IDENTIFYING KEY MODEL PARAMETERS IN MATCHING OBSERVED PAST AND POSSIBLE FUTURE BEHAVIORS FOR LAKE OGLETHORPE, GEORGIA

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Abstract. Lake Oglethorpe, a small impoundment located east of Athens in Oglethorpe County, Georgia, has been extensively studied since 1978. It currently provides a test base for some of our methods in on-going research into the long-term ecological integrity of nearby Lake Lanier. In this paper, we present the basic structure of a total ecosystem model being developed for simulating ecological processes in lake communities, and a regionalized sensitivity analysis approach for evaluating the model's constituent hypotheses. We hypothesize that long-term changes in the behavior of Lake Oglethorpe will be governed by slowly evolving processes - specifically the sediment-water interactions and fish population dynamics - typified by the time-constants within the model. We present some preliminary results of our assessment of the significant ecological processes responsible for shaping the past and future behavior of Lake Oglethorpe.

INTRODUCTION

Background.

Our objective here is to evaluate the future. However, the approach we adopt is quite different from the conventional. In a typical systems management or decision-making situation, we assemble historical, empirical evidence of the system's behavior, develop a predictive tool (say a mathematical model), attempt to reconcile the model with the evidence, draw up candidate policies/strategies, use the model to predict the outcomes of each action, and select the preferred response. Here, we are asking the "what if?" question. Alternatively, we might specify a desired outcome (or behavior), and then determine the best strategy to adopt in meeting this specified goal. In this case we ask the question, "how best?".

We depart from the conventional approach by determining whether the system can indeed attain the desired behavior, and if so, what are the key (internal) processes responsible for reaching this goal (Beck and Chen, 1999). Therefore, rather than aim directly at defining the policy actions as in the conventional situation, we focus first on the model as a tool for predicting the future behavior of the system, and its coefficients – the parameters which represent the various internal processes of the system. Policy actions can then be formulated around the key factors, while the redundant factors receive secondary consideration.

It is important to consider briefly who defines the future desired behavior. In the past, we as scientists and systems analysts, have taken on this responsibility within our studies. The trend is now moving towards public and stakeholder participation (Beck, 1997; Fath et al., 1999). For the purposes of this paper, however, we shall assume that desired behavior is defined by a set of regulatory standards as may be specified by say the Environmental Protection Agency (EPA).

The Model.

The basic structure of our total ecosystem model is presented in Figure 1. We have adopted functional groups for the biotic and abiotic substances that make up the food web of Lake Oglethorpe (see Porter et al., 1996). At the (macro-)food chain scale, our model incorporates two main hypotheses: (i) the dynamics of Lake Oglethorpe's ecosystem are controlled by bottom-up processes – nutrient enrichment and primary production – and top-down processes – i.e. the trophic cascade or food web effects (Carpenter et al., 1985); and (ii) nutrient availability is influenced by lake sediments, which entrap and release nutrients depending on the physical and chemical conditions in the water column.

