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Examining the contradiction in 'sustainable urban growth': an example of groundwater sustainability

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The environmental planning literature proposes a set of 'best management practices' for urban development that assumes improvement in environmental quality as a result of specific urban patterns. These best management practices, however, often do not recognise finite biophysical limits and social impacts that urban patterns alone cannot overcome. To shed light on this debate, we explore the effects of different degrees of urban clustering on groundwater levels using a coupled land-use change and groundwater-flow model. Our simulations show that specific urban forms only slow down the impact on groundwater. As population increases, the pattern in which it is accommodated ceases to matter, and widespread depletion ensues. These results are predictable, yet current planning practice tends to take growth for granted and is reluctant to envision either no-growth scenarios or the prospect of depletion. We propose to use simulations such as those presented here to aid in policy discussions that allow decision makers to question the assumption of sustainable growth and suggest alternative forms of development.

Keywords: sustainable development; urban form; groundwater; agent-based modelling; MODFLOW

1. Introduction

In a recent discussion with a group of colleagues, the lead author was arguing that urban growth is unsustainable, that there is no way of making it sustainable, and that we should put this conversation on the table of the public policy arena. To the question of whether she was referring to population control, followed a clarifying response that the meaning of 'economic development' needs to be reformulated based on concepts other than a form of growth that encourages the use of more resources, either by attracting population to an area or by incentivising higher rates of consumption per capita. Perhaps, rather than assuming growth, planners should be more actively considering no-growth or reduction scenarios. Moreover, planning for growth sets the mechanisms in motion that are likely to encourage it, for example, by building excess water treatment capacity in anticipation of a growing population, so maybe we should not plan for it.[1] The response to this clarification was, "So it's not about *not* growing; it's about doing it in a *sustainable* manner". This

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response illustrates the great difficulty in coming to terms with the idea of economic development that does not involve urban growth, even though there is increasing evidence that growth may not be sustainable.

One politically acceptable way out of the growth/no-growth dilemma is proposing a set of 'best management practices' for urban development that assume improvement in environmental quality as a result of specific urban forms, as exemplified by New Urbanist ideas and its offshoots (Duany *et al*. 2000, Leccese and McCormick 2000, Gillham and Maclean 2001, Lincoln Institute of Land Policy 2001). Recent work, however, shows contradicting results that question the relation between urban form and environmental quality, and declares the need to qualify such statements with consideration of physical and ecological context, temporal and spatial scale, and interactions and processes (Alberti 1999, 2005, Neuman 2005, Jones *et al*. 2009). For example, when cities are already very compact, other environmental problems may arise due to congestion; therefore, further compact development is unlikely to make them sustainable (Chen *et al*. 2008, Jones *et al*. 2009). Such congestion-related problems are often the rationale for decentralisation and suburbanisation, but these patterns may bring about the very environmental challenges that New Urbanism is trying to address (Gordon and Richardson 1998, 2000, 2001).

Analysing the complex relations among the various factors affecting land-use is difficult (Buxton and Scheurer 2007). Adding to this difficulty is the complexity of impacts arising from land-use change and the lack of ways to measure these impacts in their full extent. For example, saving land is not a complete measure of a sustainable solution if cities are compact to start with (Chen *et al*. 2008) or the potential for expansion is limited (Jones *et al*. 2009). Although many environmental benefits of compact development have been claimed, few studies have actually measured the environmental impact of different urban forms. One example is a recent study of five cities in the UK that focuses on understanding the relations between densification and ecosystem function, with the aim of clarifying whether compact cities could include ecologically functional areas to counteract the effects of congestion (Tratalos *et al*. 2007). The results of this study show that environmental deterioration increases with density, although there is considerable variability. These results suggest that there is room for environmental improvement in dense areas, depending on how they are designed, i.e. there is significant sensitivity to context, thus reducing the likelihood that standardised practices such as compact development can be successfully applied in a broad range of situations. The authors, however, point out the challenge of measuring these relations and stress that several measures should be used.

In this paper, we attempt to further illuminate the debate about sustainable growth and sustainable urban forms using an integrated model of land-use change and groundwater flow (Reeves and Zellner 2010, Zellner and Reeves 2010). We examine groundwater depletion in response to various stylised forms of urban growth by applying the integrated model to generate urban simulations in different zoning scenarios. For each scenario, growth is assumed at a constant rate, but it is accommodated in different forms. The model computes several metrics to assess the impacts on groundwater levels and exposure to water deficit corresponding to each form. The integrated land-use/water use model, called WULUMOD, was designed to explore the potential effects of planning decisions on both urban patterns and groundwater sustainability, and to explicitly capture non-linear and potentially complex dynamics between residential development and groundwater availability. The integrated model accounts for the factors affecting changes in land-use, how these changes feed back into the groundwater system, and how the state of the groundwater system affects subsequent land-use decisions. The model was built using an agent-based representation of land-use and water consumption decisions based on WULUM (Zellner 2007), and the numerical representation of groundwater flow, based on MODFLOW (Harbaugh *et al.* 2000).

Agent-based modelling was chosen over other land-use modelling tools because our research question requires the explicit representation of drivers and behaviours originated in, and modified by, the interaction of heterogeneous landscapes and actors operating at different spatial and temporal scales. The explicit representation of socio-economic, policy and natural processes in space and time and the feedback mechanisms connecting them, makes agent-based modelling useful to examine the inevitable uncertainties in complex multi-dimensional systems that other methods have more difficulties in handling (Hoffman *et al.* 2003, Parker *et al.* 2003, Zellner 2007, 2008).

Agent-based models may also be categorized as extended cellular automata that require "mobile cells" (Batty, 2007), or as agent automata or geographic automata (Torrens and Benenson, 2005, Torrens, 2007), where cells can become mobile, have geographic functionality and affect others beyond their immediate neighborhood, and where objects can be created and located on these cells to interact with others on a geographic representation. MODFLOW was chosen to represent the hydrological component of the integrated model because it is one of the most widely used and established groundwater models in the scientific community (Provost *et al.* 2009). MODFLOW provides many options that allow users to simulate different hydrologic and environmental processes affecting groundwater flow. The integrated model, therefore, can allow planners, hydrologists, engineers and other stakeholders to analyse relations between the policies and decisions influencing development, local hydrogeology and regional groundwater resources.

