LARGE LAKE ECOSYSTEMS: MODELING INTERACTIONS AMONG HUMAN, BIOLOGICAL, AND PHYSICAL PROCESSES

PROJECT SUMMARY

Goals and Objectives: Improvements in water quality in Lake Erie since 1970 have induced human responses in recreational and residential development that have substantially increased external loadings. Nutrient recycling by dreissenids, unintentionally introduced in 1986 by humans, have altered the Lake's biological structure. Both processes are hypothesized to have led to recent increases in phosphorus concentrations and harmful algal blooms. While both are likely to play a role, the relative magnitudes of these impacts are important as they have different implications for underlying biophysical and human processes and future human-lake outcomes. The project goals are to **(1) develop a coarse-scale, "simple" model of a generic large lake ecosystem with coupled human-lake linkages** in just sufficient detail to explore the role of coupled linkages in generating complex dynamics at a systems level; **(2) develop a more detailed, fine-scale model,** specified with Lake Erie data, and test its ability to explain observed human-lake outcomes; and **(3) contribute to the general knowledge of complex systems** by investigating the role of human-biophysical couplings in complex dynamics and by aggregating fine-scale models of component processes to coarse-scale models of the coupled system. We will first develop a simple, aggregate-level model that captures key linkages and the most basic components of a generic coupled system and examine the dynamical behavior under a range of plausible parameter values (**Objective 1**). We will further examine the complex dynamics of this generic coupled system by investigating how different specifications of aggregate and fine-scale processes, time lengths, and stochastic processes embedded in the couplings impact the stability of the system (**Objective 2**). A fine-scale model will be developed to elaborate the complexities of scale and interactions contained in the couplings and will be parameterized using Lake Erie data to test the model's ability to explain observed human-lake outcomes (**Objectives 3 and 4**). This will allow us to study the impacts of management policies on human and biophysical processes (**Objective 6**). We will use the fine-scale model to guide improvements to the simple model by aggregating the fine-scale results and comparing model outcomes (**Objective 5**).

Methods: A purposefully simple, aggregate-level model of a generic large lake ecosystem will be developed and analyzed using a mix of analytical and numerical simulation methods. Although the independent human and biophysical models within this model are very simple, the presence of coupled linkages—in the form of endogenous lake services that influence humans and endogenous human impacts that influence lake functioning—is likely to introduce complex dynamics. The role of coupled linkages will be examined by altering key parameters and by introducing a variety of perturbations to the system to examine how these changes alter the system's stability and robustness, e.g. changes in the average quantities of aggregate variables, fine-scale variations in spatial and temporal distributions of variables, time delayed feedbacks, and stochastic fluctuations. The simple model will be used as a guide to develop a fine-scale model that represents the couplings in greater detail and at much finer spatial and temporal resolutions. This detailed model will be comprised of two- and three-dimensional, fine-scale, cell-based models of the watershed and lake respectively. A spatially-explicit, agent-based model will overlay the watershed model to describe human actions. These models will be developed using computer simulation and the underlying processes specified using Lake Erie data on nutrient incomes, algal abundance, fish stocks, economic lake-based activities, population/land use changes, and water levels. Different aggregation methods will be explored to relate the fine-scale predictions to the coarse-scale model dynamics and guide improvements to the simple model.

Intellectual Merit: The project will make an original contribution to scientific understanding by testing hypotheses on the coupled linkages between human and biophysical large lake processes and by advancing methods used to study the stability and multiscale properties of complex, coupled systems.

Broader Impacts: We will integrate research and education by developing a new graduate-level biocomplexity course, integrating biocomplexity topics into existing courses, and training a new generation of interdisciplinary biocomplexity researchers. The research will be integrated with K-12 education programs by developing learning modules and hosting student workshops. We will build upon existing successful education programs to make special efforts in achieving science literacy among secondary school students from underrepresented groups. We will work with policymakers to perform policy analyses and identify implications regarding the management of the Lake Erie watershed, which is of economic, social and aesthetic importance to the 14 million American and Canadian stakeholders living within its watershed. These efforts will strengthen collaboration in international research and policy formulation regarding large lakes.

LARGE LAKE ECOSYSTEMS: MODELING INTERACTIONS AMONG HUMAN, BIOLOGICAL, AND PHYSICAL PROCESSES

RESULTS FROM PRIOR NSF SUPPORT

Morrison, Joel, K. Bedford, D. Culver, A. Randall, J. Reutter. Biocomplexity incubation proposal for Lake Erie. $100,000 09/01/00-12/31/01. We sponsored three workshops during the incubation study. First was a series of methodology seminars in May 2001 oriented toward methods for Integrating Temporal and Spatial Components of Biocomplexity Models, presented by nine invited speakers. This methodological workshop was complemented by an on-going workshop series on human/social dimensions sponsored by the OSU Environmental Policy Initiative (EPI). A formal workshop was held 10-12 September 2001 and was designed to directly address Coupling Mechanisms for Integrated Modeling of Economic, Biological, Physical, and Social Systems, with nine external invited participants and ten invited researchers from OSU taking part. Many of those attending this workshop have contributed directly to the preparation of this formal proposal and/or will serve in advisory capacity to our research project. The third workshop on Application of the Latest Advancements in Biotechnology, Information Technology, and Remote Sensing to Modeling Lake Erie Biocomplexity was held on December 10, 2001 and featured several non-OSU participants including Professor Charles Perrings (York University, UK). OSU's EPI funded ($24,000) a biocomplexity working group in the human/social dimensions that assembled a research team from five colleges on campus, generated a significant portion of the conceptual foundation for the modeling approach offered in this proposal and hosted outside visits from Alex Anas (SUNY-Buffalo), JunJie Wu (Oregon State University) and Dawn Parker (Indiana University) in Fall 2002 to further conceptual development and assembled an external human modeling advisory panel.

PROJECT DESCRIPTION

OVERVIEW

Increases in the quality of lake ecosystem services, including abundant gamefish, clear water, and uncontaminated water for drinking and swimming, have consistently been followed by booms in lake-based human activities. For example, substantial improvements in water quality and clarity in Lake Erie achieved in the 1970's and 1980's through the reduction in external phosphorus loadings from point sources have been followed by a period of lakeside recreational and residential development that extends through the present day; banner levels of walleye fish in the mid- and late-1980's spurred a 30-fold increase in the number of charter boat businesses; high water levels during the 1980's and 1990's were accompanied by a surge in marina development. More recently, measured concentrations of phosphorus and the frequency of harmful algal blooms (HABs) have risen, both of which have significant negative impacts on water clarity and adult fish populations and can combine with other biophysical conditions to generate "surprise events," e.g. last summer's "Dead Zone" and adult fish kills. Two competing hypotheses to explain these changes are increases in external loadings from nonpoint sources deriving from recent development within the watershed and nutrient recycling by zebra mussels (*Dreissena polymorpha*), unintentionally introduced in 1986 into Lake Erie by humans.

While both external loadings and dreissenids are likely to play a role, the relative magnitudes of these effects are important as they have different implications for the underlying biological and human structures that govern these events and for future human-lake outcomes. If recent changes are explained primarily due to **human responses to improvements in lake ecosystem services** in the form of increased development and lake-based activities, then this suggests that human-induced watershed changes have pushed the biophysical lake system across critical thresholds and led to a regime change in biophysical processes. Hence, improvements in lake ecosystem services are a double-edged sword, since they can push human systems beyond threshold points and lead to economically persistent processes, such as large-scale urban development, that, even if followed by declines in lake ecosystem services, will reverse themselves only slowly and incompletely. Alternatively, if recycling of nutrients by dreissenids that consume algae and excrete nutrients is the dominant process, then lake changes have resulted primarily from **fundamental changes in the biological structure due to human intervention**, in this case an unintentional human addition of a species into the Lake.

In either case, it is clear that the linkages between the human and biophysical systems are key drivers of these changes and thus the central research challenge is to develop a model of coupled linkages that can explain the observed dynamics. Identifying the relevant couplings and the most efficient way of representing them is a generic modeling challenge that is common to any model of a system comprised of interdependent subsystems. Developing such a model is made more difficult by the fact that, in this case as in many others, the component systems are themselves complicated and, we suspect, complex. By complicated we mean that each system contains a multitude of variables operating at varying temporal and spatial scales. While some of these variables are key in the representation of the coupled system, others are not and thus the modeling challenge is to identify the relevant set of variables and the relevant scales at which they operate. By complex we mean that both the human and biophysical systems exhibit complex dynamics, e.g., in the form of nonlinear changes over time, surprise outcomes, and multiscale interactions among variables. While such dynamics do not guarantee that the systems are complex, they are characteristic of complex systems. From this perspective, the modeling challenge is to understand the complexity of each system in its own right, but more importantly the complexity that emerges from the fundamental linkages that make these systems interdependent.

To address these challenges we propose to develop a series of structural models of large lake ecosystem processes with coupled linkages that will allow us to better understand how linkages alter the dynamics of human and biological processes and resulting human-lake outcomes. Our basic conceptualization of the coupled human-biophysical large lake system (Figure 1) involves linkages (arrows) that connect the major system components (boxes). While many interactions occur solely within the physical system (e.g., climate and hydrology), solely within the biological system (e.g., lower trophic levels and fish), or solely within the human system (e.g., land and water uses), we propose that the key linkages affecting the integrated human-biophysical system are those that cross the human-biophysical boundary (bolded arrows in Figure 1). Based on this conceptualization, our project goals are to **(1) develop a simple large lake ecosystem model with coupled human-lake linkages that is of just sufficient detail to explore how these linkages affect human-lake dynamics**, e.g. by influencing the resiliency of these processes or leading to certain thresholds and irreversibilities, and **(2) develop a more detailed, fine-scale model applied to Lake Erie to test specific hypotheses regarding large lake biocomplexity** by explaining observed outcomes such as the surprise "Dead Zone," nonlinear fish stock dynamics, and rapid land and lakeside development as the result of underlying human and biophysical processes. In addition to contributing to the science of large lake biocomplexity, our goal is to **(3) contribute to the general knowledge of complex human-biophysical systems** by examining the role of coupled linkages in generating complex dynamics in our system and investigating a series of complex systems modeling questions, including how variations in key variables, fine-scale processes, time lengths, and the inclusion of stochastic processes impact the self-correcting tendencies of our system. Lastly, we propose to develop aggregation techniques that relate detailed models of fine-scale processes to coarse-scale models of the coupled dynamic

