USING VIRTUAL 3-D CITY MODELS IN TEMPORAL ANALYSIS OF URBAN TRANSFORMATIONS

Ján Kaňuk [1], Jaroslav Hofierka [2], Michal Gallay [3]

[1, 2, 3]Institute of Geography, Faculty of Natural Sciences, Pavol Jozef Šafárik University, Jesenná 5, 040 11 Košice

[1]jan.kanuk@upjs.sk; [2]jaroslav.hofierka@upjs.sk; [3]michal.gallay@upjs.sk

Abstract

Assessing dynamics of urban areas requires sophisticated methods and tools to better understand the processes affecting the on-going changes in the city structure (morphological, functional, social, etc.). Recent developments in geospatial technology have brought new methods for 3-D data collection (LiDAR, digital photogrammetry) that enabled greater availability of virtual 3-D city models that can be effectively used in such analyses. The 3-D city models provide new possibilities to analyse specific issues related to spatial relationships and processes in urban areas, such as morphological changes of urban areas including the vertical dimension, 3-D cadastral information, multi-layer functional use of buildings and various environmental issues having impact on people living and working in the city. In this paper we present a temporal analysis of the Sekčov area within the city of Prešov, Slovakia. This area has changed from agricultural and semi natural swamp to the biggest residential area in the city with more than 30,000 inhabitants. Recently, the area has also experienced rapid development of new shopping and entertainment facilities that strongly changed the appearance and free spaces in the zone. Therefore, we have developed series of 3-D city models from the 1970 period up to the current state and we demonstrate the visual, morphological and functional changes in this part of the city. We also demonstrate the application of 3-D city models in various 3-D environmental analyses, such as visibility, light and noise pollution.

Keywords: 3-D city model, transformation, Prešov, spatial analyses

INTRODUCTION

Accessibility and production of 3D geodata for virtual 3D city modelling rapidly advanced in the last five years. The main reasons relate to the progress in methods of spatial data acquisition and means of sharing and visualising the 3D geoinformation such as Google Earth or Microsoft Bing Maps (Virtual Earth). The applications are very successful in providing publicly accessible effective visualisation of the earth surface and three-dimensional objects such as buildings, roads, or specific features of technical infrastructure. The data used for producing virtual 3D city models can be collected via a wide range of techniques. The airborne remote sensing techniques such as photogrammetry, synthetic aperture radar, and laser scanning (i.e. LiDAR) are the most applicable especially for larger urban areas. Remote sensing from mobile terrestrial platforms allows for highly detailed modelling of urban structures (Pu and Vosselman, 2009). However, smaller areas can be more effectively mapped using direct ground based measurement with tachymetry or global satellite navigation systems.

The virtual 3D city models which include also the close surroundings of the city provide a realistic approximation of the urban environment which is more effective than the 2D analysis (Pu and Vosselman, 2009; Breunig and Zlatanova, 2011). 3D visualisation and virtualisation of a landscape intensifies the spatial impression and view of the users. Further, it increases the visual accuracy thus a more realistic portrayal of the landscape. Hence, the virtual 3D city models serve as input data for simulation of geospatial processes in which the third dimension (height) is essential. Ranzinger and Gleixner (1997) summarised the main data sources, approaches and application realms for virtual 3D city models. Kolbe et al. (2005) introduced several potential uses of the models for hazard management, including examining effects of floods on building storeys under a range of scenarios. Hofierka and Kaňuk (2009) analysed distribution of solar radiation within the city of Bardejov using a simple 3D model. Law et al. (2011) demonstrated noise modelling in an urban model of Hong-Kong considering the elevation of buildings and the presence of noise barriers. Thill et al.

(2011) demonstrated the feasibility of using three dimensional urban models for novel forms of route planning and optimal placement of facilities within the buildings considering vertical movements of individuals within buildings as well as between them. Yasumoto et al. (2011) evaluated scenic amenity in a case study of the Kyoto city. Guney et al. (2012) explored the use of 3D virtual city model for assessing the city skyline form different viewpoints. By this means they also identified maximal height of buildings in order to keep the aesthetic look of the skyline. Guo et al. (in press) showed how 3D cadastre can be designed on virtual 3D city model. Wu et al. (2010) discussed technical issues of developing a virtual globe-based 3D visualization framework for publicizing urban planning information using Web Services. At present, there is a wide range of software tools for creation of 3D city models based on CAD, VRML, or other architecture which is interoperable also with GIS software (Gröger and Plümer, 2005). However, only few GIS tools exists enabling true 3D spatial analysis (Hofierka and Zlocha, 2012).

