Generating Policies for Sustainable Water-Use in Complex Scenarios: An Agent-Based Model of Monroe County, Michigan

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Abstract

In Southeast Michigan there is serious concern for rapidly declining groundwater levels, observed since the early 1990s. Hydrological studies have suggested that this decline is caused by land-use changes. The mechanisms by which land-use and groundwater dynamics are linked is not clear, however. The purpose of this paper is to present the Water-Use Land-Use Model (WULUM), an agent-based model that can serve as an analytical framework to understand how these processes interact and create the observed patterns of resource depletion, and suggest policies to revert the process. The agent-based model is empirically based on the case of Monroe County, Michigan, and informed with land-use and survey data and expert knowledge about the case. Initial testing indicate the need for further research on hydraulic conductivity of the aquifer and location decision-making of golf courses. Of the natural variables tested, medium to high hydraulic conductivity values appear to worsen depletion conditions. Overall, preliminary results showed a non-linear relationship between land-use type and intensity and groundwater levels. In addition, zoning policies may have the greatest influence on shaping the pattern of resource use than any other natural or policy variable. Future work involves more detailed examination of the independent effects of various policy and behavioral variables, as well as interaction effects. WULUM is a tool with which we can study these interactions, provide new insights about the dynamics of human-groundwater systems, and expand the knowledge about better strategies for the sustainable use of the resource.

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 to the significant land-use change occurring since the last decade. How these two observations are linked remains to be explained, however. 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 Water-use and Land-use Model (WULUM), an agent-based model that represents simple mechanisms of land-use, 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 non-linearities and the lever points where policy can be most effective in ensuring the viability of the resource.

I use WULUM to learn how soil quality, residential preferences for location, land conversion rates, zoning restrictions, and road and water infrastructure affect settlement patterns and, in turn, their effect on groundwater levels. Scenarios consist of existing, potential 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 water groundwater levels. In further stages of my research I will extend the base model to include taxes on water extraction and cooperation mechanisms in response to water scarcity. The ultimate goal of my research is to expand the theoretical knowledge and guide further empirical research of the integrated system's dynamics, and to contribute with an analytical tool that will enable to incorporate this knowledge into decision-making about groundwater sustainability in general, and about Monroe County's resource in particular.

1.1 The Case: 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 mostly focused 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 concern to commission studies from the US Geological Survey (USGS) to investigate the causes of dropping water tables. At least three reports were published since 1996 by USGS researchers (Nicholas et al., 1996; Nicholas et al., 2001; Reeves et al., 2004), all of which have confirmed a general decline in groundwater levels, particularly in the northern and northwest areas of the county (Figure 2).

Groundwater levels can decrease due to a reduction in recharge, an increase in discharge or extraction, or a combination of both. The processes 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 International Joint Commission (2002) assume that Lake Erie levels are higher than groundwater 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 (Greenwire, 2004; Morris, 2004; National Oceanic and Atmospheric Administration, 2004; Nicholas et al., 2001; Swanson, 2004; Dept. of Environmental Quality, 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 researchers 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 thus conclude that excessive withdrawals are the main cause of depletion.

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 concern for residential users and policy-makers, since about 75 percent of the total volume extracted is pumped by stone quarries. Changes in land-use have thus generated changes in the demand for groundwater, and this paper will attempt to demonstrate how these processes may have affected the resource's availability.

1.2 Methodological issues

The land-water system in Monroe County may be defined as a complex adaptive system characterized by interactions, emergence and non-linearities. The dynamics of the system is influenced both by environmental factors and by actions of individuals and institutions. Resource-use patterns emerge from interactions at different scales, and cannot be predicted by actors' or environmental characteristics alone (Hoffman et al., 2003). The complex nature of the human-environment interactions tends to be imperceptible to the human mind (Bateson, 1998). Consequently, humans are oblivious to the fact that environmental impacts of settlement patterns are being masked by diffusion through the web of feedback loops of our social and biophysical systems, and may build up into unpredictable consequences. A tool that represents complexity and makes it more understandable can provide valuable insights to inform the decision-making processes involved in resource use.

Land-water systems are inherently spatial, i.e., the location of specific land-use and water use processes makes a difference in the state of the overall system, particularly if there are thresholds effects impacting various scales. For example, the initial location of a commercial center and roads may greatly affect the direction and density of future urban expansion. The initial residential density, in turn, will affect the type of water supply that is affordable—i.e. the scale economies of municipal supply systems only emerge at high densities, for which low densities tend to overly rely on groundwater for supply. Furthermore, certain economic activities may be sustained by spatial soil characteristics and topography affecting individual decisions in the land market, then leading to agglomeration and demand for different resources. Therefore, space needs to be explicitly represented in an analytical framework that studies the system.

Policy aspects add to the complexity of the problem studied, by encouraging or restricting social or economic activity. In the same way that individual actions may diffuse through a complex system and generate environmental impacts, small or simple policy actions may seep into the system to either cause or solve complex regional issues. These simple actions are called lever points, where small changes can cause large effects. Identifying lever points and how to act on them offers an alternative approach to complexity that may be more effective—and informed—than the cautious—and more uncertain—trial and error offered by incremental approaches to urban and regional planning.

Good features of an analytical method to study Monroe County's groundwater depletion should therefore include its complex, spatial and multi-scale nature, in addition to policy goals and levers for 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 development in computer technology has facilitated the development of simulation-based tools that have addressed these difficulties. One of these tools is agent-based models, consisting of a framework or substrate in which agents representing decision-making entities have a location and interact according to their defined behaviors and attributes. Agent-based model can be applied to environmental impact assessments of human decision-making. Although there are increasing examples of such applications (Project SLUCE, 2005; Ducrot et al., 2004; Becu et al., 2003; Feuillette et al., 2003), further research is needed to transform these tools into useful analytical frameworks for policy research, especially in the empirical application of this approach.

2 The WULUM Base Model

WULUM (Water-Use and Land-Use Model) is an agent-based model built with the Java RePast[1] simulation platform. There are two integrated components of the model, one representing land-use processes and the other, water-use. 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 environment is a lattice composed of cells containing land-use, natural, infrastructure and policy attributes, including land-use type, volume of groundwater, agricultural soil quality, septic soil quality and recharge capability, roads, distance to main destinations, zoning restrictions for residential density

[1] http://repast.sourceforge.net/index.php

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 flow (diffusion) rules and points of recharge and discharge, and periodic rain events.

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 are located 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; 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 and 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.

2.1.1 The Environment

The landscape is composed of a two-dimensional square lattice of 200 by 166 cells, each one representing 16 acres. Several layers of information—quality spaces—are associated with this lattice, representing the land-use and the aquifer-related variables. Each cell on the landscape is characterized by a score for each land-use quality, including:

- agricultural soil quality
- septic soil quality
- roads
- municipal water coverage
- municipal sewer coverage
- residential density restriction (zoning)
- distance to schools
- distance to natural areas
- distance to closest city

In addition, the groundwater layers store values for the following:

- water content
- sediment thickness
- hydraulic conductivity
- recharge soil quality
- agricultural irrigation probability
- constant head boundaries

The values are used by the different agents of the model to make decisions that affect land-use change and groundwater consumption.

2.1.1.1 Land-use Conversion

At the beginning of each simulation, cells are created and assigned a land-use type either by default as farm, or according to an initial land-use map. Farm cells transition to an undeveloped type with a probability that increases with proximity to roads, poor soil quality, or neighboring development pressures. The rate of transition is a parameter of the model that defines the number of cells that are selected at random each time step to be evaluated for transition to the undeveloped state. If the sampled cell has poor agricultural soil and has a county road, it will become undeveloped. If the cell has a road, but good agricultural soil, the probability of transitioning is 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 below.

