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The Importance of the Technological Advances in the Study of Complex Urban Systems. Case Study: Cluj Metropolitan Area, Romania

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Abstract

The urban sprawl is an important anthropogenic phenomenon that should be taken into consideration within the urban and spatial planning context, especially because its effects influence the evolution of the territory, as well as the population's lifestyle and well-being level. Recent findings offer a wide variety of methods designed to facilitate the study of the existing situation of the urban space, not to mention its future forecast. The purpose of the present investigation was the assessment of the urban expansion between 1990 and 2012, in Cluj Metropolitan Area, Romania, and, additionally, its projection for year 2030. The applied model combined the cellular automata, the Markov chains and the multicriteria analysis, using GIS. The obtained results revealed a considerable tendency of spatial expansion of the surface occupied by constructions, mainly in the areas where the contiguity of the buildings was thicker.

Rezumat

Extinderea urbană este un fenomen antropogen important, care trebuie luat în considerare în contextul planificării urbane și spațiale, în special datorită faptului că efectele sale influențează evoluția teritoriului, precum și stilul de viață și nivelul de bunăstare al populației. Progresele științifice privind orașul contemporan au pus la dispoziție o gamă diversificată de metode care facilitează analiza situației existente a spațiului urban, dar și previziunile sale viitoare. Scopul prezentei cercetări este de a evalua expansiunea urbană între 1990 și 2012, în Zona Metropolitană Cluj, România, și, în plus, proiecția aceleiași zone pentru anul 2030. Modelul aplicat combină automate celulare, lanțurile Markov și analiza multicriterială, folosind metode GIS. Rezultatele obținute evidențiază o tendință considerabilă de expansiune spațială a suprafeței ocupate de construcții, în special în zonele în care contiguitatea clădirilor este mai densă.

Keywords: urban expansion; cellular automata; Markov chains; forecast; Cluj Metropolitan Area

1. Introduction

Since the 1950s, the urban area of Europe increased 78% on average, while its population has grown by only 33% over the same period [1]. These facts allow us to affirm that urbanization is one of the most evident global changes [2]. However, the urban area of Eastern Europe represents in this context a particular case, as its evolution is determined, especially before the 1990s, by political or economic factors. The continuing urban transformations and the urban growth complexity, as well as the pressures resulting from severe environmental and social problems, have attracted researchers' attention and have often undertaken a number of approaches that explore components of the dynamics of urban sprawl, including study models of possible future scenarios that can provide a basis for the elaboration and evaluation of urban policies, besides the simulation of the real system and, consequently, give a better view to the decision-making domain.

The general objective of the present paper was to evaluate the urban expansion of the Cluj Metropolitan Area and, additionally, to simulate the urban extension of the same area to the year 2030, by using the cellular automata.

The structure of this article presents five individual axes, being interconnected with each other. Firstly, the theoretical framework expresses mainly the bibliographical review, the definition of the key concepts and the highlights of the types of problems pertinent to the theme. Next, the territorial framework aims at characterizing the case study, as well as the corresponding territory. The third part comprises the description and justification of the methods used in research development. The results and discussions form the fourth part of the study and the final considerations reveal the main conclusions, verifying to what extent the objective of the research was fulfilled, showing simultaneously the usefulness of the study for future similar developments.

2. Theoretical framework

With the development of "Chaos Theory" and the tools offered by GIS and geocomputation environments, a development of spatial analysis methodologies was verified, which originated the emergence of the cellular automata (CA), which some literature considers a new area of knowledge that combines recurrent GIS approaches with other methods such as genetic algorithms [3].

The cellular automata were developed by Ulam in the 1940s and soon used by Von Neumann to investigate the logical nature of self-reproducible systems [4]. The urban modelling through cellular automata has been used to analyse and simulate / articulate the present and future of the city [5:1312], or even to produce artificial urban planning experiments [2:146], representing a powerful alternative to point out "where", "when" and "how" in the ambit of city expansion [6:2], thus being considered a challenge with outputs increasingly more satisfactory for the contemporary urban research. As a result, a number of researchers have developed studies based on cellular automata, specifically starting from the 1990s [7, 8, 4, 9, 10, 2, 11, 5, 3, 12, 14, 6, 15, 16].

Regarding the definitions of the cellular automata, they ship in various formats and structures. In a very simplified way, a cellular automaton is "an entity that has the mechanism to process information based on its characteristics, rules and external inputs" (Benenson & Torrens 2004, Liu Y. 2009, quoted by Xavier [1:12]). Precisely, the cellular automaton is a discrete mathematical model, especially useful for the representation of spatial evolutionary processes due to its own characteristics. They are still defined as promising tools for dealing with local interactions and neighbourhoods, spatial irreversibility, cumulative processes and variety of behaviours, which makes them a useful tool for simulating the use of urban space [17:7].

