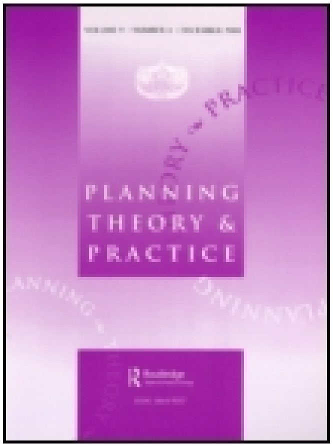

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Embracing Complexity and Uncertainty: The Potential of Agent-Based Modeling for Environmental Planning and Policy

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Embracing Complexity and Uncertainty: The Potential of Agent-Based Modeling for Environmental Planning and Policy

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ABSTRACT *Environmental degradation is often defined as a public goods problem, emerging when property rights are not clearly defined and costs are externalized to other parties. Proposing corrective regulation that enforces technological fixes or market-based approaches is often met with political resistance and doubts about its effectiveness. This is partly due to the complexity of interacting physical and socio-economic components that obscure the impacts of human decision-making on environmental functions. Yet, understanding the complexity of integrated human-environmental systems can help planners and stakeholders frame environmental problems, view their role in them and design effective policies to address them. This article examines the potential and limitations of agent-based models as metaphors that can contribute to the understanding of such complex systems, illustrating the argument with a hypothetical application in groundwater management.*

Keywords: Agent-based modeling; complexity; uncertainty; environmental planning; adaptive management; participatory modeling; groundwater management

Introduction: Evolving Approaches to Environmental Problems

The way we understand and assign meaning to our world affects how we make decisions in relation to it. Environmental planning is a dynamic field within a social and technological context that shapes its analytical and policy approaches. So, for example, in the USA the regulatory and technological approaches of the 1970s were a product of the environmental concerns that in turn were shaped by the social movements of the time and the faith in engineering solutions (Buck, 2006; Randolph, 2004). While comprehensive urban modeling fell into disrepute (Lee, 1973), systems theory fueled the development of mathematical models applied to natural resource management. The 1980s saw the rise of economic analyses and valuation methods related to environmental goods and services to use in benefit-cost analysis for policy evaluation (Buck, 2006), and of geographic information systems (GIS) for environmental impact assessments and identification of ecologically sensitive areas. These trends were supported by computational advances that permitted increasingly sophisticated analyses and models to inform policy-making

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(Buck, 2006; Randolph, 2004; Tietenberg, 2006). Notable progress has been made thanks to the contribution of these approaches, particularly in terms of conservation and point-source pollution control. There is, however, increasing awareness of—and frustration about—persistent environmental degradation, such as flooding, drought, climate change, and loss of biodiversity and open space, most of them related to changes in land use and resource consumption. These problems persist due to the diversity of actors involved (partly addressed through participatory approaches), the public goods nature and unclear dynamics of the natural resources and functions with which they interact, and the "silo approach" in various realms of public policy that does not readily recognize these interactions (e.g., while agricultural irrigation is often managed at the state level, land-use regulations are the domain of local government despite their effect on the same water resources). As much as this complexity is a problem, it is also an opportunity. While individual rational decisions around common resources can collectively result in the "Tragedy of the Commons" (Hardin, 1968), small behavioral changes are the key to prevent the tragedy and stimulate a large-scale environmental transformation. Environmental planning would benefit from tools that help us explore what those small changes could be and how different policies could trigger them, offering alternative perspectives on complexity and how we can take advantage of it. Agent-based modeling has the potential to support this kind of thinking, though this potential has yet to be fully realized in environmental planning and policy.

Groundwater overexploitation associated to land-use change helps illustrate the complexity and uncertainty of environmental problems, and how agent-based modeling can introduce new dimensions of understanding. Groundwater systems are vulnerable to overexploitation due to their open-access nature: many users can tap into the resource and no users can be excluded from accessing it, thus diminishing its availability to others, diluting responsibilities over its management and removing individual incentives to preserve it (Hardin, 1968; Mitchell, 2005; Schlager & Blomquist, 2001). Unless some institutional arrangement is enforced, groundwater will be extracted beyond the system's ability to replenish itself, leading to the collapse of the resource and of the economic activities depending on it. The natural resource management literature provides abundant examples of the depletion of open-access resources, and no conclusive evidence exists about the most effective institutional arrangement that can prevent it (Burger *et al.*, 2001). The interaction of myriad physical and socio-economic factors introduces complexity in the groundwater system, obscuring the understanding of the direct and indirect impacts of individual and institutional decision-making, and imposing the costs of these impacts on others.

We typically attempt to manage groundwater resources and eliminate this uncertainty through one-dimensional control systems, emphasizing supply over other dimensions of the problem, and emphasizing engineering solutions over other possibilities (Tarlock, 1999; White, 1986). This approach requires sophisticated models to produce accurate estimates of future groundwater yields and demand. The need for such estimates calls for expert modelers to inform policy makers and the public. Standard analytical methods (e.g., population/economic forecasting models, hydrological models to assess the impact of forecasted growth on current groundwater supply), have helped raise awareness of the issue, but have not led to the necessary changes in resource use because they do not treat the inherent complexity of groundwater systems explicitly. These methods tend to aggregate actions and natural processes as correlations, transition probabilities or stocks and flows. Important pieces of information that are the source of complexity (e.g., causality, decision making, heterogeneity, multiple feedback) are lost in the translation (Hoffman *et al.*, 2003). The loss of complex information is compounded by the rational approach to scientific analysis, perceived as objective and disconnected from the subjectivity of the policy world. Participatory processes, such as those encouraged in watershed management, have been implemented to overcome the inevitable tension arising when users compete and have conflicting values and goals for such open-access resources. The discussion, however, is often focused on reaching consensus around desired development futures but often remains separate from the analytical understanding of the system, with the danger of agreeing on unrealistic or unsustainable goals. Helen Couclelis explains this dilemma as follows: because of excessive complexity, comprehensive rational planning is extremely top-down (it requires advanced expert analysis), while the control needs to occur through local (distributed) participation. Yet, complexity is not accessible to the public, even to local planners (Couclelis, 2005). Consequently, the necessary changes do not occur because the understanding of how they connect to the bigger complex picture does not occur at the level at which the changes need to happen.

