Simulating urban growth in Mashad City, Iran through the SLEUTH model (UGM)

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Introduction

Throughout the world, urban growth both in population and spatial extent has led to alterations of the landscape. Human settlements have affected natural cover and in this way have altered the structure and function of ecosystems. In the last 200 years, while the world population has increased six times, the urban population has multiplied 100 times (Stalker, 2000). As a developing country, Iran is now witnessing an almost continual large-scale urbanization. It is occurring in a few big cities such as Tehran, Mashad, Tabriz and Esfahan. The proportion of urban population to total population of Iran in 1976 was 47% and this ratio reached 61% in 1996 (Fanni, 2006). The number of towns and cities has also increased significantly, such that a total of 199 towns in 1956 reached 825 in 2001 (Nimrozi, 2007). As the second largest city in Iran, Mashad has witnessed similarly rapid growth both in extent and population in the last two decades, mostly because of its economic, social and religious attractions (Rafiee, 2007). According to national censuses, Mashad’s population has increased from 668,000 in 1956 to two million in 2006 and at present its population comprises about 5% of Iran’s urban total (Statistical Organization of Iran, Accessed 2007).

With this rapid growth, cities exert a heavy pressure on lands and resources at their periphery (Leao et al., 2004). In the decision-making process, land managers need to carefully consider the changes brought about by urban sprawl. Land cover and land use change models are useful tools to analyze, understand and predict land cover changes and their consequences. Land use change models are also tools for understanding the causes and consequences of land use dynamics. Using these models, policy makers can analyze different scenarios of land use and land cover change and evaluate their effects, so models can support land use planning and policy (Veldkamp and Lambin, 2001). Urban modeling was started in the late 1950s and now a number of analytical and statistical urban models have been developed that are based on diverse theories such as urban geometry and size relationships between cities and economic functions. Some of these models explain urban growth patterns, instead of predicting future urban growth, so for understanding the spatial consequences of urban growth, a dynamic modeling approach is preferred and have been used more often (e.g. Batty and Xie, 1994; Wu, 1996; Clarke et al.,...
Among all documented dynamic models, cellular automata (CA) probably are the most impressive in urban growth modeling in terms of their flexibility, their simplicity in application, their close ties to remote sensing data and geographic information system (Clarke et al., 1997). CA are discrete and dynamic systems. Their behavior is totally specified in terms of the location relationships. The space is organized as a uniform grid (an array of cells), and each cell can be in one of a finite number of possible states. The state of each cell is updated in a discrete time step based on local and identical transition rules and status of the cells in the neighborhood (Takayama and Couclelis, 1997). CA was originally proposed by Ulam and Von Neumann in the 1940s to provide a framework for investigating the behavior of complex and extended systems. CA refers to cellular space as the framework of analysis and automata concerns the self-organizing behavior of the cells (Torrens, 2000).

An elementary CA is composed of four components (Torrens, 2000):
- Cell space represented by an array of cells, these cells may be in any geometric shape
- A number of finite states that qualifies the state of each cell
- Neighborhood
- Transition functions, which define the next state of the cell in the next time period, based on the given state of the cell itself and its neighborhood cells.

The application of CA in geographical modeling was originally proposed by Tobler (1979). CA has become the most widely used approach in urban study since 1980s. Batty is one of the pioneers who developed a simple framework of CA in urban modeling (Batty et al., 1989) and later he presented a class of urban models called DUEM. The dynamics of DUEM are based on theories of development associated with CA, with fine-grained data, and the simulation of the model requires software which can handle an enormous array of spatial and temporal model outputs (Batty et al., 1999). The first attempt at a real simulation and prediction of urban growth was carried out in the early 1990s by White and Engelen (1993). A few years later, Engelen et al. (1995) developed the Island model which involved some advances in the first model. Another application of CA in forecasting and simulation of urban growth was an urban growth model of San Francisco Bay Area (Clarke et al., 1997). Wu (1998) offered a model that also involved a decision-making user-defined interface to reveal the outcome of the model. This model was called SIMLAND and provided an artificial environment to test the result of policies that was offered by decision makers. In another work, Li and Yeh (2000) applied CA to develop a model called “Constrained Cellular Automata Model”. This model is based on land suitability to explore urban form for sustainable development. This model can be used as a tool to help planners search for better urban forms. LEAM (Land use Evaluation and Impact Assessment Model), is another CA-based model which was developed by Sun et al., 2005. LEAM has been developed as a comprehensive urban planning support system at regional scale which simulates land use changes across time and space.

