CHAPTER 13

An Ecological Economic Model for Integrated Scenario Analysis: Anticipating Change in the Hudson River Watershed

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THE TYRANNY OF SMALL DECISIONS

Many communities across the nation and world have succumbed to what Alfred Kahn[1] referred to as "the tyranny of small decisions." The tyranny describes the long-run, often unanticipated, consequences of a system of decision-making based on marginal, near-term evaluation. Land-use decisions made one property, one home, and one business at a time in the name of economic growth have accumulated without

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regard to social and environmental values. The tyranny results when the accumulation of these singular decisions creates a scale of change, or a conversion from one system dynamic to another, that would be disagreeable to the original individual decision-makers. In fact, if given the opportunity to vote on a future that required a redirection of near-term decisions, a community of these same individuals may have decided on a different path.

Incremental decisions made by weighing marginal benefits against marginal costs by an individual isolated in a point in time are the hallmark of traditional economics. But maximizing the well-being of both society and the individual requires an exercise in identifying and pursuing a collective will, quite different from assuming that community-held goals will result simply from individual pursuits of well-being.

At the watershed scale, the tyranny of small decisions has emerged in the form of urban sprawl — a dispersed, automobile-dependent, land-intensive pattern of development. One house, one subdivision, one strip mall at a time, the once-hard edge between city and country throughout the United States has incrementally dissolved. This pattern of development has costs and benefits to both the individual and society. To the individual, the choice to purchase or build a home in the suburbs over the city may initially carry the benefits of a larger home, more green space, and better schools, all at a more affordable price. Initially, individual costs may be related only to transportation to employment and services. However, by structuring the land-use decision problem as a series of individual choices, a tyranny can result in the loss of community services provided by watersheds, such as water supply, purification, and habitat provision – so-called *natural capital* depreciation. Associated social capital depreciation can include decline in city school quality and loss of social networks. The city often subsidizes the suburbs on services such as fire and police protection, water and sewer lines, road construction and maintenance, and health and emergency care. The total social costs (for city and suburbs) of sprawl may surpass the private benefits — an outcome that a democracy may not have chosen if given the chance, yet individuals often can not appreciate in their own land-use decisions. The point is not that this will always be the case for suburbanization, but rather that the accumulation of small decisions should be considered in the calculus of the small decisions themselves.

To emerge from the tyranny, the challenge is not to predict but to anticipate the future. *Prediction* in integrated social, economic, and ecological systems often requires a simplification of multiple scales and time dimensions into one set of assumptions. It implies a defense against alternative predictions, rather than an exploration of possible futures. Quantitative assessment and model building is often limited to one system, with others treated as exogenous corollaries.

In contrast, *anticipation* implies a process of envisioning future scenarios and embracing the complexity that is inherent among and within the spheres of social, economic, and ecological change. As a process-oriented approach to decision-making, anticipation focuses on the drivers of change and the connections between spheres of expertise, and relies on local knowledge and goal setting. Through scenario analysis, decision-makers can vary the assumptions within degrees of current knowledge, foresee the accumulation of small decisions, and decide upon group strategies that decrease the likelihood of undesirable consequences.

The following case study describes a project in Dutchess County, New York that has developed in this spirit. The next section introduces Dutchess County and its own version of the "tyranny of small decisions." "Economic Analysis, Land Use, and Ecosystem Integrity: An Integrated Assessment" describes an integrated approach to model development in Dutchess County, including economic, land-use, and ecological submodels that provide both the detail within and connectivity among their spheres of analysis. The "Scenario Analysis" section incorporates the scenario of an expanding semiconductor industry in Dutchess County to illustrate the connectivity and chain of causality between economic, land-use, and ecological submodels. "Multicriteria Decision Aid" then introduces a multicriteria decision framework to aid watershed planning efforts in the context of multiple decision criteria, social values, and stakeholder positions. The "Discussion" section concludes with a discussion of the strengths and weaknesses of this approach, and places this case in the context of other book chapters.

WATERSHED COMMUNITIES AND THE DUTCHESS COUNTY DEVELOPMENT GRADIENT

Watershed communities include the physical, ecological, and human components of a topographically delineated water catchment. Our study area is part of the larger Hudson River watershed of eastern New York State, which draws water from over 34,000 square kilometers of land (mostly in New York, but also reaching into Massachusetts, Connecticut, New Jersey, and Vermont) on its journey from the southern slopes of the High Peaks of the Adirondack mountains to the Atlantic Ocean.[2] Dutchess County (2077 km^2) is located in the lower Hudson watershed, midway between the state capital of Albany and New York City. Figure 13.1 highlights the county's two principal Hudson tributary watersheds of Wappingers (546.5 km^2) and Fishkill (521 km^2) Creeks, which together drain over half of the county landscape. The full county includes approximately 970 km of named streams that provide public water, irrigation, recreation, and waste disposal. This study incorporates models of the county's economy, land-use patterns, and the general health of the Wappingers and Fishkill systems into the design of a decision aide to support county and state land-use planners, ongoing intermunicipal efforts to improve watershed health, and local citizens' groups working to improve the quality of life of county residents.

The Dutchess economy through the mid-twentieth century was principally agrarian, specifically mixed row-crop, dairy, and fruit agriculture. While today's county economy is characterized by 203 distinct sectors, with a total employment of over 132,000, much of the recent economic history has reflected the rapid growth and then cyclical behavior of the International Business Machine Corporation (IBM). In 2000, IBM was the second largest employer (>11,000) in the county, preceded only by local government institutions (13,800), and followed by state government (7600).[3] Other major economic themes cutting across the county — identified at an early stakeholder meeting of this project — included the influence of seasonal home ownership and commuting patterns (particularly in relation to New York City wealth

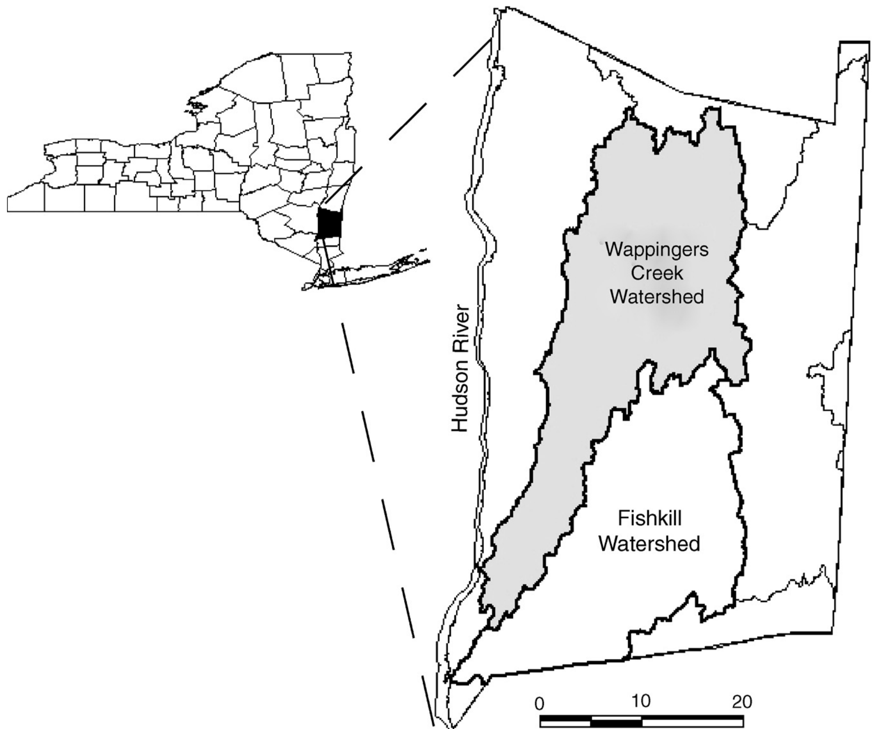

Figure 13.1 Dutchess County, New York, and its main Hudson tributary watersheds.

and employment), the decline of traditional agriculture in favor of agro-tourism activities, and the aging of the population and growth in retirement homes and services.