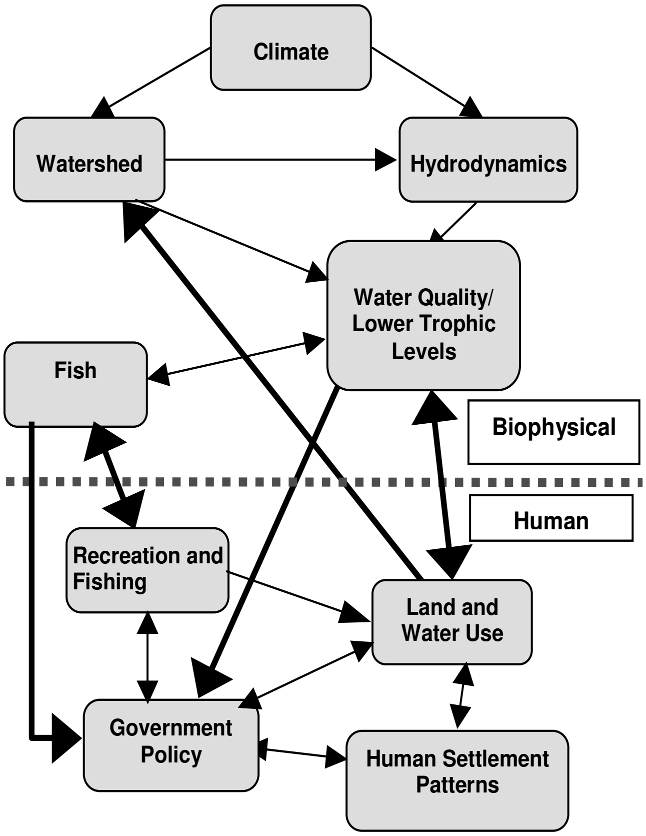

Figure 1: Interactions Among Biological, Physical, and Human Components of Large Lake Ecosystems

system. To achieve these goals, we propose a series of key questions with respect to the role of coupled linkages that will guide our model development and analysis of both the lake-specific and generic simple and fine-scale models:

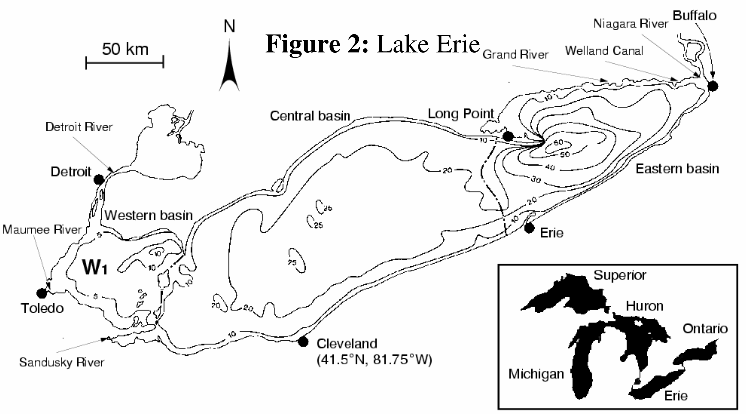

Figure 2: Lake Erie

What are the critical coupled linkages?
We define critical coupled linkages as two-way interactions between processes associated with the different human, biological, and physical subsystems. For the case of large lake ecosystems, we have identified two primary linkages that we believe are critical because of the extent to which they create human-lake interdependencies. These linkages are (1) impacts of lake-based human activities (e.g., commercial and recreational fishing, beach going) and land use (including residential, commercial, and agricultural uses) on lake functioning and (2) impacts of key lake ecosystem services as perceived by humans (including water quality/quantity and fish stocks) on human behavior. This set of linkages is also critical for policy reasons because: (i) Point sources have largely been controlled via regulation, but nonpoint sources of pollution stemming from sedimentation and nutrient run-off from urban and agricultural land uses have increased substantially. Regulation of these nonpoint sources requires a better understanding of how human behaviors are driving land use and development activities. (ii) Over time, many natural amenities (including large lakes) have undergone a transition from being primarily a provider of resources as inputs into production processes to a provider of amenities that are directly attractive to people. An understanding of how feedbacks occur between lake amenities and human behavioral responses is critical to guiding policies that seek to protect lake resources while also providing high quality amenities to people.

Lake Erie (Figure 2) is appropriate for this study because it has undergone profound changes in water quality associated with human influence and is geographically complex. As such, it is characteristic of other large lakes that "exhibit structures and processes found in ocean basins (e.g., discrete coastal zones and shelf breaks, large scale circulation patterns, etc.) yet are bounded systems with inputs and outputs that are constrainable." (SOFIS Working Group 2003). Most of Lake Erie's water input comes from the Detroit River, whereas most of its nutrient input comes from the Maumee and Sandusky Rivers, all three draining into the shallow west basin of the lake. The west basin drains into the deeper central basin, which is just deep enough to stratify thermally each summer, leaving a thin, cool layer (the hypolimnion) at the bottom that tends to go anoxic in late summer. The much deeper east basin stratifies thermally also, but is deep enough to have a larger hypolimnion volume so remains better oxygenated until fall circulation restores oxygen input from the atmosphere. The east basin drains via the Niagara River over Niagara Falls to Lake Ontario. The complicated thermal, nutrient, morphometric, and human population density gradients in the lake and its drainage basin result in profound spatial and temporal gradients in lake currents, water chemistry, and biology as well as its services to humans.

How do these coupled linkages influence the stability of dynamical variables within each subsystem?
We are interested in exploring the conditions under which coupled linkages lead to bifurcations or other "surprise" outcomes (Bar-Yam 1997; Bushev 1994) that may not occur in their absence. For example, interactions between lake ecosystem services and human recreational activities may increase the boom/bust cycle of economic activity around the lake, which in turn may push the human system beyond critical development thresholds and lead to irreversibilities in both the human and biophysical processes. In the absence of these linkages, such a phenomenon may not arise.

How do coupled linkages interact across differen oral and spatial scales and what is the influence of multiscale interactions on system dynamics? S of multiscale interactions have demonstrated that processes that operate at faster/finer resolution scales can "aggregate up" over time and space to cause small changes in processes operating at slower/larger resolution scales, which in turn can cause discontinuous changes if these changes occur at critical thresholds (Haken and Mikhailov 1993; Bushev 1994). We are interested in relating multiscale relationships and dynamics across physical, biological, and human components (Figure 4). Examples include how fast processes such as recreational day trips aggregate up over time and space to influence intermediate processes of marina and residential development around the lake, which lead to emergent, large-scale phenomena, e.g. suburbanization. Even small shifts in large-scale phenomena such as suburbanization patterns can cause discontinuous changes in faster biophysical processes, such as the response of algal growth to changes in nutrient levels or changes in fish spawning success associated with decreases in suitable spawning habitat.

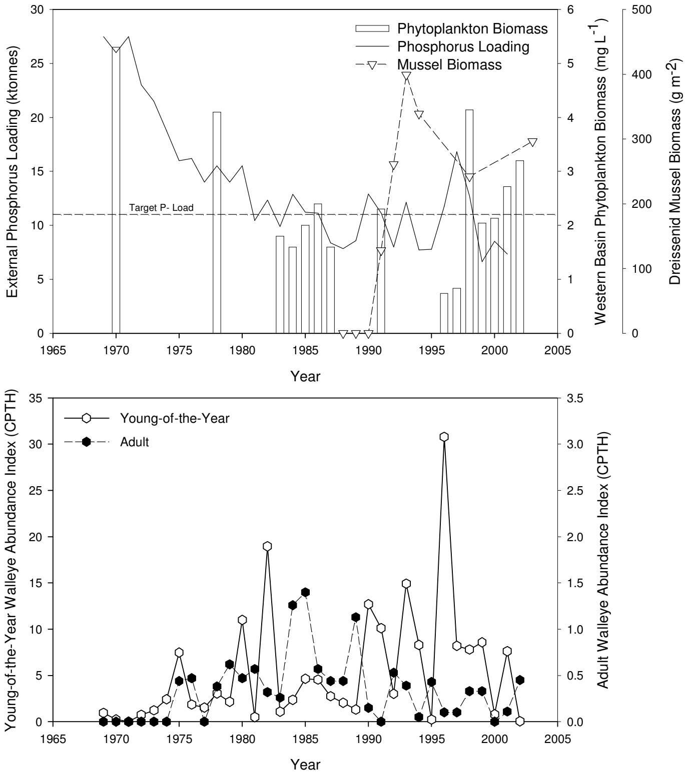

Figure 3. Recent variation in phosphorus loading, algal and zebra mussel biomass, and young-of-year and adult walleye in Lake Erie. The target P-load was determined as a likely maximum amount that would restore the health of the lake.

How does the nature of the couplings between the human and biophysical components alter the resulting dynamics? We are interested in exploring how the system dynamics are influenced by the nature of the human-biophysical couplings, including the fine-scale variations, instantaneous vs. time-delayed feedbacks, and deterministic vs. stochastic processes that may be embedded in the couplings. For example, animal populations exhibit nonlinear dynamics, including oscillations and possible deterministic chaos that are affected by the presence of predators (Tong, 1990). In recent years, Lake Erie walleye populations have shown both sudden jumps and declines (Figure 3b). While phytoplankton responded to the decline in phosphorus from the watershed (Figure 3a), and catch-per–trawling-hour (CPTH) of adult walleye (three years and older) increased in the 1980's two years after increases in young of year walleye (Figure 3b), recent adult walleye abundance appears to be decoupled from young of year abundance, causing concern by those responsible for managing the walleye populations for sport and commercial fishing (Ohio Department of Natural Resources 2003). The extent to which the change is related to the recent increase in the introduced zebra and quagga mussels (Figure 3a) and the introduced round goby, changes in commercial and sport fishing and other recreational behaviors, or policies that impact fish stocks is unknown. Nevertheless, it is possible that fluctuations in the number of sport fishers (which occur at multiple time scales because of the seasonal nature of the sport), the tendency of fishing to increase in years when fish are abundant, and the tendency for changes in recreational activities to be self-reinforcing, can synchronize with the natural population dynamics of the walleye. Such synchronization can destabilize a nonlinear system (Pikovsky, 2001).

Does a model with coupled linkages better explain observed phenomena and help identify appropriate management strategies for large lakes? Ultimately we are interested in the extent to which a coupled model offers better policy guidance by providing a better understanding of observed human-biophysical phenomena.