The outlined applications of virtual 3D city models are abundant but the potential of the 3D city models remains rather unexplored in studying the city dynamics and transformations. One of the pioneer works is presented by Acevedo and Masuoka (1997) who visualised urban transformation of the Baltimore-Washington area via a time-series animation of 2D urban landscape features draped over a digital elevation model which was viewed from a 3D perspective. Construction of virtual 3D city models as time series going back several decades into the past is challenging as it narrows the available data sources to 2D data sources such as technical documentation, historical maps or photographs. However, issues related to uncertainty arise when using historical geospatial data (Jenny and Hurni 2011). Pacina et al. (2011, 2012) used similar types of historical data to generate a dynamic virtual 2.5D model of an open-cast mining area in GIS for studying the landscape change. Applications of time series of virtual 3D city models are rare but examples either based on a series of 2D historical geodata are abundant (SITMP, 2012).

The aim of this paper is the 3D reconstruction of a part of a city for different time periods. In particular, the focus is on methodology for creation and use of virtual 3D city models in studying dynamics of urban landscape using a wide range of historical data. The methodology will be applied to the urban area of Prešov, Slovakia leading to series of 3D city models representing various stages of urban growth and development. Moreover, the 3D city models will be also used in 3D spatial analysis in order to show vast application areas of the technology.

METHODS AND DATA

The production of the virtual 3D city models for particular time period is central to the scope of the paper. In order to generate the models a retrospective approach was applied. The main idea is described in the following section. The proposed methodology for temporal analysis of urban areas using virtual 3D city models consists of three main steps: (i) production of virtual 3D city models for particular time periods as time-series, (ii) performing spatial analyses with the model time-series, (iii) identification of major factors affecting spatio-temporal changes in the urban area.

A retrospective approach to build a dynamic 3D geodatabase

Generating a digital database for 3D landscape modelling in high level of detail is a complex task. From the methodological point of view, creating the geodatabase for the current stage of landscape is relatively straightforward for great abundance and availability of relevant data sources. Performing similar task for the earlier stages of the landscape is more challenging as the range of applicable data sources becomes smaller. Historical maps are one of the most important data sources for modelling temporal snapshots of the landscape. However, generalisation, map scale and measurement accuracy limit the displayable level of detail as is discussed in Jenny and Hurni (2011) or James et al. 2012. The real landscape features are eliminated, reduced or represented by cartographic symbols which do not hold the exact location and spatial extent of the features. For example, symbol of urban fabric with gardens supposes presence of trees but the symbol does not allow for exact location and number of the trees. The maps are schematized 2D models of landscape which are to be used for extraction of 3D geographic data. In this case study, a retrospective approach was adopted to achieve this task. The main idea is based on reconstructing the earlier stages of the landscape from the virtual 3D city model of the current stage which provides the highest fidelity. The current geographic objects recorded in the 3D geodatabes are eliminated or modified depending on their existence in the historical records. The adopted approach provides advantages to digitizing floor plans of the buildings directly from historical maps. Elimination of buildings and other man-made structures from current vector data avoids introduction of uncertainty associated with the measurement and georeferencing accuracy of scanned maps, or technical plans. There were other approaches proposed, e.g. Laycock et al. (2011), where a semi-automatic approach was used to align historical maps with a current vector database. The approach applied in the paper assumes continuous evolution of the landscape reflecting the genius loci. In this way, the character of the landscape can be reliably modelled but there are limitations in expressing the absolute location, size, and number of particular objects. However, the ability to analyse spatial processes is preserved and that was important for the aim of this case study. For example, the series of 3D landscape models can be effectively used to analyse the change of skyline from a particular location. Another application is in reconstruction of the distribution of solar irradiation which relates to the changes in the quality of the environment (shadowing, heat, scenic amenity).

Study area

The research presented in this case study is based on production of a series of virtual 3D city models for the Sekčov area which is an integral part of the city of Prešov, Slovakia (Fig. 1). There are over 96 000 inhabitants living in the city in the northeastern part of Slovakia. The current stage of the Prešov City centre has been formed since 12th century but a marked morphological growth occurred in the 20th century. The change was related to industrialisation of the area which lagged behind the main stream of the former Czechoslovakia due to marginal position of the city with respect to main transportation routes, railways especially. Political and economic circumstances after the World War 2 were influenced by the Soviet Union and determined the most striking morphological expansion of the Prešov urban area. There had been a five folded increase of urban fabric since 1945 up to present. Progressively, several industrial estates were located in Prešov mainly machinery, electronics, metalworking, clothing, food and polygraphic industries. The industrialization naturally induced development of the third sector activities, transportation infrastructure, and urbanization in general. The population growth stimulated increase in housing construction focused on settlements of blocks of flats. Clusters of individual detached houses were also built.