The complex system models with geographic properties often involve spatial and temporal processes that are difficult to incorporate into a GIS environment. These models require spatial and sectoral interactions that can be manipulated and are not easily adapted to the functionalities of the GIS software. During the last few years, the various static urban models, which are still the most used in the formulation of urban policies, were challenged by more explicit urban models. These models are based on urban development processes, with the time rather than the space as central organizing principle, making their incorporation into GIS rather difficult. However, it is possible to develop software modules with special functionalities that can be interconnected with GIS in various ways. The models can be connected to GIS through inputs and outputs. Although useful, these links are based on pragmatic approaches to allow a software purpose other than the one for which it was designed [8].

Besides the cellular automata, among the techniques that can be employed and that give importance to the spatial relations are the Markov chains. These allow to define the rules in which the cellular automata operate. The Markov models begin with estimations of transition probabilities and make them dependent on the state of neighbours if such dependence is discovered. These demonstrate the conditional probability of any future event with variables defined to occur in a discrete time space, but when a cellular automata filter is applied in the projections resulted from a stochastic process, explanatory variables of change are incorporated and a result closer to the verified reality is produced [18].

The cellular automata represent a type of urban model that works quickly and consistently with GIS. In these models, the temporal processes of change are represented through entirely local actions, which occur in the immediate proximity of the various objects that compose the respective system. In the spatial systems, the objects are usually modified as cells that can assume multiple states and are summed up by what is happening in cells in their immediate proximity. Even though the cellular automata models do not necessarily need to be spatial, most models choose to represent the spatial system in a regular network. The dynamic change is thus generated as a change in a cell that is a function of the states of the cells of the first nearest neighbours [8], being that these models are based on simple reaction-diffusion equations. The state of any cell depends on a certain function that reacts to what is already in that cell and relates the cell to what is happening in its immediate neighbourhood - the diffusion component. What is peculiarly attractive about the cellular automata models to simulate urban systems is that the local action in these models can give rise to global forms that arise spontaneously, with no hidden factors directing the evolution of the macrostructure [8].

The modelling using cellular automata is one of the advances in spatio-temporal modelling techniques for the field of urban growth dynamics. Some models have shown satisfactory simulations of urban spatial expansion over time. Leao et al. [2] refer to the models developed by Engelen et al. (1995) and Clarke & Gaydos (1998), who investigated the possibilities of applying the cellular automata to mold and simulate future urban growth patterns and the model developed by Clarke & Gaydos (1998), called “UGM”, which proved to be a successful application of historical maps with remote sensing data. In recent years, new models of cellular automata, such as URBANSIM, UPLAN, SLEUTH, have been used [13].

3. Territorial framework of the study area

In an era of demographic declining cities, especially in the case of the countries of Eastern Europe, the city of Cluj-Napoca is an exception that has positioned itself favorably in the international competition due to two main advantages: economic growth and population growth, respectively. Being the main university center of the country, having a vibrant multicultural dimension, the city stands out as one of the most promising urban poles in Europe in terms of future development. Taking into account these prerogatives, one can easily deduce its present and overcoming urban dynamism.