County land-use intensity follows a development gradient from the rural northeast to urban southwest. The Wappingers Creek watershed mirrors this gradient, beginning in mostly forested headwaters, continuing through a predominantly agricultural landscape, flowing through mixed suburban use, and discharging into the Hudson in the urban areas of Wappingers Falls and Poughkeepsie. The Fishkill Creek follows a similar northeast-southwest development gradient with generally higher population densities, and enters the Hudson through the city of Beacon. The geology of both watersheds is primarily a mix of limestone, dolostone, and shale, and annual precipitation is approximately 1040 mm.[4]

These rural-to-suburban-to-urban development gradients provide a unique opportunity to model the impact of economic change on land-use intensity and watershed health. In particular, a pattern of urban sprawl that stretches up each watershed creates a gradient of increasing impervious surfaces and corresponding impacts on aquatic health. Land use is changing most rapidly in the south-central portion of the county as a consequence of high-tech industrial growth and a general push of suburban expansion radiating out from the New York City greater metropolitan area. Residential development, in particular, is rapidly converting forest and field to roads and housing. According to county planners, about 75% of the houses in Dutchess are located in the southern half, but new building is spreading north and east. Since 1980, the average annual number of building permits for single-family dwellings was 877.[5] However, this average is significantly skewed by the 1983–1989 and 1998–2000 building booms, with each year surpassing 1000 permits, compared with an off-peak annual average closer to 500 permits. The slowdown in the early 1990s can be attributed to IBM's downsizing. These layoffs "glutted the housing market, depressing prices and making houses more affordable to people looking to move out of New York City."[6]

With new households comes new income that cascades across the county economy, creating further business and household growth and consequent land-use change. With the waxing and waning of the housing market (tied in part to the ups and downs of the IBM labor force), nonresidential building permits averaged 744 between 1980 and 1995, without much annual variation. Average per capita income in Dutchess County is the seventh highest of 62 New York counties. Dutchess households have had a median buying power of $47,380, much higher than the New York State ($38,873) and U.S. ($35,056) medians.[7] Dutchess County's effective buying income (EBI) ranks 15th in the United States, with over 46 percent of county households having an EBI of over $50,000. This household income creates multipliers that are a cause for concern for some of the more rural municipalities. A planning report from the small town of Red Hook[8] in the northwest of the county states, "These factors will continue to bring commercial development pressures on any significant highway corridors, as businesses seek to exploit the growing pool of disposable income in Red Hook and Rhinebeck." Growth is viewed as both an opportunity for business and a challenge for municipalities that struggle to preserve their rural landscape and level of community and ecosystem services.

Many of these ecosystem services, including the provision of aesthetic qualities and opportunities for recreation, depend on the ecological attributes of the watershed. Ecological risks associated with current and changing land use include the loss of water quality, hydrological function, physical habitat structure (e.g., alterations of riparian zone), and biodiversity. To anticipate and perhaps avoid irreversible loss in these attributes, the challenge is to link ecological change to land-use change and its economic drivers. The next section outlines an approach to integrated modeling, combining synoptic ecological surveys with economic and land-use models in a framework capable of stakeholder-informed scenario analysis and multicriteria decision making.

ECONOMIC ANALYSIS, LAND USE, AND ECOSYSTEM INTEGRITY: AN INTEGRATED ASSESSMENT

The analytic building blocks for the integrated watershed model include a social accounting matrix (SAM) describing economic activity in Dutchess County; a geographical information system (GIS) of land-use, socioeconomic, and biophysical attributes; and an assessment of aquatic ecosystem health based on indices of biotic

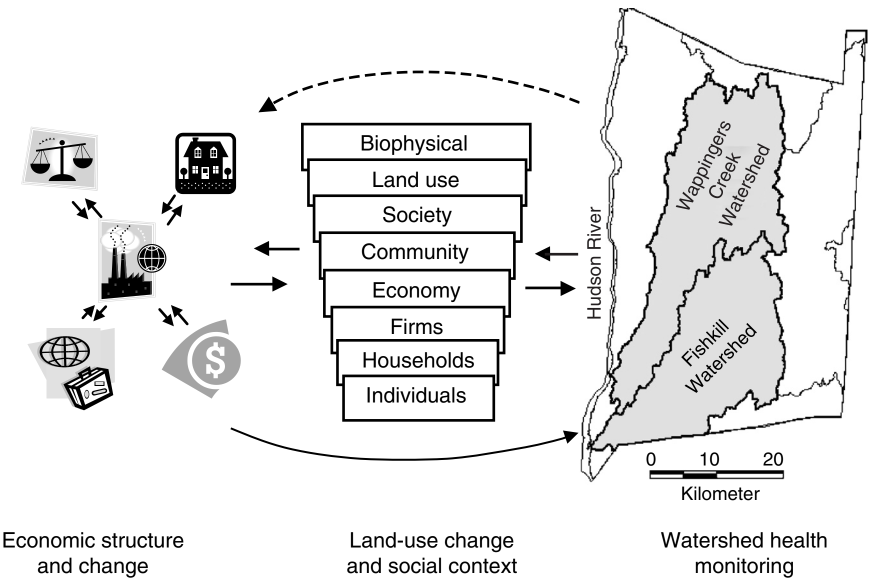

Figure 13.2 Conceptual model components and linkages.

integrity (IBI). Figure 13.2 illustrates these sequential model components, with system drivers and feedback loops denoted in solid and dashed arrows, respectively.

Starting with the left side of the diagram, regional economic activity is characterized as dollar flows between industry (in the center), households (top right), government (top left), capital markets (bottom right), and the outside economy (bottom left). The middle panel illustrates the multiple layers of biophysical and social context within which land-use decisions are made. The right panel highlights the watershed as the scale of ecosystem impact from economic and land-use change. Total economic activity has a direct effect on watershed health through material input and waste output, and an indirect effect through land use change. Land use change and ecosystem health[a] can similarly impact economic activity through feedback loops. For example, soil erosion impacts agricultural industries, water quality impacts water-based tourism, and environmental amenities influence real estate values. Drivers or feedbacks can be either marginal or episodic, accounting for system surprises.

Socioeconomic Submodel: Geo-Referenced Social Accounting Matrix

A widely used tool in national and regional economic analysis is the input–output model (IO) developed in the 1930s by Nobel laureate Wassily Leontief. As a system of accounting that specifies interdependencies between industries, IO has been used to understand how changes in final demand (household consumption, government

[a] The concept of ecosystem health is controversial (see "Planning" in Chapter 3). In this paper, the term is operationally defined using indices of biotic integrity (see also Appendix 6-A).

	Inputs ↓ / Outputs →	Agriculture	Manufacturing	Transportation	Wholesale/retail	Services	Households	Exports	Investment	Government	Total sales
		Processing Sectors						**Final Demand Sectors**			
Processing Sectors	Agriculture	34	290	0	0	0	7	137	0	1	469
	Manufacturing	25	1134	5	13	188	607	12303	27	10	14312
	Transportation	6	304	54	25	80	22	111	5	3	610
	Wholesale/retail	13	490	18	45	156	1171	723	29	11	2656
	Services	35	472	53	258	418	1387	816	573	229	4241
	Households	208	3242	252	881	1816	869	1203	0	244	8715
Payments Sectors	Imports	77	5712	83	456	892	2539				
	Depreciation	24	2157	129	805	446	489				
	Government	47	511	16	173	245	1624				
	Total purchases	469	14312	610	2656	4249	8715				

Figure 13.3 Hypothetical transaction table in input–output analysis.

expenditure, business investment, and exports) are allocated across an economy. To meet new demand requires industrial production, which in turn requires industrial and value-added inputs, which in turn requires more production, and so on. Each addition in the production chain sums to an output multiplier that accounts for the original demand and all intermediate production generated to meet this demand. Value-added inputs include income contributions from labor as wages, capital as profits, land as rents, and government as net taxes, and can be related to output to capture various income (wage, profit, rent, and tax) and employment multipliers.

Figure 13.3 illustrates a simplified, hypothetical example of an IO transactions table. Numerical values represent real dollar flows between the processing, final demand, and payment sectors of a regional economy (perhaps in millions of dollars). For instance, reading across the manufacturing row, firms in the manufacturing industry sell their output to firms in the agriculture (25), manufacturing (1134), transportation (5), wholesale and retail trade (13), and service (188) industries in the form of intermediate inputs; and to households (607), exports (12303), business investment (27), and government (10) in the form of final outputs.[a] Manufacturing itself requires inputs, read down the manufacturing column, including labor from households paid as wages (3242), imported goods and services from outside the region (5712), depreciation of capital assets (2157), and government services (511). The payment sectors are often captured as payments to labor (wages), capital (interest), entrepreneurship (profits), and land (rent), and collectively are called

[a] Households in this example are treated as a processing sector (or industry), even though they are also counted as a final demand sector. The distinction is based on a decision of what is exogenous and what is endogenous to the model. Exogenous sectors stimulate growth only in the model economy, but cannot themselves be stimulated in subsequent rounds of buying and selling. Assuming households are endogenous in an IO model implies that as industrial output expands it will generate new household income that will "induce" more household spending, which will create subsequent rounds of industrial expansion and labor income generation.

