Everglades Landscape Model (ELM), Version 2.5

Peer Review Panel Report

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EXECUTIVE SUMMARY

Introduction

The Everglades Landscape Model (ELM) is a site-specific regional-scale ecological assessment model developed to understand landscape responses to different water and nutrient management scenarios. It is designed specifically for south Florida and is one of many mathematical models that are used by the South Florida Water Management District (SFWMD) to predict and assess the response of the hydrology, water quality, and ecology of south Florida to their management activities.

The over-arching goal of the model, as described in the statement of work (SOW) for our review panel, was to "develop a simulation modeling tool for integrating ecological assessment of water management scenarios for Everglades restoration."

The niche of this current edition of the model (ELM, Version 2.5) is narrower than its ultimate goals and is one on which this committee agreed to focus most of its attention. This niche (Fitz and Trimble, 2006) is described as follows: "compare alternative management scenarios, predicting relative differences in ecological (water quality) variables from a long-term regional perspective:

- concentrations of total phosphorus (TP) in surface water
- net loading (accumulation) of TP in the ecosystem."

The Performance Measures described in our SOW are consistent with the niche:

- total phosphorus concentration gradients in marsh surface water; and
- total phosphorus net accumulation gradients in the marsh ecosystems.

Most of this review is focused on this niche.

Conclusions

We do not see any fundamental flaws in the ELM itself. There are areas of the process and form representation that will continue to improve as more site information becomes available. Uncertainties in the model are due as much to uncertainties in external forcing functions as to flaws in the model that require repair or revision.

The current model version (ELM v2.5) is robust and will produce a unique contribution, with an integrated ecosystem paradigm, to understand and predict potential outcomes of Everglades restoration projects BEFORE they are etched in stone. However, no model, including ELM, should be used by itself. To help inform management decisions, ELM results must be used as part of the overall weight-of-evidence, along with best professional judgment and ongoing empirical and modeling analysis and interpretation. It should also be understood that the ELM, once it is validated, will not be a finished product but will be continually updated and refined.

We also suggest to SFWMD that the modeling methodology itself is the message. There is a need to be aggressive in continuing to develop the ELM, but also to run it, for one major reason: to determine where the data limitations are and how to design monitoring in the Everglades to address these limitations. We think the model itself may be the primary method that SFWMD should use to guide any changes in monitoring plans in the future, not just for the ELM itself, but to monitor progress in restoring the Everglades. The current model gives results that are very important for guiding the restoration of the Everglades even when it is, of course, not a perfect model. No such perfect model exists in any science or engineering field.

Overall bias in TP concentration computed in the water column appears small. The bias could probably be removed by adjusting atmospheric loads and boundary fluxes within their ranges of uncertainty. The bias may also be affected by improved initial conditions, especially in the soil.

Computed TP concentrations in the water column and in porewater are sensitive to initial conditions. The time scale for phosphorus in the two water fractions to equilibrate with the soil is comparable to the duration of 20-year model runs. Initial TP concentrations in the water fractions do not appear to be in equilibrium with the soil; this may require a spin-up period. Due to inter-connectivity between basins, it is feasible for initial conditions specified in one basin to affect apparent phosphorus accumulation in a downstream basin (i.e. phosphorus leaching from the soil in an upstream basin can accumulate in a downstream basin). It is difficult to judge whether computed trends, if any, result from external forcing (e.g. loads) or are produced by the tendency for the model to equilibrate with initial conditions.

Recommendations

Essential recommendations

- Great care should be devoted to the specification of initial conditions and to examination of their effect on model results. If various model components (phosphorus in surface and porewater) are not equilibrated with initial conditions, we recommend an equilibration procedure as part of model initialization. It is difficult to judge the extent to which accumulation rates and gradients that are key to this endeavor are affected by initial conditions. Modelers should conduct several sensitivity runs, employing a realistic range of initial conditions, to examine the effect of initial conditions on accumulation rates and gradients.

- Behavior of the Everglades itself and ELM are highly non-linear and sometimes non-intuitive so that behavior of the model must be diagnosed, documented, and thoroughly understood. This does not necessarily reflect a flaw in the model but the complexity of Everglades ecosystem. For example, perturbation runs indicate that phosphorus accumulation in several basins responds non-linearly to changes in loads. The non-linear behavior is most often evident as a proportional increase in accumulation that exceeds the proportional increase in loading. Less often, a proportional decrease in accumulation is less than a proportional decrease in loading. An explanation of this behavior needs to be added to the model documentation.

- The SFWMD should continue to invest in the development and application of the ELM. There needs to be the addition of ecosystem modelers at SFWMD, with key cross appointments to accelerated recovery projects, hydrologic modification projects and the development of the SFWMD Regional Simulation Model (RSM).

- Model evaluation is best done with aggregated seasonal response variables due to limited data available for surface water concentrations in many parts of the Everglades. In addition to temporal aggregation, one possibility for comparison of spatial gradients would be to aggregate spatial information to some form of a basin exterior, or boundary region, and internal regions.

- Use the ELM to specify or prioritize sampling sites and variables to optimize testing and diagnostics. Continued use of additional key variables to diagnose model performance in addition to the present two Performance Measures is especially encouraged.

Useful recommendations

- Improve TP concentration boundary conditions. There should be a better way to approximate these observations than interpolation between data points. Explore statistical or other relations between phosphorus and chloride concentrations, and flow, depth, season, or other independent variates.

- Collect phosphorus accumulation data and validate the model in areas other than Water Conservation Area 2A (WCA-2A).

- Atmospheric loadings should be separated into wet and dry components, and incorporation of spatial variability should be attempted. Collection of data to support these actions should be initiated.

- Wetland modeling literature outside of papers published on ELM itself should be evaluated and referenced for appropriate algorithms. Currently the citations in the project documentation suggest a lack of knowledge of other wetland modeling peer-reviewed literature outside of ELM itself.

- The habitat division given in the model description should be simplified to a suite that can be simulated effectively. The lumping of habitat systems is a suggested direction for future model development to address and predict effects for the Comprehensive Everglades Restoration Plan (CERP).

- The downstream tidal boundary condition (monthly average of astronomical tides) should be improved for two reasons. The first is to improve ELM accuracy in the southern Everglades. The second is to make the model useful for Florida Bay studies.

- Use the model to assess the effectiveness and spatial variability of phosphorus retention and spatial patterns in the STA (stormwater treatment area) wetlands that are being constructed to protect downstream Everglades. These simulations would provide a rigorous validation of the model in completely different phosphorus conditions than the ambient concentrations in much of the Everglades proper. These simulations would also occur in data-rich wetlands.

- Model statistics such as bias and root-mean-square (RMS) error should be compared with other ecosystem models, in the Everglades and elsewhere. Statistics for each ELM version should be documented to see if the model is improving.

- A formalized uncertainty analysis should be developed that will place model predictions within a probabilistic framework that can be combined with other indicators of appropriate restoration scenarios. Using the results of the parameter sensitivity study, multiple realizations of a limited number of the most sensitive and uncertain parameters can be carried out to create a probability space of key model results of water column TP concentration and accumulation (e.g., Generalized Linear Unbiased Estimator (GLUE) methodology, Beven and Freer (2001), Gupta et al. (2006), or other approaches).

- Evaluate the source of positive bias in TP concentrations under high TP values near canals. It would be useful to use modeled and observed concentration-discharge or concentration-depth relationships in these regions to better evaluate these potential biases.

- In addition to the arithmetically averaged TP concentrations, volume (or depth) weighted averages for wet and dry periods should be used to better compare TP water column mass during these times.

MODEL SUMMARY

Goals and niche

The Everglades Landscape Model (ELM) is a site-specific regional-scale ecological assessment model developed to understand landscape responses to different water and nutrient management scenarios. It is designed specifically for south Florida and is one of many mathematical models that are used by SFWMD to predict and assess the response of the hydrology, water quality, and ecology of south Florida to their management activities.

The over-arching goal of the model, as described in the SOW for our review panel, was to "develop a simulation modeling tool for integrating ecological assessment of water management scenarios for Everglades restoration." Under that goal, more specific objectives include integrating hydrology, biology, and nutrient cycling, synthesizing hydro-ecological processes at scales appropriate for regional assessment, <u>understanding and predicting responses of landscape to different water and nutrient management conditions,</u> and providing a conceptual framework for collaborative field research. The underlined objective is the one most closely connected to the niche described for this review.

The niche of this current version of the model (ELM v. 2.5) is narrower than its ultimate goals. This niche (Fitz and Trimble, 2006) is described by a Specific Objective to "compare alternative management scenarios, predicting relative differences in ecological (water quality) variables from a long-term regional perspective:

- concentrations of TP in surface water
- net loading (accumulation) of TP in the ecosystem."

The Performance Measures described in our SOW are consistent with this niche:

- total phosphorus concentration gradients in marsh surface water: and,
- total phosphorus net accumulation gradients in the marsh ecosystems.

These were to be determined on an annual time basis along multiple-kilometer spatial gradients.

