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Modeling Phosphorus Dynamics in Everglades Wetlands and Stormwater Treatment Areas

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Longitudinal gradients in phosphorus (P) stored in the water column, vegetation, and soils develop in the wetlands where inflow P concentrations exceed background levels. Before the mid 1990's, the Everglades regional P gradient ranged from 100–200 μg L^{-1} in marsh inflows to background levels of 4–8 μg L^{-1}. Subsequent implementation of P controls, including agricultural Best Management Practices and Stormwater Treatment Areas (STAs), has reduced the average inflow concentration along the northern edge of the Water Conservations Areas to approximately 30–50 μg L^{-1}. Additional P controls are being implemented and further measures beyond those currently planned will be required to restore the entire marsh. The authors describe the evolution and application of relatively simple mass-balance models to simulate P storage and cycling processes along P gradients in the STAs and marsh. The models are practical tools with historical and future applications to designing P control measures involving source controls, water management, reservoirs, and STAs, as well as forecasting marsh responses to implementation of those control measures.

KEYWORDS: engineering, Everglades, marsh, modeling, phosphorus, wetland treatment areas

INTRODUCTION

As water with elevated phosphorus (P) moves through a wetland ecosystem, P is removed and a gradient of decreasing P concentration is produced along

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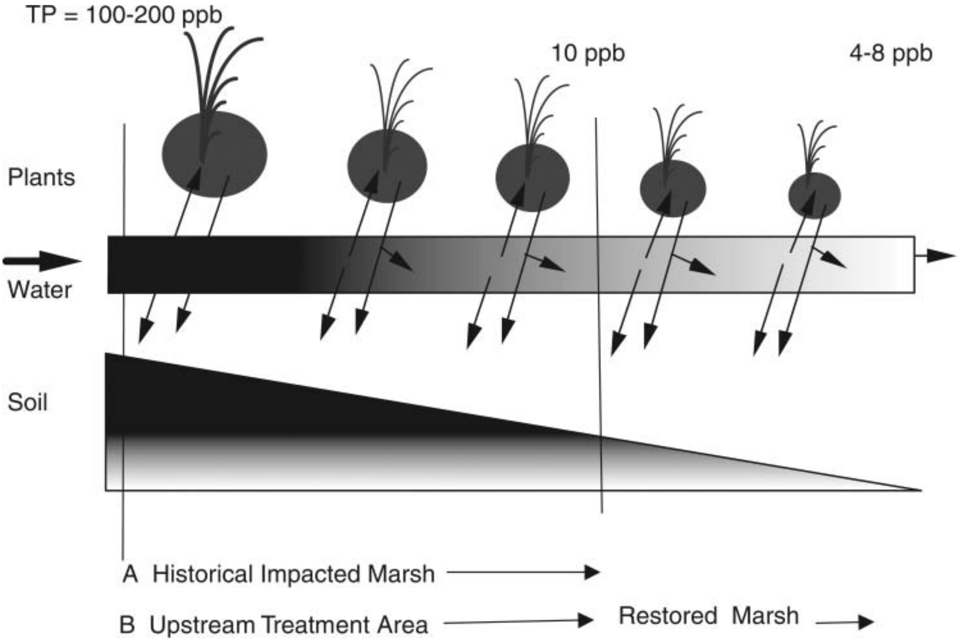


FIGURE 1. Phosphorus (P) gradient in wetland vegetation, water column, and soils under historical and restored conditions. (A) Historical conditions (before implementation of phosphorus controls). The P gradient is located entirely with the impacted natural marsh. (B) Future restored conditions (after full implementation of P controls). Most of the P gradient is moved upstream out of the natural marsh and located with wetland stormwater treatment areas constructed on adjacent agricultural lands. The remaining gradient within the marsh extends from 10 ppb in the treatment area outflows to marsh background levels.

the flow path (Kadlec and Walker, 1999; Walker, 1995). The water column P gradient is typically accompanied by gradients of P storage in vegetation and soils (Figure 1). P originating in inflows and atmospheric deposition is cycled within the marsh and ultimately stored in accreting peat or transported downstream. Historically, the water column P gradient in the Everglades marsh ranged from 100–200 μg L^{-1} at the inflows to background levels of 4–8 μg L^{-1} (Figure 2). Nearly two decades of monitoring and research by the South Florida Water Management District (SFWMD) and other agencies have established that wetland ecosystems change dramatically along the P gradient and that native slough and sawgrass communities are viable only at P concentrations below 10 μg L^{-1}, expressed as a long-term geometric mean (Payne et al., 2003). With sheet flow hydraulics, water quality at the edge of the marsh is determined by the quality of the inflows. Restoring and protecting the entire marsh is likely to require inflow P concentrations approaching the marsh P criterion. This is in contrast to lakes or other well-mixed water bodies where inflows with concentrations exceeding ambient water quality

