

USING THE SLEUTH MODEL TO SIMULATE FUTURE URBAN GROWTH IN THE GREATER EASTERN ATTICA AREA, GREECE

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Abstract

Urban sprawl is, undoubtedly, a global phenomenon that has been in effect since the dawn of civilization and has been an intriguing subject, primarily in the research field of geography. In recent years, the need to forecast and simulate real-world urban processes has led to advancements in computational methods on modeling these patterns. This paper reviews how primitive forms of urban settlements have gradually shaped into today's contemporary cities. In addition, the causes, types and impacts of urban sprawl are examined given the importance to predict negative effects when an urban project is built. Lastly, this study includes an application of a Cellular Automaton (CA) Urban Growth Model (UGM) in order to simulate future urban growth. For this endeavor, the greater area of Eastern Attica, Greece was chosen as case study due to the fact that it yet has vast non-urban areas that could be converted to urban in the foreseeable future. To produce the final simulation output, various sources of digital imagery were used and then processed according to the model's specific format. The final prediction scenario presents urban growth for the year of 2045 on Eastern Attica.

Keywords: Cellular Automata, SLEUTH model, urban sprawl, spatial modeling, GIS.

1. INTRODUCTION

It is a well-known fact that urban sprawl is a global phenomenon that has been active for centuries. It involves all the underlying processes and patterns that form the shape of cities and has an impact on its economy, its society and its environment. The increase of population on a global scale has an inherent repercussion on the rate at which urban sprawl manifests. In other words, any increase of population is bound to spatially manifest itself in the form of urban sprawl sooner or later, unless vertical expansion is possible and housing policies allow for tall buildings. It is imperative that we model and forecast urban sprawl in order to gauge its trends and patterns and examine its repercussions on existing natural habitats and ecosystems. Urban sprawl causes a chain reaction when expanding onto adjacent non-urban land uses that may be antagonistic to each other. For instance, rural land use and urban land use are rarely seen in adjacent areas due to the fact that the human actions that revolve around these land uses are in conflict. Lastly, when planners and policy makers forge a plan about future urban expansion or when they try to find measures to protect natural habitats against urban sprawl, they could use an Urban Growth Model (UGM) as a tool that can bring out the

trends of urban tissue expansion and pinpoint the areas which could be problematic in the near future. Thus, UGMs play a huge role in the effectiveness of policy making and planning in order to achieve sustainable growth.

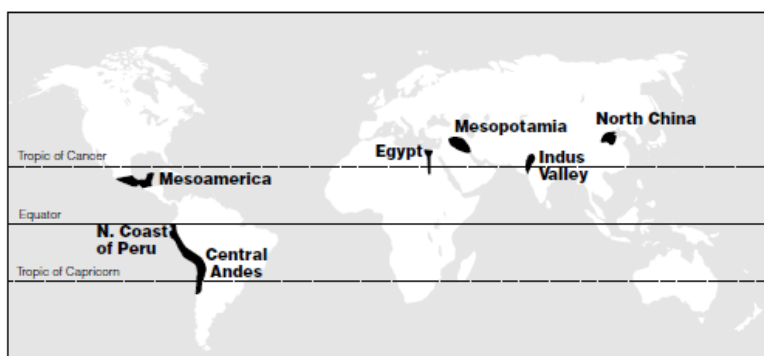
The first attempts on urban modeling were unsuccessful, producing models that were not accurate and were oversimplifications of the forms and underlying processes that cause cities to expand. They were lacking the physical, spatial and economic factors that are involved in the process of urban sprawl and hence were unable to effectively simulate the complexity of urban systems. However, the last two decades have seen a plethora of models being published and a whole new era of urban modeling. This is mainly because of the technological advancements in computer architecture that enabled more robust computational methods and environments that could facilitate the aforementioned models. In addition, the advent of the Internet has allowed for an unprecedented dissemination of high quality spatial data that could be implemented in urban model studies. In 2010, Santé, Garcia, Miranda and Crecente documented 33 models that had been published by then, presented a structured overview of their strengths and weaknesses, and highlighted the different approaches to which these models subscribe.

In this study, the second chapter includes a historical overview of how the first urban settlements gradually involved into contemporary cities and an examination of urban sprawl as a distinct and recently developed phenomenon. The third chapter refers to the causes of urban sprawl, the fourth chapter refers to theory of urban growth models, and the fifth chapter refers to the implementation of a CA model to forecast urban sprawl in the area of Eastern Attica, Greece. The final chapter summarizes the conclusions.

2. BACKGROUND

Before examining the urban sprawl phenomenon, one must first examine the “city” phenomenon as a concept and as an entity and the correlation between ancient cities and contemporary urban forms. According to Doxiadis (1971) there is a direct correlation between ancient Greek cities and modern ones through excavation findings which prove that there is a correspondence of contemporary and ancient times, for 10 ancient settlements have been found, namely in Thasos, Greece, and there were also 10 modern communities.