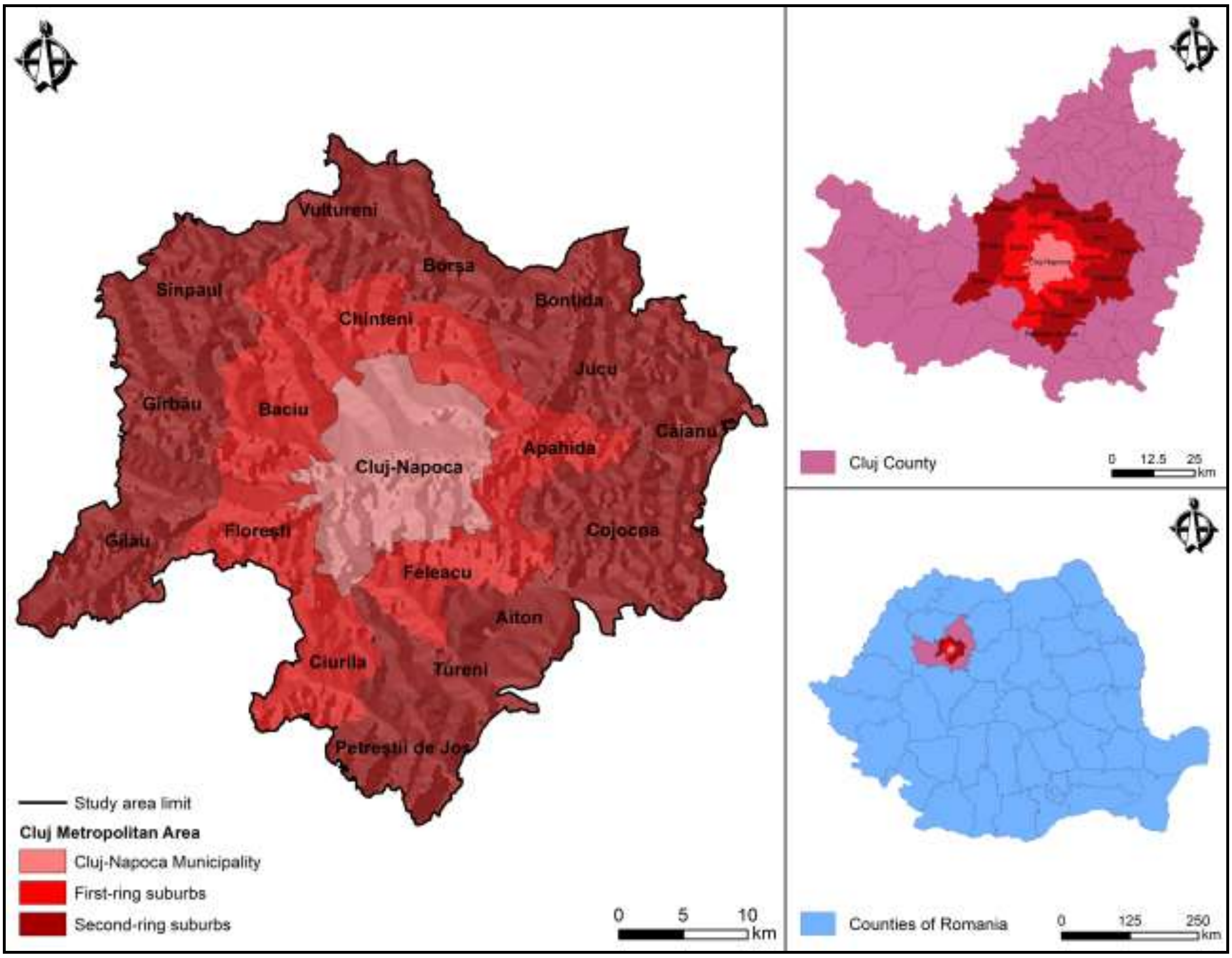

Figure 1. Geographical location of the study area

The metropolitan areas of Romania are regulated by the Romanian Law no. 351 of 2001 on Spatial and Urban Planning [19], being areas formed by association based on voluntary partnership established by law between major urban centers, urban areas and rural areas, located at distances of up to 30 km from the central municipality, and covering mutual relations of cooperation in various domains.

The Metropolitan Area of Cluj was founded in 2008 through the Decree-Law HCL 415/2008 [20] and includes the Municipality of Cluj-Napoca plus another 18 administrative territorial units (Fig. 1). Regarding its size, the area measures about 1,537.54 km² [21].

According to the population censuses, the demographic dimension of the area under study has had a positive trajectory over the last years. In 1992, the area had 388,055 inhabitants, in 2002 - 389,694 residents, while in 2011 it had a total population of 403,143 inhabitants, although in 2017 it continued to increase, reaching about 427,265 people [22]. Particular cases are the city of Cluj-Napoca, which increased during the same period from 311,674 inhabitants in 1992 to 322,572 residents in 2017, and even more evident, the administrative territorial unit of Florești, composed of 3 villages, which in 1992 had only 5,916 inhabitants, while in 2017 the total population increased more than five times, registering 31,564 inhabitants. It is also worth to emphasize the temporary residence in Cluj-Napoca of approximately 100,000 people per year, due to the academic character of the municipality.

4. Methodology

Firstly, the land suitability to new constructions map in the Cluj Metropolitan Area was carried out through Raster and Map Algebra analysis, using in this sense the slope, hypsometry, soil occupation of 2012 and distance to roads (Cost Distance). In the case of the slope, hypsometry and distance to roads, the most favourable classes were those with lower values. Contrariwise, the favourable classes for the land occupation were the categories that were most likely to be converted into urban space – e.g. continuous and discontinuous urban space, rural space, pastures and meadows, etc., with average favourability were the classes of agricultural land, vineyards, etc., while the less favourable classes concerned forests, wetlands, protected areas, extraction areas, etc. The four raster maps were further reclassified into five favourability classes (1 - unfavourable → 5 - very favourable) and summed up as a function of this value (Map Algebra). In the end, these were reclassified in the same 5 favourability classes, resulting the final land suitability map that indicates how suitable the land is for the location of new constructions.

Secondly, with the aim of predicting the urban expansion in the Cluj Metropolitan Area, data on land use, distance to roads, distance to urban area, slope and two restrictions on protected areas and wetlands were considered. For the elaboration of the empirical part of this article were used two GIS software: the ArcMap and the IDRISI, Taiga version. The first one was used to prepare and convert all the data to raster format and afterwards to ASCII, setting up for this purpose the Stereo 1970 Dealul Piscului coordinate system, since it is the standard cartographic projection system established for Romania. The data structure that best fits this method is the matrix one, in which each automaton is a cell. In order to maintain the same number of rows and columns of the matrix (205 x 205 m), as well as the resolution of the pixel, a file was created corresponding to the study area that served later as a mask to all the other layers, guaranteeing thus their equality.

