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Generating policies for sustainable water use in complex scenarios: an integrated land-use and water-use model of Monroe County, Michigan

Moira L Zellner¶
Urban and Regional Planning Program/Center for the Study of Complex Systems,
4485 Randall Laboratory, University of Michigan, Ann Arbor, MI 48109-1120, USA
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Abstract. Rapidly declining groundwater levels since the early 1990s have raised serious concern in Monroe County, Michigan. Hydrological studies suggest that land-use changes have caused this decline. The mechanisms linking land-use and groundwater dynamics are not clear, however. In this paper I present WULUM, the Water-Use and Land-Use Model, an agent-based model that serves as an analytical framework to understand how these processes interact to create the observed patterns of resource depletion, and to suggest policies to reverse the process. The land-use component includes the main groundwater extractors in the county—stone quarries, golf courses, farms, and households. The groundwater component includes the glacial deposits and the underlying bedrock acquifer. The behavior of water users is defined by simple rules that determine their location and consumption. The dynamics of groundwater are represented through infiltration and diffusion rules between each cell and its immediate neighbors. Initial explorations with the model showed that land-use patterns contributed significantly to groundwater declines, while eliminating quarry dewatering did not entirely solve the problem. Both low-density and high-density zoning restrictions improved aquifer conditions over medium-density development, suggesting a nonlinear relationship between intensity of residential use and groundwater levels. Moreover, of all the natural and policy variables, zoning had the greatest influence on urban settlement and therefore on resource consumption.

1 Introduction

In Southeast Michigan the source of groundwater is almost guaranteed by its climate and the connection to the Great Lakes system. Nevertheless, in Monroe County the rate at which this groundwater is extracted for human use has apparently exceeded the rate of replenishment since the early 1990s, causing the levels to drop and raising serious concern for the sustainability of the resource (Nicholas et al, 1996). Additional studies have ruled out other drivers of the decline, such as decreased recharge (Nicholas et al, 2001; Reeves et al, 2004). The increase in water use is associated in these studies with the significant land-use changes which have occurred in the last decade. How these two observations are linked remains to be explained. The purpose of this study is to explore how the pattern of groundwater levels relates to the process of land-use change, and what natural, economic, and policy factors are most important in generating or reverting water depletion.

Water scarcity—and the controversies around it—is difficult to anticipate and prevent due to the uncertainties of surface and groundwater dynamics, the open-access nature of the resource, the interaction of land-use and water-use processes, and the multiple scales of interest and decision making. Generating appropriate policies for water management is elusive in such scenarios, but policy making may be improved through the use of analytical frameworks that explicitly address the complexities of water – land systems. In this paper I present the Water-Use and Land-Use Model (WULUM), an agent-based model that represents simple mechanisms of land-use,

¶ Current address: University of Illinois at Chicago, Urban Planning and Policy Program (MC 348), 412 S. Peoria St, 2nd floor, Chicago, IL 60607, USA; e-mail: mzellner@uic.edu.

water-use, and groundwater dynamics, in an attempt to understand how these processes are connected to the reported changes in groundwater levels. The model thus provides the framework to identify the thresholds of the integrated system, exploring its nonlinearities and the lever points where policy can be most effective in ensuring the viability of the resource.

I used WULUM to learn how natural and policy variables affect settlement patterns and, in turn, how these affect groundwater levels. Scenarios consisted of current, plausible, and extreme conditions in Monroe County, with the purpose of explaining the current groundwater conditions in the study area and to understand broader relationships between land use and groundwater levels. The ultimate goal of this research is to expand the theoretical knowledge and guide further empirical research of the dynamics of the integrated system, and to contribute with an analytical tool that will enable incorporation of this knowledge into decision making about groundwater sustainability in general, and about Monroe County's resource in particular.

1.1 The case study: Monroe County, Michigan

Monroe County is located in the corner of southeast Michigan (figure 1). It is a predominantly agricultural area, and residential construction has focused mostly on redevelopment rather than on expansion. Since the late 1980s, however, urban development from Detroit in the northeast, Toledo, Ohio in the south and, more recently, Ann Arbor in the northwest, has increased pressure on the county, which is now facing a number of land-use decisions with uncertain effects on its natural resources.

Even though Monroe is literally surrounded by water, in the last decade several drought periods raised enough alarm to commission studies to the United States Geological Survey (USGS) to investigate the causes of dropping water tables. At least three reports have been published since 1996 by USGS researchers (Nicholas et al, 1996; 2001; Reeves et al, 2004), all of which have confirmed a general decline in groundwater levels, particularly in the northern and northwestern areas of the county. Groundwater levels can decrease due to a reduction in recharge, an increase in discharge or extraction, or a combination of both. The process by which aquifers discharge and recharge are adaptive and complex, obscuring the causes of the decline. For example, the magnitude and direction of flow between the aquifer and Lake Erie is uncertain. Nicholas et al (1996) and the International Joint Commission (2002) assume that Lake Erie levels are higher than the groundwater levels due to excessive pumping of the aquifer, so that the lake discharges into the aquifer. Few data exist on recharge and discharge flows to support this claim, however, and there is conflicting information about the trends (Department of Environmental Quality, 2004a; 2004b; *Greenwire* 2004; Morris, 2004; National Oceanic and Atmospheric Administration, 2004; Nicholas et al, 2001; Swanson, 2004).

Nicholas et al (2001) and Reeves et al (2004) have found that sources of recharge have not decreased, while extraction due to higher usage has increased. Although the precipitation levels in Monroe County during the recharge period—fall and winter—were found to be lower than long-term averages, the USGS studies considered this factor to be negligible. In their modeling of the groundwater system, reducing the infiltration rates into the aquifer had a greater effect than changing Lake Erie levels or glacial water-table levels. This implies that land-use change that reduces soil permeability has a greater effect than other possible explanations for declining groundwater levels in Monroe County. The authors, however, affirm that change in permeability is not sufficient to explain the declines observed in the county because an order of magnitude reduction in the capacity of the glacial deposits to transmit water to the bedrock aquifer resulted in a change in water level of 3 – 6 feet in wells, while actual declines ranged between 1 and 10 feet. They conclude that excessive withdrawals are the main cause of depletion.