Ever since man abandoned the wandering-hunter lifestyle and evolved into a being that could harvest the land and raise stock, the need for cohabitation became evident and crucial to his survival, and thus forced him to settle in natural space which, according to his capability, he modified to facilitate his needs creating the first primitive forms of urban settlement (Aravantinos, 2007). Between 6000 and 4000 B.C. certain inventions -such as the ox-drawn plow, the sailboat, and the domestication of new plants- allowed for the Neolithic populations to utilize these inventions in fertile regions (Figure 1), settle close to them, and form the first towns (Davis, 1955). By 3000 B.C., other inventions including writing and accountancy, bronze, the beginnings of science, and the solar calendar, made larger settlements possible in Egypt, Mesopotamia, and India; Davis (1955) coins the term “true” cities when referring to these settlements (Tsompanoglou & Photis, 2013). The first cities in Mesopotamia existed around the Tigris and Euphrates rivers, with Ur being one of the earliest cities which was the capital of the Sumerian Empire from 2300 B.C. to 2180 B.C. (Pacione, 2009).



Source: Yoffee, 2005

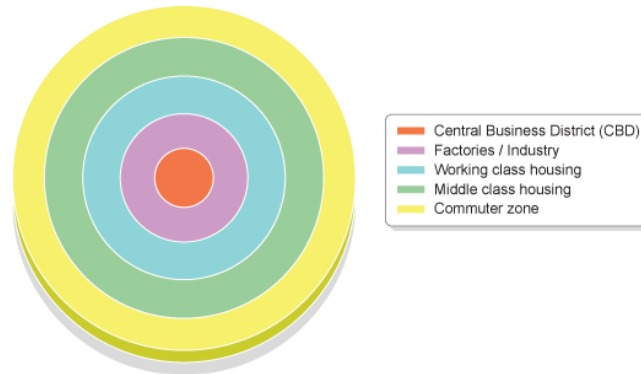
Figure 1. Earliest states and civilizations

In ancient Greece, cities were small in size –roughly 1.8km² on average- and their average population probably did not exceed 10,000 even in some of the major cities of that time, such as Athens, Corinth, Delos, Priene, Miletus, Piraeus, Olynthos and Selinus (Doxiadis, 1964). Also, Doxiadis (1964) distinguishes two primitive urban forms that were evident at that time: cities created through natural growth and cities created with the Hippodameian system. Doxiadis explains that the former form was seen at the oldest and at the cities of continental Greece with Athens being the most typical representation of this form. These cities were developed around a prominent location, usually a hill or a rock, called the Acropolis, where citizens would take refuge in case of war or attack (Doxiadis, 1964). Gradually, the city developed around the Acropolis core in wider circles, forming a second core at its lower part, called the Agora, which acted as a place for political, commercial and social gatherings (Doxiadis, 1964). The second urban form, according to Doxiadis (1964), is the Hippodameian system inspired by Hippodamus the Milesian. In this system the city is built based on a grid of parallel streets that favors simplicity and functionality presenting the simplest solution of layout with the fewest complications (Doxiadis, 1964).

Although Ancient Greeks significantly contributed to the advancement of urban planning in their time, it was the Romans who explored the full potentialities of the ancient world to support a large city (Davis, 1955). Pacione (2009) suggests that the Romans adopted the Hippodameian system in cities of Western Europe, such as London, Brussels, Seville, Cologne, Paris, Vienna and Belgrade, that they conquered and that the typical form of a Roman imperial settlement would be inscribed into a rectangular or square perimeter, have two main cross streets (the east-west and the north-south), and host the Forum (a place equivalent to the Greek Agora), the main temple, the theater and the public baths in one of the angles formed by the intersection of the two aforementioned principal streets.

Fast forwarding to the 19th century, the industrial revolution brought about urbanization at a much faster rate and reached proportions far greater than ever before, an example that verifies this assumption could be found in London where its outer ring, since 1861, has been growing more rapidly than its core (Davis, 1955). Hence, the 19th century witnessed the flowering of industrial capitalism in Western Europe and the rapid growth of the European industrial city, which was developed to fulfill the needs of capital (Pacione, 2009). Meanwhile, in the U.S. industrial cities were also prevalent and forced the department of urban sociology of the University of Chicago to conduct extensive research on the city of Chicago, which had recently expanded primarily due to industrialization (Hall, 2005). By examining the urban patterns of Chicago, Park, Burgess and McKenzie (1925) illustrated the urban form model that they came up with using a diagram of the city as a series of concentric circles (Figure 2) where the inner circle contained the central business district (CBD), the

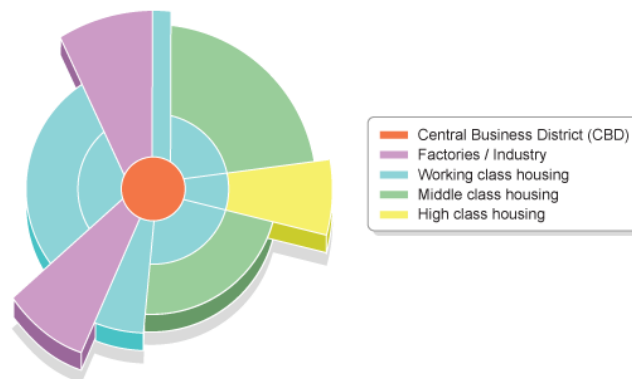
next zone housed the poorest citizens and some light manufacture, the third ring area consisted of housing for the working class, and the outer ring comprised single-family residential areas where the social elite, which could afford the long commute, lived (Bruegmann, 2005).



