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Original Research

Rapid Urban Growth in the Qazvin Region and Its Environmental Hazards: Implementing an Agent-Based Model

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Abstract

Urban growth is a prevalent challenge in many countries as it causes unexpected changes in land-uses of surrounding areas of cities and endangers the environment and natural resources. Thus, spatial planners and environmental managers always look for the models that simulate the expansion of urban land-use, and enable them to prevent unbalanced expansion of cities, and guide the developments to the desired areas.

Several methods have been devised to simulate the dynamics of land-use development. However, the complexity of urban growth is recognized as a major barrier for such simulation methods. Agent-based models as a dynamic bottom-up approach use the real actors of land-use development as their basic components. Thus, such models have found popularity in simulating land-use development and urban sprawl modeling.

This paper introduces a new agent-based model used for simulating urban land-use development in our study area located in Qazvin province, Iran. The orchards that encompass the western, eastern, and southern sides of Qazvin city are the most sensitive zones in the study area. The model uses 2005 data for the purpose of calibration and 2010 data for the goal of evaluation. A Kappa accuracy of 82.78% was finally achieved for the predication of the observed developments. Also, three zones of residential developments around Qazvin city were found to be endangered. Orchards located on the eastern side of Qazvin city are exposed to destruction and conversion into urban areas. The calibrated model can also be used as a useful tool for predicting future land-use developments and for recognizing endangered environmental zones.

Keywords: urban land-use development, agent-based modeling, environmental hazards, orchard, Qazvin

Introduction

The percentage of the population living in urban areas in developing countries grew from 27% to 40% between 1975 and 2000 [1-3]. This population growth is associated with urban and infrastructural expansion. Boundaries of cities are expanding and larger areas are being occupied by cities. This expansion causes potential and actual risk for the environment [4]. Thus, more and more towns and cities bloomed with a change in the land-use along the myriad of landscapes and ecosystems [5].

As a developing country, Iran is now witnessing rapid and continual large-scale urbanization [6]. The number of cities has also increased significantly, from 199 cities in 1956 to 1,200 in 2012 [7].

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Qazvin is an ancient city located on the north side of Iran, about 150 km from the capital. As both an industrial and agricultural city, Qazvin has seem rapid growth both in footprint and population in the last two decades, mostly because of its economic and transitional position [8]. For instance, the urban population of Qazvin has increased from 552,928 in 1996 to 777,975 in 2006 [7]. All of the cities and towns around Qazvin have been established or converted from village to city in the past 50 years. The study area of this paper includes Qazvin as the central city and five satellite cities around. Moreover, the area includes several towns, villages, and industrial regions.

Qazvin city is located in an agricultural area. A crescent shape of orchards has encompassed the southern part of this city. The rapid expansion of residential land-use endangers agriculture and environmental resources. Hence, simulation of urban land-use development enables both urban and environmental organizations to recognize the general behavior of urbanization and adopt proportional protection/management. Without using models that embrace the complexity of the urban system, it would be difficult to simulate and predict the future of urban growth [9].

Interactions between natural and social systems at different spatial scales cause changes that occur in land-use due to the complex process of urbanization [10, 11]. A group of models has recently emerged and gained popularity in simulating environmental and social phenomena [12]. These models use the real actors of land-use change as objects of analysis and objects of simulations, paying explicit attention to interactions between these 'agents.' Therefore, they are commonly referred to as agent-based models [13] that focus on individual actions and their emergence [2]. Agents have several characteristics: they are autonomous, they share an environment through agent communication and interaction, and they make decisions that tie behavior to the environment [14]. As such, agents have been used to represent a wide variety of entities, including atoms, animals, cars, people, biological cells and organizations [15-19]. Agents make inductive and evolving choices that move them toward achieving goals [18, 20].

In this paper, rapid expansion of urbanization in Qazvin area and its hazards for the environment is notified. Then, our newly developed agent-based model is calibrated for simulating urban land-use development. This simulation is an efficient facility for recognizing the behavior of developments and to detect the environmentally vulnerable areas. A large variety of models such as artificial neural networks, cellular automata, and regressions have been commonly used to simulate urban growth [5, 18, 21, 22]. Some packaged cellular and agent-based models such as SLEUTH, SLUCE, SLUDGE, LUDAS, and SAMBA [18, 23-25, 6] have been introduced for this task. Nevertheless, those models have been designed with predefined conditions and processes. Thus, adapting those models to different conditions may encounter some difficulties and limitations. We tried to construct an efficient model which is able to mimic the process of land-use development in Iran. The flexibility of our model may allow it to be used elsewhere.

