ground water

Linking MODFLOW with an Agent-Based Land-Use Model to Support Decision Making

by Howard W. Reeves[1] and Moira L. Zellner[2]

Abstract

The U.S. Geological Survey numerical groundwater flow model, MODFLOW, was integrated with an agent-based land-use model to yield a simulator for environmental planning studies. Ultimately, this integrated simulator will be used as a means to organize information, illustrate potential system responses, and facilitate communication within a participatory modeling framework. Initial results show the potential system response to different zoning policy scenarios in terms of the spatial patterns of development, which is referred to as urban form, and consequent impacts on groundwater levels. These results illustrate how the integrated simulator is capable of representing the complexity of the system. From a groundwater modeling perspective, the most important aspect of the integration is that the simulator generates stresses on the groundwater system within the simulation in contrast to the traditional approach that requires the user to specify the stresses through time.

Introduction

An agent-based land-use model was linked to MODFLOW to study the complexity inherent in land-use change and its effect on groundwater resources. Complex systems are nonlinear, chaotic, dissipative, or adaptive systems that often have multiple parts (Geyer and Bogg 2007). These parts may operate on different spatial and temporal scales and exhibit feedback across these scales, and complex systems often are difficult to understand with traditional analysis (Parker et al. 2003; Miller and Page 2007). Complexity theory and its analytical methods have been applied to a wide range of problems in natural and social science, including ecosystem and population dynamics, chemistry, physics, political science, health-policy analysis, and urbanization studies. Agent-based modeling (ABM) is one analytical method used to study complex systems that arise from the interaction of many independent parts such as ecological systems and cities. ABM relies on computer simulation of a large number of entities (agents) that represent the interdependent parts of the system. The agent-based model defines how agents grow, reproduce, or move; defines the space on which agents interact; specifies decision rules that all agents follow as they interact with each other and the spatial domain; and specifies all other features of the system such as adaptation rules or other constraints. The analysis of complex human-environment interactions with ABM can improve water resources management by illustrating the nonlinear behavior of the coupled system (Pahl-Wostl 2002; Zellner 2008).

Cities exhibit complex behavior because the dynamics and spatial form of urban systems arise from the decisions of many individuals and groups (Holland 1995; Batty 2005). For the agent-based model applied in this research, the agents are decision making entities that act at different scales (e.g., residents, farmers, businesses, and governmental agencies) according to programmed rules of behavior and to constraints such as zoning, economic requirements, and environmental conditions. The rules and

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constraints are based on theoretical, empirical, or expert knowledge. Each agent is simulated and its behavior is output by the model. Through this output, the system-level properties emerging from the interaction of many agents can be studied. While such emergent properties arise from the interaction of many individuals, they are disconnected from the actions of any one individual (Miller and Page 2007). The urban form of development, for example, sprawl vs. compact development, is one emergent property of our system. Agent-based models have increasingly been used for the study of human-environment interactions, particularly those related to land-use and land-cover change (Parker et al. 2003; Brown et al. 2004; Deadman et al. 2004; Castella et al. 2005; Evans et al. 2005;). Pahl-Wostl (2002) and Zellner (2007) proposed the use of agent-based models to simulate the interaction of urbanizing areas with water resources. The structure of these models make ABM a useful approach to exploring multiple spatial and temporal scales of land- and water-use processes (Zellner 2008).

MODFLOW and the related suite of programs (Harbaugh et al. 2000; see also, http://water.usgs.gov/nrp/gwsoftware/modflow.html) need little introduction to readers of this journal. It was selected for this research because: (1) the gridded nature of the MODFLOW model is consistent with the gridded structure of the agent-based model used in this research both in terms of the required programming to link the two models and in terms of the conceptualization of the problem for the users of the linked model, and (2) the widespread use of MODFLOW provides many potential opportunities to apply ABM. For the hydrologist, the main advantage of the linked model is that groundwater withdrawals are based on rules of behavior imposed on the agents and, therefore, the well stresses are generated within the modeling system (endogenous). Because the model now generates stresses to the groundwater system based on simulation conditions, it is akin to using the new Farm Process within MODFLOW (Schmid et al. 2006). The Farm Process, however, fixes spatial locations of stresses and focuses on changes in pumping with time in response to simulation conditions. The land-use/MODFLOW model in this study simulates the development of pumping in the modeled spatial domain through time depending on simulation conditions.

If the rules of behavior include groundwater conditions, then development will respond to changes in the system that could not be represented through traditional modeling. In traditional modeling, planners specify a fixed suite of potential development scenarios that are an input to the groundwater flow model (exogenous). The dynamics of the groundwater system cannot explicitly feedback to the development scenario. The only feedback between the groundwater system and the urban planning scenarios would have to occur outside of the modeling environment between the planner and hydrologists. This external exchange of information may work for many problems, but it may not be able to capture potential nonlinear features of the complex system and may not reveal surprising behaviors that can occur in coupled systems. There may also be other important dynamics of the coupled system that may be difficult to study if the models are not linked, for example, the coupled human-environmental system response to climate variability. Linking MODFLOW and the agent-based model allows for the study of the coupled human-environment system response to social, political, and biophysical scenarios. This approach adds a dimension of analysis that is excluded in conventional MODFLOW simulations and that enhances the understanding of land-use impacts on groundwater sustainability.

In this article, we present a linked agent-based land-use/MODFLOW model and focus on the advantage of representing water withdrawal as an endogenous stress on the system rather than an exogenous condition imposed on the MODFLOW model. An example of graphical output generated for different land-use policy scenarios is presented and discussed. The results only serve as an illustration of the point of this article, the information gained by linking an agent-based model to MODFLOW. They are not given to make specific planning recommendations beyond the implications for our case because these recommendations will vary with the socio-economic and biophysical context. Furthermore, we view the linked model to be used most appropriately in a participatory modeling setting (Pahl-Wostl 2002; van Eeten et al. 2002; Dietz et al. 2003; Zellner 2008). In participatory modeling, planners, hydrologists, and other stakeholders use models as communication tools to organize information. ABM is particularly useful because the models serve as metaphors that help explain complexity to a broad audience and thus are likely to enable more informed decision making (Zellner 2008). Therefore, the results generated by the linked model are only part of their utility; the most important aspect is setting the modeling process within a participatory framework that can inform the model and that gives meaning to its outputs.

Background

To illustrate the integrated model, we present a prototype application for Monroe County, Michigan. The linked agent-based land-use/MODFLOW model was developed using two existing initial models for this same area: (1) an agent-based land-use/water-use model (Zellner 2007) and (2) a regional groundwater flow model developed using MODFLOW (Reeves et al. 2004). These independent studies were performed because of concern about declining groundwater levels in the county. From 1991 to 2001, water levels were observed to decline from 0 to 10 m in both USGS observation wells and in the average behavior inferred from water well records (Figure 1) (Reeves et al. 2004).