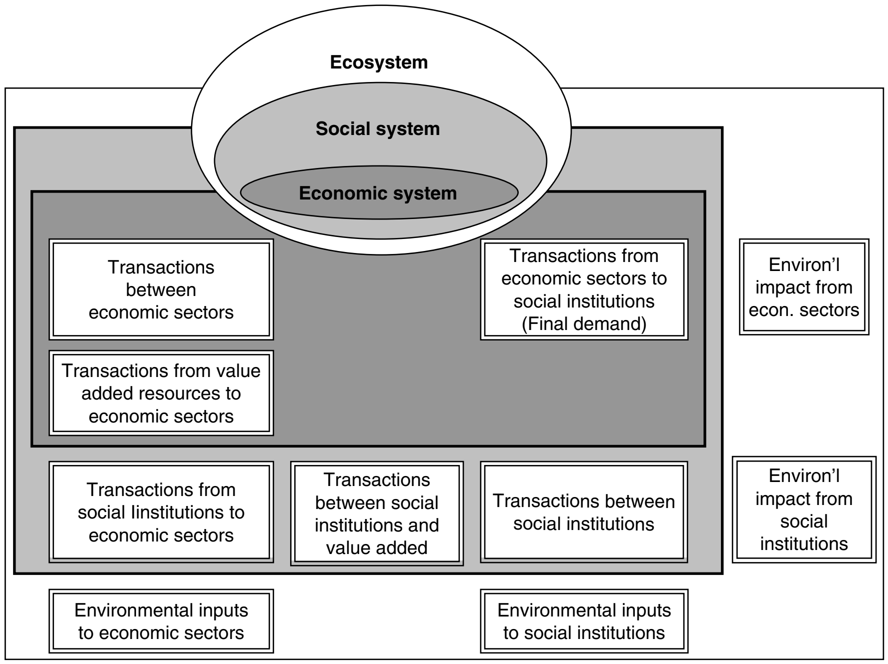

Figure 13.4 Integrated system of accounts, including economic sectors, social institutions, and ecosystem resources.

value-added inputs. The total economic production of a regional economy can be measured as either the sum of final demand or value-added inputs.

An IO system such as this forms the basis for the economic sphere in Figure 13.4. The three boxes of the economic sphere symbolize the main systems of accounts — final demand, industry production, and value-added inputs — in a traditional IO system. These accounts are specified as matrices, as in Figure 13.3, with rows read across as outputs and columns read down as inputs. For instance, reading down the column of the semiconductor industry for the Dutchess County IO table, the top ten sector inputs include other firms within the semiconductor industry, wholesale trade, maintenance and repair, computer and data processing, electric services, legal services, real estate, electronic computers, personal supply services, and banking. The sum of all these regional inputs, value-added, and any imports required from outside the region equals total inputs to the industry. Similarly, the sum of the semiconductor industry's outputs generated for other industries to use in intermediate production and final products to demand equals its total output. To balance the accounts within a particular time period, inputs must equal outputs.

By itself, the economic sphere misses key dependencies between the economic and social systems. Traditional IO has focused on the structure of production, the matrix in the upper left corner of Figure 13.4, with industry disaggregated into over 500 sectors, each with its own input–output relations specified. In contrast, the structure and detail of final demand has typically been highly aggregated, most often specified only as its four major components of household, government, business investment, and foreign consumption (as in the example of Figure 13.3). This restricted treatment of households in particular — the major driving force in economies as both consumers and suppliers of labor and capital — limits the ability of the IO model to specify income distribution, investigate the effect of welfare and tax policies, and model the impacts of changing patterns of household spending. The need for a more detailed treatment of households led researchers, beginning with the work of Nobel laureate Richard Stone in the 1960s, to expand the IO system into a *social accounting matrix* (SAM).[9,10]

In the SAM, components of final demand and value-added are called *institutions*. The interdependencies between and among industry and institutions are illustrated by the three boxes linked to the social sphere of Figure 13.4. For instance, households specified as an institution (not just as a supplier of labor) can reveal their nonlabor inputs to industry in the left box, such as land, capital, energy, and anything else besides labor that a household might supply to firms as an input. The distribution of labor income is captured in the center box. The interdependencies with other institutions are captured in the right box, for instance earnings by corporations redistributed back to households as dividends, or taxes paid to government redistributed back to households as welfare payments. Households — as consumers in final demand and labor supply in value-added — can be disaggregated into columns and rows according to criteria (and data) relevant to the policy question at hand. For instance, households have been disaggregated by income category, wage group, and skill or occupation class.

Figure 13.5 is a schematic of the Dutchess County SAM, with the six major transaction tables denoted by blocks not containing a zero.[11] The full SAM specifies 203 industry sectors, 11 occupation and skill classes, and 9 household categories as endogenous components. Exogenous changes to final demand come from government institutions, capital expenditures, trade flows (both domestic and international), and inventory adjustments.

The creation of a SAM for this study is based on a regional database called IMPLAN (IMpact analysis for PLANning).[12] IMPLAN tables are available for any collection of states, counties, or zip codes in the U.S. based on federal and state databases, which can then be modified using the best available local data. The main modification for the Dutchess County SAM was the disaggregation of IMPLAN's single labor income row into 11 occupation categories (in Figure 13.5, the *Employee Compensation and Profits* Matrix). Using Bureau of Labor Statistics data from the 2000 census, and following a procedure outlined by Rose et al.,[13] each occupation row shows the input relation to each industry column, and each occupation column shows the distribution of labor income to nine household institutions categorized by income ranges (*Industry Sales to Households* Matrix).

Finally, to complete the image of a nested system of accounts within Figure 13.4, economic activity and its distribution is linked to the ecosystem. To explore these linkages, the basic IO–SAM framework has been expanded to incorporate environmental and natural resource accounts.[14–16] In Figure 13.4, inputs from the environment to industry and institutions are tallied in the bottom two boxes, and outputs from industry and institutions to the environment are tallied in the far right boxes.

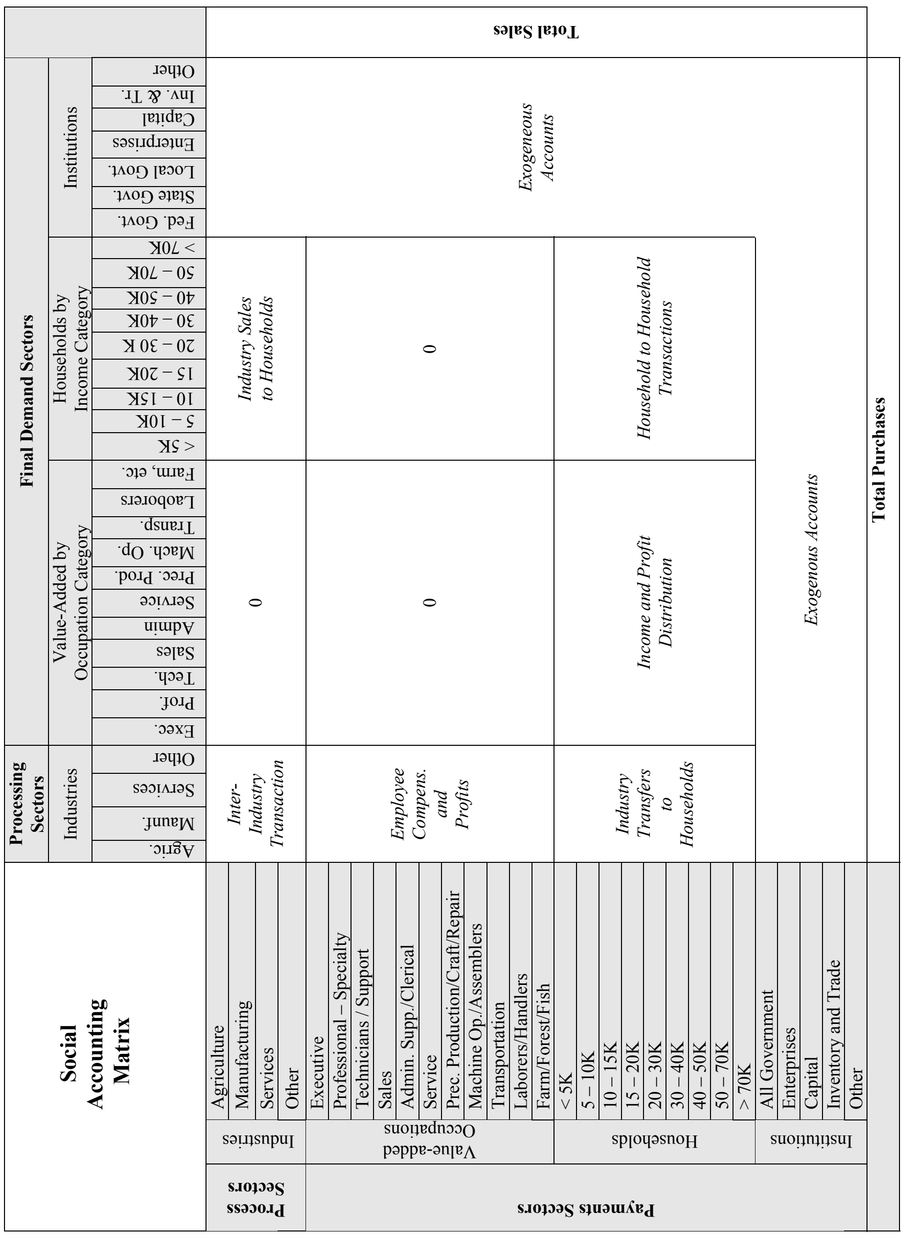

Figure 13.5 Major SAM accounts in Dutchess County model.