We propose an approach that integrates land-use factors with the agent-based model for modeling urban land-use development. This model is equipped with new methods of agents' movement and competition. The model is fed with three spatial criteria maps. Various effective factors such as environmental considerations can be considered in the maps. Observed urban land-use developments are vitally important to calibrate the model. Our assessments show that many agricultural land-uses have been converted to urban areas during 2005 to 2010. Also, many agricultural farms are not being used anymore and they are subject to land-use change. The orchards have similar conditions and a large number of them have now been abandoned. Several reasons cause this condition. Whatever these reasons are, the major routes for them are the socioeconomic changes in the study area [8].

In this research, we test several factors to find the best calibration of the model that would be the best simulator of the behavior of land-use developers. This would be valuable to predict the future developments by a model and to detect the potentially endangered areas subject to urbanization. Moreover, GIS is a versatile system and science for dealing with spatial data [26-28]. It helped us collect spatial data, implement spatial analysis, prepare proper maps, and present the results.

Model Description

In our proposed model, the agents represent land-use developers who explicitly move into the landscape seeking for proper cells to develop. The model mimics the mechanism of searching and developing land in Iran. However, this may be the case in many other countries. The agents are categorized into five groups, each of which has different aims. The development is divided into separate stages; each corresponding to a year. In each year, the mobile agents search the landscape and record the state of their visited cells (searching stage). The landscape is divided into several districts (12 districts in our case study), with each one having a primary probability to be selected by agents. The agents search a number of districts separately. Then, the most appropriate cells, which have been previously visited, will be decided by the agents to develop (developing stage). In the developing stage, some cells may simultaneously be chosen by more than one agent. In such conflicted cases, the agents compete and the winner of competition develops that cell. Once a cell is developed, the probability of the districts is changed by the agent. The details of the model are explained as follows.

Criteria for Selection of a Target Location

Many researchers have taken into account various factors such as decision-making criteria for agents to select targets for development [18, 29, 30]. Nevertheless, residential decision criteria such as household stage in a life cycle, the price of property, the demographic structure of a neighborhood, or public transport do not count for more than 20% to 30% of development choice [31]. Consequently, it has been stated that traditional microsimulation modeling, which extensively uses such databases, does not account for the interdependences among the decision factors [31, 32]. Thus, three criteria maps, namely attractiveness, accessibility, and land-price, were used in this research. The framework considers the landscape as a raster space on which agents act for developing the cells. Each cell can be developed or not-developed. Therefore, each agent should assess the undeveloped areas and decide where to develop.

Agent Classes and Their Characteristics

The categorization of agents takes place by considering the situations and goals of land-use developers. This categorization is similar to what was performed by Loibl and Toetzer, but has been modified to match the conditions of the executing environment in Iran [33]. Thus, the agents are categorized into five types, namely:

- The first type contains the young persons with moderate income who look for rather cheap cells with good accessibility.
- The second type includes the high-income developers seeking for valuable lands with admissible attractive.
- The third type consists of rich people who need highly attractive cells for recreational residence.
- The forth type includes low income people that search for the cheapest cells.
- The fifth type contains moderate- to high-income people who consider three criteria of land-value, accessibility, and attractiveness with the same importance.

Besides their type, each agent has a location in a cell of landscape, limited movement, minimum required location change (jump) in a district, and a number of districts to search.

Distribution of Agents in the Landscape

First, the agents must be located in the landscape. Undoubtedly, the landscape is not a homogeneous area and different districts can often be detected. Thus, the agents primarily choose a district for search. Districts certainly have a different chance for selection by different types of agents based on their overall characteristics. The decision of which district shall be selected is performed randomly, referring to the chosen probability distribution P_i^k for each agent, where k is the type of agent and i is the district.