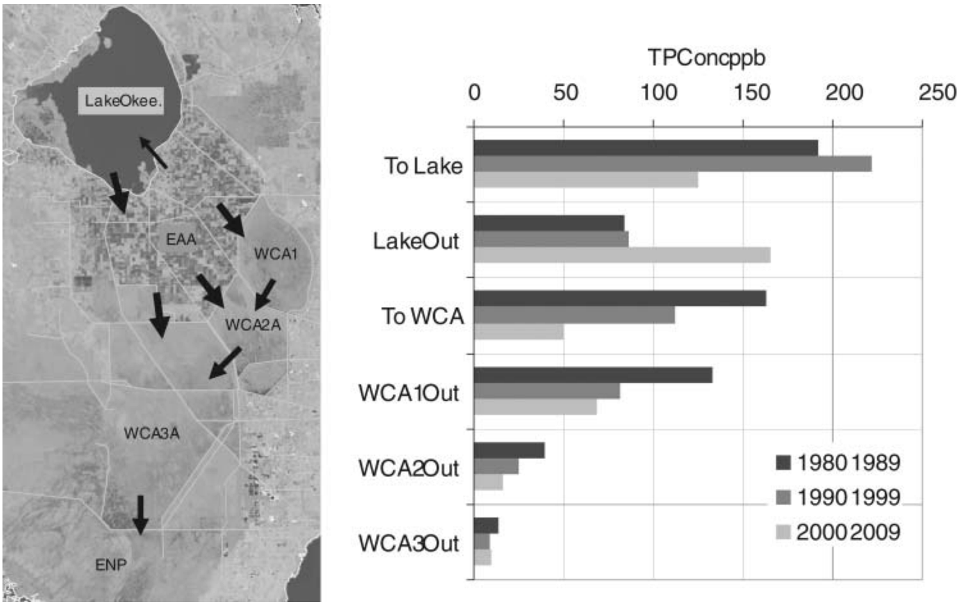


FIGURE 2. Long-term trends in the Everglades regional phosphorus gradient. Phosphorus concentrations are flow-weighted means. Flow and concentration data are from DBHYDRO (SFWMD, 2009a).

standards do not trigger violations of ambient standards because they are rapidly dispersed, diluted, or assimilated in receiving waters.

Spatial and temporal variations in the Everglades regional P gradient over the past three decades are shown in Figure 2. Substantial progress has been made since 1993 in reducing P concentrations in the inflows to the Water Conservation Areas (WCAs) through implementation of agricultural Best Management Practices (BMPs) and construction of Stormwater Treatment Areas (STAs; South Florida Water Management District [SFWMD], 2009b). As these control measures were implemented, the combined WCA inflow concentration decreased from ~160 μg L^{-1} in 1980–1989 to ~50 μg L^{-1} in 2000–2009. Inflow concentrations further decreased to an average of ~30 μg L^{-1} in 2005–2009. The latter value is likely to overestimate the long-term performance of P controls in place at that time because of relatively dry conditions. STA outflow P concentrations are expected to be higher in wet years. The historical reductions in inflow concentration have cascaded through the networks of canals and marshes to cause P concentration reductions in the outflows from each WCA (Figure 2).

The effect of the P control program is to displace the P gradient upstream of the marsh so that most of it occurs within STAs located on formerly agricultural land (Figure 1). At the same time, elevated P concentrations driving the gradient are reduced through implementation of BMPs. When long-term restoration objectives are achieved, the marsh gradient will be substantially reduced relative to historical conditions and have long-term geometric mean P concentrations ranging from 10 μg L^{-1} to background levels of 4–8 μg L^{-1}.

This paper describes the evolution of relatively simple mass-balance models to simulate P storage and cycling processes along P gradients in the STAs and marshes. In the context of the Everglades restoration effort, the models and associated software have provided practical engineering tools for designing P control measures involving combinations of source controls, regional water management, and STAs, as well as to forecasting marsh responses to variations in WCA inflow volumes and P loads.

MODEL EVOLUTION

The models described below were developed to support evaluation of multiple STA design alternatives by engineering professionals without requiring site-specific calibration data or specialized expertise in wetland modeling. Model simplicity results from aggregation of key variables and processes controlling phosphorus storage and cycling. The simplifying assumptions are supported by calibration and testing against several dozen datasets that describe phosphorus removal in experimental prototypes, field-scale test cells, full-scale STAs, and natural wetlands (Walker and Kadlec, 2001, 2005). These data sets provide bases for calibration and testing under a wide range of conditions (e.g., size, water depth, P concentration, P load, velocity, vegetation types, inflow variability) and for estimating uncertainty associated with model forecasts. While the modeling effort was initiated to support STA design, the fundamental concepts (mass balance, hydraulics, P cycling mechanisms) operating along a P gradient (Figure 1) also apply to natural wetlands. Differences between the STAs and marsh-related factors such as water depth, hydraulic loads, antecedent soils, and vegetation are considered by explicitly including those factors in the model(s) or by defining limits of application consistent with calibration datasets.

