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Regional landslide susceptibility assessment: case studies from Greece

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Abstract In this study, regional-scale landslide susceptibility mapping was conducted for two well- known landslide-prone regions in Greece, employing both qualitative and quantitative methods. The geological settings, particularly the variety of geological units, was the key difference between these areas. The Analytic Hierarchy Process (AHP) and Frequency Ratio (FR) methods were employed in both cases for six common-used predisposing factors (lithology, slope, land use, distance from faults, distance from hydrographic network and road density). The Landslide Susceptibility Index (LSI) was used for mapping landslide susceptibility level, with validation performed via ROC curves. Thus, the output maps generated by this procedure were verified by comparison with known landslides not used for training the models (prediction rates) or known landslides with an equal number random set of points free of landslides (success rates). The primary aim of this work was to evaluate the importance of conditioning factors in predicting landslide occurrences using the mentioned models. According to the results, in both areas the importance of different predisposing factors seems to vary in shaping the landslide susceptibility level. This research recognizes the critical role played by scale for landslide susceptibility modelling. Therefore, part of the aim of this work is to discuss the minimum, yet sufficient data required to develop more versatile, generalized regional susceptibility models (medium scale), that can then be used as indicators for national scale (small scale) analysis and in the exploitation of research results by local stakeholders and Civil Protection authorities.

Keywords landslide inventory, susceptibility assessment, Greece, LSI, ROC curves

Introduction

Landslide susceptibility assessment is a key component of landslide hazard and risk management, which can help civil protection authorities to establish specific landslide hazard reduction programs and strategies. Over the last three decades many researchers around the world have applied plenty of qualitative or quantitative approaches for landslide susceptibility evaluation. Regional scale landslide susceptibility maps (<1:50000) portrays areas with different levels of threat to failure. This information can be used to establish land use plans, development activities and patterns of building regulations (SafeLand 2010). Landslide susceptibility mapping relies on a rather complex knowledge of slope movements and their controlling factors. The reliability of landslide susceptibility maps mainly depends on the amount and quality of available data, the working scale, and the selection of the appropriate methodology of analysis and modeling (Baeza and Corominas 2001).

Due to the variety of information and the abundance of data provided, some interesting outcomes were reached, concerning the characteristics of the landslides, after applying simple statistical analysis.

Study areas

Corfu island

The island of Corfu in the Ionian Sea, covering an area of about 590 km². The morphological relief of the island is more pronounced in the northern part due to its geological and tectonic structure. Concerning the geology, formations from the Ionian geotectonic zone (mainly limestone), as well as Neogene and Quaternary formations, contribute to the geological structure of Corfu. The geological structure is characterized by intense folded structures, reverse faults, large transverse ruptures with a significant horizontal component, and phenomena of uplifting movements. These geotechnical conditions have increased the susceptibility to landslides, with specific types including rotational landslides, rockfalls, and land subsidence.

Landslide phenomena in Corfu mainly occur in Neogene sediments, accounting for over 65% of the occurrences.

Evritania region

Evritania region is situated in central Greece, encompassing the southern region of the Pindos Mountain range, with an area spanning 1870 km². The area's tectonic activity is notable, primarily attributed to the presence of the Pindos Mountain range, characterized by extensive folds and successive thrusts. This tectonic activity, coupled with neotectonic processes and lithological factors, has contributed to the development of an intense relief and a complex hydrological network.

The geological structure of the region is predominantly composed of formations from the Olonos-Pindos geotectonic zone, along with Quaternary formations. Landslide occurrences are predominantly associated with flysch formation and they are mostly in the completely weathered zone.

Methods

The adopted methodology consists of four stages. In particular, the first stage gathers predisposing factors, usually used to literature, which deals with landslides activation. In addition, the appropriate landslide inventories were prepared for each study area. Next, the landslide susceptibility assessment was carried out with AHP both FR methods. The overall susceptibility of an area was determined by synthesizing all the factors using an algebraic approach, resulting in a Landslide Susceptibility Index (LSI) used to map the level of landslide susceptibility. Finaly, the validation and the evaluation of results achieved in the previous stage was conducted by ROC curves.

AHP method

The application of the Analytical Hierarchy Process (AHP) method, developed by Saaty (1977), has been used by many authors worldwide, as a multi-criteria decision-making method. It involves making binary comparisons of factors within a complex problem.

After constructing a hierarchical representation of the problem, the next steps involve pairwise comparisons of factors and subfactors using a nine-point scale in a matrix table. The scale values range from 1 (equal importance) to 9 (extremely stronger importance), with intermediate values such as 2, 4, 6, and 8 indicating intermediate levels of importance (Saaty, 1977). Each factor is assessed in relation to every other factor using values from 1/9 to 9. Subsequently, the relative weights for each factor and subfactor in the decision hierarchy are estimated.

