SCENARIO ANALYSIS OF ECONOMY–ECOLOGY INTERACTIONS IN THE HUDSON RIVER BASIN

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ABSTRACT

Our primary goal is to develop an integrated, quantitative assessment tool evaluating how human economic activities influence spatial patterns of urbanization, and how land-use change resulting from urbanization affects stream water quality and aquatic ecosystem health. Here we present a prototype of a holistic assessment tool composed of three ''building blocks'' simulating the social and economic structures, spatial pattern of urbanization, and watershed health as determined by various metrics. The assessment tool is applied to Dutchess County, New York and two of its largest watersheds, Wappinger and Fishkill Creek watersheds, demonstrating how an explicit link can be established between human economic activities and ecosystem health through changes in land use.

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1. INTRODUCTION

Increasing human use of fresh water continues to reduce water quality for most of the world's population and threaten the health of aquatic ecosystems (Postel, 2000). In the short term, human water demand due to urbanization and economic development is a graver threat to water resources than global warming and climatic change (Vörösmarty, Green, Salisbury, & Lammers, 2000). In many parts of the world, urbanization is one of the most rapidly occurring changes to land cover, removing vegetation and increasing impervious surfaces. The loss of permeability has been linked to alterations in hydrology (Klein, 1979), sediment, nutrient, and toxicant loading, and general stream degradation (Forman & Alexander, 1998; Paul & Meyer, 2001; Center for Watershed Protection, 2003), with attendant loss of ecosystem function and biodiversity.

Ecosystem health may be defined as the maintenance of biotic integrity, resistance and/or resilience to change in the face of anthropogenic disturbance (Rapport, 1992; Shrader-Frechette, 1994; Rapport, Gaudet, & Calow, 1995), and includes physical and chemical environmental quality (e.g., stream temperature, conductivity, and element concentration), as well as biotic condition (e.g., diversity of fish and macroinvertebrate communities). Operationally, the urban–rural gradient is a useful framework for investigating how urbanization affects ecosystem health (McDonnell & Pickett, 1990; McDonnell, Pickett, Groffman, Bohlen, & Pouyat, 1997; Zhu & Carreiro, 1999). This gradient, along which population density and impervious surface area increase, typically promotes a suite of alterations, including such responses as increasing nitrate concentration (Zhu & Carreiro, 1999), conductivity (Limburg, Stainbrook, Erickson, & Gowdy, 2005), declines in fish fauna (Brown, Gray, Hughes, & Meador, 2005), and decreasing biodiversity and species richness (McKinney, 2002).

Land-use intensification, especially conversion into urban uses, is an important driver of stream health degradation. For example, the database from the National Water-Quality Assessment (NAWQA) Program, collected from many stations across the U.S., demonstrated decreasing water quality with increasing percent urban use (Meador & Goldstein, 2003). Past land-use change in the U.S. was dominated by large-scale conversion of forest and grasslands into agricultural use, but the expansion of urban and suburban areas is the most-important driver of land-use change at present (Naiman & Turner, 2000). The pressure for this change has been most acute around urban centers, via the process referred to as ‘‘urban sprawl,’’ defined as ‘‘the spread of urban congestion into adjoining suburbs and rural sections in an irregular, unordered, and chaotic way" (Merriam-Webster Dictionary, 2002; see also Ewing, 1994). Thus, accurate prediction of future trends of urbanization is essential to the assessment of stream ecosystem health, and is a need voiced at local to national scales.

However, it has been a challenging task to evaluate and predict urbanization patterns resulting from urban sprawl due to the stochastic nature of the process (Polimeni, 2002). The conversion of land into urban use is the result of human decisions, often made one property, one home, and one business at a time (Erickson et al., 2005), primarily based on demographic and economic factors (Li, Sato, & Zhu, 2003). For example, it has been shown that the historic land-use changes in the Choptank River Watershed in Maryland and the Greater Yellowstone Ecosystem can largely be explained by socio-economic events that occurred in the region (Benitez & Fisher, 2004; Parmenter et al., 2003). Thus, the future course of urban sprawl, and its impact on ecosystem health, can only be appropriately evaluated with the help of a socio-economic model explicitly considering the social and economic structures of the region. Such a model should assess how these structures create the demand for new land development in response to anticipated socio-economic events. However, the explicit and quantitative link among socio-economic systems, land-use change, and ecosystem health has rarely been established, primarily because those systems, with their own complexities and non-linearities, have been studied by different academic disciplines and each has been considered at different temporal and spatial scales (Veldkamp & Verburg, 2004). Although the same physical landscape is shared by human and natural systems, the boundaries and scales delineating each system (e.g., counties and towns versus watersheds and subcatchments) are not the same (Fig. 1). We note, however, the need to recognize the reciprocal roles of human versus natural systems: that is, at some scales we can consider natural systems within the context of human ones (e.g., watersheds that fall within county boundaries), but ultimately, human systems are subsets of natural ecosystems.