Agent-based modeling, widely used in the study of complexity, natural sciences and increasingly social sciences, is an alternative method that explicitly represents complexity and treats uncertainty in our analyses. These models are typically object-oriented computer programs,[1] where the objects are actors operating at various scales (e.g., residents, farmers, businesses, units of government) making rule-based decisions in an environment characterized by various attributes (e.g., presence of natural amenities, distance to employment centers, access to water and sewerage infrastructure). Agent-based models can be spatially explicit, i.e., agents may have a specific location in space, and the strength of interactions may vary with agents' location and with the spatial distribution of landscape attributes. Simulations with agent-based models constitute virtual experiments that are especially useful when such experiments (e.g., land-use policies) are costly and risky to run in real life (Axelrod, 1997; Epstein, 1999). The array of simulation outcomes provides useful insights on the effects of the agents' interaction with other agents and with their environment, a unique feature of these models. As in real-world complex systems, surprises often emerge in the agent-based simulations. The focus of the modeling, then, is on building plausible natural and decision-making processes to expand our understanding of the range of possible consequences (Axelrod, 1997; Bankes, 1993; Batty & Torrens, 2001). For example, many agent-based models of land-use change incorporate randomness in terms of how the path of development will play out spatially and temporally (Brown *et al.*, 2005). Each time the model is run with the same parameter settings the output is different, depending on how decisions are made early in the run. While it makes predictability difficult, the simulations can still provide powerful insights regarding how much variability the system exhibits, and how varying certain parameters matters. These insights are particularly useful when we couple human decision-making with the dynamics of natural processes, such as groundwater flow, of which humans are often unaware. Thus, by explicitly representing the characteristics of complexity, agent-based analyses allow us to investigate the role of complexity in both complicating management decisions and in supporting innovative solutions.

Agent-based representations of complexity are metaphorical in that real-life actions and natural processes are represented as analogous mechanisms in the model. Metaphors are not meant to be literal, and yet may be powerful comparative devices in explaining and understanding phenomena (Margalef, 1981), particularly if they are intuitive to a broad audience that includes scientists across disciplines, policy makers and community members. It is through decisions that policies have an influence on environmental patterns. The metaphorical representation of complexity allows us to connect our collective actions and knowledge to the desired environmental outcomes. Agent-based models are therefore useful as participatory planning support systems because they organize complex information into meaningful and accessible forms and identify the key actions that can make a difference. In an appropriate institutional framework, agent-based models can provide planners, managers and individuals with substantive policy and behavioral recommendations in anticipation of the plausible outcomes of their decisions.

This article lays out the theoretical background that explains the challenges associated with complex environmental problems, using as an illustration a hypothetical case of groundwater depletion in urbanizing areas. Responding to this challenge, the article delineates an agenda for environmental planning that uses agent-based representations of the complexity of human-environmental systems within a participatory institutional context. The goal of this agenda is to establish a collective learning framework for empirical exploration, model construction and validation, and policy analysis and implementation that can effectively address our persistent environmental challenges.

An Illustration of Complex Environmental Problems: Groundwater Depletion

Groundwater systems are open-access resources, which are vulnerable to overexploitation. The incentive to deplete them arises from the non-excludable nature and rival consumption of these systems, i.e., users cannot be excluded from exploiting the resource and every unit consumed cannot be appropriated by anybody else. Extensive literature supports either government regulations or market mechanisms to ensure long-term use of these resources. Empirical evidence, however, is inconclusive as to the effectiveness of either solution (Dolsak & Ostrom, 2003; Ostrom, 1990, 2001, 2003). Physical and socio-economic factors make groundwater a complex resource to manage by limiting the information about the resource and its users, and externalizing the negative effects of consumption on third parties (Aswathanarayana, 2001; Blomquist, 1994; Blomquist *et al.*, 1994; Dolsak & Ostrom, 2003; Ingram, 1990; Lee, 1999; Leopold, 1974, 1997; Mitchell, 2005; Ostrom, 1990, 2001; Reisner, 1993; Schlager & Blomquist, 2001; Tarlock, 1999). These uncertainties include:

- *Physical constraints.* The connection between groundwater and surface water systems (each with differential replenishment rates) introduces uncertainty in resource dynamics, compounded by the indirect effects of climate change and human extraction. Additionally, it is often not possible to determine the hydrological boundaries defining the resource or to measure how much groundwater is available for allocation. In contrast, users require certainty to make long-term economic decisions over the resource, favoring the implementation of water rights and regulations. Such interventions, however, introduce rigidity in the system, reducing its adaptability to changing natural and socioeconomic conditions.
- *Heterogeneity.* The multiplicity and diversity of users complicates groundwater management because no one individual or group can control its availability, and any evidence of decline will be blamed on others elsewhere in the system. The differing perceptions of management costs and benefits reduce the likelihood of coordinating agreements and enforcement. Spatial asymmetries (e.g., hydraulic coefficients affecting the size and depth of cones of depression) also lead to power imbalances among users.
- *Imperfect information and interacting scales.* The multiple and overlapping jurisdictions, water doctrines and legal definitions oftentimes override each others' conservation efforts and are often based on outdated scientific knowledge about the resource and its users, impeding the implementation of appropriate management policies.

Land-use decisions are intimately related to the emergent spatial patterns of groundwater needs. Therefore, planners need to consider land-use patterns and the factors driving them to assess the spatial dimension of groundwater depletion and assign responsibilities over the resource (Mitchell, 2005). The interaction of technological, economic, cultural, and institutional factors influencing urbanization has been extensively debated in the urban economics and geography literature, with additional insights provided by complexity studies (Anas *et al.*, 1998; Bogart, 1998; Brockner, 1992; Chin, 2002; Downs, 1994; Evans, 1985; Ewing, 1994, 1997; Heilbrun, 1987; Janssen *et al.*, 2002; Katz & Bradley, 1999; Knack, 2000; McGrath, 2005; Otter *et al.*, 2001; Rosen, 1995; Sterman, 1994; Torrens, 2000; Wiewel *et al.*, 1999). The principal factors driving land-use patterns include:

- *Technological innovations.* Changes in transportation and industrial technology have profoundly changed the development of urban areas. Cities that initially agglomerated around public transportation systems later expanded at lower densities along road and highway systems as private transportation became more affordable.
- *Individual and developers' preferences.* Whether the perspective is "natural evolution" or "flight from blight", individual preferences are expressed in choices for location as they trade off space, transportation costs and amenities. Developers may further restrict location choices by targeting only a sector of the market to secure their investments.
- *Market and government failure.* Local zoning, federal and state transportation and housing subsidies, and support for excess capacity in waste-water treatment facilities affect residential choices, contributing to land-market distortions by externalizing transportation and development costs and excluding high-density, mixed-use or affordable development. Empirical evidence of excess expansion in the fifty main metropolitan areas in the USA confirms the presence of market distortions.
- *Imperfect information and interacting scales*. The spatial flow of information, individuals and products, idiosyncratic behaviors, and the time lags between causes and effects significantly contribute to land-use decisions and emerging development patterns. Urban agglomeration and peripheral expansion arise from processes occurring simultaneously at different scales, leading to irregular and scale-dependent urban structures. Uncertainty is an important factor that can perpetuate damaging behavioral tendencies due to sunk-costs effects.