The long-term project goal is to exploit our extensive knowledge of Lake Erie to simultaneously investigate general principles of **modeling** complex human-biophysical systems and policy formulation for **managing** complex large lake systems.

Although we have significant expertise and experience among our group of researchers in modeling the various components of the human-biophysical system (Figure 1), we do not propose to simply link our existing models of the separate biophysical and socioeconomic processes to explore the research questions outlined above. The project goal is to explore the role of coupled linkages by developing the simplest structural models possible that capture the complex dynamics that result from key human-biophysical interdependencies. To achieve this goal, we will use an iterative process, starting with the simplest structural model that represents the key linkages and most basic components of a generic coupled system at a coarse scale in aggregate terms and then examine the dynamical behavior exhibited by the coupled model under a range of plausible parameter values. To further the model, a fine-scale model will be developed using the simple model as a guide and will parameterize the hypothesized structural relationships using data from Lake Erie. Our general approach in developing the fine-scale model will be to focus on modeling the key linkages, as defined by the simple model, at finer temporal and spatial scales and to model only those details of the human and biophysical component parts that are necessary for representing the coupled linkages and key system dynamics. This means that we will develop a new set of models to represent these linkages at this finer scale and will only adapt previously developed models or parts of models on an as-needed basis. The primary advantage of such an approach is that it allows us to model the coupled linkages at the relevant scales and in only so much detail as is minimally necessary for understanding the coupled system. We have already begun this process through our incubation project and our experience thus far suggests it to be a fruitful strategy.

The project will make an original contribution to scientific understanding of large lake ecosystems by analyzing the coupled linkages between human and biophysical processes and the way in which these interactions influence the self-organization and resiliency of biological and human systems. **The project will contribute to the general knowledge of complex systems modeling** by advancing our collective understanding of modeling techniques and issues involved in coupling human and biophysical systems that are both complex and complicated. We will **integrate research and education** by developing a new biocomplexity course, integrating biocomplexity topics into existing courses, and training a new generation of interdisciplinary biocomplexity researchers. **The project will promote teaching, learning, and understanding among broader audiences**. Building on our existing network of education professionals, the research will be systematically integrated with education programs starting with K-12, extending through undergraduate and graduate education levels to policymakers and the broader public to foster a better understanding of biocomplexity and why it matters. Based on the detailed Lake Erie model, **we will continue our work with policymakers to perform policy outcome analyses and identify policy implications** regarding the management of the Lake Erie watershed, which is of economic, social and aesthetic importance to the 14 million American and Canadian stakeholders living within its borders. **Because Lake Erie is an international ecosystem, these efforts will strengthen collaboration in international research and policy formulation regarding large lakes**. U.S. and Canadian policy makers have had extensive influence on the formulation of this proposal (see Supplementary Documents section of the proposal).

BACKGROUND

Large lake ecosystems are a vital component of the earth's biological and physical systems and provide numerable lake ecosystem goods and services that benefit humans. However, as in the Lake Erie case, ever-increasing impacts from humans, including substantial increases in amenity-based uses of large lakes, external loadings from nonpoint sources, and human-induced changes in biological structure, have placed strains on the biological functioning of these systems. Similar questions to those posed above apply to large lake ecosystems throughout the world (SOFIS 2003).

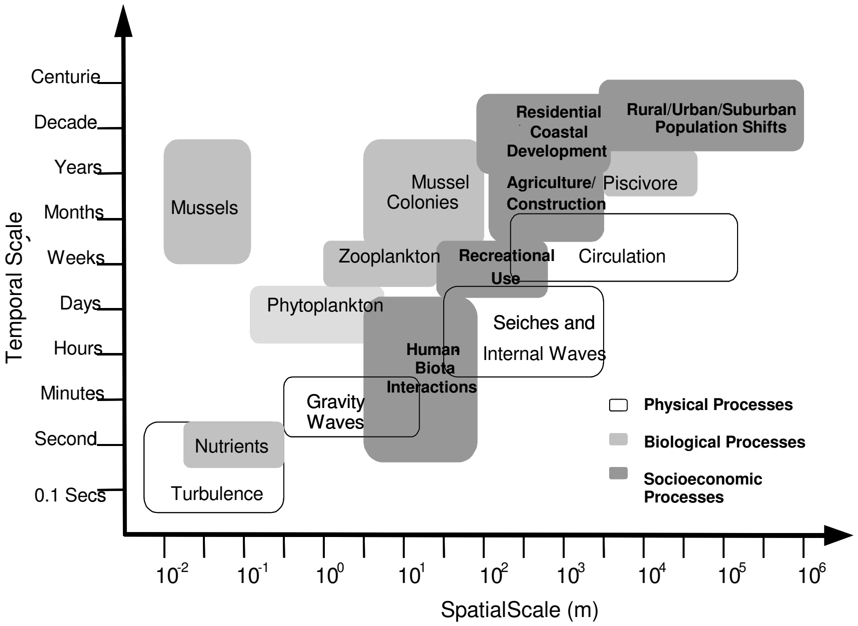

Figure 4: Temporal and Spatial Scales of Physical, Biological, and Human Processes

Despite the importance of large lakes and the fundamental linkages among human behavior, well-being, and ecosystem health that drive the complex behavior and sometimes surprise outcomes of large lake ecosystems, contemporary research is only beginning to develop models that integrate these components. To date, investigations of the dynamics of the biology of large lakes have largely assumed that: (1) the broad ranges of spatial and temporal scales of physical, chemical, and biological processes can be linearly decoupled, (2) human influences on large lakes can be adequately accounted for by measures of the inputs of toxics and nutrients, and (3) the feedbacks among these processes are for the most part negligible or only one-way. Collaborative teams of biologists, soil scientists, and hydrologists have made progress over the past ten years in improving our knowledge of the interactions between biological and physical dynamics by linking deterministic models of the physics, chemistry and biology of large lakes. At the same time, social scientists have made progress in understanding and quantifying the economic, recreational, and other benefits that humans derive from large lakes and assessing the role of government policies in improving water quality and the resulting impacts on human welfare. However, the interdependencies between human behavior and lake ecosystem functioning have largely been ignored or grossly simplified. Thus human inputs into ecosystems are treated in a fundamentally exogenous manner within biophysical models and conversely, lake ecosystem services are treated as exogenous in most models of human decision-making. As a result, we have a poor understanding of the nature and underlying dynamics of key feedbacks across the human and biophysical systems of large lakes.

Our Biocomplexity Incubation project has enabled us to recruit a team of biophysical and socioeconomic researchers to collaborate on the development of an integrated model to study the dynamics of coupled natural and human systems in large lakes. The group has constructed models of climate-watershed and climate-hydrodynamic interactions in large lakes (Bedford and Schwab 1991, Boegman et al. 2001, Boegman et al. (in prep.), Kelley et al. 1998, Limno-Tech 1995, 1997) and connected these models to water quality, lower trophic level productivity and the recruitment of fish (Cloern 1991, Culver 2000, DePinto et al. 1986, Frost and Culver 2001, Gopalan et al. 1998, Heath et al. 1995, Martin et al. 2002). Similarly, our socioeconomic researchers have modeled the interactions among land and water use, urbanization, and government policy (Carrion-Flores and Irwin 2003, Irwin 2001, Irwin, Bell, and Geoghegan 2002, Irwin and Bockstael 2001, 2002, Irwin and Geoghegan 2001); human responses to natural resource and environmental management and policy (Haab and McConnell 2002, Martin et al. 2000, Randall 1999, Randall and Farmer 1996, Sohngen and Mendelsohn 1998, Sohngen et al. 1998, 2001); and have estimated a range of impacts on human welfare generated by water quality, water levels and fish populations (Haab 2002, Haab and McConnell 1996, Haab and Hicks 1999, 1997, Murray and Sohngen 2001, Randall 1994, 1991a, 1991b, Kriesel et al. 1993, Hushak et al. 1988, 1999).

While this extensive inventory of completed research provides valuable background, our incubation project has identified three problems with simply integrating our existing models: (1) Discontinuities in time/space scales among the various constituent models (Figure 4) have led to difficulties in merging these models. For example, hydrodynamic models are often parameterized using data sets with time scales on the order of $10\text{-}10^4$ sec; plankton sampling is typically done once or less per month at spatial scales of 20 km; adult fish may be sampled and modeled on time and spatial scales on the order of 1 year and 300 km, respectively. Time scales for human models may be on the order of days to decades, depending upon whether we are considering decisions to fish or not to fish, as compared to decisions relative to purchasing boats or moving from one's home from one location to another. (2) Creating a model that connects our existing submodels with one another would create a complicated model, but not necessarily one that elucidates the complexity of the system. (3) A model whose parameters are calibrated to replicate the outcomes of a particular lake ecosystem (e.g. Lake Erie) may not be sufficiently general to describe other large lake ecosystems and is unlikely to offer generic insights regarding modeling techniques and methods for coupling systems.

Rather than simply integrating existing models of Lake Erie, we believe that a more fruitful strategy is to start with a simple, coarse-scale model of a generic large lake ecosystem that fosters a basic understanding of the underlying processes and coupled linkages and then to expand this model by increasing the spatial and temporal resolution and adding more detail to the structural relationships. This approach will allow us to do more than just develop a structural model of large lake biocomplexity that is then specified to Lake Erie. It will allow us to systematically explore characteristics of a coupled human-biophysical system that are key sources of complexity within a general framework and contribute to generic modeling methods related to coupling by examining how different specifications of coupled linkages, e.g., in terms of key variables, temporal and spatial scale, time lengths, and deterministic vs. stochastic processes, alter model outcomes.

OBJECTIVES

We propose to begin with Objective 1 and then iterate among Objectives 2-5:

1. Construct a simple, coarse-scale model of a generic large lake ecosystem with coupled human-biophysical interactions.
2. Examine a series of general complex systems modeling questions regarding the stability and robustness of the coupled system given different specifications of the human-biophysical couplings.
3. Develop a more detailed, fine-scale model by increasing the model's spatial and temporal resolution, adding more detail to the structural representation of coupled linkages, and parameterizing the model using Lake Erie data.
4. Test the fine-scale model's ability to explain observed human and lake outcomes and use the results to guide further improvements to the fine-scale model.
5. Make improvements to the simple model by aggregating predictions from the fine-scale model to the same scale as the simple model and comparing the models' results.

Given a final large lake model that is of sufficient detail to meet Objectives 3 and 4, then:

6. Use the detailed Lake Erie model to study the impacts of historical policies as well as new management strategies on human and biophysical processes.