According to Dietzel and Clarke (2006), of all the CA models available, SLEUTH may be the most appropriate because it is a hybrid of the two schools in CA modeling it has the ability to model urban growth and incorporate detailed land use data. Reasons for choosing this model are: (1) the shareware availability means that any researcher could perform a similar application or experiment at no cost given they have the data; (2) the model is portable so that it can be applied to any geographic system at any extent or spatial resolution; (3) the presence of a well-established internet discussion board to support any problems and provide insight into the model’s application; (4) a history in the geographic modeling literature that documents both theory and application of the model; and (5) the ability of the model to project urban growth based on historical trends with urban and non-urban data.

SLEUTH incorporates two models: the urban growth model (UGM) and the land cover deltatron model (DLM). The name SLEUTH has been derived from the simple image input requirements of the model: Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade. In order to run the model, one usually prepares the data required, verifies the model functions, calibrates the model, predicts the change and builds the products. The user can implement SLEUTH modeling in different modes. In running the model, five coefficients including diffusion, breed, spread, slope resistance and road gravity are calculated followed by estimation of four growth rules consisting of spontaneous growth, new spreading center growth, edge growth and road-influenced growth. The aim of this paper is to show our investigation of the dynamics of Mashad City, modeled and simulated by the SLEUTH. Also, we studied results of different scenarios of urban expansion. In this way, we were able to show how urban growth types differed from each other in our study area and also to present a method for managing the city best, in terms of environmental aspects and development.

Urban growth modeling

Mashad is the capital city of Khorasan Razavi Province, in the North East of Iran (Fig. 1). It has an area of 148 km² and its current population is 2.4 million. It has witnessed rapid growth in the last two decades, mostly because of its economic, social and religious attractions. Since 1987, its population has grown 3.6 times while its extent at the same time period has doubled (Rafiee, 2007). We used the SLEUTH model to simulate urban dynamics of Mashad. The specification of the SLEUTH model, which is a CA-based model of urban growth, has originally been described by Clarke et al., 1997.

SLEUTH model

As mentioned, the SLEUTH is a modified CA model for urban growth modeling and the name comes from the abbreviation of its data input requirements which are Slope, Land use, Exclusion Zone, Urban, Transportation and Hillshade. The model runs under UNIX or UNIX-Based operating systems and is composed of UGM (urban growth model) and DLM (deltatron land use model), the latter being optional. In SLEUTH, the dynamic urban growth is expressed by four rules: spontaneous, new spreading center (diffusive), edge (organic) and road influenced growth (Candau, 2002). Spontaneous growth simulates the occurrence of urban settlement in a new area without pre-existing urban areas and infrastructures and new spreading center controls the likelihood that a spontaneous growth will become a center of continued urban growth. Edge growth includes urban growth that occurs outward from city as well as urban infilling. Road influenced growth simulates the tendency of new settlements to appear next to transportation lines and encourages urbanized cells to develop along the transportation network (Candau, 2002).
These growth rules are controlled by five growth parameters: diffusion, breed, spread, road gravity and slope resistance. Each parameter has a range of 0–100 which is dimensionless and shows the importance of the corresponding parameter. The diffusion factor determines the overall outward dispersive nature of the distribution; a breed parameter specifies how likely a newly generated detached settlement is to begin its own growth cycle; a spread parameter controls how much diffusion expansion occurs from existing settlements; a slope resistance factor demonstrates the likelihood of settlement extending up steeper slopes and the road gravity factor attracts new settlements toward and along roads. Fig. 2 shows the relationship between the urban growth rules and the five growth parameters (Ding and Zhang, 2007).