The complexity of the coupled land-groundwater system poses a significant challenge to policy analysts and decision makers. The uncertainty and external costs that result from this complexity discourage individual protection of the shared groundwater system. Some intervention is required and justified by economic theory to introduce behavioral changes. Traditionally we have focused on linear control solutions to overexploitation and scarcity (e.g., expanding water supply) that have been successful to some degree. Despite these efforts, scarcity has repeatedly emerged as a growing challenge.

Analytical and Policy Approaches to Groundwater Management

> . . . both demand and need tend to grow in line with provision, [yet] . . . overemphasizing need can make us even needier. (Rhoads, 1996, pp. 30-31)

Solutions to water scarcity have typically focused on reducing uncertainty by enhancing the supply side of the resource: flood/flow control (e.g., dams, channel rectifications), irrigation, municipal infrastructure, and water transports or diversions. The proposed solutions were successful in overcoming water scarcity locally and in the short term, but often reinforced the problem they tried to avoid, or imposed it on other areas and interested parties (Brown & Ingram, 1987; Ingram, 1990; Reisner, 1993; White, 1986).

The synergistic combination of a supply-oriented political culture (Tarlock, 1999; White, 1986), diffused responsibilities (Blomquist, 1994; Mitchell, 2005) and sunk-costs effects (Janssen *et al.*, 2002) promotes persistent urban expansion despite increasing evidence of the environmental impacts it produces. Communities continue investing in infrastructure and residential development, reducing their flexibility to withstand resource scarcity, even as they are already facing it. Examples exist of groundwater being effectively depleted, and of scattered towns being abandoned in some metropolitan fringes in the USA after their aquifers ran dry (Power, 2001). Pressure is mounting to build pipelines transporting water from the Great Lakes to the Sunbelt region as cities in the southwest continue to expand and mine their water sources (Slack, 2007). Even in humid areas, such as the Great Lakes basin, groundwater levels and quality have responded to changes in both number and location of wells, due to both switching from groundwater to surface water systems and land conversion from agricultural and open space to urban and suburban development (Garmoe, 2006; Nicholas *et al.*, 2001; Northeastern Illinois Planning Commission, 2002; Reeves *et al.*, 2004; Roadcap *et al.*, 1993; Visocky *et al.*, 1985; Visocky, 1993).

To cater to the goal of expanding supply, mainstream analytical approaches focus on building and applying models to predict population and economic growth, to anticipate demand and plan for it. Modeling efforts focus on assessing alternative means to reach the predetermined objective of growth while minimizing or externalizing the impacts on the groundwater resource. The role of modeling remains external to the policy process, as model assumptions and alternative goals are rarely discussed prior to, or in conjunction with, the assessment of means. Figure 1 represents this interaction between scientific modeling and policy making. In this framework, stakeholders are the constituents that place demands on their representatives at a specific level of government. Policy makers at this level request scientists to predict best estimates to guide policy decisions in response to constituents' demands. Subjective discussions of value judgement are kept separate from the objective modeling activity, and yet a normative decision is taking place that is not being openly discussed (Robinson, 1992). As a result, both processes inform each other

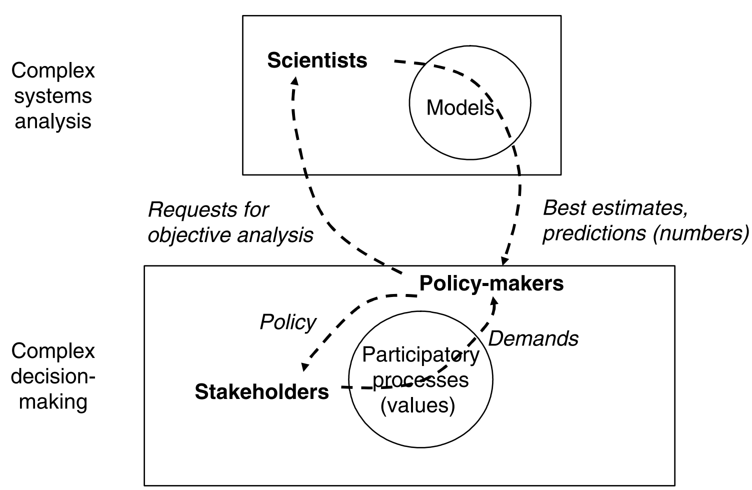


Figure 1. Traditional analytical approach to policy.

only through the outputs of their respective activities: scientific research and participatory planning. The former is unaware of the social and cultural context (Hoch, 2002); the latter, of the informational substance to assist in discussions of desirable goals and means. Because the modeling is conducted separate from the policy discussions, a valuable opportunity for in-depth discussion of the modeling assumptions and implications is missed.

Classical scientific research attempts to produce best estimates based on a history of observed pattern changes, with the purpose of assisting policy makers in anticipating future patterns. Thus the goal of most modeling is prediction (Bankes, 1993). Accurate predictability requires a realistic representation of the complex land-groundwater system, translating into comprehensiveness and detail to account for every piece of the puzzle. The effort to produce a best (numerical) estimate leads to the construction of sophisticated hydrological and land-use models that require considerable effort and data, and that are often separate from each other. An example in the Chicago area is the ongoing development of groundwater models and water flow accounts for Kane County, Illinois, a five-year investment of US$2 million (Bus & Shuch, 2006), in which the water demand scenarios are based on population projections constructed in separate exercises. While informative and valuable, such sophistication often alienates the subjects that the modeling results are supposed to target. Most resource users, developers and local policy makers are not trained to understand the internal details of these models and possible sources of error, or even the implications of the modeling results on their own land-use and water-use decisions. Additionally, integrating other information, including qualitative data and local knowledge, presents considerable difficulty when using these models. The "black-box" nature of traditional comprehensive models discourages valuable contestation of their assumptions, mechanisms and results (Klosterman, 1994; Lee, 1973). Consequently, only a small fraction of knowledge guides policy, while broader learning opportunities for both the research and the political processes remain unexplored.