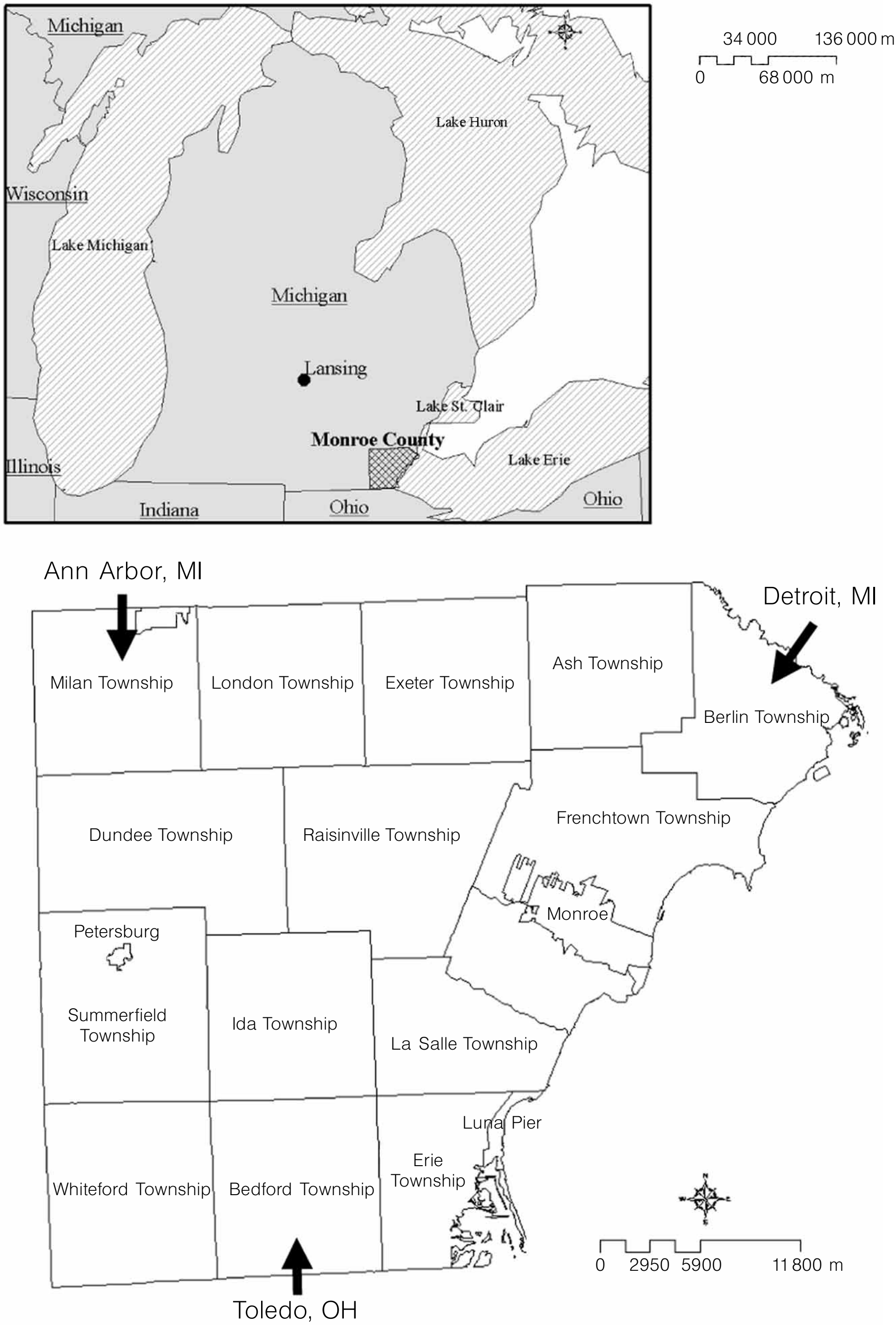


Figure 1. Monroe County, Michigan (source of upper map: SEMCOG).

The main purposes for which groundwater in Monroe County is extracted are residential consumption, agricultural irrigation, quarry dewatering, and golf-course irrigation. Other uses—municipal supply and industrial—are only minor in the county and are declining. Quarry dewatering activities are a focus of attention for residential users and policy makers, since about 75% of the total volume extracted is pumped by stone quarries. Nevertheless, changes in land use have generated changes in the demand for groundwater, and in this paper I will attempt to demonstrate how these processes may have affected the resource's availability.

2 Methodology

Good features of an analytical method to study Monroe County's groundwater depletion should include its complex, spatial, and multiscale nature, in addition to policy goals and levers for policy action. While traditional methods address some of these dimensions, they typically fail to include the more difficult aspects of complexity, such as space and heterogeneity. Recent developments in computer technology have facilitated the development of simulation-based tools that have addressed these difficulties. One type of such tools is agent-based models, consisting of a substrate or landscape in which agents representing decision-making entities have a location and interact according to their defined behaviors and attributes. Agent-based models can be applied to environmental impact assessments of human decision making. Although there are increasing examples of such applications (Becu et al, 2003; Ducrot et al, 2004; Feuillette et al, 2003; Project SLUCE, http://www.cscs.umich.edu/sluce), further research is needed to transform these tools into useful analytical frameworks for policy research, especially in the empirical application of this approach. In this vein, I developed WULUM, an agent-based model that integrates the human realm of land-use and water-consumption decisions and the ecological realm of groundwater dynamics grounded on the case of Monroe County, Michigan.

2.1 The base version of WULUM

WULUM is built with the Java RePast simulation platform (http://repast.sourceforge.net/index.php). There are two integrated components of the model, one representing the land-use processes and the other, the water-use processes and the groundwater dynamics. At its current stage, the land-use component includes the main water-extracting actors in Monroe County: residents, stone quarries, golf courses, and farmers. The landscape is a lattice composed of cells containing land-use, natural, infrastructure, and policy attributes, including land-use type, agricultural soil quality, septic soil quality, roads, distance to main destinations, zoning restrictions for residential density, and municipal water and sewerage coverage. The water component is formed by two layers representing glacial deposits overlaying the bedrock aquifer. A regional groundwater gradient emerges in the aquifer through simple cellular diffusion rules based on Darcy's law of flow, within constant boundary conditions and with periodic recharge through glacial deposits.

Farm cells transition to developable states, after which either residents or golf courses can move in, depending on residential preferences for location, concentration of residents, existing development, and zoning. Quarries may be introduced as part of the initial conditions of each run, but given that practically no new operations were opened in the time period of interest, they do not have location mechanisms in the current version of the model. As agents locate on the lattice and extract water from various sources, they change the landscape and the levels of groundwater. The new landscape conditions affect subsequent directions of development. The ability of the water resource to maintain its levels depends on the natural replenishment rates and the degree of development;

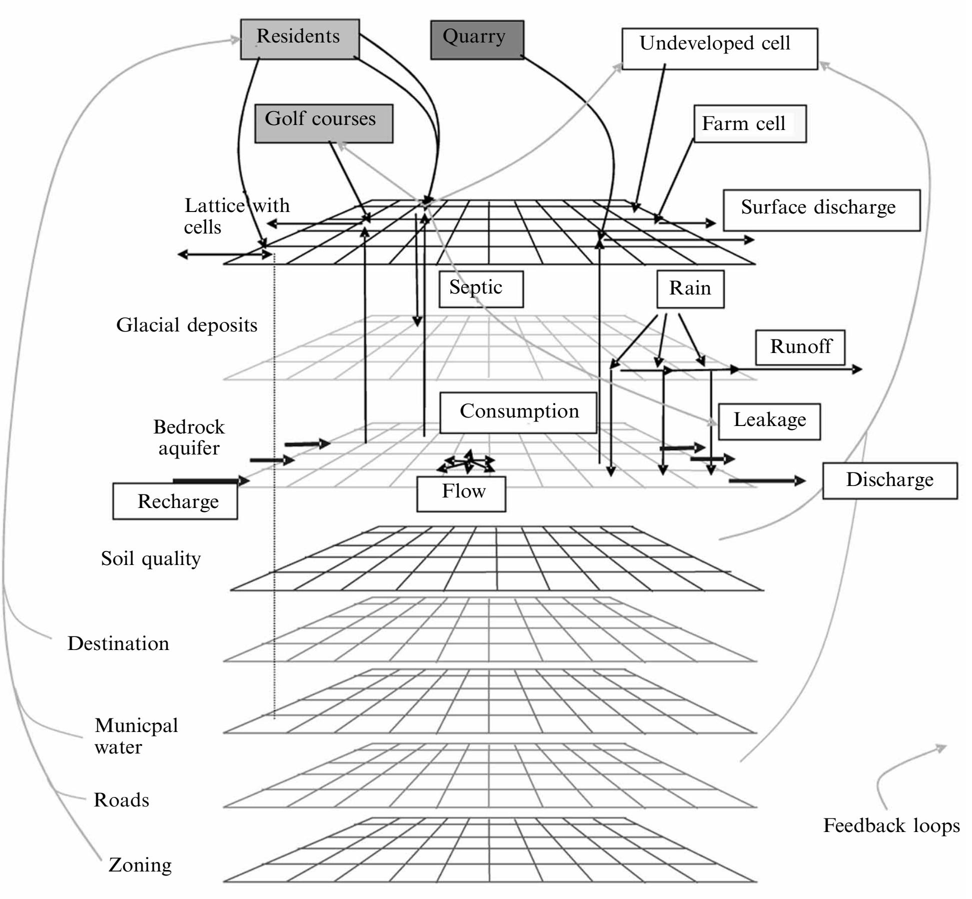


Figure 2. Integrated land-use, water-use, and groundwater dynamics in WULUM.

as paved surfaces increase, the recharge capability of the aquifer decreases. Each time step represents one year, and the model uses annual rates of residential growth, precipitation, groundwater flow, and consumption based on literature and expert knowledge about the area. As the model runs it collects land-use data, groundwater levels, and water deficit values for each cell within the study area. Figure 2 shows the integration of these key dimensions into complex dynamics that make the problem intractable with traditional analytical methods. The subsequent sections describe in more detail the landscape and agents' attributes, and the land-use, water-use, and groundwater processes.

2.1.1 *The landscape*

The landscape is composed of a two-dimensional square lattice of 200×166 cells, each one representing 16 acres. Several layers of information—called quality spaces—are associated with this lattice, representing the land-use, water-use, and the groundwater variables (table 1). Each cell on the landscape is characterized by a score for each one of these qualities. The values stored in each quality space are updated by the cells in the model, while agents access this information to make decisions affecting their location and groundwater consumption.

2.1.1.1 *Land-use conversion*

At the beginning of each simulation, cells are created and assigned a farm land-use type by default. Alternatively, an initial map containing land-use codes for each cell

Table 1. Landscape quality spaces in WULUM.

