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3D GIS Model for Flood Risk Assessment of Varna Bay Due to Extreme Sea Level Rise

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ABSTRACT

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Assessing flood hazards due to extreme events in coastal areas is an important task and key factor of sustainable coastal development. Over the last decade application of Geographic Information System (GIS) in flood risks mapping and/or modelling has been proved as a valuable tool for predictions. The study presents a 3D GIS model for flood risk assessment caused by extreme sea level rise in Varna bay, North Bulgarian Black Sea coast, where the largest coastal city is located. A high percent of country's population as well as a great deal of national economy, e.g. coastal tourism, transport, harbour activities and maritime industry are concentrated around the Bay of Varna. Topographic maps in scale 1:5000 were used to identify critical low-laying territories along the coast at different scenarios of extreme sea level rise. On the basis of satellite images an evaluation of both individual/public building resources and infrastructure in Varna Bay was performed. Application of 3D GIS model allows visualisation, interpretation and accurate assessment of coastal areas and infrastructures potentially endangered by sudden increase of the sea level. This way, spatial and mapped information on flood risks visualised via 3D GIS modelling is essential for developing local and/or regional prevention strategies (planning coastal/flood defence measures, improving public awareness through education and preparedness of communities, etc.). The results from the study indicate that using of GIS and 3D spatial modelling techniques supports a more thorough understanding of the flooding patterns towards risks mitigation and coastal prevention solutions.

ADITIONAL INDEX WORDS: *Coastal hazards, Low-laying areas, Satellite images, 3D GIS.*

INTRODUCTION

In contrast to climate change-induced sea level rise, which can be predicted over a middle-time scale, the extreme sea level rising associated with storm surges, tsunamis and rain-storms could have a short, but particular devastating impact on coastal areas. Significant coastal changes typically occur during such extreme events (ASHTON *et al.*, 2007; BOYD *et al.*, 2002). This causes as well as huge disasters, damages of near-shore infrastructures (harbour, roads, buildings and civil structures), increased human disease and even loss of life (IPCC, 2001; NICHOLLS and HOOZEMANS, 2002). As a consequence, functions and values of the coastal systems could be degraded, and public safety and economy could be affected (SZLAFSZTEIN, 2005). With the expectations for currently changing global climate, many scientists and decision-makers have become more concerned about potential risks to coastal communities and ecosystems related to the increased storm activity (ASHTON *et al.*, 2007). Various human activities in the coastal zone have also prompted possible flooding problems: growing habitation and number of developments close to the shoreline could increase the number of population and buildings at risk to inundation. Therefore, the efforts to predict extreme hazards impact and evaluate the risks of subsequent flooding could contribute to more timely and adequate reaction towards prevention or mitigation options. Over the last decades application of Geographic Information System (GIS) in flood risks mapping has been proved as a valuable tool for visualisation, modelling and predictions (SARKKILA, 2001; LONGLEY *et al.*, 2006; EVANS *et al.*, 2007).

This paper describes an application of 3D GIS modelling techniques for risk assessment due to extreme sea level rise induced flooding of the coastal areas and buildings. The research is focused on a case study of the large Bay of Varna at the North Bulgarian Black Sea coast. Based on topographic maps in scale 1:50 000 and projecting different sea level rise scenarios the most flood-prone low-laying territories along the Bulgarian coast were identified. Then, using high resolution satellite images an evaluation of both individual/public building resources and infrastructure in the inundated coastal zones of Varna Bay was implemented. The paper also demonstrates the advantages of applying 3D GIS modelling in flood risk mapping and analysis. This approach allows visualisation, interpretation and finally accurate assessment of coastal territories, infrastructure and buildings, potentially endangered by extreme sea level rise. In this way, coastal developers, stake-holders and civil protection authorities could directly benefit from the mapped information:

based on 3D GIS representation and easily illustrated cases without additional description and analysis. It could help also decision-making for future urban development projects in the area of Varna Bay.

