Reachable Futures, Structural Change, and the Practical Credibility of Environmental Simulation Models

by

Olufemi O. Osidele

ISBN: 1-58112-147-4

DISSERTATION.COM

USA • 2002

Reachable Futures, Structural Change, and the Practical Credibility of Environmental Simulation Models

Dissertation.com
USA • 2002

ISBN: 1-58112-147-4

www.dissertation.com/library/1121474a.htm

Olufẹmi Olusọla Ọsidele
Reachable Futures, Structural Change, and the Practical Credibility of Environmental Simulation Models
(Under the direction of M. Bruce Beck)

Simulation modeling is arguably the most versatile scientific tool for predicting the future environment. However, the reliability of model-based predictions is limited to the behavior domain defined by the historical data employed for conceptualizing and calibrating the model. Future changes in external inputs and internal structure tend to produce system behavior significantly different from prior predictions. To abate this seeming lack of credibility, it is now customary to qualify model predictions with uncertainty estimates. This dissertation explores the complementary approach of *back-casting* future scenarios. Centered on the analysis of uncertainty, a methodological framework is developed for the computational evaluation of environmental futures, driven by stakeholder participation as a means for establishing credibility in the model. The analysis reveals possible structural change between the observed past and speculated future scenarios by comparing the ranking of key sources of uncertainty in model outputs. Three sampling-based methods are employed: Regionalized Sensitivity Analysis (RSA), Tree-Structured Density Estimation (TSDE), and Uniform Covering by Probabilistic Rejection (UCPR). RSA and TSDE are tested for identifying and ranking the key factors that influence ecological behavior in Lake Oglethorpe, Georgia, and UCPR, for recovering parameters of a rainfall-runoff model of an experimental watershed near Loch Ard, Scotland. The framework is applied to an integrated assessment of ecological behavior in Lake Lanier, Georgia. Stakeholders' fears and desires for the future state of the reservoir are elicited and encoded for analysis. The results indicate: (i) that the desired future is more reachable, and accompanied by more significant structural change, than the feared future, and (ii) that sediment-water-nutrient interactions, secondary production, and microbial processes play a critical role in the future ecological behavior of the reservoir. Thus, it is possible to: (i) confirm or refute stakeholder concerns for the future environment, (ii) inform priorities for future environmental policy actions, (iii) identify critical gaps in current knowledge, in order to prioritize future scientific research, and (iv) promote adaptive community learning, through the continual mutual feedback between scenario-generation and systematic analysis. By bridging the gap between stakeholder imagination and scientific theory, through computational analysis, the framework provides a promising direction for integrated environmental assessment.

INDEX WORDS: adaptive community learning, credibility, futures research methodology, integrated environmental assessment, Lake Lanier, reachable futures, reservoir ecology, sensitivity, stakeholder participation, structural change, systems analysis, uncertainty, watershed hydrology

REACHABLE FUTURES, STRUCTURAL CHANGE, AND THE PRACTICAL CREDIBILITY OF ENVIRONMENTAL SIMULATION MODELS

by

OLUFẸMI OLUṢỌLA Ọ̣ṢIDELE

B.Sc., University of Ifẹ, Nigeria, 1987
M.Sc., University of London, England, 1992

A Dissertation Submitted to the Graduate Faculty
of The University of Georgia in Partial Fulfillment
of the
Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2001

Reachable Futures, Structural Change, and the Practical Credibility of Environmental Simulation Models

by

Olufẹmi Olusọla Ọṣidele

Approved:

Major Professor:	M. Bruce Beck
Committee:	Todd C. Rasmussen C. Rhett Jackson Bernard C. Patten Robert B. Lund

Electronic Version Approved:

Gordhan L. Patel
Dean of the Graduate School
The University of Georgia
December 2001

DEDICATION

To Osatohamhen, Oluwatobi, and Ayọdeji

ACKNOWLEDGEMENTS

My sincere gratitude goes to my major professor, Dr. Bruce Beck, for providing the problem setting that turned out to be a challenging and interesting research experience for me, and for supporting me with his wealth of knowledge and experience. His benign yet focussed approach to problem-solving was a key motivator during the many difficult times of my studies.