Facilitating Groundwater Management Using Complexity

Framing the study of integrated land-groundwater systems within the theory of complexity, using its analytical tools, can broaden the understanding of the impacts of individual and institutional decisions, illuminating the role of policy in encouraging sustainable resource use. Within the array of analytical tools available, agent-based models support a metaphorical representation of complexity by programming actions, decisions and mechanisms in explicit form. This form of representation is amenable to all types of information, as will be illustrated below, not only quantitative data. These models can therefore be comprehensible to a broad audience and generate new knowledge from the inferences between the model and the complex system (Bateson, 1988; Holland, 1998; Margalef, 1981). What generates meaningful knowledge is not the model itself, but its application within a social and political context. Used as metaphors, agent-based models can engage researchers and decision makers in collaborative learning activities to guide the formulation of policy affecting complex land-groundwater systems. The rest of this section discusses how complexity and agent-based modeling can enhance the understanding of these systems and support planning efforts for them. The final section in this paper sets an agenda for the participatory use of agent-based modeling as an additional component of environmental planning, to complement more established approaches.

Framing Land-Groundwater Systems Within Complexity

A complex system is composed of multiple parts, and it emerges from their interaction. Although single constituents may not remain in place and may eventually disappear, the system persists as it adapts to internal and external change. The entire system has a higher organizational level than its parts, but depends on their decentralized actions and interactions to organize, or self-organize, i.e., no centralized or external controls direct the trajectory of the entire system. Small perturbations can be amplified through the interactions, causing trajectory bifurcations into alternative paths or histories with varying degrees of success in adapting to new conditions. Matter, energy and information are continuously exchanged across spatial and temporal scales fueling the system's self-organization and supporting—although sometimes reducing—its adaptive ability. Although feedback exists between the system and its parts, it may be subtle or lag in time. Therefore, the parts base their actions on the limited information about the state of the entire system (Holland, 1998, 1995; Prigogine, 1996).

Like other complex systems, urban areas emerge and evolve as distinct entities from the interaction of multiple heterogeneous agents who buy, develop, and sell properties, manufacture and sell products and implement policies, and whose decisions are affected by cultural values, technological innovation, economic conditions and landscape attributes. The initial location of a small town often determines the direction and density of urban expansion, as well as the construction of transport infrastructure (Anas *et al.*, 1998; Arthur, 1988). Furthermore, soil characteristics and topography influence individual decisions in the land market as poor agricultural soil and steep slopes encourage land conversion to urban use, spurring agglomeration according to spatial variations of the landscape. Low-density development makes scale economies inefficient for the construction of infrastructure, and thus encourages reliance on groundwater for domestic and industrial uses. Communities may be "locked" into such patterns as a result of technological and institutional conditions. For example, septic wastewater systems have historically limited the density at which development can occur because of the land's capability to percolate the residues, while zoning policies may impose further restrictions on high residential densities.

Groundwater systems share many complex features and respond differently to human demand, depending on the link between surface and groundwater, the conductivity of the aquifer, the recharge rates and other spatial physical characteristics. Water, energy and information flow in complex cycles through the integrated land-groundwater system. Having only limited information, individual actions and policies may intensify water scarcity, as explained above. Simultaneously, policies directed to other concerns (e.g., land use and transportation) introduce perturbations that often have unexpected negative effects on groundwater availability. These perturbations nevertheless give us a clue about the opportunities for successful intervention.

How Metaphors Can Help Us Understand Complexity

To cause appropriate policy perturbations, planning research and practice need to expand our understanding of the complexity and uncertainty in human-ecological systems. Yet, our human intellect is biologically limited in its capacity to observe and analyze the complexity in which we are immersed. We are used to thinking in linear patterns, directing our actions to attain a predetermined purpose, detached from the recursive nature of the environment (Bateson, 1972). Problems of environmental degradation are systemic, however, and solutions other than simple linear or one-dimensional controls are required. Integrating multiple dimensions and recognizing that energy and matter continuously flow through them may be more conducive to a system's reconstruction and regeneration (Prigogine, 1996).

Metaphorical thought is well suited for understanding the recursive aspect of complexity because metaphors explain, not through logical linear thinking, but by highlighting the common organizing principles and processes of life, suggesting ways in which to maintain them (Bateson, 1988).[2] They generate innovative understanding by allowing us to transfer inferences and recombine the meanings and associations surrounding both the source and the target of the metaphor (Holland, 1998). To this effect, non-rational models, even false ones, may still be appropriate if they are also powerful enough to coordinate actions towards human-ecological integration and adaptability (Margalef, 1981). Therefore, metaphorical models could significantly contribute to planning around complex and uncertain environmental problems by representing actions and interactions in explicit form. Such models are comprehensible and meaningful to diverse audiences, enriching the transfer and recombination of information between the model and the observed complex system.

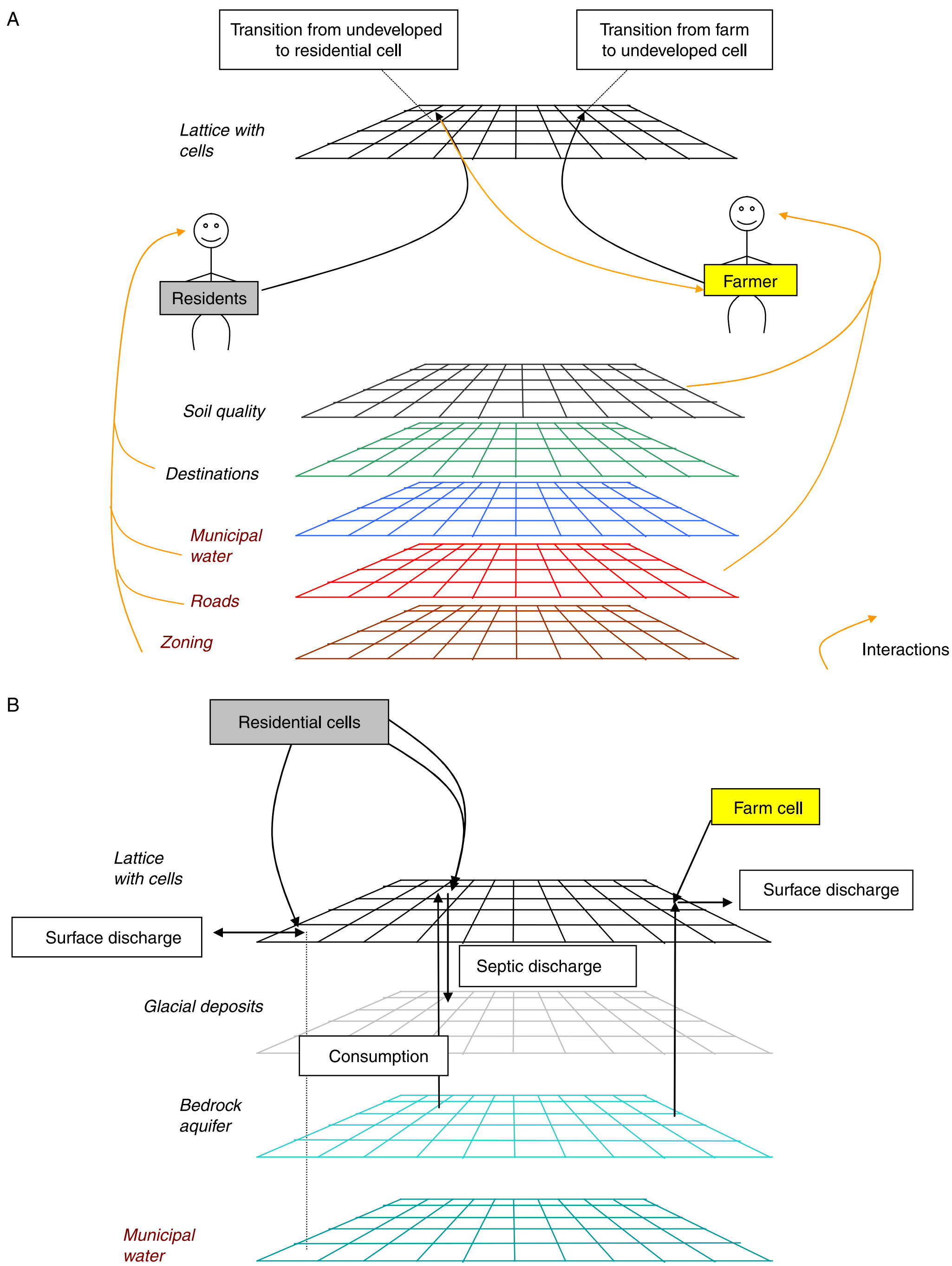
Agent-Based Models as Metaphorical Representations of Land-groundwater Complexity

