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A GIS-based approach for the assessment of Vulnerability to Natural Hazards – The case of Zakynthos island

Abstract

This research work describes the design, development and application of a GIS-based technique for the preliminary assessment of Natural Hazards Vulnerability, as a methodological framework for a systematic approach in development planning studies, which should undertake natural hazards mitigation activities. The analysis is conducted in Zakynthos island, located in Ionian Sea. The corresponding results are provided for the landslide, erosion, seismic, flood, forest fire and desertification risk assessment, and they have been spatially evaluated by using available historic data. The study illustrates that geographic information systems can play a crucial role in hazard assessment application, as a means of collecting, organizing, analyzing and visualizing data. This integrated approach includes the collection and analysis of various spatial data (i.e., topography, land use, soil), after taking into consideration different methods for the natural hazard estimation. Typically, a raster-analysis processing is performed which leads to the resulting map with the potential hazard, presented in different classes of hazard for the entire region.

Keywords: GIS, natural hazards, Zakynthos

Introduction

Natural hazards is one of the main factors that cause a negative effect on human beings and environment. The term “natural hazards” is refer to all atmospheric, hydrologic, geologic (especially seismic and volcanic), and wildfire phenomena that, because of their location, severity and frequency, have the potential to affect humans, their structures, or their activities adversely (Burton, 1993). Vulnerability assessment is of great importance as a tool to identify the in “high-risk areas”, to manage the spatial planning of a developing region and to take the proper decision for protective measures in case of an emergency. Particularly, the determination of natural hazards susceptibility and the incorporation of the results with the initial planning process may reduce infrastructure damages in the long run (Karlsson et al, 2017).

Geographical information systems (GIS) provide a powerful tool for geo-environmental evaluation in support of urban land-use planning (Dai et al, 2001). An important feature of a GIS is its ability to generate new information by integrating the existing diverse datasets sharing a compatible spatial referencing system (Goodchild, 1993). GIS technology has been widely used to assess natural geologic hazards, especially landslides (e.g. Atkinson and Massari, 1998; Crozier and Glade, 2005; Psomiadis, 2010), forest fires hazard (e.g. Chuvieco and Salas, 1996; Keane et al., 2010) and flood-prone areas (e.g., Ozcan and Musaoglu, 2010; Kandilioti and Makropoulos, 2012; Siddayao et al., 2014; Papaioannou et al., 2015).

This paper summarizes the results from the design, development and application of a GIS-based technique for the preliminary assessment of Natural Hazards Vulnerability, as a methodological framework which has been implemented in the island of Zakynthos (Western Greece). Zakynthos is a municipality of the Ionian Islands region and includes the island of Zakynthos with its nearby small islands Marathonisi, Pelouzo and Strofades. It is located 8.5 nautical miles southern of Kefalonia and 9 miles at the West of Peloponnese. The geomorphology of the island varies between the western, mountainous (Vrahionas mountain, 752 m), and the eastern, quite flat, part. The study area consists of a variety of geological formations and presents neotectonic activity. The combination of dense rainfall during winter months and erosive geological formations create a dense network of streams mainly in the lowland area, causing flooding, erosion and landslide phenomena. In summer months, forest fires is a frequent disaster for the region. The hazards selected to be studied are the landslide, erosion, seismic, flood, forest-fire and desertification. Based on various methodologies, the spatial distribution for each hazard in different classes of the abovementioned natural hazards was assessed and the results were compared the available historical data. In particular, (i) the Landslide Susceptibility Index 'LSI' was calculated for the landslide hazard mapping; (ii) the Universal Soil Loss Equation (USLE) for the mean annual soil losses mapping (erosion hazard); (iii) the maximum expected seismic intensity, based on the maximum Environmental Seismic Intensity scale (ESI 2007), was estimated for the seismic hazard mapping; (iv) a multi-criteria analysis concerning ground-based geospatial data was performed for the flood hazard mapping; (v) the methodology proposed in the framework of Forest Cities (Papanikolaou et al., 2012) was applied for the identification of areas prone to forest-fires; and, finally, (vi) the methodology proposed by Kosmas et al. (1996) and Kosmas et al. (1999) was followed for the desertification identification. The entire procedure is based on a spatial multi-criteria analysis approach using geological, geomorphological, hydrological and land-use factors. To utilize spatial multi-criteria decision support (i.e., estimation of different hazard classes), the Analytic Hierarchy process 'AHP' (Saaty, 1980) was adopted, as a method to determine each factor's relevant importance. Hazard score results from the weighted linear combination (WLC) of the involved factors and the final classes of hazard are defined, based on different clustering classification methods, such as the Jenks Natural Breaks (Jenks, 1967). Finally, findings concerning the GIS-based natural hazards susceptibility assessment correspond to the identification of the hazard-vulnerable areas and to the evaluation of the results using historic data. The structure of this paper is divided into three sections. The current section (Sec. 1) is the Introduction to the subject, Section 2 is divides into six parts, describing the methodological framework, as well as, the corresponding assessment separately for each natural hazard. Finally, Section 3 combines and concludes the results from the six individual parts.