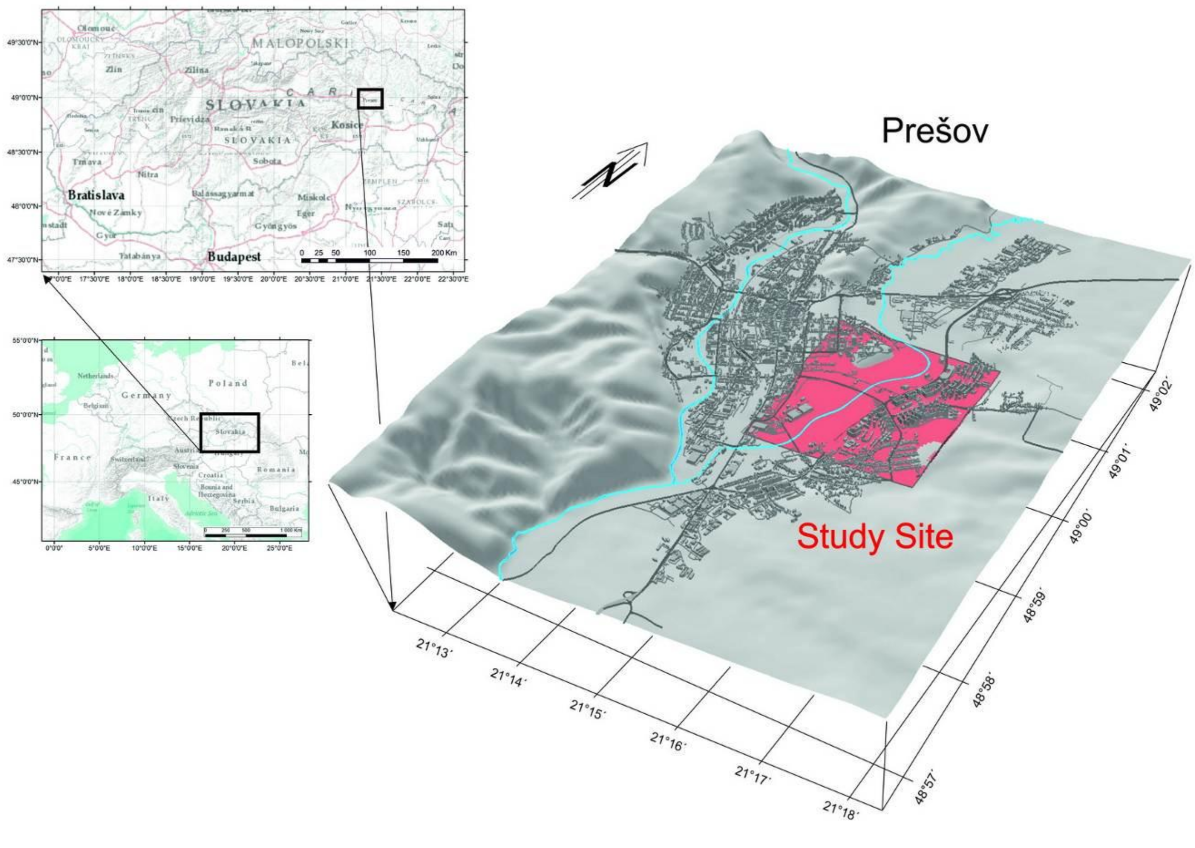

Fig. 1. Location of the study area (red square).

The approach for 3D city reconstruction is presented on the the area of the Sekčov urban settlement which is now the biggest residential area within Prešov providing home for more than 30,000 people. Originally swampy meadows on the alluvial plain of the river Sekčov were selected for their close vicinity to the city centre. The landscape was completely transformed. This process started in 1969 and construction of the first blocks of flats began in 1978. Beside the massive blocks, the construction involved public facilities for education, health care, and entertainment, small shops, hypermarkets, restaurants, etc. Construction of such facilities continues until present but the original plan was not fully achieved for political-economic changes after 1989. The original terrain parameters required specific preparation works. The river Sekčov was relocated into an artificial channel of 5 kilometres length. Its bottom is based about 2.5 meters deeper below the original terrain. The original channel was filled up. The swampy areas were meliorated and intermittent water streams were diverted into the main stream of Sekčov. These changes also affected the original land cover and other landscape features, such as hydrologic regimes, soil and microclimate.

The development of the residential area had 3 major stages: It started in the southern part of the area in 1978 and finished in 1989. The next stage (1989-1999) included blocks of flats with a complete technical infrastructure such as gas, power and water supply, sewerage, roads). Since 2000 the area has been filled-up with various commerce objects such as shops, services, etc. Currently, the new development is concentrated in new, previously empty zones.

