SL257

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Wetland Ecological Models[1]

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Introduction

Ecological models of wetlands are a diverse assemblage of tools for better understanding the wide range of wetland types distributed throughout the globe. However, these models generally share a common characteristic: they are conceptual and quantitative tools that consider the responses of some part of the ecosystem to varying magnitudes and frequencies of flooding. For some purposes, this may be as simple as an assessment of the suitability of specific ranges of water levels for different biological communities. More complex ecological modeling tools may investigate nutrient dynamics with changing surface and ground water flows. Further details in an “integrated” model may link those nutrients to plants and animals within a wetland.

Regardless of the model objectives, a principal driver of wetland models involves the hydrology of flooding and associated soil saturation. These wetland physics influence the selection of the ecological processes to be considered in model development. Assuming an introductory level understanding of ecology, this article summarizes the types of ecological models that are used to better understand “natural” wetland ecology. In particular, intermittent flooding is a definitive characteristic of wetlands, and is an important consideration in modeling those systems.

General Model Design

Defining the objectives is an important first step in modeling of any system, wetlands or otherwise. Serving an important role in this process are conceptual models, which often take the form of diagrams that indicate the relationships within the system of interest. In this article, we use some generalized conceptual models to highlight the important wetland dynamics that are implemented as mathematical simulation models at various scales of space, time, and complexity.

The development of an ecological model involves decisions on how to best aggregate (or simplify) real-world ecosystem processes such as plant or animal growth–while still capturing the essence of the overall system dynamics. Associated with such simplification are broad-reaching assumptions: a point to keep in mind is that simple ecological models tend to make complex assumptions in aggregating complex system dynamics.

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More complex models involve more equations, and more data is required to supply parameters to those equations. The intent of such designs is presumably to increase the realism as constraining assumptions are lifted. In the design process, the model developer must choose which are the most important components to consider in order to meet the objectives for the wetland study. An overview of the physics, chemistry, and biology of these wetland ecological model components are summarized below.

Wetland Model Components

Water

“Getting the water right” is a primary consideration in understanding the dynamics of wetlands, and the phrase is a driving principal behind an ambitious restoration effort in the remnants of the vast Everglades wetlands of Florida. Physical hydrology becomes the foundation for most wetland models.

At the simplest level, one may consider only the above-ground surface water in a homogenous area (i.e., without variation in land elevation or other variables in horizontal space). This concept can be extended to consider horizontal variation in land elevation and water depths in a 2-dimensional surface water model. In one of the more comprehensive spatial frameworks, a 3-dimensional model tracks water flows both above- and below- land surface, along with horizontal fluxes across space (Figure 1). Regardless of the spatial design, a principal hydrologic characteristic that should be considered is the timing and duration of the surface water flooding or soil saturation.

One of the more common design constraints for wetland ecological models is that of matching space and time scales of the hydrologic and biological processes. Water flows are often modeled with a time resolution of minutes to days, whereas upper trophic(food web) level responses of plant and animal communities operate at time scales that are orders of magnitude greater. Thus, the selection of the hydrologic characteristics to drive wetland ecological models can become a crucial factor in the endeavor's scope and objectives. The fluctuations of the water table above and below the land surface are simply fundamental to the hydrologic component of wetland ecological models.

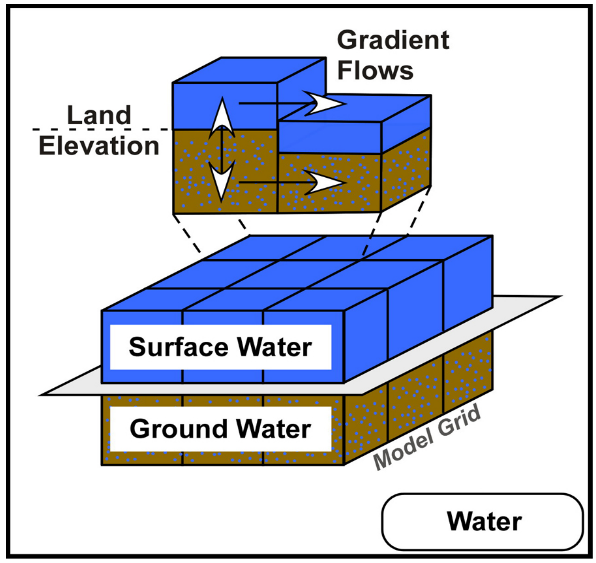

Figure 1. The spatial design of the hydrologic component of wetland models largely determines the questions that can be addressed.