PHYSICAL BACKGROUND

Almost 100 000 km^2 of Europe's territory lies below a 5 m elevation, which constitutes 2% of the total territory of 20 coastal EU (and candidate) countries. More than half of this area is located closer than 10 km zone from the sea. About 9% of all European coastal zones (12 % for EU Members States) are below a 5 m elevation. These areas are potentially vulnerable to rising of the sea level and related inundations. Netherlands and Belgium are determined as most vulnerable countries, where more than 85% of the coast is under a 5 m elevation. With the increasing likelihood of severe storm surges, the vulnerability of these coastlines becomes even more apparent. Surge heights with 50-year extreme maximums of up to 3 m above normal level are mostly observed in north-western Europe. However, individual hot spots exist along the coastlines in other parts of Europe (EEA, 2006).

The Bulgarian coast is 378 km long and is located in the western part of the Black Sea. The coastline stretches between cape Sivriburun in the north to the Republic of Romania and River Rezovska mouth in the south to the Republic of Turkey (Figure 1).

Long-term sea level changes along the Bulgarian Black Sea coast have been traced for more than 100-year period, based on the records of two mareographs located at cities of Varna and Burgas. The trend shows continuous sea level rise (e.g. PEYCHEV, 2004).

Coastal storms are extreme meteorological events that mainly occur along the Bulgarian Black Sea coast in winter with the severe N and NE winds. Such storms could have devastating effects on the natural environment and coastal infrastructure both on and offshore (BOYD *et al*, 2002; GROZDEV, 2008), but could be dramatic when are combined with additional events like surge waves, tsunamis or heavy rainfalls. There are some examples of extreme events along the Bulgarian coast: the storm in February 1979 accompanied by extreme sea level increase and the storm in June 2006, combined with pour rains. In both cases storm surges were exacerbated by the occurrence of additional events leading to extreme rising of the sea level. An absolute maximum of sea level rise up to 1.50 m was recorded during the storm in 1979 as a number of coastal infrastructures were destroyed (BELBEROV *et al*., 2003).

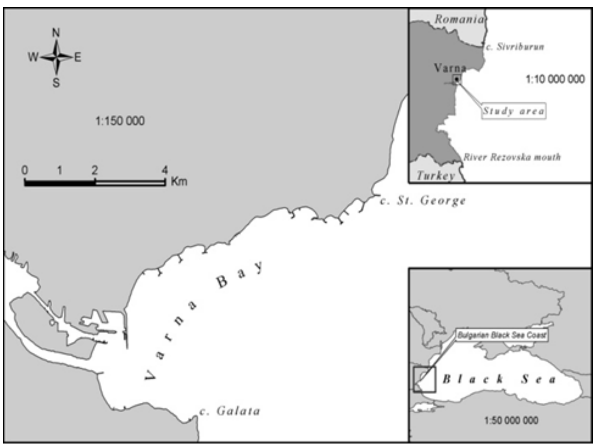

Figure 1. Locator map of study area.

The mean values of averaged sea level rise for the western part of the Black Sea vary between 1.5 and 3 mm/y (PASHOVA and JOVEV, 2007). Although such rates are not dramatic for the Bulgarian coast there would be a case of sudden sea level increase under certain meteorological events.

On the base of recorded at the meteorological station of Varna Bay monthly sea level maximums during 1975-1984, the probability of extreme rise of the sea level over 50-year is foreseen to be 1.92 m, while over 100-year period it could reach 2.29 m (GROZDEV, 2008).

The Bay of Varna is the second largest bay along the Bulgarian coast, situated at its northern part between capes of St. George in the north and Galata in the south (Figure 1). The adjacent coastline is about 18 km long with ESE general exposure mostly approaching by wind waves from N, NE and E directions. The largest Bulgarian Black Sea city of Varna is located in the study area. Varna is a regional centre, accommodating 312 889 residents according to the last Census data (NSI, 2002)) and an important resort destination attracting large number of foreign tourists particular during the summer. The area of Varna Bay is densely populated, as the number of local residents/tourists increased with 318 % over the period 1934-2001 (PALAZOV and STANCHEV, 2006). There is also well developed infrastructure, such as harbours, roads, airport and railway, commercial and industrial buildings. Urban developments on the coast of study area have been focused on the expanding economies. As a result, significant part of urban land activities (transport logistics, industries, trades, etc.) and tourism development are concentrated in the Bay of Varna. These residential activities have led to the building of new hotels, apartments and second homes in close vicinity of the coastline thus increasing the risks of flooding both for population and buildings.