We build on previous work in Monroe County, Michigan (Figure 1) to illustrate our argument (Reeves and Zellner 2010, Zellner and Reeves 2010). Our prior work focused on the potential and limitations of the modelling approach; herein we use the model to conduct controlled simulation experiments that would not be possible in real life. These simulations attempt to determine if there is such a thing as a sustainable urban form in light of increasing urbanisation by more clearly defining the relation between patterns of urbanisation and their environmental impacts on groundwater supply. Therefore the modelling scenarios are stylised and are not meant to be applied directly to Monroe County. The physical location for the modelling was selected so that the basic parameters of each component of the integrated model are realistic.

In the following sections we explain the components and mechanisms of WULUMOD, the various clustering scenarios that we used to test whether different urban patterns led to more or less sustainable groundwater dynamics, and the results from those scenarios. We conclude with a discussion of policy implications of the simulation results.

2. Model components and mechanisms

The details of WULUMOD are documented elsewhere (Zellner and Reeves 2010). We summarise here the basic mechanisms of the land-use model, the groundwater-flow model, and the integration of both models for clarity and interpretation of results. We also discuss the potential and limitations of our model to generate policy insights, and the applicability of these insights to other conditions and contexts.

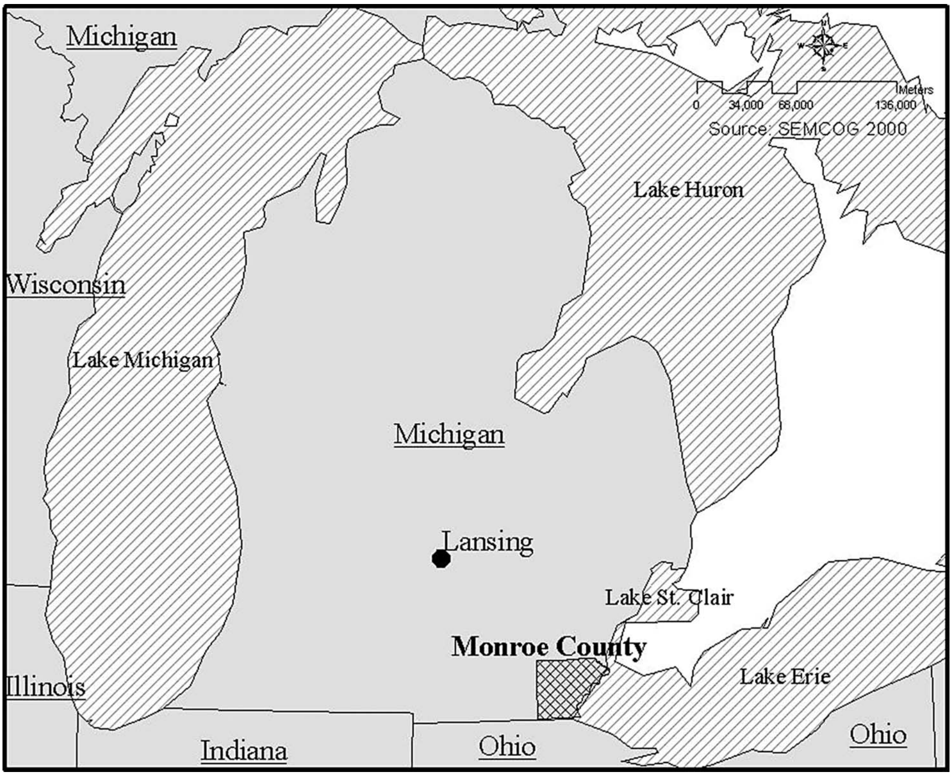

Figure 1. Monroe County, Michigan.

2.1. *Agent-based land-use model*

The agent-based land-use model was built in Java RePast.[2] The landscape in the model is a two-dimensional lattice composed of 200 × 166 identical cells representing 251 m × 251 m each (approximately 16 acres), covering the area of the county. Each cell starts out being a farm cell and each is assigned a number of natural, infrastructure and policy attributes. In this exercise we focus on zoning restrictions of residential density and distance to city centre. The agent-based model works by selecting groups of potential development sites at random at each time step of the land-use simulation. If a farm cell is selected, roads will account for 50% of the probability of land conversion to undeveloped, available for residential development, and surrounding development will account for the other 50%. In the absence of roads, the probability of conversion only depends on the adjacent development. Location decisions at one time thus affect subsequent directions of development, as adjacent development encourages the transition from farmland to residential development. Once a cell is designated as undeveloped, residents can move in, depending on their preferences for proximity to desired destinations and permitted development densities, as determined by the following hedonic utility equation:

$$U = \alpha_r \times r + \alpha_{dc} \times (1 - dc) + \alpha_{dn} \times (1 - dn) + \alpha_{ds} \times (1 - ds) + \alpha_z \times (1 - z) + \alpha_s \times s; \quad (1)$$

where:

α_r = residential preference for proximity to road;
r = cell presence of road (0 or 1);
α_{dc} = residential preference for distance to city;
dc = cell normalised distance to city (between 0 and 1);
α_{dn} = residential preference for distance to natural area;
dn = cell normalised distance to natural area (between 0 and 1);
α_{ds} = residential preference for distance to school (between 0 and 1);
ds = cell normalised distance to school (between 0 and 1);
α_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);
α_s = residential preference for either sewer coverage or septic soil;
s = cell presence of either sewer coverage or septic soil (0 or 1).

In the real system, municipal water and wastewater treatment is available to residents in parts of the county. However, to isolate the effects of development on groundwater levels, and understand how they are indirectly influenced by zoning and behavioural feedback, in our simulations below all residents depend on individual wells. As residents locate on the lattice, they extract water from the aquifer. It is assumed that wastewater will be returned to the glacial deposits that overlie the bedrock aquifer, and its effect is simulated as a boundary condition on the bedrock aquifer (see next section for details).