Monroe County, Michigan, is the most southeast county in Michigan and is bordered by Ohio on the south and Lake Erie on the east. Glacial deposits in the county are dominated by glaciolacustrine sand and clay, and clay-rich glacial till. These surficial deposits range from 0 to 50 m in thickness and have an average thickness

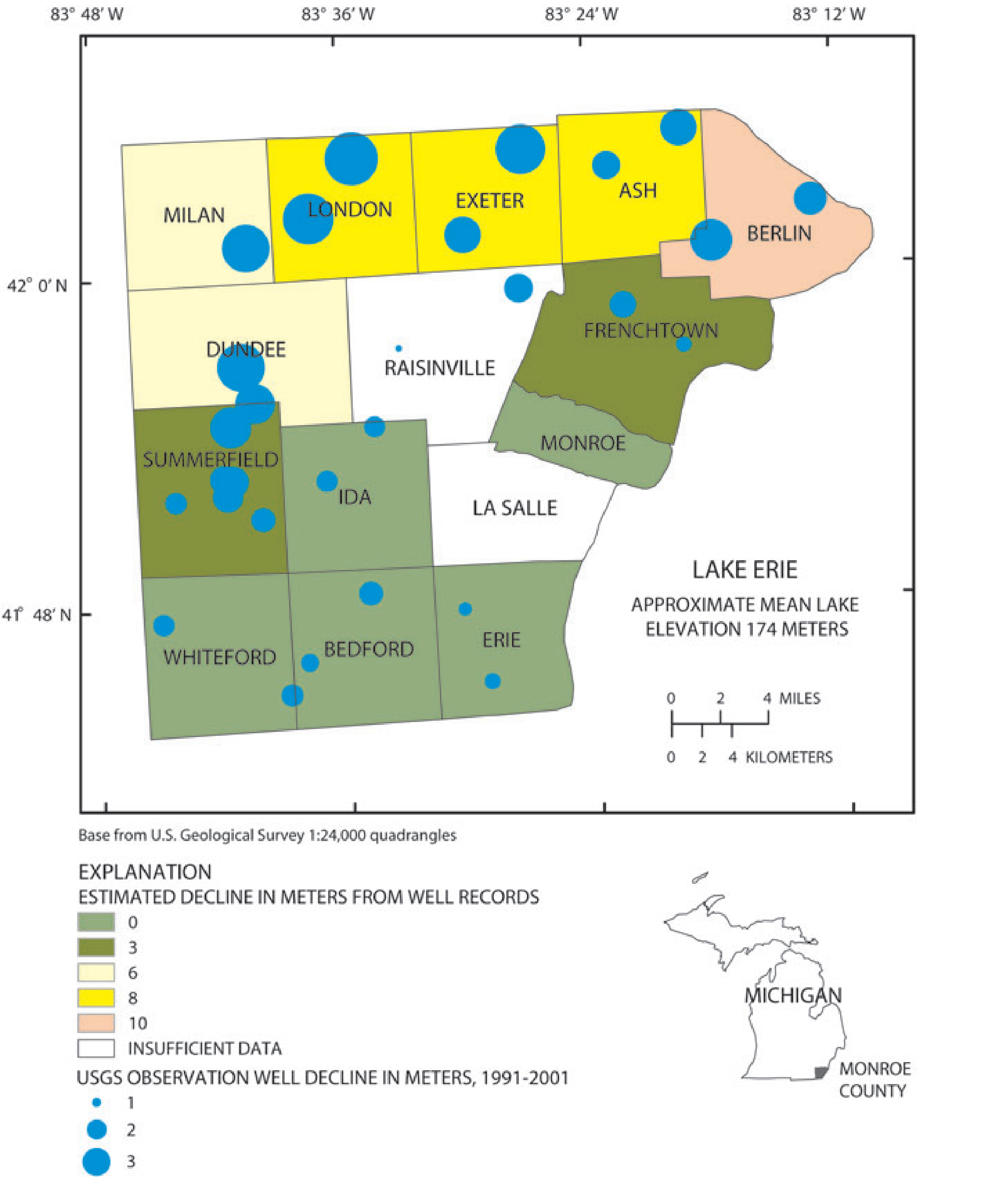

Figure 1. Prototype model area, Monroe County, Michigan, and observed groundwater level declines in USGS observation wells and estimated for townships using water well records, 1991 through 2001 (adapted from Reeves et al. 2004).

of approximately 15 m (Nicholas et al. 1996). Typically, glacial deposits yield only limited amounts of water, and bedrock aquifers are used as the primary water supply for much of the county (Nicholas et al. 1996). The bedrock aquifers are formed in Silurian-Devonian limestone and dolomite units that also may contain some interbedded sandstone and shale. The units are part of the extensive Silurian-Devonian age rocks that are a structural control for the Great Lakes Basin (Hough 1958). Where they are near the surface, these rocks may serve as both aquifers and source rocks for limestone and dolomite quarried for use in construction. In Monroe County, these bedrock units dip to the northwest into the Michigan Basin and become confined by thick shale deposits to the west and to the north (Figure 2 inset). The transmissivity of the bedrock aquifers varies and may depend on local fracture density. Two aquifer tests indicate transmissivity values from 100 to 350 m^2/d (Nicholas et al. 1996). The bedrock aquifers are thought to be recharged in south-central Ohio and Indiana. From the recharge area, groundwater moves northward until it encounters saline water in the Michigan Basin, and then it discharges either to

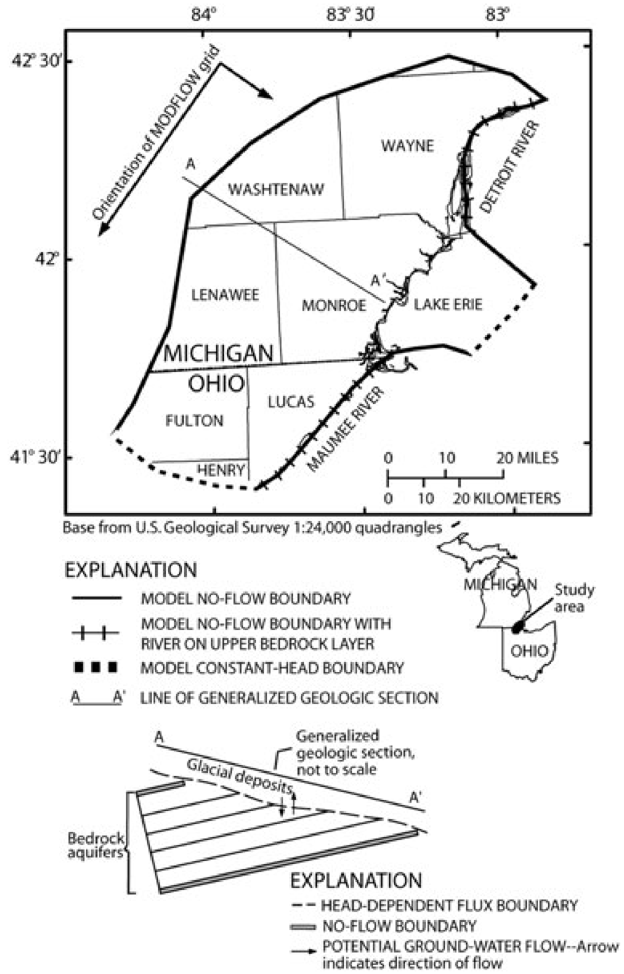

Figure 2. Model extent and boundary conditions for regional groundwater flow model developed by Reeves et al. (2004) for Monroe County, Michigan.

surface-water features in Indiana and northern Ohio or to Lake Erie (Bugliosi 1999). Under predevelopmental conditions, bedrock aquifers near Lake Erie in Monroe County often yielded flowing wells with significant heads (Sherzer 1900). Under current conditions, the bedrock aquifer also receives recharge as leakage from the overlying glacial deposits because, in many areas with in the county, the potentiometric levels in the bedrock aquifer have been lowered below the water table in the glacial deposits (Reeves et al. 2004).