Land use	Water use	Groundwater
Soil	Infrastructure	Soil
agricultural quality	municipal water coverage	recharge quality
septic quality	municipal sewer coverage	Aquifer
Infrastructure	Irrigation	sediment thickness
presence of roads	occurrence of agricultural irrigation	hydraulic conductivity
Location		Hydraulic gradients
distance to schools		water volume
distance to natural areas		constant head boundaries
distance to closest city		
Policy		
residential density restriction (zoning)		

may be provided as an input to the model, which then guides the assignment of land-use types and the creation of different agents. In the present version of WULUM, stone quarries are created only at model initialization, and cells containing them do not transition to other land uses. Farm cells transition to an undeveloped type at a rate which is defined by a parameter of the model, and which sets the number of cells selected at random to be evaluated for transition for each time step. If a selected cell has poor agricultural soil and contains a county road, it will become undeveloped. If the cell has a road, but good agricultural soil, the probability of transitioning is set arbitrarily to be at least 80%, increasing with increasing adjacent development. Alternatively, if the selected cell has good agricultural soil and no road, it will become undeveloped with a probability that increases with increasing surrounding development. Once the cell changes state, it is ready to be occupied by residents or a golf course, according to decision rules that are described in section 2.1.2 (Agents and agent behavior).

The farmland transition rates and mechanisms are based on current land-use trends in the county, expert knowledge of farmers' decisions to free up land for residential development,(1) and literature studying the role of speculation and of transportation and service infrastructure in encouraging development around existing residential areas (Bogart, 1998; Ewing, 1994; 1997). Figure 3 supports these claims for Monroe County, showing residential development closely following the grid-like road pattern. Current mechanisms and rates in the model may be changed with new empirical information.

2.1.1.2 *Groundwater dynamics*

There are three main processes that define groundwater dynamics, mainly recharge, discharge, and flow. Given that groundwater parameters are based on daily processes, each annual time step in the model is subdivided to represent an appropriate temporal and spatial scale for these processes. The volume of water in each cell is updated for the entire lattice simultaneously, once all operations of recharge, discharge, and flow take place for all cells.

Recharge and discharge: The glacial deposits receive water from periodic rain events, which leaks into the bedrock aquifer where water is stored for consumption. Maps of recharge areas can be fed into the model; for Monroe County, it is assumed that recharge occurs throughout the entire county surface. The default rate at which the aquifer is recharged from the glacial deposits is based on an aggregate value of 35.6

(1) Personal communication, 2004, with J Nassauer, School of National Resources and Environment, University of Michigan, and R Maniko, Director, Monroe County Planning Department.

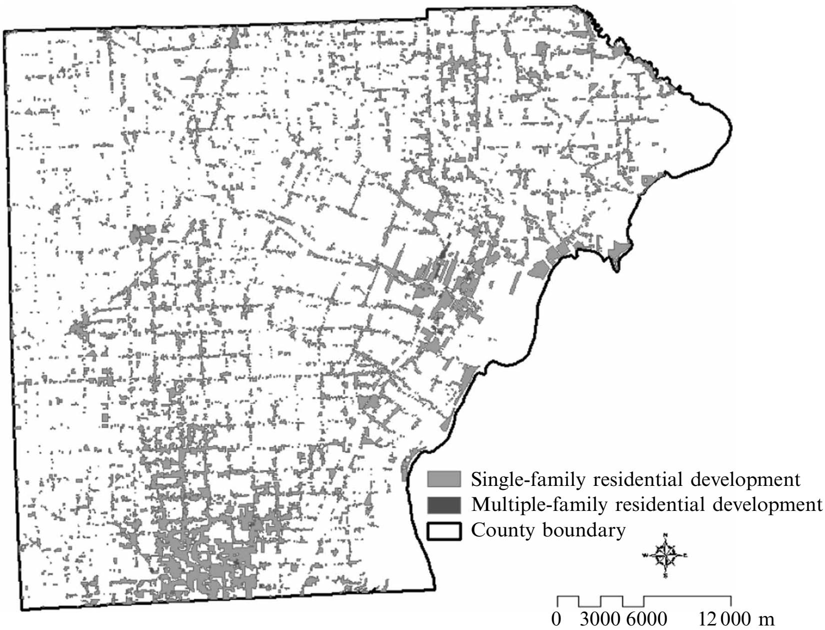


Figure 3. Single-family and multiple-family residential development in Monroe County, 2000 (source: SEMCOG).

million gallons per day provided by Reeves et al (2004) for the county and surrounding areas, which is equally distributed among the recharge cells in the lattice as an annual amount. Precipitation volumes for each time step is drawn from a normal distribution with mean and variance obtained from data of the annual recharge periods between 1991 and 2000 (Nicholas et al, 2001). Precipitation in excess of the rate of recharge is discharged as surface runoff.

As recharge cells are developed, they gradually lose their ability to recharge the bedrock aquifer, and the amount that is left in the glacial layer after leakage is added to the runoff. It is estimated that for each one-acre parking lot developed, sixteen times more runoff is produced, as compared with the recharge capability of a meadow (Runyan, 2003). In the first version of the model, it is assumed that for each resident, one acre of land is paved over, so that leakage rates in each cell are reduced sixteen times the number of residents in the cell. This value, however, will vary depending on the particular layout of the developed cell, so it is added as a parameter that can be varied in scenario simulations. Its default value, however, remains at sixteen. This mechanism does not change when cells are occupied by more than sixteen residents; the recharge capability is already much reduced at such residential densities, so that increasing density would not significantly alter the volume of leakage resulting from development.

The recharge from and discharge to surrounding areas occurs in WULUM by setting constant-head values along the county boundaries, based on hydraulic heights simulated for 1993 (Reeves et al, 2004). Water is discharged into the study area as long as the hydraulic head at the boundary is higher than the hydraulic head within the county boundaries. The reverse occurs when groundwater levels are higher within the boundaries. The base model assumes that the constant-head boundary does not change during the simulation runs. Eventually, changes in lake levels and aquifer recharge can be set as alternative scenarios to evaluate their impact on groundwater availability.

Groundwater flow: WULUM computes flow of water between each cell and its neighbors and between edge cells and the constant-head boundaries using a variation of Darcy's law of flow, by which the flow between two points is determined by the hydraulic gradient (ie the difference in hydraulic height over the distance between the points), the cross sectional area through which water flows, the resistence to flow, and the porosity of the aquifer. Since the cells in WULUM are square, the distance between two cells is equal to the side of each cell, through which water flows. After simplification, the flow equation becomes:

$$Q = -KeD\Delta h \ ,$$

where:
Q is the flow between two points;
K is the hydraulic conductivity, which measures the resistance to flow and depends on the material;[(2)]
e is the effective porosity, the empty space in a medium through which water can flow;[(3)]
D is the aquifer depth or thickness through which water flows;
Δh is the difference in water levels between two neighboring cells.
Hydraulic conductivity values vary spatially, and a default map for these values in Monroe County is based on Reeves et al (2004). An approximate value for effective porosity is 1%.[(4)]

Flow consumption is restricted to only existing water volume, so that no negative water volumes are obtained for flow between cells. If water extraction (described in section 2.1.2) is greater than the water available in the cell, WULUM saves the difference as deficit and no more extraction is permitted until the cell is recharged. Flow, therefore, will be greater towards a dry cell, forming cones of depression observed in areas of excessive extraction.

The aquifer thickness through which water flows is the minimum value comparing the aquifer depth of a cell and that of its neighbor. All flow mechanisms assume that the layer representing the bedrock aquifer extends downward from the same height to its specified depth. There is no topographic gradient, which can be safely assumed for Monroe County. A map of initial groundwater content was generated by running WULUM with default values found in the literature, until the bedrock layer approximates a dynamic equilibrium.

2.1.2 *Agents and agent behavior*

The basic agent types are households (called residents), golf courses, and quarries, who are the main decision makers regarding groundwater resources. Farms also make such decisions, but in WULUM they are defined as cell types rather than as agents. The decision to represent behavior in agent or in cellular form was determined by the level of detail and heterogeneity in the land-use and water-use process, required either in the current version or in anticipation of future versions of the model (see section 5). Residents are heterogeneous in their preferences for location, and decide to move to a cell according to how well its landscape attributes match their preferences. In future versions the behavior rules will be expanded to reflect heterogeneous location and consumption responses to drought and policies. Farm decision making is currently in cellular form because little information is available on individual farm behavior.

[(2)], [(3)] Personal communication, 2004, with A Michalak, Department of Civil and Environmental Engineering, University of Michigan.

[(4)] Personal communication, 2005, with H Reeves, Water Resources Discipline, United States Geological Survey.

When data becomes available and if more detailed behavior is required in the model, farm decision making will be restructured in agent-based form.