I also extend my appreciation to the members of my advisory committee – Drs. Todd Rasmussen, Rhett Jackson, Bernard Patten, Robert Lund, and Richard Wiegert – for their comments and discussions at various stages of this research. Special thanks also go to Brian Fath, for our numerous interactions, which helped forge my thinking about ecological systems; to Olivier Klepper, whose doctoral dissertation inspired me to further explore the computational analysis of uncertainty in ecological simulation models; to Reggie Weaver, for the valuable insights he gave me on fisheries in Lake Lanier; to Angela Pereira, for sharing her experience on citizens' participation in environmental management in Europe; and last, but not the least, to Jenny Yearwood, for her behind-the-scenes efforts to keep the Environmental Systems program on track. I also acknowledge the company of the many friends and colleagues I was fortunate to meet and work with during my studies.

To my loving wife, Cordelia, I say: thanks for enduring the rigors of the past four years, and for your support, without which I could not have made it. To our kids, Tobi and Deji: thanks for providing another life outside my doctoral pursuit. To the rest of my family: thanks for your thoughts and prayers. Above all, to God Almighty, who made everything possible: praise and glory be to your holy name.

Preface

The motivation for embarking on this course of research has come from diverse sources, not least inspiring of which was a colleague, who, at the early stages of my work, had said to me: *"don't consider modeling a system until you have collected at least some basic data"*. In other words, some form of observation and (or) data collection should precede model building, in order to obtain a preliminary (if only descriptive) understanding of the components and functions of the system, and to set a firm basis for conceptual modeling. However, this sets the analyst off on an endless quest for data, because the posterior model often reveals inadequacies in the quality and quantity of the prior data.

Let's consider the following sequence of events.

In contemplating the future of any given system, the analyst faces two issues. First, to determine and evaluate the outcome(s) of certain action(s) on the system (including the option to take no action). Second, to assess the chances that the system will attain certain speculated future states, i.e., whether and to what degree these *futures* are *reachable*. A simulation model is employed as a predictive tool for such scenario planning, and the first task is to *calibrate* the model to some historical data. However, the model fails to match these past observations according to some predefined criteria, and thus, its predictions of the future bear little credibility. The analyst then revises the model by adding more conceptual elements in the form of spatial and taxonomic sub-components. Because of its expanded scope, *verifying* the revised model now calls for more observational data, thus starting a seemingly endless cycle of {data collection} $\rightleftharpoons$ {model verification}. Eventually, the analyst breaks the cycle at a reasonable point, and proffers a statement about the future, with the caveat that the informing predictions are credible for all practical intents and purposes. Thus, by establishing reasonable *practical credibility* in the model-based predictions, the analyst can evaluate the *reachability* of speculated futures, and subsequently inform policy actions to be implemented on the system.

This rather common practice embraces two critical issues to be addressed in this dissertation. First, the very act of calibrating the model *fixes* both the conceptual structure and parameters (coefficients) that characterize system behavior. Second, practical credibility is established solely by the analyst, thereby introducing personal bias into the process.