The period of the mentioned landscape transformation is well recorded by geospatial data sources. Hence, it was possible to reconstruct particular stages of the Sekčov area as a series of virtual 3D city models of the present and its earlier stages. The models enabled dynamic modelling of selected geographic phenomena. The virtual 3D city model of the Sekčov area consists of three main feature types: digital elevation model, 3D model of buildings, and land cover model. The origin and use of data sources is further described with respect to the particular feature types. All data were measured or supplied as georeferenced in the national grid system SJTSK (EPSG: 5514, http://www.epsg-registry.org/).

Digital elevation model

The current terrain surface of the area was modelled from the ground surveyed points heights and contour lines (valid to 2010) supplied by the Municipal Office of Prešov. The Sekčov area has not experienced marked changes of the georelief in general. The parts where some changes occurred were not large enough to be represented by topographic height symbology just graphic symbols for features as (road cuts, embankments). Therefore in such circumstances, the terrain was estimated and designedly modified. For example, the area of a road embankment was elevated by 2 metres.

3D model of buildings

Current stage of the buildings was reconstructed from the data measured with electronic tachymetry supplied as a technical 2D geodatabase supplied by the Municipal Office of the city of Prešov. It was the most accurately measured data set used in the study (subcentimeter accuracy). The vertical dimension of the buildings and related facilities (e.g. chimneys, towers) was measured with a laser distance meter (submeter accuracy). The main objective was to capture the third level of detail (Köninger, A. and Bartel, 1998). In this way, the virtual 3D city model of the Sekčov area was generated and it comprised almost 1000 3D objects (Kaňuk and Babeľa, in press). The model represented the current/last stage of landscape analysed in the study valid to the end of year 2010. Modelling the dynamics of the case study area was based on the knowledge of its landscape evolution. As it was mentioned above, the area used to be mainly agricultural and comprised only few buildings before 1950. For that reason, it was possible to reconstruct the earlier stages from the current stage of the landscape for which the retrospective approach was used. The 3D building models for particular time period were eliminated from the virtual 3D city model of the current stage depending on their existence in the historical records. The attributes such as function, height, date of construction were assigned to each 3D building model. The exact date of building construction was ascertained from the date of building approval recorded in the archive data, Kohlmayer (1980) and Matlovič (1998). Modifications, destruction or changes of general shape of the buildings was not identified in the historical records for the area.

Land cover model

The models of land cover were based on polygon representation generated using the 2D technical geodatabase of the city of Prešov, and by manual interpretation and vectorization of orthophotomaps (years 2002, 2009, spatial resolution 0.5 meter) and historical maps (scale 1 : 25 000 for period 1952-57, scale 1 : 10 000 valid to 1990). The land cover was classified into the following categories: permanent grass land, arable soil, forests, gardens, roads, railways, water streams, continuous urban fabric. It should be emphasized that the main aim was to express the landscape character for which trees make a significant 3D appearance. Hence, trees were treated separately as point objects with defined tree type and height. The current stage of land cover was reconstructed with regards to the highest possible accuracy using the high detail orthophotomaps and the technical geodatabase. By this means, individual trees were exactly located while for continuous areas of trees the trees were randomly located in order to portray the landscape character. Earlier stages of the land cover were reconstructed from historical maps aided by ground level photographs (from 1950 - present) and interviewed local inhabitants. Due to generalisation and map scale issues, many features were represented as symbols (e.g. roads) in the historical maps while their spatial extent was reproducible only from the most current geodatabase and orthophotomaps. In such cases the existence of the feature was important and the spatial extent was estimated. In other case, some features were not displayed due the same cartographic reasons and we assumed their presence in the landscape as, for example, shrubs along the river or trees in the urban areas (parks, gardens, etc.).

Dynamic virtual 3D city model

The individual models for particular stages of the study area represented a chronological sequence of landscape snap shots. The dynamic model of the area is represented as animation generated by integrating the time-series into a single model. In order to ensure a smooth transition between the landscape stages the snapshots were artificially densified. It improved the perception of the landscape changes especially for cases of rapid change from arable soil to urban fabric. The inter-stages were produced by modelling the transition from stage A to stage B by estimating the change of the height and character of the land cover.

Spatial analyses

Time series of 3D city models provide a valuable dataset that can be used for various spatial and temporal analyses. While standard GIS packages provide a plenty of 2D functionality in this area, sophisticated 3D tools are still rather sparse. Most of current 3D GIS tools are limited mostly to visualization and simple data handling (Abdul-Rahman and Pilouk, 2008). It is clear that more work has to be done to develop a comprehensive toolbox of spatial operations applicable to 3D data. To demonstrate a wider applicability of our approach, we have selected 3 application areas with relatively simple methods and tools readily available within GRASS GIS and ArcGIS software packages.