The ELM is one of a family of regional ecosystem models implemented in a simulation framework developed by Robert Costanza and his colleagues. The Landscape Models are implemented and parameterized for specific regions including the Everglades, Patuxent, Gwynns Falls, and Baltimore (Costanza and Voinov, 2003, Fitz et al., 2003, Voinov et al., 2003). They are designed to integrate and link a comprehensive set of short- to long-term ecosystem, hydrologic and anthropogenic processes and factors into a systems level approach to simulate distributed landscape material fluxes and stores over dynamic landscapes. Time scales of interest may range from daily to decadal, while spatial scales typically range from 10^2 to 10^4 km^2. Given the range of spatial and temporal scales of interest, the level of process detail is driven by a balance and tradeoff of simplifying process representation while retaining sufficient dynamics to enable key feedbacks and linkage with multiple subsystems for long-term modeling**.**

While computational burden is no longer a major barrier given current hardware and software capabilities, process detail is still constrained by available data, uncertainty in current and future boundary forcing functions and conditions, as well as an incomplete and evolving understanding of certain physical, chemical and biological processes. The ELM is therefore not meant to be a first-principles model or at the level of detail appropriate to more data rich and less complex and heterogeneous environments, but is targeted to a level sufficient to address long term change in the Everglades ecosystem as a response to alternative management scenarios.

Model conceptual framework

The conceptual process basis of the ELM is evaluated relative to the "model niche" of understanding and predicting spatial and temporal gradients in water column TP concentrations and long-term ecosystem TP accumulation. The ELM framework represents a local, patch model of ecosystem dynamics within a lateral flow network. The patch level General Ecosystem Model (GEM) integrates soil-plant-atmosphere exchanges and transformations of water, carbon and nutrients (nitrogen and phosphorus) with ecological processes representing growth, aggradation, and mortality of vegetation (algae, macrophytes, trees etc.). The unit ecological (patch) model acts as a basic control volume generalized and implemented to all terrestrial/aquatic ecosystem types within the spatial domain as grid elements which are, in turn, linked by lateral hydrologic flow.

General Ecosystem Model (GEM)

The GEM represents one dimensional (vertical) flux, and stores and transformations of material and energy at the grid cell level. It includes simplified ecosystem primary production which is computed by modifying species-specific maximum rates by limiting factors (e.g. nutrient availability, soil moisture, temperature) multipliers. While there is no detailed canopy radiation term driven by photosynthetically active radiation (PAR) to set a maximum primary production rate, photosynthate is simply partitioned into photosynthetic and non-photosynthetic stores, and respiration costs are proportional to the two biomass pools.

Limited and simplified speciation of TP is incorporated, with speciation handled only implicitly using fixed ratios for different habitats. Adsorption/desorption are necessarily simplified as multiple phosphorus species are not represented. TP sinks in the water column include settling, controlled by a settling velocity, periphyton uptake, and diffusive loss. At present there is no explicit transport capacity term, and the model does not presently allow scour or enhanced deposition as flow conditions change. No sediment transport is currently incorporated, although the model may require these terms for long term deposition/resuspension of material that will be critical in developing spatial patterns of TP accumulation especially in response to hurricanes and other extreme hydrologic events. At present, these terms are planned for incorporation, but are not yet active in the model.

In the sediment, porewater TP is added by diffusion from the water column, desorption from sediment surfaces, and mineralization from organic material. Porewater sinks of TP include adsorption to sediment, macrophyte uptake, and diffusive flux to the water column. These source and sink terms can act at very different time scales, with slow decomposition and mineralization of organic matter imparting long memory behavior to the porewater and water column TP, which can have significant impacts on canopy growth and biogeochemical cycling for decadal-long restoration dynamics. This can be seen in the long term simulations carried out with varying substrate initial conditions, discussed at greater length below.

Ecological characteristics of different communities are represented by the specification of discrete habitats. Habitat sets a series of species or life form-specific model parameters controlling biogeochemical processes, growth and mortality. With the exception of periphyton, the habitats are single species without explicit competition. Succession is currently handled by "phase shifts" between dominant habitats based on levels and persistence of water depth and TP water column concentration. Depending on the number of habitats adapted and operational within the model, these phase shifts may appear to be more abrupt or gradual rates of ecosystem change. Feedbacks to biogeochemical and hydrological processes following habitat shifts or significant growth and aggradation of above ground biomass can result in significant, long term modification of water, carbon and nutrient budgets. This aspect of the model provides an important extension over most traditional water quality models.

Lateral flux

The GEM is implemented as a field of grid elements linked by lateral flux processes within a distributed hydrologic model. The raster framework provides a gradient driven flow field with a fully explicit numerical solution scheme based on forward/backward differences. Hydrologic lateral flow is implemented as uniform sheet flow over the grid cell domain. Channel flow in the drainage infrastructure of canals is implemented as a separate, but linked, vector representation. A simplified water flow model is driven by the Manning Equation (coupled to a continuity equation) using the water level depth, energy gradient and roughness, which is estimated on the basis of land cover and canopy standing biomass. The surface water flow equations assume uniform sheet flow within grid cells, do not use a momentum term or wind driven flow, and do not consider within-grid cell variation of depth, gradient or roughness. While the model has a fixed grid cell resolution within a flow field, the resolution can be varied within independent basins and between runs to investigate the impact of resolution and heterogeneity.

Transport in the surface water scheme is purely advective, without solution of a dispersion term. The surface water equation set is solved with a fully explicit scheme, and some care is taken to evaluate the effects of numerical dispersion in the transport scheme. An "anti-dispersion" algorithm is used to adjust advective flows to reproduce the approximate effect of both advective and dispersive processes as indicated by limited tracer dispersion studies, but also to control numerical dispersion. This is discussed in greater detail below. Groundwater is solved with a simple 2-dimensional Darcy groundwater flux scheme, based on an explicit numerical method and with a simplified representation of the aquifer system.

Spatial data model/representation of the Everglades landscape

The coupling of the local ecosystem and lateral hydrologic exchange models are implemented within the Spatial Modeling Environment (SME) which provides a formal spatial data model and tools for development, linkage, operation and testing of complex ecosystem dynamics (Maxwell et al., 2003). The SME is structured to allow comprehensive linkage with additional subsystem models, as well as a degree of flexibility in the level of process detail and choice in the level of coupling and complexity of internal processes and feedbacks through the use of run time selection and compilation of specific algorithms.

The SME is based on a generalized, grid based data model that allows an interface to linear flow elements (canals in the ELM). The grid representation of land elements currently enforces a single habitat per grid cell. While the SME facilitates recasting of the full domain at different resolutions, within a grid cell there is no direct mixing or competition between multiple life forms (with the exception of periphyton). There is also no representation of subgrid scale heterogeneity.

Vector representation of linear water infrastructure (e.g. canals, levees) is combined with a uniform grid representation of the marsh landscape. This scheme involves a mixed spatial topology, requiring methods to embed one-dimensional flow elements within two-dimensional flow fields. Canals are segmented with control structures forming terminal (upstream and downstream) nodes, but also allowing a ”pseudo-segmentation” of long canals to minimize numerical dispersion in the canal transport.

An important feature of the SME is the uniform grid cell size within a flow field; there currently is no capability to modify grid cell resolution in the neighborhood of the linear flow or flow barrier elements. The higher flows of water and solutes from a canal to the marsh are immediately distributed through the full neighboring grid cell area. Integration of raster-vector representations requires a specification of which adjacent grid cells exchange water and constituents (e.g. nutrients, salt, tracers) between the linear canal flow and two-dimensional marsh sheet flow field. This is determined at the model initialization by the geometry of the vector element crossing the grid cells. Actual flows (direction and magnitude) between these boundary grid cells and linear elements are controlled by Manning or Darcy flux terms that iteratively adjust canal and grid water levels.

Appropriate level of complexity/integration in the model implementation

The appropriateness of the grain of process representation is constrained by the “model niche” that is outlined for this project. This has been specified as an evaluation of model ability to predict long term (decadal) performance of different restoration scenarios based on the two key criteria of spatial gradients in water column TP concentration, and TP net accumulation in the substrate. While these key criteria appear to be very specific, they are the result of a set of short- and long-term processes and feedbacks that may be sensitive to initial conditions, and are subject to dominant atmospheric and lateral boundary conditions. In addition to potentially large uncertainty in optimal model parameter values, there still remains a significant degree of uncertainty regarding actual mechanisms as well as boundary conditions. These include the representation of nutrient cycling processes, the transport of sediment, organic material and nutrients, the magnitude and patterns of atmospheric deposition, and the spatial/temporal distribution of lateral water and nutrient boundary flux.

Under these conditions, emphasis is placed on the balance between representing key short-term feedbacks and dynamics, as well as those processes responsible for longer term “memory” in the system, such as ecological community growth and succession, and substrate organic material biogeochemical cycling. The ability of the model to use simplified process dynamics to capture observed multivariate patterns represents internal consistency, and boosts confidence that consistent prediction of the performance measures is due to adequate representation of key processes and feedbacks, rather than a specific parameter calibration procedure. In addition to the water column TP concentrations and net accumulation rates, additional patterns used by the model developers include marsh water stage, conservative tracer concentrations, and observed expansion of cattail communities. At the same time, evaluation of model performance using a richer dataset will allow better diagnostics and identification of both key parameters as well as necessary adjustments of the model structural (equation set and spatial data model) elements. As new measurements of water velocity, sediment and organic material transport and biomass aggradation are made available, the model can either incorporate these measurements for use in calibration and validation in its current state, or additional process modules (e.g. sediment, organic matter transport) can be developed to test the consistency of modeled vs. observed ecosystem interactions. The comprehensiveness of the model treatment of integrated ecosystem function and form allows an evaluation of both the ability of the model to reproduce internal ecosystem dynamics, and the appropriate level of detail required.