2.1.1.2 Groundwater Dynamics

There are three main processes that define groundwater dynamics, mainly recharge, discharge and flow. Given that many of the groundwater parameters are based on daily processes, each time step in the model is subdivided to represent an appropriate time-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.

2.1.1.2.1 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, and for Monroe County the assumption is that recharge occurs throughout the county surface. The default rate at which the aquifer is recharged from the glacial deposits is based on an aggregate value of 35.6 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 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 to 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 16 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 aquifer extends beyond the boundaries of Monroe County, and is recharged from south and west and discharges into Lake Erie in the east (Lundstrom et al., 2004). The recharge and discharge process occurs in WULUM by setting a constant head-boundary around the county limits, based on hydraulic heights simulated for 1993 (Reeves at al., 2004). Water is discharged into the groundwater system as long as the head-boundary is higher than the groundwater hydraulic head. The reverse occurs when groundwater levels are higher. In the model, excessive groundwater withdrawal will reverse the flow into the aquifer at rates that will depend on the magnitude of the hydraulic gradient between the water table and the constant head. 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.

2.1.1.2.2 Groundwater Flow

WULUM computes flow of water among cells and between cells and the constant head-boundaries using a variation of Darcy's Law of flow. According to Darcy's Law:

$$Q = -K \times e \times A \times \frac{\Delta h}{\Delta l} \qquad (1),$$

where:

Q = flow between two points,

K = hydraulic conductivity, which measures the resistance to flow and depends on the material (Michalak, pers. comm.., 2004),

e = effective porosity, the empty space in a medium through which water can flow (Michalak, pers. comm.., 2004),

A = cross-sectional area through which water flows, and

$\frac{\Delta h}{\Delta l}$ = hydraulic gradient between two points at distance l.

Since the cells in WULUM are square, Δl is equal to the width of the cross-sectional area through which water flows (the side of each cell). Consequently,

$$A = \Delta l \times D \qquad (2),$$

where:

D = aquifer depth or thickness through which water flows. Hence, equation (1) becomes:

$$Q = -K \times e \times D \times \Delta h \qquad (3),$$

where:

Δh = difference in water levels between two neighboring cells.

Hydraulic conductivity values vary spatially, and a map for these values in Monroe County based on Reeves et al. (2004) is used as a default. An approximate value for effective porosity is 1% (Howard Reeves, pers. comm.., 2005).

Flow computation is restricted to only existing water volumes, so that no negative water volumes are obtained for flow between cells. If water extraction (described in the next section) is greater than the water available in the cell—i.e. leading to negative water values—WULUM saves the resulting negative water value and no more extraction is permitted. Flow, therefore, will be greater towards a cell with negative water values, representing the cones of depression formed by excessive extraction.

The aquifer thickness through which water flows is the minimum value comparing the aquifer depth of a cell and of its neighbor. All flow mechanisms assume that the layer representing the bedrock aquifer extends downwards from the same height to its specified depth. There is no topographic gradient, which can be safely assumed for Monroe County.

An initial map of groundwater content for each cell can be generated by running WULUM using default values for the base case until the bedrock layer approximates a dynamic equilibrium. This map can then be used as an initial condition of the aquifer for the scenario simulations.

2.1.2 Agents and Agent Behavior

The basic agent types are households (called residents), golf courses and quarries, which are the main decision-makers regarding groundwater resources. Farms also may consume groundwater, but in WULUM they are defined as cell types rather than as agents.

2.1.2.1 Location

Residents enter the world at a rate comparable to current annual growth rates of the county (Monroe County Planning Dept. 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 (Detroit Area Study, 2001), and that accounts for 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 Areas 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). These values can be replaced by a normal distribution described by mean and variance values. All residents are also set to value municipal provision of water and sewer, and in cases where there is no sewerage they prefer to locate on septic soils, as indicated by spatial analysis and Nystuen (pers. comm., 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 a hedonic utility function that takes into account their preference for different cell attributes, and that has the following form:

$$U = a_r \times r + a_{dc} \times (1-dc) + a_{dn} \times (1-dn) + a_{ds} \times (1-ds) + a_z \times (1-z) + \\ + a_{mw} \times mw + a_s \times s \quad (4),$$

where:

a_r = residential preference for convenience to access places, expressed as proximity to road;

r = cell presence of road (0 or 1);
a_{dc} = residential preference for distance to city;
dc = cell normalized distance to city (between 0 and 1, with respect to maximum distance);
a_{dn} = residential preference for distance to natural area;
dn = cell normalized distance to natural area (between 0 and 1, with respect to maximum distance);
a_{ds} = residential preference for distance to school (between 0 and 1, with respect to maximum distance);
ds = cell normalized distance to school (between 0 and 1, with respect to maximum distance);
a_z = residential preference for low density;
z = residential density permitted by zoning (between 0 and 1, with respect to maximum density allowed in the county);
a_{mw} = residential preference for municipal water coverage;
mw = cell presence of municipal water (0 or 1);
a_s = residential preference for either sewer coverage or septic soil;
s = 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 one from which they derive the highest utility. The model then checks whether the zoning restriction is met. If so, the cell is withdrawn from the pool of available cells for residential development. 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.

Given the little change in quarry land-use in the period of interest, quarries are fixed as initial conditions of each scenario. Golf courses, on the other hand, 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. 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, as cited in Reeves et al. (2004) and provided by Xuan Liu from SEMCOG and Robert Peven from the Monroe County Planning Department.

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 destination 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 farm irrigation is not readily available, the base case scenario uses a random distribution that amounts to the latest records of total irrigated area in the county. Residential consumption is based on individual estimates, assuming four persons per household (the average household size suggested by the Detroit Area Study is 3.2).

Farms, golf courses and quarries 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 time lag between domestic extraction and recharge 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 they discharge to the lake (Maniko, pers. comm., 2004).

As the location of agents modifies the landscape, subsequent residents' and golf-course location choices respond to these changes. In future stages of the model, the state of the aquifer will also influence location and consumption decisions, as well as policy decisions made by the units of government.

Even though the separate processes of land conversion, agent location, water consumption and groundwater dynamics are relatively simple and represented in fairly simple terms, the integration of these processes brings forth the interaction effects and feedback mechanisms across spatial and temporal scales among the agents and the environmental features (Figure 3). It is such integration that causes the emergence of the complexity and the uncertainty characteristic of groundwater depletion, and which makes it so intractable to solve.

3 Simulations and Results

The first set of simulations for this base version of WULUM was designed to test how the model reacts to different natural and policy landscapes, rates of supply and demand for residential development, the impact of impervious surfaces, irrigation and dewatering practices, and individual preferences for location. These scenarios are compared to a base case, set up with the default parameter values for Monroe County and designed to recreate similar conditions to the ones observed in the county. A second set of tests is designed to evaluate the impact of various policies in the recovery of the groundwater levels, assuming initial conditions similar to 1978.

During general testing prior to running the simulation experiments, WULUM could not reproduce the predevelopment hydraulic gradient suggested in the USGS study, based on its parameter values. A similar gradient was only obtained when recharge from glacial deposits was deactivated. If recharge is kept active, the rate at which water infiltrates the aquifer must be homogeneously distributed across the lattice to obtain similar patterns to the USGS predevelopment gradient. This finding suggests the need for further empirical studies on the glacial recharge rates and location.