Landslide Hazard

The methodology followed is based on the semi-quantitative method of Psomiadis (2010) for the estimation of the Landslide Susceptibility Index (LSI). This is a multi-parametric approach which combines 11 factors by classifying them according to their value in a scale of integers between 1 - 7 and by estimating different factor weights. These factors are the geological formations of the region (G); the land cover type (LC) according to CORINE Land Cover (2012); the mean annual precipitation regime (P), as an indicator of soil moisture; the soil depth (SD); the relative relief (RR), which returns the absolute maximum altitude difference in a 5x5 matrix and it is used based on the idea that for the same slopes the higher altitude areas are more vulnerable due to the higher runoff and low infiltration. Three factors that can be calculated based on the DEM of the study area are the curvature (C), topographic slopes (TS) and aspect (A). The final three factors are the factors of proximity, i.e., the distance from stream network (SB), road network (RB) and active faults (FB). Finally, the LSI is calculated according to Eq. 1:

$$\mathrm{LSI} = 10\ \mathrm{G} + 10\mathrm{TS} + 8\mathrm{LC} + 8\mathrm{P} + 6\mathrm{A} + 7\mathrm{RR} + 4\mathrm{C} + 8\mathrm{SD} + 10\mathrm{SB} + 10\mathrm{FB} + 5\mathrm{RB} \quad (1)$$

Results of LSI were clustered into 5 groups of hazard and compared to the historic landslides positions (Fig. 1a). This evaluation showed a significant identification of landslide-prone areas. The most vulnerable regions are appeared away from settlements but along the road network. In the plains (eastern part), no risk is identified.

Erosion Hazard

The spatial and quantitative assessment of soil loss, as an indicator for the hazard of erosion in the island of Zakynthos was implemented using the Universal Soil Loss Equation (USLE). According to this, the annual soil loss is estimated with Eq.2:

$$\mathrm{A} = \mathrm{R} \cdot \mathrm{K} \cdot \mathrm{L} \cdot \mathrm{S} \cdot \mathrm{C} \cdot \mathrm{P} \quad (2)$$

where:
A: annual soil loss (t $ha^{-1}y^{-1}$)
R: rainfall erosivity factor (MJ mm ha^{-1} h^{-1} y^{-1})
K: soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1})
L: slope length factor
S: slope factor
C: cover management factor
P: supporting practice factor

For the implementation of USLE method, data concerning the morphology, lithology, rainfall and land use of the study area were used. Each factor was quantified and rated according to the influence in the erosion processes. The final result of the applied methodology was the mapping of an average annual soil erosion for the study area. Factor ‘R’ was calculated using the spatially distributed mean annual precipitation; factor ‘K’ results from the classification of geology; factors ‘L’ and ‘S’ were combined according to an expression proposed by Morgan (2009):

$$LS = \left(\frac{L}{22}\right)^{0.5} (0.065 + 0.045S + 0.0065S^2) \quad (3)$$

where, length (L) in m and slope (S) as percentage.
Accordingly, factor 'C' ranges between 0-1 and uses the CORINE Land Cover (2012) dataset as a background (e.g., Cebecauer et al., 2000; Bilasco et al., 2009). Finally, factor 'P' is defined by the analyst and varies between 0-1.
Results (Fig. 1b) show that about 56% of the islands appears very low 'A' factor, which corresponds to very low rate of erosion. The areas with very high soil loss are located in the eastern, south-eastern and south-western parts. High rates of soil loss are related to the possible occurrence of floods and landslides taking into consideration the historic relevant phenomena in these sites.