Solar radiation modelling in urban areas has become quite popular in solar energy applications because many solar energy systems can be installed in built-up areas, on roof-tops or even facades. This however, requires a complex spatial database with 3-D data representing buildings or other features within the area. Hofierka and Kaňuk (2009) have presented a new approach to assess the solar resource potential in urban areas using solar radiation tools such as PVGIS or r.sun of GRASS GIS. Recently, Hofierka and Zlocha (2012) have presented the extension of the r.sun module to 3D using a combined raster-vector approach. This work also includes several application examples from the Prešov urban area represented by a simple box model.

Flood-risk analysis is another common application of 3D city models . This is due to a relatively easy comparison of water table height to buildings height or other landscape features. In our study area we have a river that can pose a risk to built-up areas. To demonstrate the flooding event we have applied a simple operation. The flood level was modelled as a linear trend surface of the water table of the river Sekčov. The planar surface was raised 2.5 meters above the river level valid to the particular time period which simulates a flood wave of 2.5 metres height.

The traditional 2D parcel maps are poorly applicable to the complex urban features, such as multi-stage buildings with many owners, tunnels, underground constructions, etc. The natural solution for urban areas is a 3D cadastre. It is a discrete division of 3D urban area to 3D cadastral entities representing volumetric parcels and buildings. Using 3D cadastre we can analyse spatial relationships among volumetric parcels and parts of the building. The cadastral data can be also used to identify various functions of the cadastral entities within the building. This especially valuable as a particular building does not have a unique function, it could have several functions, for example, residential as well as commercial use of blocks of flats are quite common in Slovakia. To develop a 3D cadastre information, we need a detailed data about the building and internal structures defining cadastral entities.

RESULTS AND DISCUSSION

Using the suggested methodology and data described above, we have created 3D city models for 6 time horizons representing distinctive periods of development in the Sekčov area. Fig. 2 shows the situation before the start of development. The area has dominantly an agricultural and seminatural character. In 1969, the development started with new buildings in the older parts of the city (Fig. 3). The massive construction of the new residential houses started in 1978 along with some buildings with non-residential function (Fig. 4). This period also affected some seminatural features of the area, such as relocation of the river and terrain changes. These changes had also a very important effect on other spatial processes, such as flooding and land cover changes. Period starting in 1989 shows almost a complete residential development (Fig. 5). This period is closely related to the social changes in the Slovak republic with a major impact on economic and social situation of many inhabitants of this area. A former state-sponsored development was halted and former renters of flats were allowed to buy flats and become owners. The period of economic prosperity brought renewed interest in the development of new blocks of flats and construction of some new non-residential buildings mostly with a commercial function. After heavy construction in previous decades we can see also changes in land cover with gradual increase of shrub and tree vegetation (Fig. 6). The most recent stage of the area is associated with a rapid development of new commercial facilities, especially large-area shops (Fig. 7).