2.1.2.1 *Residential and golf-course location*
Residents enter the world at a rate comparable with current annual growth rates of the county (Monroe County Planning Department and Commission, 2004) and drawn by how much they value the landscape. They choose to locate on undeveloped cells using a hedonic utility calculation that is based on survey data from the Detroit Area Study (University of Michigan, 2001), and that accounts for convenience of access, proximity to schools, major cities, and natural areas, and density of surrounding development. These preferences are assigned to each resident as the model creates them in each time step, following a distribution similar to that described by the Detroit Area Study data for the county. Preference values were determined using the manifested level of importance that respondents gave to various location factors: 0.0 (not at all important), 0.33 (not very important), 0.67 (somewhat important), and 1.0 (very important). WULUM allows replacement of these values with a normal distribution described by mean and variance values. All residents are also set to value municipal provision of water and sewerage, and in cases where there is no sewerage they prefer to locate on septic soils, as indicated by spatial analysis and Nystuen (Urban and Regional Planning Program, University of Michigan, personal communication, 2005).

Residents decide where to locate by randomly sampling a set of 100 cells available for development or settlement, representing the knowledge they may have of the real estate market through realtors. They evaluate each cell according to their utility function of the following form:

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

where
α_r is the residential preference for proximity to road;
r is the cell presence of road (0 or 1);
α_dc is the residential preference for distance to city;
d_c is the cell normalized distance to city (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;
s is the cell presence of either sewer coverage or septic soil (0 or 1).

From the random sample of cells, each resident selects to locate on the first one from which they derive the highest utility. The model then checks whether the cell has reached the limit of density imposed by zoning. If so, the cell is withdrawn from the pool of available cells for further residential location. Otherwise, it continues being available for subsequent residents. Hence, the pattern in which residents settle depends not only on the expression of these preferences, but also on zoning restrictions to the number of residents that can occupy each cell, and how farm cells are freed up for development as they transition to the undeveloped state.

Golf courses require a critical mass of residents to locate, and they do so on a set of nine empty cells (a central undeveloped cell plus its eight undeveloped/farm neighbors) that has the highest surrounding residential density in a fifty-cell radius. If there is a tie, the location is decided by proximity to the last resident that entered the lattice. The process of golf-course location is based on actual ratios of residents to golf courses and average golf course size in Monroe County, derived from data provided by the Southeast Michigan Council of Governments (SEMCOG) and in Reeves et al (2004).

2.1.2.2 *Water consumption and discharge*
Farms and golf courses extract groundwater for irrigation, while residents consume it for domestic use. Quarries, on the other hand, extract water for their operation. In WULUM, the rates and destinations of groundwater extraction reflect these different uses and are based on literature for Monroe County (Nicholas et al, 2001; Reeves et al, 2004). Given that data on the spatial location of irrigated farm cells are not readily available, the base case scenario assigns irrigation to a random selection of farm cells, up to a total area equal to the estimated irrigated area in the county. Residential consumption is based on individual estimates, assuming 3.2 persons per household, the average household size suggested by the Detroit Area Study for Monroe County (University of Michigan, 2001).

Farms, golf courses, and quarried discharge to the surface system—directly through runoff or indirectly through evapotranspiration and precipitation—while residents discharge to their septic systems and lawn watering. Reeves et al (2004) chose to neglect domestic water use precisely because it is returned to the groundwater system. I hypothesize, however, that the spatial relationship between domestic extraction and recharge rates may be relevant in reinforcing drought conditions. Moreover, given that the recharge period occurs in the fall and winter months, most of the water used in the spring and summer for lawn watering is 'lost' from the groundwater systems to evapotranspiration. In WULUM, domestic water is discharged to glacial deposits. Residents that locate in an area providing municipal water consume surface water from the lake, and if they are provided with sewer service, they discharge to the lake.[5]

Even though the separate processes of land conversion, agent location, water consumption, and groundwater dynamics are represented in fairly simple terms, the integration of these processes and feedback mechanisms brings forth the interaction effects across spatial and temporal scales among the agents and the environmental features (figure 2). It is such integration that causes the complexity and the uncertainty of groundwater depletion, and which makes it so intractable to solve.

3 Simulation and results
WULUM is a simulation-based model designed to test how the integrated land use and groundwater system responds to different conditions of the behavioral, natural, and policy environment. To perform tests of agent-based models, scenarios are created that sweep the values of the variables of interest. In this paper, I compare the results of each scenario to a base case obtained with the parameter values observed in Monroe County. Although parameter values are expected to have changed since initial settlement of the county, it is not the goal of these analyses to recreate history or to predict future groundwater levels, but to identify the main drivers of groundwater depletion *given current conditions and our knowledge of the integrated system.*

Before conducting the set of tests with WULUM, it was necessary to conduct preliminary runs to initialize aquifer conditions and calibrate the parameter values for both the groundwater flow and the land-use mechanisms. The aquifer component of

[5] Personal communication, 2004, with R Maniko, Director, Monroe County Planning Department.

WULUM relies heavily on the parameter values provided by the USGS study (Reeves et al, 2004). Using these parameter values, however, the model could not reproduce for Monroe County the predevelopment hydraulic gradient suggested in the USGS study. A similar gradient was only obtained when the glacial recharge rate was very small, between 0 and 5 m^3/year, much lower than the default of 151.24 m^3/year. In addition, the gradient was achieved only when infiltration occurred homogeneously throughout the lattice, rather than only where there are high permeability soils. Other hydrological variables did not affect the overall hydraulic gradient. A potential source of this discrepancy is the complexity of recharge mechanisms, by which recharge rates adjust to groundwater levels, increasing as levels drop.(6) Such complexity will be incorporated in future versions of WULUM, as discussed in section 5.

With respect to land use, pretesting showed that the golf-course location pattern varied with how much residents competed for land, which increased when residents had greater knowledge of the available cells for their settlement. In addition, the actual mechanisms for location may be different from what is represented in the model because there was a bias towards the northeastern portion of the lattice, compared with observations. A reason for this bias may be that WULUM produced greater residential development in the northeast than that actually observed, which in turn was caused by relaxed zoning restrictions that may not have been implemented until recently. In general, however, much of the decision-making process for golf-course development is due to a range of factors that result in essentially random decisions—as expressed by the owners—causing greater location discrepancy than for residential development. The tests that follow are designed to show, among other things, how much this variability matters in contributing to groundwater level declines.

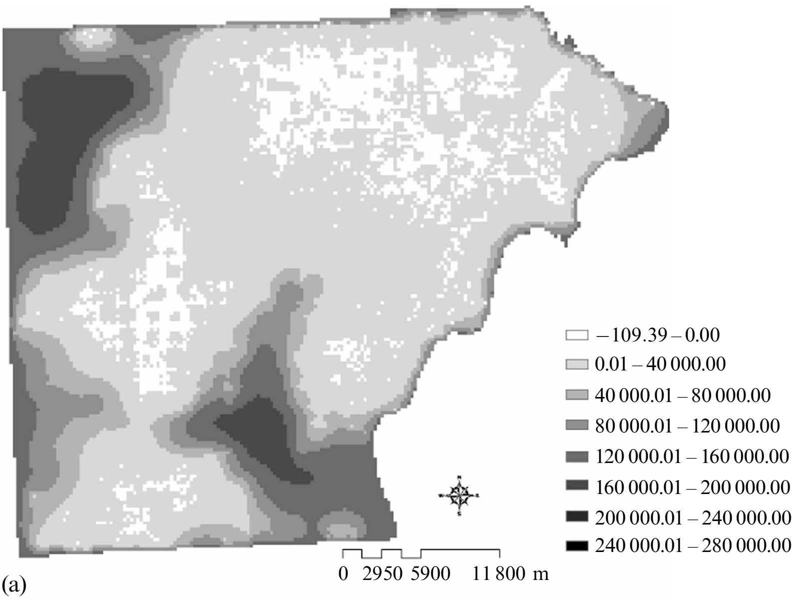
3.1 Test scenarios

The following sections describe the parameter values that were changed to test the behavior of the model. All scenarios started with a landscape entirely composed of farms and the stone quarries that had been established in the 1970s. Only farms underwent land conversion. Each simulation was run for 200 time steps, representing approximately 200 years in the development of the county, and each run was repeated ten times. At the end of each run WULUM produced spatial outputs containing data for each cell on: (a) groundwater volume, (b) land-use type and number of occupants in those that were residential, (c) the total amount of water deficit, and (d) the number of time-steps in deficit. Spatial analyses were conducted to summarize the outputs for each scenario and to compare the outputs of different tests. These analyses included computing the semivariogram of residential development patterns, the average volume of groundwater for each cell, and cross-tabulating land-use type with the number of time steps in which water deficit was experienced in each cell. The purpose of such analyses was to identify the scenarios most vulnerable to depletion and the users that were most affected by deficit; that is, the emphasis was placed on examining land-use patterns as they supported the interactions between water users and groundwater dynamics, not on determining the exact location of deficit.