Figure 3 shows P storage compartments and fluxes associated with four models that evolved over the 1995–2008 period (Kadlec, 1994, 2006; Kadlec and Walker, 1999; Walker, 1995; Walker and Kadlec, 2005). They involve different combinations of three fundamental storage compartments (water column, biota, soil) and associated net fluxes between compartments. While P generally moves in both directions between compartments via different mechanisms, the aggregated models simulate the net fluxes that ultimately drive the mass balance. Model structures represent P storage and net fluxes per unit area of marsh. These are superimposed on hydraulic models to predict water movement and P transport. Excel spreadsheet software developed to support model applications is limited to relatively simple one-dimensional

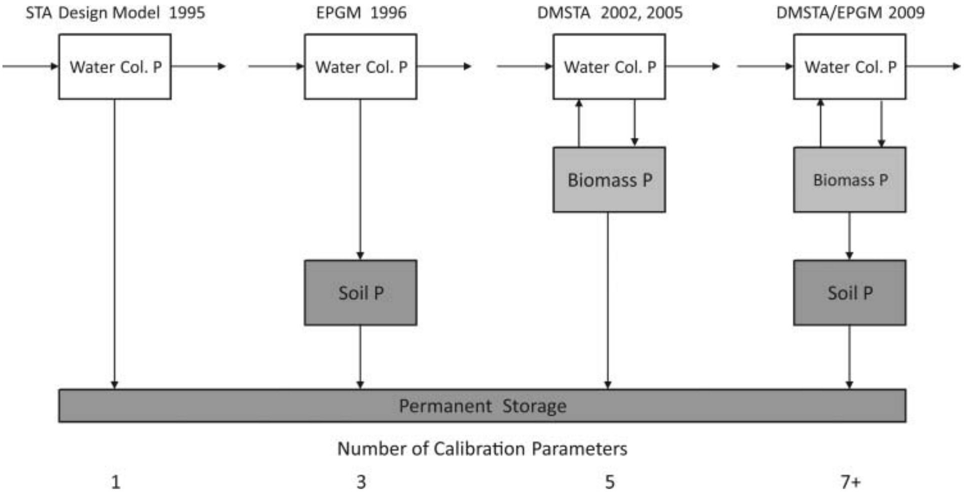


FIGURE 3. Evolution of phosphorus (P) mass balance models with increasing complexity. Aggregated P compartments and net fluxes are shown for four mass balance models developed over the 1995–2009 period. Permanent storage represents burial of stable P forms in accreting peat. The number of calibrated parameters increases with model complexity.

hydraulic models representing sheet flow along a marsh transect or STAs with individual treatment cells connected in a series or parallel. The P cycling variables and equations can be translated to more complex hydraulic models capable of predicting two-dimensional flow and mass transport in an STA or marsh (Chen et al., 2009).

Models with greater complexity have developed for describing water and phosphorus movement in STAs (HydroQual, 1998; Moustafa and Hamrick, 2002) and Everglades marsh (Fitz and Trimble, 2006; Munson et al., 2002). They generally account for two-dimensional spatial and temporal variability and have several state variables and adjustable parameters. Most require enhanced computers, long run times, site-specific calibration data, and special expertise to calibrate and apply. To our knowledge, the Everglades Landscape Model (ELM; Fitz and Trimble, 2006) is the only one in this category presently being applied in the Everglades restoration effort. It simulates system-wide variations in marsh hydrology, water quality, soils, and vegetation in response to variations in marsh inflows and other factors projected to occur in response to long-term restoration efforts.

Steady-State STA Design Model

The STA design model (STADM; Walker, 1995) was used to develop initial designs for ~29,000 ha of STAs to achieve a long-term flow-weighted mean outflow concentration of 50 μg L^{-1} (Burns and McDonnell, 1994). A modified version that places a lower bound on P concentration (Kadlec, 1994;

Kadlec and Wallace, 2009) was used in the initial design of STA-34 (Burns and McDonnell, 1999). Knowledge and experience gained through research, operation, and monitoring of the 50 μg L^{-1} STAs subsequently provided a technical basis for optimizing and expanding the STAs to achieve lower P concentrations, as well as for improving the models to support that effort (SFWMD, 2009b).

The STADM simulates the long-term average water column P gradient along a marsh transect as a function of the average inflow volume, inflow load, flow-path width, and atmospheric deposition. The model includes one P storage compartment (water column) and three P fluxes: inflow, outflow, and net removal (Figure 3). Short-term variations in P storage and cycling in vegetation and soils are assumed to cancel out over long time scales and are essentially embedded in the calibration. Because the design objective was expressed as a long-term flow-weighted mean, predictions of short-term variations in P concentration were not required to support the 50 μg L^{-1} STA designs. A steady-state model is not sufficient, however, for designing STAs to achieve lower P concentrations driven by highly pulsed inflows.