The first step involved the land use data collection for the years 1990 and 2012 (extracted from the Copernicus - Land Management Service site under the aegis of the European Union [23]) and converting it to matrix format. After establishing the urban types of use, it was created a map in binary format, where the non-urban area has received the value 0, while in the case of the urban area the value 1 has been assigned to it. The resulted map permitted to calculate the distance to urban area, as well as the distance to roads. Further, it was necessary to normalize the variables and define the transition rules, using the Fuzzy function (Table 1), with a probability scale from 0 to 1 (Fig. 2). The multicriteria analysis was used for the prediction variables integration, for which there were defined two restrictions, as previously mentioned - wetlands and protected areas, and grouped into a Raster Group File (*.rgf).

Table I – Fuzzy function

Variable	**Function**	**Favourable intervals for urban extension**
Slope	decreasing sigmoidal function	0 – 12 (degrees)
Distances to roads		50 – 2000 (meters)
Distances to urban 2012		100 – 2000 (meters)

The weights of the variables were determined applying the WEIGHT - AHP weight derivation function, which is used to develop a set of relative weights for a group of factors in a multicriteria evaluation, hence indicating the relative importance of each factor involved for the adequacy of the pixels in the scope of the activity that is evaluated.

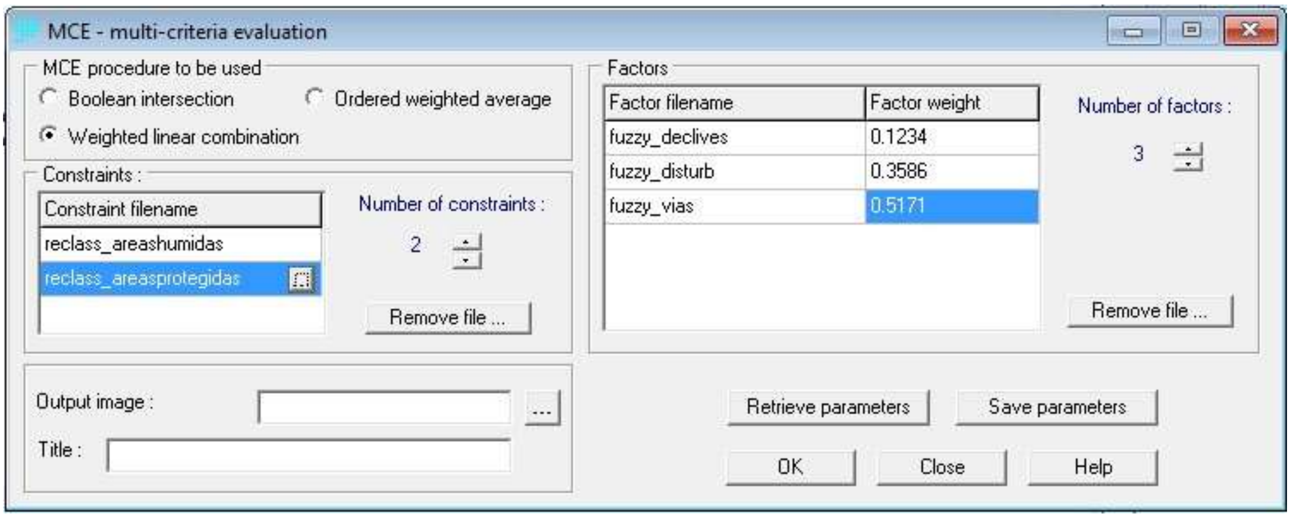

Figure 2. Weights of the variables and restrictive factors in the multicriteria analysis

Further on, the Markov chain predictive mathematical model was applied in order to forecast the number of cells that move from one class to another. For this, the land use maps of 1990 and 2012 were used, determining thus the transition probability matrix, the territorial quantitative matrix that transits between classes and a set of files of transition probability between classes. For the last step of the Markov chain method, the 2012 land use data, the file resulted from the previous step (Markov transition areas) and the Raster Group File resulted from the multicriteria analysis were utilised. It was also defined the number of iterations to 18, since the expansion forecast was for year 2030.

With the purpose of checking the veracity of the model, it was necessary to take into account the *Kappa coefficient* obtained through the *CrossTab operation*, by crossing the two classes contained in the land use files (the last year with the prediction year). This indicator varies from -1 to 1, where the negative values indicate that there is no relation between variables, values close to 0 mean a minor interrelation, while values close to 1 indicate a perfect correlation between components.