Poor water quality can be an issue in Monroe County, and, in parts of the county, potable water from the bedrock aquifer may be limited by highly dissolved-solid concentrations, sulfate, or hydrogen sulfide (Nicholas et al. 1996). Water quality typically becomes poor at depth for much of the county, and the decrease in water quality with depth may exacerbate conflicts between high capacity wells and domestic users. If a high capacity well lowers the hydraulic head in a domestic well, then simply deepening the impacted domestic well may not be an acceptable solution as the water at depth may not be of acceptable quality.

Initial Models

MODFLOW-2000 (Harbaugh et al. 2000) was used to develop a regional groundwater flow model for the bedrock aquifers used for water supply in Monroe County, Michigan (Reeves et al. 2004). This finite difference model has 10 layers, 297 rows and 194 columns of cells, and there are approximately 400,000 active cells in the model. The grid has nonuniform spacing and thickness, and the most refined cells are approximately 123×123 m. The grid is roughly aligned with the strike of the bedrock units (Figure 2), and each of the bedrock units is modeled using two numerical layers. Because the overlying glacial deposits yield only limited water and are not the focus of the regional model (Reeves et al. 2004), the overlying glacial deposits are modeled using the General Head Boundary package (Harbaugh et al. 2000) to allow for exchange of water between the bedrock aquifers and glacial deposits. The bottom boundary of the model is set to no flow at an estimated depth for a shale in the Salina formation. The resulting 10 layer model ranges from approximately 50 m to greater than 650 m thick although in any part of the county only topmost bedrock units are used for water supply and wells are generally less than 70 m deep. The western boundary is a no-flow boundary because of the presence of dense saline water in these bedrock units. The northeastern and southeastern boundaries were set as no-flow boundaries at depth with the upper cells set as river cells to simulate interaction of the bedrock aquifers with the Maumee and Detroit rivers. Lake Erie is represented through a general-head boundary near the coast and for some distance into the lake and by a constant-head boundary at the extent of the grid. Constant-head boundaries were used for the remaining numerical boundaries (Figure 2). The model was used to study the observed groundwater level declines in Monroe County, Michigan, and to test hypotheses regarding the cause of these declines (Reeves et al. 2004).

The Water-Use/Land-Use Model (WULUM) (Zellner 2007) was developed using the Java-based RePast simulation platform for ABM (North et al. 2006; see also http://repast.sourceforge.net) and applied to study the potential effectiveness of zoning to control the effect of urbanization on groundwater resources. In WULUM, the county was subdivided into a grid of cells, and there were 166 rows and 200 columns in the grid with a cell size of 251×251 m. The initial grid cells are either assigned as farm cells that may be developed or quarry cells based on locations of quarries in the county (Figure 3). Spatial data organized within a geographic information system (GIS) were used to assign values to the grid that determined how agents assess locations in the area. These data include road infrastructure, municipal water, soil quality, and destination information representing the distances to recreational areas, school, or business centers. Two agent types are used to represent major sectors that make decisions impacting groundwater: residents and golf courses. The two other major groundwater uses in the county are farm irrigation and pumping for quarry operations, and

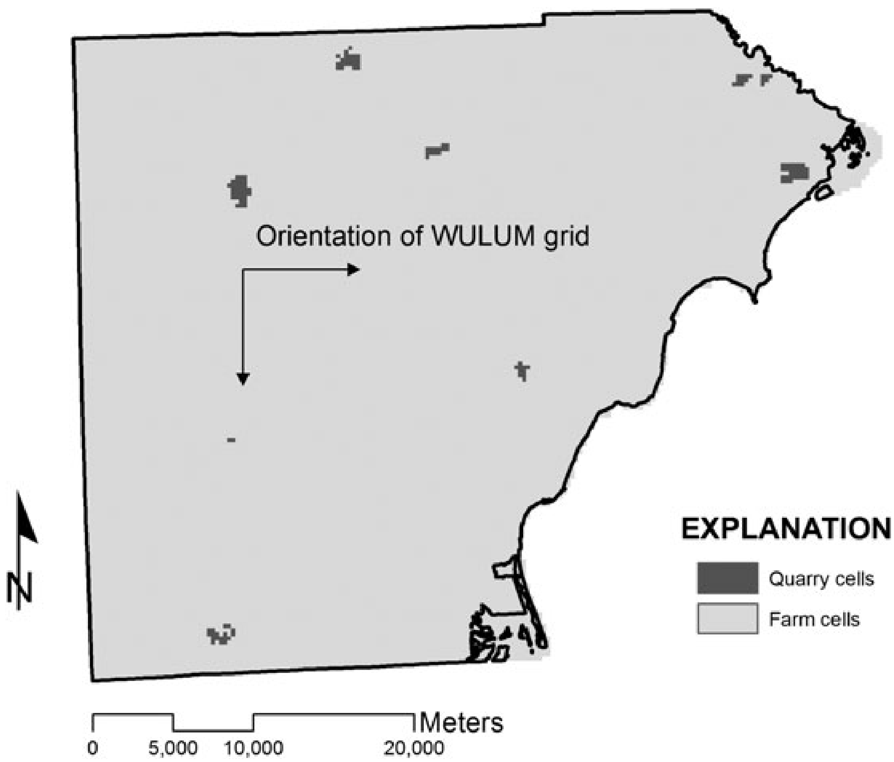

Figure 3. WULUM model of Monroe County, Michigan, showing farm cells and quarry cells at the beginning of a development scenario (from Zellner 2005).

farms and quarries were treated as a type of cell in the model, not through agents.

The WULUM was developed to study the transient dynamics of growth under different zoning and infrastructure scenarios. The dynamics were simulated using transient model trials. After establishing an initial distribution of agents and land uses on the grid representing the county, the WULUM simulation proceeds through time using 200 one-year development time periods subdivided into 16 time steps. For each development time period (akin to a MODFLOW stress period), 81 cells are converted from farm cells to undeveloped land based on rules including distances to roads, soil quality, and a random function to account for uncertainty in conversion from farmland to undeveloped land. If a neighboring cell is developed, there is a higher likelihood for a farm cell to be converted to an undeveloped cell. Following farmland conversion, 1000 resident agents are added to the simulation at each time step. Each agent randomly samples 100 cells from the pool of cells available for development as potential sites in which to locate. The pool of available cells changes for each time period because some cells become fully occupied, as determined by zoning restrictions, and are unavailable for additional development.