The STADM assumes that the average net P removal rate per unit area is proportional to the average water column concentration. No P removal is assumed to occur when the marsh is nearly dry (water depth < 30 cm). The proportionality constant (net settling rate $= 10.2 \pm 1.4$ m/year) was calibrated to peat accretion measurements along the P gradient in the WCA-2A marsh downstream of outflows from WCA-1 (Figure 2). The peat data provided an integral measure of net P removal over a 26-year period. Global distribution of fallout from nuclear bomb testing in 1963 placed a layer of radioactive Cesium-127 in the soil profile. The accumulated soil P was estimated by vertically integrating from the peak in Cesium-127 content to the surface using soil cores collected at 24 monitoring sites (Craft and Richardson, 1993a, 1993b; Reddy et al., 1991, 1993). The model was tested against limited water column concentration data along the same marsh transects (Walker, 1995). Because of the limited quantity and high variability in the water column data, the integrated peat accretion data provided a preferred basis for calibrating the model to predict long-term P removal rates. Data from wetland treatment areas sufficient to support calibration were not available at the time of STADM development.

Effects of variability in the inflows, water depth, hydraulics, and vegetation types were embedded in the STADM calibration to the marsh. In applying the model to design the 50 μg L^{-1} STAs, it was assumed that STA vegetation types and P cycling processes would be similar to those in the upper portion of the P gradient in the WCA-2A marsh used for calibration (predominantly cattail). Potentials for regulating STA inflow volumes, flow distribution, water depths, and vegetation to optimize treatment suggested that the model calibrated to a natural wetland would generate conservative forecasts of STA performance. Subsequent data from full-scale treatment cells with primarily emergent vegetation indicated an average net settling rate of 11.4 m/year as compared with the STADM calibrated value of 10.2 m/year (Walker and Kadlec, 2005). Average net settling rates computed for entire STAs with both emergent and submerged vegetation operated in design ranges have ranged from ~10 to ~25 m/year.

Everglades Phosphorus Model (EPGM)

The Everglades Phosphorus Gradient Model (EPGM) (Walker and Kadlec, 1996; Kadlec and Walker, 1999) keeps track of P accumulation in soils along a marsh transect downstream of an inflow with elevated P concentrations. While not required for STA design, predictions of soil P variations in the marsh are useful because some ecosystem components are driven more by soil P content (cattails, other rooted vegetation) than by water column concentration (periphyton, algae, invertebrates). There is substantially greater uncertainty associated with modeling the soil P compartment, as compared with modeling the water column. This uncertainty reflects inherent complexities of soil interactions with vegetation and water column, as well as limitations in soils data related to sampling artifacts and high spatial variability (Cohen et al., 2009; Grunwald et al., 2004). EPGM provides the simplest representation of the soil P compartment consistent with the data available for calibration.

The water column component of EPGM is identical to the STA design model. Both assume sheetflow hydraulics and are calibrated to data primarily from WCA-2A. Vertical mixing within the soil profile is assumed to be minimal. This assumption is supported by substantial vertical and longitudinal gradients in soil P content observed in the WCA-2A soil cores used for calibrating the STADM (Kadlec and Walker, 1999). The accumulation of soil mass in EPGM is driven by a correlation between soil mass accretion rate and soil P accretion rate calibrated to dated soil cores in WCA-2A and tested against limited data from other WCAs. This correlation determines a relationship between the average P content of accreting peat and the average P concentration in the water column (Kadlec and Walker, 1999). EPGM calibration to WCA-2A indicates that soil accretion rates vary from 0.1 to 1.0 kg/m^2/year and the P content of accreting peat varies from 500 to 1400 mg/kg as the average water column P varies from 5 to 100 μg L^{-1}.