5. Results and discussions

By comparing the evolution of the urban space over the reference period (1990-2012), the most notable urban expansion occurred from 2002 to 2006, especially in the proximity of the city of Cluj-Napoca and of the larger villages (Floreşti and Apahida). It was also verified that the urban area expanded during the same period overlaps the areas with middle-, favourable and very favourable land suitability to constructions (Fig. 3), which in a certain way indicates that the natural characteristics of the terrain determine, in fact, the evolution of the built-up area.

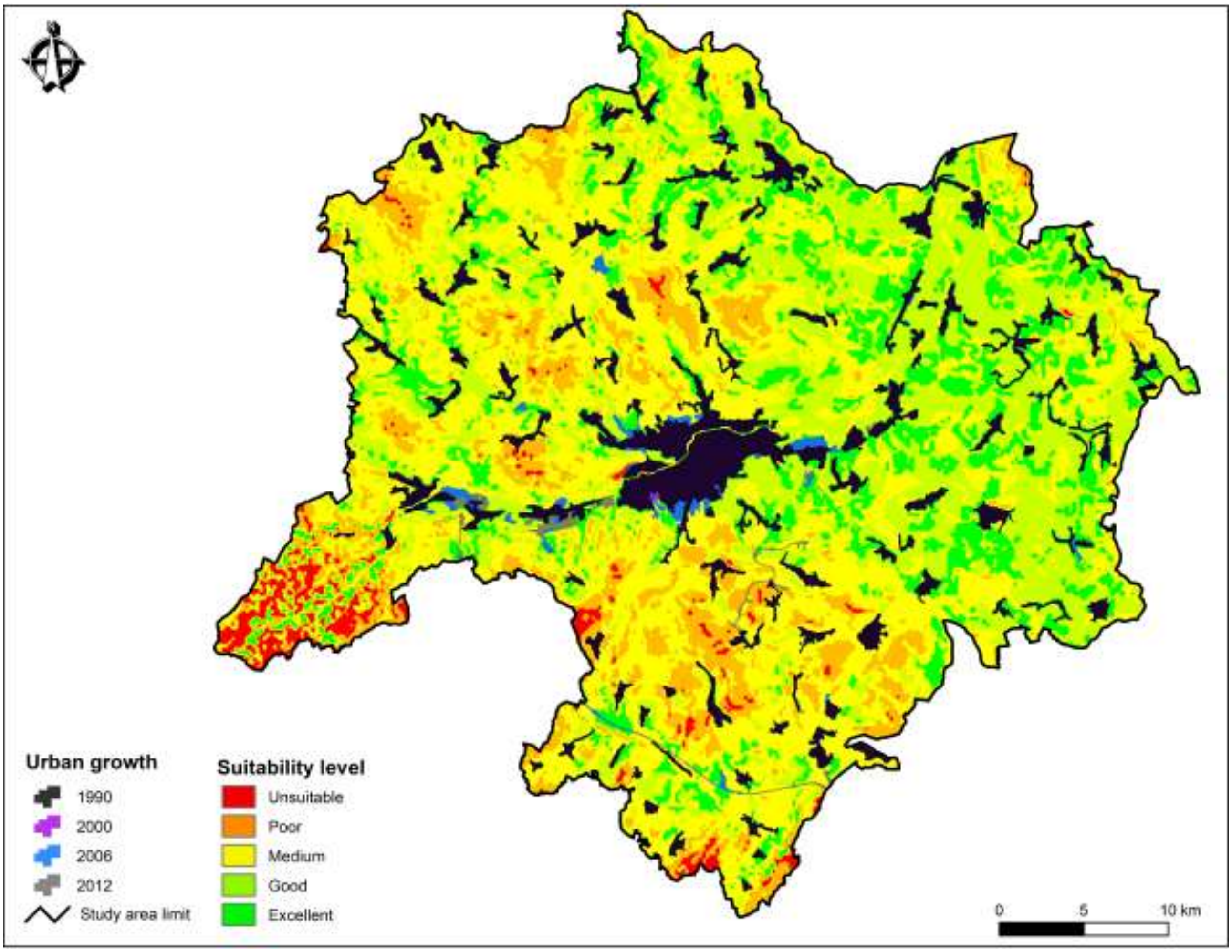

Figure 3. Urban growth between 1990 and 2012 and land propensity to new constructions

The results of the multicriteria analysis reveal, above all, a better adaptation of the urban expansion near the road network and the existing urban space. In general, the study area presents a reduced slope, which certainly supports the urban expansion. The Figure 4 reveals the combination of the various factors through their Fuzzy functions, which were applied for the distance to roads, the distance to urban and the slope, considering as restrictive factors the wetlands and the protected areas. It is important to underline that this function can integrate other variables, depending on the aims to be achieved. The probability matrix resulted from the Markov chains represents the probability of one class (urban or non-urban) to become another. In this case, there is a higher probability for the urban area to remain urban (about 99%), and 82% the probability of the non-urban area to remain non-urban. Another relevant aspect in this context is the probability of the non-urban area to become urban, with a probability of about 17%.

