Integrating Stakeholder Imagination with Scientific Theory: A Case Study of Lake Lanier, USA

O. O. Osidele

M. B. Beck

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Environmental Informatics and Control Program, Warnell School of Forest Resources, The University of Georgia, Athens, GA 30602, USA (fosidele@arches.uga.edu)

Abstract: We present a framework for computational analysis of reachable futures, centred on the analysis of uncertainty, in which stakeholder participation is integral to generating environmental foresight. In our case study, we examine the long-term ecological behaviour of Lake Lanier, Georgia, south-eastern USA. We elicit stakeholders' fears and desires for the future state of the reservoir during a foresight workshop session, from which we encode long-term behaviour definitions (scenarios) for the analysis. A generalised ecological model provides the mechanism for propagating a set of uncertain input factors – namely, process parameters, initial conditions, and forcing functions – into the future. We employ three sampling-based methods for identifying and ranking the importance of these factors in influencing the speculated future behaviours. The analysis also indicates the likelihood (*reachability*) of the scenarios, and reveals possible structural change between the observed past and speculated futures. Our results suggest that: (i) the desired future is more reachable, and accompanied by more significant structural change, than the feared future, and (ii) sediment-water-nutrient interactions, secondary production, and microbial production are key processes in the future behaviour of Lake Lanier. This information allows us to: (i) respond to the stakeholders and confirm or refute their concerns for the future environment, and (ii) suggest directions for future scientific research by identifying critical gaps in current knowledge. By engaging stakeholders and scientists in a mutual feedback between scenario-generation and systematic analysis, the framework sets a promising direction for integrated environmental assessment.

Keywords: Environmental futures; Stakeholder participation; Modelling; Uncertainty; Integrated assessment

1. INTRODUCTION

For much of the last century, environmental assessment and decision-making derived from the traditional scientific method of matching theory with independent field observations, with the aim of screening prior scientific hypotheses. The credibility of such a process was maintained through peer review, and, where systems analysis was involved, by verification and validation of mathematical models. The 1990s witnessed the emergence of the present post-normal science era [Funtowicz and Ravetz, 1993], in which scientifically lay persons – stakeholders – potentially direct the focus of scientific inquiry and environmental policy. Generating environmental foresight, as we present in this paper, features the matching of scientific theory with stakeholder imagination, in order to: (i) corroborate or refute the public's fears and desires about the future condition of the environment, and (ii) identify the key scientific *unknowns* – the conceptual and quantitative uncertainties in component entities – that might play a critical role in the future behaviour of the environmental system [Beck et al, 2002a]. This approach addresses the criticism that scientific judgment is often insensitive to concerns of lay citizens, who are the ultimate recipients of the impacts of environmental policy actions.

Our case study – Lake Lanier, impounded on the Chattahoochee River at Buford Dam, north Georgia (Figure 1) – is the subject of recent studies on the long-term ecological integrity of rapidly developing urban catchments [Beck et al., 2002b; Osidele, 2001]. This case study coincides with recent recommendations to the US Environmental Protection Agency (EPA) to develop a *futures* capability [Science Advisory Board, 1995], with the eclectic use of information, for generating foresight and improving the anticipation of future environmental problems. As scientifically lay persons, stakeholders constitute a highly independent source of knowledge and experience. Thus, stakeholder participation provides an excellent complement to the traditional scientific method for environmental assessment.

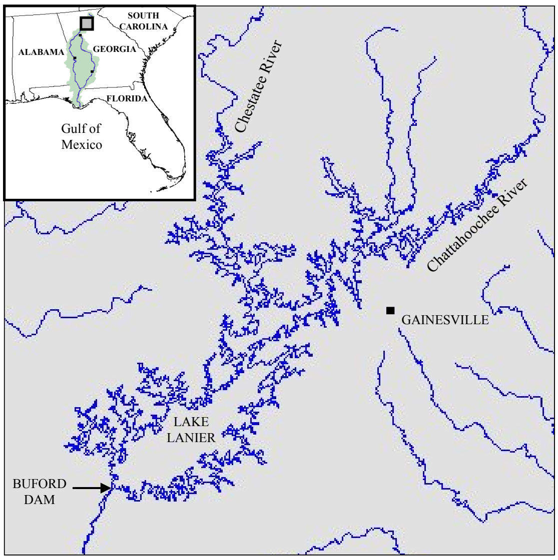

Figure 1. Location map of Lake Lanier.