Source: Urban models in MEDCs

Figure 2. Burgess's model of the industrial city

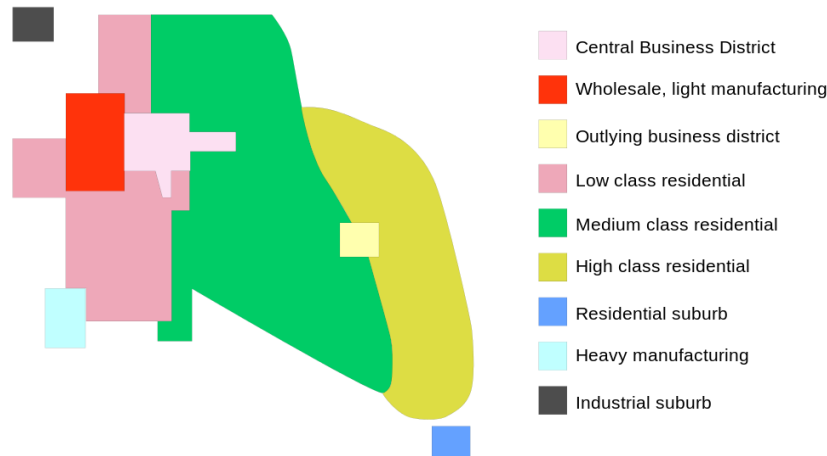
According to Bruegmann (2005), Burgess's model contained some flaws and limitations, such as the fact that industry did not concentrate in concentric bands; more likely it followed lines of water and rail lines. Another flaw that he exposes is that within each ring described in the model there were actually wide variations of income and social class. So, in order to make up for the shortcomings of this model, Hoyt (1939), after extensive research on the historical urban change in major cities of the U.S., came up with a variation of the model in which the city is clustered into sectors (Figure 3).



Source: Urban models in MEDCs

Figure 3. Hoyt's model

After the Second World War, Harris and Ullman (1945) claimed that the majority of cities at the time were not built around a single center but rather around several distinct nuclei, contradicting the theoretical base of the two previously mentioned models. Thus, in an effort to model the emerging changes in the pattern of cities, Harris and Ullman (1945) proposed a new and refined model (Figure 4) that acted as a combination of the Burgess's and Hoyt's models.



Source: Wikipedia (image under public domain status)

Figure 4. Harris and Ullman model

Although researchers had been working on modeling urban forms while the cities were developing rather slowly and maintaining most of their spatial pattern, recent decades have seen an unprecedented growth of the form of cities due to urban sprawl that has challenged efforts to model and forecast urban processes. It is evident that since 1970 the urban sprawl phenomenon has started to occur originally in the U.S. Metropolitan areas, as Table 1 depicts. It can be safely said that urban sprawl is an American phenomenon triggered by innovations such as the automobile, by government policies that favor suburban housing, by a lack of central planning and by the availability of vast peripheral land, yet suburbanization is ubiquitous and can be characterized as sprawl in European countries as well, hence the U.S. experience may be generalized (Hamidi & Ewing, 2014).

Table 1. Total Population of U.S. Metropolitan Areas, 1970-2010

Year	Suburban population	Urban population	Sprawl index
1970	49,101,068	84,283,519	36.81
1980	69,967,436	84,680,392	45.24
1990	85,239,692	92,431,065	47.98
2000	101,295,542	102,952,391	49.59
2010	114,357,186	111,554,393	50.60

Source: Lopez, 2014

As Hall (2005) aptly mentions, cities, since their initial formation, have exhibited gradual transformation through procedures such as enlargement, addition of new fragments or demolition, although these procedures can be characterized superficial since the core pattern of the city usually stayed intact. However, he also suggests that in recent decades some fundamentally different procedures have come into force and have accelerated the rate at which urbanization occurs, resulting in new conspicuously differentiated urban patterns. This leads to the conclusion that urban sprawl is a relatively new phenomenon that is now in effect and shapes the form of cities more aggressively than ever before.

3. CAUSES OF URBAN SPRAWL

There is no absolute unanimity when it comes to debating whether urban sprawl has positive or negative impacts on the life of citizens or whether it is a good or a bad practice for urban planning. It is an issue that has raised controversy among the research community. However, the majority of researchers contend that urban sprawl should be tackled in order to achieve urban space sustainability. So, it is vital that we pinpoint the causes of sprawl in order to effectively combat this issue.

