# Ecological Landscape Modeling:

## *the general application of an existing simulation framework*

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## Introduction

Simulation models are explicit abstractions of reality, and at best are tools that should provide insights into a better understanding of a particular problem. In the field of ecology, models can help organize or synthesize our data-based understanding of the ecology of a system, and this understanding may also be applied in making relative comparisons among scenarios of future ecosystem changes. Depending on the objectives, there is a seemingly limitless set of methods and tools that could be used in such endeavors. But because of the potentially high degree of difficulty (i.e., time required) in conceptualizing and implementing useful models for large or complex systems, it is quite attractive to employ existing tools if available.

Just as there are probably no truly "generic" problems in the strictest sense, it is difficult to conceptualize a truly "generic" model. Nevertheless, there are common classes of problems, and a generalized model could serve a useful purpose if the model objectives were pertinent to the class of problem. A highly constrained, well-defined portion of an ecosystem could perhaps be best assessed with a very simple model that assumes many ecological processes are invariant or unimportant to the question at hand. On the other hand, many classes of problems in ecology involve understanding ecosystems that have undergone a large, or many small, perturbation(s). The effects may be manifested in changes at varying scales and/or trophic levels, typically resulting from the direct and indirect interactions inherent among the many components of an ecosystem. In such a class of problem, the requisite understanding may become apparent through modeling the cascading interactions in the system – i.e., its integrated ecology.

For this document, we provide an overview of an existing model framework that was designed to be general enough to address objectives that involve integrated ecosystem dynamics within large spatial domains, and across decadal ecological time scales. Some aspects of the physical hydrologic drivers of this model framework were targeted to wetland environments, which is emphasized in places. However, the modeling system has been successfully applied to a wider range of terrestrial and aquatic ecosystems, at multiple scales within large landscapes.

### *Integrated ecological models*

The landscape modeling framework that is outlined here is intended to be flexible and applicable to a range of scales and ecosystems. Fundamentally, we consider the dynamic ecosystem interactions across a heterogeneous spatial domain: this model framework

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becomes an hypothesis of the physical, chemical, and biological dynamic interactions that are important to the function and structure of a simple conceptual ecosystem (Figure 1).

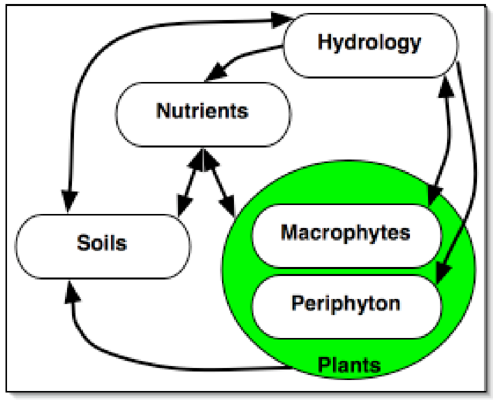


Figure 1. The pathways of dynamic interactions among primary modules of a simple conceptual ecosystem.

The physical hydrology of wetlands and adjacent habitats is an important driver of their ecosystem dynamics. To better understand the long term ecological effects of altered hydrology, it is important to assess the cumulative influence of the magnitude and timing of the changes. Interacting with these hydrologic dynamics are the nutrient transformations and transport. As the physical and chemical dynamics interact with the biological communities, the system dynamics cumulatively define the transient ecosystem states under different conditions. While the basics are well-understood, and many of the details known, there remain uncertainties in predicting all potential changes in an ecosystem. We do, however, have a reasonably good understanding of the interactions among general ecosystem processes, and of the nature of some of the changes at the landscape scale.

Interactions are the essence of ecosystem science. Ecology has been classically defined as the interactions of organisms (including plants) and their environment. For long term planning purposes, a relatively simple model is desired that can capture the cumulative, interactive nature of the ecosystem dynamics, synthesizing the state of our understanding of the general ecosystem processes. The level (or scale) of computational complexity may be relatively coarse, which is dependent upon our current scientific knowledge-base. Fundamentally, there is a need for models that can quantify the relative potential of long-term cumulative ecosystem responses to altered hydrologic and nutrient drivers across the landscape of interest. The challenge is to synthesize habitat change in the landscape, with habitats being an integrated combination of hydrologic, water quality, soils, and algal/plant variables that are simulated with a useful degree of relative certainty. With such a model, the trends in relative habitat change could be evaluated under different scenarios of hydrologic/nutrient management.