Utility functions are used to evaluate all of the 100 randomly selected cells for each agent. The utility function for each agent and each cell may be written as,

$$U = \alpha_{\mathrm{r}} r + \alpha_{\mathrm{dc}}(1 - d_{\mathrm{c}}) + \alpha_{\mathrm{dn}}(1 - d_{\mathrm{n}}) + \alpha_{\mathrm{ds}}(1 - d_{\mathrm{s}}) + \alpha_{\mathrm{z}}(1 - z) + \alpha_{\mathrm{w}} w + \alpha_{\mathrm{s}} s \quad (1)$$

where U is the utility of the selected cell for the agent; α_{r} is the residential preference for proximity to road; r is the cell presence of a road (0 or 1); α_{dc} is the residential preference for distance to closest business center; d_{c} is the cell normalized distance to closest business center (between 0 and 1); α_{dn} is the residential preference for distance to natural area; d_{n} is the cell normalized distance to natural area (between 0 and 1); α_{ds} is the residential preference for distance to school (between 0 and 1); d_{s} is the cell normalized distance to school (between 0 and 1); α_{z} is the residential preference for low density; z is the residential density permitted by zoning (between 0 and 1, with respect to maximum density allowed in the county); α_w is the residential preference for municipal water coverage; w is the cell presence of municipal water (0 or 1); α_s is the residential preference for either sewer coverage or septic soil; and s is the cell presence of either sewer coverage or septic soil (0 or 1).

The values of the preference coefficients, α, of the utility functions are based on surveys about location decisions in the region (University of Michigan 2001). The values for these coefficients for each agent are selected using a probability distribution function based on results from the survey so that each agent has its own behavior consistent with regional preferences reported in the survey. For each agent, the utility function is evaluated for all 100 cells, and the cell that provides the highest utility for the agent is chosen for settlement. Zoning rules are checked to see whether the cell reaches the maximum level of development, and if the maximum density of development is reached, then the cell is removed from the pool of available cells. The process is repeated for all 1000 agents.

The final number of simulated agents is 200,000. The simulation of this large number of agents allows the agent-based model to produce results showing emergent behavior of the system. Inter-agent variability described through variation in the coefficients of the utility function is captured by this large number of agents. Agent behavior and emergent behavior, such as urban form, however, may depend on the path (history) of the simulation because different cells will be chosen from the available pool, and, as the simulation progresses, different cells may be made unavailable for further development because of zoning restrictions. To account for potential path dependence in the analysis of different land-use scenarios, 10 trials were run for each scenario, and the average behavior of the model for the 10 trials was analyzed. Each trial is computationally intensive and 10 trials were found to be sufficient to yield stable average behavior that can be analyzed, although more trials would be expected to give improved estimates of the statistical distribution of results around the average (Zellner 2005).

The original WULUM (Zellner 2007) has a single layer groundwater flow model written directly within the RePast modeling environment (North et al. 2006). This model has fixed boundary conditions for potentiometric head at the border of the county and Lake Erie estimated using maps presented by Reeves et al. (2004). Recharge is fixed across the county using an average rate; however, the recharge rate may be decreased in cells in response to development (Zellner 2007). The hydraulic conductivity and thickness of the aquifer varies across the county and the values used in WULUM were estimated from Reeves et al. (2004). WULUM imposes withdrawals from quarries, golf courses, and residents using average withdrawal values for each agent. As a WULUM simulation progresses, more cells are developed using the approach described above, and these cells both introduce additional stress to the model and may reduce recharge. The flow model within WULUM has 16 time steps per year and computes the volume of groundwater within each cell at the end of every development time period. This volume is used to estimate areas of groundwater deficit for different land-use strategies (Zellner 2007).

The advantage of writing the groundwater flow model within the RePast environment is that the final simulator runs fairly quickly and information does not have to be exchanged between different models. The disadvantage is that all desired groundwater flow processes must be written into the RePast environment, tested, and documented. Linking the land-use component of the simulator to MODFLOW allows the developers to capitalize on the long history of MODFLOW development, the testing and documentation of this model, and the widespread application of MODFLOW at various spatial scales.

WULUMOD

The land-use component of the WULUM was linked with MODFLOW to create the integrated simulation model WULUMOD. The integration was accomplished by writing Java methods to generate MODFLOW well files for each WULUM development time period, to run the MODFLOW executable for time periods within the WULUM simulation, and to read the results of each MODFLOW simulation into WULUM for the next iteration. Recharge to the bedrock aquifer in the regional MODFLOW model is simulated through the general-head boundary package and responds to the WULUM-imposed development. The current version is only linked from the land-use model to MODFLOW. Future versions of the model, however, will adaptively change development in response to changes in available water resources by including groundwater conditions in the utility functions for the agents. For example, agents might choose to avoid cells (i.e., cells will be assigned a low utility) if groundwater levels are reduced below some threshold because of previous development.

The linked model uses the regional groundwater flow model developed by Reeves et al. (2004) to replace the simpler groundwater flow layer in the original WULUM. The steady-state predevelopment regional model was changed to allow for a 1-year transient simulation with 10 time steps and a time step multiplier of 1.21. A 1-year, one stress period, MODFLOW simulation was generated for each development time period of the land-use model. For these illustrative simulations, the specific storage for all the bedrock aquifers was set to 1×10^{-6}/m. To avoid numerical problems caused by dry cells that may be generated as new stresses are added at each stress period, every layer in the MODFLOW model was set as confined. In practice, the model should be calibrated to transient conditions and cells should be allowed to go dry if appropriate, based on field observations. This model is called after each land-use development period with a new set of stresses as determined by the agent-based model, and subsequent simulations use the heads from the previous development time period as initial conditions.

The regional model grid is quite different from the WULUM grid: it extends well beyond the boundaries of the county, it is nonuniform, and it is rotated with respect to the WULUM grid (Figures 2 and 3). To link the models, the correspondence between the WULUM grid and the MODFLOW grid was determined and provided as a data layer. The agent-based model creates an appropriate MODFLOW well file for the regional model and a name file specifying the created well file and a new set of output files for each development time period of the simulation. WULUMOD executes MODFLOW (one stress period) for each development time period, generating the corresponding head files for the entire simulation. Additionally, WULUMOD generates spatial land-use outputs. These output results are used to relate land-use change to specific groundwater impacts.

In the regional MODFLOW model, the quarries are simulated as drains with drain elevations set to approximate the conditions at the quarries. Quarry groundwater withdrawals are computed within the model, and these were used to help guide calibration by comparison to reported discharges from the facilities. The water table in the overlying glacial deposits is fixed and recharge to the bedrock aquifers is simulated as leakage from the glacial deposits. High capacity wells from golf course irrigation were imposed based on rates and locations reported to the State of Michigan. Residential use was distributed across the county in areas where domestic wells in the bedrock aquifers were recorded through water well records. These cells were assigned a uniform average withdrawal rate.

In contrast to this relatively site-specific assignment of stresses and sources of water, WULUMOD uses more general values to estimate stresses. The general approach is appropriate for WULUMOD because the purpose of the modeling is to serve as a metaphor for the system to contrast the behavior in response to different land-use and planning decisions. In WULUMOD, the quarries were located based on their actual location, but average withdrawal rates based on regional use were assigned for each facility. Residential use and golf course withdrawals were assigned average values, but they were distributed across the county using the location information generated by the land-use component of the simulator.