Each time step represents one year, and the model uses annual rates of residential growth, location preferences and groundwater consumption based on surveys, literature values and expert knowledge about the area (Nicholas *et al.* 1996, 2001, University of Michigan 2001, Maniko 2004, Reeves *et al.* 2004, Monroe County Planning Department and Commission 2004a, 2004b). More details regarding model calibration and application can be found in Zellner (2007) and Zellner and Reeves (2010).

2.2. Groundwater-flow model

MODFLOW-2000 (Harbaugh *et al.* 2000) was used to develop a regional groundwater-flow model for the bedrock aquifers in the area around Monroe County, Michigan (Reeves *et al.* 2004). This finite difference model has 10 layers, 297 rows, and 194 columns of cells, and there are approximately 400,000 active cells in the model. It is used to approximate the groundwater flow equation (Harbaugh *et al.* 2000):

$$S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W. \qquad (2)$$

Where:

S_s = the specific storage of the porous media (L^{-1});
h = the potentiometric head (L);

K_{xx}, K_{yy}, K_{zz} = the values of hydraulic conductivity in the x, y, and z co-ordinate directions which are assumed to be parallel to the major axes of the hydraulic conductivity tensor (L/T);

t = time; and

W = volumetric flux of water per unit volume into or out of the system from external sources or sinks (T-1).

Details of the application of MODFLOW to the region including Monroe County are given by Reeves *et al.* (2004). The finite-difference grid has non-uniform spacing and thickness, and the most refined cells are approximately 123 m $\times$ 123 m. The grid is roughly aligned with the strike of the bedrock units (Figure 2), and each of the bedrock units is modeled using two numerical layers. The overlying glacial deposits are modeled using the General Head Boundary package (Harbaugh *et al.* 2000) to

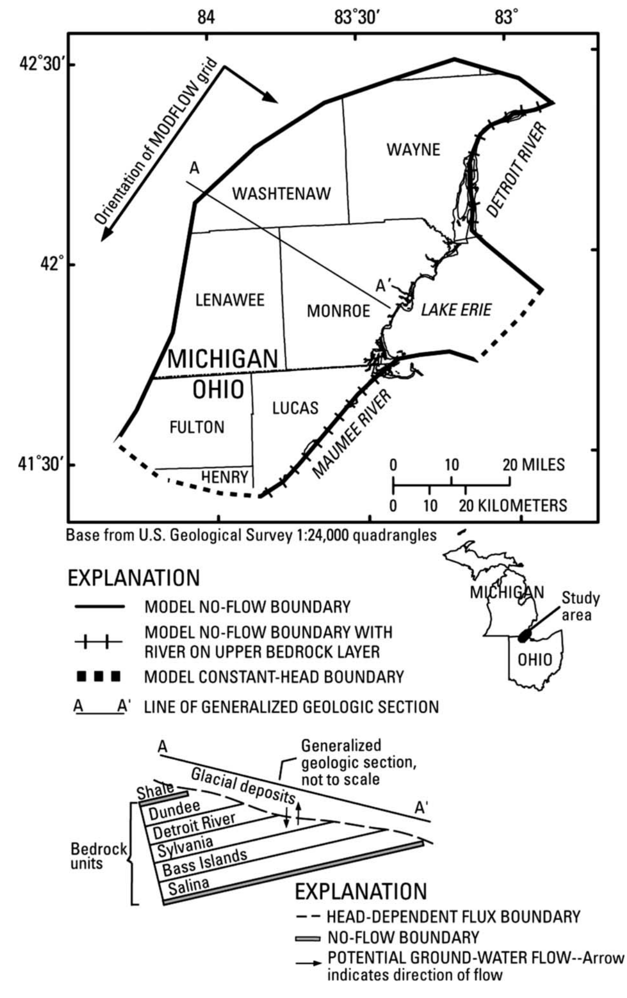

Figure 2. Model extent and boundary conditions for regional MODFLOW for Monroe County, Michigan.
Source: Reeves *et al.* (2004).

allow for exchange of water between the bedrock aquifers and glacial deposits. The bottom boundary of the model is set to no flow at an estimated depth for a shale layer within the Salina Group. The western boundary is a no-flow boundary because of the presence of dense saline water in these bedrock units. The northeastern and southeastern boundaries are set as no-flow boundaries at depth with the upper cells set as river cells to simulate interaction of the bedrock aquifers with the Maumee and Detroit Rivers. Lake Erie is represented through a general-head boundary near the coast and for some distance into the lake and by a constant-head boundary at the extent of the grid. Constant-head boundaries were used for the remaining numerical boundaries (Figure 2). Recharge to the bedrock aquifer occurs throughout the model as leakage from the overlying glacial deposits as conceptualised through the General Head Boundary package. Inherent in this conceptualisation is the assumption that groundwater levels within the glacial deposits are unaffected by development. As development occurs in the test simulations, leakage in the system will follow the observed pattern from initially upwards leakage from the bedrock aquifers to glacial deposits to downwards leakage from the glacial deposits to the bedrock aquifer in areas of development (Reeves *et al.*, 2004). The assumption that the groundwater levels in the glacial deposits are constant makes these simulations conservative in the estimate of the impact of develop on bedrock groundwater levels and focuses the analysis on the aquifer of interest. With this conceptualisation, the leakage rate depends on the water levels in the bedrock aquifers and overlying glacial deposits and the hydraulic properties of the system. The aquifer system in Monroe County also receives lateral flow from recharge areas outside of the county. MODFLOW produces estimates of hydraulic heads (groundwater levels), groundwater fluxes to boundaries and sinks within the model, and a mass balance accounting of groundwater in the system. Any of these measures could potentially be used to access the effect of development on groundwater resources, although in this work we focus on the effect on groundwater levels only.