Environmental inputs include energy, minerals, water, land, and numerous ecosystem services. Outputs discarded into the environment include the gamut of solid, liquid, and gaseous wastes.

For the current study, the main consideration is the use of land as an input to the socioeconomic system. Of particular interest is how scenarios of industrial sector change and growth lead to changes in household institutions that ultimately drive new residential land development. To link economic change and social distribution to spatial patterns of land use, the Dutchess County SAM was referenced to a geographical information system (GIS). For example, the geo-referenced SAM (GR-SAM) can place household institutions (disaggregated by both occupation class and income range) within the spatial context of race, education, age, commuting patterns, wealth, income, and numerous other census-defined household characteristics. Spatial patterns and concentrations of industry sectors can be viewed with business point data and linked to information on business size, year of establishment, and income range. The spatial dimensions of the entire economy (both institutions and industry) can be further referenced to tax parcel data with information on acreage, taxable use, zoning, infrastructure, and various ownership characteristics. These ownership units can then be linked to biophysical characteristics such as soil, slopes, wetlands, and location within watersheds.

The main advantage to this integrated system of economic, social, and environmental accounts is to visualize the interconnectivity of these system components. This can then serve as the basis to conduct scenario analysis within the confines of this snapshot in time. The main weaknesses of this approach are the linear structure of input–output relationships, the lack of any time dimensions in the analysis of multiplier effects, and the inability of the model parameters to adjust to changes in relative scarcity (for instance, price signals). The static nature of IO models has been addressed to some degree with the advent of dynamic IO models and general equilibrium models, although the data limitations are severe.[17] However, the fixed coefficient assumption implicit in most IO models is in many cases a more realistic representation of technology than traditional production functions that assume away the problems of complementarity (when certain input combinations are required for production) and sunk costs (when specific investments in capital stock are required for production). A more serious problem is the difficulty of finding and modeling the critical interfaces between economic and environmental systems. Ecosystems, even more than economic systems, are characterized by nonlinearity, threshold effects, synergistic relationships, and pure uncertainty. Economic models require that these effects and interactions be drastically simplified.

Land Use Submodel: Probabilistic Geographical Information System

Moving from the first submodel to the second outlined in Figure 13.2, scenarios generated by the GR-SAM then inform a model of land-use change. The GR-SAM is a static tool that helps to identify the source of new land demands, but not necessarily how these demands could play out on the landscape. Most economic models do not include spatial variation of activity; however, location is critical to estimating environmental loading.[18]

Of particular interest to Dutchess County is growth in residential land use. Land currently characterized on the tax rolls as vacant-residential, agriculture, and private forest provides an inventory of total vacant land potentially available for conversion to residential use. By this characterization, in the Wappingers Creek watershed in 2001 there were 19,024 parcels in residential use and 4507 vacant. The conversion from vacant to residential was modeled with a binomial logit regression procedure to estimate the probability of land conversion of individual tax parcels throughout the Wappingers Creek watershed.[19] Data were cross sectional for the year 2001 due to the limited availability of digital tax maps over time. These probabilities were assumed to depend on both tax parcel characteristics and neighborhood characteristics (defined by census blocks). Tax parcel independent variables included 2001 land assessment value per acre and distance to the nearest central business district. Neighborhood independent variables included household income and population growth (between 1990 and 2000 census years) and the 2001 density of residential land-use classes in each census neighborhood.

Polimeni provides a detailed discussion of model calibration, results, and diagnostics (including tests for spatial autocorrelation).[19] The final model provides the basis for simulating residential development patterns given changes in independent variables. For instance, if incomes or population continue to grow according to intercensus year rates (1990–2000), a Monte Carlo procedure can demonstrate where conversion to residential use would likely occur. Figure 13.6 plots the outcome of a single status quo Monte Carlo run, assuming a continuation of the 1990s decadal growth rates of 53% in per capita income and 8% in population. The average of 100 runs provides a point estimate of 1120 parcels converted to residential use. Development favors the upper (rural) watershed, with 677 new residential parcels averaging 18.39 acres each. The lower (urban) and middle (suburban) watershed includes 228 and 215 new residential parcels, with an average size of 3.3 and 8.61 acres, respectively.

The model only simulates conversion of land use class, not the percentage or acreage of parcels that become physical homes. To estimate the maximum number of new homes on new residential parcels, tax parcels were screened according to both biophysical and zoning layers. Biophysical GIS layers included slope, hydric soils, wetland vegetation, riparian river corridors, and agricultural land. Acreage can be removed from the inventory of developable land according to rules imposed by these layers. Zoning maps further limit the number of principal buildings allowed per acre. To account for development infrastructure requirements, particularly new roads, various percentages of buildable land can also be assumed. Following a biophysical screening of wetlands, hydric soils and >10% slopes, a town-specific zoning overlay, and assuming 80% buildable land on remaining acreage, the status quo scenario (highlighted by Figure 13.6) can accommodate a maximum of 10,370 new homes.

Given economic scenarios from the GR-SAM sub-model, the binomial logit model can simulate residential land conversion for the Wappingers Creek watershed. These scenario-derived land-use profiles are then used to hypothesize changing land-

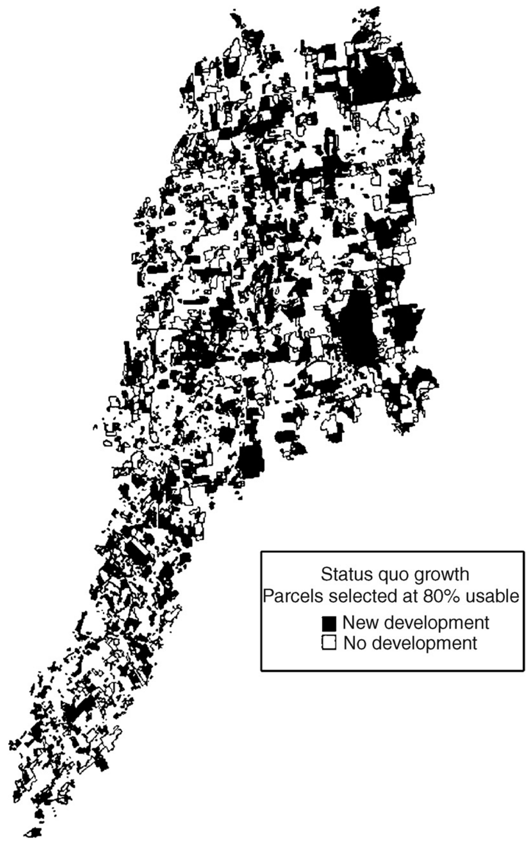

Figure 13.6 New residential land use in the Wappingers Creek Watershed under intercensus year trend in population and household income growth.

use intensity within each of the 16 subcatchments of the Wappingers Creek watershed. This provides the empirical link to the ecosystem health assessment.

Ecosystem Health Submodel: Spatially Correlated Indices of Biotic Integrity

The third component of the Figure 13.2 model overview is an estimate of ecosystem health impact based on land development scenarios. The well-worn concept of ecosystem health, while controversial (see "Planning" in Chapter 3), is enjoying resurgence as a useful means of assessing the impacts of human activities and for protecting and restoring ecosystems,[20–22] while considering societal goals.[23] Ecosystem health may be defined as the maintenance of biotic integrity, resistance and resilience to change in the face of anthropogenic disturbance, and the absence of factors that degrade population, community, and ecosystem structure and function. Ecologists have spent the past 25 or more years exploring various indicators that best reflect ecosystem responses to anthropogenic stress and have found them to vary with the particulars of the ecosystem of interest. Nevertheless, some indicator methods have emerged as robust, when adjusted to local or regional biogeographic and geomorphological constraints.

Among these is the *index of biotic integrity* or IBI method.[24,25] Karr worked out a set of criteria for assessing the health of midwestern streams and argued that fish were a good end-point for observing ecological effects. As the "downstream receiving end" of numerous complex ecological processes, fish can serve as integrating indicators of the quality of the system. A stream IBI combines a number of different metrics that reflect fish biodiversity, community structure, and health of populations. For example, a water body that has high species richness (number of species present), a high proportion of which are endemic, including a mix of species occupying different trophic positions and showing very few indications of disease or starvation would be scored with a high IBI. Conversely, an ecosystem with only a few pollution-tolerant species, low biomass, or containing only stocked or exotic species would be scored with a low IBI. The basic methods and caveats to the use of IBIs are included in Appendix 6-A.