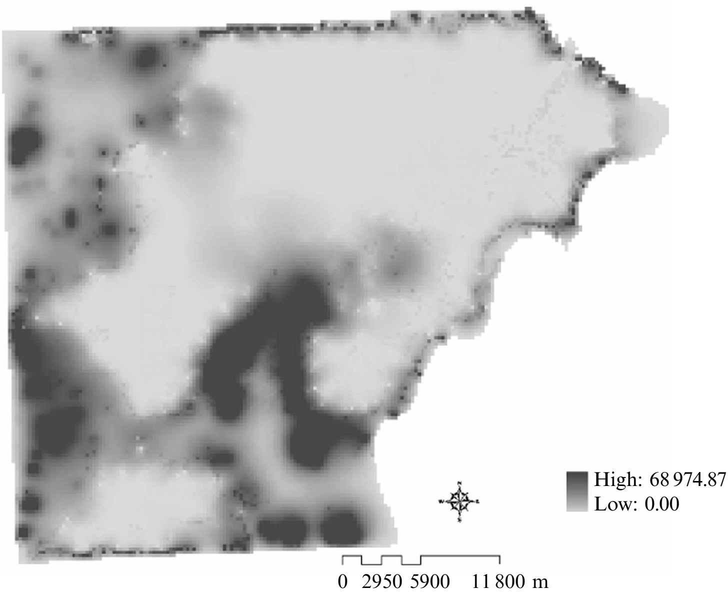
3.1.1 *The base case scenario*

In this scenario, all parameters and input maps were set to the defaults based on the available hydrological and land-use data. Figures 4(a) and (b) show the average and standard deviation of groundwater volume in each cell across the ten runs of this simulation. The greatest variance was located in areas of largest hydraulic gradients, which is where the greatest changes in water levels are likely to occur.

(6) Personal communication, 2005, with H Reeves.



(a)



(b)

Figure 4. (a) Average and (b) standard deviation of groundwater volumes (in m^3) in base case scenario after 200 time steps, averaged across ten runs.

Where hydraulic gradients were low, however, such variation was not observed, and the average of all runs provided a good description of the levels of the water table (this holds for all simulations described here). The resulting groundwater levels were low in large portions of the county, with a general trend of depletion from northeast to southwest. Compared with the reported declines, the results seem to follow the general trend. The increasing levels of water along the eastern boundary would indicate that Lake Erie is likely discharging into the aquifer, as implied by Nicholas et al (1996).

Residential development under this scenario (figure 5) followed a pattern similar to the one observed in the county (figure 3), with strong attraction to roads and higher densities close to the urban centers in the county, due to the reinforcing interactions of farmland conversion, residential preferences, and high-density zoning. Semivariograms were computed for residential development in each run, with an average range of 8141.70 m and a standard deviation of 1 371.22.

Averaging across runs, the model created 24.7 golf courses, whose general spatial distribution differed compared with actual golf-course location [figures 6(a) and (b)]. This outcome supports earlier suggestions for further study on golf-course location, including zoning restrictions in the northern portion of the county that in actuality may have discouraged development in that area compared with the simulation outcomes.

Table 2 summarizes the cross-tabulation results between land use and water deficit aggregated over all runs, for each scenario presented in this paper. Results for residential cells were grouped in seven categories of residential density. The number of residents affected by deficit was then estimated by multiplying the number of cells in each density category by the average number of residents permitted by zoning in each category. The number of golf courses was obtained by dividing the number of golf cells by the nine cells that form each course, and the number of irrigated farm cells was estimated from overall farmland conversion.

The lower-density residential cells, where 41% of the residents were located, experienced comparatively the highest rate of deficit. In each run, and average of 62 582 residents (33%) were exposed to over thirty time steps of deficit, together with fifteen golf courses (61%), and 121 farm cells (53%). Most of the higher-density cells were covered by municipal water supply, and therefore were not exposed to deficit. High-density cells that were not covered, nevertheless, exposed the many residents located in

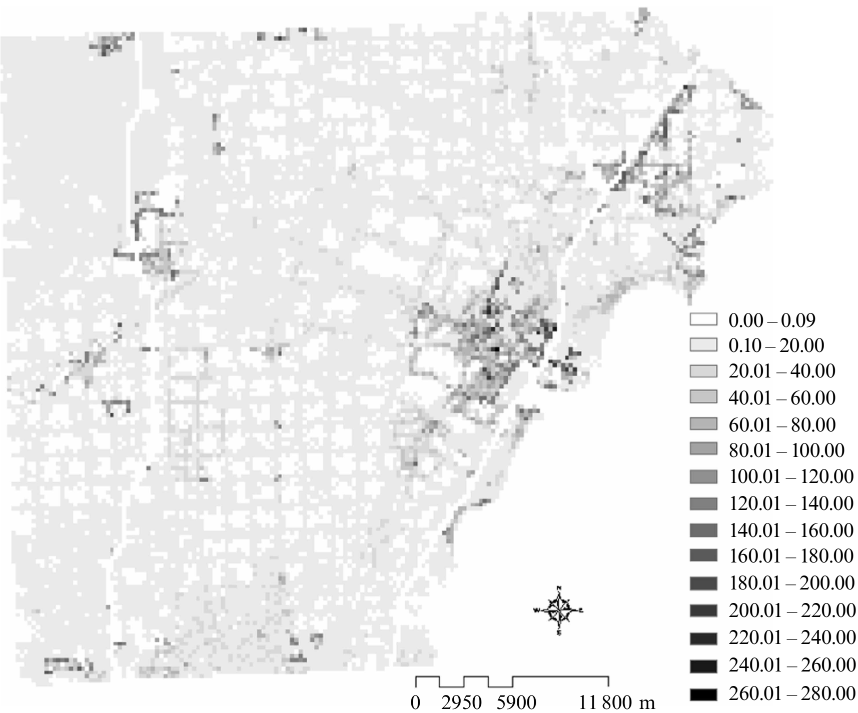
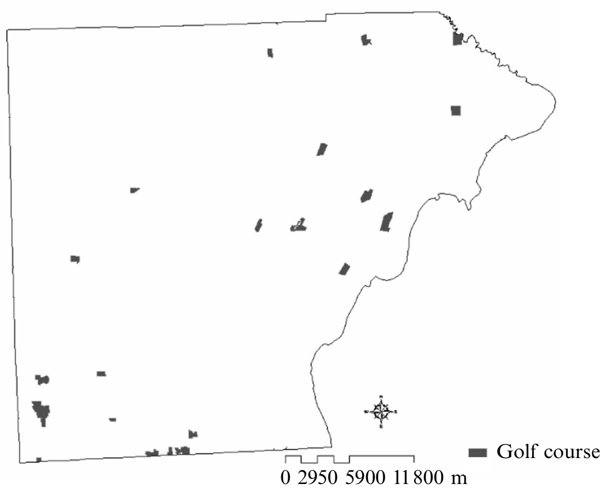
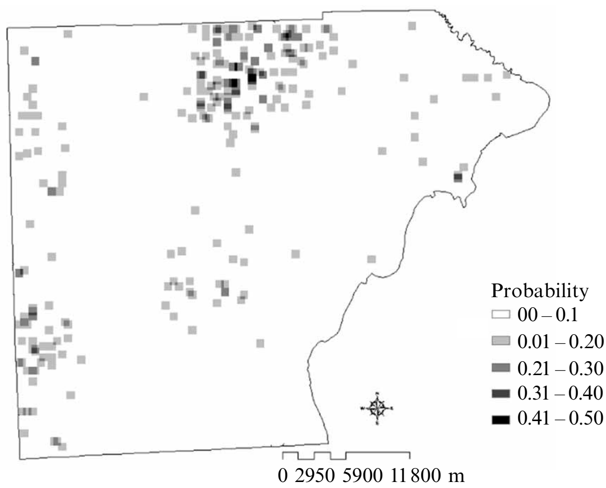


Figure 5. Average number of residents per cell in the base case scenario simulated by WULUM.



(a)



(b)

Figure 6. (a) Actual location of golf courses in Monroe County in 2000 (source: SEMCOG), compared with (b) probability of golf-course location simulated in the base case scenario.

them to deficit. Thus deficit affected low-density cells over a larger area, but affected a greater population in high-density areas. These data set a reference against which to compare the relative impact of all other scenarios.