First of all, the advent of the automobile, the improving quality of transportation networks, and the Internet have enabled the population to reside in suburbs that are separated spatially from the main urban core of the city but can be linked functionally with it and provide equal or even better quality of life than the central areas (Rui, 2013). However, in Europe, namely in London, the driving force behind the growth of suburban housing was initially the development of railroad network and public bus transportation while private automobile played little part in the development of urban sprawl (Chin, 2002; Batty, Besussi & Chin 2003). Moreover, according to Lawrence (2005), sprawl in the U.S. was caused by a series of public-policy decisions that promoted and encouraged the development of suburban areas. Specifically, she mentions that a mixture of federal, state and local policies laid the foundation for the manifestation of sprawl in the U.S. from as early as the 1930s. Finally, population growth is undoubtedly and obviously one of the most important causes of sprawl since any increase of urban population forces the city to expand upward or outward, in the latter case onto agricultural or resource land (Torrens, 2006).

4. URBAN GROWTH MODELS

UGMs are, essentially, a simplification of reality that represents urban systems in a way that highlights key elements of the system and omits complex ones that are not necessary for the simulation, and thus enable experimentation with theory in an effort to produce predictions of future situations (Batty, 2009). UGMs can also be seen in the perspective of a planning decision support system, depicting the future impacts of different scenarios of spatial interventions and thus allowing for a loop of adjustments to the proposed policies until reaching the goal at hand (Berglund, 2014).

UGMs depend on a variety of techniques and methods and can be classified accordingly. Almost every model utilizes a mathematical mechanism in order to function properly but there is a class of models that relies heavily on such mechanisms, also implementing economic theories, such as regional economic models and land market models (Rui, 2010; Parker, Manson, Janssen, Hoffmann & Deadman, 2002). Waddell and Ulfarsson (2004) mention microsimulation models as a modeling approach that is applied at the level of the individual, allowing for prediction of changes in the state of individuals or households and their choices such as residence location. Finally, another major class of models, on which this paper focuses, is the Cellular Automata (CA) models. By definition, CA models are “a class of spatially disaggregate models, often pictured as being formed on a two-dimensional lattice of cells, where each cell represents a land use and embodying processes of change in the cellular state are determined in the local neighborhood of any and every cell” (Batty, 2009). In other words, cellular refers to a representation of spatial space through a grid of cells, which can represent various land uses or just urban and non-urban ones when modeling strictly urban change. Each cell has its own neighborhood of cells with which it interacts according to a set of transition rules defined by the model creator. The word automata refers

to an iterative process that stipulates the state of each cell, according to the defined transition rules, and takes place at initialization, calibration or prediction phase of the model.

5. MODEL IMPLEMENTATION

In this study the SLEUTH model, introduced by Clarke, Hoppen and Gaydos (1997), was used to forecast urban sprawl in Eastern Attica, Greece. SLEUTH is an acronym of its required input data, which are the Slope layer, the Landuse layer, the Excluded layer, the Urban layer, the Transportation network layer and the Hillshade layer (Liu, 2008). In detail, the model requires landscape data in the form of Slope and Hillshade, although Hillshade is optional and only used for visualization purposes, Landuse layers, which are also optional, an Exclusion layer that places constraints on urban growth, at least four historical Urban layers, and finally, at least two Transportation network layers (Dietzel & Clarke, 2004). These input data feed the calibration process, a step necessary prior to the prediction phase of the model. Inarguably, the effectiveness of a model's calibration is the most crucial factor that affects the value of its predictions (Clarke, Hoppen & Gaydos, 1996). During calibration, the model produces Monte Carlo simulations using all possible combinations of the five coefficients (diffusion, breed, spread, slope resistance and road gravity) that control the system's behavior and subsequently compares each simulation to the historical (actual) data that the user provides as model input (Clarke et al., 1997).

5.1 Study area

Eastern Attica includes the municipalities of Pallini, Rafina-Pikermi, Spata-Artemida, Markopoulo, Koropi and Peania (Figure 5). This agglomeration of municipalities is known as Mesogheia and was designated as study area for this application. Its boundaries derived from the latest regulations of Kallikrates Project that came into force in 2011.