Agent-based models have been extensively used in the study of complexity. They are composed of agents whose behavior results from specific rules based on the individual characteristics and the interaction with other agents and the environment. The environment may be spatially explicit, i.e., agents may have a location that is represented as coordinates in a two- or three-dimensional lattice. Each location within the lattice may contain various physical and institutional attributes. The simple representation of distinct, yet interacting, social and natural mechanisms allows the explicit treatment of complexity and uncertainty. What follows is a description of the main components and mechanisms of a generic model of groundwater depletion in a hypothetical urbanizing area, for the purposes of illustrating the agent-based representation of the complexity of an environmental problem and how that representation can inform environmental planning and policy. This generic model structure can be adapted to explore policies for sustainable groundwater use in a specific empirical case or for other complex environmental issues, by modifying inputs, parameter values, actors and behaviors according to case-specific information. In the development of any application, the research and policy questions should ultimately guide the appropriate level of resolution of the model components and corresponding mechanisms and parameters.

The land-use component of the model (Figure 2a) involves farmland conversion into land for residential development. The decision to undergo conversion is influenced by surrounding urbanization (i.e., how much residential development occurs in the neighboring cells) and poor agricultural soil quality. In turn, resident agents decide their location after evaluating a sample of cells in terms of their preference for, for example, proximity to employment centers, access to good schools, connection to municipal water supply, and presence of natural amenities. Zoning policies restrict the residential density at which any one location may develop.

Agents make decisions on water consumption depending on agent type and location (Figure 2b). Farmer agents may rely on groundwater for irrigation, extracting the resource from the underlying aquifer and discharging some of it in surface systems, while the rest is absorbed by the crops and lost to evapotranspiration. Resident agents rely on groundwater if municipal water supply is not available, and discharge into septic systems that eventually return water to the aquifer.

Finally, groundwater flow may be represented as a diffusion model, where water flows from higher to lower hydraulic gradients using Darcy's law of flow (Figure 2c). Boundary conditions are an input to the model, so that water flows into the area of study, depending on the relationship between hydraulic gradients at the boundary and within the study area.