Calibration provides nothing beyond circumstantial evidence (based on historical data) of model validity for predicting the future. It discounts the possible occurrence of *structural change*, brought about either by natural causes (e.g., climate change) or anthropogenic influences (e.g., introduction of exotic species), which can significantly alter the future behavior of the system. The expression *structural change* itself bears different connotations in systems analysis and ecosystem ecology – the two major disciplines involved in this dissertation. Thus, it is appropriate to establish a working definition at this point. According to ecological terminology, *structure* and *function* define ecosystem behavior. *Structure* depicts the organization of the system's components (state variables), and the flow paths of material, energy and information among them, and between the system and its environment. *Function* quantifies these flows, and therefore includes the process parameters contained in the associated mathematical functions. Structural change therefore refers *strictly* to change in community structure (species composition) and component interactions. In systems analysis, *model structure* refers to the set of concepts that describe the internal behavior of a system, and the mathematical representation of such concepts. Thus, when applied to ecosystems, model structure combines ecological structure and function. Throughout this dissertation, appropriate context will be provided to distinguish the usage of the words *structure* and *function* in systems analysis and ecology. Since (ecological) structural change is often accompanied by functional change (at some scale of resolution), the term *structural change* will be used in the sense of combined (ecological) structural and functional change.

While the current practice of peer review has somewhat limited the personal bias in model evaluation, such evaluation is still restricted to within the scientific community. In recent times, citizens – so-called *stakeholders* – have become more conscious about the quality and integrity of the natural environment, and are beginning to question the credibility of the science that informs environmental decision-making. This dissertation adopts an *extended* peer review community in a *participatory* process that involves these scientifically lay citizens. Traditionally, stakeholder participation has been largely characterized by the expression of opinions in debates and discussions. Models have played a useful supportive role in this process, allowing stakeholders to simulate and observe the impacts of various human actions on the natural environment. But still, the process is rendered subjective by value judgements. Subjectivity is inevitable; indeed, it is what makes the process more appealing to the stakeholder. However, there is a lot to desire of a closer integration of *qualitative* stakeholder opinions with *quantitative* scientific models. This dissertation will explore extant computational methodologies, in an attempt to bridge this *quality-quantity* divide, and to demonstrate a consistent, practical and defensible framework for the analysis of reachable environmental futures.

Fẹmi Ọṣidele
University of Georgia, Athens

TABLE OF CONTENTS

CHAPTER

Appendix

Chapter 1

Introduction

> *"In the Information Age, the perception of time is more open. Hence, the contemporary focus on forecasting to determine what is possible and desirable, . . . a far more complex task, requiring a range of methods."*
>
> Jerome C. Glenn, in *Futures Research Methodology*,
> The Millennium Project on Global Futures Research.

1.1 Contemplating the Future Environment

In a report to the US Environmental Protection Agency (EPA) titled *Beyond the Horizon: Using Foresight to Protect the Environmental Future* [124], the Science Advisory Board (SAB) uses the term *Foresight*, defined as futures analysis and research, to label the process already being employed by government, private businesses and non-governmental organizations to anticipate future change. Likewise, within the context of environmental management, *futures analysis* can be defined as the evaluation of speculations about the state of the local and global environment in the short- and long-term future. The objective of futures analysis is *not* to predict that particular environmental conditions will occur in the future, but rather, to organize information that supports policy decisions and actions to prevent future environmental problems. In other words, the purpose of futures research is not to know the future, but to help make better decisions today [61]. The SAB report finally recommends that:

> "...the EPA should include, among its repertoire of technical and analytical skills, a capability to routinely and *systematically* study the range of possible environmental futures ahead, and advise the nation on possible actions in response."

Systems analysis provides a potential foundation for developing such technical capability, due to its origins in the physical and engineering sciences. Given a problem situation in the present time, and a desired solution sometime in the future, traditional systems analysis follows a critical path of: (i) building and verifying a model of the system of interest (i.e., system identification), (ii) defining a number of optional solution strategies, (iii) using model simulation to shortlist candidate solutions, (iv) using model-based optimization to select the best solution strategy, and (v) using the model to predict the outcome of the selected strategy, and to inform decisions and policy actions, including infrastructure development. The foregoing typifies a *forward-reasoning* approach, the objective of which is to inform the decision-maker on the appropriate policy action(s) to take in order to resolve the present problem situation; in other words: *what external influences should be brought to bear on the system in order to achieve the desired future conditions?* Therefore, in order to effectively apply systems analysis, the decision-maker should, ideally, have a *thorough* understanding of the system in question; be able to *accurately* predict the outcome(s) of a number of solution options; and be well informed to select the *best* option. In reality, however, this is not quite the case.