### *Wetland ecological models*

While wetlands have a wide range of characteristics, ecological models of these systems share at least one general goal: to understand the ecological responses to varying magnitudes and frequencies of flooding. Regardless of the specific objectives and the level of model complexity, a principal driver of wetland models is flooding and associated surficial sediment saturation. These wetland physics influence the selection of the implicit or explicit ecological processes to be considered in model development. The hydrology is thus an important consideration in the spatial and temporal scales of the model (Figure 2).

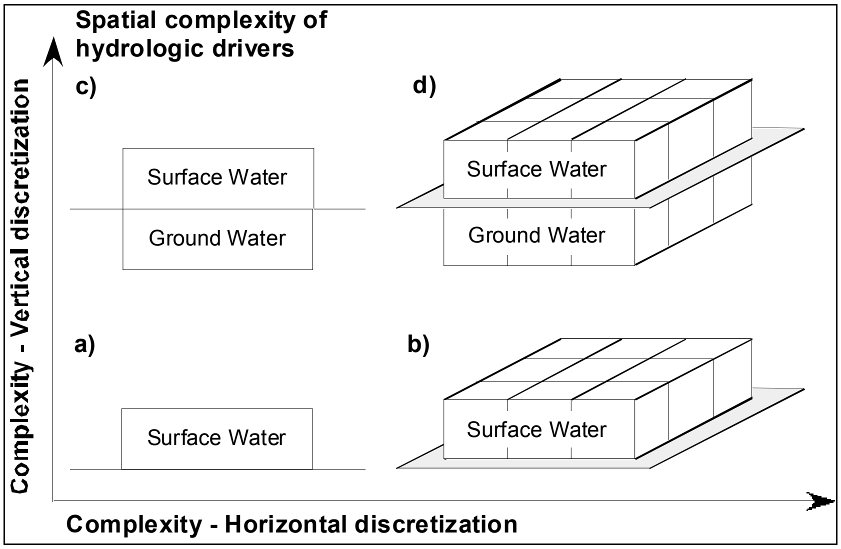


Figure 2. Spatial discretization of the hydrologic component of wetland models largely determines the questions that can be addressed. a) Simplest case, with ponded surface water depths of a single unit area; b) Horizontal extension of surface water across multiple spatial units; c) Vertical stratification of surface and ground water storages; d) Complex case of both vertical and horizontal spatial discretization, which is implemented in the model(s) discussed here.

Horizontal and vertical transport processes establish the basis for biogeochemical transformations of nutrients in shallow surface waters and the upper sediment layers. Sediment accumulation and loss combine with vegetative and algal dynamics to lead to varying trajectories of habitat type in space and time. Integrated models across this spectrum of ecological process complexity are usually limited by our state of knowledge, particularly over long time scales. In combination with directed research and monitoring, the diversity of ecological modeling in wetlands is leading to improved understanding of wetland dynamics. In an era of increased management of wetlands, judicious application of this model-based knowledge should aid in more informed decisions regarding the fate of wetlands.

## Modeling framework

The Everglades Landscape Model (ELM, http://my.sfwmd.gov/elm) is a model application that serves as an integrated simulation framework for wetlands and adjacent upland habitats in the greater Everglades region. As an existing application that is available for assessing Everglades restoration (http://www.evergladesplan.org) alternatives, it has been thoroughly scrutinized. Most recently it was reviewed by an independent panel of experts, who affirmed its utility for such applications (Mitsch et al. 2007).

While this specific model was refined for Everglades applications, its design was "specifically" crafted to be general to a range of ecosystems and scales. Consisting entirely of Open Source software, the model uses the highly configurable Spatial Modeling Environment (SME) that solves General Ecosystem Model (GEM) algorithms for a range of ecosystems and scales. With appropriate (GIS-based) map inputs, and changes to database parameters and environmental forcing data, the modeling (code and data) system can be implemented for a variety of landscapes. Indeed, we are making across-ecosystem comparisons a priority research application of this model.