Nutrients

Wetland modeling of nutrients not only involves a strong degree of coupling to hydrologic flows for nutrient transport, but nutrient chemistry is highly dependent on biological processes. This dependence, however, is again directly related to the hydrology via intermittent flooding or saturation of the wetland soil, which largely determines the relative degree to which aerobic (oxygenated) or anaerobic rates and processes are operative. Rarely is surface water very deep, if present at all in a generalized wetland. This results in a high surface area of soil and vegetative biological interactions relative to the water volume, compared to systems such as lakes, for example. Modeling wetland nutrients involves determining the most useful combination of the physical hydrologic drivers and the biological mediation of nutrient transformations.

Because of the potential assimilative capacity of wetlands for nutrients due to the high biological activity, “water quality” modeling in these systems has been of interest in a variety of nutrient management contexts. The efficiency of engineered/constructed wetlands in assimilating nutrient runoff from farms or urban areas has been investigated using a range of modeling techniques. Some of these efforts are based on single equations of highly-aggregated nutrient losses from surface water storages (Figure 2). The residence time of a water parcel as it flows through the wetland biological sieve becomes a primary consideration in determining nutrient assimilation of the wetland.

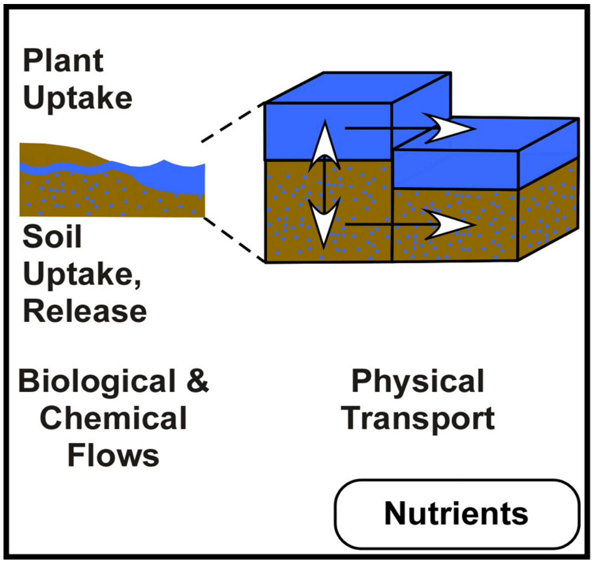

Figure 2. Nutrients are transported across space with water flows, while their fate is mediated by biological and chemical processes.

Habitat-Plants

For the purposes of this modeling overview, wetland habitats are simply considered to be combinations of soil and plant community characteristics. Principal characteristics of a generalized wetland habitat include the function of soil accretion and the related structure of the macrophyte and algal/periphyton communities.

Water and nutrients are two primary drivers of the development of wetland habitats. Modeling those dynamics over short time scales of months to years provides a snapshot of insight into the ecological interactions within given habitat types. However, the succession of macrophyte communities and accretion of soils tend to become observable at multi-year or decadal time periods, with infrequent disturbances being a third major driver of the long-term habitat trajectories.

Plant communities are a conspicuous component of wetland habitat structure, and processes associated with their population dynamics comprise an important part of wetland function. The extent to which nutrient dynamics interact to limit plant growth varies widely among model objectives. One of the more characteristic components of wetland plant models involves the need to develop response mechanisms for hydrology that may range from flooded to very dry, multiple times within a plant generation (Figure 3).

Beyond such relatively brief time scales, models of wetland vegetative succession provide insight into long-term habitat trajectories. The most appropriate time scales range across multiple decades (to perhaps centuries), particularly for long-lived trees in mangrove, cypress, or riparian bottomland forests. Depending on the objectives, these models vary along a continuum of spatial and ecological process complexity. Implied or explicit equations of competition for space and/or resources are commonly employed.

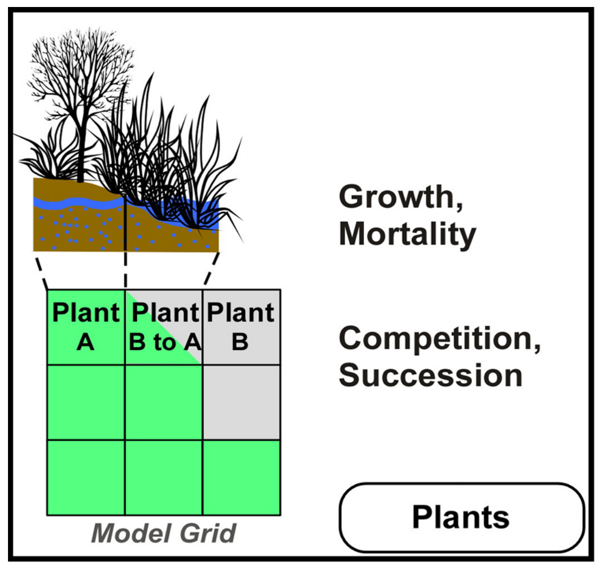

Figure 3. Plant growth, mortality, and other ecological processes respond strongly to water levels, with varying species responses leading to transitions among dominant plants in space and time.