Implementation of SLEUTH in a new region is done in five steps: model compilation, data input preparation, calibration, prediction and result output (adapted from Yang and Lo, 2003). We downloaded and compiled the model under Cygwin using a gnu C compiler (gcc). Then, we ran a test mode of the model to ensure that the model functions correctly.

Data input preparation
All of the input data for calibration of the model was compiled in a geographic information system (GIS). We clipped data to a similar extent and converted them into 28 m resolution raster grids. The dimensions of the grids were 748 columns by 752 rows. These layers were used in calibration and prediction steps. All input data were then converted into grayscale gif format, a requirement of the model. Urban layers were derived from reclassification of detailed land cover classified maps. We applied a supervised classification with training sites purification (Salman Mahiny, 2005) to Landsat MSS, TM, ETM and IRS images to map land cover of the years 1972, 1987, 2001 and 2006 in the Mashad area. These images were co-registered with an acceptable RMSE using nearest neighborhood algorithm. The maps were then converted into binary urban/non urban layers to depict the profile of Mashad City dynamics since 1972 (Fig. 3). Transport layers were derived from visual image interpretation and on screen digitization of the same satellite data and the resultant vector layers were converted into raster. Slope layer was created from a 10 m DEM which was obtained from National Cartographic Center (NCC) of Iran. This layer was transformed to percent slope. Then, all values beyond 100% in the slope layer were changed to 100 and the layer was resampled to 28 m resolution using the nearest neighborhood algorithm. Also, from the same DEM we created the Hillshade layer for the study area. Excluded layer consisted of airport with 1 km buffer, railway station and local green spaces (Malek Abad, Mellat, Razavi Garden and Torogh Rest Area Complex) which were digitized on the IRS 2006 satellite image. Table 1 shows the input data set for the SLEUTH.
Model calibration

The main assumption of the SLEUTH application is that the way a region has changed in the past is the rule for its change in the future. Hence, the model uses this information to forecast a reasonable future change for the study area (Clarke et al., 1997). In the calibration phase, the model is calibrated by fitting simulated data to real historical data collected from the study area. The purpose of the calibration phase is to derive a set of values of parameters that can effectively simulate urban growth during the historical time period. There are a few methods for calibration such as what was described by Jantz and Geotz (2005). However, we applied a standard method of calibration to simplify the procedure and shorten the time required for this purpose which at times can become very lengthy. This procedure in the SLEUTH was completed through a number of Monte Carlo iterations. Because the SLEUTH utilizes Monte Carlo iterations stochastically to generate the multiple simulation of growth and each parameter may take values between 0 to 100 independently, the model requires a fast CPU to explore parameter values. So, calibration is carried out in three phases, Coarse, Fine and Final.

In the coarse phase, we considered the widest range of parameters (0–100), a large value (25) for incrementing the parameters and the lowest spatial resolution through re-sampling images to 1.4 of the original (112 m). The result of the coarse calibration phase was evaluated using the fit statistics generated during the model run leading to a narrower range of the best fit set. In the fine calibration phase, this range was narrowed down even more and the size of increments and the number of Monte Carlo iterations were increased to improve modeling results. According to the standard calibration method of the SLEUTH, in this phase we set the Monte Carlo iteration as seven with a half resolution for inputs. During calibration phases a series of indices are calculated to assess the modeling fit which is described in Table 2. The result of the calibration phases for modeling Mashad City growth is given in Table 3.