2. FRAMEWORK

The framework for participatory futures analysis is designed to integrate stakeholder imagination, portrayed as scenarios of speculated future system behaviour, with scientific theory, represented by a mathematical simulation model of the system. As depicted in Figure 2, the scenarios provide a set of *behaviour definitions* as inputs to a composite methodology that comprises three sampling-based computational procedures: (i) Regionalised Sensitivity Analysis (RSA) [Spear and Hornberger, 1980], (ii) Uniform Covering by Probabilistic Rejection (UCPR) [Klepper and Hendrix, 1994] and (iii) Tree-Structured Density Estimation (TSDE) [Spear et al., 1994].

The computational methods integrate qualitative stakeholder-derived behaviour definitions with a quantitative simulation model, in order to rank the relative importance of a set of uncertain input factors under the imposed behaviour definitions. The input factors characterize three major sources of uncertainty in model predictions: (i) process parameters (coefficients); (ii) forcing functions; and (iii) initial conditions. These input factors are parameterised (i.e., quantified and assigned a range of feasible values) for the analysis, to reflect the current state of scientific knowledge about attributes of the system. Thus, the ranks derived for the input factors indicate how critical the uncertainties in the corresponding process are to the future behaviour of the ecosystem.

3. FORESIGHT WORKSHOP

We employ a foresight workshop to elicit concerns of the stakeholders for the future quality of Lake Lanier. The workshop is aimed at generating specific future scenarios that express the fears and desires of people who have detailed knowledge about Lake Lanier, natural resource managers, and people who use the reservoir for recreation [Cowie, 2001]. To facilitate integration with the model, activities are designed to capture opinions that can be encoded in some numerical form.

Participants perform the following tasks: (i) identify trends likely to affect Lake Lanier over the next 30 years; (ii) describe future scenarios for the reservoir; and (iii) quantify expected changes in selected water quality criteria for each scenario. This culminates in a graphical illustration of their feared and desired future scenarios. Each participant marks the direction and magnitude of speculated change relative to the current value of each criterion, on a predefined logarithmic scale of –10 (i.e., one-tenth of the current value) to +10 (ten times the current value).

Table 1 shows the distribution of responses from the participants in the form of quantiles for 10%, 25%, 50% (the median), 75%, and 90%. The quantiles generally reflect the traditional concepts of reservoir limnology. Under the feared future scenario, nutrient concentrations (Total Nitrogen and Total Phosphorus) are expected to increase, leading to increased algal production (Chlorophyll *a*) and a decrease in transparency (Water Clarity). Increased water temperature reduces the available habitat for fish, the majority of which prefer the cooler hypolimnetic waters. Higher temperatures also lead to faster rates of respiration and microbial decomposition, which further starve the fish of dissolved oxygen. These directions of change are all reversed under the desired future scenario, as indicated by the signs of the medians in Table 1.

In spite of the general consistency in each scenario, the distribution of responses for each water quality criterion indeed reflects considerable uncertainty in the overall foresight for Lake Lanier. For example, under the desired future scenario, 80% of the participants (the 10% to 90% quantiles) expect fish population to fall between one- and eight-times the current levels. Such uncertainty informs the domain of speculations (i.e., the behaviour definitions) for the long-term future condition of Lake Lanier.