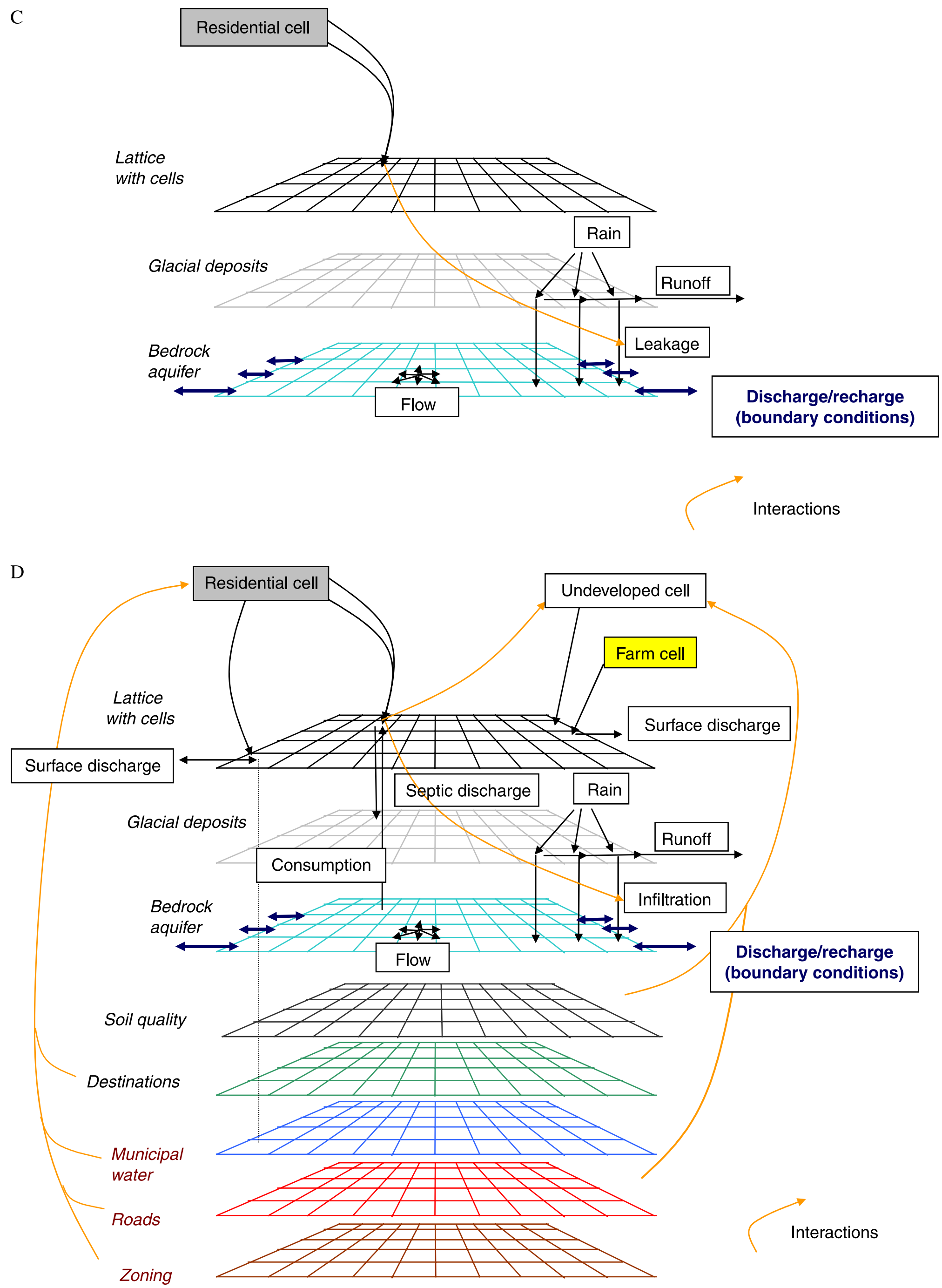


Figure 2. (A) Land-use decision-making; (B) water-use decision-making; (C) groundwater flow; (D) integrated land-use decision-making, water-use decision-making and groundwater flow.

Recharge occurs after precipitation events, affected by the area of paved surfaces that is assumed to increase with residential development.

The sources of complexity described in the second section of this paper are thus explicitly represented as policy, infrastructure and physical landscapes, localized groundwater flow mechanisms, and heterogeneous agents that, having limited information about other agents and their environment, respond to and reinforce urbanization trends and compete for groundwater. The representation of landscapes, agents and local interactions is relatively straightforward, yet complexity and uncertainty emerge when the various scales of interactions are combined to create a metaphor of the integrated land-water system (Figure 2d). To understand how natural, social and political factors may influence groundwater levels through such a complex web of interactions, the agent-based model can be used to run simulations with different input spatial data (e.g., location of natural amenities, road infrastructure, municipal water coverage) or changing relevant parameters of the model (e.g., demographic distribution of location preferences, aquifer recharge rates). Analyzing the history of individual runs can provide a rich understanding of both micro- and macro-level phenomena. This, however, may be misleading because of the randomness inherent in complex social simulations (Axelrod, 2006). Typically, several simulations are run to establish trends and measure the variability within each scenario, indicating the likelihood of specific outcomes.

Policies affect groundwater availability only indirectly by influencing land-use and water-use decisions. Hence, it is important to represent actual individual behavior and policy intervention points (often called "levers" in complexity studies) within a network of interactions. These levers can be made active or inactive (e.g., well permit requirements), varied within a numeric interval (e.g., tax increments for groundwater withdrawals), or changed in their spatial layout (e.g., land-use plans). The format of the policy levers is analogous to that of the actual policy implementation, so outputs of these simulations are easily translatable into policy recommendations. The multi-dimensional representation of impacts (visual/numeric, spatial/aspatial, aggregate/disaggregate, historical/cross-sectional) expands the range of meaning of the simulation results. Providing a range of perspectives may facilitate policy formulation in light of the spatial and temporal complexity of the integrated land-water system. A single output measure would likely be insufficient.

The greatest potential of agent-based modeling is in generating explanations for the phenomena we observe. Predictive power becomes its greatest weakness, however. In complex systems, a pattern is just one of many possible outcomes that may emerge from the same micro-level behaviors, natural processes and interactions (Axtell & Epstein, 1994). Path-dependence (how current events depend on the past and influence the future) determines what unique history or path plays out among all the possibilities. Therefore, the path-dependence of complex systems (and of the agent-based models that represent them) introduces surprises that, by definition, cannot be predicted. Consequently, complexity permits us to construct plausible models that may explore and explain processes and generate robust results, but not reproduce exact patterns in time and space (Bankes, 1993; Brown *et al.*, 2005). Nevertheless, when managing a complex reality, understanding the range of possibilities provides opportunities for policy adaptation and preparation for alternative and surprising scenarios (Bankes, 2002). Batty and Torrens (2001) further argue that plausibility of causes rather than replicability of patterns is what makes a model believable and educational for the purposes of distinguishing levers for policy intervention.

A related limitation of this approach is that agent-based models of complex systems cannot be validated, precisely because validation requires evaluation of the predictive ability of a model by comparing its results with an independent set of data. Increasing the level of detail (which is very easy to do with agent-based models) creates "an illusion of realism", but does not help with validation (Bankes, 1993). Confusing validation with realism results in overly complicated models that generate large amounts of data from which it is hard to draw policy recommendations. Complexity and path-dependence need not make agent-based models invalid, however. We simply need criteria other than predictive ability to evaluate the models and their results (Bankes, 1993, 2002; Bankes *et al.*, 2002; Costanza *et al.*, 1993). New criteria include "authenticating" model mechanisms and assumptions through open scrutiny with experts and stakeholders (Becu *et al.*, 2003), assessing the degree of path-dependence (Brown *et al.*, 2005), and evaluating the occurrence of expected and unexpected emerging patterns (Axtell & Epstein, 1994; Bankes, 1993). North and Macal (2007) also recommend ensuring that the model fits with the questions it is meant to answer and that the data used in the model are validated, and assessing the validity of the theory informing the model and how it is implemented. In this manner, validation provides "a better understanding of [a] model's capabilities, limitations, and appropriateness for addressing a range of important questions" (North & Macal, 2007, p. 227). The next section applies some of these validation criteria to the entire process of modeling, policy exploration and implementation through a participatory framework.