Due to the self-modification of the SLEUTH model, parameter values are constantly altered through a run from the first date to

### Table 1

<table>
<thead>
<tr>
<th>Input layer</th>
<th>Source</th>
<th>Format and year</th>
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</thead>
<tbody>
<tr>
<td>Slope</td>
<td>DEM generated by NCC</td>
<td>Raster</td>
</tr>
<tr>
<td>Hi/llshade</td>
<td>DEM generated by NCC</td>
<td>Raster</td>
</tr>
<tr>
<td>Excluded</td>
<td>On screen digitization</td>
<td>Rasterized from vector</td>
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### Table 2

<table>
<thead>
<tr>
<th>Index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>A composite index which is the result of all scores multiplied together</td>
</tr>
<tr>
<td>Compare</td>
<td>Comparison of modeled final urban extent to real final urban extent</td>
</tr>
<tr>
<td>$r^2$ Population</td>
<td>Least square regression score of modeled urbanization compared with actual urbanization for control years</td>
</tr>
<tr>
<td>Edge $r^2$</td>
<td>Least square regression score for modeled urban edge compared with actual urban edge count for control years</td>
</tr>
<tr>
<td>$R^2$ cluster</td>
<td>Least square regression score for modeled urban clustering compared with known urban clustering for control years</td>
</tr>
<tr>
<td>Leesalee</td>
<td>A shape index, a measurement of spatial fit between the modeled growth and the known urban extent for control years</td>
</tr>
<tr>
<td>Average slope $r^2$</td>
<td>Least square regression of average slope for modeled urbanized cells compared with average slope of known urban cells for control years</td>
</tr>
<tr>
<td>$X - r^2$</td>
<td>Center of gravity[$x$]: Least square regression of average $x$ values for modeled urbanized cells compared with average $X$ values of known urban cells for control years</td>
</tr>
<tr>
<td>$Y - r^2$</td>
<td>Center of gravity[$y$]: Least square regression of average $y$ values for modeled urbanized cells compared with average $Y$ values of known urban cells for control years</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Index,Step</th>
<th>Coarse</th>
<th>Fine</th>
<th>Final</th>
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<tr>
<td>Product</td>
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<td>0.29</td>
<td>0.15</td>
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<tr>
<td>Compare</td>
<td>0.96</td>
<td>0.89</td>
<td>0.98</td>
</tr>
<tr>
<td>$r^2$ Population</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Edge $r^2$</td>
<td>1.0</td>
<td>0.99</td>
<td>0.89</td>
</tr>
<tr>
<td>$R^2$ cluster</td>
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<td>1.00</td>
<td>0.78</td>
</tr>
<tr>
<td>Leesalee</td>
<td>0.44</td>
<td>0.40</td>
<td>0.36</td>
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<tr>
<td>Average slope $r^2$</td>
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<td>0.97</td>
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<tr>
<td>$X - r^2$</td>
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<td>0.91</td>
</tr>
<tr>
<td>$Y - r^2$</td>
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<td>0.98</td>
</tr>
<tr>
<td>Diffusion</td>
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<td>1</td>
<td>6</td>
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<tr>
<td>Breed</td>
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<td>95</td>
<td>97</td>
</tr>
<tr>
<td>Spread</td>
<td>100</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Slope</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Road gravity</td>
<td>50</td>
<td>85</td>
<td>85</td>
</tr>
</tbody>
</table>

Fig. 3. The extent of Mashad City and the associated road networks since 1972.
the last date and the best calibrated parameters of the stop date are selected. Thus, use of the best parameters derived from calibration and running of the SLEUTH for the historical time period will produce a single set of stop date parameters to initialize forecasting. However, due to the random variability of the model, averaged parameter results of more Monte Carlo iterations will produce a more robust forecasting parameter set (<http://www.ncgia.ucsb.edu/projects/gig/v2/Lmp/imCalibrate.htm#forecast>). So, we used the best parameter values in 100 Monte Carlo iterations with one step increment to derive an average for each parameter. We present the average for the parameters in Fig. 4.