This section is a brief overview of the different component tools that are used in this modeling. The information is mostly from the instantiation of the Everglades application of the SME/GEM; in addition, these modeling tools were used in the watershed of the Patuxent River (Maryland, USA), to develop the Patuxent Landscape Model (Voinov et al. 1999, Costanza et al. 2002). Related to these efforts are earlier process-oriented landscape simulations in the coastal marshes of Louisiana: the CELSS (Sklar et al. 1985, Costanza et al. 1990) and BTELSS (Reyes et al. 2000, Martin et al. 2002) used simpler "unit" models than described here, and specialized computer code for the modeling environment.

### *Spatial Modeling Environment*

The Spatial Modeling Environment (SME v.2) (Maxwell and Costanza 1995) is the high-level modeling environment that we have used and modified in ELM development. The spatial modeling services of the SME (Figure 3) may be thought of as a comprehensive modeling toolkit for spatial ecological models, with hierarchical modules (C language functions) that perform tasks such as linking spatial map (GIS) data with ecological algorithms, spatial interpolations, and flexible management of input/output. Spatially explicit data including habitat type, elevation, and canal/river vectors are maintained in GIS layers that are input to the model. Other databases store time series inputs (e.g., rainfall) and parameters that vary with habitat (e.g., growth rates). The comprehensive data structure organizes the information and alleviates the need to recompile the model code when evaluating the results of different model scenarios.

While we no longer employ the SME's functionality of translating icon-based, non-spatial simulation programs (i.e., Stella™) into a spatial model, the next-generation SME v.3 expanded on those capabilities. With an advanced graphical user interface, the SME3 (Maxwell et al. 2002) may be adopted as an updated spatial modeling framework for our future model refinements.

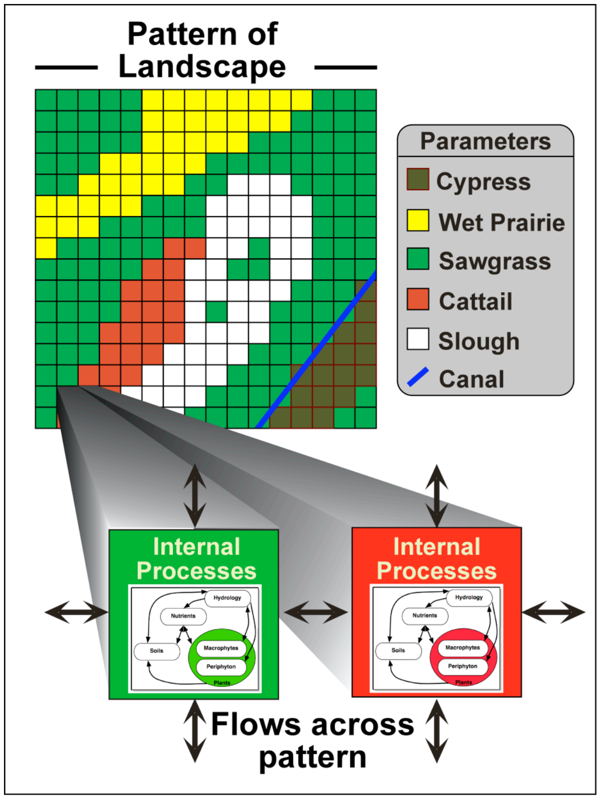


Figure 3. The Spatial Modeling Environment (SME) conceptualization of how the "unit" model of general ecosystem dynamics is applied across the heterogeneous spatial grid of different habitat types. Each habitat type within the patterned landscape can be parameterized differently, affecting the internal process dynamics within different grid cells. In turn, the results of the internal processing can affect the direction and magnitude of the flows of water and nutrients across the landscape pattern. Succession, or switching, of habitat types can occur as cumulative conditions warrant.

Raster cell surface and groundwater flows in the horizontal dimension are solved using a finite difference, Alternating Direction Explicit technique, providing for propagation of water and water-borne constituents (e.g., salt and nutrients) across space. Vertical integration of surface and groundwater flows are calculated within the groundwater module, using an iterative mass balance approach that evaluates storage potentials following overland and groundwater flows.