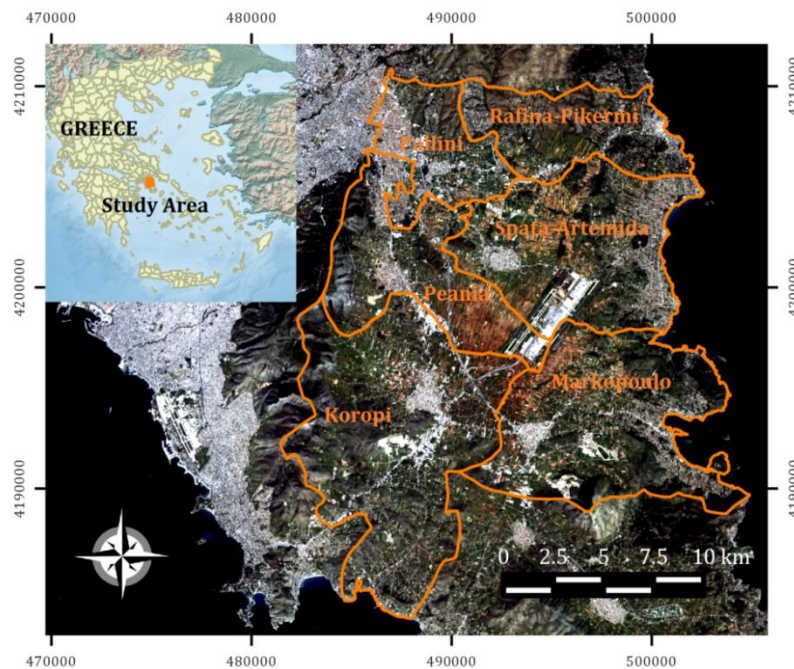


Figure 5. Location of the study area

The main reason that Mesogheia was chosen as a study area is because, unlike the main Attica basin, it is an area with vast lands available for future urban growth. In Figure 6, it is clear that the Attica basin, seen on the left of the picture, is almost fully saturated when it comes to urban tissue and a study of future growth on that area would be pointless. This fact gives incentives for residents to move from the core of the Attica basin into the adjacent Eastern Attica area and settle there, thus it is almost certain that in the future the Eastern Attica will experience significant urban growth. Hence, applying a CA model on that area would produce predictions that would be beneficial for planning purposes and future policies.

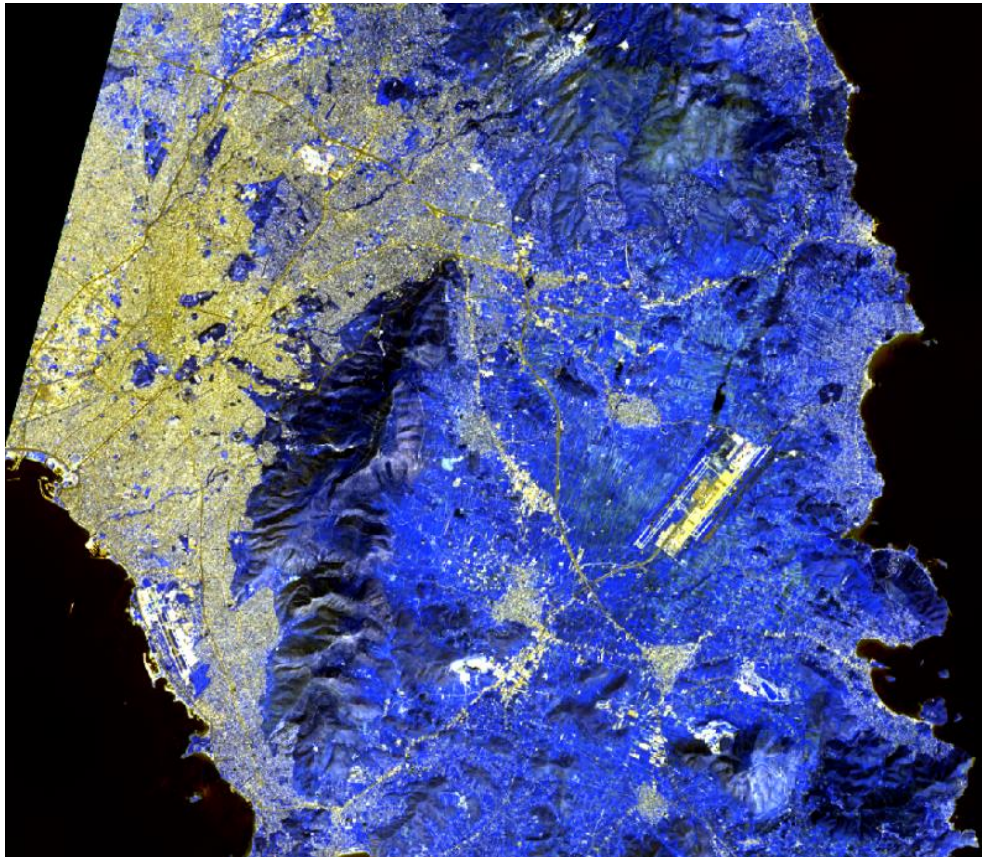


Figure 6. Landsat 8 composite (channels 7-6-4) showing urban pixels in shades of yellow

As seen in Figure 7, starting from 1984, the major urban nuclei settlements comprising the main urban land cover of Mesogheia began to expand as a result of the local population growth and the immigration from the Attica basin showing signs of organic growth along with road-influenced growth occurring near areas of the main road network that connects the urban centers of the municipalities. It can be observed that by 2015 the amount of urban land was almost four times bigger than what it was back in 1984. Mesogheia used to be a purely rural area that contained some villages with low population. In recent years, there have been significant improvements in its infrastructure, such as the Suburban Railway, the Athens International Airport in Spata, the Attica Tollway and the Imittos Western Peripheral Motorway which have consequently shaped the current urban form and have attracted population from the Attica basin.