Seismic hazard

Seismicity in Ionian Islands is one of the most frequent natural hazard. The methodology followed determines the effects triggered by the earthquake in the natural environment based on the maximum Environmental Seismic Intensity scale (ESI 2007: Michetti et al., 2007). This approach requires an extensive study of the historic seismicity and definition of active faults that may influence the area in case of an earthquake. After the faults identification, the relationship of Wells and Coppersmith (1994) was used as a means of linking the fault's length (SLR) to the Maximum Magnitude (M):

$$M = 5.08 + 1.16\log(SLR) \quad (4)$$

In the framework of the current study, only faults with length longer than 5.8 km were taken into account. The placement of 'hypothetic epicenters' according to their focal mechanism (see also Roberts et al., 2004) and the establishment of areas of same mean seismic intensity followed, where:
If M≤6.4, then three zones with radius of 15, 31 and 53 km for intensities of VIII, VII and VI are defined.
If M>6.4, then four zones are defined (12, 25, 46, 77 km for IX, VIII, VII VI, correspondingly).
The final step of the process concerning the expected intensity of ground shaking in terms of peak acceleration takes into consideration the response of the geological formations, based on the classification of Table 1. Therefore, if the bedrock is very coherent, then the expected seismic intensity reduces by 1, else, in case of a very low-quality subsoil, then the expected seismic intensity can be increased up to +1.5.

Table 1. Bedrock classification for seismic intensity

Subsoil	**Average change in intensity**
Rock (e.g., granite, gneiss, basalt)	- 1.0
Firm sediments	± 0.0
Loose sediments (e.g., sand, alluvian deposits)	+ 1.0
Wet sediments, artificially filled ground	+ 1.5

The formulation of the condition described above leads to the reduction or increase of the seismic hazard, according to the bedrock of each region. Finally, 18 faults were analyzed and the corresponding map of average (among 18) maximum expected seismic intensity, combined with the seismic behavior of bedrock, is presented in Figure 1c.

Flood Hazard

The preliminary identification of areas prone to flooding was based on hazard-enhancing factors, such as the low topography, the percentage of imperviousness, the land cover and the existence of settlements. There are several examples in literature which take into consideration different factors. The current approach combines the most decisive ground-based factors driving the occurrence of the phenomenon and the resulting map is evaluated according to the available historic data. Six factors were standardized according to the Equation 5:

$$\mathrm{x_i} = \frac{(\mathrm{FV_i} - \mathrm{FV_{min}})}{(\mathrm{FV_{max}} - \mathrm{FV_{min}})} \cdot \mathrm{SR} \qquad (5.\mathrm{a}) \qquad \text{or} \qquad \mathrm{x_i} = 1 - \frac{(\mathrm{FV_i} - \mathrm{FV_{min}})}{(\mathrm{FV_{max}} - \mathrm{FV_{min}})} \cdot \mathrm{SR} \qquad (5.\mathrm{b})$$

Where, FV_{min}, FV_{max} correspond to the minimum and maximum factor values, respectively, and; FV_i the value of each raster cell, which then corresponds to the standardized value x_i. The equation $(5.b)$ is performed in factors which affect mostly the phenomenon when value is minimum (e.g., slope). In GIS, this step is being implemented through the Raster Calculator separately for each criterion. A pairwise comparison (Saaty, 1980) in criteria was followed in order to estimate the proper factors' weights for the flood hazard (FH) identification. Finally, FH was calculated according to the Equation:

$$\mathrm{FH} = 0.3\ \mathrm{S} + 0.25\ \mathrm{I} + 0.15\ \mathrm{GP} + 0.15\mathrm{SET} + 0.1\mathrm{STR} + 0.05\mathrm{FL} \qquad (6)$$

where:
S: Slope
I: The percentage of imperviousness or Soil Sealing, provided by Copernicus Land Monitoring Service in spatial resolution of 20 m
GP: permeability of geological formations
SET: Euclidean distance from settlements
STR: Euclidean distance from streams
FL: flow length raster (the downstream distance along the flow path for each cell).
All factors were considered as normalized and the layer of historic flood events was not involved in the entire procedure in order to be used as an evidence in the results evaluation. The resulting map was classified according to the optimization method of classes' distribution natural breaks (Jenks 1967). The Jenks natural breaks classification method is a data classification method designed to determine the best arrangement of values into different classes (Stefanidis and Stathis, 2013). Findings (Fig. 1d) were considered satisfactory; mainly three zones of high FH are identified and evaluated according to the historic floods: (i) the city of Zakynthos, (ii) the Alykes-Alykanas plain and (iii) the Laganas plain. High FH is also observed individually in same settlements (e.g., Elaties, Maries, Agalas), due to the impervious surfaces.