Using Agent-Based Models for Participatory Modeling and Adaptive Groundwater Management

The multiplicity of dimensions and objectives in a coupled land-groundwater system imposes an obstacle to determining clear courses of action. Integrated analysis can support the decision-making process to a certain extent, but its success will be limited if analysis is external to the frame of reference of the various stakeholders in the system (Giampietro & Ramos-Martin, 2005). Alternatively, the stakeholders can judge the relevance and validity of an analytical tool as they learn about the integrated system and explore the possible effects of different scenarios. Moreover, "non-technology" stakeholders can add key knowledge to the technical analysis by virtue of their direct experience in the study area (Berkes & Folke, 2002; Gonzalez, 2002). Stakeholder participation in the modeling becomes necessary. Therefore, the model and its implications must be accessible to all participants. Furthermore, participation enables trust to develop and a common language to evolve, becoming itself an integrated comprehensive model of adaptive decision making around the complexity of groundwater management (van Eeten *et al.*, 2002). While groundwater management policies benefit from sophisticated modeling of physical and human dimensions, there is a lot to gain from collective interpretation and construction of historical and spatial information, assumptions and values, shared understanding and alternative management paths. Agent-based modeling has significantly contributed to the study of key parameters affecting land-use dynamics (e.g., Deadman *et al.*, 2004; Hanley & Hopkins, 2007; Otter *et al.*, 2001; Parker *et al.*, 2003; Rand *et al.*, 2002). Increasingly, researchers are finding that agent-based modeling is a convenient tool with which to study coupled social and water systems (e.g., Becu *et al.*, 2003; Ducrot *et al.*, 2004; Feuillette *et al.*, 2003). However, fewer studies focus on evaluating land-use and environmental policies (e.g., Brown *et al.*, 2004; Zellner, 2007; Zellner *et al.*, in press), and even fewer have been conducted within institutional and social contexts (e.g., Lynam *et al.*, 2002). Because of the metaphorical representation of diverse decision makers, landscapes and interactions, these models can help scientists across disciplines, policy makers and community members understand the complexity of groundwater-related problems and the implications for their decisions. Such opportunities are often missing when stakeholders find it hard to relate to, for example, a set of differential equations and the meaning of their parameters and outputs. Agent-based modeling would thus be central to policy making, rather than an isolated analytical exercise informing it (Figure 3).

The process-oriented focus of agent-based models also enables integration, coordination and discussion of various forms of knowledge: quantitative and qualitative, rational and pragmatic, social and natural, positive and normative, top-down and bottom-up, all necessary for environmental planning and policy (Bankes, 2002; Berkes & Folke, 2002; Costanza *et al.*, 1993; Couclelis, 2005; Norton *et al.*, 1998; Hoch, 2002; Wolford, 2003). Researchers and decision makers can use these tools to transform implicit information into useful forms (Bankes, 1993), and so explore the environmental implications of disjointed policy and individual decisions on the efforts to manage the shared resource, informing policy at all scales, and contributing to future groundwater availability. For example, external costs and benefits—originated in the complexity and the open-access aspect of groundwater resources—can be recognized and addressed, and the effects of local development policies can be assessed against the groundwater conservation efforts implemented at the state level.

In addition to the analytical contributions of agent-based modeling in policy contexts, a shared understanding of complexity permits a broad audience to collectively discuss the behavioral assumptions and consequences on natural and socioeconomic processes—typically the exclusive domain of modelers—and to examine their values and development goals—traditionally the domain of policy makers and constituents. Within this framework, all participants are stakeholders, i.e., the analysis of the system is not separate from the policy discussion, as in Figure 1. Instead, collaborative model construction, discussion of values and policy implementation inform each other interactively, directing future empirical research, which is particularly useful when data collection is costly. The knowledge generated in collaboration feeds back into a new cycle

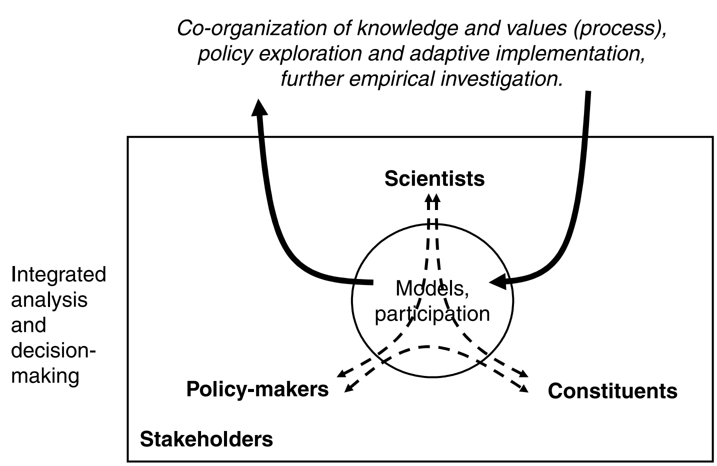


Figure 3. Alternative approach to integrated analysis and policy making.

of modeling, discussion, and policy exploration. As proposed, the framework is a vehicle for ongoing and reciprocal learning through which a wide range of knowledge is represented, respected and legitimized. The collaboration of diverse participants promotes innovative solution building (Page, 2007), a key adaptive trait to deal with changing conditions and crises (Harrison & Burgess, 2003; Westley *et al.*, 2002).

To generate meaningful and relevant policy recommendations, agent-based models need to be simple to engage all stakeholders while still capturing the relevant complexity of the integrated land-groundwater system. Moreover, Bankes (1993; 2002) and Bankes *et al.* (2002) argue that it is more helpful for policy analysis to develop a suite of models, each highlighting a different aspect of the system, than one seemingly realistic but incomprehensible model. A good model is informative in the context of a particular problem, and oftentimes unrealistic models are appropriate tools to construct an argument. If exploratory models represent what we know and we obtain unexpected results, they can indicate in which new direction to expand our knowledge. Partial information is better than no information, and a plausible explanation is better than no explanation at all. This is an inductive/experimental, rather than a deductive/theoretical approach to both science and policy that can expand our intellectual ability in new directions (Bankes, 1993, 2002; Bankes *et al.*, 2002).This approach shifts our attention from comprehensiveness (Bankes' "illusion of realism") to comprehensibility (Mitchell's integration of key dimensions), from predictability to plausibility. In coupled land-groundwater systems, *correct* policy solutions may not be readily identifiable, but *appropriate* policies can be suggested based on their robustness, i.e., their consistent effect across a range of plausible scenarios or models (Bankes, 1993, 2002; Bankes *et al.*, 2002; Costanza *et al.*, 1993; Holland, 1998).

The same process that enables learning also validates the agent-based modeling and its application to groundwater management. The validity of the integrated process of modeling, exploration and implementation is in the continuous review and interaction, rather than in comparing modeling outputs and data. Figure 3 supports an open scrutiny of these models as proposed by Becu *et al.* (2003), through iterative exploration, discussion, monitoring and policy re-evaluation among all participants. The agent-based representation of complexity facilitates this form of validation.