METHODS

OBJECTIVE 1. Construct a simple, coarse-scale model of a generic large lake ecosystem with coupled human-biophysical interactions. Our initial conception (Figure 5) is a generic model of a large lake ecosystem that captures only the very basic components of each system in a highly aggregated manner and that purposefully represents these components in a highly stylized manner. We assume an aspatial world in which the human system is described by a regional economy that produces and consumes a specified set of goods. This market economy results in a total population level within the lake basin that is endogenously determined and an allocation of land to residential, industrial, recreational, and agricultural uses. The lake is represented as single-dimensional, i.e., varying only with depth, and having rapid equilibration of any horizontal variation in inputs or outputs. Population and the amount of land allocated to each use impact lake functioning through external loadings, which influence the growth of algae in the lake. The total amount of recreational services and fishing directly impacts fish stocks. Here we focus on just a few of the key lake ecosystem services that influence human decision-making: (1) water clarity, determined by phosphorus and algae concentrations; (2) fish density, a non-linear function of dissolved oxygen and phosphorus concentrations; and (3) beach closings, determined by coliform bacteria and phosphorus concentrations. Human demands for recreational services and residential housing are influenced by these lake services, as is the production of recreational services and sport/commercial fishing. The next steps in the development of this model are to explicitly link the lake ecology functions with human impact and lake service functions and add adult fish stocks to the lake ecological component.

Once fully specified, the model will first be analyzed by solving the human and biophysical systems separately for independent, equilibrium solutions. The minimal human system is a simplistic, equilibrium-based model of a regional economy in which the solution is driven by market clearing conditions that equate total demand and supply of each good. Given specific functional forms, this model can be readily solved for the equilibrium quantities of each good, total population, and land use allocations. The minimal biophysical system is represented as a suite of physical, biological, and chemical interactions minimally necessary to describe a generic eutrophic lake. Thermal stratification of the water column is included as are water level changes, weather-driven mixing, and sunlight. Bacteria and dissolved oxygen are included to capture certain ecosystem services (e.g. beach closings) and the possibility of an anoxic zone in eutrophic lakes. The remaining components are those found minimally necessary to describe eutrophication interactions through the zooplankton levels. Solving these systems first independently provides a means of comparing the model results with equilibrium solutions available from the existing literature, i.e., solutions that have been extensively analyzed for equilibrium conditions.

The next step in this objective is to determine the equilibrium behavior of the coupled system. Although the independent human and biophysical models are very simple, the presence of coupled linkages is likely to introduce complex dynamics. The linkages introduce a heretofore unmodeled process of dynamic adjustment between the human and biophysical systems that may alter the time scales of these processes, and introduces the possibility of newly observable destabilizing or stabilizing behaviors. For example, changes in lake services can lead to changes in the production and consumption of goods, which will alter the allocations of land to different uses. Small changes in land uses that alter the amount or concentration of loadings can cause discontinuous changes in the time path of these concentrations, which can have nonmarginal impacts on algal growth and, in turn, on lake services such as water clarity and even beach closings. A mix of analytical and simulation methods will be used to solve the model. Empirical orthogonal functions, eigenfunction/value analysis and correlation profile analysis (Maslov et al. 2003) will be used to quantify the differences in system response to perturbations in the input variables and to identify the fixed points, attractors and corresponding stability conditions. Given a characterization of the baseline coupled system dynamics, we will explore the role of coupled linkages with these methods by altering key parameter values that govern their behavior. To investigate the influence of coupled linkages on equilibrium and/or stability, we will “turn off” linkages one-by-one and instead treat each as exogenous. The dynamics of this constrained model will be compared to the unconstrained model to study the extent to which each link alters system dynamics and under what conditions its presence creates a stabilizing or destabilizing influence. Of particular interest is the existence of possible multi-state outcomes for each set of input conditions.

This simple model omits any direct representation of policy responses, but it is possible to investigate the impacts of certain exogenously imposed policies, e.g. a hypothetical limit on the total annual catches of adult fish. In Objectives 3 and 4, when more detail is added to the model, we will consider the effects of actual policies (e.g., the effects of changing the catch and possession limits for walleye from 10/day to 8 to 5 to 4 and now 3, and the limitation of the number of commercial gillnet fishing licenses) and will make policy endogenous—i.e. the result of changes in lake functioning or human behaviors.

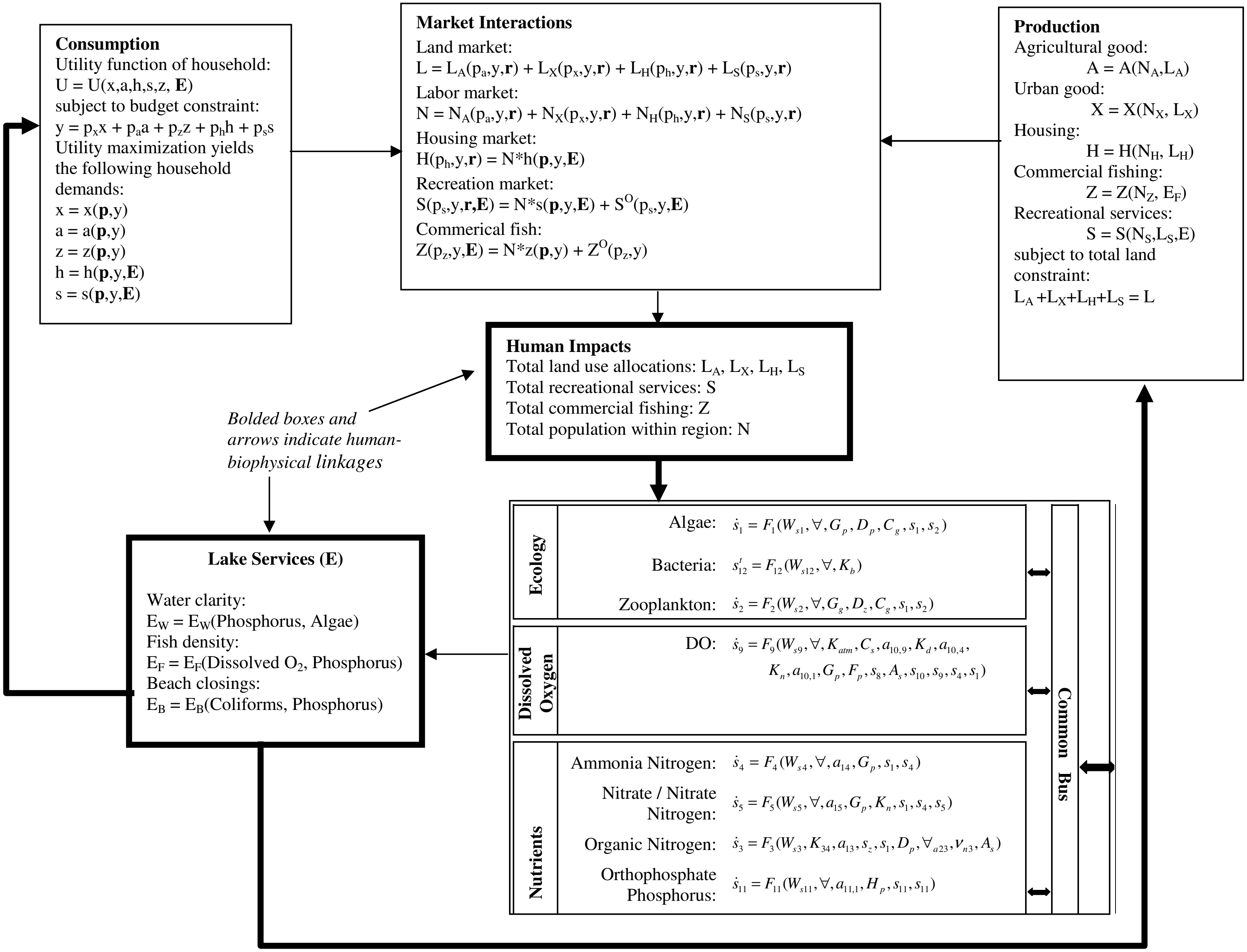

Figure 5: Draft of minimally complex integrated model of a generic large lake with coupled human-biophysical interactions

Key to Figure 5

Socioeconomic Variables

A = total agricultural good
X = total urban good (composite good)
H = total housing
Z = total commercial fish production
S = total recreational services
S^O = outside demand for rec. services
L = total amount of land in region
L_X = land allocated to urban production
L_S = land allocated to rec. services
N_A = labor allocated to agr. production
N_H = labor allocated to housing production
N_Z = labor allocated to commercial fishing

a = household demand for agricultural good
x = household demand for urban good
h = household demand for housing
z = household demand for commercial fish
s = household demand for rec. services
Z^O = outside demand for commercial fish
L_A = land allocated to agricultural production
L_H = residential land
N = total labor (population)
N_X = labor allocated to urban production
N_S = labor allocated to rec. production

p_a = price of agricultural good
p_x = price of urban good
p_h = price of housing per square foot
p_z = price of commercial fish
p_s = per unit price of rec. services
r_a = agricultural land rent
r_x = urban land rent
r_h = residential land rent
r_s = recreational land rent
y = unit wage (exogenous income)
$\mathbf{r} = (r_a, r_x, r_h, r_s)$
$\mathbf{p} = (p_a, p_x, p_h, p_s)$

Biophysical Variables

E_W = water clarity
E_F = fish density
E_B = number of beach closings
$\mathbf{E} = (E_W, E_F, E_B)$
A_s = surface area of lake
a_{ij} = production ratio of species I to species j
C_g = grazing rate of zooplankton on phytoplankton
C_s = dissolved oxygen saturation concentration

D_p = phytoplankton death rate
D_z = zooplankton death rate
E = turbulent exchange coefficient
F_i = functional form of the s_i constituent equation
G_p = phytoplankton growth rate
G_z = zooplankton growth rate
I = solar insolation
K_b = bacteria decay rate
K_d = CBOD decay rate

K_n = decay rate for nitrogen
K_{ij} = loss rate of species i to species j
K_{atm} = atmospheric reparation coefficient
$s^{\bullet}_i$ = time rate of change of ith constituent
s_i = ith constituent concentration
$\forall$ = lake volume
v_{ni} = settling velocity of the ith constituent
V_w = wind speed
W_{si}= net lake throughflows

OBJECTIVE 2: Examine the stability and robustness of the coupled system given different specifications of the human-biophysical couplings. We will use the simple model, both in its initial (Objective 1) and modified (Objective 5) forms, to investigate how a variety of perturbations to the system and different specifications of the couplings might alter the self-correcting tendencies of the system. In examining this question, the goal is to contribute to the science of complex systems by exploring the stability and robustness of a simple human-biophysical system under a variety of conditions and to make methodological contributions along the way, e.g., in developing aggregation methods for relating fine-scale and coarse-scale models of the same system.