Neighborhoods of an initially developed area are disposed for development. So, in each district the agents first start from the neighborhoods of an initially developed area. Each agent moves around and after a limited movement changes its location to another position in the same district (jumps). The agents only traverse the undeveloped cells. The agents might also change their district and do the same activities in the new one.

Agents' Movement

Wherever the agent starts, it assesses the state of the current (standing) cell and also its eight adjacent cells. State means the value of three criteria maps in a given position. Then the agent moves to its best neighboring cell or if more than one cell achieves the same score, chooses one of them randomly. The agent records the position and the state of all its traversed cells and their undeveloped neighbors. Traversed cells and their undeveloped neighbors are called visited cells. Finally, when the agents finished their search in the landscape they have lists of the states and positions of their visited cells. This list can be assumed as the agent's investment list.

Decision to Develop

Once an agent finishes its search it should decide which cells to develop. To do this task the agent sorts its investment list in descending order, so the most suitable cell lies at the top of the sorted investment list. Next, the agents are randomly selected. Then the selected agent picks up the top-scoring cell from the top of its sorted investment list and develops it if there is no competitor. This procedure continues while all of the agents develop their desired number of cells.

Competition

It is highly probable that one cell is required by more than one agent for development. Such a cell will certainly be developed. In such conditions the conflict is dissolved by competition. The issue is to determine the dominant agent. The winner of the competition is determined by the scores that competing agents gain. Score is a unitless value that depends on the type of agent and the number of times the agent loses a cell in the previous competitions. The score is calculated through the following formula:

$$Score = W_{Type} \times Score_{Type} + W_{Frustration} \times Frustration \quad (1)$$

...where $Score_{Type}$ is the score assigned to each type of agent, *Frustration* is a digit that shows how many times an agent has lost a cell, and W_{Type} and $W_{Frustration}$ are the weights considered for $Score_{Type}$ and *Frustration*, respectively. The value of *Frustration* is equal to zero for all agents at the beginning. However, whenever an agent loses a cell in a competition, its *Frustration* value increases by one. This increase means that the agent in the next competition will have higher propensity to develop a cell. W_{Type}, $W_{Frustration}$, and $Score_{Type}$ are determined by the experts via considering pair by pair conditions of the competitions among the agents.

Changing the Probability of Districts

Each district has a probability of being selected. These probabilities are initially extracted based on the observed developments. However, the probabilities are changed by the activities of the agents. When the selection of the cells is completed, the first half and the first quarter of the sorted list of agents is considered to calculate the statistical distribution of the districts. These statistical distributions are treated as the probabilities of districts. Next, a weighted summation of the probabilities from the first quarter and the first half is calculated. Because of the higher significance of the first quarter cells, they are weighted twice as much as the weights assigned to the first half.

Subsequently, the result is compared with the previous probabilities and for each district the difference is calculated. The differences, which can be positive or negative, are multiplied by a coefficient named the coefficient of communication (COC). The result is then multiplied by another coefficient, namely the number of searched districts over the number of total districts. Finally, the results are added to the previous probabilities.

Study Area

The study area is located in Qazvin province of Iran. It is 45 km long and 36 km wide (Fig. 1). The landscape is composed of 162,000 cells of 100×100 meters.

This area contains Qazvin as the central city of the province and five nearby cities. Moreover, the area includes several towns, villages, and industrial regions. The development mostly occurrs in the prepared lands around the cities. However, increasing request for land has caused some illegal developments. Therefore, unexpected developments that destroy agriculture and natural resources are challenges for environmentalists in Qazvin. Fig. 2 shows the orchards and agricultural lands in the study area. Unfortunately, there is neither natural forest nor wetland near Qazvin. Hence, the orchards are the most important green-lands of Qazvin.