Our primary goal is to develop an integrated, quantitative assessment tool evaluating how human economic activities influence spatial patterns of urbanization, and how land-use change resulting from urbanization affects stream water quality and aquatic ecosystem health. However, we acknowledge that the interactions of Fig. 1 are not unidirectional. Human choices affect and are affected by nature through various feedback links (Settle, Crocker, & Shogren, 2002), often mediated by changes in landscape features shared by humans and other organisms.

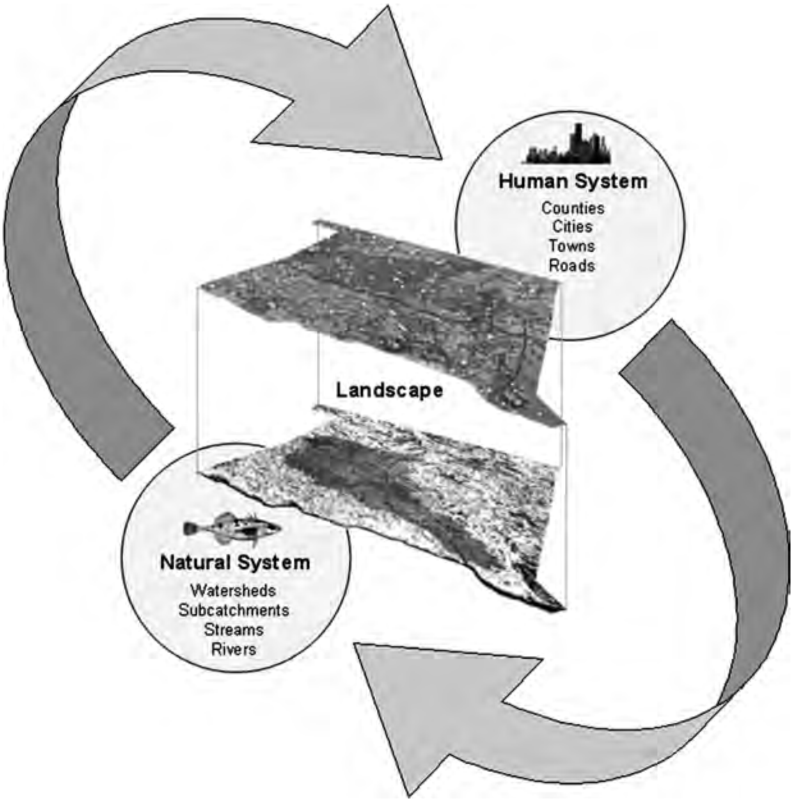
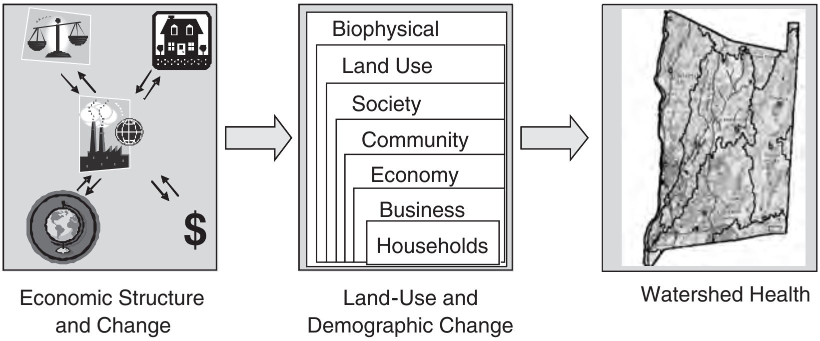


Fig. 1. Conceptual Diagram Showing Interactions among Landscape, Human, and Natural Systems. The Human System Alters the Landscape through Urbanization Processes, Affecting Ecosystems within the Landscape. As these Ecosystems Degrade, Resources Decline, and this May Send Direct or Indirect Signals Back to the Economy.

