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A Multi-Level Spatial Urban Pressure Analysis of the Giza Pyramid Plateau in Egypt

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Abstract

Urban sprawl has deleterious effects on natural and man-made landscapes and therefore, on the attractiveness of visitor and tourist areas. The spread of urban land use has prompted a significant loss of biodiversity and an increasing vulnerability of fragile natural and man-made systems. A prominent example of this threat for cultural heritage is the urban pressure on the Giza Pyramid Complex in Cairo, Egypt. This paper analyses urban growth trends within the Greater Cairo Metropolitan Area, especially the city enclave that is encroaching on the Pyramid Complex. A distinction is made between macro- and micro-level spatial analysis of urban growth, focusing on the micro-level dimension, with direct consequences for the conservation of cultural heritage and architectural monuments. Clearly, if no actions are taken, the unique architectural legacy of the Pyramids of Khufu, Khafre and Menkaure, might be lost. By combining spatial land use information with location awareness of the pyramid complex, this paper aims to shed light on the relevance of spatial analysis and urban growth models as tools to analyse the endangerment of valuable cultural heritage. The paper also suggests new directions for architectural heritage management, within the framework of micro-spatial analysis of the historico-cultural legacy in urban regions.

Keywords: cellular automata, geographic information systems, land-cover maps, pyramid plateau, remote sensing, system theory

1. Introduction

Regional planning strategies can make great use of spatial information for decision-making purposes. The pervasive use of Geographic Information Systems (GIS) has led to the development of new strategic and predictive tools that, combined with spatial modelling capacities, enable territorial information to be used for planning purposes (Nijkamp and Scholten, 1993). As such, urban growth models (UGM) have joined Remote Sensing and GIS as increasingly important tools for predicting land use change in urban environments (Tobler, 1970; Clarke et al., 1997, Yeh and Li, 1998; Pijanowski et al., 2002; Torrens, 2006).

City growth is having a profound impact on ecosystems, as well as on natural landscapes and cultural heritage. These problems seem to be endemic in underdeveloped countries, where governments are facing socio-economic pressures which make it difficult to maintain the stability of sustainable development. However, many underdeveloped countries have a great inheritance of both natural beauty and historic monuments. The conservation of the vast historic legacy of certain landscapes in underdeveloped countries is a key factor in attaining sustainable development. Regional and urban planners in countries like India, China and the African continent need, therefore, to seriously reflect on how the economic driving forces influencing the human impact on the landscape can be reconciled with its conservation. One of the emerging factors that is affecting cultural and natural landscapes within the framework of economic development is tourism. However, the consequences of tourism for cultural heritage must be analysed very carefully within a synergy of different disciplines (Vaz et al., 2009, 2010). In addition, mismanaged urban growth may have direct negative consequences not only for quality of life, but also for economic growth.

The developing landscape of urban areas calls for a better understanding of the impacts on those existing special features which represent the trademarks of specific cities and regions. One of the often neglected aspects in environmental spatial information management is the consequences of urban growth on cultural heritage, and its importance in the sustainable preservation of this legacy for future generations (Silverman and Ruggles, 2007). This is the subject matter of the present study.

This article is organized as follows: Section 2 describes the valuable cultural heritage context of the Giza Plateau, and examines the current and past strategies concerned with this remarkable site. Understanding the importance of the area from a socio-economic perspective means appreciating the value of the Pyramid Complex as a unique architectural heritage feature, which is being adversely affected by the proximity of creeping urban sprawl, and endangered by air pollution and urban land-use change. To study these far-reaching changes we need proper analytical tools, in particular, dynamic models and GIS, complemented with spatial interaction tools based on cellular automata. These are described in Section 3. In view of the pressures of urban growth within the area, land-use change is assessed in Section 4 at the macro-level for the Greater Cairo Metropolitan Area (GCMA) in order to understand the regional impact of the relentless urban growth. In addition, thanks to ancillary satellite imagery, we are able to make a micro-level spatial analysis of the pyramid plateau and the growing Nazlet el Samman district. By forecasting the urban expansion until the year 2008, the study includes all those areas on which urban planners and conservationists should focus. Section 5 then discusses the direct consequences of urban growth for a less discussed issue – architectural heritage – demonstrating the importance of predictive spatial models as a tool to protect fragile heritage, as well as to better understand the dimensions of urban growth within the regional context. And finally, Section 6 offers some concluding remarks.