Results and Discussion

Three sets of results are shown to illustrate the performance of the integrated model, WULUMOD. The first set examines the base simulation for the county and compares results of the regional MODFLOW model to those generated by WULUMOD which has the water withdrawal stresses as endogenous features in the simulation. The second set demonstrates the use of WULUMOD to explore the response of the groundwater system and spatial patterns of development in response to different sets of zoning restrictions. The third set tests the coupling between the two components of WULUMOD to investigate whether the MODFLOW component needs to be simulated for every development time period, which can be computationally expensive. The tests examine whether a loosely coupled approach, where MODFLOW is only run at the end of the land-use simulation after all 200,000 agents have been distributed on the model domain, will produce similar results.

Base Case

Despite some fundamental differences in how some of the stresses were simulated, as outlined in the previous section, the two models produce generally consistent results (Figure 4). The consistency arises because the regional MODFLOW and WULUMOD models use the same boundary conditions, the aquifer properties assigned are the same, and the recharge to the bedrock is computed as leakage from the overlaying glacial deposits with a fixed water table. The major difference between the simulations is in the northern part of the county where most quarries are located and significant differences between quarry water withdrawal rates appear to be reflected in the MODFLOW results but not the WULUMOD results. WULUMOD could be altered to simulate the quarries as drains if this difference hampered discussion of land-use scenarios.

Zoning Simulations

WULUMOD was used to examine the response to different zoning scenarios (Figures 5 and 6). Three zoning options were simulated: maximum density (allowing no more than 311 households per cell), average density (allowing no more than 25 households per cell, the weighted average for Monroe County), and minimum density zoning (allowing only one household per cell). These zoning scenarios only affect the residential agents in the agent-based model, yet they have consequences on golf course development and farm irrigation. Golf courses are created based on the amount and location of residential development, which will vary with zoning restrictions. As development occurs, farmland is converted for residential or golf course use, thus changing the location and amount of groundwater withdrawals. The quarry stresses are the same for the three simulations. Maximum and minimum zoning show the least drawdown in the potentiometric surface. Maximum zoning has the largest number of residents and many of the residents relied on municipal systems, which draw their water from Lake Erie rather than the aquifer. Minimum density zoning has the fewest residents, and although most of these residents rely on wells, the low absolute numbers and relative densities do not lead to excessive drawdown. Average density zoning results in the greatest impact on groundwater resources because a greater number of the residents in this set of simulations are located in areas without available municipal water, significantly stressing the aquifer.

This example set of simulations illustrates the advantage of generating stresses within the integrated model. Zoning restrictions were specified for each simulation and the resulting distribution of water withdrawals was generated through the agent-based model and imposed on the regional MODFLOW model. In a participatory modeling framework (van Eeten et al. 2002; Zellner 2008), the WULUMOD simulator could be used to illustrate the link between land-use practices, emergent land-use patterns, and groundwater resources. Traditional analysis would require planners to generate the urban response to different land-use practices and provide the resulting demands for water resources to the hydrologist. The hydrologist would then model the groundwater dynamics for each of the provided scenarios and return the results to the planners. This separation of land-use considerations and water resources response can obscure the links and potential complexity of the system. WULUMOD is intended to remove this separation to examine the behavior of the integrated system.

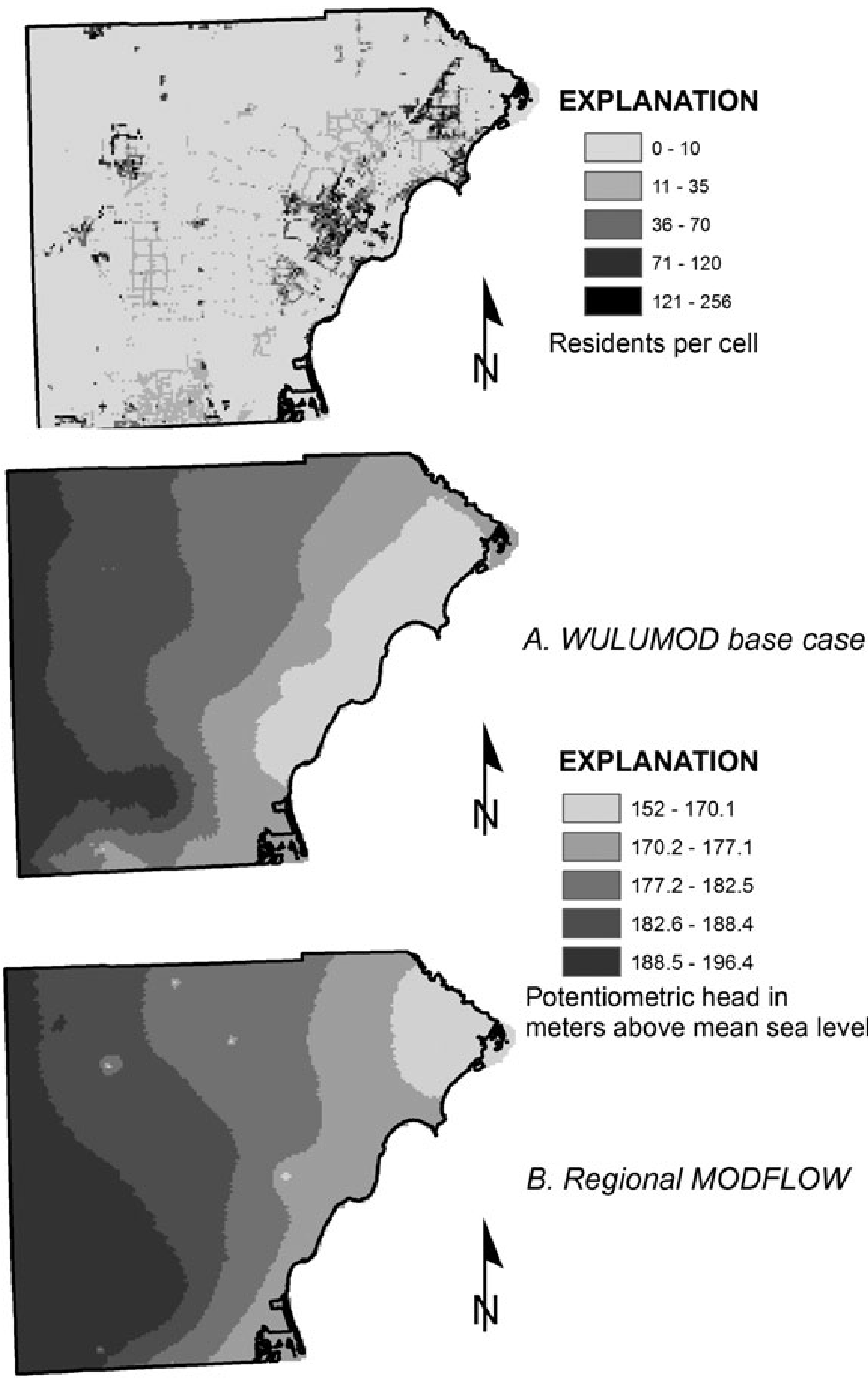

Figure 4. Residential development pattern generated after 200-year simulation and potentiometric surfaces from (A) WULUMOD and (B) regional MODFLOW at the end of the simulation for base conditions.