Rivers and canal/levees are represented by a set of linked vector objects that interact with a specific set of raster landscape cells. This allows for horizontal flux of water and dissolved constituents over long distances (along multiple grid cells) within a time step. Within each vector (e.g., canal) reach, water and dissolved constituents are distributed homogeneously along the entire reach, with an iterative routine allowing exchange among the grid cells along the vector.

Succession of one habitat type into another is simulated with a simple switching algorithm based on the cumulative effects of environmental variables. For example, in the ELM, counters were incremented based on the time that levels of soil phosphorus concentrations and of ponded water depths exceeded their respective thresholds for each simulated habitat type. Other rules can be quickly encoded to evaluate alternative hypotheses of habitat succession depending on the simulation objectives.

### *General Ecosystem Model*

The horizontal fluxes of water and constituents that were described above largely define the 2D physical transport in a landscape. The vertical solutions of the landscape simulation are calculated in modules of the “unit” General Ecosystem Model (GEM) (Fitz et al. 1996), which was updated in the ELM (Fitz and Trimble 2006). As implied by its name, this GEM code was designed to be generic, and applicable to a range of scales and ecosystems. For example, parameters are modified to accommodate different latitudes (e.g., for solar insolation), and the algorithms and associated parameters can be considered independent of the horizontal spatial scale of the application. Partly because the GEM was to be applied as a unit model in a large spatial domain, we strived to constrain its computational complexity and data requirements, aggregating ecological processes into those that were hypothesized to be primary drivers of an ecosystem. Concomitant with this rationale for simplicity was a desire to compare differently-structured ecosystems, while using a common model code structure. We avoided process-specific details that may differentiate distinct ecosystems, such as upland forests vs. gramminoid wetlands: instead, we strived to characterize the commonalities in ecosystem processes, keeping each module simple and general. In this context, habitats as diverse as upland pine forests and wetland sloughs were successfully simulated in the ELM application of GEM.

The GEM is comprised of linked modules for different ecosystem components, currently including water, phosphorus, salts, algae/periphyton, macrophytes, detritus, and soils (Figure 4). Modifying or adding individual modules is easily accomplished, and such further development is anticipated in ongoing collaborations. In its spatially distributed application, user-selected GEM modules are executed for each grid cell within a landscape. (All selected modules must be run in all grid cells). The grid cells in the modeled landscape are assigned an initial habitat (i.e., ecosystem) type, with different habitats potentially having unique parameter values that define processes such as nutrient uptake kinetics or surface roughness for overland flows. Thus, the pattern of habitats in the landscape can influence material fluxes among cells in the landscape, and the within-cell ecosystem dynamics can lead to succession that alters the pattern of the landscape.