Previous reviews

This section is based on the October 15, 2002, document “Everglades Landscape Model - Agency/Public Review of ELM v. 2.1a,” (Fitz et al., 2002). The document summarizes review comments from eight individuals in six government agencies and incorporates detailed responses. Complete, original review comments are provided as an appendix. Comments were solicited under six headings:

- Questions
- Concerns
- Model Limitations
- Use of the Model
- Critical Recommendations
- Non-Critical Recommendations

The range of reviewers’ opinions was wide, with one reviewer describing ELM as an “indispensable tool” while another opined “ELM is in no condition to be trusted.” The majority of opinions were between these two extremes. The comments were more favorable than unfavorable although each reviewer expressed concerns and reservations.

No point exists in listing each comment and response since these are available in the Fitz et al. (2002) report. What follows is our opinion of the most significant reviewer comments and responses from the ELM team. A few caveats are worth noting. First, this summary is based on review comments in the Fitz et al. (2002) report, not on original materials provided to the ELM v2.1a reviewers. Misinterpretations or prejudices expressed by the previous reviewers may be unintentionally propagated by this review. Second, since this summary does not follow the six original headings, responses by the ELM team are pulled from different sections of the report and may be out of context.

Simulation period

The application period for the ELM v2.1a was 1979 – 1995. Several reviewers advised the simulation be extended to include the period 1996 – 2000. Reasons for this advice included:

- The added period allows classic model validation in which the model is evaluated against an independent data set;
- The added period provides additional quantity of data and data of a kind not available in the 1979 – 1995 period; and,
- The added period includes significant alterations in the driving forces, including phosphorus load reductions.

The modelers provided some lengthy arguments as to the nature of model “validation” and whether the additional years would provide additional confidence. The most significant response, however, was that the modelers were acquiring and processing 1996-2000 data for use in the model.

Atmospheric loadings

Reviewers expressed several concerns about the magnitude and treatment of atmospheric phosphorus loading. These included:

- Atmospheric loading is modeled at a uniform level across the system but rainfall is not uniform. Consequently, the spatial distribution of atmospheric loading may not be correct; and;
- Wet and dry deposition should be modeled separately. The need to separate these can be critical in the dry season when rainfall is minimal but dry deposition may occur.

Response from the modelers indicated that an improved rainfall time series was being implemented and that available data do not support separating wet and dry deposition.

Boundary conditions

Boundary conditions are critical to the application of predictive models. The reviewers expressed concern regarding the specification and application of boundary conditions for use in scenarios. Areas of concern included:

- The model is of limited utility without the ability to accept changing boundary conditions;
- Model results are limited by field data availability and boundary conditions; and,
- Phosphorus concentration in the outflows from STAs is modeled as constant.

Response from the modelers indicated that the present model code allows for time-varying boundary conditions. Boundary conditions are based on best available data and improved data are employed as they become available. For scenarios, phosphorus concentration in STA outflows can be derived from a regression based on outflow as the independent variable.

Data availability

The data requirements for a multiple-parameter model such as the ELM can be tremendous. Arguments will always exist whether available data are sufficient to parameterize and calibrate a complex, mechanistic environmental model. These exact accusations were hurled at ELM v2.1a and responded to vigorously by the model team. One comment on data was of genuine concern since it carries through the ELM v2.5. The reviewer expressed doubt that the model could be trusted in the southern Everglades. His premise was that the marl prairies and rocky glades differ significantly from the soils in the northern system. Yet parameters for soil physics and chemistry were transferred from the northern Everglades to regions in the south.

The modelers' response indicated that both understanding and data acquisition in the southern Everglades has lagged the northern portion of the system. Recent data collected in the southern portion were being examined and algorithms specific to the south were being evaluated. In the meantime, the model demonstrated that TP concentrations in the water column of the southern Everglades were correct.

Hydrologic calibration and predictability

Correct representation of hydrology, especially overland and canal flows, is essential to the ELM. The ELM should also have predictive capability to evaluate the hydrologic response to managed alterations in South Florida hydrology. Three broad areas of the modeled hydrology attracted significant attention. The first involved validation of transport processes. According to the Executive Summary, the model "was calibrated to match observed data on water stage." Reviewers commented that calibration to depth alone was not sufficient. Validation of transport was required. This validation might take the form of calibration of the model to transport of total dissolved solids or another conservative substance.

The modelers replied that quantitative measures of transport were unavailable for the calibration period. The model would be compared to velocity measurements and tracer concentrations as data become available.

A second area of concern revolved around the transferability of hydrology from the South Florida Water Management Model (SFWMM). The crux of the issue was that flows at key structures were transferred from SFWMM while other parameters (e.g., evapotranspiration and vegetative resistance) were calculated within the ELM. Reviewers questioned whether the combination of flows specified from the SFWMM and processes independently calculated within the ELM were consistent such that flow in overland areas was correctly calculated. Reviewers also questioned whether potential changes in vegetation, computed as a result of model scenarios, could be appropriately combined with information from the SFWMM.

The modelers noted that the ELM, as applied, did not consider habitat change but did compute varying vegetative biomass. The range of computed variation in vegetation, over the calibration period, had negligible effect on flows at structures. Some discrepancies between computed and observed water stage may be attributable to vegetation effects.

The third concern centered on numerical dispersion and the relation of numerical dispersion to actual dispersion in the system. Numerical dispersion is artificial mixing introduced by the discrete numerical solution to the differential equations that describe momentum and transport. Under certain conditions, the magnitude of numerical dispersion can be large such that the solutions obtained to the transport equations are unrealistic and do not approximate true solutions. Physical dispersion was ignored in the ELM v2.1a under the implicit assumption that the effect of numerical dispersion was equivalent to physical dispersion.

The modelers responded to the reviewer comments with a series of calculations and model investigations. An initial conclusion from the calculations was that numerical dispersion at the 3,000-m model grid scale was “very high.” The model was used to investigate the effect of three grid scales (100 m, 500 m, 1000 m) on computed quantities under highly-transient conditions. Computed results were sensitive to grid scale although the relevance of this high-velocity transient simulation to conditions in the Everglades is questionable. The key response from the modelers was a comparison of the magnitude of numerical dispersion to dispersion computed from a dye study. They argued the magnitudes were similar and, since the model adequately reproduced observed spatial concentration gradients, more sophisticated treatment of dispersion was unwarranted.

Other concerns

Two other comments were of significance. The first maintained that fire has a dramatic effect on nutrient cycling in the Everglades and that no model that ignores fire (i.e. ELM) can be considered calibrated. The second comment noted that neglect of density-driven transport in the saline portions of the lower Everglades is detrimental to transport calculated in this region.

The modelers contended that the ELM was demonstrably calibrated despite the absence of fire effects. Fire would be included in a future version. The influence of density on transport could be included, in some fashion, if the need for this process could be conclusively demonstrated.

Model improvements

Documentation of the ELM v2.5 includes a chapter entitled “Model Refinement” that lists a host of improvements over ELM v2.1a. Listing of significant improvements requires, in addition, inspection of the entire report as well as consideration of the previous reviewer comments. The most significant improvements appear to be the following:

- Extension of the simulation period to the year 2000. The model simulation period now includes the years 1981 – 2000;
- Updated data base. The model-data comparisons incorporate new data from the 1996 – 2000 period as well as revised data from the earlier, previously modeled, period;

- Calculation of spatial and temporal distribution of chlorides. Calculation of this conservative tracer supplements the hydrologic calibration that was previously based exclusively on stage;
- Calculation of habitat change. The model calculates change from sawgrass to cattail habitat. Previously no habitat change was calculated; and,
- Explicit accounting of dispersion. The model now uses an “Anti-Numerical Dispersion Algorithm” and accepts specified values of physical dispersion

CURRENT REVIEW

Compatibility of data and model

In this section we address the availability of data with appropriate spatial and temporal support sufficient to test model predictions and behavior. Support refers to the spatial and temporal patterns of measurement from which area-aggregated information is generated. With specific reference to the ELM, this includes the levels of statistical uncertainty for estimating specific variables or parameters at the length and time scales used in the model.

South Florida is one of the more densely instrumented regions in the nation, although specific measurements are sparse, especially in the less accessible, interior Everglades regions. As discussed in the documentation, while the water conservation areas (WCA) are more densely instrumented and therefore better suited for formal model evaluation, they have less complex environments than the Everglades Nutrient Removal (ENR) area.

Spatial scale/support of model and field observations

The ELM implementations will use a range of grid resolutions, dependent on specific restoration projects, experiments and the extent of the spatial domains. For the full model domain, typical model resolutions are 1 km, while smaller grid cell sizes are used to evaluate the impact of heterogeneity on model behavior and to investigate more location specific processes. The measurement spatial support includes point samples of water stage and concentrations of solutes and particulates at sensors or water quality grab samples, as well as meteorological stations and water flow gauges in the canal system, the latter of which integrates over larger drainage areas. The SFWMD maintains a dense set of precipitation gauges, augmented by Next Generation Radar (NEXRAD) precipitation estimates, as well as flow measurement and control structures in the canal system. The distributions of key soil variables are aggregated to a depth of 30 cm and separately interpolated from a number of soil profiles using kriging in each major basin.

A common difficulty in comparing point sample patterns with predictions of gridded numerical models is the significantly different scales of the quantities compared. Typically, a single or small number of sensors are implicitly used to represent the mean value of the measured quantity within the model cell. The quantities measured at point sensors in south Florida include variables that may show substantial variation at short length scales, including water depth and velocity, water column TP concentration, floc depth, and soil chemistry.