Several different types of perturbations to the system will be considered: (a) changes in the average quantities of aggregate variables defined at coarse scales contained in the simple model, (b) variations at a fine-scale that hold constant the average values of aggregate variables, e.g., a change in the spatial variation of nutrient loadings that holds constant the average weekly loadings into the lake, (c) variations in the time lengths associated with the feedbacks between human and biophysical processes, and (d) fluctuations due to a specified stochastic process that is exogenously imposed, e.g., a stochastic lake temperature variable. While the first three types of perturbations may occur in a fully deterministic, dynamic system, the latter perturbation is due to one or more random fluctuations that are extrinsic to the system. Each of these is discussed in turn:

(a) **Perturbations in average values:** Due to nonlinearities, small variations in the average values associated with human processes may be propagated through the coupled system to produce large changes in biophysical outcomes or vice versa, small variations in biophysical variables may produce large changes in human outcomes. For example, certain aquatic populations, including phytoplankton and many adult fish stocks, are known to exhibit nonlinear dynamics, e.g., due to density dependence (Higgins, et al., 1997; Stollenwerk et al., 2001). Such nonlinearities imply that seemingly small alterations in human activities, including small scale variations in the amount and spatial pattern of land development or fishing activity, can propagate through the system to generate threshold behaviors. We will investigate the robustness of states predicted by the simple model to changes in the average values of key aggregate-level variables in the simple model, paying particular attention to how small alterations in key variables associated with one subsystem (e.g., human) may generate large-scale changes in the predicted states associated with the other subsystem (e.g., biological).

(b) **Fine-scale variations:** The lake-human ecosystem considered here is characterized by extreme spatial and temporal heterogeneity, e.g., species composition are fundamentally different across nearshore and offshore regions of the lake; the value of land varies with distance from the lake, population centers, and a variety of other locational attributes. There are many different yet plausible spatial and temporal distributions of key variables. Some may correspond to the same aggregate values of these variables (as represented in the simple, coarse-scale model), but could have very different implications for the dynamics of the system. For example, increased run-off due to seasonal variations in land development could entrain other seasonal cycles of the lake, e.g., eutrophication, and affect the dynamics of phytoplankton and adult fish stocks in a nonlinear fashion, depending on the relative spatial distributions of these processes. That is, an increase in phosphorus inputs in the west basin in August and September due to home building is more likely to stimulate toxic algal blooms than the same amounts of phosphorus entering the central basin in March. To better understand how changes in fine-scale variations scale up over time and space, we will use aggregation techniques to compare different model outcomes predicted by the fine-scale model developed in Objectives 3 and 4. By aggregating the predictions of the fine-scale model up to the same scale as the simple model, we will be able to examine how fine-scale variations are propagated through the system to generate larger-scale changes in system dynamics. See Objective 5 for more details on possible aggregation techniques.

(c) Time delays: Time-delayed feedbacks destabilize systems and can introduce a host of complex dynamics, e.g., they can create a greater tendency for a system to oscillate (Glass and Mackey, 1988; Kuang, 1993). While our initial simple model assumes instantaneous feedback between the human and biophysical linkages, a more realistic and interesting representation is one that accounts for time delays in these couplings. We suspect that human-biophysical linkages are characterized by substantial time delays, e.g., due to finite propagation speeds of biophysical processes and finite reaction times among humans. For example, incremental changes in water clarity are not likely to result in corresponding incremental changes in demand for recreational services and lakeside housing; rather, human responses to these changes will occur much more slowly, e.g., over the time span of months and years, and may be punctuated by policy interventions that occur in response to threshold events, e.g., an algal bloom. Even in the absence of large-scale policy interventions, network effects in information diffusion are likely to cause delayed human responses. To explore such dynamics, we will first examine the role of time delays within the human, biological, and physical subsystems separately to understand how time delays can alter the dynamics contained within each component. Then, keeping the specification of the subsystem models constant, we will introduce time delays in the couplings and explore the conditions under which time delays between human and biophysical processes cause the system to become destabilized.

(d) Stochastic processes: Although the initial specification of our large lake ecosystem model is deterministic, it is clear that both human and biophysical processes are subject to considerable extrinsic fluctuations. Random variations in a variety of key human or biophysical variables are plausible, e.g., lake temperature, water levels, storm patterns, nutrient loadings, population growth, or household incomes. In this case, noise-induced transitions could play a major role in determining the system dynamics, e.g., stochastic forcing can induce transitions between different attractors and can even lead to transitions to new states in multi-stable dynamical systems (Longtin et al., 1991; Moss et al., 1994). We will examine the role of noise in our coupled system by specifying stochastic processes associated with key variables and examining how the resulting fluctuations alter the system dynamics. To elucidate the role of coupled linkages, we will focus on how stochastic fluctuations associated with biophysical processes alter the dynamical behavior of key human variables and vice versa, how fluctuations in human processes alter the dynamics of key biophysical processes. We will consider different specifications of the stochastic processes—for example, additive or multiplicative forms and fluctuations that are either independent or correlated across time or space. Time-series data on key variables will be examined to specify the distributions of these stochastic processes.

OBJECTIVE 3: Develop a detailed, fine-scale model by increasing the model's spatial and temporal resolution, adding more detail to the structural representation of coupled linkages, and parameterizing the model using Lake Erie data. For a variety of reasons, we expect that our simple model as initially developed in Objective 1 will offer useful, but incomplete insights regarding the observed dynamics of large lake ecosystems. First, this model does not allow for key sources of spatial heterogeneity (e.g. hydrology, roads, coastline, bathymetry) that have large impacts on economic activities and lake functioning. Second, it assumes a large degree of homogeneity in other aspects. For example, all households are homogeneous in preferences and incomes, whereas we know that differences in preferences for environmental amenities and housing choices will generate human choices that differentially impact lake functioning. Third, it ignores interdependencies that exist at finer temporal and spatial scales within human and biophysical processes, across these processes, and across different scales that are sure to drive complex behavior at a systems level.

For these reasons, a fine-scale model of a large lake ecosystem will be developed that will represent the human and biophysical processes and the coupled linkages in greater detail and at finer temporal and spatial scales. The simple model developed in Objective 1 will be used as a guide to developing this fine-scale model. Specifically, more detail will be added to the structural representation of the key coupled linkages specified in the simple model and the representation of the corresponding human and biophysical components will be expanded as needed. In addition, the exploration of complex dynamics in Objective 2 will indicate which linkages and variables are key drivers of complexity and therefore need more detailed representation in the fine-scale model.

Specification of the model will require a host of Lake Erie data (see Progress To Date section) and, in some cases, empirical analyses to identify key structural parameter values. The resulting dynamics and outcomes that are produced by this model will then be explored for a range of parameter values that are relevant to Lake Erie. In doing so, we will maintain a process-based approach in which we seek to identify the underlying values of the structural parameters of our model using historical data. Such an approach is very different from a pattern-based approach, in which data on observed outcomes (e.g. land use patterns) are used to calibrate the model so that it predicts qualitatively similar outcomes.

While not all the specifics of the fine-scale model can be described at this point, since the exact model evolution will depend on completion of Objective 1 and results from Objective 2, we can describe certain aspects of a significantly more detailed model based on previous experience. We do so at the risk of appearing to simply string together disparate models, since the discussion that follows is more oriented to the various biophysical and human components rather than being centered on the details of the key couplings. We emphasize that this will not be the approach that will ultimately be used to actually develop the fine-scale model. The development of a fine-scale large lake ecosystem model of key human-biophysical couplings is one of the primary goals of this research and is something that has not yet been accomplished by us or anyone else. The discussion below reflects our expertise and experience as modelers within our respective disciplines, something which is a prerequisite to accomplishing the much more ambitious goal of developing a new model of the key coupled linkages.

Two and three-dimensional, fine-scale, cell-based models of the watershed and lake respectively will form the common core of the model. A fine-scale, spatially explicit framework is used to integrate across different spatial and temporal scales (Martin et al. 2002, Martin et al. 2000) and integrate across the land/water interface (Costanza et al. 1990, Martin et al. 2002). A spatially explicit watershed model will simulate the effects of cross-scale, spatial changes in land use and population on external loadings of nutrients from the watershed, through rivers, to the coastal zone (Martin et al. 2002, Reyes et al. 2000). The landscape will be divided into relatively small grid cells (e.g., 1 km^2 on land, near-shore areas and offshore). The relationships within each cell will be described by a unit model that is specific to either water or land habitats. A hydrodynamic model based on MIKE 21 (Danish Hydraulic Institute) will connect the grid cells and provide for the transport of water, nutrients, and other materials across the watershed and lake.

In addition to the watershed model described above, the lake circulation, transport, water quality and food web model will also be embedded into the fine scale framework. The core of the lake model is comprised of two existing components, the models comprising the Great Lakes Forecasting System and the water quality/ecological modeling system developed by J. DePinto at LimnoTech for use in Saginaw Bay, Lake Huron, calculations (LimnoTech 1995, 1997). The base model of the Great Lakes Forecasting System is the Mellor-Blumberg (Blumberg and Mellor 1987, Mellor 1998) Princeton Ocean Model, a model used in over 150 site-specific applications around the world. The model is a fully three-dimensional, hydrostatic pressure based code that has full accommodation for sub-hourly heat flux and wind stress inputs as well as tributary inflows from the major rivers. This formulation has proved extremely accurate in predicting the three-dimensional currents, temperature, and sediment as well as the two-dimensional distributions of wind waves and water levels resulting from storms. The code presently operates at 20-minute time intervals and 2-km horizontal grid intervals. A 12-slice terrain-following coordinate system is also employed. For this project the horizontal grid spacing will be decreased to 1x1 km. By use of the DePinto formulations mentioned above and the interaction functions identified from Objectives 1-3, the model will be used to examine the localized effect of nearshore land use activities on water quality and lower food web interactions as well as processes involved in the formation of planktonic and other patchiness in the lake and their aggregation into data required by more integrated or volume-averaged models. The detailed model will more directly relate to process rate coefficients that are observed at points in space and time in the field or even in the laboratory.