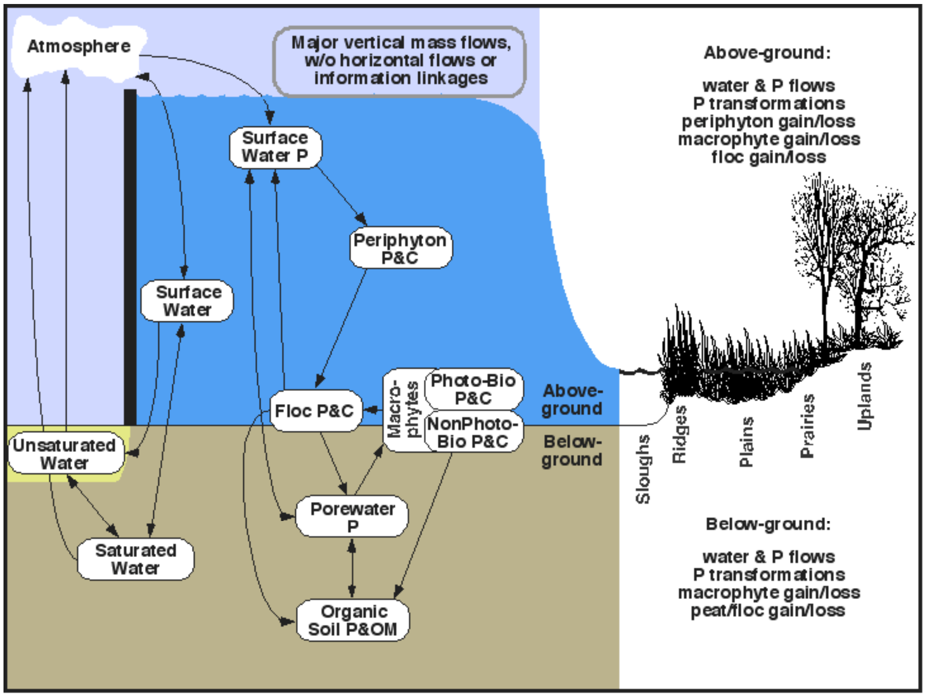


Figure 4. The details of the conceptual model of vertical solutions of ecosystem processes. Model state variables are in oval boxes, linked by the major flow pathways among those variables. The Periphyton (algal/microbial community) state variables can be considered functionally equivalent to an aquatic algal community. Abbreviations: P = Phosphorus; C = Carbon; OM = Organic Matter; Photo-Bio = Photosynthetic Biomass of macrophytes; NonPhoto-Bio = NonPhotosynthetic Biomass of macrophytes; Floc = Flocculent detritus layer on/above soil.

For the ecological process modules, we explicitly incorporated the feedback interactions among the physical, chemical, and biological dynamics of a simple, yet fully-integrated ecosystem. For example, growth of macrophytes and of algal/periphyton communities responds to available nutrients, water, light and temperature. In turn, hydrology responds directly to the vegetation via changes in overland flow roughness, and via dynamic canopy area that alters transpiration losses. Phosphorus cycling includes plant uptake, mineralization, sorption, diffusion, and organic soil loss/gain. While each individual module is a highly aggregated component of the real ecosystem, module integration leads to realistic, complex system behaviors – dynamics that can lead to somewhat involved efforts to calibrate individual processes in addition to the overall model performance measures. A critical advantage of this integrated, process-oriented approach is that the model has a higher potential to realistically respond to future conditions that are outside the envelope of past inputs and behaviors: forecasting relative benefits among alternative futures, and subsequent model validation exercises, may be done with higher confidence and success relative to more statistically-based models that lack mechanistic integration of all of the primary ecosystem drivers.

Applying this in a spatial framework, we have been able to make useful predictions on a wide spectrum of ecological dynamics that describe ecosystem function in various habitat types in temperate and subtropical landscapes (Fitz and Sklar 1999, Voinov et al. 1999, Costanza et al. 2002, Fitz et al. 2004, Fitz and Trimble 2006). Two critical ecosystem drivers in the Everglades landscape are hydrology and nutrient dynamics. We have calibrated and validated the ELM for these dynamics at a range of spatial and temporal scales. With appropriate simulation of the physical and biogeochemical dynamics of the Everglades, we have effectively simulated the response by macrophytes and algal communities, including their feedback on the system physics and chemistry. Evolving the landscape through vegetative succession in a simulation depended strongly on these dynamics.

### *Open Source code*

The code and data necessary to build and run an ELM project is freely available (under the GNU General Public License) on the WWWeb. Not only is the raw code available, it is rigorously documented in hopes of facilitating collaboration among other developers and/or users. The model is thoroughly documented at a hierarchical level of detail, ranging from the broad goals & concepts targeted to lay-audiences, to details of code and data that are mostly pertinent to model developers. For example, the goals of simulating hydrologic flows among canals and marshes are generally described in the documentation Chapters of "Introduction, Goals & Objectives" (Chapter 1) and "Conceptual Model" (Chapter 3). The associated algorithms are described graphically, verbally, and mathematically in the "Model Structure" Chapter 5, as partially indicated by the example graphic of Figure 5.