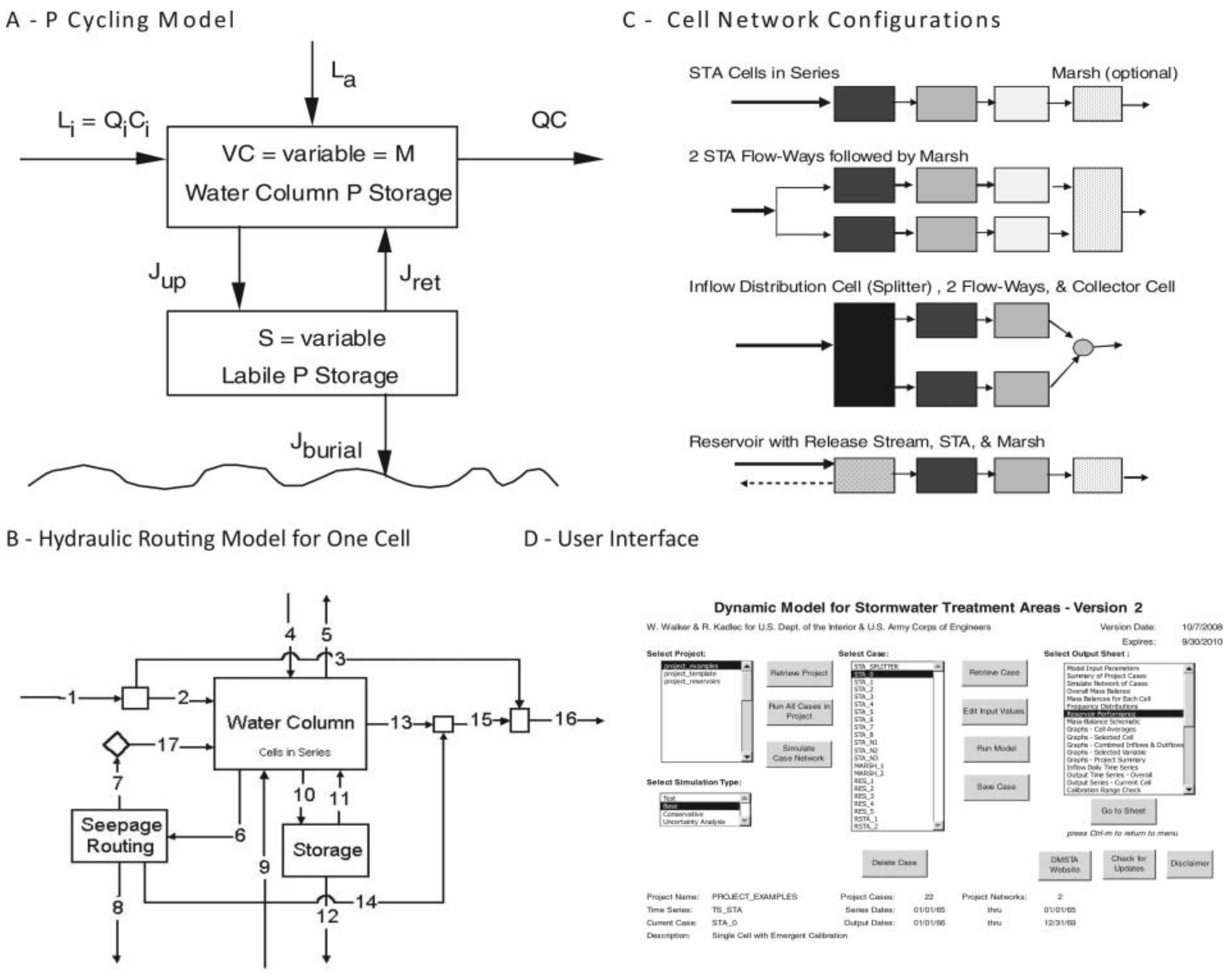
EPGM has been applied to evaluate the potential impacts of distributing STA outflows with a P concentration of 50 μg L^{-1} into previously unimpacted marsh areas along the northern edge of the WCAs (Walker and Kadlec, 1996). Impacts are expressed in terms of marsh areas exceeding water column and soil P criteria as a function of time as the soil P gradient (Figure 1) develops downstream of the STA outflows. Cattail densities are also predicted based on an empirical correlation with soil P contents. The development of steady state soil P profiles requires one or more decades, depending on the inflow concentration, initial soil P content, depth of soil being tracked, and marsh hydroperiod. Once the soil P profile is fully developed, the EPGM calibration to WCA-2A indicates that marsh areas with water column P concentrations exceeding 10 μg L^{-1} correspond to areas with steady-state soil P contents exceeding ~650 mg/kg.

Dynamic Model for Stormwater Treatment Areas

The Dynamic Model for Stormwater Treatment Areas (DMSTA; Kadlec, 2006; Walker and Kadlec, 2001, 2005) was developed to support design of STAs to achieve outflow TP concentrations approaching the 10 μg L^{-1} criterion. Achieving low P levels requires designing an STA to operate within limited ranges of inflow P concentrations and loads, as well as optimizing vegetation types, water depths, and hydraulics to treat highly pulsed basin runoff. Considering these factors required a dynamic model with an additional P storage compartment to represent labile phosphorus stored in vegetation and litter (Figure 4). This compartment regulates P uptake, recycling, and generation of stable P residuals stored in accreting peat. The initial structure and equations were similar to the autobiotic wetland P model described by Kadlec (1997). Those equations have been refined and calibrated to various emergent and submerged vegetation types (described subsequently) based on data from South Florida wetlands and treatment areas.