The golf-course location pattern greatly varies with how much competition for land there is with residents, which in turn increases when residents have greater knowledge of the available cells for their settlement. In addition, the mechanisms for location may be different from what is represented in the model because there is a bias towards the northeastern portion of the lattice, compared to actual observations. A reason for this bias may be that there is greater residential development in the northeast than what is actually observed, which in turn is caused by relaxed zoning restrictions that may have not been implemented until recently. Interviews with golf course developers could help identify the key factors involved in their location, for which there is not much basis in terms of data. Some of the tests below are designed to show whether their location matters in relation to groundwater use, and therefore if such interviewing effort is warranted.

3.1 Test scenarios

The following sections describe the parameter values that were changed to test the behavior of the model. Each simulation was run for 200 time steps, after which WULUM produces spatial outputs of groundwater content, land-use type and intensity (if residential), and water deficit for each cell. Spatial analyses were conducted to summarize and compare the outputs of different tests. These analyses include the semi-variogram of the residential development patterns, the trend of the bedrock surface, and identifying the distribution of deficit and the number of residents exposed to it. In addition, the number and location of golf courses is recorded for each test.

3.1.1 The base case scenario

The base case scenario consists of all parameter values and digitized spatial information in the model that to the best of my knowledge describes the land-use, water-use and groundwater dynamics in Monroe County. In this scenario, the groundwater levels drop significantly in almost the entire county, with a general northeast to southwest trend (Figure 4). Compared to the reported declines, the results seem to follow the general trend. The higher levels of water in the eastern boundary would indicate that the Lake Erie may be discharging into the aquifer.

There are fewer golf courses created in the model and their general spatial distribution differs compared to existing golf courses in the county, supporting earlier suggestions for further study on these agents' location decision-making (Figure 5).

Residential development follows a pattern similar to the one observed in the county (Figure 6a and 6b), with strong attraction to roads. Higher densities develop on the eastern areas, partly due to preference and partly due to high density zoning. The semi-variogram for the residential development is shown in Figure 6c, and is a reference for other scenario results to compare with. The descriptive statistics produced for the semi-variogram sample of residential cells are:

Number of Samples: 733
Attribute Mean: 26.8895
Standard Deviation: 50.7111
Variance: 2571.61

Groundwater deficit indicates where water consumption could not be satisfied by the yield of groundwater in a cell. Water deficit can occur in some cells where there is no hydraulic conductivity value. Excluding those cells, we can observe the influence of golf courses on the overall demand on the aquifer (Figure 7) as it competes with residential pressure on the resource, and at lower hydraulic heights of the aquifer. Consistent with observed declines in groundwater levels, water deficit seems to concentrate in the north and west, although there are smaller and more scattered areas of deficit in the southern and eastern portions of the lattice as well. Figure 8 shows the cell distribution of deficit, and sets the baseline to which all other scenarios will be compared. Of the total 183,209 residents (households) in the lattice, 53% are located in cells exposed to deficit.

3.1.2 Varying the natural landscape

A first series of tests consisted of varying soils, in terms of agricultural and septic quality. The different spatial layouts for these attributes were high values (1) homogeneously distributed across the lattice, low values (0) homogeneously distributed across the lattice and random distribution of low and high values. Hydraulic conductivity was changed for a homogeneous value, estimated as the weighted average of conductivity values in the county.

Of these natural factors, hydraulic conductivity has the greatest impact on the gradient formed by the groundwater levels. In the base case, areas with higher groundwater levels coincided with those of lower 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. Hence, the effect is most likely originated from the value of conductivity, rather than its homogeneity in space. Fifty-four percent of the residents are exposed to deficit, not much higher than in the base case scenario. This may be due to the tradeoff between cells with originally higher conductivity values and those with lower conductivity values than average. The impact on other water users, however, was greater. The histogram of deficit follows a similar distribution to the base case, but a higher number of total cells registered water deficits.

While hydraulic conductivity does not affect land-use, soil quality does. When larger areas of poor agricultural soil are present, greater opportunities for residential and golf-course development arise. Average residential density tends to be higher with a wider distribution, but paradoxically the percentage of households exposed to deficit remains approximately the same, slightly under 53%. Spatially, however, the distribution of deficit indicates that there are more cells with greater deficits than in previous cases. Rich agricultural soil, on the other hand, reduces opportunities for residential development, although such development still occurs mostly along roads. Residential densities are lower, and much fewer golf courses are created. As a result, groundwater levels are higher than the base case in some areas, fewer cells register water deficit, and 51% of the households are exposed to deficit. Random distribution of agricultural soil quality results in even stronger impacts on land-use and water deficit than the effect of homogeneous distribution of poor soil. Average residential density and standard deviation values are similar in both cases, but there is more heterogeneity in the random scenario. At the aquifer level, deficit is more widespread, with a larger number of residents being exposed to it (54%). However, more cells have lower deficits and fewer cells have higher deficits compared to the scenario with homogeneous poor soil.

In terms of septic soil quality, average residential density and standard deviation are slightly higher when soils do not support septic systems than in the base case scenario. Given their preference for sewerage service, residents tend to concentrate in cells where it is provided, making more land available for golf-course development. As a result, a slightly lower percentage of residents are exposed to water deficits (52%), but there are more cells of all types that experience greater deficits. With spatially homogeneous soils of good septic quality, average residential density and standard deviation are slightly higher than when soils are poor. Fewer golf courses can be created, probably due to increased competition for vacant land, and consequently fewer cells experience large water deficits. Finally, a random distribution of septic soil quality results in residential density and deficit distributions similar to those of the base case, although there are more cells with higher deficits. A larger number of golf courses may explain this difference, although it does not seem to increase water scarcity among residents.

3.1.3 Varying land-use policy

A second series of tests involved varying policy variables, starting with zoning restrictions to residential density. The initial conditions for zoning ranged from a homogeneous layout of minimum density (1 resident per cell), a homogeneous of maximum density (311 residents per cell), and a random layout between those extreme values.

The effects produced by zoning are much more dramatic than those described in the previous section. With homogeneous low-density zoning, there is uniform low-density development in all directions, severely restricting the number of residents that can settle in the county (10519) and thus preventing any golf course development. The water levels are maintained throughout the county, except in the areas where quarry dewatering produces cones of depression (Figure 9). Only 7.5% of residents are exposed to deficit and water deficit tends to be less severe than in the cases described above.

Figure 10 shows the gradient produced when zoning is set to allow maximum residential density. Interestingly, although conditions are obviously worse than when low density is enforced, they are better than the base case scenario, where high density is allowed in only a few areas. Many more golf courses are created, and they surround the high residential density that concentrates around pre-defined city centers. Of the 199000 residents that enter the county, only 964 (0.5%) are affected by water deficits. This may be explained by the concentration of residents in cities, which typically provide municipal water service, thus reducing the impact of groundwater deficit on the population. The distribution of deficit among cells is more even across deficit volumes, and mainly occurs due to golf-course irrigation.

Finally, applying random zoning restrictions across the county results in the greatest pressure on the groundwater resource (Figure 11). Golf-course development is more scattered than in the previous scenario, although the total number is the same. Similarly, the same number of residents moves into the county but settles in scattered clusters of medium density. Here, 25% of the residents are exposed to water deficit, which in turn seems to spread over more cells. It is worth noting that the last two cases have exactly the same number of residents and of golf courses. However their spatial distribution makes a significant impact on the state of the aquifer.

4 Implications for Water Management

The initial findings suggest that there are non-linear relationships between land-use diversity and intensity and groundwater levels that depend on the interaction between natural, policy and infrastructure variables. Zoning has a greater impact on the state of the aquifer than any of the natural factors tested. Of the latter, high values of hydraulic conductivity seem to cause more significant declines in water levels. The effects of high hydraulic conductivity may be partially offset by land-use policies that manage the densities of development and thus the amount or rather the speed at which groundwater is drawn from the aquifer.