Loose vs. Tight Coupling

The final simulations examine a numerical aspect of the WULUMOD simulator. The integrated simulator takes longer to run than the original WULUM for equivalent tests because of the additional computational burden imposed by the larger MODFLOW model and the time required for file generation to exchange information between the components of the simulator. We tested whether the component could be more loosely coupled by only running MODFLOW on the final distribution of agents after 200 development time periods. This test would not be valid for simulations where feedback between development and groundwater resources is important, but in this case the utility function does not feed back groundwater conditions to the agents. The potentiometric head results generated from tightly coupled

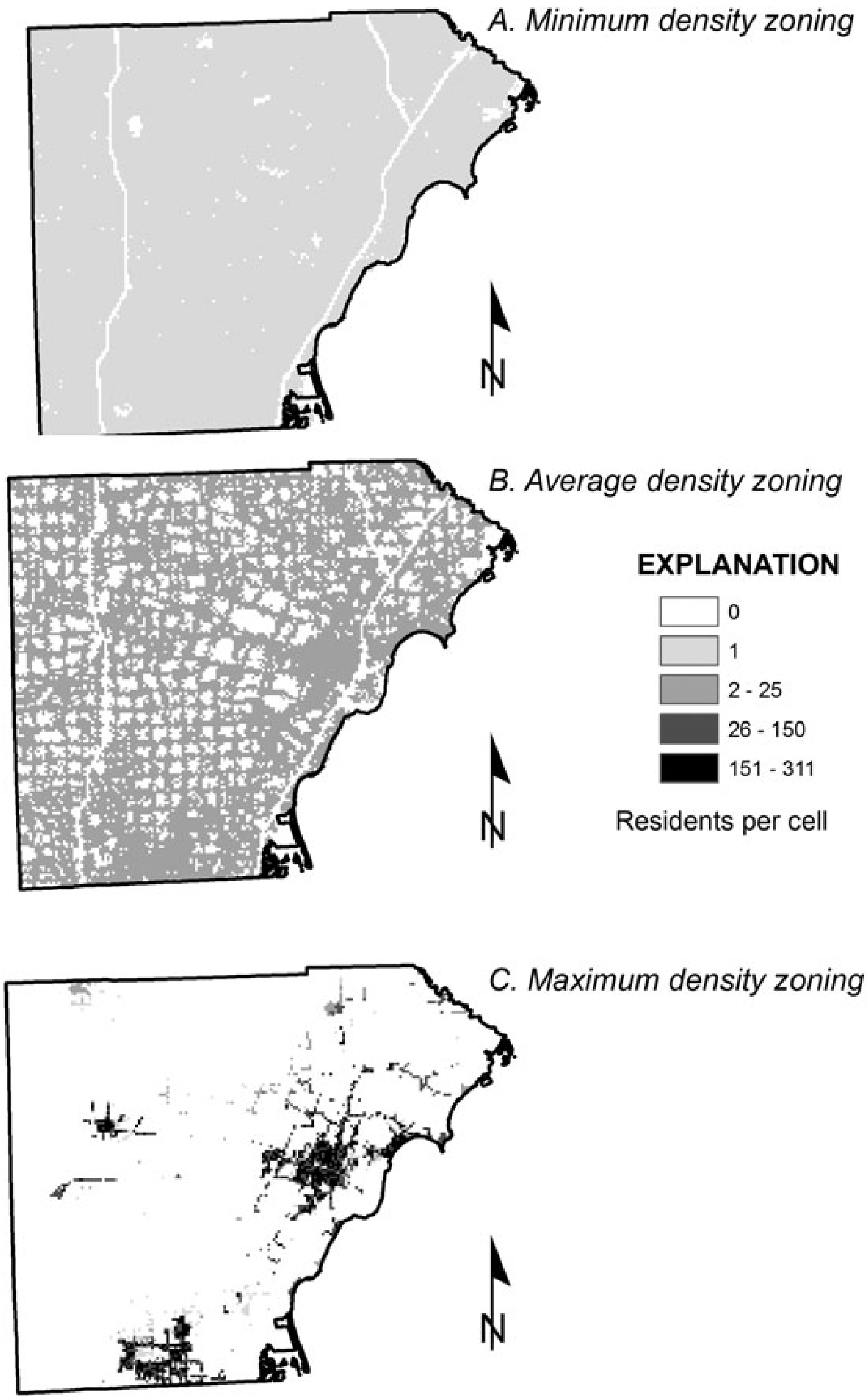

Figure 5. Urban forms generated by the WULUMOD simulator after 200-year simulation for minimum, average, and maximum density zoning scenarios.

WULUMOD, in which a MODFLOW simulation is run every development period (Figure 6), are different from a loosely coupled WULUM-MODFLOW simulator wherein only one MODFLOW simulation is run after 200 land-use development periods (Figure 7). These results imply that the sequence of development and associated stress may be important in the final impact of groundwater resources: history matters. By generating stresses within the integrated simulator in each time period, WULUMOD adds path dependence to the MODFLOW groundwater simulations, illustrating how impacts can accumulate over time.

Advantages, Challenges, and Opportunities

The advantages of coupling MODFLOW to the land-use model of the agent-based WULUM are: the approach to the land-use model can be applied to many areas across the country with existing MODFLOW models, the