2.3. Coupled land-use/groundwater-flow model

The land-use planning and groundwater-flow models are coupled by the exchange of data between the models using input and output files. The overlapping grids from the two models are mapped to each other to account for variations in cell size and orientation (Reeves and Zellner, 2010). This approach to link the two components allows other MODFLOW models to be used in future applications with different agent-based grids. For each time step of the simulation, the land-use model simulates first land-use changes and new water use is estimated wherever residents are located. The land-use model then creates a file with this information that is an input to MODFLOW. MODFLOW then simulates new hydraulic heads (groundwater levels) in response to the change in water use or other imposed external changes (for more details on this integration, see Reeves and Zellner 2010 and Zellner and Reeves 2010). As the integrated model runs, it collects land-use data and groundwater deficit values for each cell within the study area. For the purpose of this study, groundwater deficit is defined as a drawdown of 6.10 m ($\sim$20 ft) relative to the initial groundwater levels (or hydraulic heads). Residents and cells are considered exposed to deficit when the cell is in deficit for 30 time-steps or more in a 100- or 200-time-step simulation. This drawdown was chosen to allow for some development without triggering deficit while indicating a point where residential wells may experience problems because groundwater levels may fall below pump intakes or poor-quality water at depth may migrate towards the pumping wells.

Depending on the degree of coupling of the model, information regarding the changes in groundwater levels is fed back into the land-use decision making of the following time step. To allow for this feedback, the residents' utility function (1) is modified to account for water scarcity in the form of a cost for lifting water from a well; this feedback is made active in some of the scenarios in this paper. The greater the lift of water in a cell, the greater the cost and the greater the reduction in utility that a resident could derive from that cell. Greater lift also implies greater risk that groundwater levels will fall below pump settings causing the residential well to 'go dry'. In the specific case of Monroe County, greater lift also may imply greater potential for poor quality water to migrate to the well. The lift is computed as the distance between the current hydraulic head and the elevation of the cell, divided by the maximum lift in the region in order to normalise the value between 0 and 1. Given this value, the utility of the cell may be reduced accordingly. The following term, then, is added to equation (1):

$$u = (1 - l) \times \alpha_{\mathrm{MW}}; \qquad (3)$$

where:

α_{MW} = residential awareness of water scarcity;
l = normalised lift (between 0 and 1).

The feedback mechanism is active when residents' preference for water (α_{MW}) is set to 1, so that the state of the aquifer feeds back into decision making. When residents' α_{MW} is set to 0, the MODFLOW component computes aquifer responses to land-use stresses for each time step, but groundwater levels do not affect location decisions. We test different zoning scenarios using these two levels of feedback to gain insights into the effects of the policy and behavioural variables on the resulting urbanisation patterns and, consequently, on groundwater sustainability.

2.4. Model limitations and use of models as metaphors

The specific models used in this analysis provide a physical basis for the hydrogeologic parameters and decision variables, but use of these models imposes some limitations on the results and their extrapolation to other contexts. Every model has inherent assumptions; for example, the groundwater level in the glacial deposits in the groundwater-flow model is assumed to remain constant: it is not affected by pumping, by how much water is returned to the glacial deposits by users through septic systems or by changes in runoff caused by development. Essentially, our simulation results are conservative because recharge to the bedrock aquifer is guaranteed and the potential for recharge is unaffected by development or extraction. The simulated response of groundwater levels in the bedrock aquifer will change, i.e. will be more severe, if this assumption is relaxed and groundwater levels in glacial deposits are included in the simulation. In the same way, coefficients in the utility equation (1) are derived from local data (see above) and may be different over time and in other regions. We use the site-specific models to provide a realistic physical and socio-economic basis for the suite of synthetic simulations presented below. This basis allows the results to be interpreted and questions posed regarding the factors that affect sustainability. In this way, the specific models are meant to serve as metaphors that illustrate general relations between development and groundwater resources and allow users to explore the complexity of the system (Holland 1998, Zellner 2008). Planners, engineers, hydrologists and other stakeholders could use similar integrated models to explore specific locations by applying the same modelling principles, and adapting them to reflect the data and assumption appropriate to the specific situation analysed. We expect that similar basic behaviours observed in our simulations below would be obtained, even if the specific timing or spatial patterns differed.

3. Scenarios and simulation results

All simulations started with agricultural cells that could potentially be converted for residential development, depending on both landscape conditions and residential preferences, as described in the previous section. In order to test whether the effects of urbanisation patterns on groundwater level change over time, we ran a set of simulations for 100 time steps and a second set for 200 time steps. We thereby used a short-term and a long-term time frame to assess if the relation between urban form and groundwater depletion patterns would hold over time as growth continued. The growth rate remained fixed at 1000 residents (households, assumed to be composed of several people) per time step for all scenarios. This rate is based on County data (Monroe County Planning Department and Commission, 2004a, 2004b, Zellner, 2007). To gain a sense of the range of possible outcomes given the random sampling of cells for residential location, each scenario was run 10 times and the results averaged for residential development and drawdown. These distributions were then used to determine statistically significant differences across scenarios, which are indicated for the simulations below.

Table 1 lists the default WULUMOD parameter values. We only varied zoning restrictions so that in all scenarios the total area designated for high density was the same, but only the layout differed. We matched the location of urban centres with the centre of the areas designated for high-density (Figure 3). Road density was also maximised in these areas. The purpose was to force the urbanisation pattern into clusters of different sizes through land-use policies and transportation infrastructure

Table 1. Default Parameter Values for WULUMOD runs.