Varying natural attributes revealed that residential in various high density clusters may be advantageous for the state of the aquifer, even if it translates into more widespread, yet less intense, deficit. Zoning for maximum density allowed for greater land-use intensity, yet restricted the aquifer area exposed to groundwater consumption; on the other hand, the base case and the random zoning scenario fared worse than when maximum density was permitted. As explained above, given that highest residents concentrate at high densities in cities providing municipal water supply, areas that provide surface water supply should be allowed to zone for maximum density to reduce the impact on the groundwater resource. A broader implication is that the interaction of land-use type, density of clusters and area of clusters results in a series of impacts that could be classified by intensity (volume) and magnitude (area affected). Further study will focus on such classification.

The experiments presented also imply that a spatial scale of action may be appropriate for some, but not all, scales of problems. Stone quarries, greatly resisted by neighbors and a concern of county officials, may cause local stress on the aquifer that most likely requires local action. However, residential and golf-course development may actually have a greater regional impact on the aquifer and deserve more attention given its non-linear response to natural, policy and economic factors.

5 Future Research

The next steps in this research involves testing the independent effects of road and water supply infrastructure, as well as varying individual behavior on location decisions and groundwater consumption, and changing the impact of development on the rate of glacial recharge. Other scenarios will test for the aquifer’s ability to recover from depletion. In this set of experiments, I will use initial land-use and groundwater levels for 1978 and run simulations to assess whether recovery of the aquifer would be possible through changes in zoning or in the provision of municipal water supply, or if quarry dewatering and golf-course irrigation were eliminated. Once the independent effects are tested, a new set of simulation experiments will involve testing for interaction effects among simultaneous policy approaches. A question arising from the experiments above is how zoning makes a difference if no municipal water is provided.

For a more complete evaluation of the scenarios, other measures may be more appropriate, including statistical analyses of various runs for each scenario. These analyses would aim at exploring if the trajectories of groundwater levels converge temporally and spatially, and if specific natural or policy conditions make the resource system becomes unstable.

A final goal is to create a classification of impacts on groundwater levels originated in land-use characteristics, and in turn, to the natural and policy drivers in the system. WULUM is a tool with which we can study these interactions, provide new insights about the dynamics of human-groundwater systems, and expand the knowledge about better strategies for the sustainable use of the resource.

6 Acknowledgement

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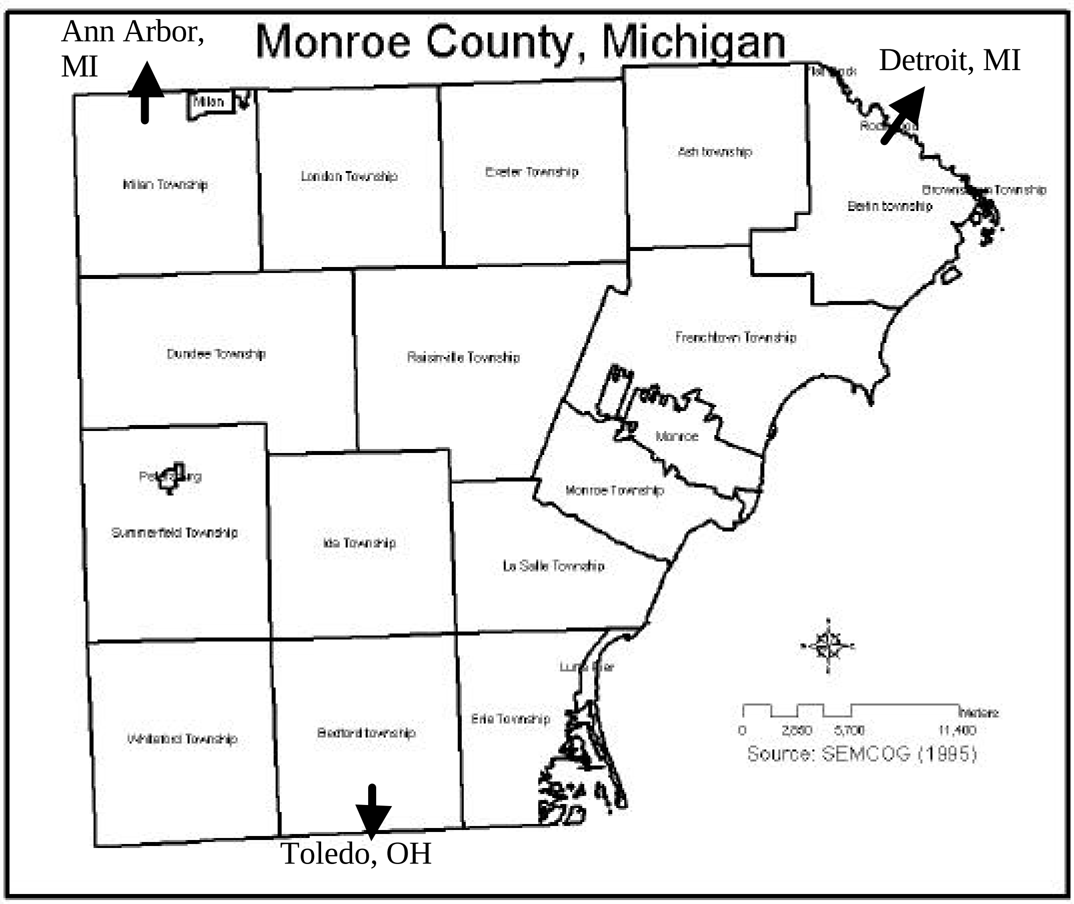