Natural systems comprise a complex network of physical and biochemical interactions, and as such are difficult – if not impossible – to completely understand. As a result, models do not completely describe system behavior, the future is not exactly predictable, and thus, policy decisions are made under considerable uncertainty. Therefore, it should be no surprise that the eventual outcome differs significantly from that predicted by the model. The consequences may include huge investments wasted in infrastructure that fails to perform to predicted expectations, or detrimental effects on human and environmental health. Furthermore, the model is discredited as an analytical tool for decision-making.

On close examination, the traditional forward-reasoning approach to systems analysis can be faulted on three grounds. First, it assumes that the structure of the system is time-invariant. Second, by calibrating and verifying the model against historical observations, before simulating the outcomes of candidate strategies, a fallacious stamp of *truth* is placed on the model, and errors at this critical stage are carried forward, often unchecked. Third, unexpected events – *surprises*, such as climatic change, or the introduction of non-native species into an ecosystem – may lead to future system behavior that differs significantly from the model predictions, and thus render the original solution(s) inappropriate.

Surprise, by strict definition, cannot be anticipated. However, on a global scale, it may be hard to conceive of an entirely unexpected event or outcome. For this reason, Schneider *et al.* [123] propose a pragmatic alternative expression – *imaginable* surprise – which also describes an unexpected outcome, but *relative* to a local group of observers. In other words, an event or outcome is defined as an imaginable surprise, if it falls outside the range of expectations of a specified community, be it of decision-makers, scientists, or other stakeholders directly impacted by the outcome of the event. In spite of surprises, the credibility of models – and indeed of the systems analysis process – can be preserved by demonstrating more convincingly that due consideration was given to the imaginable surprises. How to achieve this involves nothing other than expanding foresight – in other words, improving anticipation of future events – in order to reduce the impact of surprises.

One way to minimize the impact of surprises, while preserving (and possibly promoting) the credibility of models as predictive tools, is to reverse the traditional approach to systems analysis. This study does so by adopting a *backward-reasoning* approach that determines whether or not future patterns of behavior are technically reachable, given current understanding as depicted by the model. Furthermore, through the device of the model, this study seeks to answer the questions: *what are the critical gaps in current knowledge, and what change(s) within the system, if any, should occur in order to attain desired future conditions?*

1.2 Objectives of the Study

The main objective in this dissertation is to explore the utility of systems analysis methodology – in particular, the analysis of uncertainty – for supporting environmental foresight, in a bid to: (i) evaluate the *reachability* of feared (or desired) speculated future states of the environment, (ii) detect future structural change in environmental systems, and (iii) establish practical credibility in environmental simulation models. It is believed that these three acts will improve the anticipation of future environmental problems, minimize the impact of surprises, and promote the use of models to support environmental policy and decision-making.

Analysis of uncertainty in model-based predictions of water quality has been contemplated since the late 1970s [6, 16, 57]. However, in the face of complex natural systems, existing methods have not given very satisfactory results. Put another way, it has been difficult to establish sufficient practical credibility in environmental models. There has been little incentive in recent times for methodological developments in the analysis of uncertainty [136]. Decision-makers are often constrained by time and money, and as such are willing to skip detailed consideration of model uncertainties in the urgency to reach a decision. However, the numerous lessons learned from erroneous predictions emphasize the essence of incorporating uncertainty analysis at the early stages of systems analysis.