Fig. 2. 3D city model representing the Sekcov area in 1959

Fig. 3. 3D city model representing the Sekcov area in 1969

Fig. 4. 3D city model representing the Sekcov area in 1979

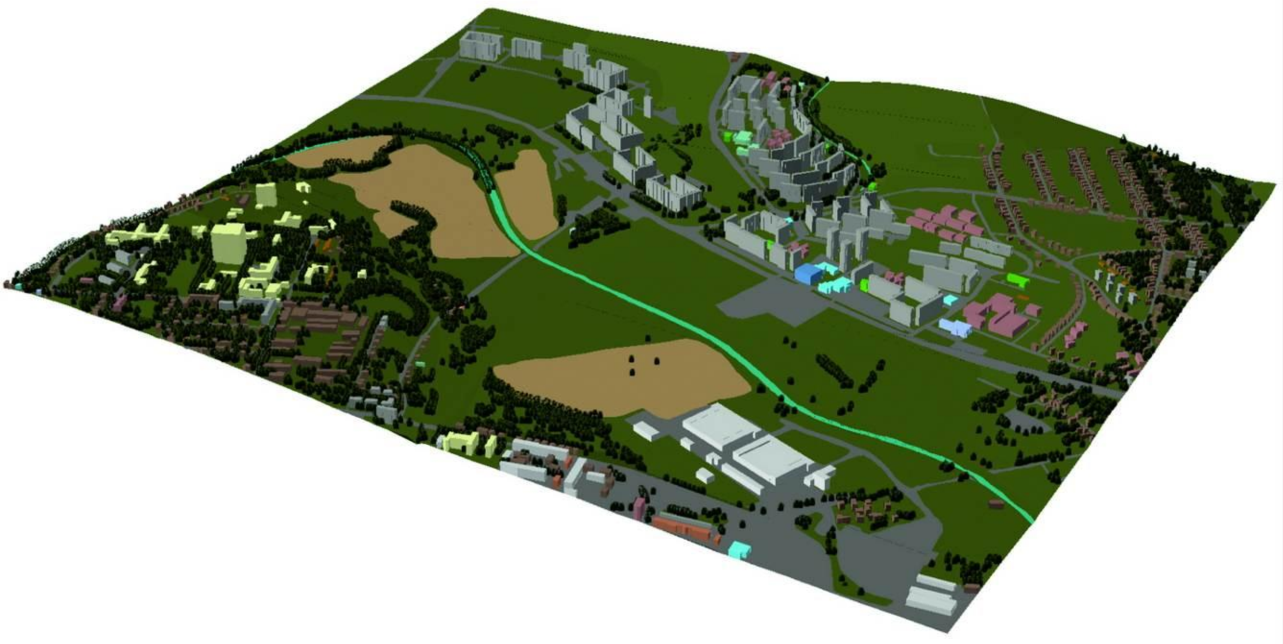

Fig. 5. 3D city model representing the Sekcov area in 1989

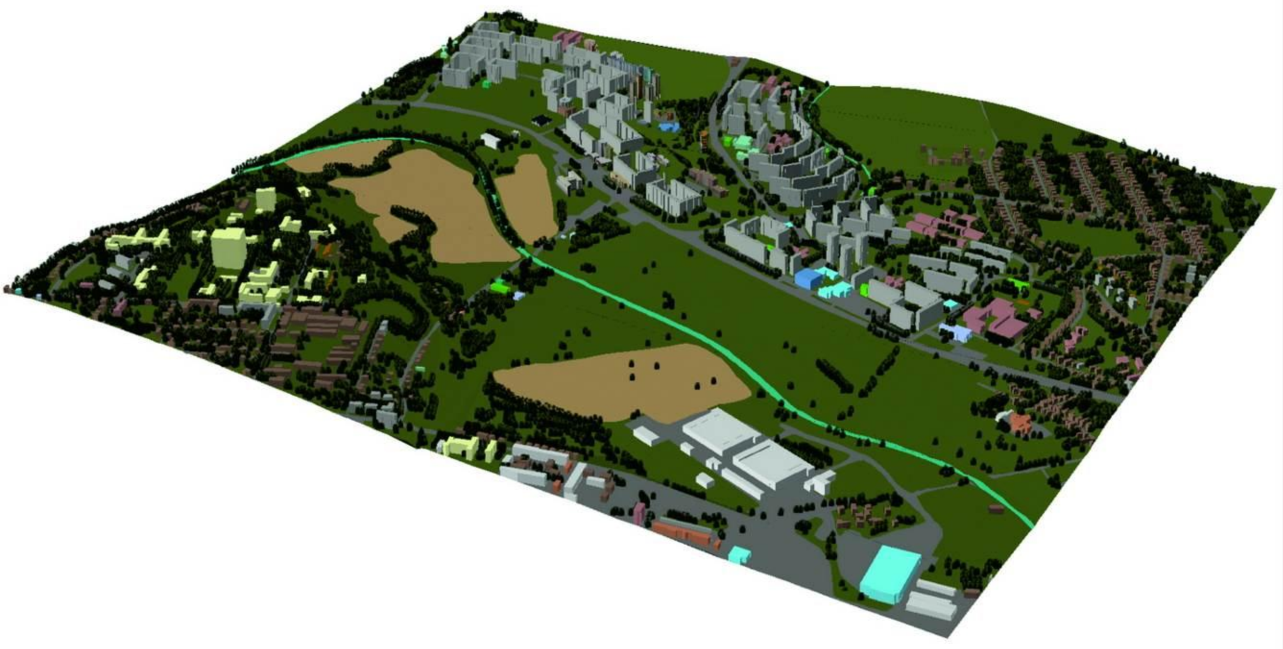

Fig. 6. 3D city model representing a development of the Sekcov area in 1999

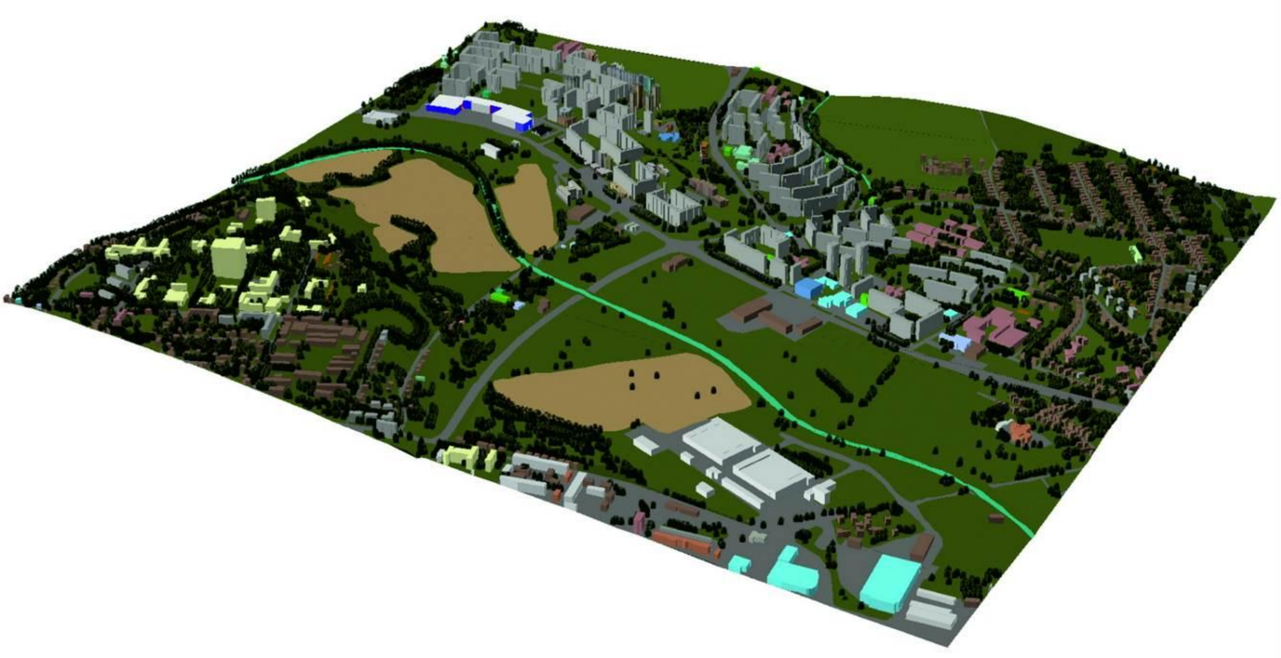

Fig. 7. 3D city model representing a development of the Sekcov area in 2012

To demonstrate a wider applicability of temporal series of 3D city models, we applied a simple flood-risk analysis to our study area with different time horizons. Figure 8 displays the scenario before any major changes in the landscape occured. The flood level is set to be 2.5 meters above the Sekčov river table at that time. Figure 9 shows the scenario valid for the current stage of the landscape after melioration works and relocation of the river into an artificial channel which was cut ca. 2 meters deeper into the ground than the original channel. The flood level is set 2.5 meters above the river level in 2010 and the flood risk was clearly reduced. This demonstrates how spatial-temporal changes of landscape influence the flooding hazard a risk to human activities. The third dimension of the model allows not only for identification a building flooded but also up to which floor it is likely to be flooded.