As an example, consider the following scenario: development to stimulate a local economy may include attracting an expanding industry. Aside from providing new employment for area residents, demand for new homes increases. Such demand will attract developers and increase the real-estate value of lands within some given distance. This may stimulate owners of large holdings (farmers and foresters) to parcelize, thus increasing building activity. However, over time, the increased development may in turn raise taxes, driving out farmers and foresters, resulting in even more land



Economic Structure and Change

Land-Use and Demographic Change

Watershed Health

Fig. 2. Three "Building Blocks" Comprising the Current Assessment Tool.

available for development. Construction of homes, roads, and malls increase impermeable surfaces, causing flashier streams, washouts of plants and invertebrates, and unstable habitat for fish communities. Ultimately, development could achieve a scale at which local natural amenities decline, making it no longer attractive as a destination, leading to the decline of small lake-side resorts, bed and breakfasts, local restaurants, etc., while strip malls blossom. The character of the landscape is changed, supporting lower diversity of natural ecosystems, as well as lower economic diversity. Degraded ecosystems may produce downturns in the economy.

Over the past 4 years, we have developed a prototype (Fig. 2) of a holistic assessment tool composed of three "building blocks" simulating the social and economic structures (Nowosielski & Erickson, Chapter 8 in this volume), spatial pattern of urbanization (Polimeni & Erickson, Chapter 9 in this volume), and watershed health as determined by various metrics (Stainbrook, 2004; Limburg et al., 2005; Limburg & Stainbrook, 2006). To implement these in decision making, we have begun to work with multi-criteria decision methods in order to bring together disparate perspectives and demands, and build consensus for environmental planning (Hermans & Erickson, Chapter 10 in this volume).

2. THE STUDY SYSTEM

Our study focused on Dutchess County, New York and two of its largest watersheds. The county (2,077 km^2) is located on the eastern side of the

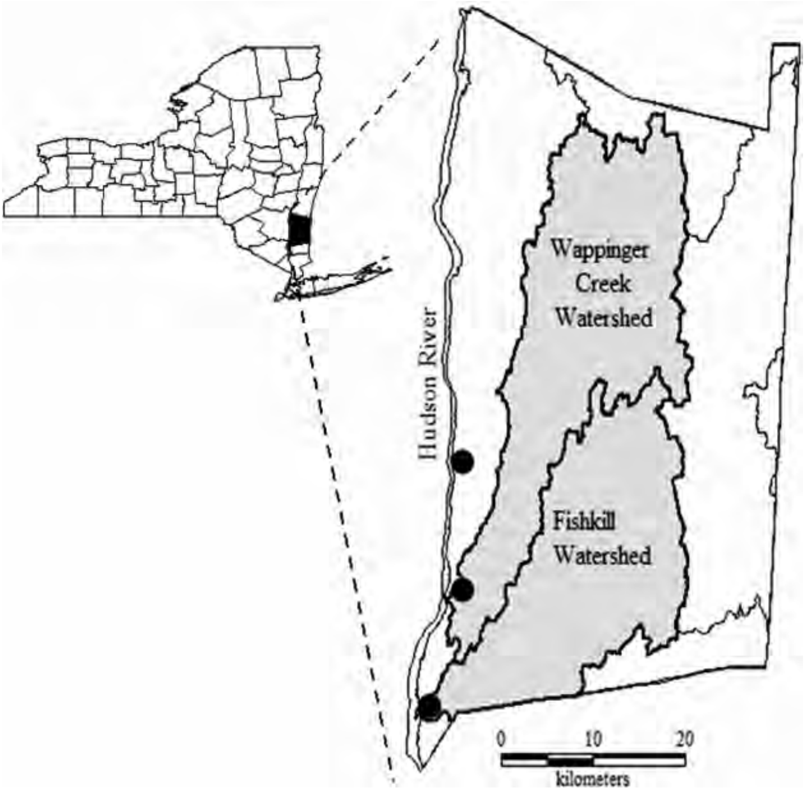


Fig. 3. Map Showing New York State Counties; Dutchess County and its Two Major Watersheds Comprise the Focus of Our Study. *Source:* Limburg and Stainbrook (2006).