Limited data are available to characterize surface water concentration and ecosystem net accumulation of TP from basin boundary to interior locations. Measurements are largely concentrated in the WCAs, requiring extrapolation of model performance from these sites to ecologically different central Everglades locations. The potential undersampling of information required for sufficient estimation of the spatial means limits the ability to support comparisons of critical gradients that are called for in the model performance criteria. Consequently, as reported in the documentation, model evaluation at the present time is best done with aggregated response variables. In addition to temporal aggregation, one possibility for comparison of spatial gradients would be to aggregate spatial information to some form of a basin exterior, or boundary region, and internal regions.

With few exceptions, largely within the WCAs, point sensors for water depth and water column TP concentrations are widely spaced, with little replication within the length scales commensurate to the model resolution. Adequate estimates of the levels of heterogeneity in the support region and the precision and accuracy of the estimation of the mean could be achieved by limited, higher resolution sampling and estimation of the block variance of key measures within the grid cell length scale in different parts of the field site. This would require specific, short-term sampling with a nested design and would significantly improve the quality of the information base for model validation. This information would improve empirical estimates of critical gradients.

Temporal support of observations

The frequency, consistency, and period of record of sampling are also critical for developing adequate estimates of temporal gradients. While water levels are recorded continuously in a number of sites, nutrient concentrations are typically sampled at low and irregular frequency. Given the potential for the flux and transformation of nutrients to be subject to the "hot spot and hot moment" phenomena recently discussed by McCain et al. (2003), the infrequent sampling of nutrient concentrations within the model domain and at the boundaries limits data of sufficient support to estimate boundary flux conditions, calibrate the model, and compare and validate model performance. We also emphasize the critical nature of maintaining these measurements at sufficient sampling frequency for sufficient record lengths to observe the response of the system to management and natural perturbations.

Sampling rates for water column TP concentrations range up to monthly or less. As with spatial analysis, temporal trends are aggregated to seasonal or annual levels, which is appropriate given the current sampling rates. If it is feasible given data availability, comparisons of responses to major events (before/after) may be carried out opportunistically, although it is recognized that the sampling and sensor system is most stressed during these times. While annual trends are specifically called for in the ELM v2.5 review, the arithmetically-averaged seasonal responses provide important information on wet/dry season variations, consistent with characteristic time scales of system dynamics. However, in addition to the arithmetically-averaged TP concentrations, volume (or depth)-weighted averages for wet and dry periods are also needed to better compare TP water column mass during these times.

Comprehensiveness of measurements

The nature of the scientific and management problem addressed here emphasizes comprehensive treatment of interacting processes and feedbacks over multiple length and time scales. The ELM contains a large number of state and flux variables as well as adjustable system parameters. One concern with models of this complexity is model identification – the ability to specify a unique and optimal model structure and parameter set that adequately fits a target validation data set. If the model is calibrated to fit only one or two time series, it may be possible to find a number of parameter combinations and, potentially, model structures, that would achieve roughly equivalent performance. A key characteristic of a successful sampling strategy to improve the identifiability of the model is the availability of information characterizing the complexity of the system within the same locations. This takes the form of a nested "place-based" sampling strategy to provide multiple system variables to diagnose model consistency, located at critical and representative sites, as a trade-off for attempting to sample with similar support and fewer variables over the full domain. By constraining a parameter optimization with a greater number of observed state and flux variables, the degrees of freedom in adjusting parameters and gaining equally "valid" model forms are reduced.

The WCAs are better sampled, but are less complex in terms of habitat heterogeneity than the Everglades. As management and restoration will be ongoing for decades, improved sampling to evaluate responses to specific restoration activities and the ability of the ELM to capture dynamics in the more complex landscape are recommended.   Given the priority that SFWMD is giving to evaluation of the ELM, the model can be used to specify or prioritize sampling sites and variables to optimize testing and diagnostics, rather than relying on whatever data is made available through separate studies. Continued use of additional, key variables to diagnose model performance in addition to the two performance criteria is especially encouraged. As stated above, these would include both fast-response and slow-response variables such as water velocity and stage, and above ground biomass. Key locations for sampling these variables may be outlined by model predictions of important gradients or transitions in the marsh landscape, as well as the boundary zones between canals and marsh.

Habitat choices

Habitats as used in the ELM are described by Fitz and Trimble (2006) as combinations of plant communities and soil/sediment characteristics. Habitats are really ecosystems in themselves, i.e., ecological communities with their abiotic environment. The challenge of including habitats in ecological models is to illustrate a dynamic landscape. Habitat types can change quickly due to eutrophication, droughts, floods, and extreme events (fire, hurricanes etc.). The landscape also changes in a progressive and predictable way that we refer to as succession or development. This contrasts with variables that most water resource modelers deal with. For example, with water quality models a state variable called total phosphorus always remains total phosphorus. With succession or introduction of high nutrients, a sawgrass community can become a *Typha* marsh.

Water and nutrients are the two primary drivers used to determine habitat in the ELM (Fitz and Trimble, 2006). This is a reasonable starting point although wetland ecosystem succession is much more complicated than that basic assumption. For example, in wetlands, the accumulation of peat, whether done in low or high nutrient conditions can lead to different ecological systems. It is not clear from the model if peat accumulation can ultimately lead to tree islands and other similar features. In many wetlands, *Typha* dominance is simply a successional sere toward more stable ecosystems. It could be that the *Typha* systems developing in the water conservation areas will become shrub or forested wetland systems over a several decadal timescale.

There are potentially 28 habitats identified in the ELM (Table 1 from Fig. 4.17 Fitz and Trimble, 2006). These "habitats" include five different sawgrass habitats and three different cattail

(*Typha*) habitats. The ELM switches from sawgrass to *Typha* and low-density to high-density *Typha* based on phosphorus concentrations and a time lag. Typically the conversion is shown as unilateral, i.e., switching from low to high nutrient conditions. But the ELM does have the possibility for eventual reversal of succession if, for example, there is sufficient flushing out of phosphorus.

Table 1. List of Possible Ecological Habitats in the ELM

Habitat Type	Number of Types	Identifiers
OPEN WATER	1	Open Water
FRESHWATER MARSHES		
Sawgrass Marsh	5	Plain, RS Pristine, Slough, RS Degraded, Marl Prairie
Cattail (*Typha*) Marsh	3	High density, med density, low density
Other Freshwater Marshes	5	Gramminoid mix, wet prairie, slough with Gramminoids, slough w/o gram., muhly grass
FORESTED FRESHWATER SWAMPS		
Hardwood swamps	3	Mixed hardwood, hardwood scrub, brush
Cypress (*Taxodium*) swamp	2	Swamp forest, savannah
Pinelands	1	Savannah
COASTAL WETLANDS		
Mangrove swamp	2	Forest, scrub
Buttonwood	2	Forest, scrub
Salt marsh	1	Salt marsh
INVASIVE		
Brazilian pepper	1	
Melaleuca	1	
Human Influence	1	

The most important habitat changes that are within the current model niche are those that involve the change of sawgrass (*Cladium*) communities to cattail (*Typha* sp.) communities. This occurs through a succession-switching algorithm that occurs based on the history of water depth and soil phosphorus. While much of the rest of the model is based on difference equations, this switching from one community to the next based on nutrients and water depths is probably the least understood and documented part of the habitat model. It will be much more difficult if and when the model is used to switch between ecological communities of dramatically different structure, i.e., macrophytes to tree islands, etc. With the so-called restoration of the Everglades as one of the major reasons for the development of the ELM, it needs to work toward these dramatic landscape shift paradigms. It is also unclear, although we were told verbally, how the model can “go backwards” i.e. how the reduction of phosphorus will eventually lead to a switch back to sawgrass from *Tyhpa*. Natural ecosystems have resilience to change and there are clearly hysteresis curves on return of ecosystems to previous conditions. But the value of having “habitat” features in the model is that, with appropriate remote sensing techniques, it provides an incredibly useful way to calibrate and validate a landscape model.

The principal habitat modules used in ELM v2.5 are macrophyte modules that are described (generic at least for sawgrass and cattail) as a combination of net primary productivity, translocation, and mortality (Section 5, Fitz and Trimble, 2006). While this is a reasonable description of macrophyte behavior, it relies on two sets of published information—a very limited number of recent studies in the Everglades and old limnological literature (see citations on p. 5-50 of Fitz and Trimble, 2006). The modeling of freshwater wetlands has advanced well beyond this capacity and it would be prudent for the model developers to be aware of wetland modeling and wetland cause-effect literature (e.g., Mitsch et al., 1988; Mitsch and Reeder, 1991; Christensen et al., 1994; Cronk and Mitsch, 1994; Fennessy et al., 1994; Ozesmi and Mitsch, 1997; Wang and Mitsch, 1998, 2000; Mitsch and Wang, 2000; Mitsch et al., 2005).

The unit macrophyte model does have a feedback to the hydrologic cycle with the density of stems/trunks affecting the Manning coefficient in the hydrology model. Simulations that show the importance of this feedback on overall model behavior of phosphorus plumes would be interesting. It is of course clear how this could effect the short term hydrologic fluxes but unclear if it is needed for the overall phosphorus accumulation questions being addressed here. Running the model with and without this feedback should be relatively simple.

Model time and space scales

Appendix A of the SOW for this review panel suggests several criteria for evaluation of model spatial and temporal scales. These include:

- How well does the model represent spatial dynamics relative to the needs of variables associated with CERP performance measures?
- Is the resolution sufficient to capture fine-scale sub-regional gradients (circa 1 km)?
- How well does the model represent temporal dynamics relative to the needs of variables associated with CERP performance measures?
- Can the model capture long-term decadal trends, annual changes, and seasonal changes?
- Can the model be applied at sub-regional scales that may provide useful information to evaluation of individual CERP projects?