Whereas the STA design model assumed simple sheetflow hydraulics downstream of the inflows, DMSTA allows simulation of full STA designs involving multiple treatment cells in a series or parallel with seepage, bypass constraints based on water depth or pump capacity, and outlet hydraulic controls (SFWMD, 2009b). Design optimization generally involves specification of cell areas, configurations, depth regimes, hydraulic features, and target vegetation communities to achieve treatment objectives in a cost-effective manner. The model also has a capability for simulating regional networks of STAs and reservoirs, driven by 35-year daily flow time series generated by SFWMD's regional hydrologic models (SFWMD, 2005). Marsh responses downstream of the STAs can also be simulated using the appropriate calibrations. The spreadsheet interface and limited input data requirements facilitate development and comparison of alternative STA designs (Figure 4)

The first version of DMSTA (Walker and Kadlec, 2001) was calibrated to phosphorus balance data from approximately 70 treatment cells and wetlands ranging in size from 10^{-1} to 10^{7} m^2. Most of the treatment cell data sets were from experimental tanks and small-scale test cells with different vegetation types operated with constant inflows and water depths over periods of one to three years. Data from a treatment wetland (Boney Marsh) and a full-scale test facility (Everglades Nutrient Removal Project; Chimney and Goforth, 2006) provided the primary bases for calibration. Calibrations were developed for periphyton, emergent vegetation, and submerged vegetation based on data



Version Date: 10/7/2008
Expires: 9/30/2010

Project Name: PROJECT_EXAMPLES
Time Series: TS_STA
Current Case: STA_0
Description: Single Cell with Emergent Calibration
Project Cases: 22
Series Dates: 01/01/65 thru 01/01/65
Output Dates: 01/01/66 thru 12/31/69
Project Networks: 2

FIGURE 4. Components of DMSTA.

from the largest prototype in each category. A fourth category represented a transition from submerged vegetation to periphyton over a decreasing P gradient. Data from the smaller experimental platforms were used for testing calibrations in each vegetation category. This version of DMSTA was used in initial feasibility studies for enhanced STA designs (Brown and Caldwell, 2002; Burns and McDonnell, 2002).

With operation and intensive monitoring of the STAs by SFWMD, substantially more data from full-scale treatment cells and wetlands with dynamic inflows and water depths were available to support development of the second version of DMSTA (Walker and Kadlec, 2005). This most recent version includes calibrations for four wetland types (emergent, submerged, periphyton, and mixed vegetation on natural wetland soils), as well as a calibration for open-water reservoirs. The reservoir calibration is based on data from shallow lakes in Florida (Burns and McDonnell, 2004) and developed to support evaluation regional plans involving networks of STAs and storage reservoirs planned for hydrologic restoration purposes (U.S. Army Corps of Engineers, 2009).

Steady-state solutions of DMSTA's P cycling equations are mathematically equivalent to the K/C* model (Kadlec, 1994), which is similar to the STA Design Model (Figure 3). Calibrated settling rates are 13–22 m/year for emergent vegetation, 43–64 m/year for submerged vegetation, 18–31 μg L^{-1} for periphyton, 27–46 m/year for mixed vegetation on natural wetland soils, and 3–9 m/year for reservoirs. Each calibration is applicable under specific ranges of depth, velocity, and concentration, as determined by the calibration datasets. DMSTA is applicable to treatment cells that have reached a stable operational phase, a process that typically requires 1–3 years after construction to allow time for the establishment of vegetation and associated P cycles, depending on antecedent soils, water depths, and vegetation.

The second version of DMSTA has been applied in several feasibility and design studies providing treatment of additional flows and P loads from the source basins as well as the integration of STAs and storage reservoirs south and north of Lake Okeechobee (ADA Engineering, 2005; Black and Veatch, 2006; Brown and Caldwell, 2002, 2005, 2007; Burns and McDonnell, 2002, 2003; Camp, Dresser, McKee, 2007; HDR, 2006; Tetra Tech, 2008; URS, 2005). While developed primarily for use in STA design and optimization, DMSTA can also be used as a diagnostic tool to facilitate interpretation of real-time monitoring data from the STAs. Variations in measured STA outflow concentrations reflect variations in inflow volumes, inflow P loads, water depths, climate, management, P cycling within wetland communities, measurement errors, and other random factors. It is difficult to evaluate the inherent P removal performance of the STA wetland community in the context of data variations induced by the other factors. DMSTA factors out the effects of hydrologic variations and STA operations that distribute inflows across cells and regulate water depths. This filtering provides a clearer signal of vegetation function and long-term performance relative to design simulations and management expectations.

With continued operation and monitoring of the STAs, the database to support further refinement of DMSTA expanded more than three fold between 2005 and 2009, measured in terms of cell years. Future versions will provide updated calibrations and additional features useful for design and diagnostic applications.

Coupled DMSTA and EPGM

A fourth model under development links DMSTA and EPGM to simulate three aggregated P storage compartments (water column, vegetation, and soil; Figure 3). In the initial version, the structures and calibrations of the DMSTA and EPGM components are unchanged. The soil P compartment is driven by the predicted net accretion from the vegetation P storage compartment of DMSTA. The accretion rates are time-variable, as compared with the original EPGM driven by the steady-state water column concentration profile generated by the STADM.