The issue of structural change dates back to the 1980s [5]. Traditionally, models are assumed to be *correct* and *invariant* representations of the real system, and their deterministic predictions are used as a basis for screening candidate management and control strategies. *Structural error*, according to Beck [9], is a measure of the extent to which the expression of what is *known* (i.e., the model) diverges from the *truth*. Structural error is inevitable, since the scale of resolution of models will always be macroscopic relative to reality. Within such error lie the seeds of *apparent* structural change, whereby processes previously hidden below the resolving power of the model come to dominate system behavior in the future, and vice versa. This often results in re-calibrating the model to additional data that may be acquired in the future. Indeed, computational procedures are now required to detect the potentials for structural change, and to forecast in spite of such possible change.

Futures analysis is a relatively new subject in environmental management [10, 60]. The scope of inquiry into environmental futures extends beyond mere model-based predictions, and tends to turn the traditional procedure (i.e., build model→predict future→screen alternative actions) on its head, thus placing more emphasis on the ability to anticipate future changes in system behavior. Two current studies serve as motivational examples. First, Keesman [79] asks: given a target future scenario, and a set of prescribed control strategies, what parametric changes within the system will be required to produce such target behavior? This inquiry indicates what structural change(s) could occur between two given points in time. Second, Kryazhimskii and Beck [90] pose the following question: given a model and a target future scenario, to what extent does the reachability of this future target depend on the availability of historical data? Such an inquiry reveals the value of additional information, and, more importantly, could support robust management decisions in the face of uncertainties in the model and data.

1.3 Approach to the Study

Redundant models

A common approach to analyzing large models is to reduce complexity by stripping away component state variables and parameters that are adjudged irrelevant to a specific task. Such a reduced scope of the model facilitates parameter estimation, by reducing the number of degrees of freedom in the model, which in turn abates the tendency for parameter interaction and non-uniqueness. However, in so doing, the capacity of the model to detect future structural change is curtailed, and limited to the extent supported by the remaining state variables and parameters. This poses a severe handicap, especially when it becomes apparent in the future that the prior omitted components have emerged to dominate behavior of the real system. By incorporating redundant processes in the model structure prior to analysis and propagation of uncertainty, it becomes possible to examine various modes of future system behavior, and to identify the proximate and remote causes and effects relating to any particular attribute of the system.

Backward-reasoning

By defining future patterns of system behavior, either as multiple trajectories or bounded intervals, several random realizations of model predictions can be evaluated. Inferences about structural change in the real system can then be made by analyzing the predictions themselves, and the corresponding model structure and parameters. Since fears and desires about the future are often complementary – i.e., the reachability of a desired future implies otherwise for a feared future, and vice versa – backward-reasoning provides the benefit of considering what it takes to both *hit* as well as *miss* a future target, unlike forward-reasoning, which only seeks optimum inputs required to hit the target.

Stakeholder participation

When combined with backward-reasoning, the creative imagination of stakeholders provides the scientist an extremely independent source of information, against which to compare the results of rigorous scientific analyses. The consensus (or otherwise) achieved through the use of such disparate sources of knowledge and experience certainly provides an opportunity to improve communications and mutual understanding between scientists and the public, and will perhaps make the scientists' efforts more relevant to the society at large. By responding to stakeholder concerns for the future, scientists can direct research towards more realistic and relevant problems, while at the same time, the stakeholders obtain a formal assessment of their fears and desires for the future.

Parameterization of external inputs and forcing functions

In contemplating the future behavior of a defined system, the assumed patterns of variation of future external inputs and forcing functions are also unknown, and hence constitute a critical source of uncertainty. For example, climate change today presents a serious threat to the integrity of natural resources, and is the subject of many investigations from regional to global scales [122]. Failure to consider the environmental impacts of climate change, especially its effect on the external inputs and forcing functions that drive critical processes in natural systems such as lakes and reservoirs, can invalidate the most rigorous analysis of environmental futures. Parameters describing external inputs and forcing functions will be combined with those describing internal processes in the analysis of uncertainty. This will enable the propagation of uncertainties in input functions into model predictions, with the potential to facilitate the development of robust management strategies that incorporate uncertainties in the future pattern of environmental change.