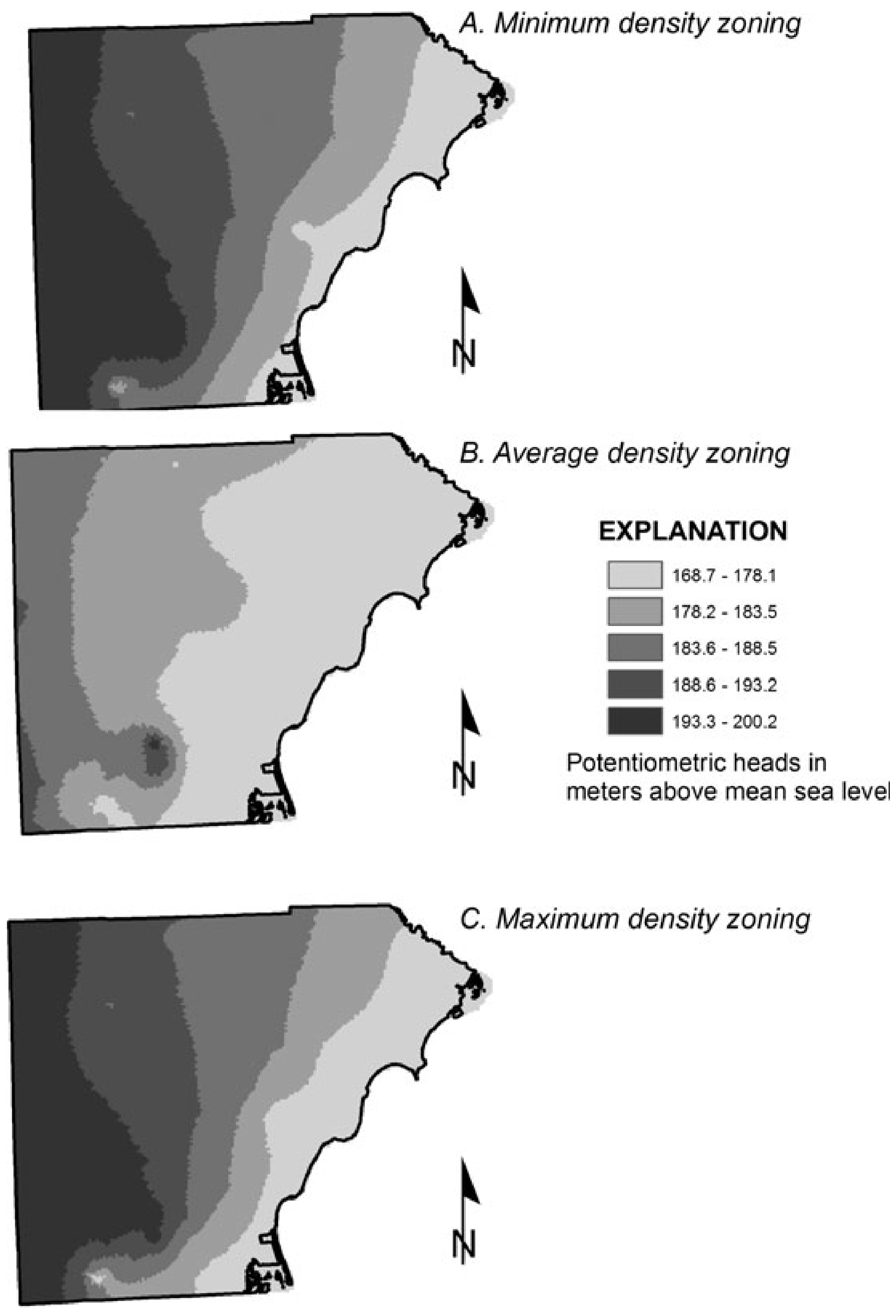

Figure 6. Potentiometric heads generated by the WULUMOD simulator after 200-year simulation for minimum, average, and maximum density zoning scenarios.

agent-based model does not have to be refined continually to simulate the range of processes already included in the suite of MODFLOW processes and packages, and MODFLOW serves as an example for other water resources models, including surface-water models, that might be more applicable for other urbanizing areas. Because MODFLOW is run as a batch process with well-documented input and output files, linking of MODFLOW within the RePast system was relatively straightforward. Full integration of the models to simulate the potential feedback of changes in groundwater conditions on urbanization, however, presents more challenges for model development and application.

The development and application of the integrated agent-based/MODFLOW model presents several challenges to both hydrologists and planners. The groundwater flow model should be well calibrated and robust for a range of stresses imposed on the system, and the hydrologist should be aware that the ABM may generate stresses beyond those used in calibration. In its current configuration, the uncertainty inherent in the groundwater flow model is not explicitly modeled. The hydrologist should provide information regarding the sensitivity and uncertainty in the model and help evaluate the impact of this uncertainty on the policy analysis. The hydrologist must recognize the subjectivity of the policy world, although

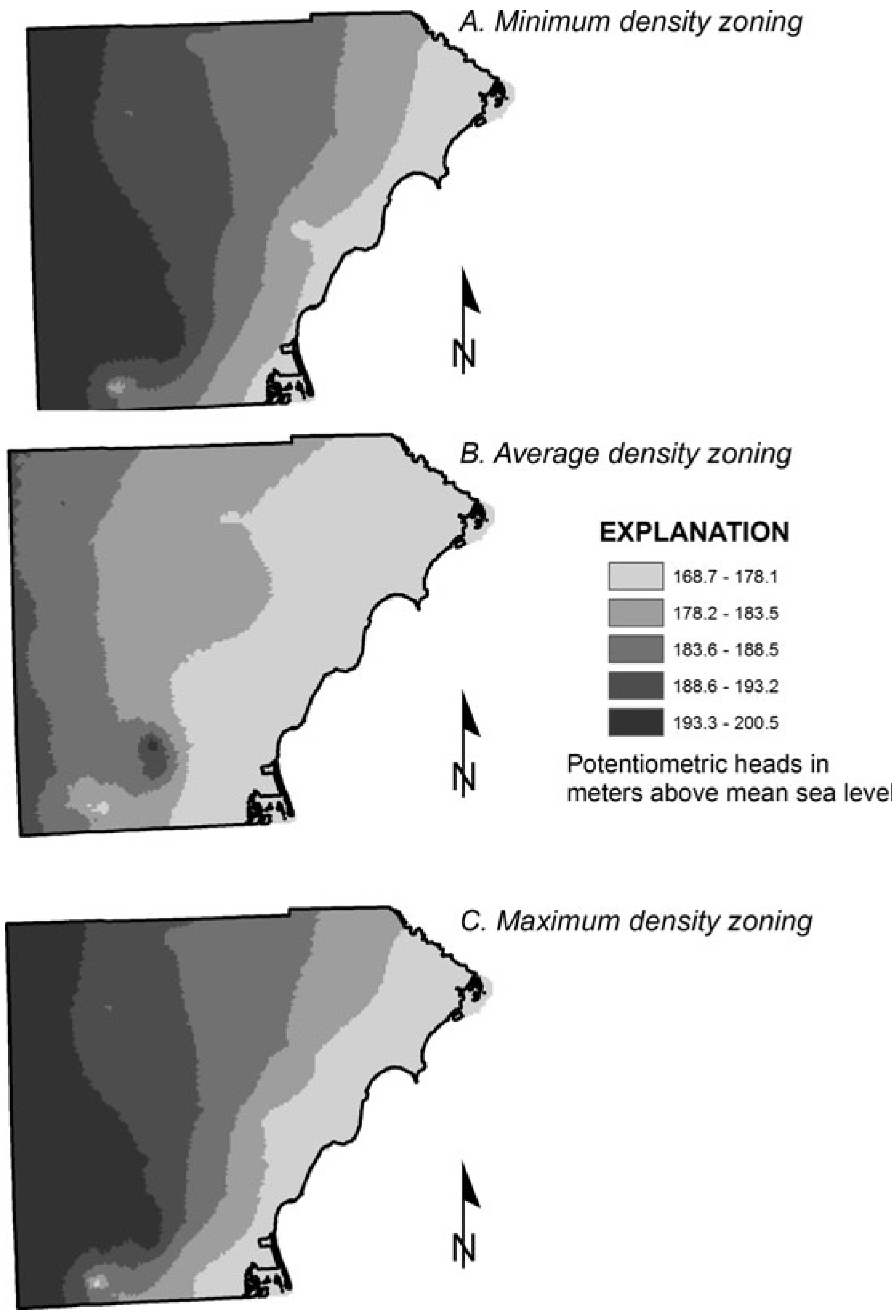

Figure 7. Potentiometric heads generated after 200-year simulation for minimum, average, and maximum density zoning scenarios using a loosely coupled WULUM-MODFLOW simulator.

use of these integrated tools may help develop the appreciation of urban planning challenges. Finally, in the application of ABM to urban planning, model calibration is complicated by competing goals to both: (1) capture stochastic processes that may produce different outcomes for repeated simulations because of the inherent random behaviors simulated in the model and (2) reproduce observed patterns of urban development. The calibration process must balance these two goals not just rely on traditional matching of simulation results to observed conditions (Bankes 2002; Becu et al. 2003; Brown et al. 2005).