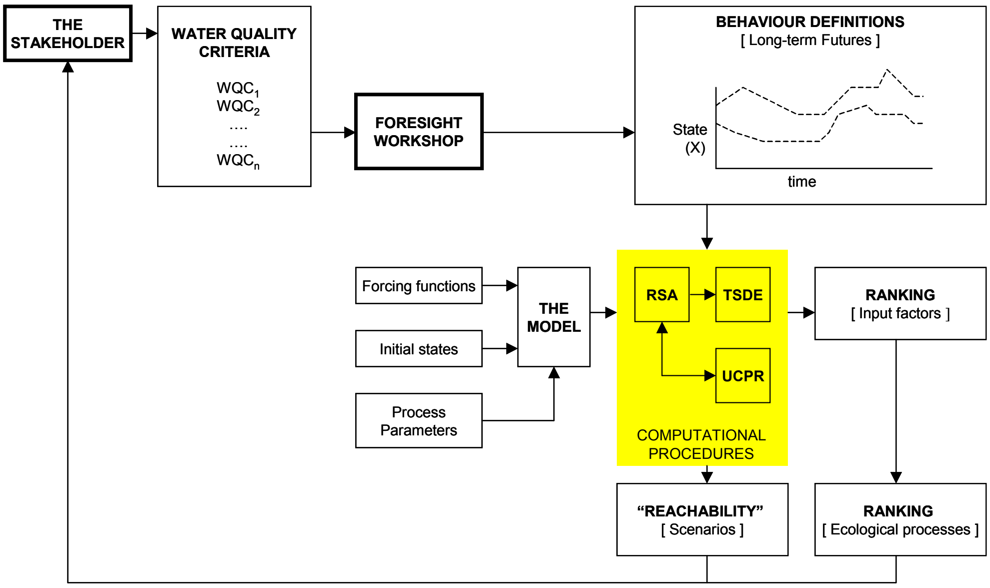

Figure 2. Framework for participatory futures analysis.

Table 1. Quantiles for the distribution of speculated changes[1].

Water quality criterion	[*quantiles*, %] →	Feared future 10	25	50	75	90	Desired future 10	25	50	75	90
1	Total Nitrogen	-3.7	2.4	3.7	4.6	6.4	-6.4	-4.2	-2.1	-1.5	1.0
2	Total Phosphorus	3.7	4.6	4.6	6.4	8.2	-4.6	-4.2	-2.8	-2.1	-1.5
3	Water Clarity	-10.0	-6.4	-5.7	-3.3	-2.8	1.5	2.1	2.8	2.8	4.6
4	Chlorophyll *a*	2.8	4.2	5.5	8.2	8.2	-4.6	-3.9	-2.6	-1.7	1.0
5	Fish Population	-10.0	-8.7	-6.4	-4.6	-2.8	1.0	1.9	2.8	4.6	8.2
6	Av. Ann. Water Temperature	70	75	76	76	79	62	64	68	70	70

[1] Speculations for future water temperature are absolute values.

4. BEHAVIOUR DEFINITIONS

A critical step in this analysis is the translation of the speculated changes in Table 1 into a set of numerical constraints that define the future state of Lake Lanier. This defines a *corridor* of uncertainty for model evaluation. The behaviour definitions are specified in terms of three criteria (selected from Table 1) that correspond directly to state variables in the simulation model: (i) phosphorus, (ii) Chlorophyll *a*, and (iii) fish. The 10% and 90% quantiles set the lower and upper bounds of the constraints for each criterion, thus capturing the opinions of 80% of the workshop participants. The behaviour definitions cover the May-September period of the annual cycle, as follows:

Feared future scenario:

- soluble reactive phosphorus (SRP): peak and mean concentration should not exceed 30µg.L^{-1} and 16µg.L^{-1}, respectively, in the epilimnion;
- Chlorophyll *a*: peak concentration should not exceed 25µg.L^{-1} and mean should be between 5–16µg.L^{-1};
- larval-juvenile fish: mean biomass should be between 3–9Kg.ha^{-1}.

Desired future scenario:

- soluble reactive phosphorus (SRP): peak and mean concentration should not exceed 5.0µg.L^{-1} and 2.0µg.L^{-1}, respectively, in the epilimnion;
- Chlorophyll *a*: peak concentration should not exceed 3.0µg.L^{-1} and mean should be between 0.4–1.9µg.L^{-1};
- larval-juvenile fish: mean biomass should be between 25–205Kg.ha^{-1}.

As a point of reference for assessing structural change, the following set of behaviour definitions represent the current scenario for Lake Lanier:

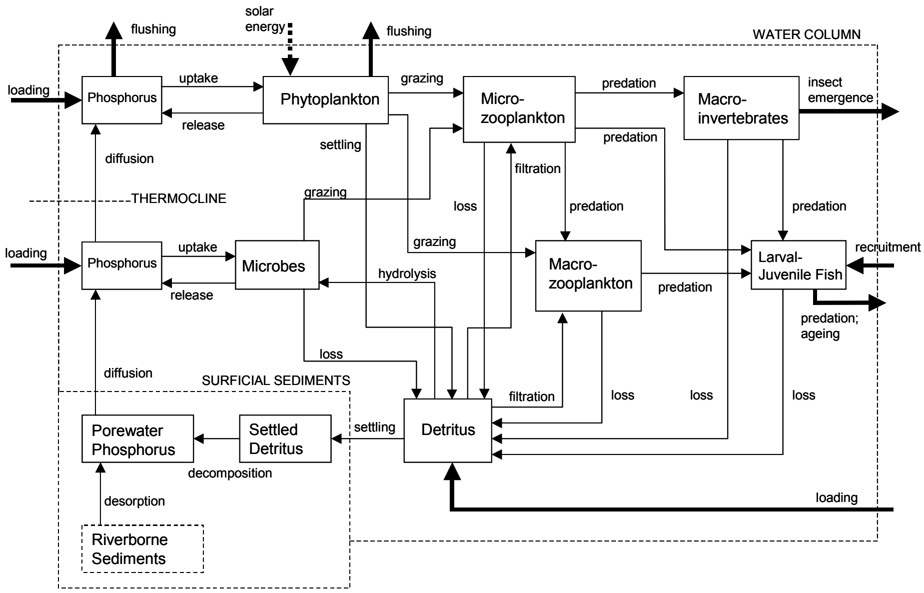

Figure 3. Conceptual reservoir ecological model of Lake Lanier.

Current (immediate past) scenario:

- soluble reactive phosphorus (SRP): peak and mean concentration should not exceed 7.0μg.L^{-1} and 4.0μg.L^{-1}, respectively, in the epilimnion;
- Chlorophyll *a*: peak concentration should not exceed 16μg.L^{-1} and mean should be between 2.0–8.0μg.L^{-1};
- larval-juvenile fish: mean biomass should be between 20–50Kg.ha^{-1}.

5. THE MODEL

Our model (Figure 3) simulates the annual cycle on a daily time step, based on generalised reservoir ecological principles. In particular it features a mechanistic representation of a recent concept that integrates the conventional (phytoplankton-based) aquatic food chain with the microbial loop in freshwater ecosystems [Porter, 1996]. In Figure 3, the microbial loop is depicted by the pathway: Detritus-Microbes-Zooplankton-Fish. In order to account for thermal stratification and the resulting vertical gradients of SRP concentration, we apply the *simplest seasonal approach* [Simons and Lam, 1980] that separates the water column into two vertical compartments: the (top) epilimnion with SRP and phytoplankton, and the (bottom) hypolimnion with SRP, microbes and detritus. The remaining state variables are modelled for the entire water column. Suspended solids (omitted from Figure 3 for clarity) contribute to light extinction in the water column, and settle into the underlying sediment layer. Release of sediment-bound phosphorus into the water column is modelled as a diffusion process, driven by the SRP concentration gradient between the water column and sediment pore water.

6. INPUT FACTORS

Each selected process parameter is assigned a range of feasible values from the general literature and previous studies on Lake Lanier [Hatcher, 1994]. For the tributary inflow, 35 different annual patterns are extracted and indexed from the 43 years of data (1958–2000) published by the US Army Corps of Engineers. Likewise, for solar radiation, an index is assigned to each of the four years (1996–1999) of daily data recorded at the city of Gainesville, adjoining Lake Lanier. For water temperature, a sinusoidal function is fitted to data from the EPA's Clean Lakes Program [Hatcher, 1994], using three parameters: the annual mean, range, and offset from the first day. In addition, insect emergence and fish spawning are parameterised by time of onset and duration. A total of 94 input factors are selected for analysis, comprising: 57 process parameters, 12 initial conditions, and 25 parameters representing the external inputs and forcing functions.

7. COMPUTATIONAL PROCEDURES

7.1 The RSA Procedure

The objective of the RSA procedure is to rank the importance of the uncertainties attributed to the model input factors, with respect to matching the prescribed behaviour definitions, and on this basis, identify the key and redundant processes in the reservoir ecosystem.

Monte Carlo simulation is performed with samples from a joint distribution of (parameterised) input factors. The model outputs are then classified as *behaviour* {B} or *nonbehaviour* {NB} simulations, depending on whether or not they fall within the constraints of the behaviour definitions. For each input factor, a Kolmogorov-Smirnov two-sample test is performed on its marginal distribution, in order to assess the statistical difference between the sets of values that produced the {B} and {NB} simulations. A significant difference indicates a critical input factor, and hence a key system process. On the other hand, an insignificant difference suggests a redundant input factor and ecological process.