Although the model is designed to be “scaleable,” the present application determines several spatial and temporal scales. The fundamental scale in the surface plane of model wetlands is determined by the grid resolution, one square km. The vertical scale in wetlands is not well-defined. Apparently the model extends from the atmospheric interface down to bedrock. A meaningful vertical scale may be that of an active soil layer, 30 cm. The saturated water surface moves up and down within this 30 cm layer. The fundamental time scale is determined by the model solution step and by boundary forcing functions. The solution step for vertical integration is one day as is the update interval for forcing functions such as boundary conditions. Shorter time steps may be used for numerical solution to transport equations in the longitudinal and lateral directions but this shorter step is a function of model numerics and does not imply meaningful simulation of transport at intervals less than a day.

Canals are one-dimensional conveyances. The significant dimension is along the axis of the canal. Spatial scale is determined by the distance between control structures and may be multiple km. Longer canal reaches are partitioned into shorter stretches through the use of "virtual structures." Segmenting through the use of virtual structures is a device employed to reduce numerical dispersion within the canal. No attempt is made to accurately model spatial variation in total phosphorus concentration in canal segments between physical control structures. Although shorter time steps may be used for numerical purposes, the appropriate time scale in the canals corresponds to the daily update of flows at control structures.

For reporting purposes and for statistical summaries, model information is aggregated up from the basic scales determined by grid size and time step. A key spatial aggregation is into 15 basins. This spatial aggregation is useful for reporting quantities such as phosphorus accumulation. Portions of the basins are split out into indicator regions, which total more than 40.

A key temporal aggregation for water column TP concentration, the quantity of primary interest in the ELM v2.5, is into seasonal (wet and dry) means. Seasonal means of observed and computed TP concentrations are then employed in various graphical and statistical summaries. This kind of averaging can result in significant bias if care is not taken. The problem originates with different numbers of computations and observations in each season. The model has one computation per day. Observations are sparse, maybe one per month. Consequently, events may be modeled that are not observed. The effects of these events are considered in the model mean but not the observed mean. Conversely, observations may coincide with an event that dominates their mean but represents a small portion of the modeled sequence. To avoid these biases, seasonal means of model computations are best computed using only days on which observations are available. Our understanding is that the modelers followed the recommended procedure and that seasonal means are based on one-to-one comparisons of observations and model computations.

The potential for the model to resolve computed quantities on a spatial scale of 1 km and a temporal scale of 1 day far exceeds the resolution required for CERP performance measures. The model scales meet requirements to discretize spatial properties and forcing functions. No claim is made that the model can be validated on these scales. For validation and reporting, appropriate spatial and temporal aggregation of computations is required. Several questions posed in the SOW regarding the ability of the model to discern spatial trends and temporal differences cannot be readily answered because sufficient information was not provided in the report. The spatial trend in total phosphorus was shown in WCA-2A only. The question can only be addressed in this region. Similarly, we did not see computations and observations aggregated and differentiated by seasons. Consequently, an opinion on the ability of the model to discern seasonal differences is difficult to form. Decadal trends should be identified in the data and compared to the model before judgment on the adequacy of the model can be passed. The questions are reasonable and they can be addressed if sufficient information is provided.

Reality check--calibration/verification/validation

Environmental models cannot fully reproduce all the complexity of natural or modified landscapes, necessitating a choice of the level and types of simplifications to be implemented. In process-based environmental modeling applications, the systems of equations representing biological, chemical, physical and (sometimes) socioeconomic processes are implicitly accepted as universally applicable, with only adjustable parameters that need to be carefully chosen for each area. The ELM represents the integration of a set of different process representations integrated over a heterogeneous landscape. Necessary simplifications of both process and environmental conditions, including background substrate biogeochemistry, atmospheric deposition and lateral boundary flux contribute to uncertainty in model predictions. Given the scale filter of the one kilometer uniform grid cells as well as process uncertainty, parameters act as effective quantities that will maximize some measure of goodness of model fit to a limited set of measurements.

As extensively discussed in the ELM documentation, validation generally assumes an accurate validation data set, independent of the calibration data set. The sparse nature of the TP data, with the exception of the WCA, may preclude adequate “validation” through the rest of the domain until more empirical information is generated. In addition to a formal validation procedure evaluating specific time series of water stage, TP and chloride concentrations, a “weight-of-evidence” approach is taken, as previously discussed, that emphasizes fit to water column TP concentrations and phosphorus net accumulation, but makes use of additional, important variables identified by the modeling team and available from field data. An additional improvement to this approach would allow the modeling team to specify variables and sampling strategies to be carried out, as indicated by the model results that would best test model behavior.

The nature of model validation is extensively discussed in the ELM documentation. It is well recognized that a “validation” procedure results in a decision as to whether the validation data set can “falsify” a model parameter set or structural equation set, but does not guarantee model performance through additional time periods well beyond the calibration and limited validation time period or outside the specific areas these were carried out. This is an important point for the ELM (or any model used for Everglades restoration planning) as its application is planned for estimating system response over decades. However, the validation exercise with an independent data set is important to build confidence in a specific model structure, while understanding that further model modification and development will be ongoing. Model structure and parameter sets should be continually improved and updated as new information becomes available.

The independent calibration and validation procedures carried out for ELM v2.2 were not completely repeated with ELM v2.5. Instead, the full 1980-2000 dataset was used to calibrate ELM v.2.5 with water and TP information, but evaluation was carried out for these variables and extended to additional variables (e.g. TP net accumulation, habitat conversion) within the same time frame. It would be very useful to test the current calibration with information recently generated by the Everglades Long-Term Ecosystem Research (LTER) Project, and additional information generated in the rest of the domain during the 2000-2005 time period. This evaluation will likely provide the modelers valuable new information for updating and extending both parameter values and model structure.

The recent publication of a greater number of observations on several important model variables in the Everglades LTER (*Hydrobiologia*, Volume 569, No. 1, October 2006) provides greater resources for testing the generality of the parameter calibration. A second special issue (*Ecological Engineering*, Volume 27, No. 4, 2006) on the ENR project could provide useful data for the model as well, especially Reddy et al. (2006).

Adjustable parameters, methods of calibration

Calibration of these parameter values involves minimizing the departure of a set of simulated variables from their measured counterparts. This can be done either in a formal and automated method or by manual adjustments guided by an experienced modeler. In the case of the ELM, manual calibration with a set of different measurements is carried out. A validation exercise would involve a similar comparison of measured and modeled information, but carried out with an independent data set (not used in the calibration exercise). As discussed above, in addition to the two performance criteria, incorporation of additional constraints in the form of key system variables should reduce the number of model forms or the range of near optimal parameter combinations.

The calibration procedure described for the current applications of the ELM follows a hierarchical approach. The model was first subject to an extensive sensitivity analysis to determine which of the adjustable parameters resulted in significant changes in model results. Once identified, the parameter values are first adjusted to fit water metrics (largely stage information as velocity measurements are extremely sparse) with the ecosystem component of the model inactive. Once the water stage distributions are optimized, the hydrologic parameters are fixed and the calibration is expanded to achieve a good fit to the TP, and finally to incorporate other ecosystem measures. This approach, while not a formal multi-parameter optimization, does aim at developing internal consistency in model form and performance. As TP measurements are sparse in some parts of the ELM domain in both space and time, the most effective calibration is carried out in the better studied WCAs with less ability to effectively calibrate the model in other areas.

It is acknowledged that there is no guarantee of the “uniqueness” of a calibrated parameter set, either within the well-studied WCAs or the more sparsely sampled areas of the model domain, but efforts are made to identify both a parameter set as well as structural equation set that consistently fits both the primary TP variables, as well as other observed variables. This could be accomplished using a set of formal calibration or uncertainty analysis methods in which the parameter sets that give acceptable results (termed “behavioral” models) are successively constrained by application to multiple observed data sets (e.g., Beven and Freer, 2001).

Goodness-of-fit measures

Statistical comparison of modeled and observed ecosystem variables were expressed with four different goodness-of-fit measures: bias, root-mean-square-error (RMS), the coefficient of determination (R^2), and the Nash-Sutcliffe Efficiency. In addition, graphical methods of model evaluation were used including stage hydrographs, plots of seasonally averaged TP concentrations, cumulative frequency distributions of stage, TP and chloride, and modeled and empirically estimated maps of these variables.

Time series of water stage, TP and chloride concentrations

Within the limits of available data, the combination of measures of goodness-of-fit and graphical plots generally show good correspondence of the major trends of surface water stage, as well as seasonally averaged TP and chloride concentrations. Median bias is low when averaged over all locations and times. However, these data are weighted towards the well-studied WCAs, and are less representative of the southern Everglades. In addition, there appears to be some evidence (discussed in the documentation) of positive bias for water column TP concentration in locations near canals which are characterized by high values. Figure 1 shows model bias in water column TP concentration over a set of different distances from a canal, and levels of measured water column TP. Figure 2 shows the same graph restricted to the first 5 km from a canal and projected along the TP and bias axes. The two graphs suggest that positive bias tends to occur at locations close to the canal and under high TP concentrations.