Hudson River estuary (Fig. 3). The Wappinger Creek (546.5 km^2) and Fishkill Creek (521 km^2) watersheds compose over half the drainage area. Both the Wappinger and Fishkill creeks arise in eastern highlands and flow southwest toward the Hudson River.

Land use within Dutchess County is a mix of urban, suburban, agriculture (dairy, pasture, row crop, and orchard), and undeveloped woodlands. Historically, agriculture dominated land use before 1950 (Swaney, Limburg, & Stainbrook, in press), but beginning in the 1940s, job growth increased in industrial sectors; IBM became a major employer in the county (Erickson et al., 2005). The largest urban centers are located in the southwestern part of the county along the Hudson River (Fig. 3); the cities of Wappingers Falls and Beacon sit at the mouths of the Wappinger and Fishkill creeks, respectively. Urban flight from New York City, 120 km to the south, has also stimulated development in Dutchess County, primarily in its southern half. Today, the northeast is the least-developed part of the county. Because of the more intensive development to the south, we hypothesized that Fishkill Creek would display lower ecological health than the Wappinger Creek watershed.

3. OVERVIEW OF THE APPROACH

In research supported both by the Hudson River Foundation and the National Science Foundation, we asked the following three questions: (1) How does economic activity create the demand for new land? (2) How does new land demand change the spatial pattern of land-use? and (3) How does land-use change affect watershed health? Each of these questions was explored in separate analyses, and resulted in three different models; a socio-economic model developed by Nowosielski (2002), a land-use model developed by Polimeni (2002), and an ecosystem health assessment developed by Stainbrook (2004). Recently, these three approaches were integrated as three "building blocks" or "sub-models" of an assessment tool (Hong & Limburg, under review).

The socio-economic sub-model (Nowosielski & Erickson, in this volume) is based upon a social accounting matrix (SAM) providing an expanded view of economic activity and interconnections between industries, household income characteristics, and social institutions in the area. The socio-economic sub-model constructs the SAM mostly from the IMPLAN (Impact Analysis for Planning) database and uses it to calculate the Leontief inverse, which shows the requirements from each sector of the economy needed to deliver a dollar's worth of product to final consumers. Although the model is a static "snapshot" of the economy, users of the model can specify various economic-impact scenarios, such as what sectors to increase or decrease, impact location, and percent commuters in the region. The model then estimates the total economic impact for each industrial and household sector individually, using the Leontief inverse. The socio-economic sub-model also estimates the number of households required to meet the new demand by the industries resulting from the economic impact. For example, Fig. 4 shows the new household requirements by various industrial sectors in Dutchess County, produced by the socio-economic sub-model

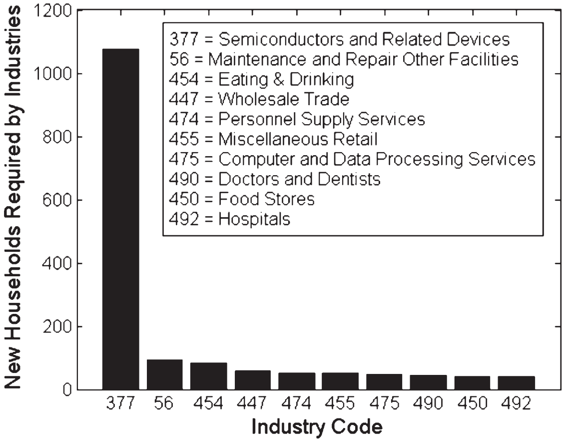


Fig. 4. Bar Graph Produced by Socio-economic Sub-model Showing New Household Requirements Due to a Scenario of an Expanding Semi-conductor Industry.

under a scenario in which the semi-conductor industry expands with 1,000 new jobs.