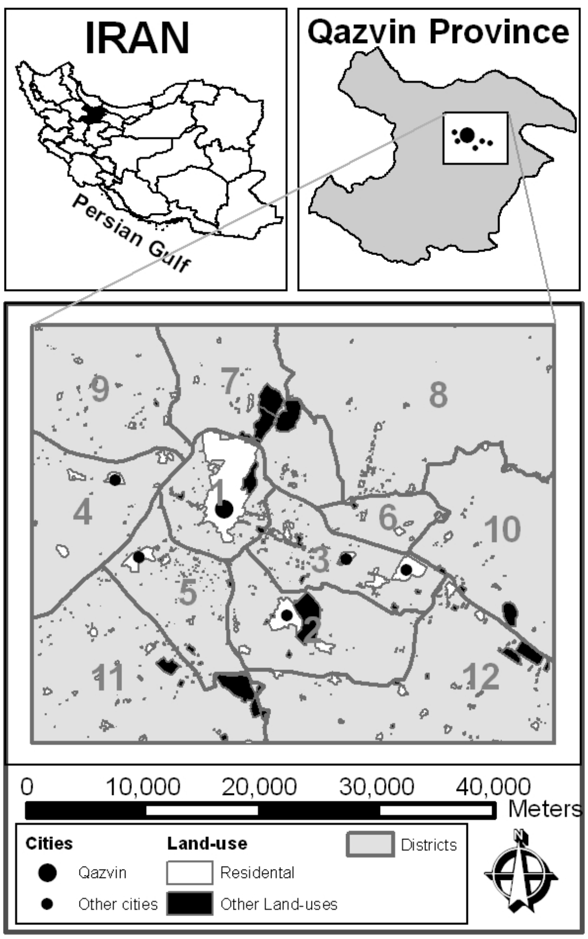

Fig. 1. Study area.

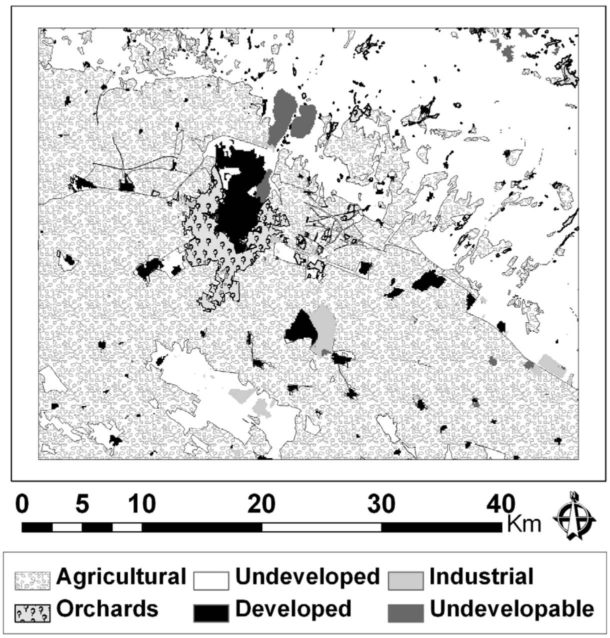

Fig. 2. Major land-use in the study area.

Data Preparation

Three criteria maps (layers), namely land-value, attractiveness, and accessibility were used in this study. Fig. 3 shows three criteria maps. Each criteria map reflects some factors. For example, the land-value map was generated by considering land price, disposing of land for development, slope, and soil quality. The accessibility map was generated by evaluating the shortest time of reaching a cell to the central city. To produce the attractiveness map, proximity to the green zones, visibility to the central city, and the local temperature were considered. All maps were normalized to have values between 0 and 1. A map of districts was also used (Fig. 1). To produce this map, 12 districts were recognized in the landscape. Then the probability of each district was calculated by dividing the developments of that district (between 2005 and 2010) to the total development of the study area (Table 1).

The land-use/land cover maps of 2005 and 2010 as well as the other maps were taken from the National Cartography Center (NCC) of Iran. Then the residential area and other land-uses were detected. The scale of reference maps are 1:25,000 and greater. We used ArcGIS 9.2 for preparing maps, GIS analysis and representing the results. Also, NetLogo 4.1 with its GIS extension was used for developing our agent-based model.

Setting the Parameters

Before running the model, its parameters must be set. Parameters of the model and the assigned values are pre-

Table 1. The initial probabilities of districts.

District	1	2	3	4	5	6	7	8	9	10	11	12
Probability (%)	38.2	8.5	19.9	10.5	8.1	6.9	1.1	1.5	2.1	1.3	0.7	1.2

sented in Table 2. To set the parameters we used three approaches: the ideas of experts, the existing data, and examining the various configurations of the model.