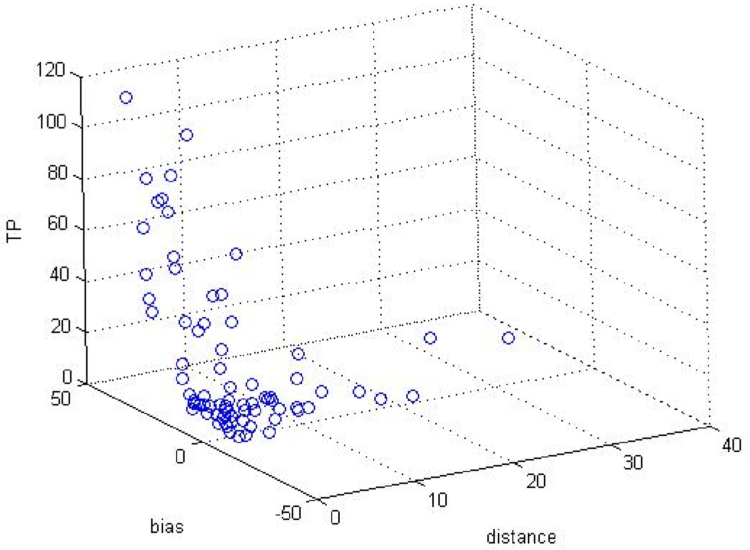

Figure 1. Plot of model bias for water column TP concentration as a function of distance from a canal and measured TP concentration. The pattern shows that bias approaches zero at greater distances from a canal, but that measurement sites close to canals with high TP concentrations tend to have a positive bias that increases with TP.

It is difficult to tell whether this is a result of boundary flux errors, problems with the vector-raster data model (canal-grid cell) interactions, or internal ecosystem or transport model problems. A similar bias is seen in the chloride data. As the chloride is conservative, it suggests that the bias may be due to either bias in boundary flux error or transport, but not in biogeochemical reactions.

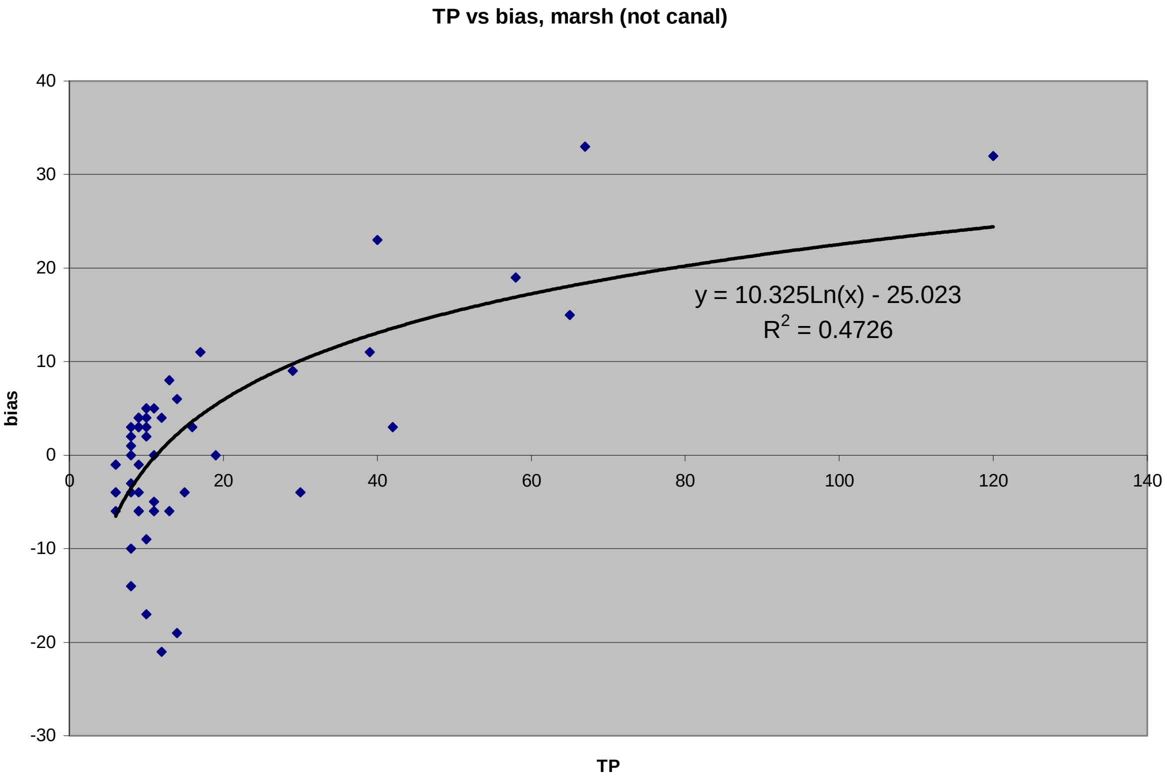

Figure 2. **Plot of model prediction bias versus water column TP concentration. This plot shows more clearly that higher bias tends to occur at high TP concentrations.**

It would be useful to express mean bias in specific locations or stations as depth-weighted biases rather than arithmetic. The interaction between water volume flux (q) or depth (d) and nutrient concentrations (c) can be quantified by the analysis of concentration-discharge (depth) relations. Similar analysis should be carried out for chloride levels for comparison of conservative element dilution. The method of vector-raster interaction used in the ELM, described above, may result in specific effects on modeled ecosystem transport and retention of TP. It is possible that the methods of determining where and how marsh cells interact with the linear canal or levee elements may advect TP too rapidly into the marsh in the immediate vicinity of the canal without sufficient retention, resulting in the positive bias. The positive bias could also be the result of errors in boundary flux of TP based on improperly specified c-q relations in the canal.

The c-q or c-d relations can be considered signatures of system behavior and are useful emergent properties to compare between modeled and observed information as a diagnostic of model performance and consistency. These analyses are recommended to evaluate the apparent bias in Figure 1, but also more generally in other parts of the model domain.

TP accumulation gradients

Graphical comparison of TP net accumulation rates indicates that simulated values appear to follow sampled trends in the steeper eutrophication gradients in the WCAs, but this information is limited. More information on system P aggradation should be generated by ecological studies within the model domain, and particularly outside of the WCAs in the southern Everglades. Simulated peat accumulation rates also appear to follow observed trends by comparison to limited transect information. Extension/densification of sampling of both TP concentrations and net accumulation beyond the WCAs should be an ongoing priority.

Weight-of-evidence with additional ecosystem gradients

Continual evaluation of model performance and behavior with the observational base should include the two performance measures, but should also include a set of key “intermediate” variables that can be defined as precursors, as well as associated variables. The documentation describes a set of additional variables that have been used for this purpose, which boosts confidence in the model structure based on the consistency of the model’s ability to capture overall system behavior, beyond the reproduction of specific time series. This is carried out as part of the hierarchical calibration procedure, and should be formally reported for the “validation” phase, while recognizing the primary nature and emphasis on the two chosen performance criteria. The method could be formalized following the GLUE methodology described by Beven and Freer (2001) and recently reviewed by Pappenberger and Beven (2006).

Spatial evolution of ecological patterns, particularly above ground biomass and succession of vegetation cover, are used as an additional model diagnostic. Although the model shift between sawgrass and cattails are not based on specific processes, but instead are mapped in response to dominant nutrient and water depth levels, comparison of sawgrass to cattail transformations in response to nutrient loading and changed hydrology provides larger scale, longer time period system dynamics and provides secondary level of evaluation.

Other emergent properties may be identified that can provide useful comparisons, in addition to standard goodness-of-fit statistics. These include responses to specific perturbations, such as hurricanes, changes in external water and nutrient loading, and other disturbances. Specific comparison of modeled and observed system behavior before and after some of the large hurricanes in the 1991-2000 time period, or extension to the major events of 2000-2005 would be useful to further evaluate model behavior.

Finally, given the constraints of the conceptual basis and the observational system, a formalized uncertainty analysis that incorporates multi-parameter, multi-criteria approaches is recommended that will place model predictions within a probabilistic framework that can be combined with other indicators of appropriate restoration scenarios. Different approaches that have become commonly available (including GLUE) within the field have recently been described by Gupta et al. (2006).

Boundary conditions/initial conditions

Initial conditions, spin-up times and system transience

Models of long-term ecohydrologic processes that simulate historical time periods require initial condition specification for some time in the past. Depending on the time domain of the simulation, this may include time periods for which little data are available. Current use of 1980 initial conditions is necessarily uncertain due to limited sampling at that time. Potential sensitivity to errors in initial conditions can be evaluated based on the transient dependence of system state to the initial conditions, and by using a perturbation, or ensemble model approach based on running multiple model realizations with perturbed initial conditions. This has been carried out in some sense by the 20- and 100-year runs, although a more formal approach to ensemble model evaluation (using a set of perturbations to the initial conditions) could be carried out.

Methods of initial condition estimation

Elevation and topographic gradients contribute to the computation of the lateral water flux, as well as the hydroperiods in different parts of the ELM domain. These values can change based on surface aggradation, but likely do not vary strongly over the simulation period. Digital elevation data were generated from a variety of different sources ranging from manual surveying to airborne lidar. While the digital terrain data were often interpolated to 30m resolution, the model is operated at 1 km with no subgrid variability and the assumption of uniform sheetflow which precludes the use of the higher resolution terrain information. The absence of subgrid variability, specifically the representation of the ridge and slough topography, introduces some uncertainty in the transport of dissolved and particulate material. The experiments carried out with 125 and 250 m resolutions that resolve ridge and slough should be further investigated to estimate the potential uncertainty and bias of the smoothed topography and uniform sheet flow.

Soils and groundwater have the longest residence times for water, organic material and nutrients. Critical soil information is derived from soil physical, chemical and biological observations. Standard kriging, using a spherical semi-variogram model, was used to generate maps of soil depth, bulk density, initial TP concentrations, organic material and other variables, based on information measured at a series of soil pits in the 1970s (for surficial soil information) and in the last decade for deeper soil information that was not thought to be significantly changed over this period. Kriging was carried out separately for each variable and in each of eight subregions that are generally delimited by levees. As the soil initial conditions have the potential to impart long memories to ecosystem processes, it would be useful to generate the expected variance from the kriging as well, and to use this information to drive ensemble initial condition perturbation runs, or to bound the expected error to place the perturbation runs described below in context.