2. The Giza Plateau

The Giza plateau comprises the great pyramids of Khufu, Khafre and Menkaure, eight subsidiary pyramids, and numerous tombs (see the map in Figure 1). The Sphinx, situated in this complex, was carved from residual Upper Mokkatam limestone (Gauri, 1984), formed in the middle Eocene and abundant in the plateau's core. Evidence shows the rapid disintegration of the limestone material (Tanimoto et al., 1995).

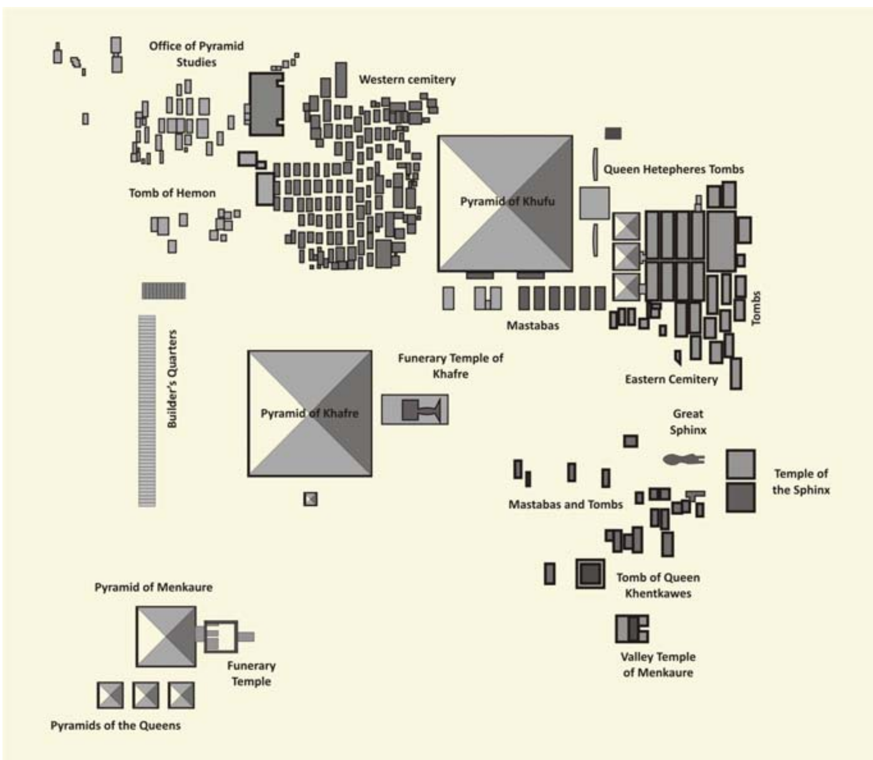

Figure 1 – Pyramid Complex of Giza

Disintegration is a consequence of degradation due to pollution from surrounding urban areas which form an enclave around the plateau. In relation to the air pollution brought by acid rain containing sulphate compounds, several authors (Reddy et al., 1986; Sabbioni and Zappia, 1991) have shown that acid rain falling on old limestone, may seriously damage ancient heritage sites.

Because of the evident deterioration of the pyramid plateau in the 1990s, the United Nations Educational, Scientific and Cultural Organization (UNESCO) engaged in a joint effort to preserve the plateau and redefine the use and availability of infrastructures within the area. The master plan to preserve the surrounding area is intended to achieve the following objectives (Hawas, 1997):

1. A ring road around the plateau will limit the use of cars within the plateau and their resultant effects on the monuments.
2. Two cultural centres will provide educational programmes for tourists. One is to be located at the entrance to the plateau, and the other south of the third pyramid.
3. At a site south of the third pyramid, stables are being built to house horses and camels. These noisy, dirty, and smelly creatures are currently stabled in front of the plateau near the Mena House Hotel. The current location is an eyesore, and contributes to the loss of the sacred atmosphere of the plateau. Riding camels and horses will not be allowed within the pyramid area; this activity should be restricted to the proposed ‘ring road’ area.
4. A picnic area will be established for the visitors. This area would help to divert from the main complex those who are not interested in the history and archaeology of the site, but instead merely wish to have a place to pass the time and enjoy the scenery.
5. A conservation lab will be established for the preservation of the artifacts. Antiquities offices could also be established. The Archaeological Engineering Centre, at Cairo University, is currently working on a master plan.

Other important steps have also been taken. A training programme for young archaeologists, architects, craftsmen, conservators, and other scholars has been put into effect. It will allow these trainees to participate in the ambitious programme of site management once they begin their career. The government has also stepped in with a decree, made by the Governor of Giza, Omar Abdoul Akher, to halt the urban housing that is encroaching five kilometres away from the Giza plateau.