In order to set the weights of the districts, the idea of experts was used in this study. The experts were also asked to determine the scores of agents (Equation 1). For this purpose, the experts considered all of the possible dual conditions among various types of agents in the competition. As a consequence, W_{Type} and $W_{Frustration}$ were determined as 9 and 10, respectively.

The number of agents for each type also should be set. In order to determine the number of agents of each type, the existing data was considered in this research. Comparing the land-use map of 2005 with 2010 showed that the urban land-use development grew by 1,200 ha. These developments were then evaluated and analyzed based on the three criteria. Therefore, on the basis of land-value, accessibility, and attractiveness of development, 110 ha were verified as developments of type 1, 90 ha for type 2, 10 ha for type 3, 20 ha for type 4, and 10 ha for type 5 in each year.

In order to determine the other parameters, various configurations of the model were examined. For this, type 5 of our agents was regarded as the reference. We assumed that agents can search 50, 70, or 90% of districts. We also assumed that each agent is able to develop 1, 2, 5, 10, or 15 ha every year. Furthermore, the number of traversed cells was considered to be 10 or 15 times more than that of the developing cells. Moreover, the number of jumps for the reference type was assumed to be equal to the number of cells each agent develops per year. For the other types, however, the number of jumps is one more. The quantitative results are illustrated by Kappa coefficient. Kappa is a popular index that shows how much a classification matches the other basic one [34, 35]. Kappa is calculated based