Habitat-Soils

Whatever the method of simulation, habitat change in wetlands is strongly affected by the cumulative effects of water depth and duration – which are directly linked to changes in land surface elevation. Land elevation patterns are modified naturally by water velocity and associated erosion or deposition. With such physical dynamics operating in very short time-scales, further challenges remain in effectively aggregating their effects within models that consider multi-decadal soil dynamics.

A significant component of elevation changes in wetlands is due to positive feedback from the accumulation of above- and below- ground plant detritus. Root growth and mortality accumulate organic matter in the soils, and above-ground plant dynamics add to that elevation potential. Countering this potential increase is the oxidation of the soil's organic matter. Rates of this microbially-mediated decomposition are dependent on the quality of carbon (e.g., the lability of the carbon detritus), available nutrients, and the degree of oxygenation of the soil matrix. Flooded soils typically are characterized by anaerobic pathways of microbial metabolism, while lowered water tables expose the soils to increased oxygen availability and increased oxidation rates (Figure 4).

Directly affected by water levels, water flows (erosion and deposition), and plant dynamics (growth and mortality), soils are integrated indicators of the relative “health” of wetlands- modeling these soil dynamics is a valuable approach to understanding long term, integrated wetland function.

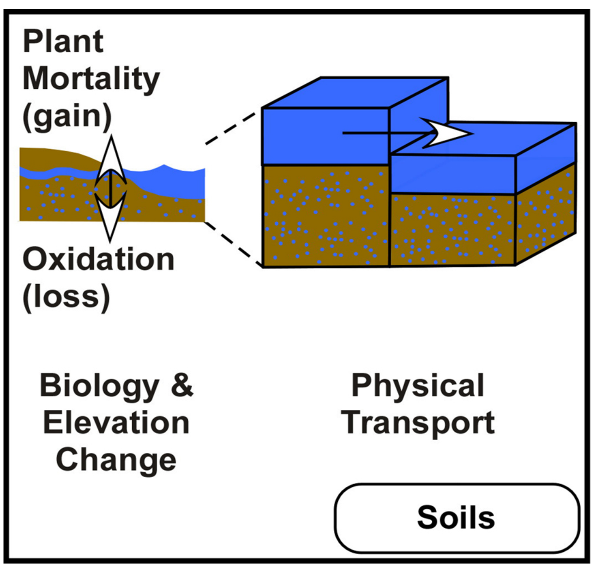

Figure 4. Particulate soil matter may be differentially eroded and deposited, depending on water velocities; soils accumulate mass and height with plant mortality, but are oxidized at rates that vary significantly with water depth in the soil profile.

Animals

Beyond their effect on habitat structure itself, water level fluctuations are a fundamental determinant of the temporal and spatial availability of habitat to animal populations. The periodicity of this availability ranges from the daily flooding of intertidal wetlands to slower recession of water levels in flooded wetlands with the onset of a dry season (Figure 5). Particularly in wetlands, the challenge of modeling animal trophic dynamics becomes one of representing the interactions within and among populations in the context of habitats that may be dynamically varying with hydrology.

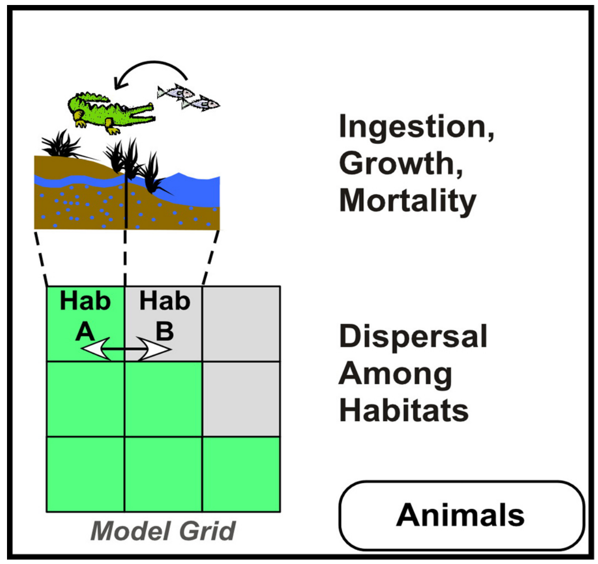

Figure 5. Motile animals can disperse to habitats with more favorable hydrologic conditions, the quality of which may affect animals physiology and their susceptibility to predation or other interactions.