The high score in spread parameter reflects the high probability of urbanization outward of the existing urban centers. Also, the breed parameter is high – that manifests high probability of establishment of new urban centers. This high probability and a high spreading likelihood are deemed responsible for some of the dispersive urban growth in Mashad City. For Mashad City, the score for slope resistance was so low that implied that topography was not a limiting factor for urban sprawl. This fact was confirmed by field checks and current data on new residential areas. The high score of road gravity showed urban growth has been affected by road networks significantly. Finally, the low diffusion parameter showed that Mashad has a compact form of growth with its main urbanization occurring near the existing urban areas and urban cores. We found that establishment of the new urban centers near the main city center through spontaneous growth has a low probability.

**Model prediction**

After we calibrated the model successfully, the average values were used in prediction mode to simulate the future of Mashad City. Prediction was completed using the full resolution data and 100 Monte Carlo iterations. The result of executing the prediction mode is a probabilistic map which shows the probability of grid cells being urbanized in the future. The map was produced for every year from the first year to the last year set at 2050. The frequency histogram of the final year’s probability map was evaluated to provide clues as to the cut off point for urbanization (Fig. 5).

As can be seen in Fig. 5, somewhere around 90%, there is a sharp increase in the number of cells converting to urban. The frequency histogram is just one tool for selecting the urbanization threshold on the probability map. Another method is based on projection of population increase and the associated urban growth through demographical and statistical methods. One other method is defining a set of scenarios for urban area expansion based on historical data and assessing the likely areal coverage of the city in the final year. We used the results from 100 Monte Carlo iterations and the frequency histogram and as one possible figure, considered every cell with a probability above 85% would convert to urban. The SLEUTH provides a simulation environment to explore the consequences of policies taken by decision makers. In this research, we simulated Mashad City under three scenarios; historical urban growth (HU) which allowed urban expansion without any limitation and a continuation of the historical trend. In the environmental protection (EP) scenario, the urban growth was limited according to the environmental considerations. The third scenario was a specific form of urban growth (SUG) which allowed urban growth based on the historical trend but under limitation of construction in steeper areas. Scenario definition and application has been dealt with partly by Xiang and Clarke (2003). In their paper, Xian and Clarke suggest three criteria including plausible unexpectedness, informational vividness, and cognitively ergonomic design for every set of acceptable scenarios. To show the usefulness of the modeling methods and also to provide a context comprehensible for the city managers, we defined the three simple scenarios. These scenarios, however simple, are rooted in some facts of Mashad development in the past. Urban development is partly controlled by the master plans derived from regional land use

![Fig. 4. Parameters averages for forecasting.](image1)

![Fig. 5. Frequency histogram for the probability map of urbanization for the year 2050.](image2)
Fig. 6. The urban extent of Mashad City from the year 2020–2050.
planning. Also, municipalities set upper boundaries to the area of development for each town. In practice, a mixture of the results of land use planning and the controls exerted by the municipality and in some cases unharnessed housing is shaping some of the major cities and towns in Iran. Mashad is no exception, where managers of the Holy Imam Reza Shrine add a new dimension to the governance of the city and play an important role in shaping it. These operators create a complex situation in which definition of accurate or plausible scenarios becomes rather hard. Hence, the case of the three scenarios in this study serves only as a general guide for the city managers, to help them realize the potential of the modeling approach and some of the results of different development policies. In this way, it is also possible to convene a larger audience from influential parties in city development and make them reach a common ground on Mashad City growth, through conducting ‘what-if?’ experiments.