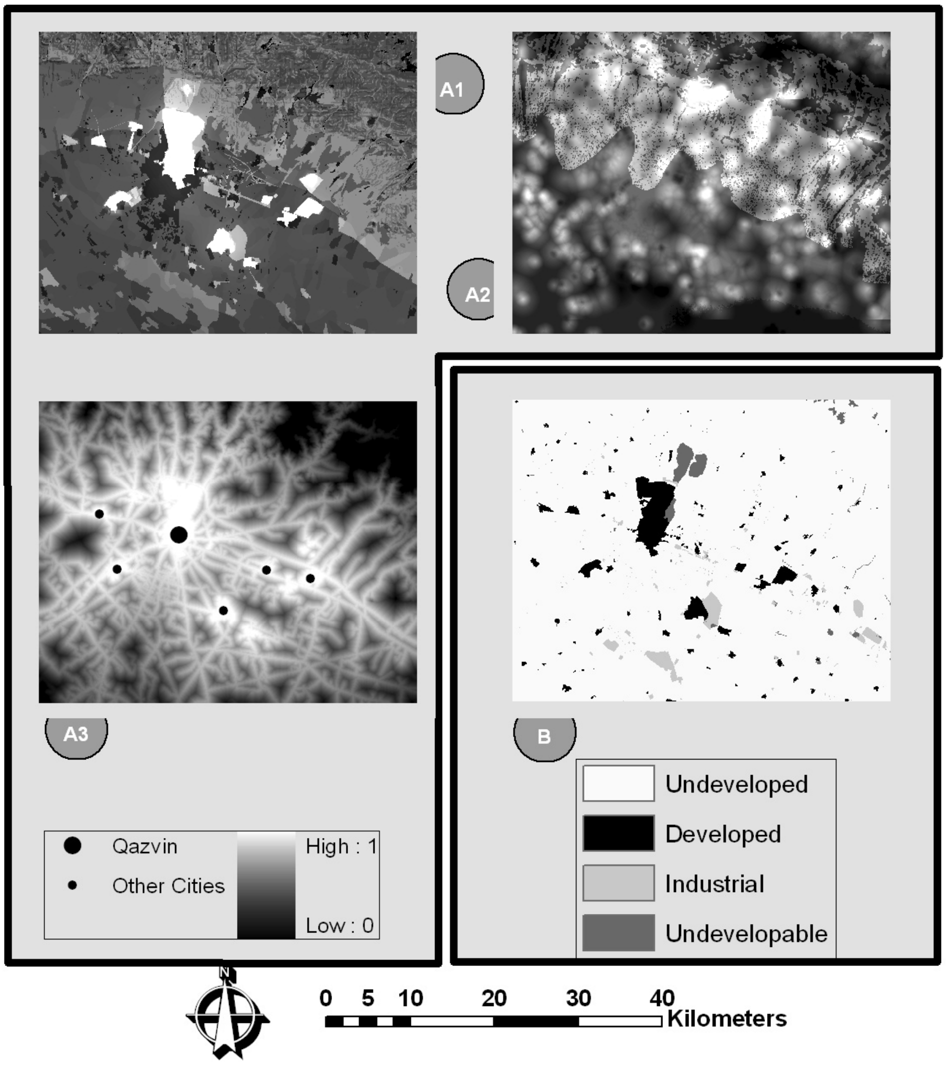

Fig. 3. The criteria maps (A1: land-value, A2: accessibility, A3: attractiveness) and B: development map of 2005.

Table 2. The final parameters of the model.

Type of agent	1	2	3	4	5
Count	11	9	1	2	1
Weight of accessibility	3	1	1	2	1
Weight of attractiveness	1	2	2	1	1
Weight of land-value	2	3	1	1	1
Number of searching districts	9	9	9	9	8
Number of traverse cells	120	110	130	110	100
Number of cells to develop per year	10	10	10	10	10
Number of jumps in each district	11	11	11	11	10
$Score_{Type}$	2	5	5	1	3

on the predicted and observed values over the entire area by the following formula [34, 35]:

$$Kappa = \frac{P_0 - P_c}{1 - P_c} \quad (2)$$

...where P_0 is the percent correct for the model output, and P_c is the expected percent correct due merely to chance. A value of Kappa between 60 and 80 percent has been considered a good agreement between the predicted and observed maps [36]. Table 2 shows the final parameters set for the model.

After setting the above parameters, two other configurations were also tested. In all of the previous runs of the model, in order to sort the visited cells the agents used the weighted summation (WS) of the values for each criteria map at the position of each cell. Also, the COC was zero. Two cases were tested afterward:

1) considering a COC equal to 0.25, 0.5, 0.75, and 1,
2) using Ideal Point (IP) [37] instead of WS for sorting the visited cells.

Results and Discussion

Because of the stochasticity of the model, it was run 10 times for each configuration. For each run, Kappa index is calculated. Therefore, for each configuration, there is a minimum, average, and maximum calculated Kappa. In order to show to what extent the results of the model are convergent, standard deviations of the Kappas were also calculated. These values are tabulated in Table 3.

The average Kappas of more than 80% indicates that the model is successful in simulating urban land-use developments, especially in our regional scale study area. Simulating and modeling urban sprawl is the subject of many other studies [38]. However, the situations and conditions of each case make it special. For example, the study area and its extents, simulating model, and method of evaluating the results vary throughout the studies. Therefore, direct quantitative comparison of the models is too difficult. Nevertheless, in order to discuss this, the results of some other studies are briefly mentioned.

Zhang et al. [39] developed an agent-based model to simulate urban land-use development in Changsha, China. They considered different agents such as residents, peasants, and governments. The precision of the simulation reached more than 68% using the cell-by-cell method of comparing simulated and actual changes [39]. Jokar et al. [40] simulated urban growth in the Tehran metropolitan area, Iran. They designed an integrated ABM-Markov chain model approach to model urban growth. To model the major determinants controlling urban development, three agent groups were defined, namely: developer agents, government agents, and resident agents. For validation purposes, the model was estimated using 2011 data and then validated based on actual urban expansion. Given the accurate predictions of the Markov Chain Model, further predictions were carried out for 2016 and 2026 [40]. Tian et al. [35] simulated spatiotemporal dynamics of urbanization with an agent-based model in the Phoenix metropolitan region, USA. The combination of agent-based model and spatial regression model was employed to predict the future urban development of the Phoenix metropolitan region. The model simulated the behavior of regional authorities, real estate developers, residents, and environmentalists. Also, three scenarios were defined, namely: baseline, environmental protection, and economic development priority. Based on the land-use map for 2000, they evaluated urban expansion in 2010 and the values of Kappa were around 83% [35].

In our study agents play the role of developers. Roles of other effective groups in land-use development are hidden in criteria maps. For instance, government can directly change

Table 3. Values of Kappa in various configurations of the model.