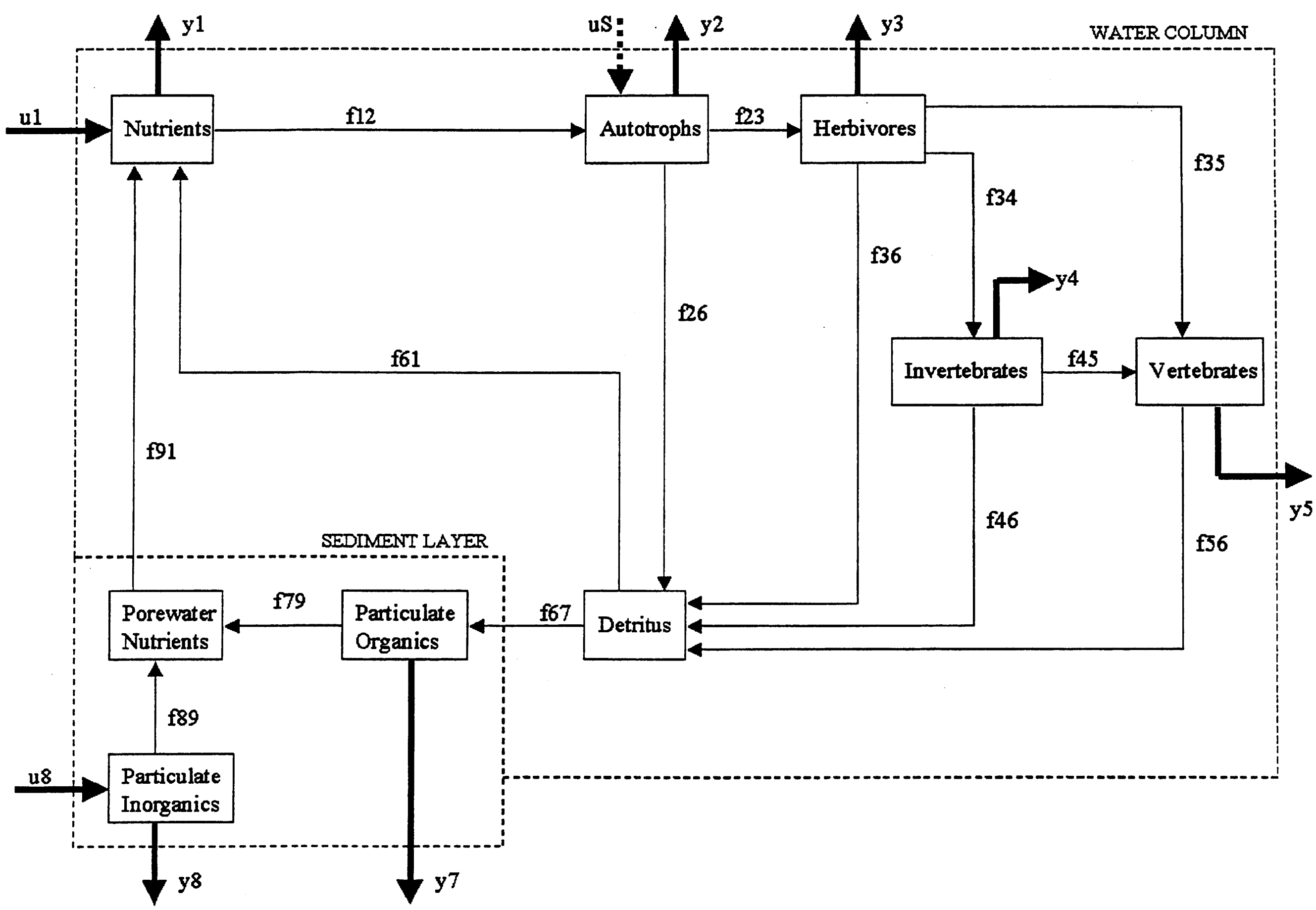

Figure 1. Schematic representation of the compartments and interactions of Lake Oglethorpe's ecosystem.

The model comprises nine state variables. Six of these - nutrients, autotrophs, herbivores, invertebrates, vertebrates and detritus - are within the water column, and three in the sediments beneath the lake.

Nutrients comprise soluble reactive phosphorus - the limiting nutrient for primary production. Autotrophs comprise phytoplankton and other algae. Herbivores are the zooplankton community in the food web. In Lake Oglethorpe, invertebrates are mainly *Chaoborus,* and vertebrates - the top predators - comprise all size and age classes of fish. Lastly the detritus compartment is a sink for all plant and animal carcasses, and biotic excretory products.

The sediment layer comprises settled plant and animal detritus (particulate organics), deposited river sediments (particulate inorganics), and dissolved phosphorus compounds in the sediment interstitial water (porewater nutrients). Suspended river-borne sediments – predominantly clay minerals, onto which phosphorus compounds adsorb easily – represent a potentially significant source of nutrients for the algae.