This study uses the metrics developed for a recently published New England fish IBI[26] and a benthic macroinvertebrate index developed by the New York State Department of Environmental Conservation.[27] In addition, several other parameters are being examined, including whole-ecosystem metabolism,[28,29] nonpoint source enrichment of ^{15}N as indicated by the $\delta^{15}N$ isotopic ratio of standardized ecosystem components, and water quality parameters — including their variability, as this varies with degree of urbanization.[30] These system-level metrics and water quality parameters are known to vary with land use.[31–34]

A series of synoptic surveys were conducted in 2001 and 2002 at a total of 33 stream sites in the two watersheds. The surveys included physical habitat assessments, using a modification of the U.S. Environmental Protection Agency standard protocols,[35] fish surveys, macroinvertebrate surveys, and water chemistry surveys. Surveys also included collection of materials for stable isotope analysis, focusing on the simplified food chain of seston (suspended organic particles), macrophytes (rooted plants), and a cosmopolitan fish species (blacknose dace, *Rhinichthys atratulus*). A short-term study of diurnal oxygen variation was also carried out simultaneously in six subcatchments with different land use. Diurnal oxygen variation generally followed expectations from first principles, with the least variation (and hence, least ecosystem metabolic activity) in the forested catchment and the highest in the suburbanized catchment, which not only had less canopy cover but also had high nutrient concentrations (Figure 13.7).

Although much of the data analysis is still in progress, patterns are beginning to emerge. As expected from visual impressions, variation is high and patterns of some parameters would likely not be visible without geographic presentation of the entire dataset. For example, Figure 13.8 shows an index of anthropogenic nitrogen (the percent of total N in the inorganic forms of nitrate and ammonia) over the watersheds. The Fishkill, the more developed watershed, has significantly higher inorganic N to total N ratio than does the Wappingers Creek. In general, nutrient and conductivity values follow degree of urbanization.

The next step is to correlate such metrics with land-use intensity within each watershed. We have also observed that many indicators of human activity in the watersheds are strongly correlated with distance away from the tributary confluence with the Hudson River (Figure 13.9). This also corresponds to an elevation gradient, with the least-developed portions of the watersheds being the most remote headwater areas. We suspect that this will often be the case in urbanization studies; analysis of environmental metrics in relation to anthropogenic disturbance will have to be corrected for this strong geographic influence.

In the analysis to date, only one fish community in the study area was severely depressed, and the rest, by the IBI index, vary widely. The reasons for this are complex but include factors such as degree of shading by riparian cover, benthic habitat type, and the presence of physical structures that might serve as attractive habitat.

One indicator of health that is comparable to past studies has been species richness. The New York State Conservation Department (NYSCD) undertook a comprehensive biological survey of watersheds across the state in the 1920s and 1930s, with the lower Hudson and its watershed being assessed last.[36] Schmidt and Kiviat also surveyed the Fishkill system in the 1980s and made comparisons of their findings with unpublished NYSCD data from the 1950s, 60s, and 70s where possible.[37] Tables 13.1 and 13.2 compare these surveys with work completed in 2001 on the Fishkill mainstem and Sprout Creek, one of the largest tributaries in the Fishkill system. This characterization of fish community structure and change offers two main observations. First, the mix of species in any given time frame differs, reflecting natural ecological processes (e.g., competition, predation) as well as anthropogenic drivers (e.g., water quality alteration, species introductions). Second, there has been a general decline in species richness at all sites, with the greatest percent decline (36%) in the Sprout Creek. Overall, most of the change has occurred since the 1936 survey. The 1950s species minimum in the Fishkill Creek mainstem may have been associated with pollution from small industry, and the rebound in species numbers is likely associated with water quality improvements.

Further analysis and synthesis are in progress. The ecological data sets will be used to develop statistical relationships between ecological variables and land use, indicators of urbanization (e.g., catchment imperviousness)[38,39] and associated economic activities. These relationships can be displayed as graphs, and as suggested by Karr[40] become "ecological dose-response curves" that "show a measured biological response to the cumulative ecological exposure, or dose, of all events and human activities within a watershed." These statistical relationships will then form the basis of ecological indicators of economic and land-use scenarios. Early analysis has hinted at the complexity of the relationship between anthropogenic drivers and metrics of ecosystem health. Indicators will not likely point in the same direction, and that information may be the key to understanding how the upstream inputs are responding to human activities on the landscape.

SCENARIO ANALYSIS

To follow the progression within and between the three submodels described above, this section illustrates a scenario analysis based on growth in the Dutchess County

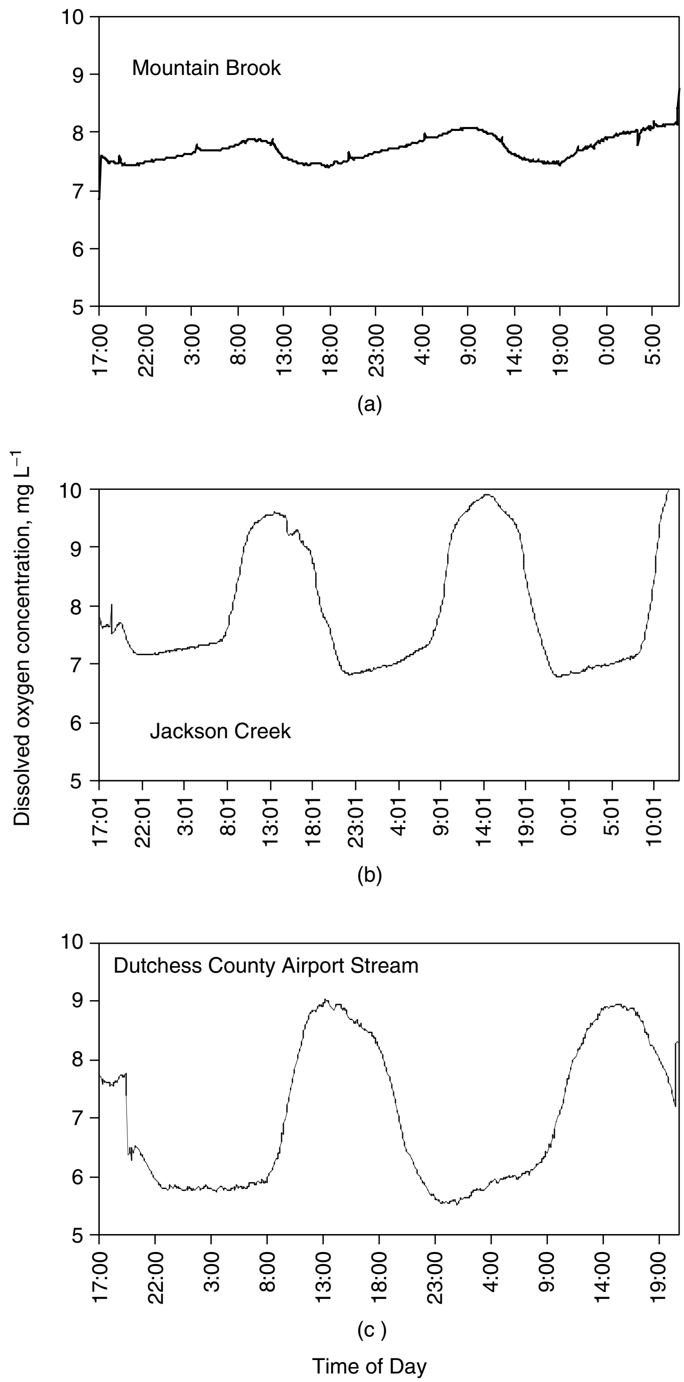

Figure 13.7 Dissolved oxygen profiles collected simultaneously, August 13–15, 2001 in (a) forested, (b) agricultural, and (c) suburbanized watersheds within the Wappingers and Fishkill drainages.