In order to simulate different scenarios through the SLEUTH, usually three methods are applied. The first concerns changing parameter values that affect urban growth rules and consequently determine the form of urban growth (e.g. Leao et al., 2004). In the second method, different levels of protection values to specified areas in the excluded layer are assigned (e.g. Oguz et al., 2007) and finally, in the third method the self organization constraints are manipulated (e.g. Yang and Lo, 2003). In this research, we used the first method of changing the parameter values to benefit from its flexibility. For the first scenario, we set 7, 98, 97, 1 and 90 for diffusion, breed, spread, slope resistance and road gravity, respectively. This combination assumed that the current status would be maintained and the future growth would occur according to the historical trend. In the second scenario, we reduced the spread and breed parameter values to half. These parameters mainly describe the trend of urban sprawl and the effect of road gravity on establishment of urban settlements near the road networks. Despite the land use planning protocols in Iran (Makhdum, 1993), which limits construction of buildings in areas steeper than 9°, the historical trend showed that Mashad City has grown in some steep areas in the south. In the third scenario, we explored the urban future under more limitations with respect to urbanization in steeper areas. For this scenario, we ran the model prediction mode with the same parameters of the historical trend, but the slope resistance was increased to 80. This could also be done through other ways such as masking out steep areas or resetting of the critical slope parameter in the calibration files. The results of the urban future extents modeled and predicted through the SLEUTH are presented in Fig. 6 and a comparison of the three scenarios is given in Fig. 7.

The historical growth shows that there is no limitation against urban expansion. The area of the city expanded about 70% from 2006 to 2050 where 1% of urbanization was occurred in unsuitable areas with regards to slope. This scenario showed the highest expansion causing degradation of land and its natural resources. The EP scenario showed the smallest increase of the urban extent in the future as compared to the historical scenario. Under this scenario, the city area was expanded 21% from 2006 to 2050 and of this, only 0.7% occurred in unsuitable areas with respect to slope. This form of urban expansion showed compact city growth which saved 75 km² of lands from development. We predicted that urban area in the third scenario will cover approximately 250 km² by 2050, a 60% increase in the city extent with only 0.3% of urbanization in unsuitable areas. Given these findings, the EP scenario saved large areas of land and resources and also dictated a compact form of growth which facilitates provision of urban services by city managers. Hence, the EP scenario was preferred against other forms of growth for Mashad City. Also, as large areas within and beyond the city are managed by the foundation of the Holy Imam Reza Shrine, this policy can prevent and lessen some of the disputes that may arise when people develop housing without regard to rules defined by the Foundation, land use planning prescriptions and municipality controls.

Conclusion

Urban sprawl throughout the world has led to consumption of land resources and degradation of vast areas of suitable lands and their conversion into impervious surfaces. In many cases, these alterations have occurred without an understanding of their consequences. In order to analyze land conversion in cities, models can be used as innovative tools to support spatial urban planning for sustainable development. Application of robust change detection and modeling methods can reveal past changes and simulate future scenarios of city expansion.

In this research, we successfully calibrated the SLEUTH model for Mashad City based on historical data covering the time 1972–2006. The coefficient values of goodness of fit derived for each metric of the model demonstrated the usefulness of the SLEUTH to predict the urban growth and three scenarios were generated to evaluate the consequences of urban growth in the future. These scenarios represented different growth strategies available to planners, but we noted that urban growth is a complex process which is also affected by population increase, infrastructures and socioeconomic factors. Furthermore, in the case of Mashad City, development is controlled not only by land use planning results, municipality decisions and sparse unharnessed development of built-up areas without regard to these factors but also the Foundation of the Holy Imam Reza Shrine which is rather influential. The SLEUTH model only considers road networks of the set of infrastructure parameters possibly involved in urban expansion. However, socioeconomic data with a suitable temporal accuracy is, in most of the developing countries, not readily available. Hence,
SLEUTH can be regarded as a useful modeling tool in these circumstances. The results of SLEUTH or any other models do not exactly match reality and at best produce approximations. We found that the results of the SLEUTH modeling method are useful to compare the consequences of different scenarios.

Lastly, we noted the convenient link between the GIS and CA in applying the SLEUTH model. Thus, we easily prepared and handled the input data for modeling in a raster based GIS environment. Also, the result of the model was easily imported into the same GIS environment for presentation purposes. Being readily available to derive the results of different scenarios of urban development, the model also serves as a decision support tool and helps city managers realize the outcome of possible actions they might take.

References