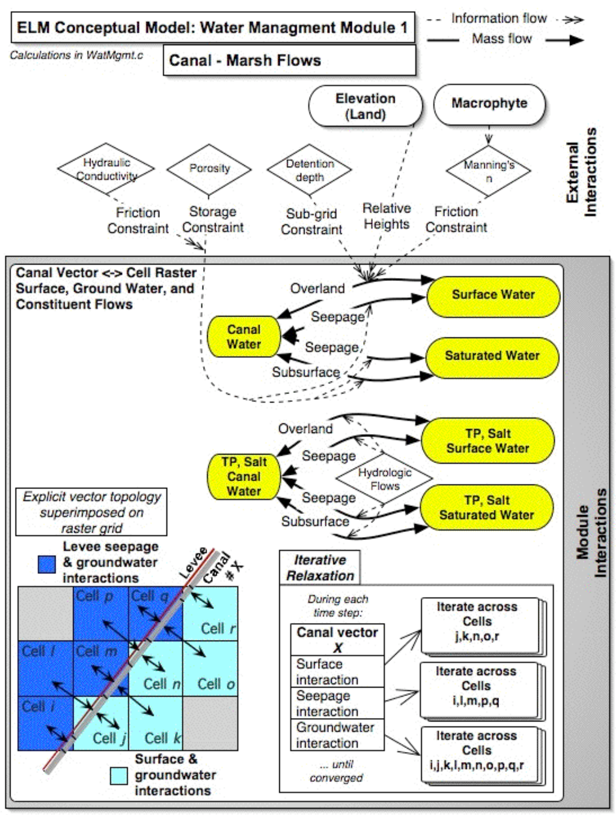


Figure 5. Example graphic from the (ELM) model documentation (Chapter 5, Model Structure), describing the interactions of canal vectors and grid cells. The complete documentation is available in the "Documents: v2.5" tab at http://www.my.sfwmd.gov/elm .

For more detailed information needs, the model source code, including all variable/parameter definitions and hierarchical module dependencies, is fully documented for the entire code project using Doxygen (Figure 6). This Open Source application automatically generates hyper-linked pages of source code documentation, allowing developers to most rapidly understand the relationships inherent in the code hierarchies.

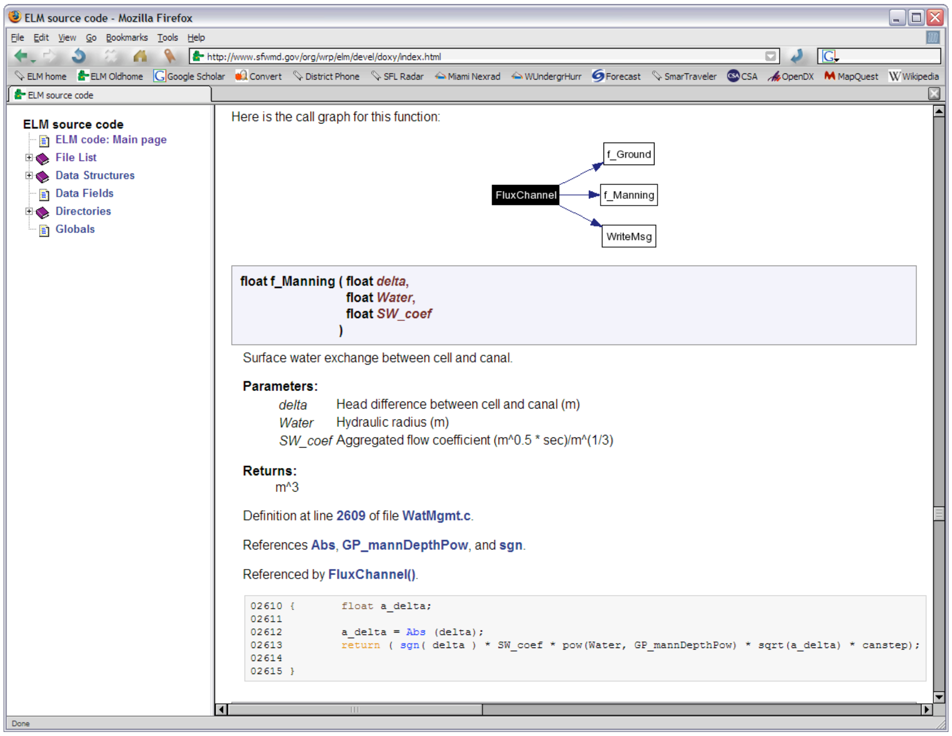


Figure 6. Example from the (ELM) model source code documentation, generated using the Open Source application "Doxygen". Primarily intended for an audience of programmers, this is an example of the web-based documentation of a function in the C source code of ELM. After the ELM developers populated the source code with specific "tags", Doxygen automatically generated well-structured web pages that describe all functions compiled in the ELM project, showing call graphs, descriptions of the purpose of each function, hyperlinked dependencies, definitions of data structures, variables, and many other aspects of the source code, The call graph shown was actually generated for the preceding function (that calls "f_Manning"). For the Doxygen-generated documentation, see the "Development" tab, and open the source code documentation link at http://www.my.sfwmd.gov/elm .