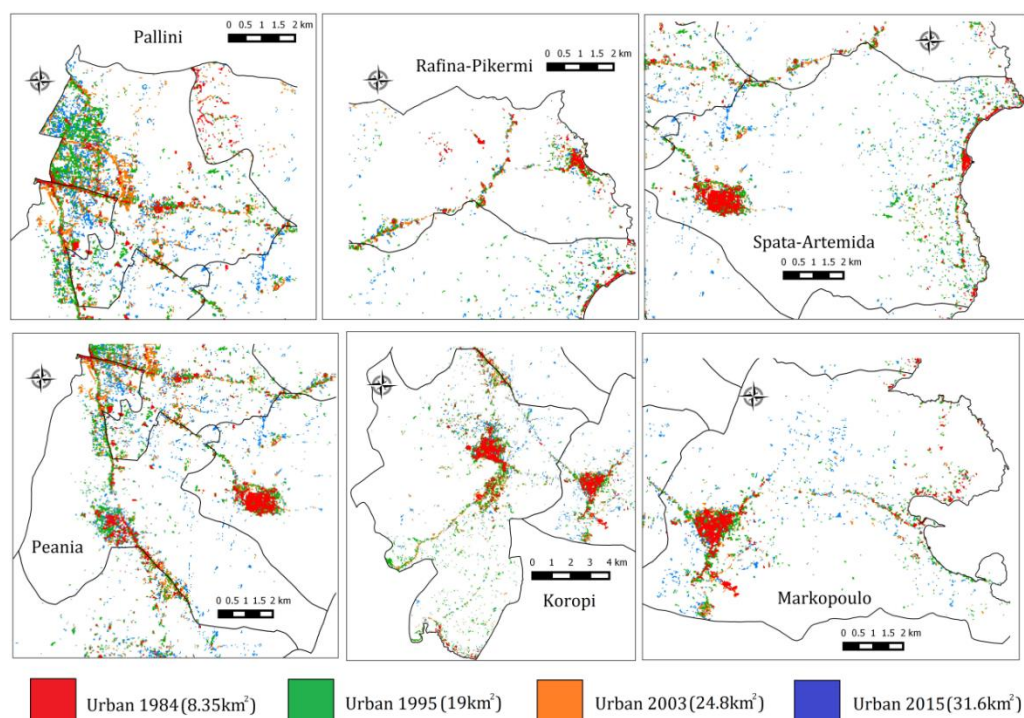


Figure 7. Urban growth change for Mesogheia between 1984 and 2015 time period

5.2 Model input

SLEUTH needs certain levels of information in order to function and predict urban growth (Table 2). These are the Slope, Land-use (optional), Excluded land, Urban areas, Transportation network and Hillshade. In essence, all the input data are grayscale, 8-bit images of GIF format that must all have the same dimension. If land-use is to be modeled as well, then the Deltatron model comes in play that supplements the Urban Growth Model (UGM) of SLEUTH and runs subsequently. In this study the Deltratron model was not used.

Table 2. Model input of SLEUTH

Model inputs	Number of layers
Slope	At least one layer is needed. The pixels of that layer have values that represent the percent slope
Land-use	Optional layer. If Land-used is to be simulated, at least two layers of Land-use are needed that must match, historically, the oldest and the newest Urban layers respectively
Excluded	At least one layer is needed
Urban	At least four layers are needed deriving, usually, from three distinct past years and one from the current year
Transportation	At least two layers are needed that must match, historically, the oldest and the newest Urban layers respectively
Hillshade	Optional layer that is used for enhanced visualization

Figures 8, 9 and 10 depict the input data used for the implementation of SLEUTH. The majority of primary data were obtained from Landsat 5 and Landsat 8 imagery available through the online database of USGS. That data were processed using GIS software in order to transform the images into the format that the model requires.