Vegetation type is initialized from a combination of remote sensing and air photographic interpretation into a large set of classes that are then generalized into the habitats used by the ELM. Initial macrophyte biomass is estimated assuming 25-35% of habitat specific biomass, adjusted to nutrient gradients with a one year spin-up. It would be useful to know if the one year spin-up is adequate to produce macrophyte biomass initial conditions, or the degree to which long term models are sensitive to initial macrophyte biomass. Operating the spin-up for a longer period with a range of initial biomass conditions would answer this question.

Degree of system “balance” in specific initial conditions

The ELM and other models will be used to assess the effects of management-driven changes to boundary fluxes and internal circulation patterns, compared to what has evolved over the last half-century or more. This involves prediction of a potential ecosystem shift from the current state or trajectory. It would be useful to carry out sensitivity analyses on these initial conditions by perturbing key initial state variables. Results of these analyses would be useful for identifying sensitive variables that may require careful initiation.

Several of the graphics from the 100-year perturbation runs indicated a transient adjustment from initial conditions. These included macrophyte biomass, pore-water TP concentrations, and other state variables. For the results shown to us, the transient response ranged up to several decades for the soil variables. In order to gain stable estimates of current system state and trajectory, the model needs to either be initialized with a degree of balance in water, nutrient and carbon stocks approaching the actual field condition, or the model should be run for a spin-up period to achieve balanced conditions. These balanced initial conditions should be used for all management forecasts. This is necessary to avoid transient response to unbalanced initial conditions that do not reflect actual system development. Substrate (soil) biogeochemistry may have long turnover rates, requiring much longer spin-up periods to balance errors arising from initialization methods. The 20- and 100-year spin-ups can be used to assess the extent of system transience and memory to initial conditions, and the amount of time that may be necessary to begin stable simulations. The careful production of initial conditions should only be done once for each model version to create a common set of initial conditions for all management forecast scenarios.

Lateral boundary flux of water and TP

Water flux boundary conditions are taken from the SFWMM 2x2 model at all control structures, with internal boundaries between canals and marsh set by the vector/raster interaction described above. The methods of estimation of boundary TP and chloride flux from the control structures involve interpolation of concentrations from the nearest (in time and space) measurements. The frequency of measurement varied considerably between different sampling sites, ranging from frequent, automated methods to above one month. This method has the potential to introduce bias in the boundary mass flux of TP and chloride, especially during high flow events if there is any significant relation between the concentration of these constituents and flow. Concentrations during these events are interpolated from surrounding observations during lower flow, which could have biased concentrations relative to the current flow. As an example, if there are significant dilution effects during high flow, interpolated concentrations from lower flow conditions could explain the positive bias in water column TP concentrations observed near the canals at high concentrations. To evaluate this potential source of bias, c-q or c-d relations at the boundary measurement sites should be determined from available data. If there is a trend the concentration should be estimated from discharge or depth. An uncertainty analysis of these boundary fluxes could be carried out by creating multiple realizations of the concentrations based on the uncertainty of the concentration discharge or depth relationship.

Atmospheric deposition

The current atmospheric deposition of phosphorus is given as a spatially constant rate intermediate between low measured values in the Everglades interior and higher rates along the boundaries more proximal to agricultural areas. As the boundary regions already receive higher phosphorus input through agricultural drainage, it is important that the atmospheric deposition inputs follow actual gradients as these may contribute to threshold responses of TP transport, periphyton growth or habitat succession. As errors in the atmospheric deposition rates may provide significant errors to the phosphorus budgets in the oligotrophic interior regions, greater effort needs to be expended by the SFWMD to measure these rates with a well designed sampling plan. The ELM model documentation notes that a spatially variable phosphorus deposition scheme has been developed for application post-ELM v2.5. This is an important development and should be further supported with resources for additional measurements to improve estimates of this critical input.

System response times/ perturbation analysis

Inspection of the ELM v2.5 calibration alone provides minimal information to judge the suitability of the model for use as a predictive tool. At the request of the review panel, several perturbation runs were performed. These were intended to illuminate model response to altered external loading functions. The runs also provided insight into the effect of initial conditions on model results. Five system-wide perturbation runs of 20 years duration were completed. The runs were:

- Double external phosphorus loads, employ initial conditions from calibration run;
- Halve external phosphorus loads, employ initial conditions from calibration run;
- Eliminate external phosphorus loads, employ initial conditions from calibration run;
- Zero (or near zero) initial phosphorus conditions, loads from calibration run; and,
- Doubled initial phosphorus conditions, loads from calibration run.

The perturbation runs produced an enormous volume of output. Our comments are based largely on summaries provided for key basins (ENP East Buffer, WCA-3A, WCA-2A) and for one indicator region (Basin 15) selected for its demonstrative behavior. The perturbation runs were extremely valuable in illustrating model behavior. They also raised numerous questions to be addressed by the model team. Issues raised by the perturbation results included:

- The effect of initial conditions on the magnitude of TP net accumulation in individual basins was small. However, the change in accumulation rate (positive or negative) in response to alterations in initial conditions was irregular and required investigation;

- For many basins, the change in TP net accumulation rate was not proportional to the change in external loading. Several basins exhibited changes in accumulation that exceed the change in loading. This behavior required investigation; and,

- The response of pore water TP concentration to alterations in loading and initial conditions was counter-intuitive and required investigation.

Initial conditions

Inspection of the "P Accumulation Comparison, Selected Basins/Indicator Regions" (new Chapter 11 in Fitz and Trimble (2006)) provided examples of satisfactory, intuitive responses of TP net accumulation to initial conditions. Responses were generally small relative to the accumulation rate under base conditions. Several basins demonstrated behavior suggesting one or more processes in the model (e.g. the distribution of TP between soil and water) were moving towards equilibrium. When initial TP concentration was reduced, accumulation rate increased; when initial TP concentration was increased, accumulation rate decreased (e.g. Indicator Region 36). Inspection of other Indicator Regions, however, illustrated counter-intuitive behavior. In Indicator Region 15, doubling the initial conditions increased the rate of phosphorus accumulation.

Porewater TP concentration demonstrated non-linear, counter-intuitive behavior. In Basin 36, the initial porewater concentration was essentially zero under calibration and perturbation conditions. Under calibration conditions, porewater concentration accumulated 1 mg/L over 20 years. When initial conditions were doubled, porewater concentration accumulated 2 mg/L over 20 years. Basin 15 also showed accelerated increase in porewater concentration as a function of initial conditions.

External loading

An expectation of the model is that TP net accumulation rate should be proportional to external phosphorus loading. This expectation is not true, however. In Basin 36, accumulation of 600 mg/m^2/year under base conditions increased to 1300 mg/m^2/year when external loads were doubled. Accumulation more than doubled when load doubled. This identical phenomenon occurred in WCA-3A.

Basin 15

Basin 15 is an indicator region in the northern portion of WCA-3A. The basin is close to the model domain boundary and is transected by a canal that conveys loads from the north. Basin 15 demonstrated multiple behaviors that were puzzling and merited investigation. The sensitivity of porewater to initial conditions has already been mentioned. In fact, porewater TP concentration was far more sensitive to initial conditions than to external loading. When porewater TP concentration was initialized to zero, it stayed there. Halving the loads did not decrease porewater concentration down to the level maintained when initial conditions were zero. Surface water TP concentration also demonstrated interesting response to initial conditions. The magnitude of response to doubled initial conditions was equivalent to the response to doubled external loads. In fact, at the end of the 20-year simulation, TP concentration in surface water in response to doubled initial conditions exceeded the TP response to doubled external loads. Macrophytes showed virtually no response to load changes but did respond to alterations in TP initial conditions.

100-Year perturbations

Six perturbation runs of 108 years duration were completed, in part to resolve the origins of behaviors noticed in the 20-year perturbation runs (new Chapter 11 in Fitz and Trimble (2006)). These runs were conducted on a 10 km x 10 km indicator region located within WCA-3A. Flow in the region ran southeast from a canal along the northern edge. Perturbation runs included:

- A nominal run based on observed initial conditions and sequential use of three 36-year hydrologic sequences 1965 – 2000;
- Double all external TP loads, employ initial conditions from nominal run;
- Multiply canal TP loads by ten-fold, leave atmospheric TP loads at nominal level. Employ initial conditions from nominal run;
- Eliminate external TP loads, employ initial conditions from nominal run;
- Zero (or near zero) initial TP conditions, external loads from nominal run; and,
- Increase the spatial gradient of initial TP conditions, leaving systemwide total initial phosphorus concentration at nominal level. All external loads at nominal level.

These runs indicated that TP net accumulation in the soil can be affected by initial conditions. When soil TP was initialized at high levels, net accumulation rate was reduced compared to runs with lower initial conditions. The explanation was that mineralization rate in soil is dependent on phosphorus availability. At low concentrations, bacteria that facilitate mineralization are phosphorus-limited and mineralization rate is low. At high concentrations, mineralization proceeds at a faster rate and greater quantities of phosphorus are mineralized and exported, resulting in reduced net accumulation.

The runs indicated that effects of increasing overland load did not propagate more than a few km from the canal. Beyond this few km boundary region, loads from the atmosphere were greater than from the canal. This behavior and load magnitudes suggest that atmospheric loads are the prime determinant of TP net accumulation in interior regions of the Everglades.