The long-term decreasing trends in WCA inflow and outflow concentrations (Figure 2) suggest that water column P concentrations respond relatively rapidly to reductions in inflow P, despite the substantial of amounts of P stored in the soils of impacted marsh areas, the release of which would delay the water column response. DMSTA testing results also indicate that explicit simulation of the soil P compartment is not necessary for predicting water column P variations in the natural marsh or in treatment cell outflows in response to trends in the inflow volumes or concentrations once STA vegetation (DMSTA P storage pool) is stabilized. Further testing against data in lower P ranges will be possible as STA performance improves and the marsh responds to decreasing P loads. Effects of soil P storage and exchanges with the water column and vegetation are essentially embedded in DMSTA calibrations. Despite greater uncertainty, explicit predictions of soil P are potentially useful for forecasting the spatial and temporal scales associated with restoration of rooted vegetation and other ecosystem components that may respond more to soil P variations than to water column P variations.

The existing calibrations of DMSTA and EPGM provide a basis for estimating the time scales required for P stored in each compartment to equilibrate following a change in the long-term average water column P concentration (Figure 5). These scales depend on the ratio of stored phosphorus to the average input P flux to each compartment computed from a steady-state solution of the P cycling model. Equilibration of storage compartments to an ambient P concentration of 10 μg L^{-1} involves time scales ranging from ~1 to 3 years for the vegetation P storage compartment, ~10 years for the 0–2 cm soil horizon, and ~50 years for the 0–10 cm soil horizon. Response times

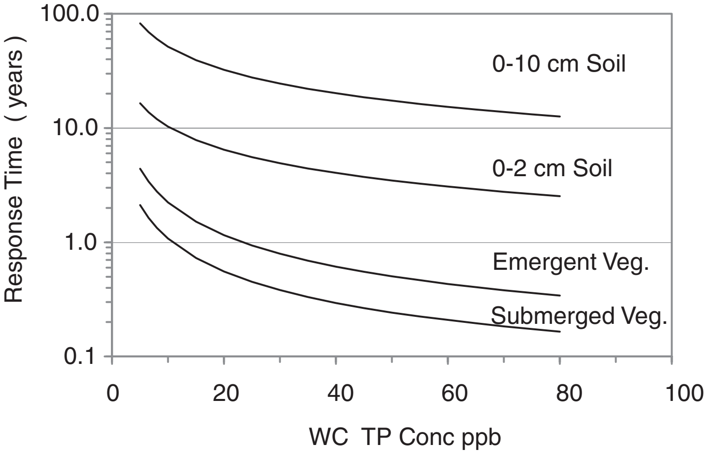


FIGURE 5. Time scales of phosphorus storage in wetland soils and vegetation. Represent approximate time required for P storage compartments to adjust to a change in the long-term average water column P concentration. Computed from EPGM and DMSTA calibrations.

are shorter at higher P concentrations because of increases in the P cycling and soil accretion rates.

The temporal and spatial scales of marsh response to increasing or decreasing P loads are further illustrated in Figure 6. The preliminary model has been applied to simulate variations in P concentration and storage along the WCA-2A marsh transect in response to variations in inflow volume and P load over a 100 year period. The 1963–1995 period represents historical conditions when the marsh P gradient developed in response to increases in P load starting in the 1960s. P loads gradually decreased between 1995 and 2007 with implementation of upstream P controls and flow diversions. A hypothetical reduction of inflow concentration to a long-term flow-weighted mean of 12 μg L^{-1} (approximately equivalent to a geometric mean of 10 μg L^{-1}) is imposed in 2008–2062 simulation period. Year-to-year variations in inflow volume and concentration around 12 μg L^{-1} have been estimated from variations in the historical time series. Soil P content in 1963 is initialized at 400 mg/kg based on vertical soil P profiles in WCA-2A. Marsh response is expressed as areas exceeding various water column P and soil P criteria in each compartment. As expected based on the steady-state analysis (Figure 5), labile P storage in vegetation responds within a few years to the reduction in inflow concentration, whereas the soil compartments respond over several decades.

Processes not directly reflected in the existing model, such as soil P recycling induced by peat oxidation or mining of soil phosphorus by rooted vegetation, may decrease response times for P stored in the soil but increase the time scales for P stored in the vegetation and water column. One