Forest-fire Hazard

Forest-fire (FF) hazard assessment was performed via a standardized process as it is described in detail by Papanikolaou et al. (2012). This methodological framework combines six factors of different weight coefficient and the resulting map ranges between 0 (for very low hazard) and 1 (extremely high hazard) through the WLC of Equation 7:

$$\mathrm{FF} = \mathrm{LC}\ 0.45 + \mathrm{TS}\ 0.15 + \mathrm{A}\ 0.05 + \mathrm{RB}\ 0.12 + \mathrm{DB}\ 0.1 + \mathrm{SB}\ 0.13 \quad (7)$$

where:

LS: Land Cover according to CORINE (2012), grouped into six general categories

TS: Topographic slopes in percentage, in three classes for low, medium and high slopes

A: Aspect of surface, in three classes. The highest score corresponds to the southern aspect, as it is characterized by drier conditions.

RB: distance from road network (buffer zone of 50m)

DB: distance from power-electricity network (buffer zone of 30m)

SB: distance from settlements and landfills (buffer zone of 400m and 100m correspondingly).

The analysis and the comparison with the historic data showed that the methodology appears to generally underestimate the hazard of forest-fires. This weakness can be attributed to the causes themselves, as an anthropogenic factor. However, areas of high hazard are consistent with historic records in general.

Desertification Hazard

The assessment of desertification as a measure of the sensitivity to land degradation was carried out by means of calculating the Environmental Sensitive Areas Index (ESAI), which has been developed in the MEDALUS (Mediterranean Desertification and Land Use) project funded by the European Commission (Kosmas et al., 1996, 1999). This index incorporates data regarding vegetation, management practices, soil and climate characteristics. The calculation of ESAI is based on the geometric mean of four key-indicators; the soil quality index (SQI, Eq. 8), the climate quality index (CQI, Eq. 9), the vegetation quality index (VQI, Eq. 10) and the management quality index (MQI, Eq.11).

$$\mathrm{SQI} = (\text{texture} * \text{parent material} * \text{rock fragment} * \text{depth} * \text{slope} * \text{drainage})^{1/6} \quad (8)$$

$$\mathrm{CQI} = (\text{rainfall} * \text{aridity} * \text{aspect})^{1/3} \quad (9)$$

$$\mathrm{VQI} = (\text{fire risk} * \text{erosion protection} * \text{drought resistance} * \text{vegetation cover})^{1/4} \quad (10)$$

$$\mathrm{MQI} = (\text{land use intensity} * \text{policy enforcement})^{1/2} \quad (11)$$

In order to estimate the SQI, data regarding the geology of the region (i.e., the granulometry, the parent material, the soil horizon's depth, the characterization of coarse materials, the terrain slope and the hydromorphy) are required. These data are either vector or raster that both are reclassified into standard classes of values. The second index requires a raster file with the spatial distribution of the mean annual precipitation, the drought index 'BGI' estimation via the mean annual temperature and the Aspect raster layer resulting from the digital elevation model (DEM) of the region. THE VQI is a function of the FF hazard, the soil protection from erosion, the drought tolerance and the percentage of vegetation cover. All these factors can be estimated based on the CORINE Land Cover (2012). The MQI incorporates the land use intensity and the applied management policy. The resulting values are separated into eight classes of hazard, as they are summarized in Table 2.

Table 2. The ESAI classification

Category	Subcategory	Description
[C] Critical ESAs	C1, C2, C3	Areas already degraded
[F] Fragile ESAs	F1, F2, F3	Areas where a small change in the physical system or little human intervention can lead to desertification
[P] Potential ESAs	P	Areas that may be threatened following a significant change in the physical system, or after extensive human activity aggravating the area
[N] Non-threatened areas	N	Areas not threatened by desertification

The spatial distribution of ESAI is shown in Figure 1f. In Zakynthos island, about 60% of the total area corresponds to C1-C2 category and fragile ESAs follow with 29%. Only the 3.7% of the island is characterized as non-threatened. It should be noted that Continuous and Discontinuous urban fabric areas (grey color in Fig. 1f) have not been included in the analysis through the estimation of ESAI.

Conclusions

The objective of this research work was to illustrate the GIS capabilities in applications relevant to natural hazards assessment. The collection, analysis and visualization of geospatial data (e.g., topography, land use, soil type) for the island of Zakynthos and the implementation of different methods for the natural hazards estimation and classification led to six hazard maps, for the main natural catastrophes (i.e., landslide, erosion, seismic, flood, forest fire and desertification).