Figure 1. Monroe County, Michigan

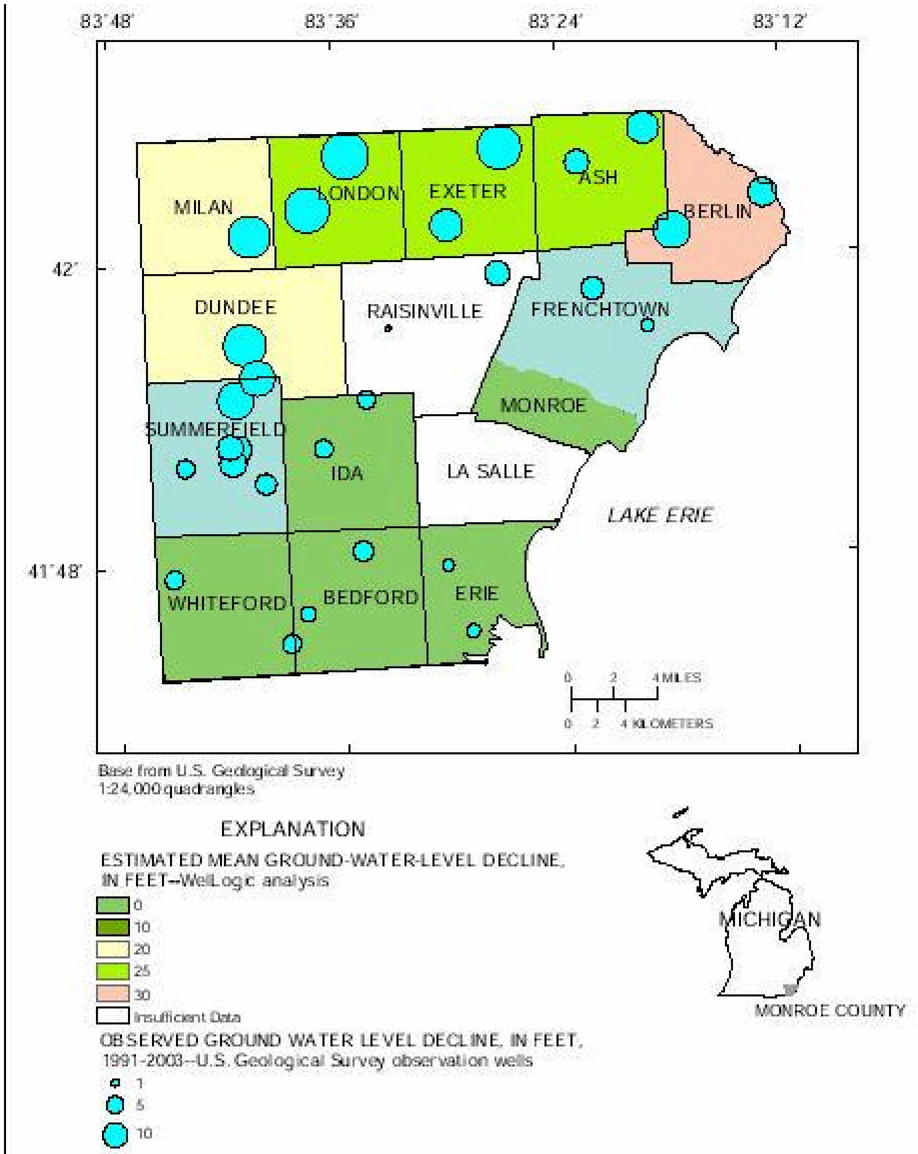

Figure 11. Estimated and observed ground-water-level declines, Monroe County, Michigan, 1991-2001.

Figure 2. Groundwater decline in Monroe County (1991-2000).
Source: Reeves et al. (2004)