The development and application of the integrated model present several opportunities to both hydrologists and planners. The major opportunity is the explicit link of a calibrated groundwater flow model to decision making and policy analysis. The importance of policy decisions on water resource dynamics is clearly represented in the integrated model and presented through both maps and statistical analysis. Future study will involve using the linked model in participatory settings to help guide land-use policy in areas sensitive to water scarcity. Additional model features such as changes to recharge or aquifer properties in response to development or simulation of water quality are desired. Finally, scenarios incorporating both urban growth and changes in climate are envisioned. Potential feedback between climate change, water demand, urban growth, and water resources dynamics could be simulated to provide information on this complex system for planners and stakeholders.

Summary

An agent-based land-use model linked with MODFLOW simulates the potential interaction between an urbanizing system and groundwater resources. This linked model generates stresses on the groundwater system internally (endogenous) and is able to produce results consistent with a regional MODFLOW model developed with observed stresses imposed as boundary conditions (exogenous). Results of the linked simulation model show the potential effect of different zoning policies on groundwater levels and urban form. This new tool will be most effectively used within a participatory modeling framework bringing together planners, hydrologists, and stake holders (van Eeten et al. 2002; Zellner 2008). In this manner, different forms of knowledge and values can be integrated and help treat the complexity and uncertainty of coupled human-natural systems. Use of such modeling tools may improve water resources planning to avoid the "tragedy of the commons" that may arise when individuals interact with open-ended resources with incomplete knowledge of the system (Dietz et al. 2003; Zellner 2008).

References

Bankes, S.C. 2002. Tools and techniques for developing policies for complex and uncertain systems. *Proceedings of the National Academy of Sciences* 99, no. 3: 7263–7266.

Batty, M. 2005. *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*. Cambridge, Massachusetts: MIT Press.

Becu, N., P. Perez, A. Walker, O. Barreteau, and C. Le Page. 2003. Agent based simulation of a small catchment water management in northern Thailand: Description of the CATCHSCAPE model. *Ecological Modelling* 170: 319–331.

Brown, D.G., S.E. Page, R. Riolo, M.L. Zellner, and W. Rand. 2005. Path dependence and the validation of agent-based spatial models of land use. *International Journal of Geographical Information Science, Special Issue on Land Use Dynamics* 19, no. 2: 153–174.

Brown, D.G., S.E. Page, R. Riolo, and W. Rand. 2004. Agent based and analytical modeling to evaluate the effectiveness of greenbelts. *Environmental Modelling and Software* 19, no. 12: 1097–1109.

Bugliosi, E.F. 1999. The midwestern basins and arches regional aquifer system in parts of Indiana, Ohio, Michigan, and Illinois—Summary. U.S. Geological Survey Professional Paper 1423-A.

Castella, J.C., T.N. Trung, and S. Boissau. 2005. Participatory simulation of land-use changes in the northern mountains of Vietnam: The combined use of an agent-based model, a role-playing game, and a geographic information system. *Ecology and Society* 10, no. 1: 27.

Deadman, P., D.T. Robinson, E. Moran, and T. Brondizio. 2004. Colonist household decisionmaking and land-use change in the Amazon Rainforest: an agent-based simulation. *Environment and Planning B: Planning and Design* 31, no. 5: 693–709.

Dietz, T., E. Ostrom, and P.C. Stern. 2003. The struggle to govern the commons. *Science* 302, no. 5652: 1907–1912.

Evans, T.P., D.K. Munroe, and D.C. Parker. 2005. Modeling land-use/land-cover change: Exploring the dynamics of human-environment relationships. In *Seeing the Forest and the Trees: Human-Environment Interactions in Forest Ecosystems*, ed. E. Moran and E. Ostrom. Cambridge, Massachusetts: MIT Press.

Geyer, R., and J. Bogg. 2007. Introduction. In *Complexity, Science and Society*, ed. J. Bogg and R. Beyer. Abingdon, Oxford: Radcliffe Publishing.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. Mcdonald. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the Ground-Water Flow Process. U.S. Geological Survey Open-File Report 00-92.

Holland, J.H. 1995. *Hidden Order: How Adaptation Builds Complexity*. Reading, Massachusetts: Addison-Wesley.

Hough, J.L. 1958. *Geology of the Great Lakes*. Urbana, Illinois: University of Illinois Press.

Miller, J.H., and S.E. Page. 2007. *Complex Adaptive Systems: An Introduction to Computational Models of Social Life*. Princeton, NJ: Princeton University Press.

Nicholas, J.R., G.L. Rowe, and J.R. Brannen. 1996. Hydrology, water quality, and effects of drought in Monroe County, Michigan. U.S. Geological Survey Water-Resources Investigations Report 94-4161.

North, M.J., N.T. Collier, and J.R. Vos. 2006. Experiences creating three implementations of the RePast agent modeling toolkit. *ACM Transactions on Modeling and Computer Simulation* 16, no. 1: 1–25.

Pahl-Wostl, C. 2002. Towards sustainability in the water sector: The importance of human actors and processes of social learning. *Aquatic Science* 64, 394–411.

Parker, D.C., S.M. Manson, M.A. Janssen, M. Hoffman, and P. Deadman. 2003. Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers* 93, no. 2: 314–337.

Reeves, H.W., K.V. Wright, and J.R. Nicholas. 2004. Hydrogeology and simulation of regional ground-water-level declines in Monroe County, Michigan. U.S. Geological Survey Water-Resources Investigations Report 03-4312.

Schmid, W., R.T. Hanson, T.I. Maddock, and S.A. Leake. 2006. User guide for the farm process (FMP1) for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, MODFLOW-2000. U.S. Geological Survey Techniques and Methods 6-A17.

Sherzer, W.H. 1900. Geological report on Monroe County, Michigan. Geological Survey of Michigan, Vol VII, Part I.

University of Michigan. 2001. *Detroit Area Study 2001*. Ann Arbor, Michigan: Taubman College of Architecture and Urban Planning. http://www.tcaup.umich.edu/workfolio/DAS2001/stdescript.html (accessed August 2004).

van Eeten, M.J.G., D.P. Loucks, and E. Roe. 2002. Bringing actors together around large-scale water systems: Participatory modeling and other innovations. *Knowledge, Technology, & Policy* 14, no. 4: 94–108.

Zellner, M.L. 2008. Embracing complexity and uncertainty: The potential of agent-based modeling for environmental planning and policy. *Planning Theory and Practice* 9, no. 4: 437–457.

Zellner, M.L. 2007. Generating policies for sustainable water use in complex scenarios: An integrated land-use and water-use model of Monroe County, Michigan. *Environment and Planning B: Planning and Design* 34, no. 4: 664–686.

Zellner, M.L. 2005. Generating policies for sustainable water use in complex scenarios: An integrated land-use and water-use model of Monroe County, Michigan. Ph.D. diss., Urban and Regional Planning, University of Michigan, Ann Arbor, Michigan.