Given the more detailed specification of lower trophic dynamics, we will subsequently add in the processes involved in the survival of each year's cohort of fish hatchlings as a function of plankton dynamics and nutrients and the role of zebra mussels in observed changes over and above those caused by changes in point and non-point loading. These additions will allow us to explore the effects of human impacts from the watershed vs. human impacts on changes in biological structure due to the unintentional introduction of another species. Dynamics of adults of major sportfish species will be based on Catch-at-Age Analyses (CAGEAN) models of abundance data from the Great Lakes Fishery Commission's Lake Erie Committee, who annually summarize fish abundance from commercial fishing data, gillnet sets, trawling surveys, and creel surveys of fishermen and then sets sport and commercial fishing catch limits.

Outputs from the fine-scale biophysical model will be spatially delineated lake ecosystem services that feed into the human decision-making model. A spatially-explicit, agent-based model that overlies the cell-based watershed model will form the core human component of this model with households, landowners, and producers of recreational services as the primary agents. Multiscale interactions among agents and between agents and the environment will be key drivers of agent behavior. Agents make choices over a range of different time lengths, e.g., choices among recreational activities operate on fast time scales (daily or weekly); residential location choices occur over an intermediate time length (months or years); and changes in regional land use patterns evolve on a slow time scale (decades). Spatially mobile households derive utility from recreational activities, housing consumption, and other goods and are heterogeneous in income and their preferences over lake amenities, housing, and neighborhood amenities. Landowners face choices regarding the use of their land in a residential, recreational, commercial, or agricultural state and will make a decision to convert land or maintain it in its present use based on expectations over net returns to land conversion. Lastly, producers of recreational services make choices regarding the location and type of recreational lake services they will offer (e.g. marinas, charter boats, businesses, vacation home development), based on the cumulative demands from households and the supply of land. Agents operate within an environment that is defined by a two-dimensional grid of the lake basin, which contains the lake coastline and individual parcels of land that may be occupied by agents and used for residential, recreational, commercial, or agricultural purposes. Key sources of spatial heterogeneity within this landscape include road networks, natural features (e.g. hydrology, slopes, and soils), urban centers, and other public infrastructure (e.g. public sewer and water lines). In addition to the coupled linkages that create endogenous environmental amenities in the form of lake services, other environmental features will also be treated as endogenous to human activities (e.g. landscape patterns, transportation networks, and public services provision). We will make use of previous research in the Lake Erie region on land use and recreational decision-making to specify the model. We also plan to conduct new research with the support of additional grants (e.g., Irwin and Haab will begin funded research in Spring 2004 on demands for lake services and their influence on land use patterns) that will provide opportunities for more data collection and empirical analysis via statistical and experimental methods. Once specified, the model will be executed using a low-level object-oriented programming language (e.g. Java or Objective C), using either RePast or Swarm libraries, both of which are agent-based modeling software programs.

The more detailed representation of the human, physical, and biological components will allow us to represent the coupled linkages between human behavior and lake functioning in a spatially explicit and disaggregate manner. For example, the watershed model will map changes in land use and population into external loadings of nutrients from the watershed by aggregating up from parcel-level to larger grid cells of the landscape (e.g., drainage basins). The cumulative effects of discontinuous changes in the rate and pattern of development will be captured through this model by the rate, concentration, and spatial pattern of external loadings to the lake. Likewise, the spatial distribution of lake services (e.g. water clarity, fish stocks, and beach closings) will be explicit and allow modeling of the spatial patterns of recreational choices and land use conversion that occur along the lakeshore and in the lake basin. This allows consideration of how competition over highly desirable locations will influence agent behaviors, e.g., in terms of bidding up prices for land, influencing the pattern of development, and introducing congestion effects, all of which can have differential impacts on lake functioning. This more detailed approach will also allow us to capture the impacts of incongruent human-lake, multiscale interactions as well. For example, water levels exhibit trend persistence (Mandelbrot, 1983) over multiple years, so that levels may be persistently high for a decade, but human responses to high water levels may occur on a different time scale, e.g., marina construction occurs more rapidly than this. Developers who build marinas during high water years face the risk of being left high and dry when the waters recede. Additional construction therefore becomes necessary to safeguard investments, but the effects of such construction on nearshore lake functioning remain unknown.

OBJECTIVE 4: Test the fine-scale model's ability to explain observed human and lake outcomes and use the results to guide further improvements to the fine-scale model. As a means of testing the fine-scale model and providing guidance for model improvements, we will conduct an "applications test" in which the model is evaluated based on its ability to predict observed lake and human outcomes. For example, we anticipate testing the model's ability to explain changes in things such as phosphorus levels due to loading management and the frequency of harmful algal blooms (HABs) with respect to cultural eutrophication. Eutrophication describes the natural aging process of lakes—as lakes age, they become shallower, warmer, and often more productive due to nutrient enrichment. By the term "cultural eutrophication," we mean the biophysical process of nutrient enrichment as modified (most often accelerated) by human behavior. In Lake Erie, these eutrophic conditions have occurred due to excess phosphorus, which has in some years caused over 90% of the water below the thermocline in the central basin to become anoxic and thus unable to support bottom fish like yellow perch and walleye there in many summers. Since the Cuyahoga River caught fire in 1969, management agencies have been remarkably successful in reducing the annual loading of phosphorus to the lake from approximately 29,000 metric tons in 1969 to the target of 11,000 metric tons and even lower in some years, primarily by introducing tertiary treatment on domestic sewage treatment facilities. However, phosphorus concentrations in the Lake began to rise again unexpectedly in 1995. The extent to which this change is due to sustained development and land use change within the watershed or the invasion of dreissenid (zebra and quagga) mussels is unclear. We will use the fine-scale model developed in Objective 3 to investigate both hypotheses.

We will assess the model's performance vis-à-vis its ability to predict observed lake and human outcomes and, based on this assessment, will expand the representation of the underlying structural relationships, e.g., by adding or subtracting detail in the representation of the coupled linkages or the corresponding human or biophysical components. Such an approach will allow us to identify characteristics of the more detailed structural relationships that are critical in generating complexity in a way that is tractable and avoids the problems associated with a big, "black box" model.

OBJECTIVE 5: Make improvements to the simple model by aggregating predictions from the fine-scale model developed in (3) to the same scale as the simple model and comparing the models' results. We suspect that the initial conceptualization of the simple coupled system in Objective 1 will omit or misrepresent key linkages and variables. Therefore we propose to make improvements to the simple model developed in Objective 1 by comparing the results from the fine-scale model developed in Objectives 3 and 4. We will use aggregation techniques to scale the results from the fine-scale model up to the same scale as the simple model and compare the model outcomes. It is highly likely that these results will differ, perhaps dramatically, in which case we will adapt the simple model by changing the couplings, adding what we believe to be new key variables, or changing the scale at which key variables operate. Improvements in the simple model will enhance the analysis of coupled linkages and system stability detailed in Objective 2. In addition to making model improvements, we will make a methodological contribution to the general literature by investigating aggregation techniques to link coarse-scale, aggregate models with fine-scale models that contain many, disaggregated components.

The central challenge of this step is in aggregating results from the fine-scale model to a much coarser spatial and temporal scale in a way that preserves the important variations exhibited at the finer scales. There are several methods that appear potentially fruitful that we will investigate, including singular value decomposition (Press et al, 1992; Golub and Van Loan, 1996), also known as Karhunen-Loe`ve expansion in pattern recognition and as principal-component analysis in statistics, and network analysis techniques (Dorogovtsev and Mendes 2003). Both approaches offer means for identifying macroscopic patterns from variations in fine-scale processes. Singular value decomposition provides a mathematical approach for summarizing as much of the observed variation at as fine a scale as possible in a few macroscopic variables. Network analysis provides a means of summarizing the size of the network comprised by the individual components contained within the system, e.g. the number of vertices and links, and the total and mean degree of the network, as well as a characterization of the number of levels of structural organization in the network and the scales over which they operate. An additional consideration is whether a probabilistic framework is required in order to embed the effects of the rapid, localized, and intense effects of random fluctuations such as storms and other extreme events. These methods have been effective within individual component areas of complexity analysis—we will test whether or not they work for models linking physical, biological, and socioeconomic models together. Lastly, once we have aggregated from a fine to coarse level, additional aggregations of variables may be possible by identifying pairs of similar components that can be combined to form one component. For instance, all gamefish could be combined or ortho-phosphate and organic phosphorus could be combined. The predictions of the model will be tested after each aggregation and if they deviate significantly from the data, the aggregation will be reversed and individual components restored to the model. By following this process we will identify more detailed components that should be maintained to accurately represent the lake-human system and eliminate unneeded detail.

OBJECTIVE 6. Use the detailed Lake Erie model to study the impacts of historical policies and new management strategies on human and biophysical processes. Once we have developed the detailed model specified to Lake Erie, we will use this model to investigate historical and alternative policies. Although the predictability of complex systems is limited due to nonlinearities and the potential for apparently trivial historical events to influence large-scale outcomes (Williams 1997; Kaplan and Glass 1995), we can use the model to understand the range of outcomes that are plausible for given changes in parameter values that government policies may influence. We are particularly interested in determining whether this model suggests ways in which policy interventions and management decisions made in the past could have been improved had we better understood the coupled dynamics of human and biophysical components of the lake. For example, building the St. Lawrence Seaway enabled sea lampreys (along with pollution and overfishing) to decimate the lake trout population in Lake Michigan resulting in overpopulation by the introduced alewives. Initial stocking rates of salmon in Lake Michigan to control alewives were so high that native bloater chub fish populations were severely threatened as well. Given the time lags that characterize many of the coupled linkages, it is plausible that policy interventions occurred "too late" in the past and, rather than stabilizing system dynamics, resulted in the opposite. In addition, we will examine how policies not directed at lake management may nonetheless influence lake functioning and human behaviors, particularly in nonlinear ways. For example, a change in agricultural subsidies will alter both the amount of land planted in a given crop and the spatial distribution of that land. This, in turn, will alter the flow of sediment and nutrients into Lake Erie, with effects on algae, fish, and the recreational economy of the lake. A change in land use regulations that affects the rate of suburbanization could also influence the dynamics of sedimentation and nutrient loading (Tramer 1987). Such linkages among policies, human behaviors, and lake functioning, poorly understood in the past, are the heart of our study domain. As a start, we will re-consider the model used in the 1970's to determine how to manage Lake Erie eutrophication (essentially the bottom right portion of Figure 5) by re-examining this question with the fully coupled human-biophysical model to determine whether the management outcome (lowering of phosphorus loads) was indeed optimal.