Parameter	Default value
Size of grid	200 by 166
Surface of each cell	63,000 m^2 ($\sim$16 acres)
Initial land-use	Farms
Initial groundwater levels	Presettlement conditions in Monroe County
Roads	1 in high-density areas, 0 otherwise
Residential zoning	311 in high-density cells, 0 otherwise
Proximity to cities	Between 0 and 1, following high-density centres
Transition rate to undeveloped	81
Residents per time step	1000
Residential preference for all factors	Between 0 and 1, Monroe Co.' s population
Residential awareness of water cost	0
Residential water use	1.04 m^3/(day/resident)

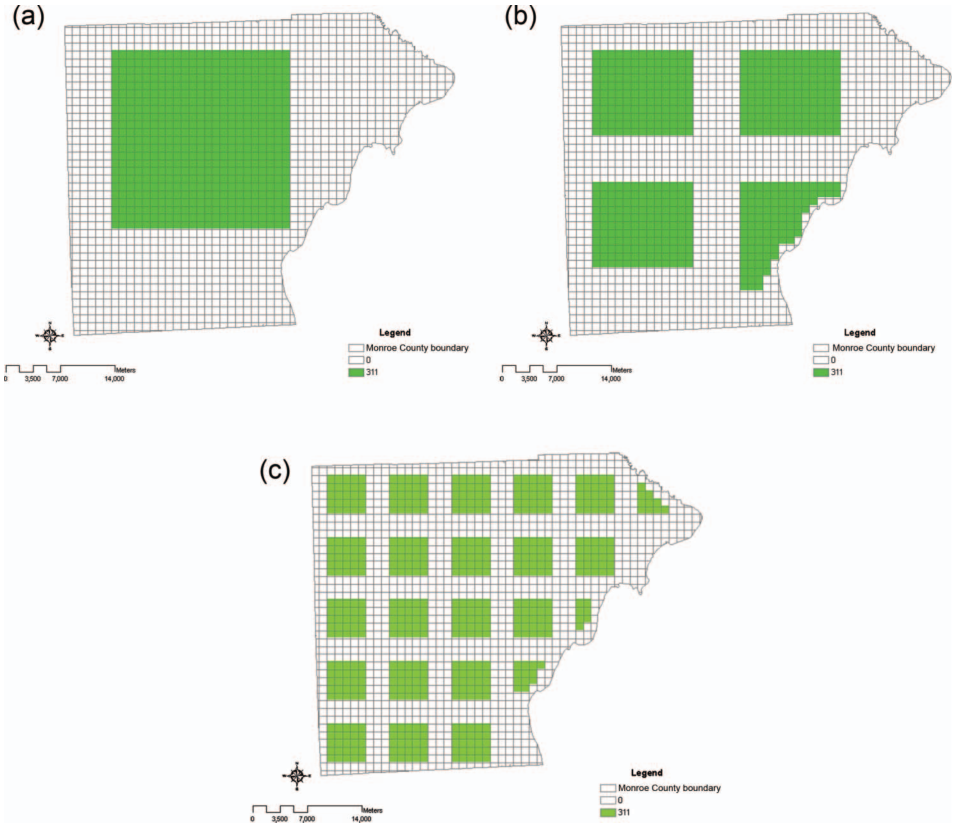

Figure 3. Zoning inputs for: (a) large cluster zoning; (b) medium cluster zoning; and (c) small cluster zoning (shaded area = high-density zoning of 311 residents/cell).

because these factors are under the influence of planning decisions. Initial groundwater levels are those for presettlement conditions (Reeves *et al*. 2004). In the following subsections we discuss the modelling results in terms of development and impacts on groundwater levels.

3.1. Short-term impacts

We first examine the effects of different forms of clustering over 100 time steps (Figures 4 to 6, Table 2). We observe that with no feedback of groundwater levels on residential location decisions, there are no significant differences for number of residents in deficit among the three scenarios (Table 2). In terms of residential area in deficit (as indicated by the number of residential cells in deficit in Table 2), there was very little difference between large and medium clustering, but both had less area in deficit than small clustering. The aggregate values only show how many residential cells are exposed to deficit, but histograms of the distribution of drawdown for all cells provide a different perspective of the impact of different land-use patterns (Figure 6). The histograms confirm the finding that small clustering fares worse than medium clustering because more cells experience large drawdowns. As development concentrates in larger clusters, there are cells with even larger drawdowns, but they

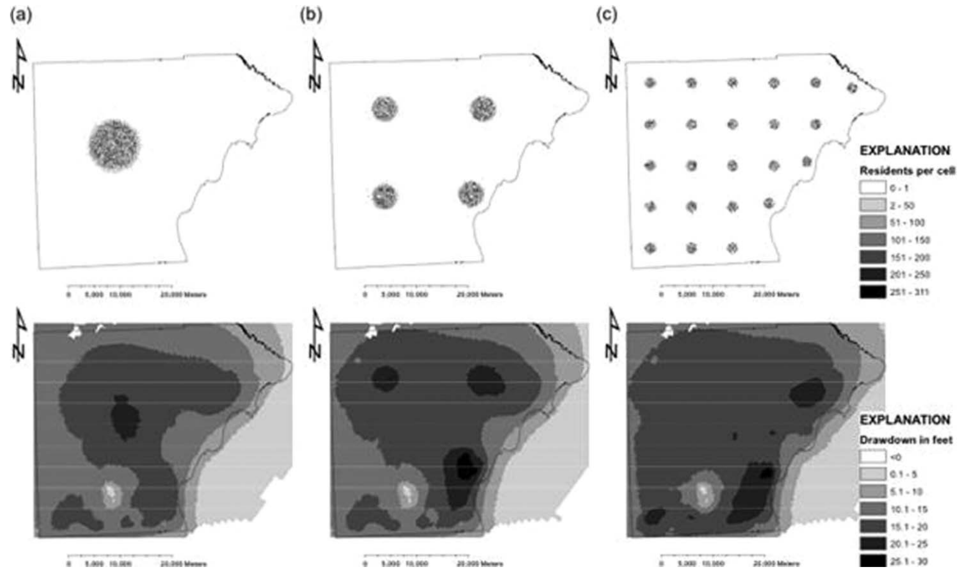

Figure 4. Residential development (top row) and drawdown (bottom row) for (a) large, (b) medium, and (c) small clustering, T = 100, no feedback, averaged over 10 simulations.