3.1.2 *Identifying key natural, policy, and behavioral variables*

A series of tests were conducted, varying alternately the spatial layout of septic and agricultural soil quality, hydraulic conductivity, water and road infrastructure, and zoning restrictions on residential density; changing the parameter values of supply and demand for residential development, residential preferences for location, and impact of impervious surfaces, and deactivating agricultural and golf-course irrigation and stone-quarry dewatering. The following sections describe the subset of tests identifying the factors that most affected groundwater levels in the simulations.

Table 2. Exposure to thirty time steps or more of groundwater deficit per run, aggregated for ten runs.

Scenarios	Land-use type							
	residential				golf		irrigated farm	
	population	% in deficit	cells	% in deficit	courses	% in deficit	cells [a]	% in deficit
Base case	1 877 795	33	67 568	24	247	61	2275	53
Average hydraulic conductivity	1 890 231	31	67 224	16	272	55	2277	28
No agricultural irrigation	1 883 099	33	67 327	22	259	61	0	–
No quarry dewatering	1 888 541	30	67 139	16	243	14	2282	32
Zoning								
minimum density	108 034	1	108 034	1	0		1747	16
average density	1 483 350	54	59 334	54	0		2420	76
high density	2 814 050	0	43 085	0	1580	29	2448	19
random	2 732 500	15	45 442	8	1580	57	2415	40
high density where municipal water	1 946 901	0	50 183	0	1580	28	2350	20

[a] Estimated, based on overall farmland conversion.

3.1.2.1 *The effect of hydraulic conductivity*

Of all the natural factors tested, hydraulic conductivity had the greatest impact on the gradient formed by the groundwater levels (figure 7). For this test, the default map of heterogeneous hydraulic conductivity was replaced with a single value for all cells, estimated as the weighted average of conductivity values in the county. Simulated groundwater levels leveled out through the county compared with the base case, in which high groundwater levels coincided with areas of low hydraulic conductivity. Low values of conductivity represent a higher resistance to flow and a relative protection from neighboring areas that may be more water demanding. If extraction rates are high, however, low conductivity slows down replenishment from neighboring areas and groundwater levels drop. On the other hand, higher hydraulic conductivity generates shallower cones of depression of larger diameter, increasing potential for recovery but also negatively affecting a larger area. Hence, the relationship between the spatial distribution of hydraulic conductivity, the values of conductivity, and the intensity of groundwater extraction determines to what extent local depletion influences the regional aquifer conditions.

The leveling effect of homogeneous conductivity is also seen in the cross-tabulation of times of deficit and water users (table 2). The proportion of residents in deficit (31%) was slightly lower compared with the base case. In general, low residential densities discourage the location of golf courses, which in turn tend to locate near areas of residential concentration. Consequently in this scenario, both golf courses and high-density residential cells affected a larger number of surrounding cells, which were typically higher-density residential. This may explain why, compared with the base case, more low-density cells were spared in this scenario and also why fewer irrigated farm cells were subject to deficit (28%), as they could take advantage of faster recovery rates.

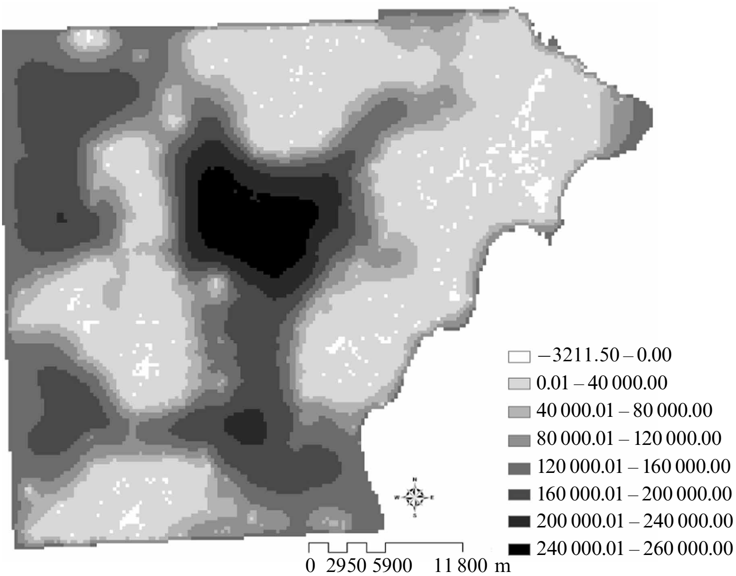


Figure 7. Groundwater volumes after 200 time steps, averaged across ten runs in a scenario with homogeneous hydraulic conductivity.

3.1.2.2 *Varying stone quarry dewatering and irrigation*

This set of simulations tested alternative restrictions on groundwater extraction by farms, quarries, and golf courses. Farms cells were tested in two extreme scenarios, either allowing irrigation throughout the county, or eliminating it entirely. Quarry and golf-course consumption rates were set to zero simultaneously and alternately, forming three combined scenarios.

Although farm irrigation in Monroe County is considered a less intensive use of groundwater, it has grown in the last decade, and as farmers are pressured to increase their productivity, they may expand their irrigation practices further. When farm irrigation was simulated across the entire county, practically no water was left in the aquifer, and almost all residents, golf courses, and farms were subject to deficit. Eliminating all farm irrigation did little, however, to improve the conditions of the aquifer over the base case scenario (table 2). These results stress the importance of monitoring and reporting the use of groundwater for agricultural irrigation, which currently does not occur in the county.

Being the main groundwater extractors in the county, stone quarries are a primary concern of neighbors and planning authorities. In explorations with WULUM, eliminating dewatering activities in stone quarries made a greater impact on the aquifer and its users than eliminating golf-course irrigation, and groundwater levels clearly improved (figure 8). While the impact on all water users was tempered and the area subject to deficit shrunk, approximately one third of the residents suffered water deficit for thirty time steps or more (table 2). This implies that shutting down quarry operations would be beneficial for the county in the short term, but longer-term measures would need to focus on the direction and rate of land-use change.

3.1.2.3 *Modifying zoning restrictions on residential density*

The effects on the groundwater levels were most pronounced in the zoning cases because of its strong influence on land-use patterns, by limiting the location and area of high-density settlement and consequently the number of residents moving into the county.

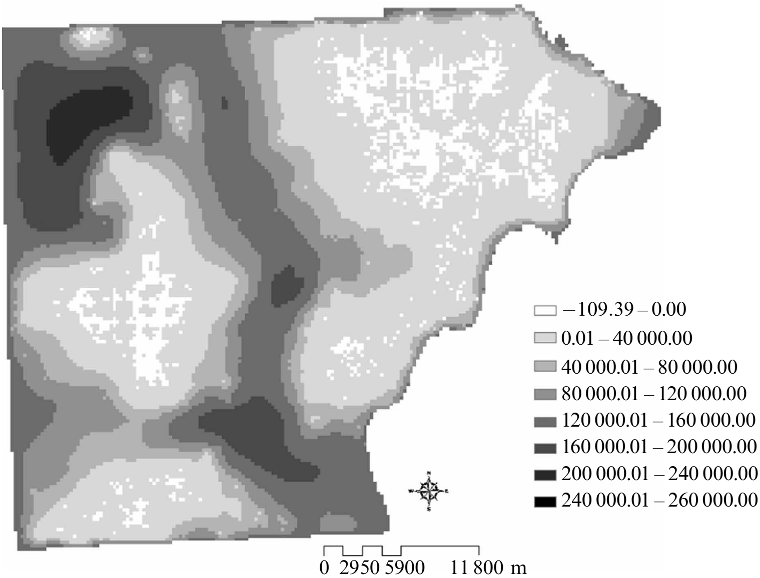


Figure 8. Groundwater volumes after 200 time steps, averaged across ten runs in scenario with no quarry extraction.

The initial conditions for zoning involved setting homogeneous lot-size restrictions, using: (a) the minimum density (1 resident per cell); (b) the county average density, weighted by area (26 residents per cell); and (c) the maximum permitted density (312 residents per cell). An additional setting in this group involved assigning every cell a random density restriction selected from a uniform distribution between the extreme values (1 and 312). To test if maximizing density in areas with existing water infrastructure reduced the impact on the aquifer, a final scenario used such a zoning layout in combination with existing municipal water coverage in Monroe County.