Environmental inputs to the ecosystem include soluble phosphorus (u1), suspended sediments from the tributary stream (u8), and solar radiation (uS). Food web flows comprise nutrient uptake for photosynthesis (f12), zooplankton grazing (f23), invertebrate predation (f34), fish predation (f35; f45), compartmental losses (f26; f36; f46; f56) due to excretion, mortality etc., decomposition of organic matter and nutrient regeneration within the water column (f61), and sedimentation (f67). The sediment model flows are: decomposition of settled detritus and nutrient regeneration (f79), desorption of sediment-bound phosphorus compounds (f89), and nutrient release from the sediments to the water column through porewater diffusion (f91). The losses to the environment from the water column (y1; y2; y3; y4; y5) are due to lake outflow and human fishing, and those from the sediment (y7; y8), to compaction and burial.

The model comprises nine first-order ordinary differential equations, based on mass conservation across each compartment. A total of 35 parameters are specified for 21 ecological processes, characterizing the food web and sediment flows (f), and the losses from the lake (y). The parameters include growth-rate and, half-saturation constants, assimilation efficiencies and loss rate-constants for the biotic compartments; settling velocity, diffusion coefficient and desorption rate-constant; bacterial activity is represented by the decomposition rate constants in the water column and sediment.

METHODS

Regionalized Sensitivity Analysis (RSA).

The RSA procedure was originally developed for application to poorly defined systems, i.e. for which available information on past behavior is insufficient to adequately characterize the internal processes (see Hornberger and Spear, 1980; Spear and Hornberger, 1980). The RSA thus provides guidance for further research work on such poorly defined systems. Here we apply the method not only to past observations – which in the case of Lake Oglethorpe may be regarded as comparatively well defined – but also to speculations about the future behavior of the lake – which at best can only be qualitative. By comparing the results of analysis of past and future behavior, we intend to identify any changes in the critical factors (processes) controlling the behavior of the lake ecosystem. Consequently, we shall proceed to contemplate what critical factors (processes) control transition from past to future behavior (Beck and Chen, 1999).

The RSA takes the model as an acceptable representation of the real system, albeit poorly defined. The model's constituent hypotheses incorporate a number of (constant) coefficients, or parameters, which characterize the internal processes of the system. Thus, for example, primary production in lake algal communities will be characterized by such parameters as growth-rate constants, nutrient uptake efficiencies and temperature control constants. In this study, we use the RSA to compare model outputs with past (observed) or future (speculated) behavior of the lake's ecosystem. The RSA involves two main principles – a qualitative definition of system behavior, and a binary classification of model outputs based on the specified behavior definition. The behavior definition includes a set of thresholds, ceilings and time bounds derived from available information (or from speculations about the future), thus defining a "corridor" through which the model outputs should pass in order to qualify as an acceptable simulation of the system. The binary classification defines the model as exhibiting "the behavior" (B) if the outputs fall within the defined constraints, and "not the behavior" (NB) if otherwise.

In executing the RSA, we define a range of values for each of the model parameters, reflecting the uncertainty in the model's constituent hypotheses. Several combinations of parameter values are drawn at random from the specified parameter range. Such random sampling requires that the entire parameter domain be covered uniformly. Thus, the number of combinations required will increase with the number of parameters in the model (and hence its complexity). However, we have improved our sampling efficiency by adopting a Latin Hypercube strategy, which essentially spreads the sampling more evenly over the parameter range (Chen, 1993). This allows us to obtain statistically robust results with as few as 3000 samplings. Each combination of values so generated constitutes a candidate parameter vector, to be fed into the model to generate a set of outputs, which when compared with the behavior definition, results in a B or NB classification for the respective candidate parameter vector. Eventually, we obtain a set of binary elements indicating which simulations produced the defined behavior, and which did otherwise. For each parameter, we distinguish a set of values in the behavior-producing (B) simulations, and another in the nonbehavior-producing simulations (NB). Finally, using the Kolmogorov-Smirnov two-sample statistical test, we determine whether the distribution of B values differs significantly from that of the NB values. A significant difference indicates a sensitive model parameter, and in the real system, a process which is critical to producing the defined behavior. An insignificant difference indicates a redundant process. Furthermore, significance levels are used to rank the model parameters in order of sensitivity, and in the system, the processes in order of significance.