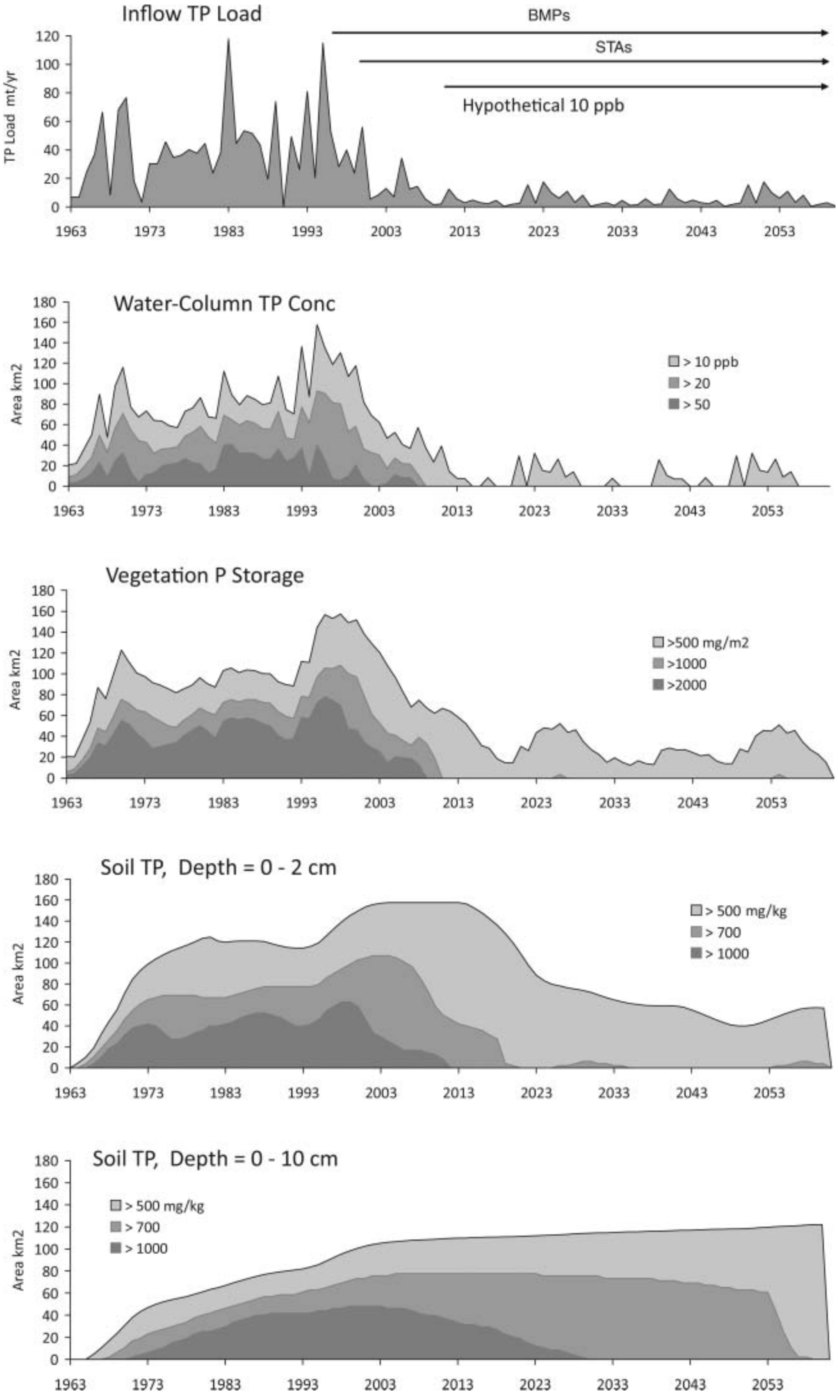


FIGURE 6. Simulation of WCA-2A response to reductions in inflow P concentration using the coupled EPGM/DMSTA models.

limitation of the EPGM component is that it was calibrated to soil cores collected in 1990–1991 and reflected marsh response to an increase in P load over the 1963–1990 period, when inflow P loads were generally increasing. Substantial data collected since then provide a basis for refining the structure and calibration in the coupled EPGM/DMSTA model. Recent data also provide a basis for testing the model in a recovery mode as the WCA2A marsh responds to further decreases in inflow P load. Data from soil and water column transects in other WCAs are also available to support further refinements (SFWMD, 2009b).

FUTURE APPLICATIONS TO EVERGLADES RESTORATION

Restoring the Everglades will require delivery of water with sufficient volume, timing, and quality to achieve hydrologic and water quality objectives. Implementation of hydrologic restoration measures will alter the quantities and timing of marsh inflows (U.S. Army Corps of Engineers, 2009). Changes in timing could have positive or negative impacts on STA performance, depending on how they affect peak inflow volumes and P loads. DMSTA can play continued roles in engineering solutions to achieve both hydrologic and water quality goals. These solutions are likely to involve combinations of the following measures:

1. Additional BMPs to further reduce runoff P concentrations
2. Diversions to balance flows and P loads across STAs
3. Integration of storage reservoirs to attenuate peak inflows to the STAs
4. Further optimization of the hydraulics, vegetation, and operation of existing STAs
5. Additional STA expansion

Further refinement of the modeling tools will be possible with continued research and monitoring conducted under Florida's Long-Term Plan (Burns and McDonnell, 2003; SFWMD, 2009b).

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