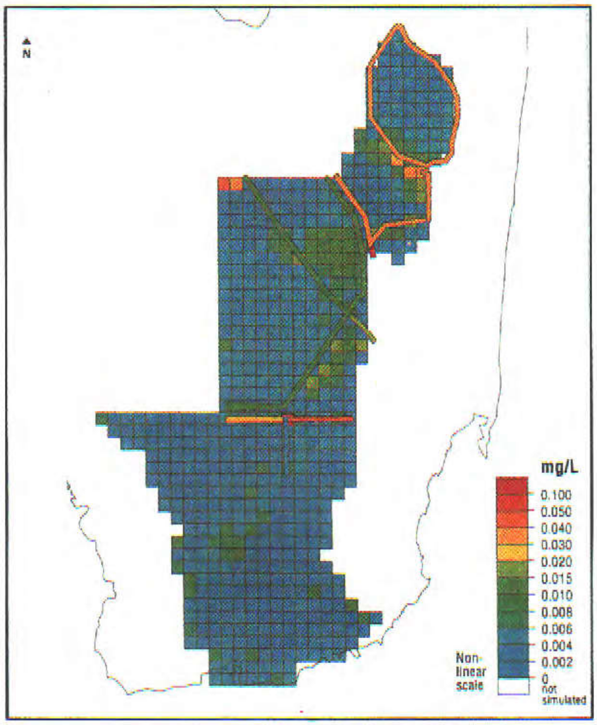


Fig. 9

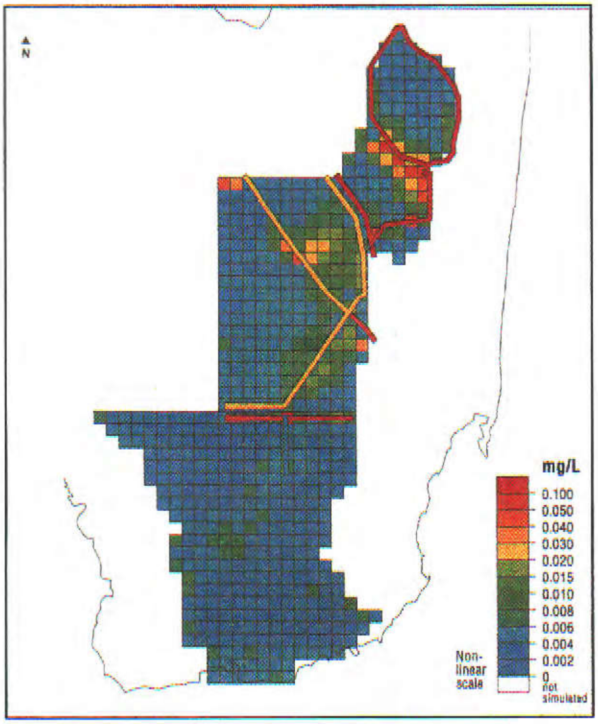


Fig. 10

Fig. 7. Total phosphorus concentration, 129-month average, atmospheric total phosphorus deposition equals zero mg/m^2 per year.
Fig. 8. Total phosphorus concentration, 129-month average, atmospheric total phosphorus deposition equals 127 mg/m^2 per year.
Fig. 9. Total phosphorus concentration, 129-month average, loads halved for structures S5, S6, S7, S8, and S150.
Fig. 10. Total phosphorus concentration, 129-month average, loads doubled for structures S5, S6, S7, S8, and S150.

with a S.D. of ± 8.2 ug/l (Fig. 11). These values are comparable to the mean measured flow-weighted concentration of 11.8 ug/l with a S.D. of ± 3.7 ug/l during 1978–1990 (Walker, 1999). When concentrations leaving structures S5-A, S6, S7, S8, and S150 were set at 50 and 10 ug/l, the corresponding average concentrations at the S-12 structures were 7.1 ug/l, with a S.D. of ± 2.1 and 2.2 ug/l with a S.D. of ± 0.5 ug/l, respectively (Fig. 11). Clearly, the model suggests that the combination of on farm BMPs and STAs, as required by settlement agreement to achieve a long-term average annual total phosphorus concentration of 50 ug/l, will be sufficient to reach (on average) the default criteria of 10 ug/l total phosphorus at the ENP boundary. However, it would not be sufficient to reach a default total phosphorus criterion of 10 ug/l if the criterion was applied throughout every segment of the modeled Everglades. In that case, additional phosphorus removal capacity would be required.