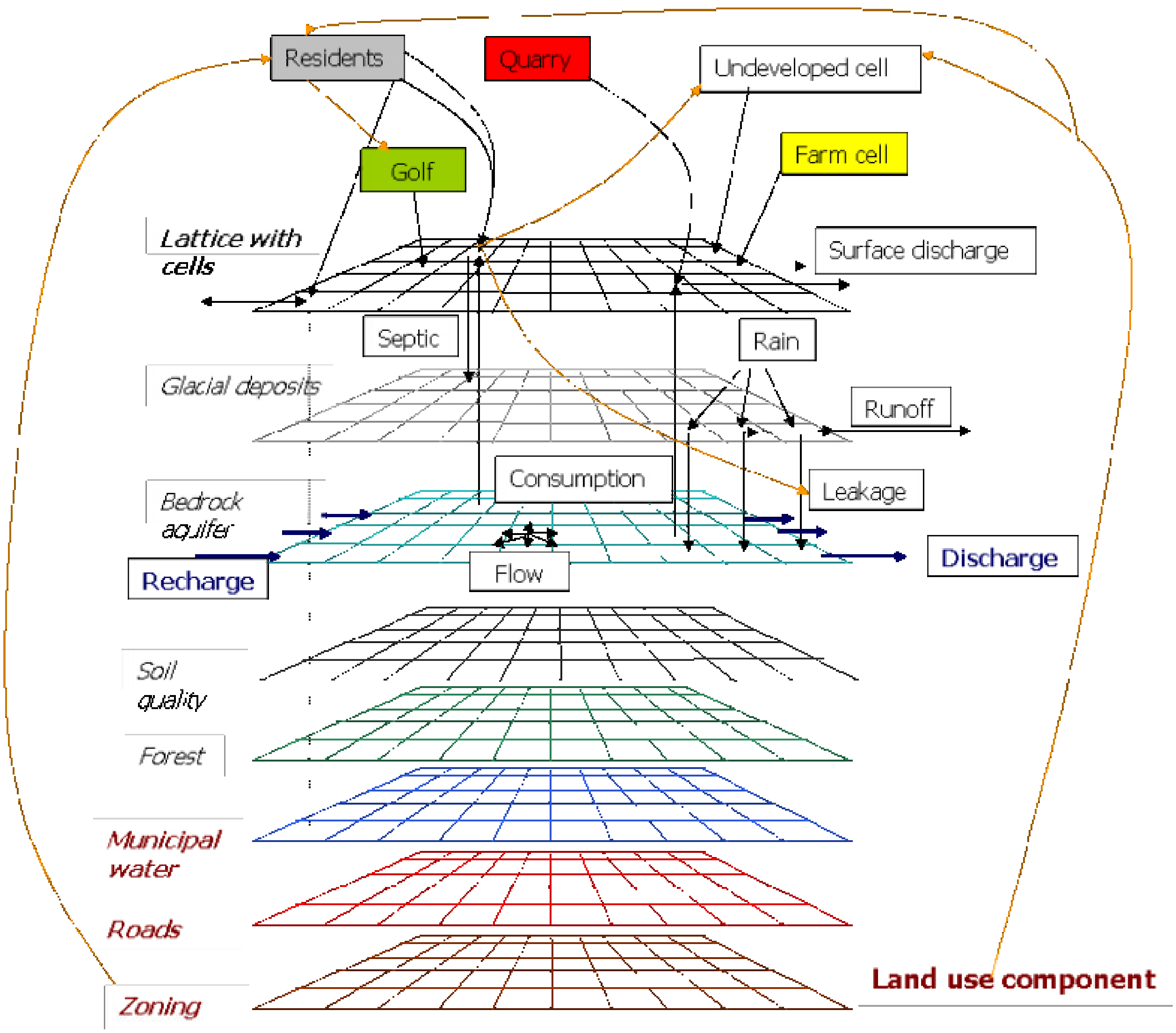

Figure 3. Integrated land-use, water-use and groundwater dynamics in WULUM

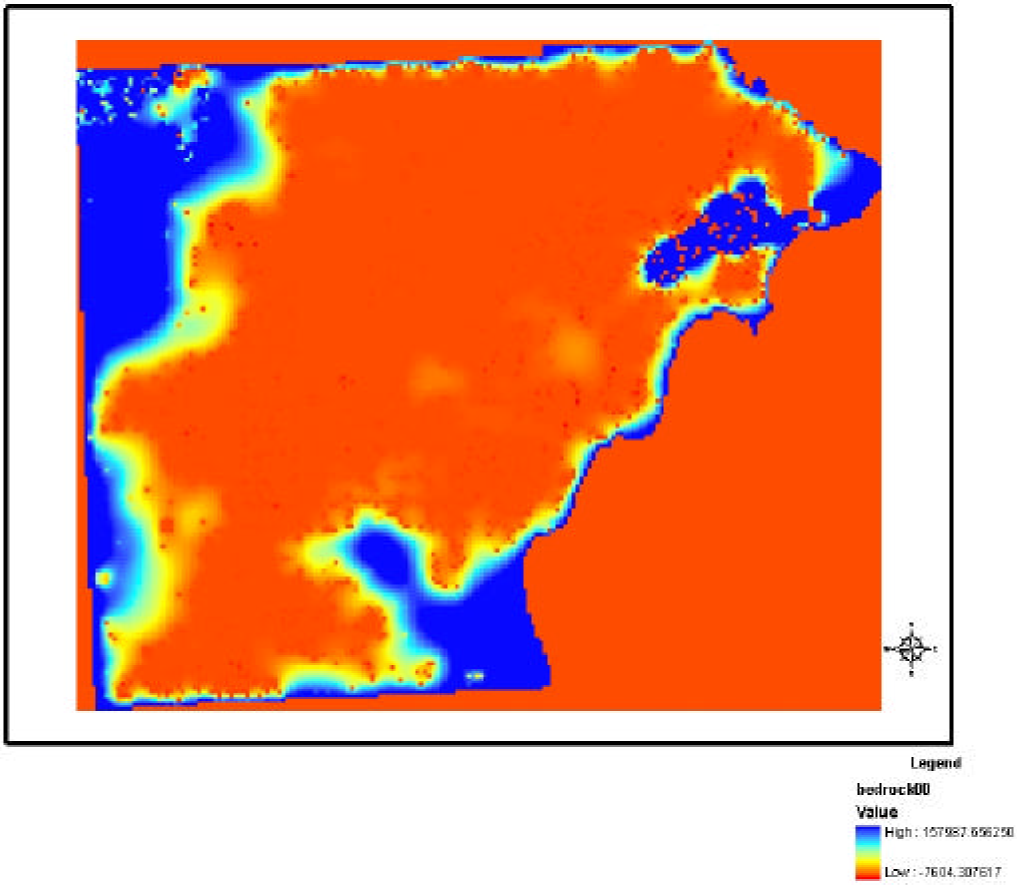

Figure 4. Groundwater volume (m^3) resulting from the base case scenario

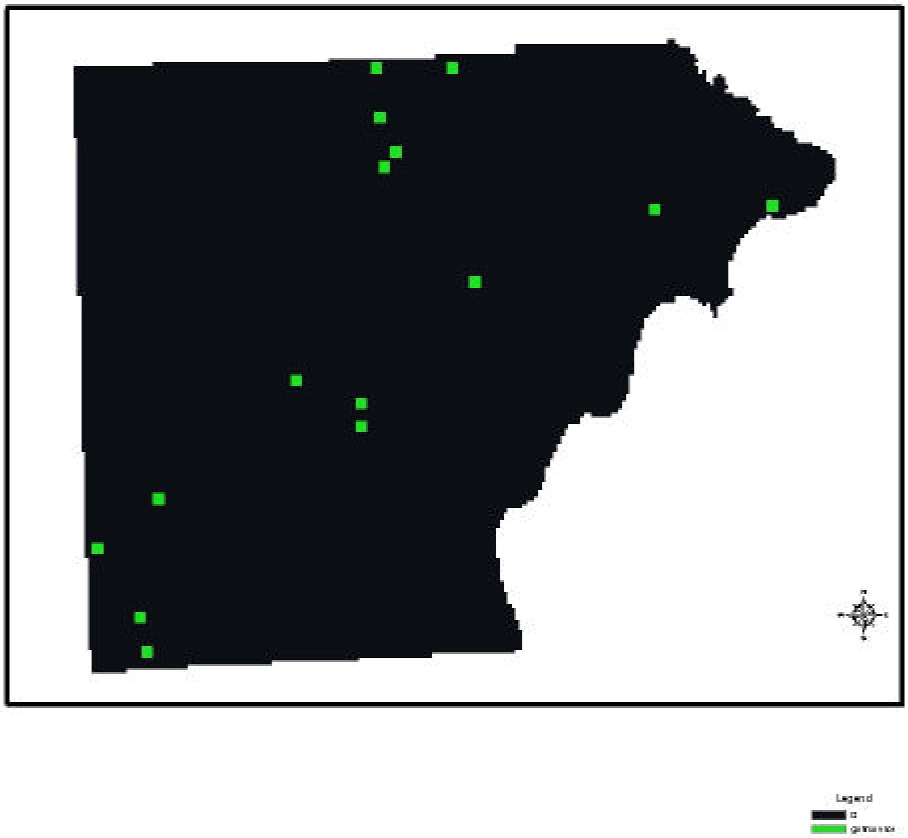

Figure 5. Golf courses resulting from base case scenario

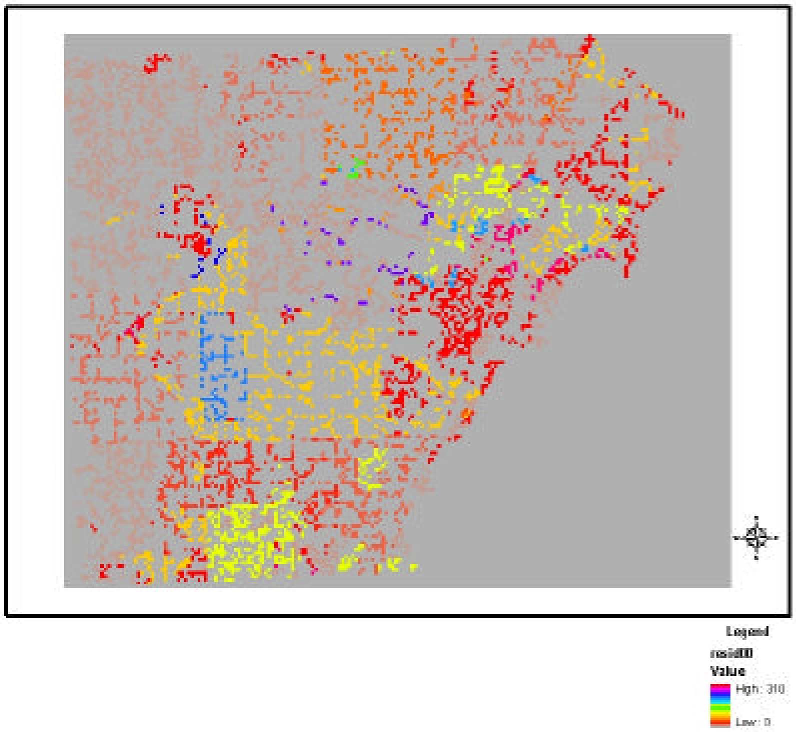

Figure 6a. Residential density resulting from the base case scenario

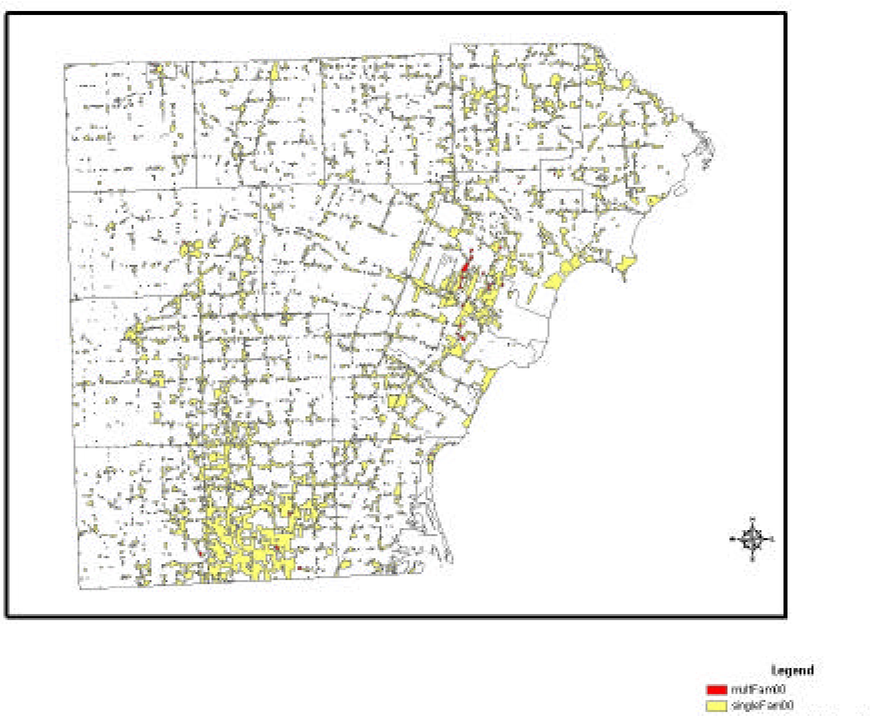

Figure 6b. 2000 single and multiple family residential development in Monroe County