In sum, the framework in Figure 3 uses agent-based models to integrate different forms of knowledge and facilitate a shared understanding of the complex spatial and temporal interconnections of groundwater and socioeconomic systems. In this way, the framework contributes with additional substance to participatory planning processes. Concerns and responsibilities can also be acknowledged and shared by all stakeholders. The ongoing examination of agent-based modeling and policy experiments ensures that both analytical and policy instruments remain relevant and meaningful, and that they are adjusted in innovative ways if they cease to be so. The sense of ownership of the groundwater management problem is thus expanded to include ownership of the analysis and of the solution, identifying and validating opportunities for collective learning, adaptability and sustainable use of the shared groundwater resources.

An Empirical Application

An empirical implementation of the generic model proposed in this paper was developed to examine the role of resource-use and land-use decision making in the groundwater depletion observed in Monroe County, a rapidly suburbanizing area of southeast Michigan, where legal conflicts arose as stone quarries created cones of depression that affected the groundwater levels in residential wells (Zellner, 2007). Prior hydrological studies had found that stone quarries alone could not explain the observed declines in groundwater levels and that land-use changes were a likely factor (Reeves *et al.*, 2004). The purpose of the model was to understand how the land-use and hydrological processes interacted to create the observed patterns of resource depletion, and provide suggestions to policy makers to reverse the depletion.

To adapt the above model structure to the empirical case, digitized data were obtained from the county planners and the University of Michigan School of Natural Resources and Environment for land use, soil quality and permeability, hydraulic conductivity, zoning, roads, and municipal water and sewerage supply. These data were rasterized[3] to create the inputs for the agent-based model. Additional raster maps were created to assign each cell a distance to central business districts, natural areas and schools. Proximity to these destinations and convenience of access to places in general were found to be important factors affecting residential location, as reported in a regional survey (University of Michigan, 2001). Preferences were assigned to agents based on the preference distribution found in this study. The county planners provided their expert information and reports on the urbanization trends in the county, which informed the growth rate and rules for farmland conversion and residential location (Maniko, 2004; Monroe County Planning Department and Commission, 2004a, 2004b). The hydrological and groundwater extraction parameters were adjusted to those reported in several studies produced by the US Geological Survey (Nicholas *et al.*, 1996; Nicholas *et al.*, 2001; Reeves *et al.*, 2004). Further implementation details are provided in Zellner (2007).

Initial explorations with the model showed that land-use patterns could greatly influence groundwater declines, whereas focusing on controlling the stone quarries only improved groundwater levels in the short term. Over all other social, policy and natural factors, zoning had the strongest influence on urban settlement and therefore on resource consumption. Both low-density and high-density zoning restrictions improved aquifer conditions over medium-density development, suggesting a non-linear relationship between intensity of residential use and groundwater levels. In some scenarios, zoning restrictions were relaxed where municipal water and dense transportation infrastructure were provided, which supported economies of scale while limiting urban expansion and its negative impact on the groundwater resource. Agricultural irrigation also showed a significant potential to compromise the sustainability of the aquifer, suggesting the need for detailed monitoring of withdrawals, a practice that is currently not implemented.

Several challenges were encountered throughout model development, not the least of which was the difficulty in mapping complex processes into simple and understandable mechanisms that could still capture the complexity of the integrated land-water system. Particularly for the representation of groundwater flow, consultation with hydrologists was essential. Nevertheless, more work needs to be done and is currently underway to align this simple representation with more established hydrological models, without losing transparency in the process. Additionally, the model was not designed to reproduce historical development and accompanying groundwater declines, and could only be informative in relative terms, i.e., to evaluate scenarios with respect to a base case. Reproducing historical development would have required historical data about decision rules, preferences and inputs which were not available. Finally, some assumptions had to be made where data were not available. For example, there were no records of the specific location of agricultural irrigation, only estimates of total irrigated area. Irrigation was thus assigned to random cells across the grid, amounting to the total area recorded.

County planners were also engaged in a continuous dialogue through model development. The frequent interaction and the metaphorical representation of land-use and hydrological processes facilitated the flow of information in all directions between the investigator, the hydrologists and the policy makers. Everyone contributed to model development by assessing the representation of the model mechanisms and providing empirical and expert information. This collective approach allowed a common understanding of the model, its assumptions and limitations, and the policy implications derived from it. The participatory and adaptive management aspects have yet to be developed and tested in this case. County officials have expressed strong interest in learning how to use and modify the model for the purposes of further analysis and for negotiation with local governments, developers and resource users, and believe these tools hold great promise for future development decisions in the county.

An Agenda for the Use of Agent-Based Modeling in Environmental Planning

Agent-based modeling offers significant, yet undeveloped, potential to inform environmental planning with unexpected insights derived from the explicit representation and open discussion of the complexity of human-natural systems. While much further work is needed to realize this potential, the proposed participatory modeling approach allows us, at the very least, to collectively reflect on the various dimensions of complex environmental problems and their solutions. As a fully developed approach, collaborative agent-based modeling and exploration can integrate the top-down approach of comprehensive planning and the bottom-up approach of participatory planning. On an ongoing basis, it can foster collective responsibility over environmental problems, providing the type of flexible "nested" framework needed for sustainability, in which information would flow between the local and the regional scales of policy making (Costanza *et al.*, 2001). The open (and open-ended) process ensures that this framework is responsive to changing natural, socioeconomic and institutional conditions as we learn about them. Within this framework, agent-based models should not be considered as finished or stand-alone products. Ideally, they would be one among other modeling elements and sustainability indicators, adding to the diversity of analytical and institutional approaches and increasing the adaptive ability for complex problem solving (Hong & Page, 2004; Page, 2007). Agent-based modeling would be just one piece of the proposed framework, but one that would directly contribute to new meanings of complexity, recognizing it as part of the problem and embracing it as part of the solution in environmental planning.

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Notes

1. Popular platforms for the development of agent-based models include SWARM (http://www.swarm.org/wiki/Main_Page), REPAST (http://repast.sourceforge.net/), ASCAPE (http://www.brook.edu/es/dynamics/models/ascape/), MASON (http://cs.gmu.edu/~eclab/projects/mason/), CORMAS (http://cormas.cirad.fr/indexeng.htm) and NetLogo (http://ccl.northwestern.edu/netlogo/) which are supported by various object-oriented programming languages (e.g., Java, Objective C). These are sets of libraries that define common classes, interfaces and primitives specifically designed for the programming of agent-based models.
2. Gregory Bateson (1988) wrote an inspiring essay around the "syllogism in grass" to illustrate the insights that can be derived from metaphors, to appreciate the beauty of nature and to understand its complexity.
3. Raster images represent a grid of picture elements (pixels) whose color reflects a value for that element, and which can be viewed in a monitor or printed in paper. Rasterization involves converting a vector graphic (a polygonal representation defined by mathematical equations) into a raster image.

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