7.2 The UCPR Procedure

The UCPR procedure is a full-fledged approach to the analysis of uncertainty in environmental models [Klepper and Hendrix, 1994]. However, for this analysis, its sampling routine provides a means for enhancing the statistical power of the RSA procedure, by increasing the sample size of input factors, especially in the *behaviour* {B} simulations. In essence, it is capable of searching the input factor domain for those values that produce {B} simulations. The algorithm iteratively selects trial values in close proximity (distance-wise) to the current set of {B} factors, applies them to the model, and replaces a {NB} factor for every {B} factor it finds.

7.3 The TSDE Procedure

The aim of the TSDE procedure is to identify interactions among the input factors in the {B} simulations, and assess the relative importance of individual model input factors. Thus, it supports the univariate RSA procedure with a qualitative multivariate analysis, and also confirms or refutes the RSA's ranking of input factors.

Using a simple density estimate, the original RSA sampling domain is recursively partitioned, in a sequence of binary splits, into low- and high-density subdomains. This process is analogous to constructing a histogram in one dimension. The result is a binary tree, in which the nodes represent the subdomains and the branches (the splits) are determined by the key input factors.

Tracing a high-density terminal node from the root node is equivalent to locating those regions of the factor space with a high probability of producing {B} simulations. The sequence of input factors in the trace identifies the set of input factors that interact to produce a {B} simulation. Thus, the number of high-density terminal nodes that each input factor helps define is directly related to its relative importance in the model and system. More importantly, the combined volume of the high-density terminal nodes, in proportion to the overall sampling domain volume, indicates the probability of realizing the specified behaviour definition, in other words, the *reachability* of the corresponding speculated future scenario (Figure 2).

8. RANKINGS AND REACHABILITY

For each scenario (immediate past, feared future, and desired future), we perform five replicates of the composite RSA-UCPR-TSDE methodology, each based on 5000 model simulations. Table 2 summarises the final outcomes of the analysis.

The reachability of the speculated futures suggest that the stakeholders' desires for the future state of Lake Lanier are about three times as likely to materialise as their fears. However, the rankings of key ecological processes suggest that the desired future may be accompanied by a more significant structural change in the ecosystem, as compared to the current scenario. Whereas the ranking is unchanged for a transition to the feared future, it changes significantly in a transition to the desired future. In particular, the scientific uncertainties associated with the release of phosphorus from the sediments and the microbial loop seem to be more critical to the reachability of the desired future.

As it happens, current limnological research on Lake Lanier focuses, in part, on the sediment-water-phosphorus interactions [Parker and Rasmussen, 2001]. Recent observations show that the classical paradigm, derived from historical data on lakes in temperate regions of Europe and North America, do not explain the pattern of phosphorus cycling in Lake Lanier. Studies now seek to demonstrate that, due to the strong potential to bind with phoshorus, the iron-rich clay soils that dominate catchments in the south-eastern US play a critical role in phosphorus cycling in reservoirs.

There is no clear explanation yet for the emergence of microbial production in the ranking. Indeed, the mechanisms by which microbes engage with detritus in generating organic material fluxes is an issue of research interest in contemporary aquatic ecology [Azam et al., 1990]. Perhaps the very low phosphorus concentrations speculated for the desired future favour microbes, which are known to have competitive advantage over phytoplankton at low nutrient concentrations.

Table 2. Ranking of key ecological processes and reachability of speculated future scenarios

Rank	Observed past	Feared future	Desired future
(1)	Phosphorus loading	Phosphorus loading	Phosphorus loading
(2)	Fish production	Fish production	Sediment-water interactions
(3)	Zooplankton production	Zooplankton production	Fish production
(4)	Sediment-water interactions	Sediment-water interactions	Microbial production
Reachability:		2.70% – 4.56%	8.10% – 13.83%

9. CONCLUSIONS

We have developed a framework that engages the social and natural sciences in an assessment of environmental futures. Its effectiveness depends *equally* on the quality of tools employed in both sciences. The integration of a foresight workshop, a mathematical model, and computational analyses under a single case study sets a promising direction for post-normal science and integrated assessment. Feedback to the stakeholder (Figure 2) completes a cycle of mutual exchange between the elicitation of stakeholder values, and exploration of their feasibility in terms of a science-based model. The continuous dialogue between stakeholders and scientists provides more information, hence a better understanding of the behaviour of Lake Lanier. Indeed, this is the purpose of adaptive community learning.

10. ACKNOWLEDGMENTS

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