The consistency ratio (CR) is then calculated to validate the AHP results and prevent arbitrary choices in the matrix. The CR is considered valid if it is equal to or less than 0.1 (10%) (Saaty, 1978). The equation for calculating the consistency ratio is:

$$CR = (CI/RI)*100 \quad [1]$$

where RI is the random consistency index and CI is the average consistency index calculated as:

$$CI = (\lambda_{max} - n)/(n - 1) \quad [2]$$

where λ_{max} is the maximum eigenvalue of the comparison matrix, and n is the number of factors.

FR method

The Frequency Ratio (FR) model, as a statistical approach, based on the analysis between distribution of landslides and each landslide-related factor, to reveal the correlation between landslide locations and the factors in a specific area (Lee and Pradhan 2007). Therefore, the frequency ratios of each factor class were calculated from their relationship with landslide events. According to the method, the number of landslides in each class is evaluated and the frequency ratio for each factor class is found by dividing the landslide ratio by the area ratio (Lee and Talib 2005). If the ratio (FR) is grater than 1, then the relationship between a landslide and the factor's class is strong while if ratio is less that 1, the relationship is weak.

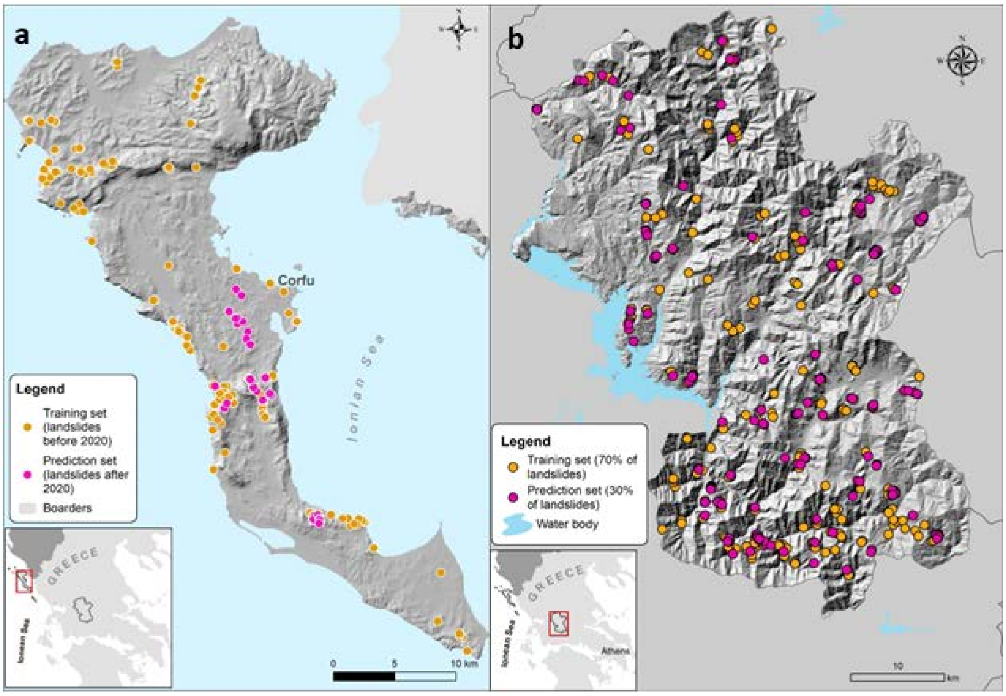

Figure 1 Landslide inventory maps of a) Corfu island and b) Evritania region.

Input data

Six commonly used predisposing factors were chosen reflecting general natural settings in the study areas. Initial landslide predisposing factors considered were as follows: (a) Lithology is based on the engineering geological mapping scale of 1:50000, (b) Slope is calculated from the DEM of Greek Cadastral with a pixel size of 50 m, (c) Land use is at an original scale of 1:100000 provided by Land

Corine 2018, (d) road density map (km/km^2) based on Open Street Map road network, (e) distance from faults in meters, as they have mapped on the relevant 1:50000 Hellenic Survey of Geology and Mineral Exploration (HSGME) geological map sheets of these areas and (f) distance from hydrographic network in meters. Therefore, all the thematic layers for each area, Corfu island and Evritania region, were prepared in 1:50000 scale.