3. Dynamic Models, Cellular Automata and GIS

In recent decades, ecologically – and archaeologically – rich areas have become vulnerable regions, due to urban expansion and infrastructure development. A rational identification of sustainable planning options calls for an integrated multi-level perspective on complex spatial systems, in which the consequences of the behaviour of conflicting actors are mapped out in a systemic way, e.g. by identifying the various stakeholders. We may refer here to Ludwig von Bertalanffy's work on 'General Systems Theory': "*There exist models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relationships or "forces" between them. It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general.*" (Bertalanffy, 1950). Intrinsically, this statement calls for a convergence or interface of different disciplines, sculpting a new kind of science that finds its roots in biology, physics, geography, sociology and many others.

Thanks to the advances in technology and computer aided processes, agents can be represented, and their 'behaviour' can be specified by a set of variables in such a way, that one may create behavioural non-linear approaches to estimate and predict patterns in a virtual environment on the computer, enabling a complex systems approach to spatial environmental modelling (Benenson and Torrens, 2002).

Within this socio-ecological system, local and regional environments are influenced by economic, demographic and political decisions (Anderies et al., 2004). Such information may be represented through geophysical and spatial georeferenced data (Miller and Small, 2003), leading to a spatially-enabled complex system of analysis. Depending on the scale of this socio-ecological spatial system, information may be analysed regarding its change at the macro- or the micro-level.

The importance of understanding the dynamics of environmental change is strongly linked to the possibilities of creating a more economic and social sustainable environment, within a multi-task approach to science and governance (Costanza et al., 1993). Complex Systems theory can be applied effectively to multi-scale dynamics which need to be assessed when attempting to understand the linkage between science and governance, as well as the synergy necessary for sustainable development (Gallopín, 2003), given the constraints of spatial sustainable development, which involve concepts such as the ecological footprint (Moffatt, 2000).

In any model of an agent that aims to simulate his behaviour, time is a crucial variable that reflects the dynamics of change of the agent in a temporal context. Thus, models that allow the representation of such agents and the context in which their patterns are studied are known as ‘dynamic models’, in which the temporal factor is a crucial one in studying the dynamics of change. Hence, Agent-Based Models are the logical next step that combines dynamic models with intuitive agents that, relying on a set of variables, allow the prediction of behaviour. These specific kinds of models have their roots in computational sciences and can be used in many related areas. As they are capable of clearly reflecting the performance of groups and biological variables, they have been used quite extensively in the social sciences, because "*computers offer a solution to the problem of incorporating heterogeneous actors and environments, and nonlinear relationships (or effects)*" (Lansing, 2002).

One of the ways of exploring and modelling these systems is with the use of cellular automata. Cellular automata are discrete mathematical models that consist of a grid of cells that allow the interaction of variables within the designated system, involving the variable time, thus representing a dynamic system in which patterns of behaviour may be observed.

The applications of cellular automata (CA) are manifold and are mainly used in any area which studies a system that is inherently dynamic and where one wants to predict a set of behaviours over time, given a number of rules. Because of their intrinsic nature (as a grid-based system with a specific number of cells), they are quite adaptable to a Geographical Information System (GIS) environment. Given the necessary software and programming experience on attachable models, one can adapt CA easily to the context of a GIS and generate predictive multi-temporal dynamics of change at a relevant geo-spatial level.

One of the most important activities of GIS is to monitor ecological change, in order to see directly the ecological effects of land-use change. The combination of GIS with CA makes it possible to accurately track and assess the changes in land use and may act as an important guide for regional policies and stakeholders. In this sense, one of the important uses of CA in a GIS context is the possibility to measure and predict urban growth in a given area. This context is nothing new and was already applied in the 1960s (Wilson et al., 1974). But it is with the development of computer hardware and software that finally CA has added an extra dimension to the possibility of giving reliable results that can also explain dynamics visually, if interpreted in a GIS context. Urban growth and land use is inevitable, but nevertheless, the analysis and interpretation of results can have a direct impact on how the change may be oriented and controlled. Cellular Automata must be seen in this context as a positive tool for monitoring dynamics in order to answer questions such as "What if urban growth continues to evolve in such a way?". This simple question and its complex answer may be assessed with Urban Growth CA, this is a step towards the preservation of fauna, flora and cultural heritage resources. Built-up areas will continue to grow, but perhaps with the help of information technology in a more humane and sustainable form.