The land-use sub-model, described in more detail by Polimeni and Erickson in Chapter 9 of this volume, is based upon a binary logit regression model estimating the developmental probabilities of vacant tax parcels in the simulated region. Different sets of independent variables for the logit model (e.g., population variables, income variables, land assessment value, and distance to the central business district, obtained from tax parcel, census, and GIS data available in the region) produce different probabilities of land conversion. The land-use change model uses Monte Carlo simulation to predict the spatial pattern of land development in the near future with or without economic impact, using the estimated developmental probabilities of vacant tax parcels and new household requirement obtained from the socio-economic sub-model. Further refinements to the model include varying assumptions about the employment status of the region (e.g., percent unemployed, socio-economic status), possible restrictions to development (e.g., hydric soils, wetlands, steep area, or otherwise protected lands), other zoning restrictions (e.g., noise pollution), and distribution of new households in relation to the distance to the impact location. The simulation result can be exported to GIS for graphical presentation. Fig. 5 shows an example of land development in 2011 in Dutchess County predicted by the land-use sub-model under the expanding semi-conductor industry scenario.

Fig. 5. Relative Probability (%) of Conversion of Vacant Tax Parcels within Dutchess County to Residential use from 2001 to 2011 under Expanding a Scenario of a Semi-conductor Industry, Predicted by the Landuse Sub-model.

In order to assess the impacts of land-use change on ecosystem health, we conducted extensive empirical studies of the Fishkill and Wappinger Creek watersheds (Stainbrook 2004; Limburg & Stainbrook, 2006; Limburg et al., 2005). These studies indicated that both watersheds have been degraded by long-term land-use patterns, but that the press of urbanization is most intense in the Fishkill Creek watershed. Nevertheless, the differences manifested at the whole watershed scale were relatively small, suggesting perhaps some resilience in the systems.

A holistic approach is important in making decisions because different interest groups have different preferences and priorities (Stinner, Stinner, &

Martsolf, 1997). For example, although “urban sprawl” is a somewhat value-laden term implying a negative view of increased traffic, decreased water and air quality, and loss of green area and open space, others may see it as a positive sign of increased regional economic activity and more employment opportunity (Steiner, 1994). Decisions from policy makers among different management strategies (e.g., adopting zoning restrictions, enforcing protected lands, etc.) should be based on quantitative evaluation and comparison of possible consequences on the socio-economy, landscape, and environment.

We have been working with a multi-criteria decision assessment methodology (MCDA) (Hermans & Erickson, in this volume). MCDA is a framework transparent to decision-makers, adaptable to many situations across multiple metrics and scales, and amenable to both expert and local stakeholder pools of knowledge. The MCDA process starts with a clear definition of a goal, which is facilitated by some form of participatory process (in this case, aided by the simulation model). This is followed by identification of alternatives to achieve the goal. The future outcome of each of these alternatives is then characterized by a suite of indicators. Criteria are then measured in multiple units (both quantitative and qualitative) and dimensions (both spatial and temporal). Once the MCDA problem is structured, the next step is to elicit the preferences of the stakeholders using one of several methods within the family of MCDA frameworks. For example, PROMETHEE (Preference Ranking Organization Method of Enrichment Evaluation) is a specific sort of outranking method commonly used in MCDA (Brans, Vincke, & Mareschal, 1986). PROMETHEE requires criteria-specific and stakeholder-identified: (1) choice of maximizing or minimizing, (2) weight of importance to the overall decision, (3) preference function that translates quantitative or qualitative metrics to consistent rankings, and (4) various decision threshold parameters for each function (for example, indifference thresholds identify ranges where a decision-maker cannot clearly distinguish their preferences). This exercise is carried out by each stakeholder in a decision problem. During sensitivity analysis, criteria weights, preference functions, and decision thresholds can all be varied to estimate stability intervals for the rankings of alternatives and evaluate both imprecision of criterion measurement and uncertainty of preference. The outcome of PROMETHEE includes both complete and partial rankings (depending on the incomparability of decision alternatives), and both pairwise and global comparisons of decision alternatives. Global comparisons can be illustrated with a GAIA (Graphic Analysis for Interactive Assistance) plane diagrams that represent a complete view of the conflicts between the criteria, of the characteristics of the actions, and of the weighing of the criteria. With multiple stakeholders, MCDA analyses can be used to visualize conflict between stakeholder positions and opportunities for compromise, alliances, and group consensus, or to revisit and redefine the goal, alternatives, and criterion themselves (Macharis, Brans, & Mareschal, 1998). The advent of spatial decision support systems (SDSS) provides an important new opportunity for the evolution of MCDA methods and applications (Malczewski, 1999) including extensions of our work.