A modeling approach that is increasingly being used for such purposes is that of Individual Based Models. As with simulations of forest succession due to interactions among individual trees, such models incorporate individual variation in the quest for understanding dynamics of larger populations. Relaxing some of the broader assumptions of population homogeneity, these modeling approaches explicitly incorporate some aspect of how individuals respond to dynamics of biological and/or physical changes in their environment. In understanding such potential interactions through the collective response of individuals, potential emergent properties of the population(s) can be explored in a highly dynamic wetland environment.

Integrated ecosystem

An integrated simulation model can take on a range of definitions. Largely dependent on the specific objectives, this may involve the interplay among physical, chemical, biological, and socioeconomic sciences. As indicated in the discussion above, a comprehensive understanding of wetland ecology involves a rather complex suite of properties. Integral with these “natural” properties are the effects of anthropogenic drivers–the human degradation or restoration of wetland systems. In planning for projects involving wetland modifications, data is usually limited, and comprehensive understanding of long-term, fully integrated wetland dynamics is elusive.

Simple, statistically-oriented models based on past wetland behavior may serve to guide initial plans for some wetland management goals. However, as noted previously, such relatively simple models tend to make complex assumptions regarding long term wetland landscape trajectories. Outside of the envelope of past observations, the uncertainty of such models can become problematic (depending on the goals). Moreover, such models tend to lack explanatory power. Relative to a project's goals, it is desirable to determine the minimum set of ecosystem properties that will interact to lead to long-term trajectories of wetland structure and function. Understanding the fundamental physical, chemical, and biological interactions–at some minimal level–becomes a goal for ecological simulations of wetland dynamics in this context.

From the perspective of systems dynamics theory, there is a core suite of variables and processes the integration of which into simulated models may provide insight into understanding long term wetland dynamics. The preceding overviews of the modeling at varying trophic levels outline the basic nature of some desirable levels of integration, shown in conceptual form in (Figure 6). The emergent characteristics revealed by integrated simulated models reflect the unique character of wetland dynamics and further our understanding of the physical drivers of intermittent flooding, and the chemical and biological interactions that lead to varying trajectories of habitats and resident animals.

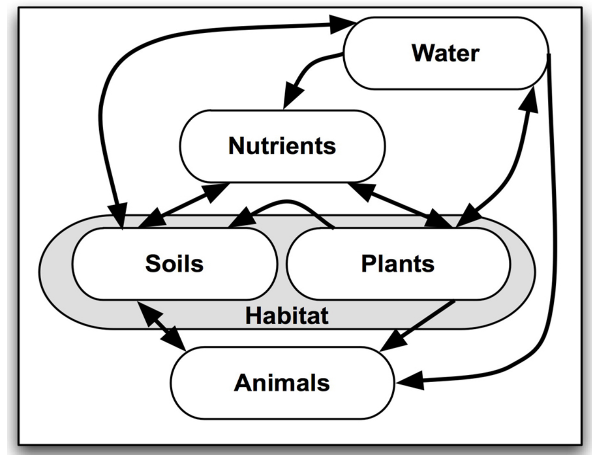

Figure 6. Interactions among each model component are shown as process-oriented feedback (of information or matter) within an integrated wetland model.

Everglades Example

Few wetlands in the world are sufficiently understood to fully implement such a complex integrated model. However, one of the most comprehensively studied wetlands in the world is the Everglades of Florida. A range of hydrologic, statistical, and ecological models are in use, or are under development, in order to better understand how to manage and restore the Everglades landscape (Figure 7). Considering more than 10,000 km^2 of coastal mangroves, freshwater marshes, and upland ecosystems, some of the ecological models integrate components of the ecosystems throughout the region.

None of these modeling tools provides sufficient understanding to forecast results even a mere 50 years from now, particularly given large uncertainties in the effects of regional drivers such as climate change or future societal priorities. Hand in hand with simulation tools that evaluate the relative risks and benefits of future scenarios, comprehensive monitoring is being implemented to adaptively assess and modify plans as the landscape responds along unforeseen trajectories. As scientific understanding evolves, so do the models that assimilate that knowledge, leading to tools that can help in this process to evaluate the relative benefits of alternative scenarios of restoring this unique system.

Figure 7. An experimental mesocosm within the Everglades of South Florida. In parallel with long term monitoring and research, numerous ecological models have been developed in order to better understand and restore this wetland mosaic. Credits: Courtesy of Everglades Division, South Florida Water Management District

Further Reading

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