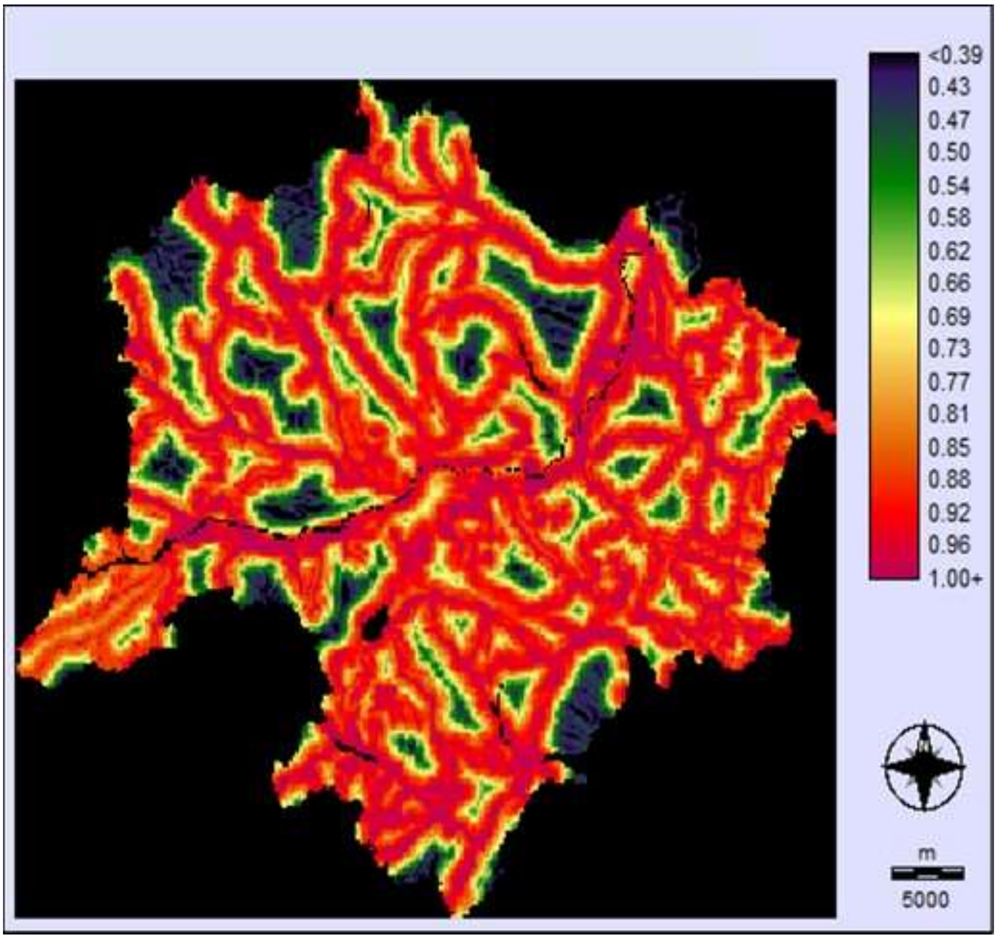

Figure 4. Adequacy of the land to urban expansion, according to the multicriteria analysis

Considering the Cluj Metropolitan Area forecast model, the Kappa index resulted from the cross-reclassification of the land use of 2012 and the land occupation projected through the Markov operation, was 0.9764, indicating a very strong correlation between the classes. In addition, the same operation generated the number of cells that would transit from one class to another. In the case of the non-urban class, 720 cells are expected to transit to the urban class. It should also be noted that the model considered that 252 urban class cells will transform into non-urban class during the same period, which in fact is very unlikely. Specifically, the absolute values of the extension of the urban class from 2012 to 2030 (see Fig. 5 and Fig. 6) are 19.66 km².