When minimum density was permitted, the water levels were maintained throughout the county, except in the areas where quarry dewatering produced cones of depression [figure 9(a)]. Land was homogeneously developed at the lowest density across the county, producing significantly different semivariogram ranges of residential patterns with respect to the base case scenario. The number of residents that could settle in the county was restricted to approximately 10% of the base case and thus prevented any golf-course development. Only 1% of residents and 16% of farm cells were exposed to over thirty steps of deficit (table 2).

In contrast, zoning at average density depleted the groundwater resources almost entirely [figure 9(b)]. The development pattern was similar to the one produced in the minimum density zoning scenario, but with a higher intensity. Consequently, water was drawn from across the entire county area, except in those places where municipal water was provided. In this case, residents moved into the county in similar numbers as in the base case (1 483 350 and 1 877 795, respectively), while 54% of them were subjected to more than thirty steps or more of deficit, together with 76% of farm cells (table 2). Therefore, the spatial distribution of water users greatly affected the sustainability of the aquifer, even though larger consumers such as golf courses were prevented from locating in the county because of competition for land.

Interestingly, zoning at the maximum density of 312 residents per cell drastically improved the conditions of the aquifer, having a similar effect to zoning for minimum density [figure 9(c)], yet allowing many more residents to move into the county.

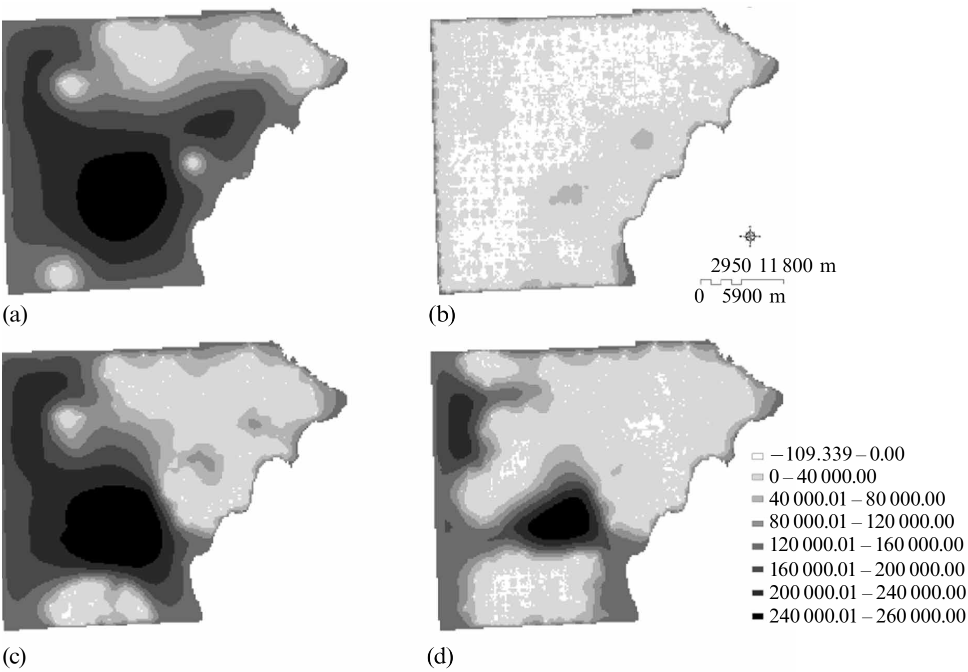


Figure 9. Groundwater volume (m^3) resulting from (a) minimum-density, (b) average-density, (c) maximum-density, and (d) random-density zoning scenarios, at $T = 200$, averaged across ten runs.

The land-use pattern that emerged was of greater variability of residential clusters, with significant differences in semivariogram ranges with respect to the base case. Residents tended to locate at higher densities closer to their destinations of preference. Less than 1% of the residents experienced deficit, and practically all of it occurred in the low density cells. Residents concentrated in cities that typically provided municipal water service, thus reducing the pressure on the aquifer. The lower competition for land allowed for a more active development of golf courses (an average of 158 per run) which tended to surround the high residential density, yet less than one-third of them were exposed to drought. Fewer irrigated farm cells (19%) were in deficit after at least thirty time steps (table 2).

Random zoning provided an improvement over average zoning, but did not fare as well as when either minimum or maximum zoning was allowed [figure 9(d)]. The land-use pattern was similar to the one for maximum-density zoning, but with greater variability across runs and a larger number of urbanized cells, although still well below the area developed in the base case. A lower percentage of residents was affected by deficit than in the base case (15%). Golf courses, similar in number to the scenario with high-density zoning, added to the pressure on the groundwater resource for which over half of them experienced drought.

3.1.2.4 *Combining zoning and infrastructure policies*

The results above suggest that zoning for maximum density in areas already covered by municipal water service would be an appropriate policy to maintain existing groundwater levels in the county. In this scenario, zoning allowed a maximum density of 312 residents per cell in areas currently serviced by surface water, while the rest of the county only allowed 1 resident per cell. The impact on the aquifer levels was similar to that of maximum-density zoning, an improvement over the base case and all other

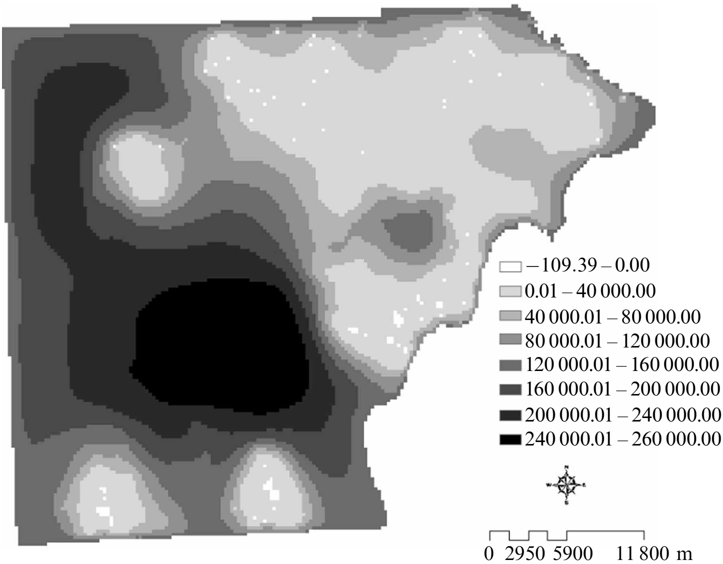


Figure 10. Groundwater volumes after 200 time steps, averaged across ten runs in a scenario with maximum-density zoning coinciding with municipal water coverage.

zoning scenarios, except where low density was enforced across the county (figure 10). Cross-tabulation with deficit confirmed that only low-density cells experienced drought, and these were most likely neighbors of the stone quarries and therefore affected by the cones of depression they formed. Although more golf courses were formed than in the base case, less than one-third of them experienced deficit. Golf courses tended to concentrate around high-density residential areas, and some of them were also affected by the stone-quarry dewatering activities. As in the scenario permitting high-density throughout, fewer irrigated farms were exposed to deficit (20%) (table 2).

4 Implications for water management

While there certainly is room for model improvement, which will be discussed in section 5, the tests conducted with WULUM suggest ways in which land-use development in Monroe County could have contributed to the drought conditions reported. Simulations showed that the problem of declining groundwater levels would not be solved by eliminating stone-quarry extraction alone. Residential development may inflict more widespread and long-term damage on the aquifer if the pattern of settlement encourages reliance on well-water to meet residential needs. Given the faster urbanization and accompanying creation of golf courses in the last decade in Monroe County, the immediate future course of land-use change is a matter of concern for the sustainability of the aquifer, in particular because it takes longer for the resource to recover than to be depleted.

Of the various factors shaping land-use patterns in the simulations, the most significant were the zoning restrictions on the density of residential development, even more so than location preferences. The effect of residential density on groundwater levels was nonlinear; both low-density and high-density development helped maintain water levels in the aquifer, while average densities reinforced drought conditions. Zoning policy should therefore discourage medium-density development, additionally considering the relationship between rate of extraction, its spatial distribution, and hydraulic conductivity, and the consequent tradeoff between groundwater recovery rates, surface area affected by groundwater depression, and user exposure to deficit. It is also advisable to establish a reporting and monitoring system for golf-course and agricultural irrigation, beyond registering high capacity wells, to collect data on actual location and flow. Simulations showed that expanding irrigation, particularly agricultural, may lead to widespread groundwater depletion, yet no detailed data exist for Monroe County.