The Behavior Definitions.

For the case of eutrophication in Lake Oglethorpe, we define the system behavior in terms of two widely accepted indices of trophic state (see Raschke, 1993) – the nutrient levels and algal biomass during the growing season (April – October). Figure 2 shows a definition of past behavior (for algal biomass) and a typical behavior-producing simulation; Figure 3 shows similar illustrations for the future speculated behavior. Past behavior definitions are derived from data obtained during the various studies on Lake Oglethorpe (Porter, et al., 1996), while future definitions are in terms of assumed regulatory standards that may be set for nutrient levels and algal biomass. Raschke (1993), from a regional study of eutrophication in 17 small piedmont lakes, recommends a mean growing season limit of 25µg/L chlorophyll-a (which converts to 1.7mg/L dry weight, using a 1.5% factor). We set this as a test standard for the future, and also set an upper limit of 4.5mg/L for the peak growing season algal biomass. For soluble phosphorus (nutrients), we set a maximum concentration of 50 µg/L for the growing season – about 50% of historical peak concentration.

RESULTS & DISCUSSION

Table 1 gives the sensitivity ranking of the 21 processes, derived from a similar ranking of the 35 parameters. The sensitivity analysis for past behavior pointed to two key processes - the growth and loss of autotrophs within the lake (f12, f26 and f23), and the regeneration (or otherwise) of nutrients within the water column. In order to attain the high algal biomasses during the growing season (see Figure 2), primary production (f12) must be high, grazing (f23) by the herbivores must be low, and non-predatory losses of algae (f26) must be low. In addition, bacterial decomposition (f61) must be fast enough to regenerate nutrients from detritus in the water column before they settle (f67) into the sediment layer. For the strictly regulated future, the results indicated that algal growth and loss still remain critical, while grazing becomes redundant, perhaps because the low levels of algal biomass cannot sustain the herbivore populations. Nutrient regeneration from bacterial decomposition also remains critical, and we noticed the rise to prominence of the desorption and diffusion processes (f89 and f91) in the sediments. The regulated future requires such low nutrient levels that these slower, hitherto insignificant processes, now contribute significantly to the supply of nutrients required for survival of the algal communities.

The results obtained from the RSA serve two purposes. First, for the system manager involved in planning for the future, the RSA provides an evaluation of the feasibility (reachability) of future target scenarios. If reachable, then policy action and resources should be devoted to supporting the critical processes identified. For the research scientist interested in improving knowledge of the system, the critical processes that determine past behavior should then be the focus of further scientific investigations.

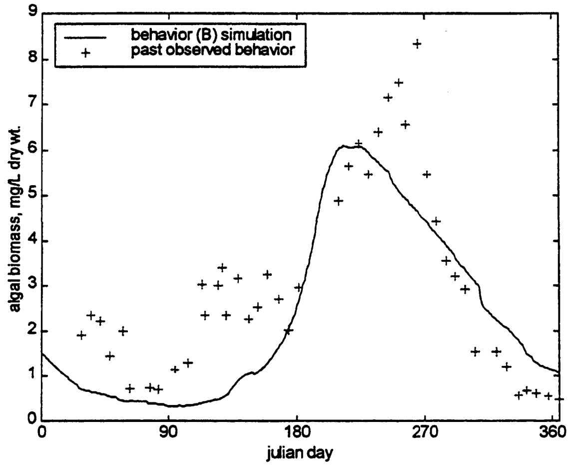

Figure 2. Past behavior definition and behavior-producing simulation for algal biomass