PROGRESS TO DATE

Our project is intentionally multidisciplinary in nature and follows on a series of collaborations among the PIs, the senior personnel, and numerous others. As part of our NSF Biocomplexity Incubation Grant, we organized symposia and workshops to bring together teams of researchers to identify ways to study the role of coupled interactions in generating large lake biocomplexity. We have also modeled various aspects of integrated human-biophysical systems (e.g. Irland et al., 2001; Lindern et al. 2002; Sohngen and Mendelsohn 1998; Sohngen et al. 1998, 2001; Wu and Irwin 2003). Irwin and Martin initiated funded research in September 2002 to develop an integrated spatial model of land use and habitat changes in the Sandusky watershed within the Lake Erie basin. Jayaprakash, Warren, and Irwin have begun development of an agent-based model of household location with endogenous environmental amenities. Most recently, we have made progress on the minimally complex, generic model as a draft model for Objective 1 (Figure 5). In addition, we have made progress on the following:

Biological and Physical Components. The development of the Great Lakes Forecasting System (GLFS) (Bedford and Schwab 1991, 1994) has produced hydrodynamic calculations with a time-dependent, primitive equation, coastal ocean circulation model (Blumberg and Mellor 1987), and meteorological models are coupled with code (Kelley et al. 1998). From April to December of each year, GLFS produces remarkably accurate predictions of water level, temperature, current velocity, etc. four times per day on a 2 km x 2 km grid. Though not released as part of the standard GLFS Web product stream, GLFS also produces proprietary forecasts and nowcasts for coliform bacterial contamination and beach closure warnings, sediment transport, selected metals and toxics, and three types of radionuclides. Additional collaborative research has connected physical and biological processes in large lakes (Ackerman et al. 2001, Boegman et al. 2001, Boegman et al. in prep). Accomplishments have also included the coupling of hydrodynamic and ecological models to simulate ecosystem dynamics at the interface of land and water environments (Martin et al. 2002). Landscape models have been developed and applied to predict the consequences of Mississippi River management upon habitat change and water quality within the Mississippi Delta (Martin et al. 2000, Reyes et al. 2000). We have also made excellent progress on modeling effects of climate on the watershed interaction with lake water quality and the dynamics of the lower trophic levels (algae, zooplankton, benthos, juvenile fish), as well as the survival and growth of adult fish so they can be managed by state and federal agencies for sport and commercial use. In addition, seasonal variation in nutrient dynamics, algal production, zooplankton abundance, and the recruitment of a new cohort of juvenile fish have been studied and modeled extensively (e.g., DePinto et al. 1986, Gopalan et al. 1998).

Human Components. We have studied the influence of water-based amenities and other features of neighborhoods, communities, and the surrounding landscape on residential location and land use change (Bockstael and Irwin 2000, Irwin and Bockstael 2001, 2002, Irwin and Geoghegan 2001, Bell and Irwin 2002, Sohngen et al. 2000). A spatially explicit, spatial econometric model of residential land use change for a part of the Lake Erie Basin (Medina County) has been developed using parcel-level data and other geographically referenced data (Carrion-Flores and Irwin 2003). Randall and Taylor (2000) studied incentive methods for influencing behavior of individuals generating nonpoint source pollution from agricultural land uses. In addition, environmental amenities, including water levels (Kriesel et al. 1993) and open space (Irwin 2001), affect neighboring housing values, which can be used to estimate changes in future residential growth patterns of a region. Kim (1992) estimated the welfare loss from flooding and bluff erosion due to high lake water levels, as reflected in the market for shoreline housing, and Kriesel and Randall (1994) have established the economic viability of cooperation among homeowners to provide shoreline protection. Recent research illustrates the profound economic implications of accidental introductions of aquatic nuisance species in the Great Lakes (Thomas and Randall 2000, Randall and Gollamudi 2001); Gollamudi and Randall (1998) designed an efficient monitoring scheme for Great Lakes shipping to intercept subsequent nuisance species, some elements of which have been adopted by the Coast Guard. Abundant research shows how individuals value improvements in lake-based goods and services, including recreation demand for beaches, boating, and fishing (Haab 2002, Haab and McConnell 1996, Haab and Hicks 1999, 1997, Haab and Whitehead 1999, Murray and Sohngen 2000, Randall 1994, 1991a, 1991b, Sohngen et al. 1999). Haab is tracking recreation behavior across a full boating/fishing season through a multi-period survey of boaters and anglers. He will model multiple-site decisions over multiple-choice occasions incorporating temporal and spatial correlation between choices. We have estimates of the economic importance of Lake Erie in the regional economy and the extent to which it is an input into the production of goods and services within certain sectors, e.g. tourism, manufacturing, commercial fishing, sport fishing, and construction (Hushak and Lichtkoppler 1990, 1993; Morse et al. 1986). Lastly, we have expertise in estimating the welfare effects (i.e. benefits and costs) of changes in the level of environmental amenities. In particular, Randall has been a major contributor to the development of theory and methods in welfare measurement (Randall 1999, Randall and Farmer 1996, Chen and Randall 1997, Hoehn and Randall 1989, 1987) and Haab has made major contributions to research on environmental and natural resource valuation (Haab and McConnell 2002, 1997, Haab et al. 1997).

Data Available. USGS provides discharge values for most streams in the drainage basin plus chemical and toxic compound concentration data, allowing calculations of loading values. Temporal and spatial variation in nutrient, dissolved oxygen, phytoplankton, and zooplankton abundances are collected by a consortium of individuals associated with the Erie Lakewide Management Plan (LaMP) sponsored by the USEPA, state and provincial departments of natural resources, the National Water Research Institute (NWRI) at the Canada Centre for Inland Waters, and USGS. Phytoplankton, chlorophyll, and zooplankton samples collected by the Ohio Division of Wildlife, NWRI, and the Ontario Ministry of Natural Resources from 1995-2002 (and in 2002 and 2003 by Culver and his graduate students on a total of five 6-day cruises of the USEPA's *RV Lake Guardian*) have been analyzed in Culver's lab, helping him build the largest database on Great Lakes plankton ever constructed. He has results from as many as 80 open lake stations visited 10 times per year. Fish management data (trawl surveys, sportfish creel surveys, and commercial fishing catch data) are also collected and coordinated by many of the same institutions plus the Great Lakes Fishery Commission. The USEPA performs water quality and biotic surveys of all the Great Lakes twice per year, and has data from 1968. In addition to these data, we also have extensive data from monthly cruises in 1970 when the lake was maximally eutrophic. Land use/land cover data are available from satellite and aircraft over-flight images and, for some counties, digitized county land parcel records are available, as are primary data on Lake Erie beach visitation (Murray et al. 2000). Further, in separate projects, data collection is occurring on specific segments of boaters and fishers, including steelhead anglers (who concentrate their effort on streams that feed Lake Erie) and charter boats carrying anglers seeking to catch yellow perch and walleye. Additional secondary data on boaters, anglers, marinas, state park usage, and other data related to recreational uses of Lake Erie are available from a variety of state agencies, including the Ohio Department of Natural Resources' Watercraft Division, Coastal Management Program and Department of Wildlife. Sub-county population and socioeconomic data are available to us from the decennial Census of Population. County-level agricultural and economic data are available from the Census of Agriculture and the Economic Census, respectively, both of which are conducted every five years.

EDUCATIONAL PLAN

Education is explicitly included in our study design, effectively becoming a seventh objective. We will **(1)** train a new generation of interdisciplinary researchers incorporating socioeconomic, physical, and biological components and **(2)** integrate research and education by educating and training undergraduate and graduate students via the development of a new, biocomplexity course as well as via existing courses and programs. More specifically:

Training a New Generation of Researchers. Our target groups are junior faculty, graduate students, and undergraduate students. We have recruited six junior faculty members to work with us on the modeling activity, with four given co-leader status on our working groups and one as Co-PI. Five graduate students at two universities will work on all phases of the project, providing excellent opportunities for cross-fertilization of ideas and concepts during fieldwork and analytical collaborations. We will maximize the opportunities for education by involving faculty at all career levels in the project, with explicit mentoring activities included in the interaction among PIs, senior personnel, and project participants; financially supporting the work of graduate students interested in developing an expertise in biocomplexity theory and methods; serving on graduate committees of one another's students; and hosting a series of faculty/graduate student seminars and 1-2 workshops on biocomplexity through OSU's Environmental Policy Initiative (EPI) (Randall, director). EPI will continue to support this project with personnel, resources, and funding, such as the EPI-sponsored biocomplexity working group comprised of faculty and students from approximately eight different departments with regularly scheduled working sessions.

Integrating Research and Education. In addition to publishing the results of our research collaboratively, we will build on the following interdisciplinary efforts and established patterns of coordination between research and teaching by project researchers: **(1)** We will develop a course on biocomplexity to be team-taught by members of our research group in 2005 and 2007 and, if successful, will make it a regular course thereafter. **(2)** Existing courses taught by PI's and senior personnel will incorporate biocomplexity concepts, methodologies, and results from the project. These include **(a)** a shipboard limnology course sponsored by the USEPA, Ohio Sea Grant, and OSU's Stone Laboratory, **(b)** a graduate-level seminar "Fluid Mechanics of Aquatic Systems: a matter of scale," (taught in conjunction with Kent State University using the OSU's telecourse classroom system), **(c)** an interdisciplinary course on the economics of growth and sprawl and an environmental economics course, both of which attract undergraduate and graduate students from environmental policy, planning, geography, economics, fisheries and wildlife management, forestry, and environmental sciences; **(d)** biocomplexity concepts and the policy implications of the biocomplexity research will be incorporated into all of twenty-five college-level courses taught at Stone Laboratory each summer to students from all over the world. **(3)** Lastly, we will build on existing collaborations across certain fields: **(a)** Coordinated class field trips and summer courses at Stone Laboratory provide opportunities for interaction between graduate and undergraduate students in Civil Engineering and Biological Sciences through weekend field trips in October (Plankton class) and May (Limnology class) each year. **(b)** Cooperation between faculty in the Agricultural, Environmental, and Development Economics Department and the School of Natural Resources enables graduate students to complete complementary coursework that provides students with a broad expertise in both economics and ecology.