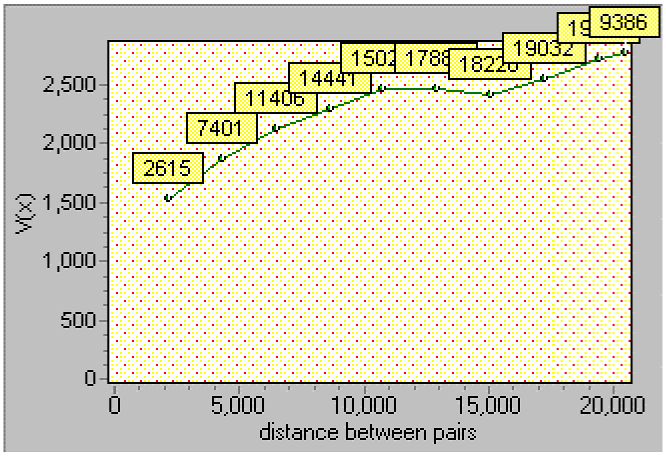

Figure 6c. Semi-variogram of residential cells resulting from base case scenario

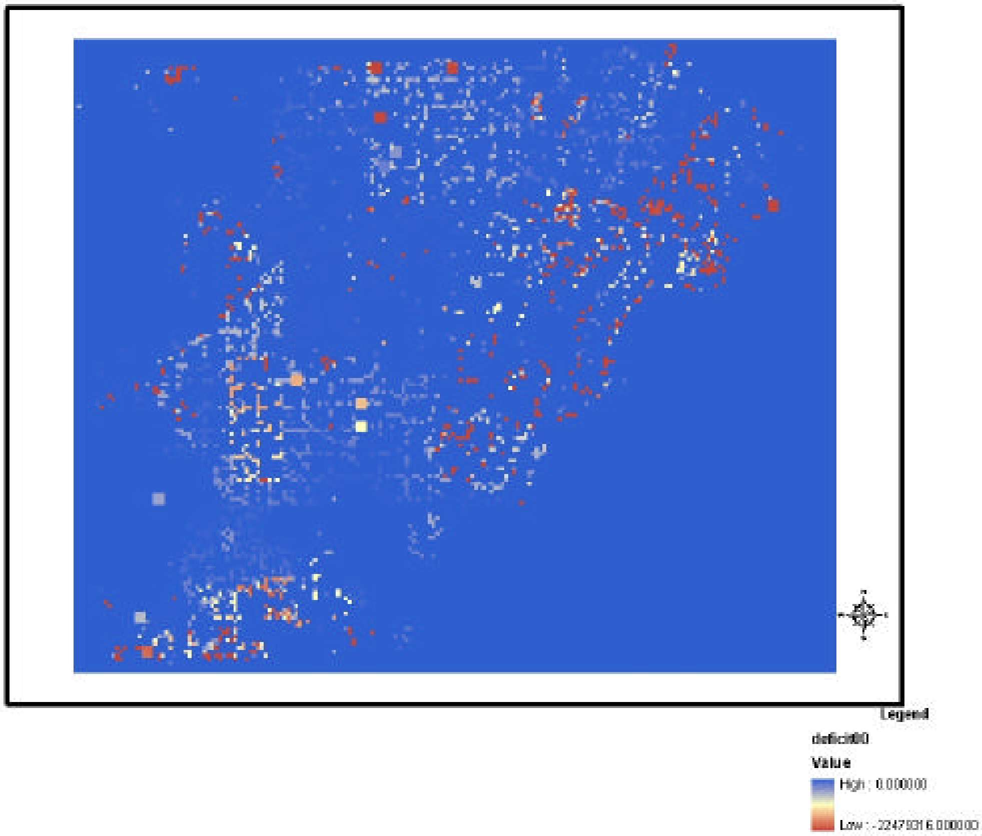

Figure 7. Groundwater deficit resulting from the base case scenario

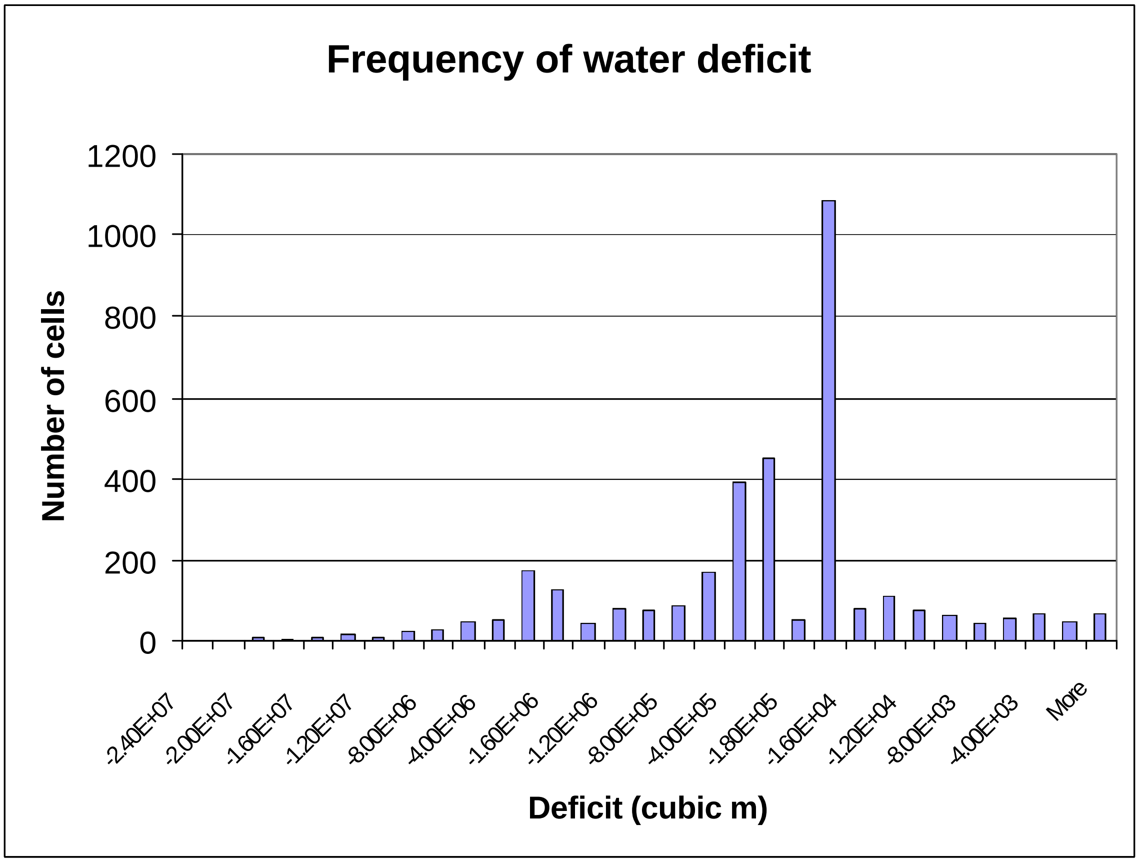

Figure 8. Cell distribution of water deficit resulting from base case scenario