Concentration of residential population promotes economies of scale for the provision of surface water supply—and other services—further reducing the impact on the aquifer. One strategy for accommodating growth without greatly affecting the aquifer is to allow maximum density where municipal water service is provided—the source of which is Lake Erie—and restricting density in the rest of the county. This would require, however, that the water extracted from the surface system were returned to the system at the same rate to maintain the levels of Lake Erie, and thus prevent excessive discharge from the aquifer into the lake. The increased tax base resulting from this strategy could help pay for the operation and maintenance of the water infrastructure, rather than having to rely on expansion to capture clients—which starts a vicious cycle of expansion to cover the costs of expansion (based on conversations with Monroe County planners). If expansion is still decided, it is important to keep the coverage with a small perimeter to area ratio, in order to reduce the development pressures on adjacent areas. Similarly, road infrastructure could be enhanced in the high-density areas covered by municipal supply, further containing urbanization processes within these areas.

A final question is whether growth is an objective for the entire county, and if governmental agencies responsible for land-use and infrastructure decisions could consider that other options are in fact less costly. A smaller tax base may not be desirable at first glance, yet it also means that fewer services need to be provided, greatly reducing public expenditure. In addition, public officials will need to consider the character of their jurisdictions, and the impacts of preserving or changing it. This is ultimately a moral judgment, yet it still needs to be made with the information available, uncertain as it may be. WULUM can be incorporated into such deliberations as a tool that can represent the complexity involved in such decisions, integrating different types of information and defining the scope of uncertainty in the integrated system.

5 Future research

The process of constructing WULUM was in itself a way of organizing and acquiring knowledge about the mechanisms affecting groundwater depletion in Monroe County. WULUM not only informs by creating scenario simulations, but also by guiding the formulation of relevant questions about the system's processes as they are being built into the model and tried out in successive stages. Among the questions raised, for example, the first and perhaps most important is about the recharge rate from the glacial deposits to the aquifer. The immediate next step in improving WULUM is to allow this rate to adjust to changing groundwater levels in the aquifer.(7) Another unknown is the thickness of the bedrock layer—even though tests were inconclusive as to the relevance of this parameter in the resulting hydraulic gradient, a more realistic spatial distribution of its values may produce similar profiles to those of Reeves et al (2004). The discrepancy between the predevelopment conditions generated in each study suggests that it is worthwhile to identify its source, be it either the empirical values reported or the mechanisms represented in the approach of each study.

(7) Personal communication, 2005, with H Reeves.

Golf-course irrigation on occasion may impose added stress on the groundwater resource, for which golf-course-location mechanisms should be better understood. According to the information obtained through informal interviews, the conditions for golf-course location are unique and almost random. A few general rules could be extracted from the description of these decisions, which also have changed through history. It would be useful to conduct more systematic survey research, interviews, and economic analyses to learn more about the mechanisms behind golf-course location. Until a county monitoring system can be set up, surveys could also inform about site location and actual extraction rates for both golf-course and agricultural irrigation wells. It also becomes important to understand the factors driving irrigation, whether it is drought, soil conditions, type of crop cultivated, or others.

As further information is collected to improve the current version of WULUM, the same scenarios will be tested, with more repetitions of runs in each one to strengthen the statistical analyses and support the application to policy. Other scenarios will be added, including:

- The effect of changes in the levels of Lake Erie. This would involve changing the values of the constant-head boundary of the aquifer in the eastern portion of the county.
- A combination of policies that include zoning, and road and water-supply infrastructure, to assess the advantage of scale economies.

WULUM will also be extended to include new mechanisms to respond to dropping levels of groundwater, for example:

- Residential behavior: voluntarily reducing consumption, demanding municipal water supply, or moving to other areas. In this case, residents would include information about deficit in their utility function.
- Government behavior: apply user taxes on groundwater extraction, implementing well permits, requiring stone quarries to discharge into ponds for groundwater recharge, changing zoning or expanding water infrastructure in response to residential demand.
- Surface – groundwater connection: recording runoff and allowing feedback from rivers and wetlands. Policy impacts would then be examined, not only on the aquifer, but also on Lake Erie water.

Other models would be useful complements to WULUM. The importance of zoning as a main driver shaping urban patterns indicates that the process by which it is implemented and revised requires in-depth study. Previous research has incorporated simple dynamic mechanisms in a land-use agent-based model studying the interaction of zoning and individual preferences (Zellner et al, 2003). It would be useful to obtain more detailed information about how zoning changes occur in Monroe County, and, in particular, find out who are the major stakeholders in the local planning boards, how they reach decisions, and if these decisions can be structured in the form of simple rules for modeling purposes.

The successive versions of WULUM and simulation results were displayed at work meetings with the Monroe County Planning Department. The graphical user interface and the openness of the modeling approach facilitated the communication and interaction in these meetings, promoting discussion and furthering our collective knowledge of the complex problem, informing land-use and water-management policies, and defining future directions of research. Planning officials expressed interest in their continuous involvement and training to improve WULUM and to apply it to policy making through discussion with municipalities, agricultural organizations, and other stakeholders. Further directions for research are expected to arise in these discussions and as more information is made available.

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References

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

Bogart W T, 1998 *The Economics of Cities and Suburbs* (Prentice-Hall, Englewood Cliffs, NJ)

Department of Environmental Quality, 2004a, "Background information on lake levels in the Great Lakes", http://www.michigan.gov/deq/0,1607,7-135-3313_3677_3704-12566%2D%2D,00.html

Department of Environmental Quality, 2004b, "Great Lakes map", http://www.michigan.gov/deq/0,1607,7-135-3313_3677-15926%2D%2D,00.html

Ducrot R, Le Page C, Bommel P, Kuper M, 2004, "Articulating land and water dynamics with urbanization: an attempt to model natural resources management at the urban edge" *Computers, Environment and Urban Systems* **28** 85 – 106

Ewing R H, 1994, "Characteristics, causes, and effects of sprawl: a literature review" *Environmental and Urban Issues* **21**(2) 1 – 15

Ewing R H, 1997, "Is Los Angeles-style sprawl desirable" *Journal of American Planning Association* **63** 107 – 126

Feuillette S, Bousquet F, Le Goulven P, 2003, "SINUSE: a multi-agent model to negotiate water demand management on a free access water table" *Environmental Modelling and Software* **18** 413 – 427

Greenwire 2004, "Great Lakes: challenges remain on water quality and diversions", 16 September, copy available from Greenwire, Environment and Energy Publishing, Washington, DC

International Joint Commission, 2002 *Protection of the Waters of the Great Lakes: Three Year Review* The International Water Uses Review Task Force, http://www.ijc.org/rel/pdf/tf_finale.pdf

Monroe County Planning Department and Commission, 2004 *2003 Summary of New On-site Construction Activity and Manufactured Housing Development in Monroe County, Michigan* Monroe County Planning Department and Commission, Monroe, MI

Morris J, 2004, "Water levels slightly higher on Lake Erie" *Dayton Daily News (Ohio)* 20 May, page C2

National Oceanic and Atmospheric Administration, 2004 *Great Lakes Water Levels* http://www.glerl.noaa.gov/data/now/wlevels/lowlevels/plot/Erie.png

Nicholas J R, Rowe G L, Brannen J R, 1996, "Hydrology, water quality, and effects of drought in Monroe County, Michigan", Water-Resources Investigations Report 94-4161, United States Geological Survey, 12201 Sunrise Valley Drive, Reston, VA

Nicholas J R, Blumer S P, McGowan R M, 2001, "Comparison of hydrologic data from Monroe County, Michigan, 1991 – 2001", Open File Report 01-498, United States Geological Survey, Lansing, MI, http://mi.water.usgs.gov/pubs/OF/OF01-498/OF01-498LW.php

Reeves H W, Wright K V, Nicholas J R, 2004, "Hydrogeology and simulation of regional ground-water-level declines in Monroe County, Michigan", Water Resources Investigations Report 03-4312, United States Geological Survey and Michigan Department of Environmental Quality

Runyan C, 2003, "Studies find sprawl exacerbates drought, threatens farmlands" *World Watch* **16**(1) 10

Swanson A, 2004, "Analysis: water diversion thorny issue" *United Press International* 9 September, http://washingtontimes.com/upi-breaking/20040909-024325-5687r.htm

University of Michigan, 2001, "Detroit Area Study 2001", http://www.tcaup.umich.edu/workfolio/DAS2001/stdescript.html

Zellner M L, Riolo R, Rand W, Page S E, Brown D G, Fernandez L E, 2003, "The interaction between zoning regulations and residential preferences as a driver of urban form", in *Proceedings of the 2003 UTEP Distinguished Faculty and Student Symposium* http://sitemaker.umich.edu.urrcworkingpapers/all_urrc_working_papers/da.data/1522520/Paper/zellner0706.pdf