BROADER IMPACTS

We have identified several ways in which we will extend this research to generate broader impacts: **(1)** training K-12 teachers and their grades 4-12 students by incorporating biocomplexity issues into science educator courses and Student Workshops held at Stone Laboratory; **(2)** developing exciting non-formal biocomplexity education programs for the general public; **(3)** working with resource managers throughout the Great Lakes region to apply research results the pressing policy concerns related to biocomplexity; and **(4)** improving participation of underrepresented groups. Reutter will coordinate this work with the assistance of his Associate Director, Dr. Rosanne Fortner, an environmental education expert in the School of Natural Resources. More specifically:

Teacher Training. Each summer 7-10 graduate-level science courses for teachers are offered at Stone Laboratory. We will incorporate components on biocomplexity into each of these courses and will investigate the possibility of developing a new three-credit course—"Biocomplexity for Teachers."

K-12 Education. Each year Stone Laboratory hosts approximately 175 one- to three-day workshops for students in grades 4-12 totaling over 5,000 participants. A lesson/module on "Biocomplexity in Lake Erie" will be developed and offered for each of these workshops beginning in 2005, continuing after the project is completed.

Public Education, Information Dissemination and Outreach. The Ohio Sea Grant and Stone Laboratory web site (www.sg.ohio-state.edu) that attracts over 1 million visitors each year will host our biocomplexity pages with links to other biocomplexity projects funded by NSF. Part of this site will enable the public to learn more about critical issues, such as the Lake Erie "Dead Zone"—a perfect opportunity to introduce biocomplexity in an informative and easily accessible way. We will also publish at least two articles each year on biocomplexity in Ohio Sea Grant's award-winning newsletter "Twine Line." During the first year we will prepare and distribute a one-page fact sheet for the general public and elected officials on the significance of biocomplexity and the Coupled Natural and Human Systems Biocomplexity initiative. During the second year, a Biocomplexity Symposium will be held at Stone Laboratory during the Annual Summer Meeting of the Great Lakes Ecosystem Research Consortium (GLAERC). During years 3-4 we will work with the leadership of science museums in the region to develop and display modules on biocomplexity. Dr. Reutter has been successful in efforts of this type with the Great Lakes Science Center (GLSC) in Cleveland and the Lake Erie Nature and Science Center (LENSC) in Bay Village, Ohio. The project will also create an opportunity for us to collect survey instruments to evaluate knowledge levels and the success of our educational materials.

Benefits to Society. The scientific community and research managers throughout the Great Lakes region are currently struggling to understand the causes of the Dead Zone in the Central Basin of Lake Erie. The modeling efforts in this project will directly address that issue and many others that coastal communities are facing—urban sprawl, loss of green space, loss of agricultural lands, hardening of our shorelines, increased sediment loading, increased chemical loading, and increases in impervious surfaces within watersheds. Members of our team hold key leadership positions on numerous commissions and boards that influence management and utilization of the Great Lakes. Therefore, this project is addressing one of the most pressing issues facing large lakes in general, and the project leadership is positioned to assure that the results of the work are immediately utilized within the Great Lakes region. This is all in addition to the other educational and scientific benefits of this work.

Integrating Diversity. Because the biological and economic health of the state and region depends on improving participation of underrepresented groups, OSU has ongoing commitments to recruit the participation of all citizens in its activities, including women and men, underrepresented minorities, and persons with disabilities. Consistent with these ongoing efforts, we will make particular efforts in our outreach and education efforts to include citizens from all racial, economic, educational, and physical backgrounds. While the pool of persons of color at the graduate level is small, we are proactive in recruiting a diverse group of graduate students to our campus. We are also proud of the diversity of the stakeholders with whom we make contact via our outreach activities via Sea Grant programs and publications, Stone Lab, and the GLSC and LENSC. Our proposed activities at Stone Lab will continue to work to change what Rita Colwell refers to as the "Valley of Death" for science literacy (i.e., grades 5-8) into a "Valley of Life," through our highly successful workshops for Grades 4-12, and graduate-level science courses for teachers and science students. All these activities have participants from a wide diversity of racial and economic backgrounds and over 50% of the participants are women or girls.

Timeline	**Activity**
Year 1	Objs. 1, 2, & 3. Complete development of simple model and begin investigation of coupled linkages and complex system dynamics. Collect and collate data required to parameterize the fine-scale model.
Year 2	Objs. 2, & 3. Continue investigation of complex dynamics of system using simple model. Begin development of fine-scale model and specification of model using Lake Erie data.
Year 3	Objs. 3, 4, & 5. Complete development of fine-scale model. Test model's ability to predict observed human-lake outcomes in Lake Erie and make improvements to fine-scale model. Aggregate predictions from fine-scale model and make improvements to simple model.
Year 4	Objs. 2, 4, 5 & 6. Complete analysis of fine-scale model. Complete aggregation of fine-scale model and improvements to simple model. Explore complex dynamics predicted by modified simple model. Evaluate management of large lakes using the detailed models.
Ongoing	Academic, educational, and mentoring activities. Implement broader education and outreach programs to generate broader impacts

MANAGEMENT PLAN

Given the size and complexity of our research group (one PI, four Co-PIs, seven non-Co-PI senior personnel, four off-campus personnel on subcontracts, five graduate students, four off-campus advisors, and three staff members), we have divided our group into one Integrated Modeling Team that will focus on Objectives 1, 2, and 5 and four interdisciplinary subsystem modeling teams that will focus on Objectives 3-6 (Figure 6). Each subsystem modeling team is co-led by a Co-PI and a junior faculty member and all the teams are overseen by PI David Culver. Team membership is overlapping, so that each researcher is a member of at least two (and in some cases three) teams. Construction of interdisciplinary teams with overlapping membership assures that activities do not devolve to isolated activities within academic departments and that communication is maintained across teams. In addition, a full-time Graduate Research Associate (GRA) will work with each team on the OSU campus, plus one on the Kent State campus. Collaboration of the GRA with the team members will foster interdisciplinary work and create synergies among team members. Students will have other members from their team on their graduate committees, providing another means of interdisciplinary integration. The management structure is designed to evolve during the four years of the project, as part of our continuing mentoring plan for junior faculty.

The **Integrated Modeling Team,** led by Jayaprakash, will develop the coarse-scale, simple model. Team members include Bedford, Culver, Irwin, Martin, and Warren. All project personnel will be arranged into interdisciplinary teams based on our original conceptual model to study the system linkages central to our project. The **Water Quality/Lower Trophic Level Human Interactions Team** studies interactions among the Watershed, Water Quality, Lower Trophic Levels, Human Welfare, and Land and Water Use. It is co-led by Reutter and Irwin and includes members Bedford, Bierman, Culver, DePinto, Haab, Martin, and Murray. The **Fish-Human Interactions Team** studies the interactions among Adult Fish, Water Quality and Lower Trophic Levels, Human Welfare, Recreation and Fishing, and Policy and Governmental Regulation, and is co-led by Culver and Haab, with team members Bierman, DePinto, Enflo, Heath, Randall, Reutter, and Stein. The **Abiotic Systems Team** studies the interactions among Climate, the Watershed, and Hydrodynamics, and is co-led by Bedford and Martin with team members Culver and DePinto. The **Land Use Dynamics Team** studies the interactions among Urban Spatial Structure, Land and Water Use, and Policy/Government Regulation and is co-led by Merry and Murray, with members Irwin, Randall, Reutter, Stein, and Warren. As outlined in the Progress To Date section of the Project Description, Biographical Sketches, and Current and Pending Support sections, each of these researchers has extensive research experience in biological, physical, or socioeconomic sciences, and most have previously published interdisciplinary work on the Great Lakes.

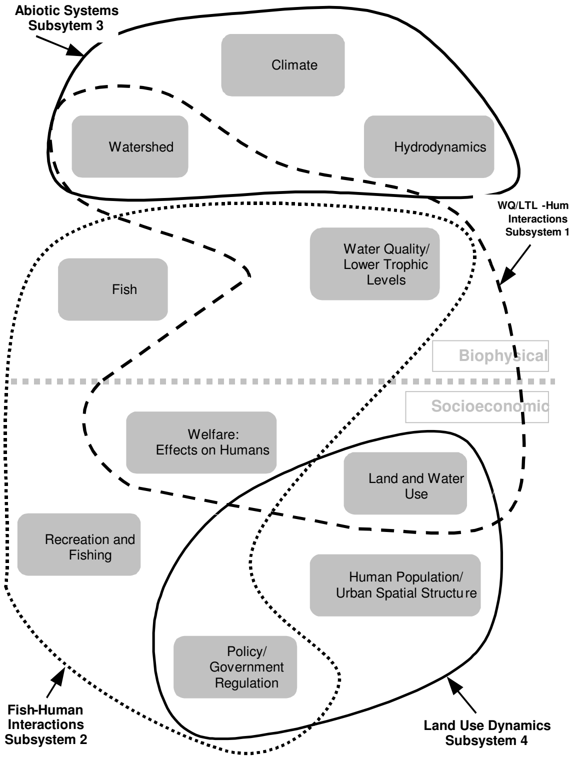

Figure 6: Linked Subsystems of Large Lake Ecosystems

Our experience with large modeling efforts (e.g., the Great Lakes Forecasting System (GLFS)) has demonstrated the utility of a full-time computer programmer and data base manager who will provide a central point for developing and maintaining programs and databases, will maintain and archive a password-protected listserv for intrateam communication, and who will facilitate the transition from the PC-based programming stages associated with Objectives 1 and 2 to the supercomputer analyses required for work on Objectives 3 through 6. This person will also assist graduate students and investigators with programming and data management. Culver will supervise the full-time computer specialist and Merry will supervise the secretary. Reutter will supervise a part-time webmaster who will maintain a Biocomplexity Web Site at the Center for Lake Erie Area Research, OSU, with linkages to the Ohio Sea Grant Web Site to provide up-to-date communication of results to the public and to other biocomplexity research groups.

Each of these teams will hold regularly scheduled (weekly or biweekly) working sessions during active research periods. In addition, the whole research team will meet each Fall at Stone Lab, where each of the four subsystem teams plus the integrated modeling team will make oral presentations (formal publication in scope) on their research results for the year. The entire group will then make recommendations for subsequent-year activities for each team on each of the objectives, relative to the proposed Research Time Table. In addition to these meetings, a small panel of external experts will convene approximately four times during the duration of the project to provide feedback and guidance on model development and results. At the present time, the following individuals have agreed to participate in this role: Dr. Alex Anas (urban economic systems modeler); Dr. Dawn Parker (agent-based land use modeler); Dr. JunJie Wu (urban economic and land use modeler), and Dr. Charles Perrings (ecological economist, invasive species modeler, founding member of the Resiliency Network).

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