DATA SOURCES AND METHODS

Data used

In order to identify flood-prone territories along the Bulgarian coast and generate 3D GIS model of Varna Bay different sources of spatial data were used:

-topographic maps in scale 1:50 000 (1983)

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-QuickBird`s satellite images gained free from the Google Earth (*http://earth.google.com*), Catalog ID: 10100100059B1A00; acquisition date: May 3, 2007; Pan MS1.

Medium-scale topographic data (1:50 000) were used to locate low-laying areas along the entire coast, but the large scale topographic maps (1:5 000) were essential to represent a detailed ground elevation surface of the Varna Bay. Since the actual information for infrastructure developments is not presented on the topographic maps, very high resolution satellite images from 2007 were valuable for accurate assessment of building resources and infrastructure affected by flooding at extreme sea level rise. Because local geodetic network and topographic maps are in metric coordinate system from 1970, it was necessary to transform coordinates of the initial data in geographic coordinates (φ and λ) in datum: WGS_1984 (World Geodetic System 1984).

All estimations then were preformed in metric Projected Coordinate System: WGS_1984_UTM (Universal Transverse Mercator)_ZONE_35N. This projected coordinate system employs a projection to transform locations expressed as latitude and longitude values to *x*, *y* metric coordinates (ESRI, 2000). Then, topographic maps and satellite images were geo-referenced and rectified with ArcInfo 9.2 GIS to remove the effects of distortion using Ground Control Points (GCPs). These GCPs were determined from large scale topographic maps (1:5 000) as a set of easily visible objects both on the maps and satellite images. After geo-referencing process the topographic maps were digitalized in ArcInfo GIS environment and a 2D contour features were generated to cover land area up to 20 m elevation using written values of the contour levels.

Through ArcEditor tool all recognizable on the satellite image human buildings (private houses, hospitals, schools, fair and police stations, railway station, factories, stores, shops, etc.), located in the identified low-laying areas were digitised. Using then an XTools Pro extension the areas of building's infrastructure were calculated.

3D GIS modelling

A number of GIS tools were applied to generate an accurate assessment of risks to inundation for the Bay of Varna. Advanced flood modelling is based on 3D terrain models, as they could cover all existing elements of terrain including human objects on the ground like various type of buildings and other infrastructure (SARKKILA, 2001). After pre-processing of spatial data into GIS environment, the next step was to model the land surface (terrain) using an ArcGIS 3D Analyst extension. 3D Analyst provides advanced tools for three-dimensional visualization, analysis, and surface generation. This special GIS extension enables to create dynamic 3D models and interactive maps that elevate the visualization and analysis of geographic data (ESRI, 2000-2002). Using 3D Analyst is easy to convert a two-dimensional contour features extracted from topographic maps to 3D features and to create surfaces such as Triangulated Irregular Network (TINs). TINs are fast and efficient vector-based representations of surfaces that can be derived from any existing ArcView GIS feature theme. TIN is a data structure that represents a continuous surface through a series of irregularly spaced points with values that describe the surface at that point, for example, an elevation (ESRI, 2000-2002). With 3D Analyst, Surface Analyst/Contours from generated TINs model a linier 3D features were created at every 1 m. Using Xtools Pro extension the linear features covering low-laying territories in the study area were then converted in polygons at given scenarios of extreme sea level rise with intervals of 1 m (between 0 and 5 m above mean sea level).

RESULTS AND DISCUSSION

On the base of 1:50 000 scale topographic maps the low-laying territories along the Bulgarian coast potentially endangered to risks of flooding were identified (Figure 2). The performed analysis shows that 14 towns, 17 villages, 13 sea resorts and 7 small campsites would be affected by extreme sea level rise of 5 m. Number of affected coastal population counts almost 100 000 from all 549 765 residents in these sites. Low-laying areas around Varna Bay, Kamchia resort, Burgas city, Pomorie town and coastal section between Albena resort and Kranevo village were identified as most vulnerable to inundation. Total area of 26 500 000 m^2 along the entire Bulgarian coast would be flooded by extreme rise of the sea level up to 5 m.

An accurate 3D model of the Varna Bay was generated through processing large scale topographic maps (1:5 000). Figure 3 illustrates a part of the performed GIS flood modelling. It was found that territory of 2 000 000 m^2 in the study area will be affected by extreme rise of the sea level up to 1 m above the mean level. A coastal territory of 5 700 000 m^2 would be flooded in case of sea level rise up to 5 m (Figure 4). This means the area of Varna Bay embraces almost 25% of all low-laying territories along the entire Bulgarian coast.