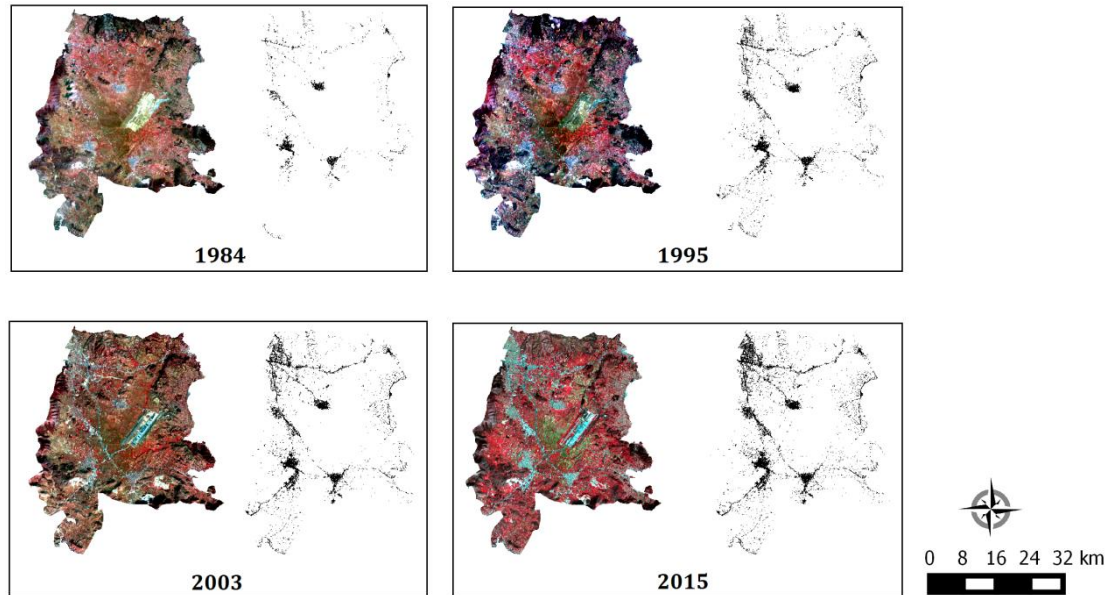


Figure 8. Urban extent layers for different time periods

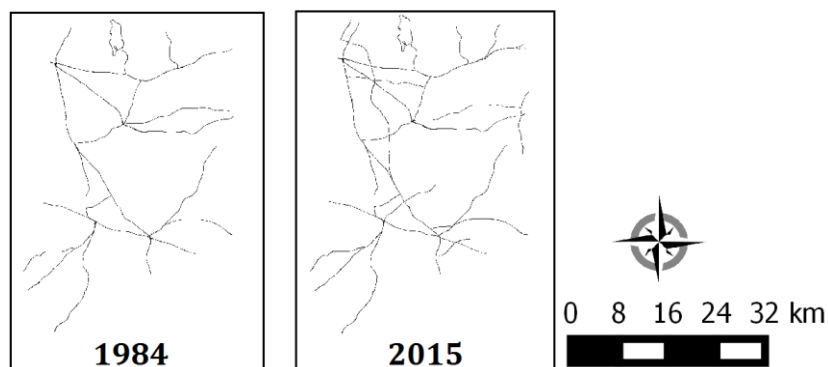


Figure 9. Road network layers for different time periods

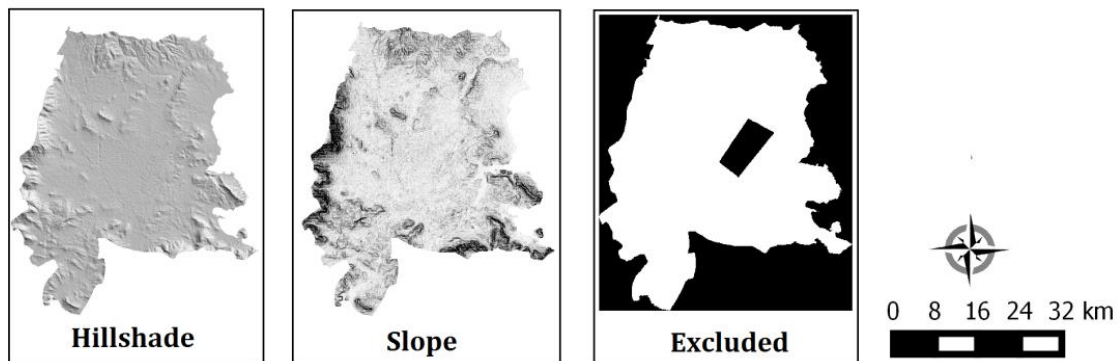


Figure 10. Hillshade, Slope and Excluded layers

For the years 1984, 1995, 2003 and 2015, the Urban extend layer was produced by a semi-automatic classification algorithm so that all pixels of the Landsat images were classified into urban and non-urban. The transportation network was produced from manual digitization of Landsat images. The Slope and Hillshade layers were the product of a Digital Elevation Model provided by the ASTER satellite.

5.3 Prediction phase

After the initialization and calibration of the model, the optimum set of coefficient values (Table 3) that fit the historical data has been determined. The prediction output depicts a scenario of urban growth for period from 2015 to 2045. The final output, in essence, is a probability map with each color representing a probability that a certain pixel will become urban in the year 2045. The color representation of each range or probabilities is shown in Table 4 along with its corresponding number of pixels.

Table 3. Final set of growth coefficients

Growth coefficients	Values
diffusion	1
spread	30
breed	1
slope resistance	6
road gravity	38

Table 4. Probability color table

Urbanization probability(%)	Probability color	Number of pixels	Area (x1000km ²)
100-90		21230	19107
90-80		9693	8724
80-70		6706	6035
70-60		5622	5060
60-50		5049	4544
50-40		5025	4523
40-30		5225	4703
30-20		5731	5158
20-10		7717	6945
10-0		15971	14374

The prediction scenario of 2045 urban growth (Figure 11) shows a somewhat mild growth expanding outward from existing urban settlements. This growth can be characterized as organic, although some new urban nuclei can be seen as a result of spontaneous growth. This type of forecast brings out the more probable trends of urban growth according to the calibration results that manipulate the prediction process. This is why calibration is the most

crucial step of the model implementation because it is responsible for the accuracy of the prediction phase.