	Minimum κ	Average κ	Maximum κ	Standard Deviation
IP, COC= 0.00	77.13%	78.49%	80.90%	1.13%
WS, COC=0.00	79.64%	81.07%	82.15%	0.73%
WS, COC= 0.25	79.85%	81.40%	82.47%	0.92%
WS, COC= 0.50	79.12%	80.94%	82.15%	0.91%
WS, COC= 0.75	78.28%	80.81%	82.78%	1.59%
WS, COC= 1.00	80.27%	81.64%	82.78%	0.88%

land-value by determining the legal and illegal sites for development. On the other hand, land-use development is a complex system and considering the behavior of an entire factor is almost impossible. In this study we explicitly considered land-use developers as mobile agents. However, we tried to make the behavior of agents mimic the behavior of developers as much as possible. In consequence, the results of the model are convincing.

The results also show the superiority of the WS method over the IP method. Also, the larger standard deviation of Kappa of the IP method, i.e. 1.13%, signifies the disadvantage of the method compared to WS. For these reasons, the IP method was not considered for further consideration.

Then, we tested the WS method with 4 different cases for which COC was not equal to zero. If COC is not zero, the agents are able to change the probabilities of districts based on their experiences. Therefore, we tested the model with 4 values of COC. Calculated Kappas confirms that employing a non-zero COC, which is equivalent to allowing the agents to change the probabilities of the districts, increases the quality of the results in general. Among the four values considered for COC, the value equal to 1 produced the best results, i.e. the largest Kappas. Thus, this configuration of the model was chosen for further operations. The changes in probabilities of districts guide agents to have better selections. It is noticeable that about 0.1% difference equivalents to 1 ha difference in simulation. Fig. 4 represents the changes in probability of district 1 as the most likely district during the five years of simulation by a diagram.

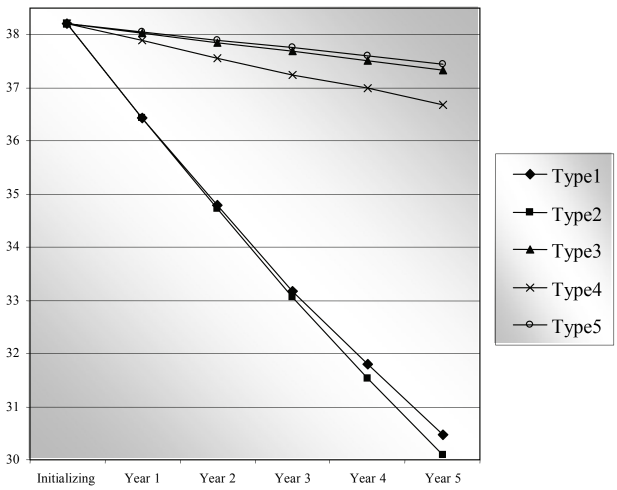

Fig. 4. Changes in the probabilities of district 1 during the 5 years, grouped by types of agents. Vertical axis shows the percent probability.

As can be observed in Fig. 4, all types of agents have reduced the probability of district 1. The larger the number of agents, the higher their impact on changing the probability. As well, Fig. 4 illustrates that the type of agent also influences changing the probabilities. For instance, type 2, which has 9 agents, has a larger impact on the probability of a district compared to type 1, which has 11 members. This proves the different behavior of agents of various types.

Fig. 5 represents the observed and simulated development in the study area. The simulation map belongs to the most proper result of simulation with Kappa of 82.78%.

Fig. 5 demonstrates that the model is more successful in simulating the developments occurring near the cities. A weaker prediction of the sprawl developments indicates that the criteria of these developments are less known in the criteria maps. Except for a narrow strip on the north side of Qazvin city, almost all of the developments have taken place in agricultural areas. This reveals that rapid urban growth in the study area is a serious threat for the environment and other green land-uses. Due to the lack of natural forests in the study area, the agricultural area and the orchards, in particular, play a vital role for the existing residential regions. Indeed, the orchards around Qazvin city are the lungs of this city. Three endangered zones were detected in the green land-use areas (Fig. 5). On the eastern side of Qazvin city most of the orchards are now abandoned. These areas are highly susceptible to rapid urban development. Thus, continuing close control of these areas