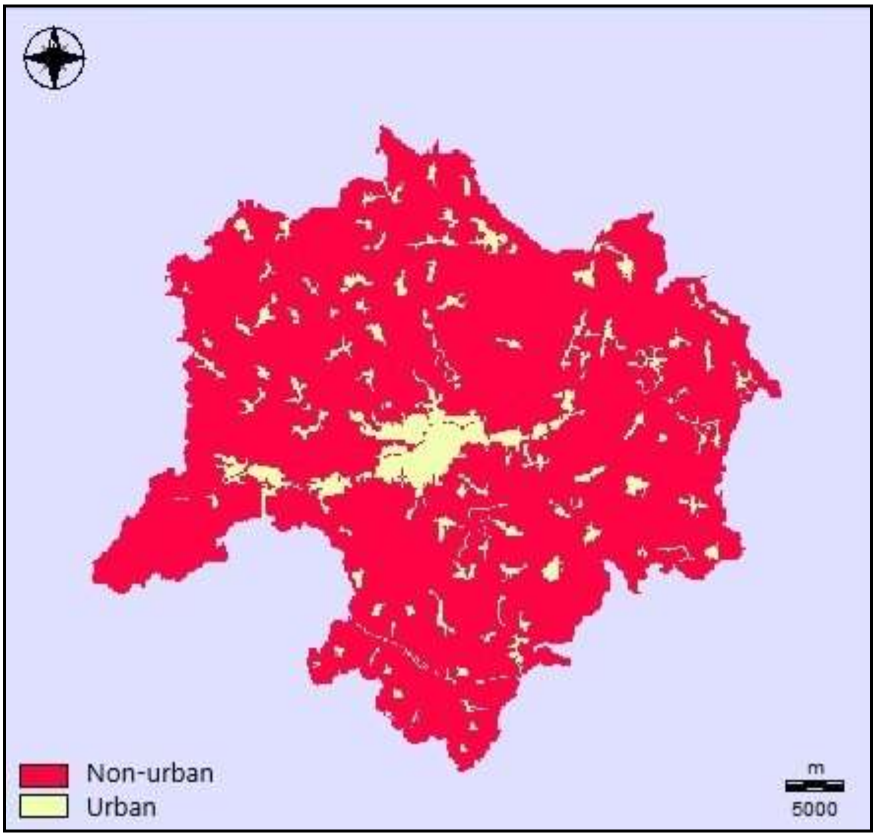

Figure 5. Soil occupation model as of 2012

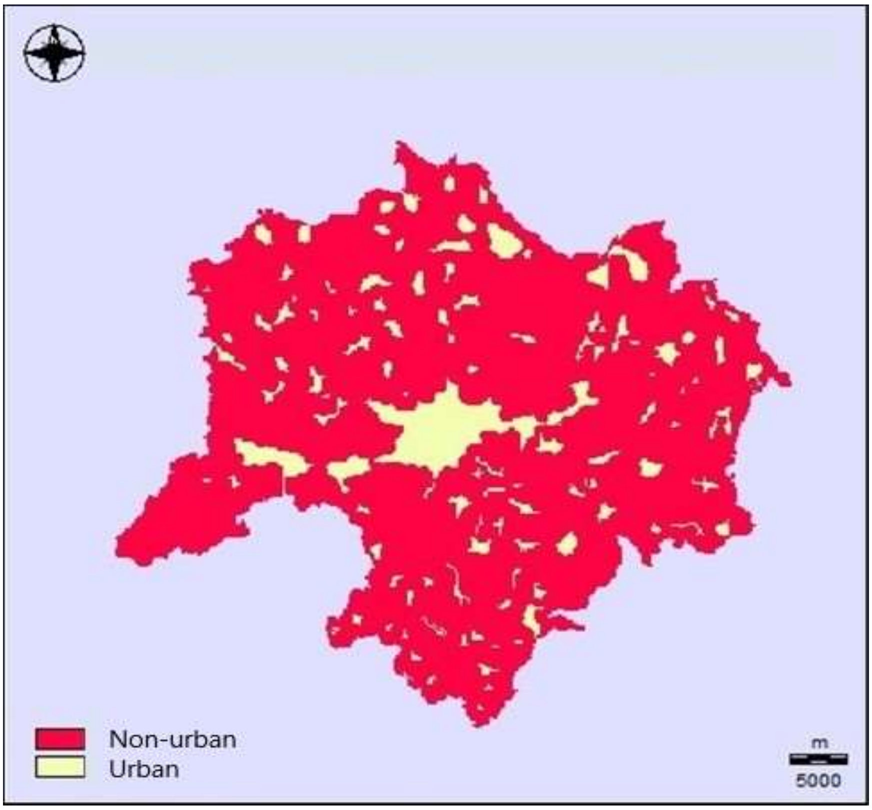

Figure 6. Soil occupation model projected for 2030

With regard to the configuration of the projected urban area, a greater degree of compaction can be observed (Fig. 6 and Fig. 7), this signifying a reduction of the urban space fragmentation when compared to that of 2012 (Fig. 5). On the other hand, there is also a clear spatial correlation between the urban space that already existed in 2012 and the urban area projected through the simulation, precisely in the case of Cluj-Napoca, Floreşti, Apahida, Bonţida, and Borşa.