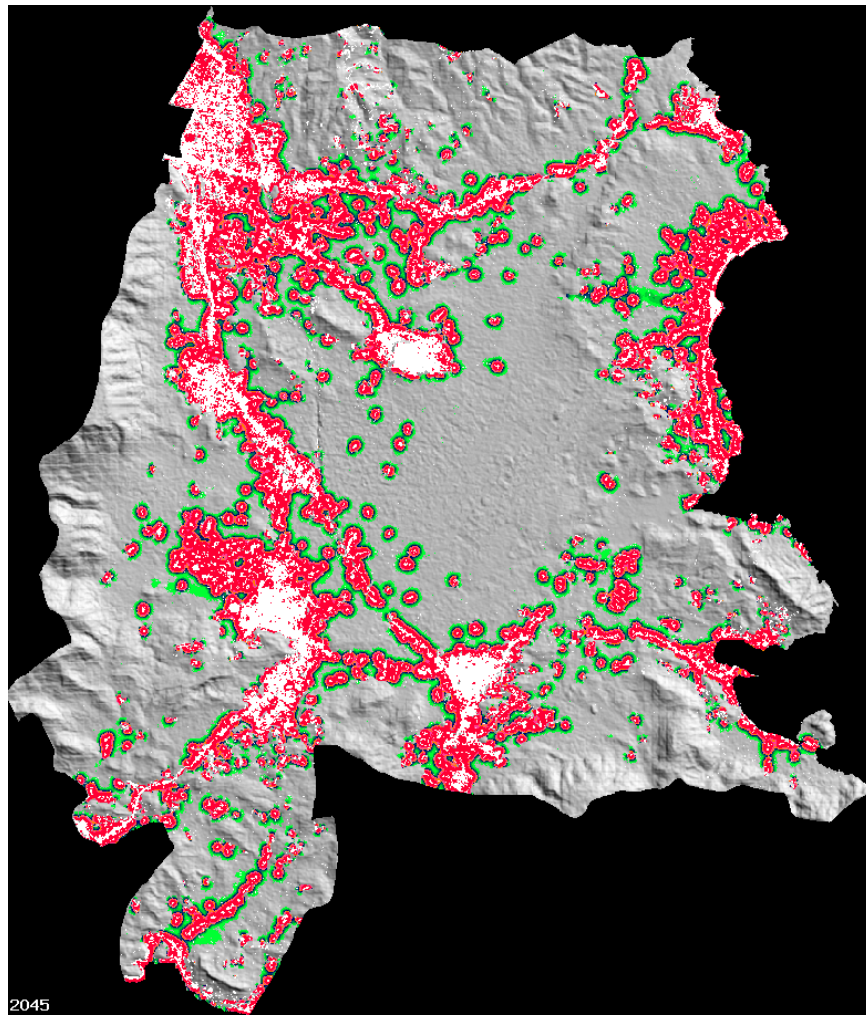


Figure 11. Urban growth prediction for 2045

More specifically, Pallini and northern Peania seem to form a more dense urban tissue around the 2015 urban centers that are shown in white color, filling in any previous non-urban gaps. Generally, throughout the study area, growth is observed parallel to the primary road network, probably as a result of the road gravity coefficient that had the value of 38 which is high enough to justify that kind of behavior. In eastern Artemida, the predicted urban areas consist of a new buffer that expands radially from the coastline. Meanwhile, the core of Koropi seems to be expanding to the northwest and attaching the small urban fragments that existed there in 2015 to its main urban core.

6. CONCLUSIONS

Through the literature review of the evolution of cities that is presented in the second chapter, it is evident that, in recent decades, the way cities evolve and expand has changed. Nowadays, technology allows seamless functionality between areas that are hundreds of kilometers apart. This new era has sparked a trend in the location of residency of citizens, who are now able to live away from the central parts of cities and settle into the suburbs without sacrificing any of the amenities found in the central areas. Sprawl, however, poses

serious threats to rural areas and natural resources and thus is an unsustainable practice that must be monitored. To this end, it is highly imperative that future policies on new housing place constraints to uncontrolled and arbitrary vertical expansion of suburbs. A very useful tool that can aid in this endeavor is a UGM. A UGM implementation can bring out trends of urban growth and pinpoint areas where natural resources might be threatened. For instance, if forest area is to be protected, then planners can experiment with different scenarios of urban growth constraints in order to find which scenario results in minimum deforestation. UGMs can model not only urban landuse but also every other landuse that may be significant in order to achieve sustainability. Overall, UGM implementation should be an integral part of the decision-making process of urban and regional planning because forecasting can reveal where negative impacts might occur and can provide feedback for the planning process.

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