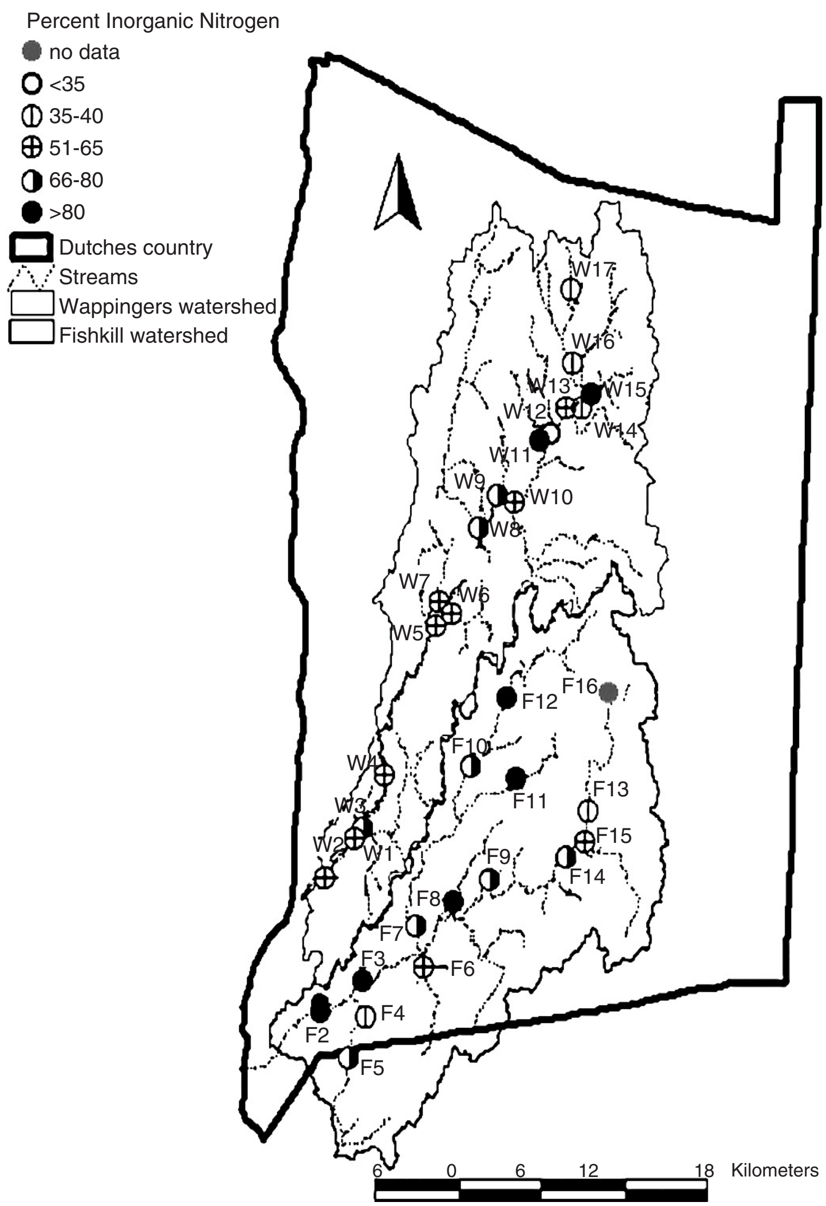

Figure 13.8 Mean percent inorganic nitrogen (May–August) measured at sites in the Wappingers and Fishkill watersheds, Dutchess County, New York.

semiconductor industry. During the first project workshop — with state and county planners, representatives of local and regional nongovernmental organizations, and technical advisors from academia and local research institutes — growth in the semiconductor industry was identified as a priority scenario. In particular, IBM was building a semiconductor plant in East Fishkill that would employ approximately 1000 people

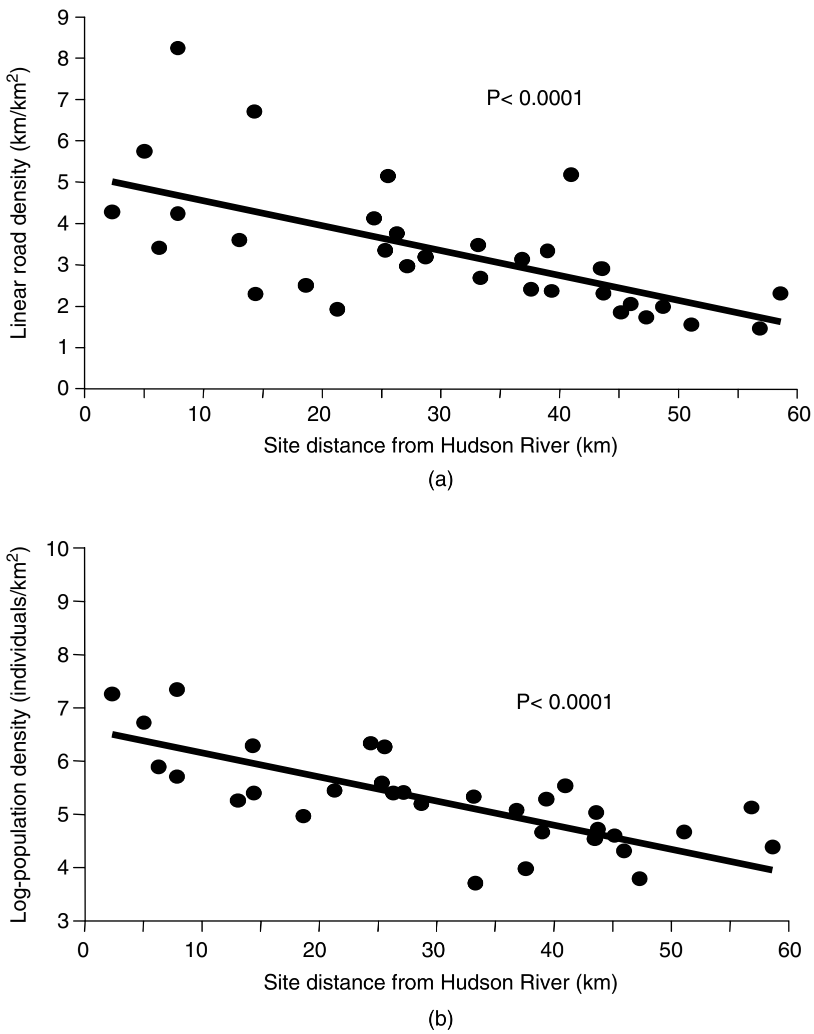

Figure 13.9 Plots of (a) road and (b) population densities versus distance from Hudson River for sites within the Wappingers and Fishkill watersheds, Dutchess County, New York.

when operational in 2003. An existing building at IBM's Fishkill site was to be adapted and remodeled to house the chip plant, an activity expected to create another 1400 temporary construction jobs.[41] IBM was expected to invest $2.5 billion in the plant,[42] and the county was promoting the project by offering IBM tax exemptions valued at $475 million, as well as grants and loans worth $28.75 million.[43]

The first step in the scenario analysis is to identify the semiconductor industry within the GR-SAM and estimate its input–output and spatial linkages with other components of the regional economy. The semiconductor industry of Dutchess County was identified as a key sector based on both its relative size and its connectivity to regional industry and households.[11] In relative terms, it has the highest

Table 13.1 Changes in Fish Species Present in the Fishkill Mainstem Over Time

Species	Common name	1930s	1950s	1980s	2001
Anguilla rostrata	American eel			x	x
Esox americanus americanus	redfin pickerel	x	x	x	
Ameiurus natalis	yellow bullhead				x
Ameiurus nebulosus	brown bullhead	x	x		x
Catostomus commersoni	white sucker	x	x	x	x
Carassius auratus	goldfish	x			
Cyprinus carpio	carp	x		x	
C. auratus X C. carpio	goldfish-carp hybrid	x			
Cyprinella spilopterus	spotfin shiner			x	x
Erimyzon oblongus	creek chubsucker	x			
Exoglossum maxillingua	cutlips minnow	x	x	x	x
Luxilus cornutus	common shiner	x	x	x	x
Notemigonus crysoleucas	golden shiner	x			x
Rhinichthys atratulus	blacknose dace	x	x	x	x
Rhinichthys cataractae	longnose dace	x		x	x
Semotilus atromaculatus	creek chub	x	x	x	x
Semotilus corporalis	fallfish	x		x	
Oncorhynchus mykiss	rainbow trout				
Salmo trutta	brown trout	x	x	x	x
Salvelinus fontinalis	brook trout			x	
Fundulus diaphanus	banded killifish			x	
Ambloplites rupestris	rock bass	x	x	x	x
Lepomis auritus	redbreast sunfish	x		x	x
Lepomis gibbosus	pumpkinseed	x	x	x	
Lepomis macrochirus	bluegill	x		x	x
L. gibbosus X L. auritus	pumpkinseed X redbreast	x			x
Micropterus dolomieu	smallmouth bass	x	x	x	
Micropterus salmoides	largemouth bass	x	x	x	x
Pomoxis nigromaculatus	black crappie	x			
Etheostoma olmstedi	tessellated darter	x	x	x	x
Percina peltata	shield darter	x			
Perca flavescens	yellow perch	x		x	x
Total number of species		**26**	**13**	**22**	**19**

Current study compared with NYSCD[36] and Schmidt and Kiviat.[37]