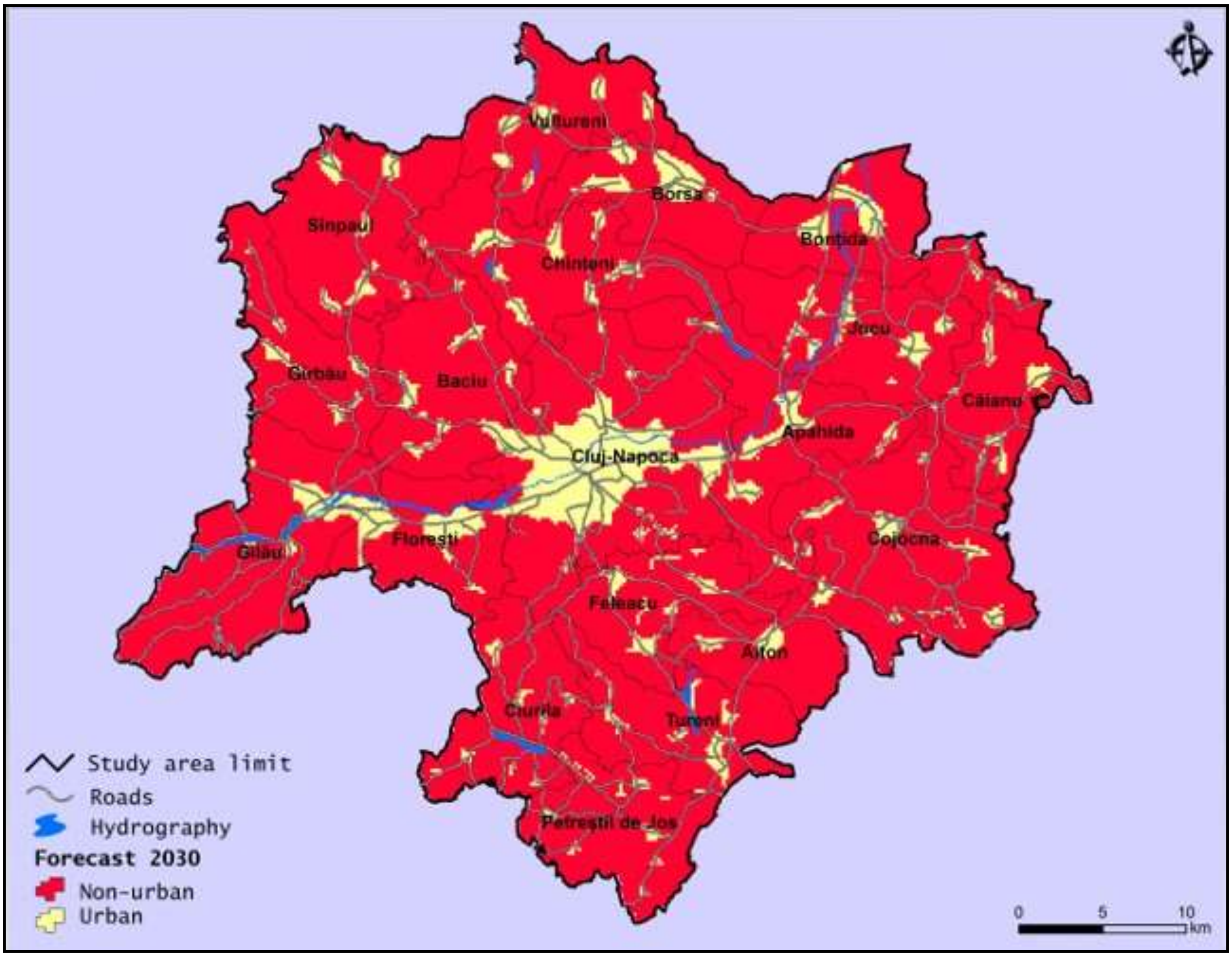

Figure 7. Land occupation prediction for 2030

6. Conclusions

The applied cellular automata model may be considered original for two reasons: first and foremost, there is a significant absence of similar studies in the national literature and, secondly, it combines the methods of Markov chains and cellular automata with spatial planning and GIS methods (land suitability to new construction, multicriteria analysis and Fuzzy analysis).

Uncontrolled land-use changes can produce serious problems, both socially and in environmental terms, being therefore of a great importance in the spatial planning context.

The forecast model elaborated represents an idealized form of the dynamics that could generate future changes for the studied area. What makes it appropriate for this type of study is the fact that it interconnects the concepts of space and time with the dynamics of the system under study in a very simplified way, even if it is characterized by complexity.

The prediction for year 2030 of the area occupied by constructions in the Cluj Metropolitan Area shows a continuous trend of urban expansion that has taken place over the last years, with a greater intensity near the municipality of Cluj-Napoca or in the proximity of the larger villages (e.g.

Floreşti, Apahida).

As in any other predictive model, the results obtained can present a certain margin of error when compared to the reality, this fact being determined mainly by the data complexity and integrity or, in certain cases, even by the researcher's profile.

The simulation of the urban expansion in the Cluj Metropolitan Area can be a valuable source of public policy and decision-making for local authorities. If it is of interest to make the forecasting results even more accurate, additional analyses, preferably combined with other related methods, should be carried out.

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