4. A Macro-Spatial Urban Growth Analysis of the Greater Cairo Metropolitan Area

The use of raw satellite imagery allowed us to assess different evolutionary patterns and associated land-use dynamics in the Greater Cairo Metropolitan Area. Depending on the spatial resolution of satellite imagery, the accuracy of local analysis within territories regarding change dynamics has significantly improved over the past years (Hall and Hay, 2003). Land-use maps as such, have become increasingly important tools to understand land-use changes as well to improve the potential of regional and urban planning, especially in Third World countries where lack of both data and a cross-transdisciplinary approach may hinder sustainable development strategies (Bocco et al., 2001). The use of remote sensing imagery is therefore a starting point for better decision making, because of the possibilities for regional geomorphological mapping of remote areas. Static land-use maps per se do not focus on the possibilities of urban growth. However, the combination of satellite imagery as supporting data of urban trends with given time-lags, enables us to analyse the most probable future dynamics of city growth.

In this connection, we were able to get a much better understanding of the urban growth trends in the Greater Cairo Metropolitan Area (see Vaz et al., 2010). The micro-analysis of architectural heritage within the Pyramid Complex was only feasible because of the higher spatial resolution of the land-cover maps, which could reveal with great accuracy the individual location of the relevant Giza complex areas.

Based on the generated land-cover maps, urban growth was forecast for the year 2038. Probability changes were measured for the different temporal frames of 1984, 2000, and 2008, and stochastically projected to 2038 (Vaz et al., 2010). Correct classification was achieved by ground truth analysis for kappa testing of a total of 200 known points classified as urban. Of those total points, 88% were correctly classified for the period of 2008. While 2038 was also projected and leads to a better understanding of urban change in the future, for this paper the results for 2008 were specifically used, as the final purpose of this study is the design of micro-spatial analysis models.

Using ancillary sensibility maps, cellular automata created iteration rules of urban growth simulation, that was simulated by the stochastic evaluation of geophysical dynamics. A clear tendency of loss of vegetation to the built environment could be observed. Furthermore, the district of Nazlet el Samman showed an increasing growth rate, suggesting the further endangerment of the Pyramid Complex of Giza.

While the consequences of regional and urban growth (in particular, urban sprawl) have been previously assessed for the Greater Cairo Metropolitan Area, the assemblage of Landsat imagery only allowed an analysis of global change in the region. It was previously understood however, that urban growth has negative consequences for the entire Cairo region, and within the knowledge on growth tendencies in certain districts (like the case of Nazlet el Samman), it is of increasing importance to complement the regional results with further data acquisition from a higher spatial resolution satellite imagery. Thus, the micro-spatial growth model outlined in the next section, shows a solution based on matrices to uncover the local dimension of urban change in the context of the specific location of the pyramid complex of Giza.

5. A Micro-Spatial Growth Analysis of the Pyramid Plateau of Giza

City growth and resulting urban sprawl will continue to be an endangering reality for the Pyramid Complex of Giza. Between 2000 and 2008, an increase of urban areas was taking place on the East and West peripheries of the Greater Cairo Metropolitan Area (GCMA). The important archaeological heritage existing on the west bank of the Nile and around the urban periphery of the GCMA might then be irremediably lost.

Landsat-generated land-use maps allowed us to scale up to a higher resolution for the micro-level spatial assessment of urban change. City growth and resulting urban sprawl will continue to be an endangering reality of the pyramid complex of Giza. Between 1984 and 2008 severe growth has been registered in the district of Al-Jizah. The important archaeological heritage in which future growth is expected is increasingly at risk. Up till now however, it has been difficult to measure the growth rate affecting the pyramid complex.

The solution of constructing an integrative approach for measuring the impacts of urban change affecting historical valuable monuments is a multiple-stage process (Figure 3): the information gathered from raw satellite imagery allows creating multiple land-cover maps (to generate these land-cover maps, assisted or non-assisted classifiers may be used). This leads to the necessary valuation of the constructed land-use maps, which have to be validated on existent or known ground truth. Clearly, this approach calls for the usage of remote sensing approaches, while the validation and filtering of the sub-groups of urban classes need further spatial analysis. The existence of land-cover imagery for multiple timeframes allows the computation of multiple temporal land use in the area of investigation. For the different temporal intervals, an urban matrix is generated for the given study area.