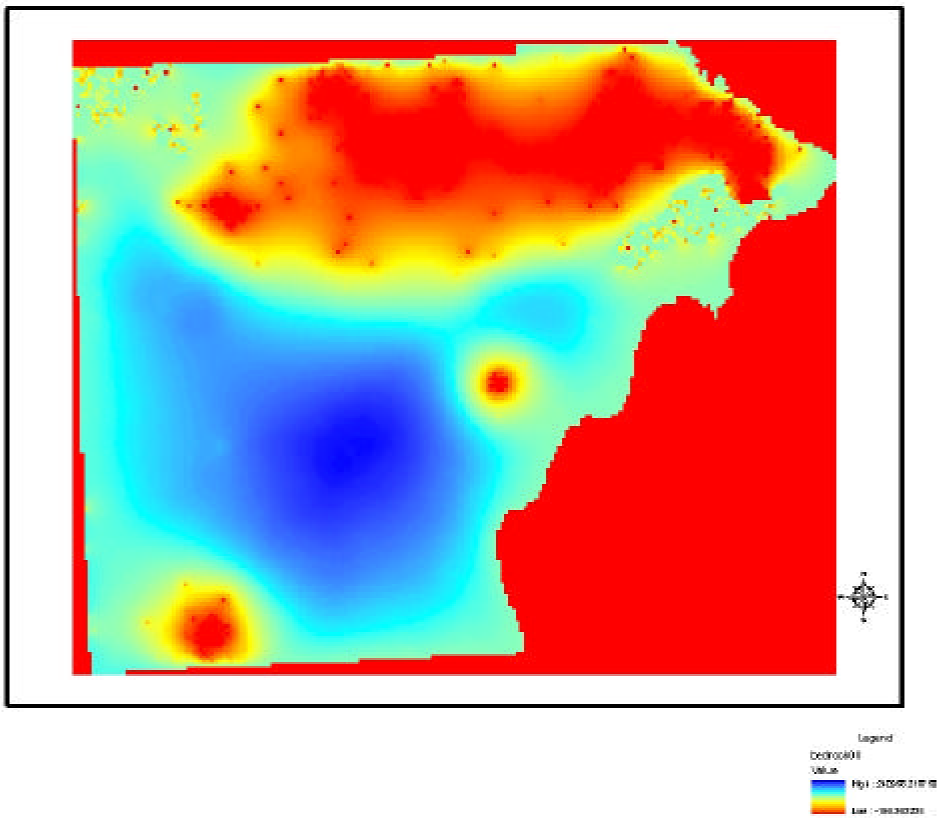

Figure 9. Groundwater volume (m^3) resulting from the minimum density zoning scenario

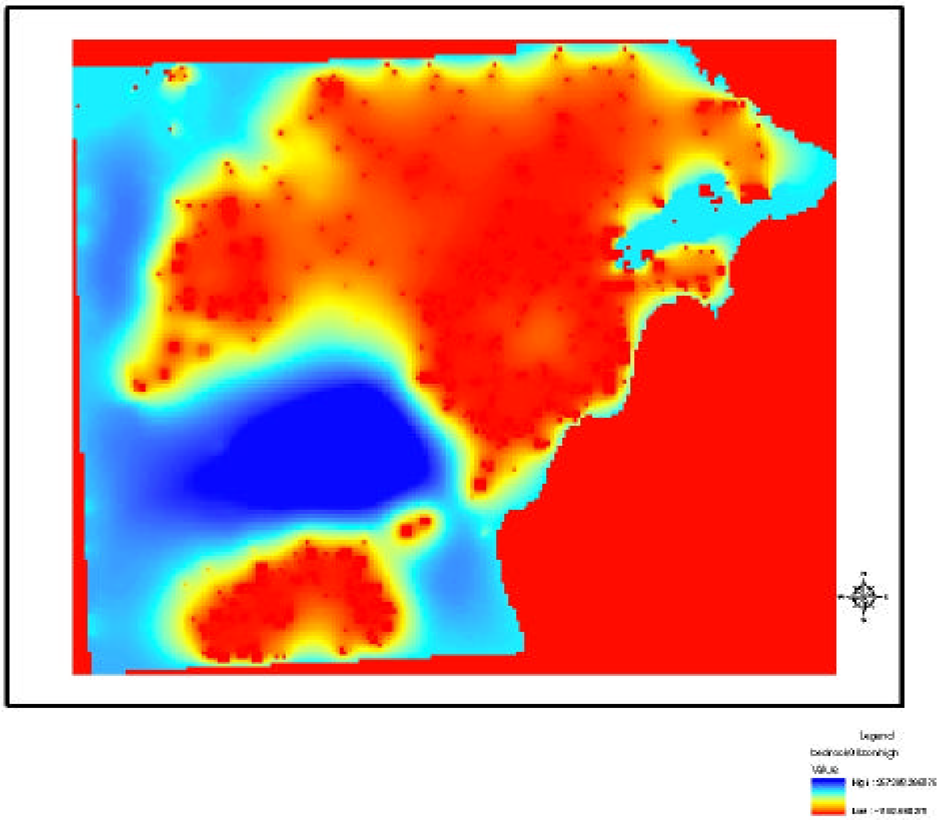

Figure 10. Groundwater volume (m^3) resulting from the maximum density zoning scenario

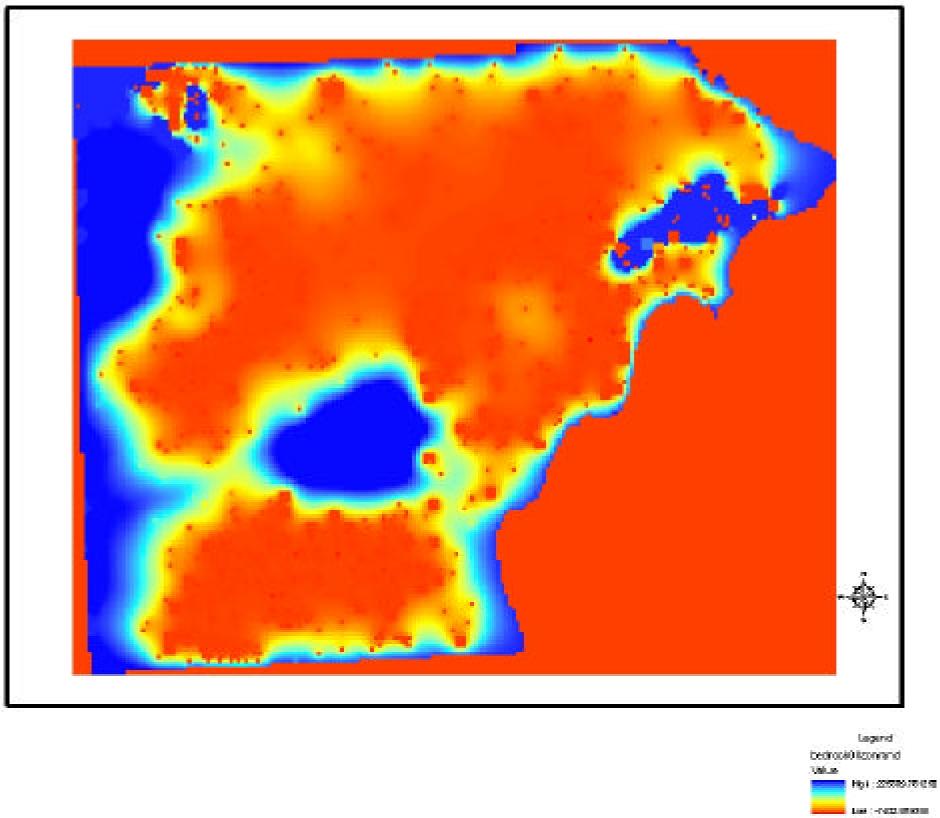

Figure 11. Groundwater volume (m^3) resulting from the random zoning scenario