4. Conclusions

The EWQM reasonably matches the magnitudes and trends in total phosphorus concentration data but shows deviations in some areas. There is good agreement between in situ long-term peat PAR and model predicted accretion rates where data were available to make such comparisons. Atmospheric loads were found to largely determine total phosphorus concentrations in pristine areas of the Everglades. Conversely, areas in close proximity to principal inflow loading structures are not sensitive to atmospheric loads. Canals are crucial to the fate and transport of total phosphorus in the Everglades. Canal-to-canal and canal to open-water interactions result in nutrient transport to regions far from the initial discharges. Simulated phosphorus concentrations and fluxes entering the ENP are sensitive to the EAA loads. Based on the model's ability to reproduce measured PAR and water column phosphorus concentrations, the EWQM can be used as a

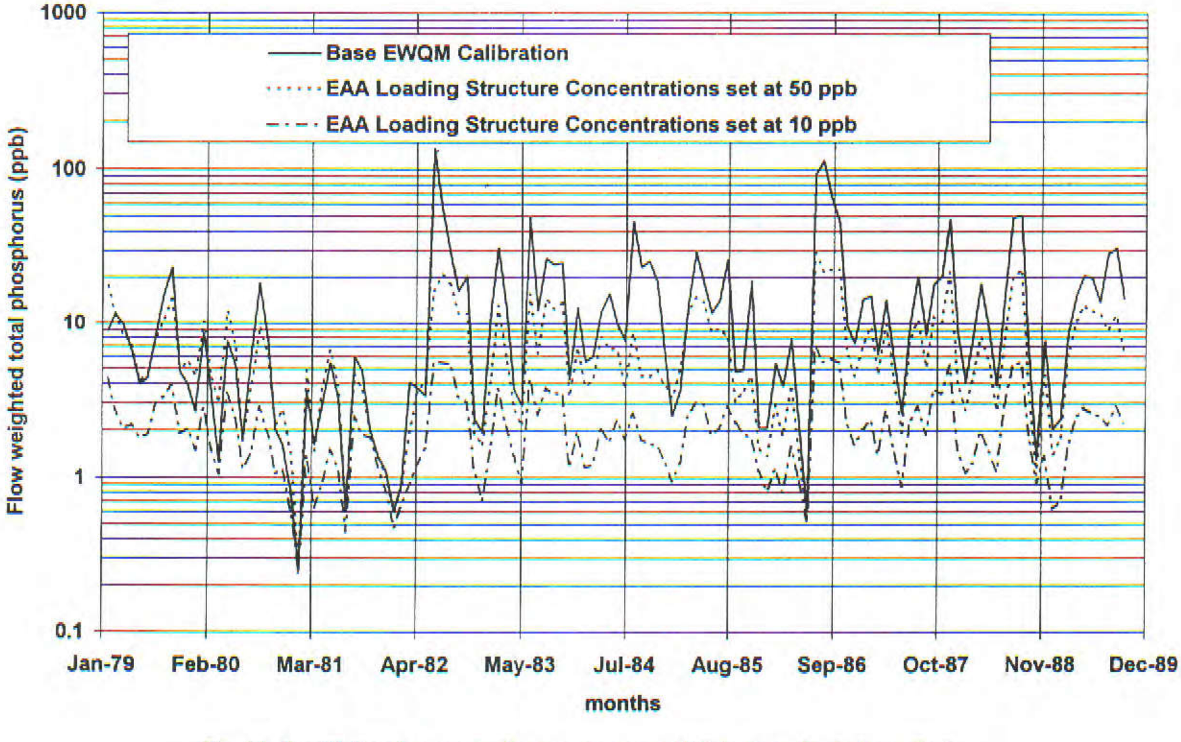


Fig. 11. Sensitivity of concentrations at structures S12 A–D to loads from EAA.

screening tool to assess the fate and transport of nutrients in the Everglades under proposed restoration scenarios that involve changes in hydrology and nutrient inputs.

This version of the EWQM represents an initial attempt to model the fate and transport of phosphorus in the Everglades. Phosphorus dynamics of the Everglades were intentionally aggregated in the model using simple, empirical relationships. This was necessary due to lack of data for parameterizing a more realistic process model such as those developed by Martin and Reddy (1997), Van der Peijl and Verhoeven (1999), Wang and Mitsch (2000). To improve simulation of regional phosphorus dynamics and their relationship with hydrologic conditions, several changes to model structure have been identified. Currently, the apparent net settling rate approach used in the EWQM represents the combined effect of all biogeochemical processes on unidirectional movement of water column phosphorus to the sediments. It, therefore, lacks the ability to isolate the effects of individual processes that affect phosphorus dynamics in the Everglades. For example, the present approach cannot simulate phosphorus release from sediments when re-flooded after a dry period, or concentrations resulting from equilibrium partitioning of water column and sediment phosphorus. Adding computational routines to simulate these processes separately could improve the model's ability to simulate phosphorus dynamics more accurately. Another area needing improvement is the canal segmentation scheme. Constrained by the configuration of the SFWMM, the EWQM currently treats each canal as a homogenous segment, thereby precluding simulation of phosphorus gradients within canals. A refinement in canal segmentation can capture the in-canal phosphorus gradient and improve the overall representation of phosphorus exchange between canals and adjacent open-water areas. Finally, the values of the apparent net settling rate parameter were derived from long-term sediment accumulation records, so the ability of the model to predict phosphorus dynamics is greatest over long-time scales. Finer temporal prediction will be improved by obtaining settling rates for finer temporal scales. The EWQM remains, however, a useful tool for screening the effects of nutrient reduction scenarios in support of Everglades restoration.

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