As indicated in the User's Guide (Chapter 10) of the documentation, the model project can be built on an inexpensive desktop or laptop computer running a unix operating system, such as RedHat Linux, SUSE Linux, Apple Darwin, etc. Runtimes on a modern laptop (MacBook Pro, 2.33 GHz Intel Core 2 Duo) are approximately 25 minutes per decade of simulation for the regional ELM application, which encompasses a domain with more than 10,000 1 $km^2$ grid cells superimposed by ~100 canal and river vectors.

### *Open Source data*

No model is complete without data. As with the source code, all data required for implementing the ELM project are freely available on the WWWeb. Many of those data (e.g., spatial time series database of daily rainfall) are mainly applicable to the landscape of the Everglades. However, many of the ecological parameters may be representative of similar ecosystems in other regions of the world, if only as initial estimates when site-specific data are lacking.

As in the case with source code, the data are defined in detail within the "Data" Chapter 4 of the ELM documentation, and the data types in the model are summarized in the following Executive Summary from that Chapter. This summary should provide an introductory understanding of the data needs of a typical application, including the complexity associated with the engineering infrastructure of a managed hydrologic network.

### *Executive Summary, Data Chapter 4, ELM v2.5 Documentation Report:*

There are three primary types of data used in modeling projects: observed input data, observed "target" data, and simulated (output) data. The principal focus of this [Data] Chapter [4] is on documenting the observed data that were used in the project, fully describing the input data that affect the model dynamics. Additionally, at the end of this [Data] Chapter [4] are summaries of the observed "target" data that were used to assess model performance.

The simulated data that are output by the model are described in the [ELM documentation] User's Guide Chapter, in which output selection and interpretation are covered. The [ELM documentation] Chapter on Model Performance Assessment compares simulated data to observed data, while the [ELM documentation] Chapter on Uncertainty describes some of the important uncertainties associated with both simulated and observed data. *The Uncertainty Chapter is an essential component of understanding the model, data, and concomitant performance expectations of the ELM.*

*Domain & static attributes*

The spatial domain (grain and extent) of ELM is defined by an input map, and the vectors and points (grid cells) of the water management infrastructure are superimposed on this raster map via inputs from two databases. Two other databases contain the model parameters: one documents the parameters that are global across the domain, while the other contains parameters that are specific to the habitats distributed across the domain.

*Initial conditions*

These habitats (defined by macrophyte communities) are initialized by an input map, as are other dynamic spatial variables that involve water depths, soil nutrients, land surface elevation, and macrophyte biomass. In the current version, variables such as periphyton biomass and nutrient content are initialized by calculations involving global and/or habitat-specific parameters (i.e., without specific input maps).

*Boundary conditions*

The dynamic drivers of the model include spatially explicit, historical time series of rainfall, potential evapotranspiration, stage along the periphery of the domain, water flows through all managed water control structures, and nutrient concentrations associated with inflows into the model domain.

*Data usage*

The model was designed to provide the flexibility of modifying the scenario(s) of simulation entirely through Open Source database files, without need to modify the source code of the model. While we necessarily provide details on the derivation of some of the data in this documentation Chapter, the metadata associated with all data sources should impart a sufficient degree of understanding for their usage. An overview of the input methods for these data is provided in the [ELM documentation] Model Structure Chapter of this documentation, while the [ELM documentation] User's Guide Chapter describes the relatively simple steps necessary to run model applications.

### *Current documentation*

The most recent public-release version of the ELM (v2.5) is associated with a comprehensive documentation report, along with numerous web-based supplements. Associated with each subsequent public release will be updates to that documentation set. The following Chapters are contained within the documentation report. All documentation is found on the ELM application web site: http://my.sfwmd.gov/elm.