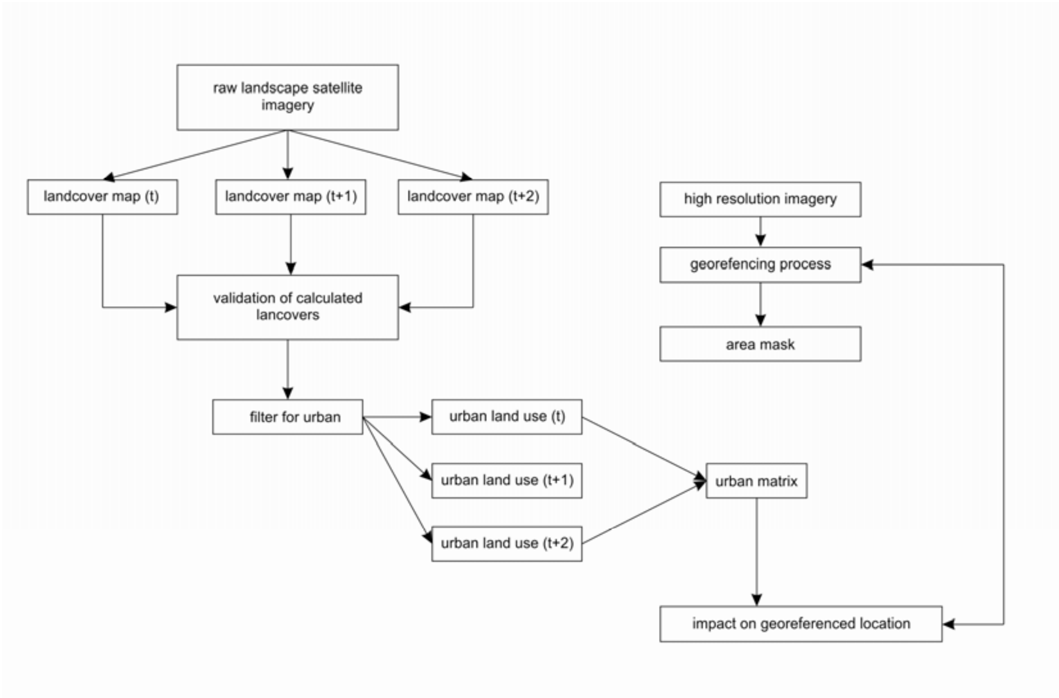

Figure 2 – Interpretation methodology and MLS construction

The urban matrix corresponds to the creation of a refined grid system with equal-sized cells on which basis the urban land-use is re-calibrated so as to correspond to a binary matrix of the intersection of cells per parcel of urban land.

On this matrix a very high resolution satellite imagery is referenced. The objective of this additional georeferentiation allows for the correct positioning of historical heritage features which then can be spatially interpreted within the registered urban change. The combination of these information leads then to a micro-spatial impact matrix in which the trajectory of urban change can be monitored at a proper resolution with the exact and detailed location of historical heritage, in our case, the pyramid plateau and the pyramids of Giza specifically.

Within a framework of raster models, it was also possible to measure a refined land use change by using the available land covers for the GCMA and the current state of the enclave up to the year 2008 in the region. A fishnet mesh of 50 by 50 cells was generated for the area at hand, in which with a high satellite resolution imagery the specific location of the pyramids was depicted.