4. DISCUSSION

The conceptual frameworks linking human economic activities to ecosystem health have been proposed by many researchers (e.g., McDonnell & Pickett, 1990; Stinner et al., 1997; Alberti et al., 2003; Nilsson et al., 2003; Peterson et al., 2003a). Their conceptual models have similar components (humans, the physical environment, and the ecosystem), and processes interconnecting them. They differ in the levels of detail describing each component (e.g., "one-box" versus detailed food web) and the nature of processes relating them (e.g., unidirectional cause–effect relationships versus feedback loops).

In terms of evaluating the usefulness of each of these frameworks as an assessment tool, one should consider whether all the components in the model and the connections among them are explicitly and quantitatively expressed. After careful consideration, Nilsson et al. (2003) suggested that the uncertainties in the available data and the gaps in our knowledge about complex, non-linear processes are so large that the quantitative description of these systems in an integrated, holistic framework is not yet feasible. Peterson, Cumming, and Carpenter (2003a, 2003b) suggested a way of circumventing overwhelming uncertainties through "scenario planning," in which the responses of future economies, landscapes, and ecosystems to different management strategies are illustrated to the decision-makers as possible outcomes that emerge from quantitative-assessment simulation models. Clark (2002) suggested that the uncertainties in our knowledge should not be used as an overt justification for avoiding the use of quantitative tools in the decision-making process, but rather that the assessment models should deal with the existing uncertainties more rigorously and explicitly. Currently available tools for quantitative assessment of anthropogenic land-use change and resulting stream health (e.g., Costanza et al., 2002) do not have algorithms performing rigorous uncertainty analysis. Ultimately, we intend to develop an assessment tool that will have the full capability of uncertainty analysis, enabling the policy-makers to make decisions based on the quantitative evaluation of possible outcomes, while appreciating the uncertainties in the model predictions at the same time. In addition, a successful decision support system should be truly holistic (Stinner et al., 1997), have multiple endpoints (Santelmann et al., 2004), show explicit linkages among different systems (Young, Lam, Ressel, & Wong, 2000), help the user to select various scenarios and construct decision trees (Djodjic, Montas, Shirmohammadi, Bergstrom, & Ulen, 2002), and have an easy-to-use GUI communicating with the user (Young et al., 2000). We are working toward addressing each of these.

Nilsson et al. (2003, p. 671) state:

> "…environmental forecasting is subject to a variety of technical and resource limitations, many of which will require massive intra and interdisciplinary efforts in the fields of economics, quantitative spatial analysis, hydrology, geomorphology, and ecology to overcome or ameliorate. If researchers can fill – or at least reduce – these gaps, thus improving our ability to forecast environmental change and to advise on the potential effects of different land-use changes on running waters, ecology will play a significant role in formulating land-use policies in the future. This is one of the greatest ecological challenges of our time, yet it is an area where we can reasonably expect to see major breakthroughs."

We echo these sentiments, and feel that we have already come a considerable way toward meeting the goal of linking together these diverse disciplines. We are now poised to continue this exciting work; collectively, we have a rare combination of the transdisciplinary, analytical expertise necessary to take on this challenge. The next step will be to continue to evolve the linkages of the models to include uncertainty analysis, feedback loops, and scale effects. Undoubtedly, such model structures are capable of producing surprising results which may manifest some of the complexity inherent in studying these coupled systems. Not only do we hope to advance the field of environmental assessment to a new level, but in doing so we will address fundamental themes in ecology, economics, geography, hydrology, and geomorphology: namely, the effects of scale, and quantification/ramification of uncertainty.

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☐ *Uncited references:* This section comprises references that occur in the reference list but not in the body of the text. Please position each reference in the text or delete it. Any reference not dealt with will be retained inthis section

Queries and/or remarks

Location in Article	Query / remark	Response
AU:1	Please provide the year of publication for reference Hong and Limburg (under review).	
AU:2	Please provide the year of publication for reference Swaney, Limburg and Stainbrook (in press).	