Phosphorus availability can either increase or decrease phosphorus net accumulation, depending on the amount available and its location in the ecosystem. As noted above, increased soil phosphorus may lead to diminished accumulation due to enhanced mineralization. In contrast, increased external loading can lead to enhanced macrophyte growth and increased accumulation.

Although the 100-year runs did not address the specific questions raised by the 20-year runs, the longer runs did illustrate processes that can lead to the behaviors demonstrated in the 20-year runs. The 100-year runs generally served to enhance model credibility. These runs also emphasized the importance of proper specification of initial conditions in computing TP net accumulation.

Context of ELM and relationship to Everglades restoration

The restoration of the Everglades (CERP) is an enormously important and expensive (>$8 billion) project being jointly supported by the State of Florida and the nation. As such, the entire nation is watching with anticipation of what the results will be from this restoration with Federal funds only approved at the beginning of this century.

While the ELM was under development prior to the CERP and even the Everglades Forever Act in Florida, six years have now passed since the Federal government bought into the Everglades restoration. The ELM should be at the point of providing the leadership simulations to predict many of the enormously expensive restoration techniques (e.g., reservoirs, P-removal wetlands, accelerated response research, etc.) that are being carried out rather than only re-checking algorithms. With the Everglades restoration probably continuing through 2050 but the plans put in effect now, SFWMD does not have the luxury of taking another decade to refine this model.

It is the opinion of this Peer Review Panel that the ecosystem modeling effort is not being given the fiscal and/or personnel support that it deserves. The very essence of Everglades restoration is predicated on the return of natural "habitats" and not simply on the return of water depths and phosphorus accumulations. Those are causes, not effects. The SFWMD should continue to invest in the development and application of the Everglades Landscape Model. There needs to be the addition of ecosystem modelers at SFWMD, with key cross appointments to accelerated recovery projects, hydrologic modification projects and the development of the SFWMD Regional Simulation Model (RSM).

The operative word on these new assignments should be "ecosystem" which includes integration of water, biogeochemical, and ecological features of the Everglades. What is needed is an infusion of ecologists who are process-oriented and mathematically literate (modeling more than statistics). GIS and remote sensing, as well as dynamic modeling are needed. Major work is needed on developing macrophyte, habitat, and eventually animal dynamics in this important wetland system.

The habitat division given in the model description documents is much more complicated than could ever be simulated effectively. Twenty years of data collection would be needed to develop coefficients similar to those that exist for better-developed limnological and hydrologic models. The lumping of habitat systems (Table 1) suggests a direction for ultimate model simplification. We have suggested lumping according to the wetland types described by Mitsch and Gosselink (2000) but there may be other combinations that are more useful. The point is that there has simply not been enough explicit determination of productivity, mortality, and translocation processes in all 28 habitat systems to ever allow complete modeling of the Everglades with this level of detail. This would be analogous to water quality models being developed for the Laurentian Great Lakes with 28 different algal communities. The usual Great Lakes models combine algal communities into chlorophyll-a biomass and occasionally split out blue-green algae (the "cattails" of lacustrine systems).

The ELM is an actively developing model and we expect that this development will continue as new observations and Everglades ecosystem knowledge increases. However, the current version (ELM v2.5) is robust and will produce a unique contribution, with an integrated ecosystem paradigm, to understand and predict potential outcomes of Everglades restoration projects BEFORE they are etched in stone. Clearly, the modeling effort, if it involved more participants, will also meet one of its other goals of "providing a conceptual and quantitative framework for collaborative field research." One of us (Mitsch) sat on a review panel in 2005 on accelerated recover research and witnessed little reference to the ELM in that presentation. In fact our report (Davis et al., 2005) gave as one of its recommendations: "bring in, or develop, a team that can develop a systems modeling component to the research plan." That systems modeling component should logically involve the algorithms that are part of the ELM.

Documentation

The primary documentation of the model is web-based. At the web site, reports and related documents are available in Adobe pdf format. A notable feature of the web site is availability of documentation for earlier model versions. Web sites are inevitably ephemeral as are electronic formats. Archiving of all documents in hard copy is recommended if this practice is not already observed.

Appendix A of the SOW for this review panel lays our five criteria for judgment of the model documentation. Is the documentation sufficient to understand:

- model objectives?
- input data?
- key assumptions?
- algorithms and model functionality?
- output data and model performance?

The documentation report on the ELM v2.5 includes an "Introduction" that clearly lays out the overall objectives of the ELM, the specific objectives of the current version, and objectives of future versions. The overall objective is to develop a simulation modeling tool for integrated ecological assessment of water management scenarios for Everglades restoration. Key to this assessment is understanding and prediction of relative responses of the landscape to different water and nutrient management scenarios. The ELM is an ambitious undertaking involving simulations of hydrology, biology, and nutrient cycling. Development of the model is proceeding in phases or versions. The specific objectives of the ELM v2.5 are to compare alternate management scenarios involving the prediction of:

- concentration of total phosphorus in surface water; and,
- net accumulation of total phosphorus in the ecosystem.

The modelers employ the term "data" in a loose sense to mean "information." In this sense, they refer to input data, target data, and output data. The information required to run the model is summarized in a report chapter entitled "Data." The chapter thoroughly defines the nature of required information and either reports this information or, for large files, directs the reader to a location where the information may be obtained. As with all on-line information, the modelers are advised to keep archival hard copies of the model inputs that are stored on line. Original sources of information are cited in the text or in the files that contain large data bases. Various manipulations (interpolation, kriging) employed to process original information for the model are amply described in the text.

No explicit list of model assumptions exists nor is an exhaustive, unified list of all assumptions expected. Rather, assumptions must be gleaned by the reader from text and listings of model algorithms. The model structure is largely described in two chapters entitled “Conceptual Model” and “Model Structure.” The description of model algorithms is no doubt the weakest part of the report and the algorithms cannot be considered sufficiently documented. The use of what is effectively computer code is extremely difficult to understand. There are algorithms that this reviewer simply could not decipher. Nowhere did this reader find such fundamental information as a list of model state variables. Neither could the “Anti-Numerical Dispersion” algorithm be deciphered. Documentation should consist of clear text and explicit equations, not computer code.

An environmental model such as the ELM generates an enormous quantity of information. Examining and interpreting this information is usually a more demanding task than executing the model itself. Interpretation requires a synthesis of the output to produce a manageable quantity of information that can be compared with observed quantities. Processing the model outputs and fundamental comparisons with observations are detailed in the chapter “Model Performance.” The chapter details the processing of model information into a variety of formats including:

- color spatial plots;
- time series plots;
- plots along longitudinal axes;
- tabulations; and,
- statistical summaries.

The procedures employed to process the information are well documented and the statistics are defined explicitly. Documentation of the model output within the current report is sufficient.

Capabilities/applications/limitations of ELM v2.5

We are asked to judge two primary performance measures:

- computed TP concentration in the water column; and,
- computed TP net accumulation in the ecosystem.

Overall bias in computed TP concentration is small. The bias could probably be removed by adjusting atmospheric loads and boundary fluxes within their ranges of uncertainty. The bias may also be affected by improved initial conditions, especially in the soil.

In response to the second question, judgment must be reserved everywhere except WCA-2A since this is the only region where data are available. Computed net accumulation along two transects shows reasonable agreement with three independent data sets. The computed spatial distribution of net accumulation suggests exponential decrease with distance from the canal phosphorus source, indicating a rough first-order removal process. Two questions remain regarding these comparisons, however:

- The data are TP net accumulation in the soil. The model is TP in all components of the ecosystem. Can it be shown that the modeled net accumulation in the components other than soil is negligible?

- Two data sets used in the ELM calibration suggest an increase in TP net accumulation beyond km 8. The model does not show this at all. Is the observed increase real or an artifact of sampling variability? If the increase is real, is there any explanation?

Overall, it appears that discrepancies between computations and observations are more a function of uncertainty in forcing functions and initial conditions rather than flaws in model formulation or operation.

Can it be one of the tools used to address management questions?

Given resolution/evaluation of the issues raised above and specific caveats, the ELM v2.5 should be used as one of the tools to address and evaluate management questions. As with all other models, this requires continued model evaluation as process understanding and data availability become more available. A formalized uncertainty analysis (not to be confused with a sensitivity analysis) would provide a better assessment of risk to specific management activities.

Can it be used to address TP load-response relationships?

See response above. Specific issues to resolve include potential for higher positive bias at high water column TP concentrations typically adjacent to canals – boundary flux or model derived?

Can it be used to design STAs?

Using the model algorithms on the STAs, where there is an enormous amount of habitat, water quality, soils, and hydrology data, is exactly were it needs to be used to provide some calibration of ecological variables.

Is ELM v2.5 better than Best Professional Judgment?

Yes. Because it provides a systems approach that integrates long-term development of the ecosystem with short- to medium-term processes, the ELM provides a quantitative spatial framework for evaluating primary forcing and complex system feedbacks. As such, it provides enormous potential to tie together the various disciplines working on Everglades restoration. Engineers, ecologists, microbiologists, hydrologists, and landscape scientists can use it as a common language on which to discuss the Everglades—what is important for ecosystem function and what needs further research. Within this context, specific model results and behavior should be used in conjunction with empirical data analysis, conceptual understanding and best professional judgment as part of a "weight-of-evidence" approach to determine appropriate restoration activity and evaluate its effectiveness. The development and evaluation of the ELM, and any other effective model, does incorporate all of these additional sources of information as part of model conceptualization, implementation and operation.

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