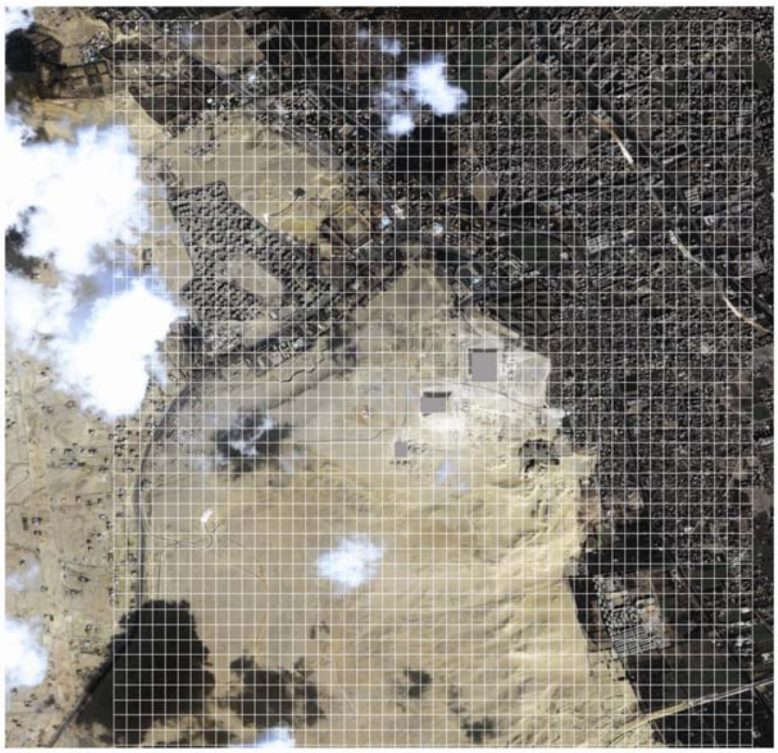

Figure 3 – Micro-level spatial analysis of city growth

The mesh corresponded to a total are of 6.30km long and 4.60km wide. Each cell had a total size of exactly 125.44m long and 92.39m wide. This corresponded to a matrix A=(aij), where aij is a square matrix of i=j=50 (see Figure 3). This property allowed to create a comparative calculation of the existing different timeframes of urban land use in 1984, 2000 and 2008, where aij(1984), aij(2000) and aij(2008) were used as benchmarks for the calculation of changes in the matrices.

A comparison of the identified and geo-referenced location of the pyramids within the matrix model was made for the Khufu pyramid at matrix cells a27,22, a28,22, a27,23 and a28,23 (occupying four cells), for the Khafre pyramid at cells a24,25 and a24,24 (occupying two cells) and Menkaure a29,22 (occupying one cell). A binary matrix was next generated for the known time periods of 1984, 2000 and 2008. This binary matrix was created by the location of urban segments in each cell overlaying the grid matrix.

Figure 4 – Micro-level spatial analysis of city growth

While urban pressure is clearly increasing from the North and East in the area concerned, the location of the main road network connecting the GCMA could exert additional pressure on urban density in the area. Queen Hetepheres' tombs as well as the Eastern cemetery and the Western cemetery will be endangered mostly from this urban pressure. Furthermore, it is predictable that acidity as well as pollution from the more dense urban areas to the North and East of the area will lead to an accumulation of acid rain and may affect the pyramids of Khufu, Khafre and Menkaure even more. The pyramid of Khufu, the tallest pyramid of the antique world, will be endangered the most because of its increasing proximity to the concentration of urban land-use. It is predictable, that about 40 per cent of the current Pyramid Complex may be directly affected by the continuing urban pressure. Subsidiary elements of historico-architectural importance may become degraded too, for example, the Sphinx and its surrounding area. The degradation of such monuments, as well as of the archaeologically relevant Mastabas, is clearly reason for great concern from a conservationist perspective. Not only may urban pressure lead to a future loss of the economically important, prosperous tourist industry, but it will also affect the scientific development of continuing archaeological research on the plateau. Our analysis turned out to be able to map out the most vulnerable spots in this plateau.

6. Conclusions

The present paper has investigated and traced the consequences of urban growth from a cultural heritage and conservationist perspective (Berling-Wolff and Wu, 2004). The use of complex systems tools such as cellular automata applied to cities (Batty and Xie, 1994) within a framework of understanding social, economic and natural factors, allowed a better recognition of the spatial dimension of heritage endangerment, also in a context of micro-spatial modelling. By focusing on urban growth models derived from satellite imagery with moderately high spatial accuracy, an urban growth model for 2008 was assessed at a macro-level. It brought to light the clear tendency of increasing city growth in the Greater Cairo Metropolitan Area. Because of the higher spatial accuracy, the use of a smaller spatial scale allowed the micro-level assessment of the ongoing endangerment of the Pyramid Complex of Giza. The main focus of the micro-level spatial approach was the consequences of continuing city growth in the Al Jizah district. Such a future growth may contribute to the fragility of the eastern and northern parts of the designated study area of the Pyramid Complex. Urban growth has therefore clearly been identified as an endangering factor for cultural heritage, not only from a regional perspective but also from a micro-level spatial analysis. It is evident from our forecasting experiments that not only the Pyramid complex of Giza is under severe threat in the near future, but that also cultural tourism will encounter major drawbacks as a result of the degradation of this unique archaeological site. This study has also demonstrated the need for sophisticated data analysis tools that form a link between micro-behavioural forces and macro-systemic forces. In this regard, CA and GIS have proven to be indispensable tools for an operational contribution to sustainable cultural heritage planning in cities.

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