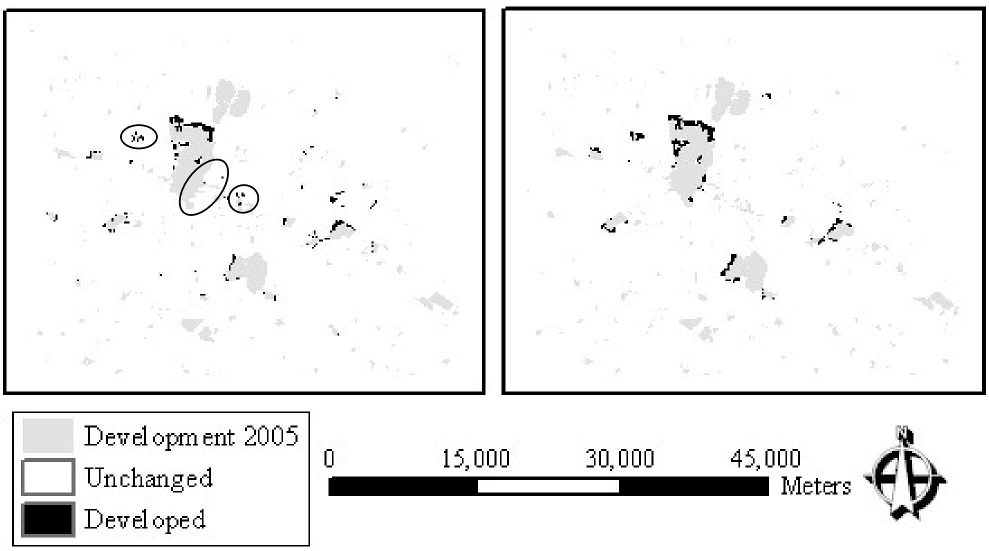

Fig. 5. The urban developments observed (left) and simulated (right) during 2005 to 2010, the endangered zones are illustrated with dark borders.

is necessary. On the western side of Qazvin city in the illustrated endangered zone, a village is experiencing rapid residential development. Proximity to Qazvin city and good accessibility are two major reasons for this phenomenon. Consequently, this rapid development is destroying the surrounding agricultural area.

Locating the cities of the study area in an agricultural land has made its land-use developments very susceptible and risky. A recent increase in the population is the most important reason for such an observed urban land-use development. However, the increase in population is unavoidable in a short time. Because of this, the increasing request for housing is also inevitable. To avoid the expansion in bounds of cities, inside construction and construction of tall buildings is necessary. Identification of appropriate sites with the lowest environmental impacts for constructing a new residential area is another parallel solution. In addition, serious control and supervision on construction is necessary to prevent illegal construction, which mostly occurs in orchards. Our proposed model is successful in simulating most of the occurred urban land-use developments. For instance, there are some sites predicted by the model as regions of development, but are not really developed in practice. These regions can be considered risky areas which should be highly taken care of. Moreover, the model can be used for predicting developments in the future. This enables the environmentalists and governmental organizations to detect the endangered zones of development.

Conclusions

Urban growth is a prevalent challenge in many countries. This rapid growth causes unexpected changes in land-use of surrounding areas of cities and endangers environment and natural resources. Accurate monitoring of urban land-use expansion helps us recognize the behavior of development. With good cognition of this phenomenon, using simulation models enables us to predict the future development and its hazards for environmental resources and other land-use.

In this study, we developed a new agent-based model for simulating urban land-use development in our study area located in Qazvin province, Iran. The orchards that encompass the western, eastern, and southern sides of Qazvin city are the most sensitive zones in the study area. The model was calibrated with historical data of 2005 and 2010. This model is a scientific tool that allows us to simulate urban land-use development.

To evaluate the results of the model, the 2005 data were used as the input and the 2010 data were used for checking the results. Various configurations of the model were tested to achieve the best one. As the Kappa index rose up to 82.78%, the results of the simulation were closely similar to the observed development.

The observations and the results of simulations recognize three endangered zones of residential development around Qazvin city. Orchards located at the eastern side of Qazvin city are exposed to destruction and conversion into the urban area. The calibrated model is recommended to be used as a useful tool for predicting future land-use developments and recognizing endangered zones.

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