Fig. 8. Estimated flood impacts in 1959

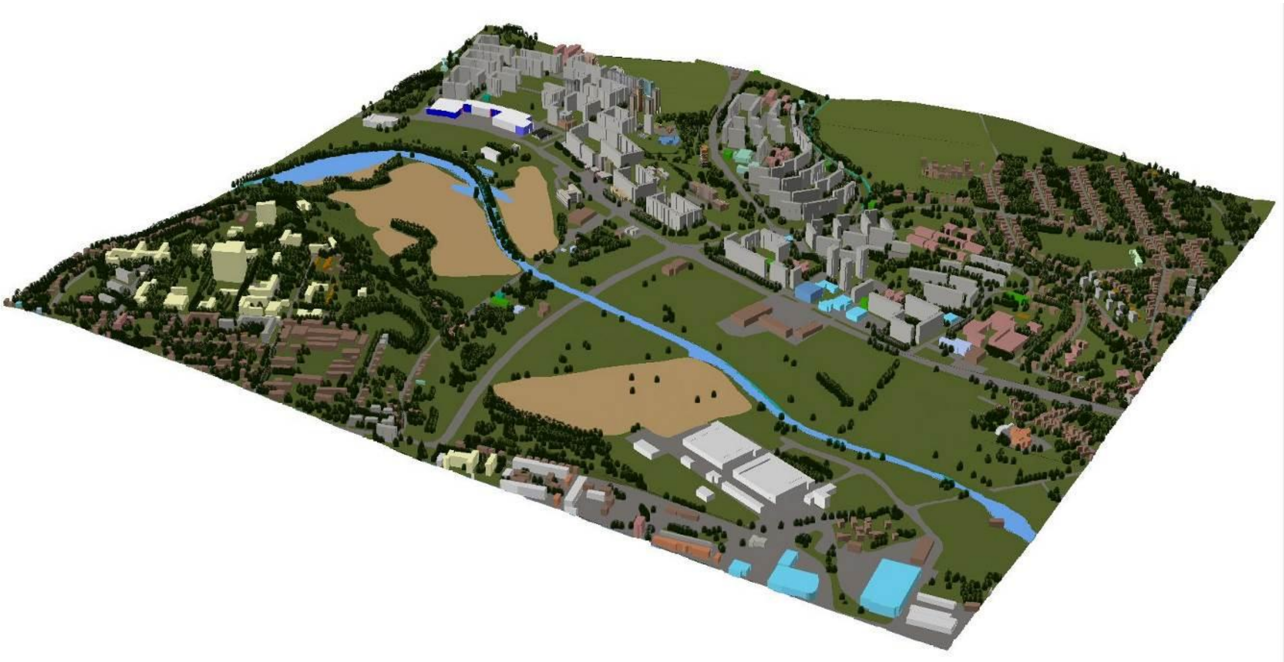

Fig. 9. Estimated flood impacts in 2012

Over the last 5 decades our study area experienced rapid changes in many landscape featues. These morphological changes are clearly visible only using 3D city models. However, thanks to profound societal changes that started in 1989, we can found also very important functional changes in several buildings. Many residential buildings were state-owned, later former renters were allowed to buy flats and become owners. Moreover, some part of these blocks of flats lost a purely residential function and became polyfunctional buildings (Fig. 10). Without 3D city modelling it would be very difficult to express in a GIS database all spatial context and relations. This information is also needed for 3D cadaster that is planned to be implemented in Slovakia.

Fig. 10. Data from a multipurpose 3D cadaster show different functions of the building

The reliability of the generated 3D city models depends on the character of the reconstructed landscape features. The spatial location and geometry of buildings is the most reliable as the most accurately measured data were used for their reconstruction and also for buildings being the most stable features in the study area in terms of their change in time. Current stage of land cover features is also highly reliable because it is based on the current and accurate data. The reliability of the 3D model decreases proceeding back to past. The reason is that the older stages are modelled mainly from 2D maps which portray just the general character of landscape relatively reliably. Due to cartographic generalization it is not possible to judge the exact location, account and height of land cover features. From the methodological point of view, the 3D reconstruction of an urban landscape as a time series is in fact an approximation of the past reality. It depends on understanding the landscape and knowledge on the landscape of the particular expert. Hence, it is difficult to automate the generation of the 3D model although it is possible into some extent. A database comprising the dates of building approval (construction finished) allows for dynamic rendering of particular time stages. Succession of vegetation could also be automatically rendered by estimating the ratio, density and height of trees, scrubs and grass species.

CONCLUSIONS

A greater availability of virtual 3D city models has brought new possibilities in research of dynamics and spatial changes in current cities. In this paper, we have presented a simple methodology for creation and use of virtual 3D city models derived from various data sources including old historical maps. Virtual 3D city models provide a unique new tool to better understand the morphological changes in built-up areas, considering the vertical dimension. This has profound implications for urban growth research and analysis, as well as many other application areas. In comparison with a traditional 2D visualisation, the 3D models provide improved perception of the landscape which is more natural for human understanding and can not be achieved with 2D maps.

Using the case study of the Sekčov area of Prešov, Slovakia, we have shown rapid changes in this segment of the city that included not only buildings but also georelief and land cover. The dynamic virtual 3D city model consists of a sequence of digital models representing important landscape features, such as georelief, buildings, land cover or other city features having impact on the further development. Using a temporal analysis of this model the researcher can assess trends and various implications for future development of the area. New 3D spatial analysis tools present very important part of the methodological equipment for any researcher dealing with urban areas. These methods can identify critical spots or segments of the area that need a more targeted planning or different development plans. We have explored 3 application areas of spatial analysis using 3D city models to identify possible problems in our study area: solar radiation modelling, flood-risk analysis and analysis of 3D cadastre situation to demonstrate the applicability of the adopted approach. The presented reconstruction was undertaken for a city part constructed on a green field. If the historical evolution of the modelled area is more complex (e.g. construction, demolition, and new construction of buildings) additional approaches should be also explored. The presented methodology can be applied for other types of urban landscape bearing in mind that relatively accurate and diverse data are available.

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