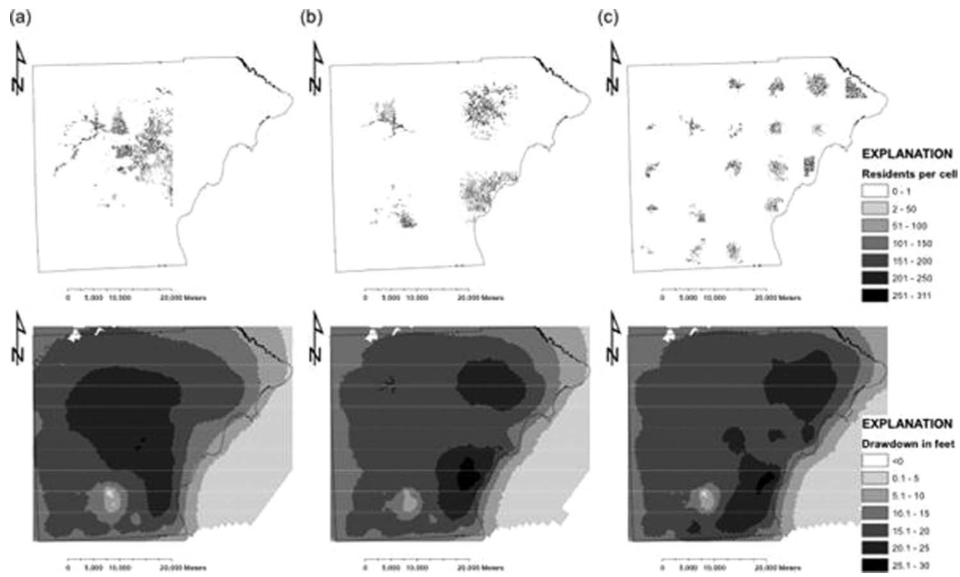

Figure 5. Residential development (top row) and drawdown (bottom row) for (a) large, (b) medium, and (c) small clustering, T = 100, with feedback, averaged over 10 simulations.

are fewer in number. Large clustering may be the best scenario of all three because even though some cells have larger drawdowns, the effect is localised to fewer cells. These results are also reflected in the drawdown maps, showing large drawdown concentrated in one area for a single large cluster and distributed drawdown areas for medium and small clusters (Figure 4). This would imply that concentrating

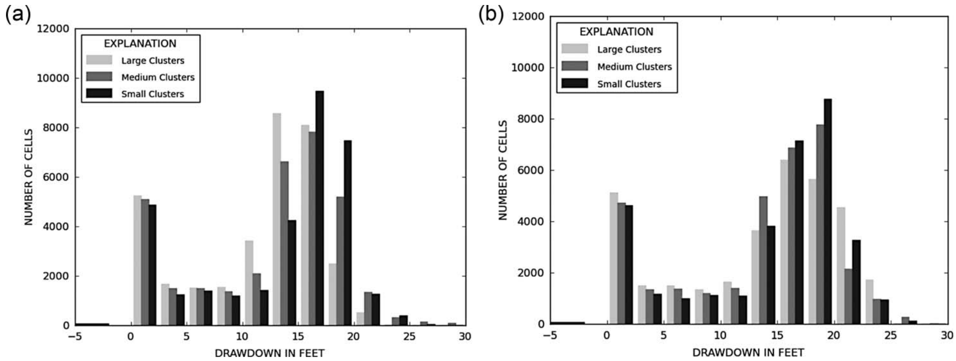

Figure 6. Distribution of drawdowns for all clustering scenarios (a) no feedback and (b) with feedback,T = 100, averaged over 10 runs.

Table 2. Aggregate results for T = 100, averaged over 10 runs (T = simulation length, α_{MW} = residential awareness of water scarcity, SD = Standard Deviation).

Cluster Zoning	α_{MW}	Residents	SD	Residents in deficit*	SD	Residential cells	SD	Residential cells in deficit*	SD
Large	0	99,000	0	70,000	0	456	8.71	456	8.71
	1	99,000	0	70,000	0	508	4.40	508	4.40
Medium	0	99,000	0	70,000	0	458	7.61	458	7.61
	1	99,000	0	69,471	295.04	561	8.71	558	9.10
Small	0	99,000	0	70,000.0	0	468	11.84	468	11.84
	1	99,000	0	69,851	205.49	497	9.77	496	9.35

Note: *Residents and cells in deficit are those that have experienced 30 time steps or more of drawdowns in excess of 20 feet.

population in fewer large clusters would be more beneficial than dispersing it in a greater number of small clusters, even if these small clusters are densely developed.

The differences in the simulated water deficit results are less pronounced when information on groundwater levels feed back into location decisions, but the distribution of drawdown remains similar (Figure 5). In terms of population facing deficit, large clusters are now the worst scenario, followed by small clusters and finally by medium-sized clusters (Table 2). In terms of residential area exposed to deficit, medium-sized clusters are the worst, followed by large clustering, and then by small clustering. These results contrast with those generated when groundwater levels do not feed back to agent development decisions. As resident agents interact with environmental information, they respond to prior development and groundwater-level declines and may locate in patterns that do not follow the order imposed by zoning (Figure 5). As these patterns become dispersed – in this case, as a response to the external costs that agents impose on their neighbours when they draw groundwater levels down – some of the gains in concentrating high density development are lost. The higher concentration of agents located in large clusters cause a greater drawdown in their immediate neighbourhoods, greatly reducing the utility that agents derive from these locations, causing new agents to disperse more. Because the dispersion is limited to a central large cluster, residents are in a way trapped where drawdowns occur, so the population affected is greater than in other scenarios (Table 2). As pressure is relieved into a few more areas of medium size, the interference with other agents is reduced, so that fewer agents are affected, but the area affected is larger as resident agents have more options for location. In the tested scenarios, this relation is non-linear. Increasing the number of areas with high-density development by zoning for small clusters leads to a greater number of residents in deficit compared to medium clustering, but the larger concentrations of population in medium- to large-clusters causes greater interference in larger areas. Dispersing development into a greater number of smaller clusters relieves the pressure on the aquifer as residents extend over a larger area (Table 2, Figure 5 and Figure 6).