For assessment of risks to flooding for built environment in the study area an individual GIS layer was created as polygon feature. This layer consists of the following next GIS sublayers:

(1) Public buildings (hospitals, schools, fair stations, police

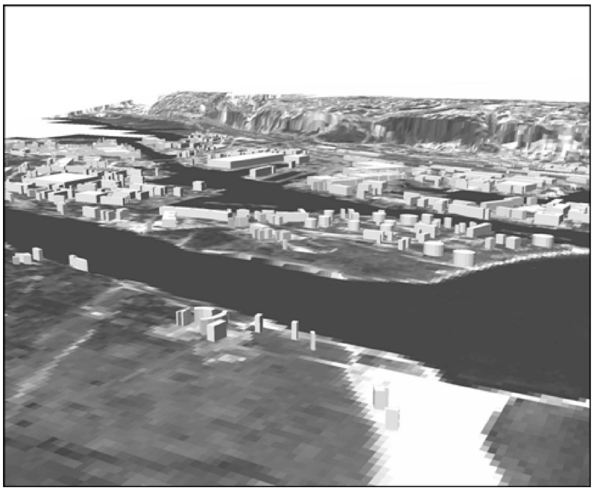

Figure 3. A fragment of 3D GIS model of Varna Bay.

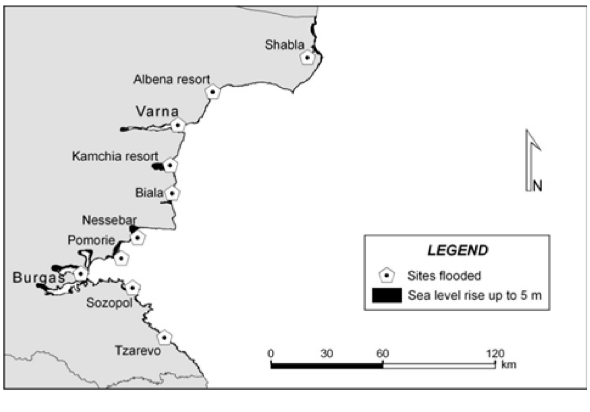

Figure 2. Low-laying territories along the Bulgarian coast.

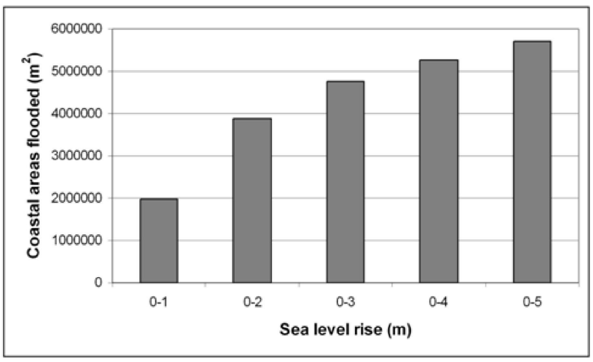

Figure 4. Coastal areas of Varna Bay potentially affected at different sea level rise scenarios.

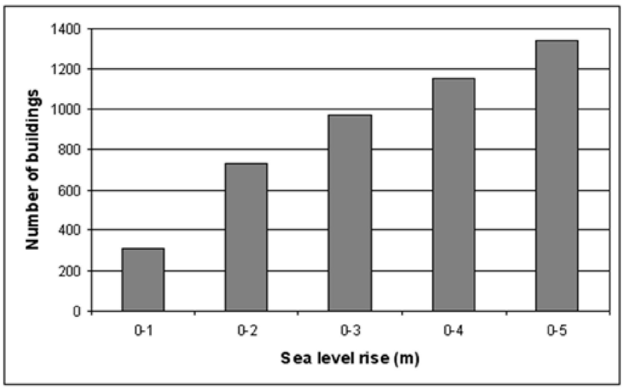

Figure 5. Number of buildings vulnerable to flooding.