Table 13.2 Changes in Fish Species Present in Sprout Creek Over Time

Species	Common name	1930s	1960s	1980s	2001
Anguilla rostrata	American eel			x	x
Esox americanus americanus	redfin pickerel	x	x	x	x
Ameiurus nebulosus	brown bullhead	x			
Catostomus commersoni	white sucker	x	x	x	x
Erimyzon oblongus	creek chubsucker	x			
Exoglossum maxillingua	cutlips minnow	x	x	x	x
Luxilus cornutus	common shiner	x	x	x	x
Notemigonus crysoleucas	golden shiner	x			x
Rhinichthys atratulus	blacknose dace	x	x	x	x
Rhinichthys cataractae	longnose dace	x	x	x	x
Semotilus atromaculatus	creek chub	x	x	x	
Semotilus corporalis	fallfish	x	x		x
Oncorhynchus mykiss	rainbow trout				x
Salmo trutta	brown trout	x	x	x	x
Salvelinus fontinalis	brook trout	x			
Micropterus dolomieu	smallmouth bass	x			
Micropterus salmoides	largemouth bass	x	x		
Ambloplites rupestris	rock bass	x	x	x	
Lepomis auritus	redbreast sunfish	x	x	x	x
Lepomis macrochirus	bluegill	x	x	x	
Lepomis gibbosus	pumpkinseed	x	x	x	
Etheostoma olmstedi	tessellated darter	x	x	x	x
Perca flavescens	yellow perch	x			
Cottus cognatus	slimy sculpin	x	x		x
Total number of species		**22**	**16**	**14**	**14**

Current study compared with NYSCD[36] and Schmidt and Kiviat.[37]

location quotient[44] in the county economy (a relative measure of importance of the industry locally as compared to the national average), followed closely by the related industries of computer peripheral equipment and electronic computers. By further combining location quotients with data on input–output linkages, keystone sectors are identified as those with both high location quotients and strong linkages to other high location quotient industries.[45] This method further highlights the semiconductor industry's relative importance to the Dutchess County economy. A final step in the keystone sector description delineates those sectors with strong forward linkages (i.e., selling proportionately larger amounts of inputs to other sectors within the region), as well as those with strong backward linkages (i.e., purchasing larger amounts of inputs from other sectors in the region's economy).[46] The semiconductor industry demonstrates above-average forward and backward linkage to other regional industries.

Within this context, the next step is to understand how an increase in employment in the semiconductor industry translates into countywide income and employment change, distribution of income amongst households and wage classifications, and generation of new households. An increase of 1000 new employees in the semiconductor industry multiplies into nearly 2300 economy-wide jobs in the model economy. The industry has the eleventh-highest earnings per employee ($79,604) in the county, contributing to a relatively large countywide income increase of over $238 million. About 70% of the impact is direct (due to semiconductor wages, profits, etc.), with 17% indirect (due to inputs from other sectors) and 13% induced (due to new household income expenditures). The top five industries affected are semiconductors (by a large margin), maintenance and repair facilities, eating and drinking (due primarily to induced household expenditures), wholesale trade, and personnel supply services.

Growth in employment by wage and household income category is next translated into new households. The cases of both local full employment and unemployment within the occupation classes were considered. The percentage of new commuters from outside the county economy was also considered when estimating new within-county household generation. Depending on the degree of local production assumed to fill new input demands from the semiconductor industry, new households are estimated to be between 1777 and 2051. The full employment scenario was assumed more likely as unemployment in the county is generally low, and IBM currently employs many high-skill workers at their other facilities. However, commuting may play a factor. The IBM facility in Poughkeepsie employs several people who live in neighboring Ulster County.

To locate new households, the binomial logit model can be employed to estimate the most likely tax parcels to convert to residential. The degree of new home construction will depend on the amount of real estate on the market, the distance workers are willing to drive to a new IBM plant, and other locational variables considered in the logit model. Using the GIS system, the high-probability vacant parcels can be identified within various radii from direct, indirect, and induced business locations in the GR-SAM. Various biophysical and zoning constraints can also define subscenarios that would shape development patterns.

To complete the scenario, new residential land use identified in the GIS is translated into land-use indices by use class and impervious surfaces in each subcatchment impacted. The correlation with human disturbance and ecosystem health is then drawn according to estimated statistical relationships. An ecological risk assessment can then be viewed in the full light of its primary determinants, spatial relationships, and potential for amelioration by economic and land-use policy.

MULTICRITERIA DECISION AID

A major challenge for effective watershed management is to direct and control economic growth while balancing the often conflicting goals of diverse stakeholders. Scenario analysis is illustrative of the potential economic, land-use, and ecological consequences of a particular development impact, and thus is a form of impact analysis (see "Complementary Analyses" in Chapter 5). By visualizing the accumulation of small decisions at the watershed scale, the approach portrayed in Figure 13.2, and illustrated with the semi-conductor scenario, is capable of informing a decision-making process. The next step is to frame the multiple attributes of scenarios — including descriptors of economic, land-use, and ecological change — into a decision-making framework capable of evaluating trade-offs and compromises in the formulation of management and policy alternatives.

To place scenario analysis in this decision-making context, a multi-criteria decision aid (MCDA) is under development to assist in identifying and prioritizing land use plans in the Wappingers and Fishkill watersheds. MCDA is a framework that is transparent to decision-makers, adaptable to many situations across multiple metrics and scales, and amenable to both expert and local stakeholder pools of knowledge. An explicit consideration of multiple objectives and viewpoints is in contrast to decision frameworks that seek to maximize one objective or reach an optimal solution from the perspective of a "representative" decision-maker. MCDA attempts to structure this complexity, as opposed to conventional economic tools such as cost–benefit analysis that seek to reduce complexity to a single dimension, unit, and value system.[47]

Figure 13.10 illustrates the typical hierarchy of multicriteria decision problems including goal, decision alternatives, general criteria, and specific indicators. In Dutchess County, one of the chief architects of goal formation at the watershed level has been the Dutchess County Environmental Management Council (EMC), a not-for-profit organization focused on providing research based, nonadvocacy educational resources to the community. Funded through the County and with third-party grants, the EMC works with volunteers — including members of 21 town Conservation Advisory Commissions and Conservation Boards, 11 at-large members appointed by the Dutchess County Legislature, and other interested community members — to identify, research, and prioritize environmental goals. One of the functions of the EMC is to coordinate watershed management between municipalities. A key planning body within the Wappingers watershed is the Wappingers Creek Intermunicipal Council (WIC), formed in 2000 by the umbrella Wappingers Creek Watershed Planning Council with the express goal of fostering intermunicipal cooperation in land-use decision-making.

With this charge the WIC, composed of representatives from all 13 municipalities in the watershed, has been meeting throughout 2003 to establish planning goals, craft a shared vision for their joint future, and make specific policy recommendations to their constituents. Figure 13.10 is an example of a decision hierarchy under development, which the integrated modeling effort can inform. Each constituency of the watershed has a different vision of how something like the semiconductor growth scenario might play out on the landscape to meet a goal of sustainable watershed management. The alternatives range from a rejection of the residential housing growth stimulated by an IBM expansion (an unrealistic option at this point) to letting the growth occur where it may (completely undirected according to estimated development priorities). In between these two extremes are a series of directed growth alternatives, including prioritizing urban in-fill, protecting riparian buffers and current agricultural land, or pursuing riparian buffers alone. Specific policy instru-

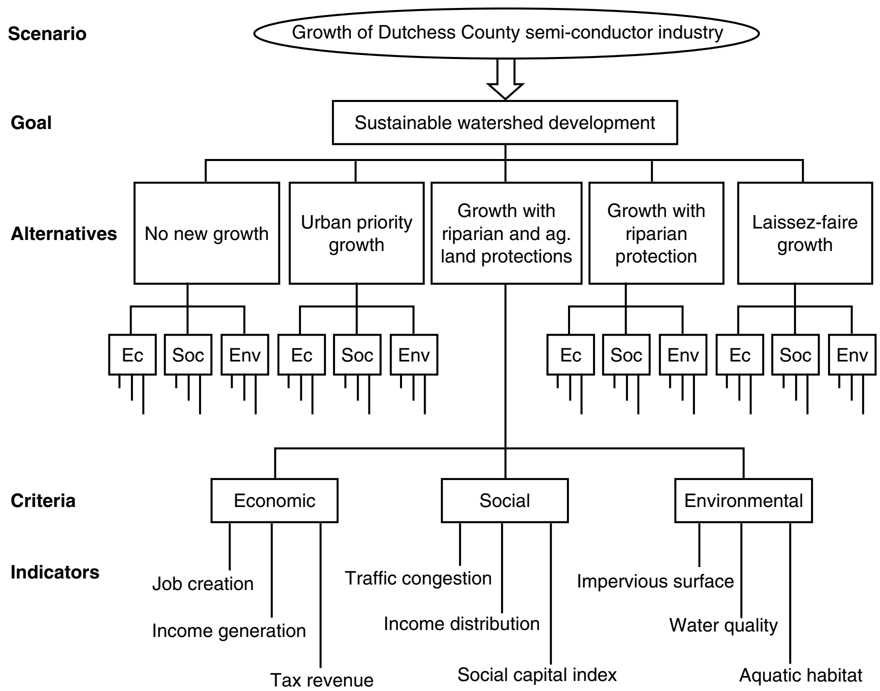

Figure 13.10 Decision hierarchy in watershed management problem.

ments to achieve these alternatives — for instance zoning, tax incentives, or purchase of development rights — might become part of a secondary MCDA, informed by the goals set by the first.