3.2. Long-term impacts

We ran simulations for the same zoning and behavioural scenarios as above, but over 200 time steps to examine if the relation we observed between development patterns and groundwater drawdown in the short term held as urbanisation progressed (Figures 7 to 9, Table 3). In the scenarios without feedback from groundwater levels to the agent, the only significant difference was observed in the area in deficit. The area was larger in the small clustering scenario than in the large clustering scenario (Figure 7, Table 3), a result similar to the one obtained with shorter simulation times. The distribution of drawdowns (Figure 9) confirms that small clustering leads to more severe impacts than medium clustering because many more cells have large drawdowns, even though in medium clusters there are a few that have more extreme drawdowns. This is again understandable, since the clusters are larger, but there are fewer of them. The large clustering scenario shows a shift towards more cells with less drawdown and is more benign than the other scenarios.

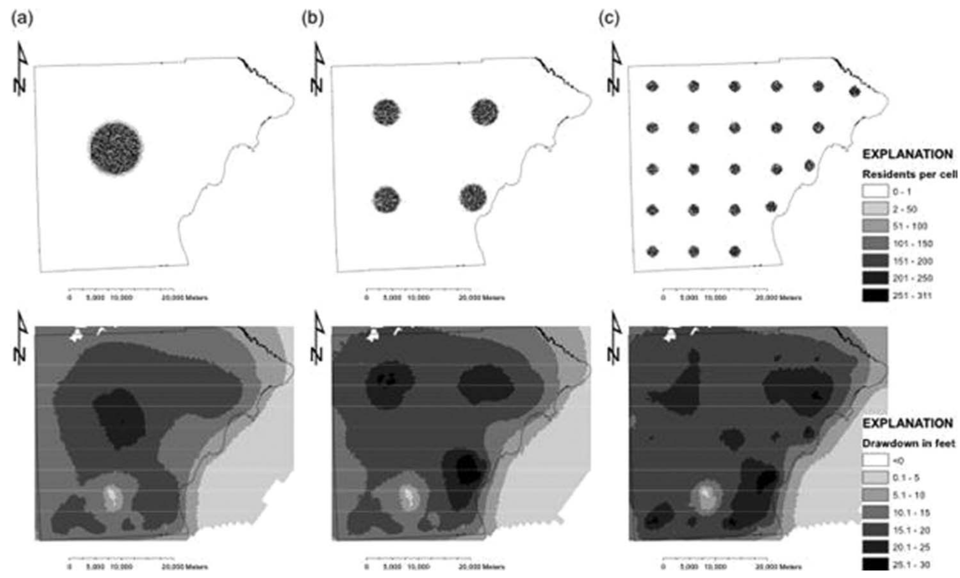

Figure 7. Residential development (top row) and drawdown (bottom row) for (a) large, (b) medium, and (c) small clustering, T = 200, no feedback, averaged over 10 simulations.

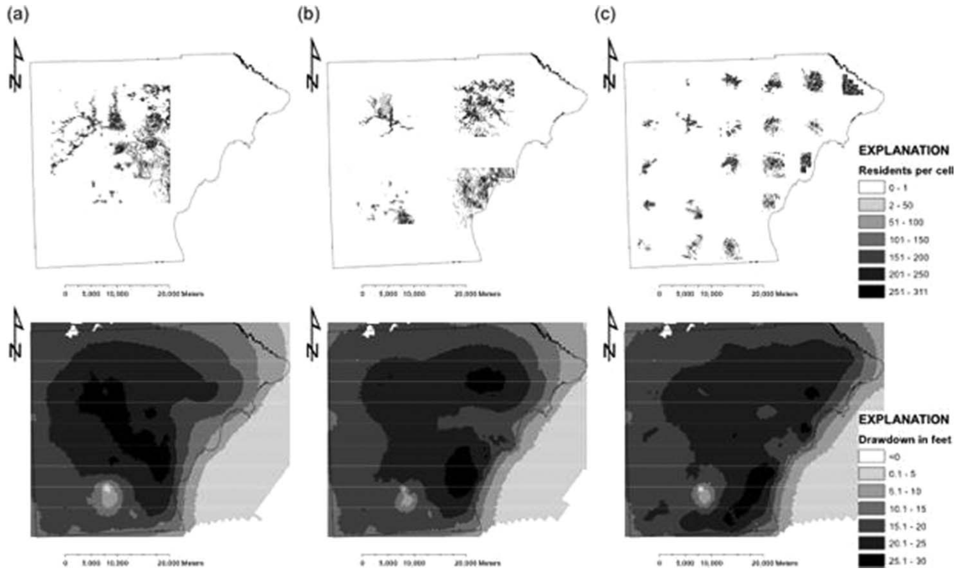

Figure 8. Residential development (top row) and drawdown (bottom row) for (a) large, (b) medium, and (c) small clustering, T = 200, with feedback, averaged over 10 simulations.

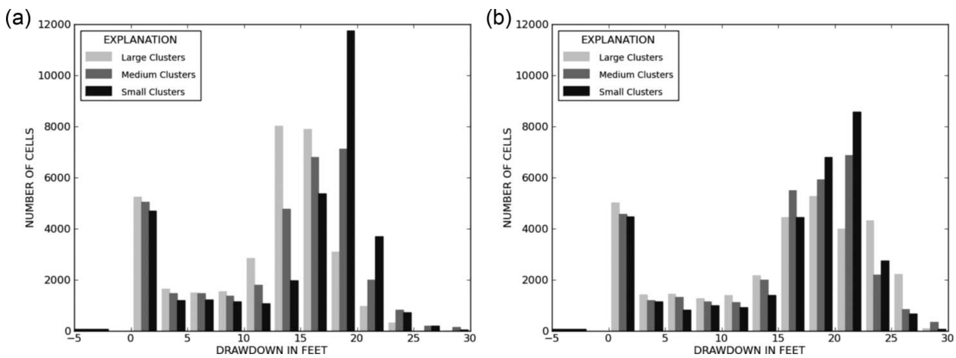

Figure 9. Distribution of drawdowns for all clustering scenarios (a) no feedback and (b) with feedback, T = 200, averaged over 10 runs.