- Chapter 1: ***Introduction*** to the Everglades and the model ***Goals & Objectives***.
- Chapter 2: General overview of ***Wetland Ecological Models***.
- Chapter 3: Graphical and verbal descriptions of the South Florida and General Ecosystem ***Conceptual Models*** on which the ELM is based.
- Chapter 4: Graphical, verbal, and statistical-summary descriptions all of the ***Data*** that are used in the model.
- Chapter 5: Graphical, verbal, and mathematical descriptions of the ***Model Structure*** and algorithms (including links to source code).
- Chapter 6: Analysis of ***Model Performance*** relative to the historical period of record (1981 - 2000).
- Chapter 7: Aspects of ***Uncertainty*** in the model and associated data, including sensitivity analysis, appropriate model expectations, and model complexity.
- Chapter 8: Descriptions of potential ***Model Applications*** for research and management.
- Chapter 9: Descriptions of past and planned ***Model Refinements***, including an overview of its current limitations.
- Chapter 10: A ***User's Guide*** that provides the simple steps to installing and running this Open Source model.

## General applications

The SME/GEM has been developed for a broad class of ecological landscape model applications, and the ELM is a "mature" and well-tested instance that continues to be refined and applied. With the greater Everglades region encompassing diverse ecosystem types, this application serves as a useful test bed for continued collaborative developments in landscape modeling in general. From estuarine mangrove forests, to freshwater cypress swamps and gramminoid marshes, and to prairies and upland pine habitats, the landscape poses stimulating challenges to ecological synthesis. Given the range of systems that have been modeled, this framework has significant potential for application outside of south Florida.

### *Scalability*

Different problems call for different scales of analysis. In the Everglades, assessment of regional water quality gradients is accomplished using the ELM with a grain of 1,000 meters across a broad landscape domain larger than 10,000 square kilometers. The same model is being used to explore local ecosystem processes that are responsible for fine-scaled landscape patterns at resolutions of tens to hundreds of meters. Simply changing the input maps and boundary conditions allows the model framework to be used to assess landscapes at a wide range of spatial and temporal scales: the ELM has been applied at annual, decadal, and century time scales, in spatial domains differing by orders of magnitude, to explore research hypotheses or to support landscape management decisions. To the extent possible, this inherent scalability of applications will be maintained as the model framework is further developed.

### *Module extensions*

The ecosystem processes considered in the GEM unit model are a core component of the modeling framework, with spatial interactions being integral to understanding the evolution of the landscape. For the Everglades region, and for other applications, there are a suite of extensions and enhancements that have been identified for further development. For example, while "hooks" for their incorporation have been designed in the ELM, spatially explicit fire disturbance modules have not yet been incorporated, and are important to exploring vegetative succession in such a fire-impacted landscape. Similarly, the algorithms for succession itself may be enhanced with other rules for neighborhood interactions within a gridded landscape.

More generally, refinements to the vertical solutions of the GEM unit model have been identified. For application within south Florida and elsewhere, particulate sedimentation and erosion in aquatic systems can significantly alter the structure of the landscape. Nitrogen is assumed to be un-limiting in the Everglades application of GEM, and consumer dynamics are not considered. While all of these dynamics were encoded in the original development of the GEM, they were "excised" from the Everglades application for simplicity. For future applications, these modules may be reinstated into the modeling framework. However, a potentially more attractive approach may be to incorporate other more recent modules, making use of libraries of modules (Voinov et al. 2004) that may best meet the overall objectives. For these and other objectives, we hope to obtain guidance from other experts to best advance the tools available in this framework.

### *Collaborative modeling*

Over the years, the SME/GEM framework has been developed and refined depending on the particular application needs – as indicated earlier, a truly generic model likely does not exist for most ecological problems. However, to avoid the "reinventing the wheel" problem, our modeling framework provides tested code and data that have been successful in a range of applications. We hope to encourage continued development within this general framework, both in terms of extending the ecological processes that are included, but also in the broader framework itself – to enhance its ease of use, and better evaluate the model results and their uncertainties.

Thus, one of our overarching goals is to stimulate collaborations that enhance and extend the (partial) successes we have had in SME/GEM applications. These are indeed partial successes, because the modeling is meant to inform, and with new information comes new questions that illuminate our uncertainty in model synthesis. The model framework will be partial or incomplete as long as we are uncertain of ecological dynamics – i.e., a very long time!

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