A raster-analysis processing is performed, which leads to the resulting map with the potential hazard, presented in different classes of hazard for the entire region. As expected, the results vary according to the methodology followed (i.e., the factors taken into account, the factor weights in the WLC and the classification method).

Particularly for Zakynthos, it was found that the eastern part, which gathers the main human activities is systematically more vulnerable in all hazards, but, among them, the most important ones are the flood and seismic. Landslides and desertification follow, and finally, the forest-fire and erosion hazard are the two of lower intensity.

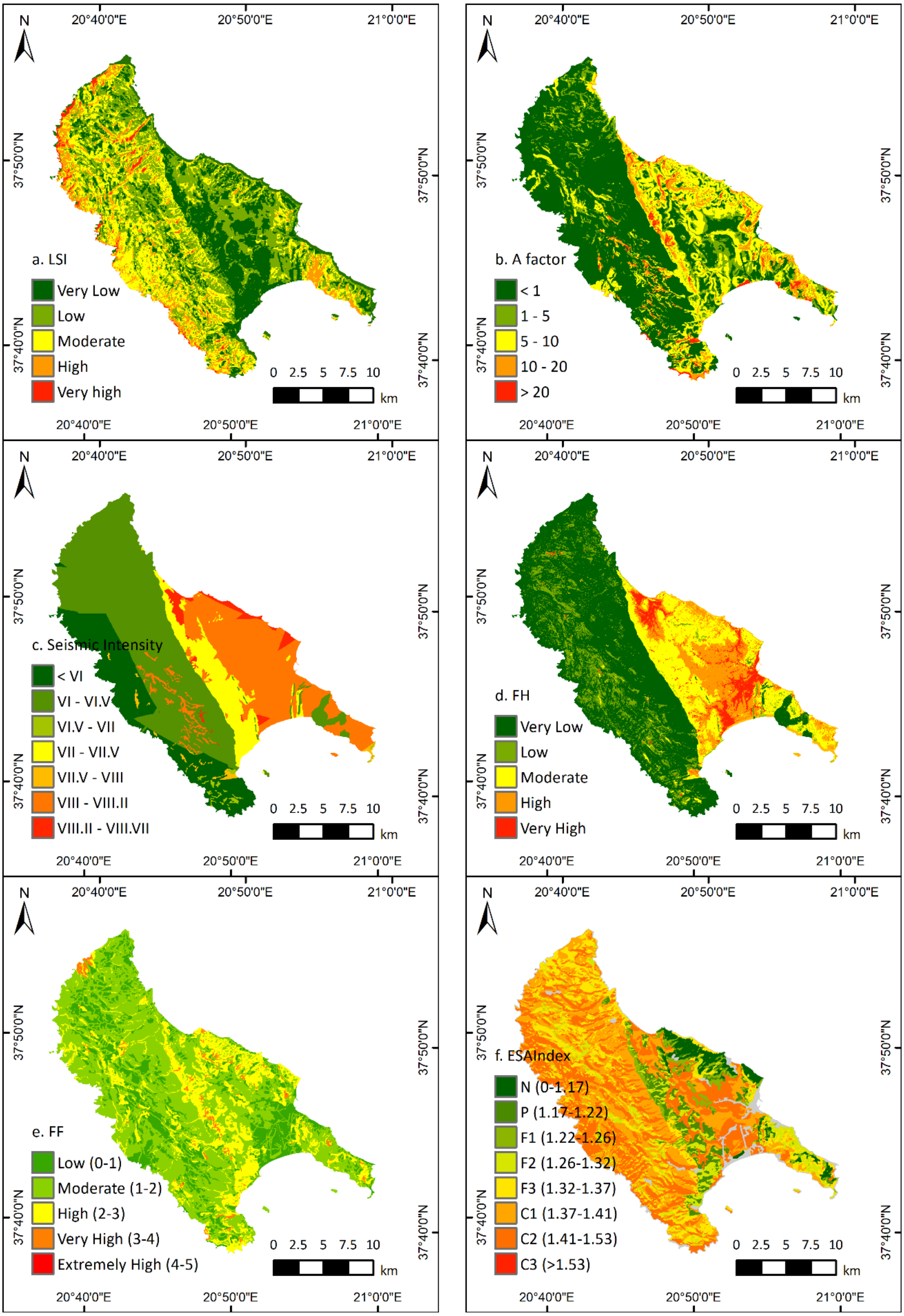

Figure 1. Maps of natural hazards assessment

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