The relation between urban form and impact when feedback is active is also maintained over time in terms of population exposed to deficit (Table 3). We again see a non-linear relation where medium-sized clustering is slightly better than either extreme, but here the difference between medium and small clustering is less pronounced. In other words, as population is added to the area, the benefits of the 'sweet spot' of mid-sized clustering indicated in the short-term simulations are lost. Large clustering now has the least residential area in deficit, followed by small- and then medium-sized clusters. The alleviation of deficit through greater population of dispersal is lost as population increases over time, so that clustering into larger areas becomes more effective in containing the impact over a smaller area, much like in the scenarios with no feedback, even though this concentration exposes a larger population to water deficit (Table 3, Figure 8). Looking at the distribution of

Table 3. Aggregate results for T = 200, averaged over 10 runs (T = simulation length, α_{MW} = residential awareness of water scarcity, SD = Standard Deviation).

Cluster Zoning	α_{MW}	Residents	SD	Residents in deficit	SD	Residential cells	SD	Residential cells in deficit	SD
Large	0	199,000	0	170,000	0	870	6.94	870	6.94
	1	199,000	0	170,000	0	1011	9.62	1011	9.62
Medium	0	199,000	0	170,000	0	874	11.66	874	11.66
	1	199,000	0	169,895	172.46	1137	18.96	1136	18.40
Small	0	199,000	0	170,000	0	880	15.19	880	15.19
	1	199,000	0	169,969	98.35	1048	21.03	1047	21.12

Note: *Residents and cells in deficit are those that have experienced 30 time steps or more of drawdowns in excess of 20 feet.

drawdown (Figure 9), smaller clusters seem to have a slightly worse effect than medium clusters, which concentrate larger drawdowns in fewer cells. However, in the medium clustering there are more cells with smaller drawdowns. With large clusters, there are again more cells with more extreme drawdowns, but also more cells remain relatively unaffected. The three scenarios become more similar, however, with larger populations and with the effects of groundwater depletion feed back into location decisions.

4. Policy implications

The simulations suggest that there are no differences in the effects of urban form on the total population affected by groundwater drawdown caused by residential development. Moreover, a large proportion was affected in a short term to start with (note that the way that deficit is measured – as agents experiencing 30 or more time steps of deficit – excludes the last 30,000 agents from the computation). In terms of area affected, however, concentrating development in a large cluster resulted in smaller areas affected by drawdown. The implication is that large cities might be more sustainable than smaller neighbourhoods, no matter how dense the small clusters might be. Moreover, extreme low densities may be more desirable than concentrating development in small clusters (Zellner and Reeves 2010) since it reduces the overall load on the aquifer and distributes the impact, thus reducing the interference among residents. If higher populations are to be sustained because of other environmental considerations (e.g. energy use, transportation), large clusters should be favoured over small clustered neighbourhoods. This layout, however, does not ensure water sustainability – quite the contrary. The population is still exposed to drawdown and the greater the population, the greater the problem. The same applies to other environmental dimensions, as the concentration of pollutant emissions, for example, increases with the concentration of people.

As soon as environmental information feeds back into location decisions, the relation between urban form and water levels becomes less clear-cut. Concentrating residential development in smaller clusters seems to have more benign impacts on the aquifer as pressure is alleviated with greater dispersion of the population. Over time, however, this distinction becomes less clear. All measures of deficit increase, i.e. the benefits of spreading development are only temporary, and beyond a certain load on the aquifer urban form does not matter. Note that these scenarios assume that all residents obtain water through individual wells. At some level of density, communities typically shift to municipal supplies. The stress on the aquifer, however, may not be decreased if the community supply relies on groundwater. The effect, however, could be approximated to the large clustering scenario, where the groundwater withdrawals are concentrated in a smaller area.

In sum, urban form matters to some degree for the sustainability of groundwater, but its influence decreases with increasing population and complexity. These results apply to the hydrogeologic conditions for the model area, yet we expect that different aquifer configurations would give similar results in terms of overall patterns, even if the timing and details of the response might differ. Furthermore, our simulations likely underestimate the effect of development on groundwater levels because we assume great potential for recharge by leakage to the bedrock aquifer from an infinite source, coming both from glacial deposits and lateral flow. While the recharge through treated wastewater is not explicitly represented in the glacial dynamics of our model, the resulting increase in glacial hydraulic heads would be partially offset by the impact of development, which is currently not accounted for in the model. Additionally, even if all the water extracted were to be returned, in practice it can never be at a rate equal to extraction. Not only are there inefficiencies, i.e. water losses, whether human-induced or not, but there are also time lags caused by the inherent limitations of conductivity of both the glacial deposits and the underlying bedrock aquifer, so that rates of withdrawal are higher than rates at which the aquifer can be recharged. Our conservative assumptions, therefore, strengthen our argument about the unsustainability of urban growth. In other words, even under benign development conditions, the county would face depletion with continued growth. While water conservation could partly compensate for this effect, it would only signify a delay in the need for some other action, which becomes more costly once land is developed for residential use. The bottom line is that beyond a certain point, urban growth that is dependent on local groundwater supply is not sustainable, no matter what form it takes. Where this point is depends on the specific biophysical characteristics of the aquifer and the decisions on groundwater associated to specific land-uses, but perhaps finding this point is less important than understanding that it exists. New definitions of development are needed that are based on factors other than growth. We hope that tools such as the ones presented here can help planners and stakeholders engage in the difficult – yet inevitable – discussion of no-growth or reduction planning, and ultimately make decisions with a fuller understanding of the tradeoffs involved.

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Notes

1. While there is recent interest in shrinking cities (one notable example being Flint, Michigan), these processes arise from economic crises, rather than economic growth. It would be worthwhile, however, to study how being proactive and creative about stopping

growth could be far less traumatic and wasteful than having to shrink after expanding in excess.

2. http://repast.sourceforge.net/index.php

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