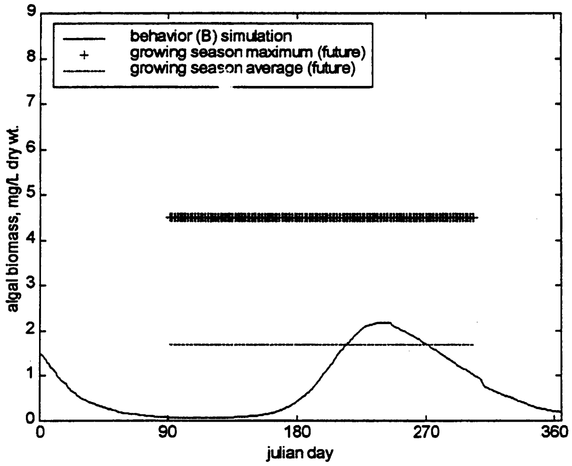

Figure 3. Future behavior definition and behavior-producing simulation for algal biomass

Table 1. Sensitivity ranking of model flows and corresponding system processes. [1=critical; 2=important; 3=redundant]

Model flow / system process		Sensitivity rank past behavior	 future behavior
f12	nutrient uptake / photosynthesis	1	1
f23	grazing on primary producers	1	3
f34	predation on herbivores	3	3
f35	predation on herbivores	3	3
f45	predation on invertebrates	3	3
f26	autotroph excretion, respiration, mortality etc.	1	1
f36	herbivore losses excretion, respiration, mortality etc.	2	3
f46	invertebrate losses excretion, respiration, mortality etc.	3	3
f56	vertebrate losses excretion, respiration, mortality etc.	3	3
f61	bacterial decomposition in water column	1	1
f67	sedimentation (of organic matter)	1	1
f79	bacterial decomposition in the sediment	3	3
f89	desorption of phosphorus from sediment particles	3	1
f91	release of phosphorus from sediment by diffusion	3	1
y1	nutrient losses (in lake outflow)	3	3
y2	autotroph losses (in lake outflow)	3	3
y3	herbivore losses (in lake outflow)	3	3
y4	invertebrate losses (in lake outflow)	3	3
y5	vertebrate losses (in lake outflow / fishing)	3	3
y7	sediment losses (compaction and deep burial)	3	3
y8	sediment losses (compaction and deep burial)	3	3

Having identified the processes that are critical to sustaining future speculated behavior, the next task should be that of deciding what actions need to be taken to ensure that the system evolves either to the future behavior if desired, or avoids it if undesired. For this we hypothesize that, depending on the time scale of projection into the future – i.e. medium- or long-term – the slowly evolving processes will become the key determinants of the path of system evolution. We intend to address these issues during the later stages of our studies, when we shall be dealing with the larger ecosystem of Lake Lanier.

CONCLUSIONS

In this paper, we have presented the framework of a total lake ecosystem model, that incorporates nutrient enrichment, primary production, trophic (food web) effects, and sediment-water interactions as constituent hypotheses. We have also presented and applied a regionalized sensitivity analysis (RSA) approach for screening these constituent hypotheses, and ranking them in some order of significance. We have also demonstrated with the RSA, that some structural change (system evolution) is required to take a given system from the past (or indeed present) to certain desired (or feared) state in the future, and formulated a working hypothesis that the structural evolution will be dominated by slowly evolving processes within the system.

Subsequent stages of our work will be dedicated to the following tasks; (i) expanding the model by resolving the functional groups into their respective component species, (ii) designing field experiments to study the critical processes identified from the RSA procedure, (iii) exploring algorithmic improvements to the RSA procedure, to improve its computational efficiency, (iv) developing ways and means of evaluating the evolution process from past to future behavior, (v) parameterising the environmental inputs (i.e. u1, u8 and uS in Figure 1), in order to explore how long-term climate and watershed changes may influence future behavior. Ultimately, the methods developed and tested on the Lake Oglethorpe case study will be applied to Lake Lanier.

ACKNOWLEDGMENTS

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