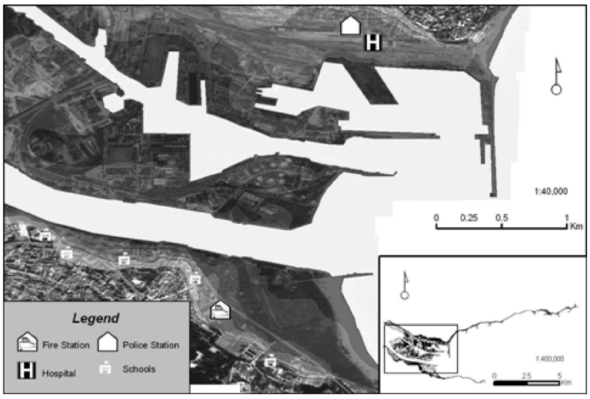

Figure 7. Locations of critical facilities.

stations, railway station and Port of Varna)

(2) Commercial buildings (public or private such as manufactories, markets, storehouses, offices, military and custom buildings, restaurants, swimming pools, etc.)

(3) Houses

(4) Archaeological sites

The number of buildings that would be flooded at given scenarios of extreme sea level rise (Figure 5) was determined by means of high resolution satellite mosaic scene of the study area. Total number of 305 single buildings (including the commercial ones and part of Port of Varna) would be affected by sea level rise of 1 m. Projecting the most severe scenarios of sudden high sea level up to 5 m it was found that total number of 1341 buildings will be exposed to flooding. This number includes 320 public/own houses, one railway station, the Port of Varna, one police station and more than 1000 commercial buildings. It is obvious that direct economic losses from flood hazards under extreme sea level rise would be mostly related to damages of houses, commercial buildings and main transport communications. Such losses could also have indirect economic and social impacts on coastal community as it can cause lost of jobs, damages of cultural heritage and population distress (BOYD *et al*, 2002).

Identifying building infrustructure that could be impacted during the flood events is important information both for coastal developers and community protection. Using XTools Pro GIS extension the areas of buildings endangered at given sea level rise scenarios were estimated and added in the attribute table. Sea level rise of 1 m will damage total buildings area of 190 000 m^2, but at 5 m increase of the sea level these areas will reach 602 000 m^2 (Figure 6).

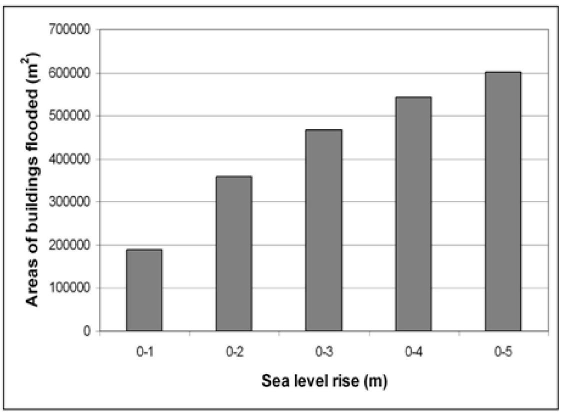

Figure 6. Areas of buildings vulnerable to flooding.

As BOYD *et al*., (2002) defined in their research, for flood assessment is important to identify also the locations of critical facilities, for example schools, hospitals and homes for the elderly, fire and police stations, communication facilities, etc. Since these facilities and buildings play a vital role particularly during and immediately after an extreme event, their destruction could have a negative impact on local coastal community. Hence, determining the locations of such facilities, being at highest risk during sudden sea level rise could help mitigation actions and support future protection decisions. Figure 7 shows the locations of critical facilities determined around the Bay of Varna. One hospital, one police and one fair stations were identified as most vulnerable to risk of inundation and potentially affected by sea level rise of 3 m. Sea level increase of 4 m would endanger three schools, while at scenario of 5 m level rise a total number of five schools would be affected by flooding.

CONCLUSIONS

The study performed produces advantages of using modern techniques such as 3D GIS models and high resolution satellite images in flood risk assessment of the area of Varna Bay, Bulgarian Black Sea coast. Generated detailed and precise flooding map of the study area could be used as an efficient tool to predict potential hazards for coastal areas and different types of buildings at extreme sea level rise. Spatial and mapped information on flood risks visualised via 3D GIS modelling would be essential for developing local prevention strategies (planning coastal/flood defence measures, improving public awareness through education and preparedness of communities, etc.). Thus, 3D GIS modelling approach could also provide coastal developers and stake-holders with required basic information to facilitate the emergency response and efforts coordination during and after the extreme events.

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