The future outcome of each of these alternatives is then characterized by a suite of indicators, broadly captured in Figure 13.10 as economic, social, and ecological criteria. For example, economic criteria may include job creation, income generation, and tax revenue estimated by the input–output model. Social criteria may include traffic congestion, income distribution, and a social capital index estimated by the social accounts and the probit model of development. Ecological criteria may include impervious surface, water quality, and aquatic habitat indices estimated by the probit model scenarios and spatially correlated biotic and chemical data. Each criterion can be measured in its own units (both quantitative and qualitative) and dimensions (both spatial and temporal), each evaluated by a particular stakeholder position.

These economic, social, and ecological criteria are all at the societal level, and try to anticipate the accumulation of separate multicriteria problems solved by each individual in the system. For example, the costs to the individual of longer commute times due to traffic congestion may be less than the benefits of a larger, more-inexpensive home in the suburbs. However, the watershed-wide MCDA problem tries to anticipate the accumulation of hundreds of these individual decisions and to evaluate the tradeoffs at the societal level. Additionally, a criterion such as impervious surface may itself capture criteria such as green space, stormwater run-off, and flood potential that are set aside to help simplify the comparisons. However, water quality, which also relates to impervious surfaces, may be evaluated on its own merits depending on the priorities of stakeholders.

To quantify these trade-offs, our research team is conducting two workshops in the spring of 2004 to help structure the MCDA problem: the first with municipal representatives from the WIC, and the second with representatives from various stakeholder groups in the county (as a follow-up to our first project workshop). 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. We have selected PROMETHEE (Preference Ranking Organization METHod of Enrichment Evaluation)[48] and the associated Decision Lab 2000 software package[49] after reviewing current models for flexibility to handle indifference and uncertainty, ease of use and understanding in a workshop setting, and the ability to visualize a group-based process of goal-setting and compromise.[47]

PROMETHEE requires criteria-specific and stakeholder-identified information, including: (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 his or her 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 to 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 GAIA (Graphic Analysis for Interactive Assistance) plane diagrams that represent a complete view of the conflicts between the criteria, characteristics of the actions, and 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 criteria themselves.[50] In a group context, the entire MCDA process has been described as a group decision support system (GDSS), and examples of its use can be found in resource planning and management, forest management, watershed planning, public policy planning, pollution cleanup, transportation planning, and the siting of industrial and power facilities.[51–54]

The advent of spatial decision-support systems (SDSS) — the family of MCDA models that our study most closely contributes — provides an important new opportunity for the evolution of MCDA methods and applications.[55,56] Examples where SDSS and GDSS have been used together include an examination of riparian revegetation options in North Queensland, Australia,[57] land-use conflict resolution involving fragile ecosystems in Kenya,[58] watershed management in Taiwan,[59] housing suitability in Switzerland,[60] and water quality issues in Quebec.[55]

DISCUSSION

The complexities involved in economic and watershed systems are enormous. Both are evolutionary systems characterized by nonlinearities, historical contingencies, and pure uncertainty. The task of analyzing either of these systems alone would be daunting. Economic analysis is particularly hamstrung by a long history of reliance on static equilibrium models that have proved to be of limited value in modeling evolutionary change. Models of land-use change typically ignore any connection to the economic system. Similarly, ecological studies focus on point estimates of current conditions, which are divorced from landscape and economic change. Granted, there are many key gaps in knowledge and data preventing accurate forecasts of the ecological response to land-use change.[61] However, the goal of this study is to begin to integrate disciplinary expertise for the pieces of the puzzle to help visualize and inform current stakeholder decision-making processes at the watershed scale.

These pieces have been extensively used elsewhere, and thus the modeling framework doesn't avoid the limitations of any one piece. Social accounting is most limited by the static nature of characterizing the economy, lack of regional data, and lag in national structural data. The probit analysis captures only broad relationships between residential land use and assessment and census data, and is also lacking in time series data and any supply and demand dynamics in the real estate market. The chemical and biological assessment is similarly a shapshot in time and depends on the interpolation of satellite imagery to tease out relations between aquatic variables and landscape characteristics. Each component also comes with its own degree of uncertainty and variability, which is compounded when the economic, land-use, and ecological spheres of analysis are integrated. In separate publications, we deal extensively with varying model assumptions, results of Monte Carlo experiments, and variability analysis.[11,19,62]

Our integrated modeling and evaluation approach is in step with the conceptual approach outlined in Figure 9.1 and Figure 9.4. Assessment planning and problem formulation led to the integrated conceptual model of Figure 13.1 and the generation of particular development scenarios (illustrated by the semiconductor industry scenario). As shown in Figure 13.11, analysis and characterization of alternatives via economic, social and ecological criteria is the explicit outcome of the three submodels comprised by our approach (Figure 13.2). Comparison of decision alternatives under various economic change scenarios is conducted through an MCDA outranking procedure. Although not described in detail here, the MCDA can potentially lead to a negotiated decision on intermunicipal watershed cooperation. Consultation with both expert and stakeholder peer communities has occurred throughout model development, scenario characterization, alternative development, and criteria measurement with the aim to develop a decision tool amenable to adaptive management, evaluating changing conditions, priorities, and goals.

The social accounting approach proved to be flexible enough to capture the major economic drivers of Dutchess County and was amenable to the scenario approach crucial to this study. Collecting and analyzing land-use data was straightforward and proved to be a reliable way to link economic and ecosystem changes. Ecological metrics are proving complex, but some have shown promise in capturing the relationship

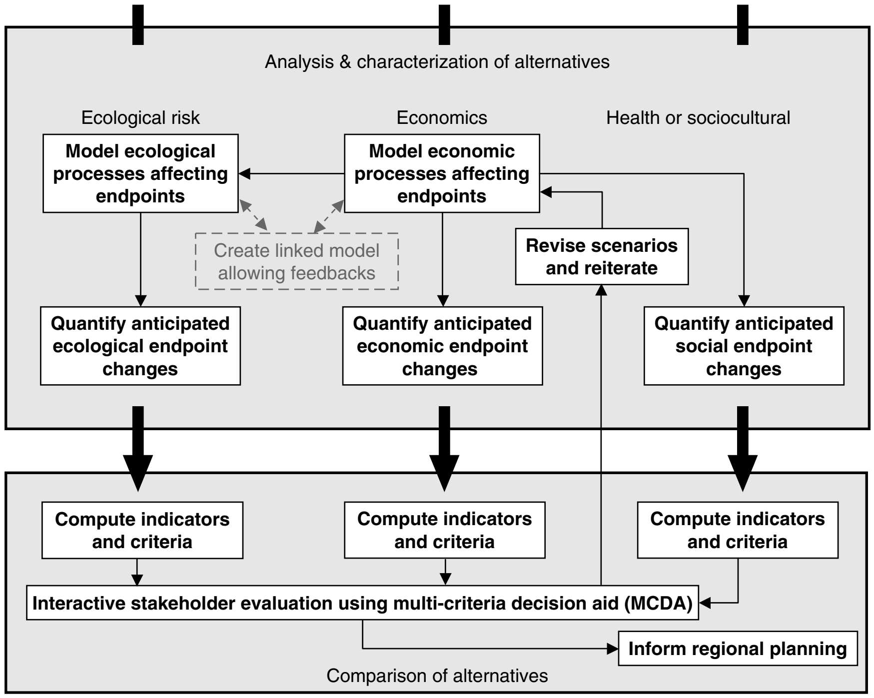

Figure 13.11 Techniques used for analysis, characterization, and comparison of management alternatives in the Hudson River watershed, as compared to the example shown in Figure 9.4. White boxes and bold type show features included in this analysis.

between land-use patterns and the biological health of the streams studied. Where this study falls short of the process outlined in Figure 9.4 is estimating any potential feedbacks from the ecological impacts to the social and economic drivers. For example, water quantity or quality could eventually become a limiting factor to locating new industry and constructing new homes.

Within the field of sustainability studies, few support traditional economic analysis as the sole guidepost for societal planning. Rather, a pluralistic view that espouses different perspectives, analytic frameworks, and metrics is seen as a more robust means to anticipate the future.[63] In addition, anticipating the future means that one should also anticipate surprise, with the practical implication of building some buffering capacity into the system. On the ground, this may translate into decisions such as not to build out completely, but rather to preserve some areas in anticipation of unspecified change, for example due to climate. This study provides a framework upon which to build a transparent model that can illuminate interconnections among economy, society, and ecosystems, and provide a basis for planning decisions. To emerge from under the tyranny of small decisions will require such tools that envision long-run change, help to shape shared community goals, and encourage dialogue between local and credentialed expertise.

ACKNOWLEDGMENTS

This research was made possible by a grant from the Hudson River Foundation entitled "Modeling and Measuring the Process and Consequences of Land Use Change: Case Studies in the Hudson River Watershed."

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