Landslide inventory

Using the National Database of Landslides provided by HSGME and conducting extensive field surveys, ensured the accuracy of landslide spatial distribution and captured their distinctive features. More precisely, in Corfu island 203 landslides are recorded since 1959 while in Evritania region 483 since 1963. However, a second inventory independent of the main one was mandatory to be generated, under the purpose of verification. Here, the secondary landslide inventories were drawn up as proposed by Remondo et al. (2003). Thus, at Evritania region the initial inventory was randomly split into two groups, one for the susceptibility analysis (70% of the total) and one for validation (30% of the total). In the case of Corfu island, the analysis was made using landslides activated in a certain period (before 2020), and validation was performed by means of landslides that occurred in a different period (after 2020) (Figure 1).

Results

Utilizing AHP in both areas, the calculation commenced with pairwise comparisons of all possible pairs of factors in a matrix based on expert knowledge. Subsequently, values and weights were determined, and in the final step, the consistency index (CI) and consistency ratio (CR) were calculated. Based on the results of the hierarchy process nalysis (Table 1), the landslide susceptibility map for each area using AHP model was constructed using the following equations (Figure 2a and Figure 3a):

LSI_{Corfu}= 0.037 * Landuse + 0.328 * Lithology+ 0.303 * Slope + 0.089 * Road densisty + 0.095 * Distance from rivers + 0.148 * Distance from faults [3]

and

$LSI_{Evritania}$= 0.045 * Landuse + 0.271 * Lithology+ 0.353 * Slope + 0.085 * Road densisty + 0.098 * Distance from rivers + 0.147 * Distance from faults [4]

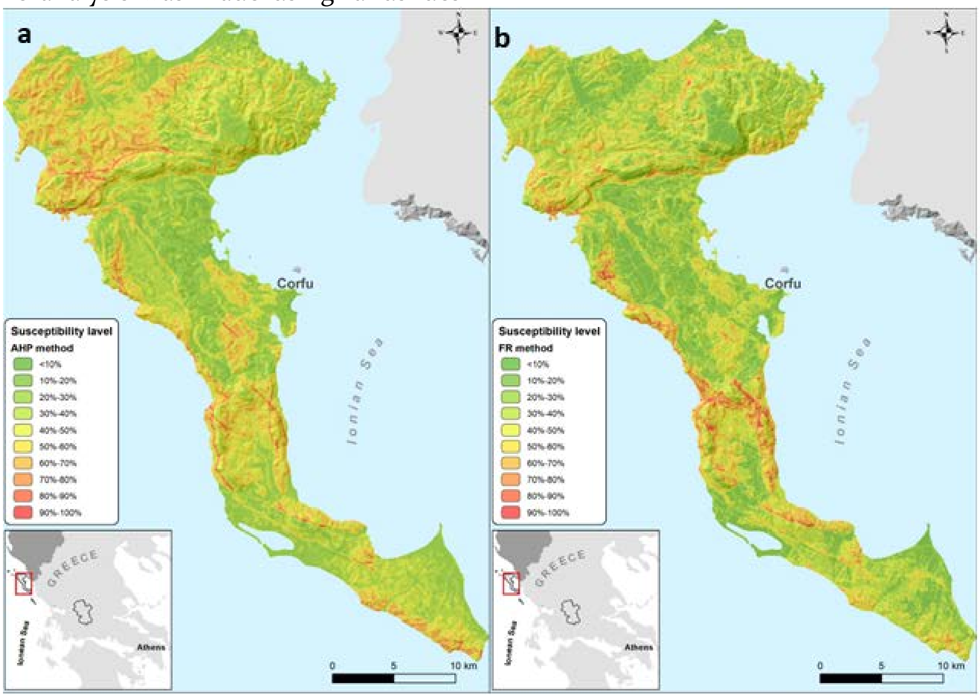

Figure 2 Landslide susceptibility map of Corfu island a) AHP method and b) FR method

Table 1: Relative weights from pairwise comparison with AHP method in both areas.

Factors	Weights	
	Corfu	Evritania
Slope	0.303	0.353
Lithology	0.328	0.271
Land use	0.037	0.045
Road density	0.089	0.085
Distance from faults	0.148	0.147
Distance from rivers	0.095	0.098

For Corfu, the CR was found to be 0.056, while for Evritania, it was 0.034. For both cases, CR values are considered valid as they are less than 0.1. Therefore, the weights determined through the AHP are accepted for use in landslide susceptibility mapping.

It is noted that, at Corfu island LSI_{AHP} ranges between 0.04 to 0.32 and for Evritania region LSI_{AHP} takes values between 0.06 to 0.34.

To simplify the legibility and the comparisson between the landslide susceptibility maps, the LSI range was subdivided into susceptibility zones of 10%. The lower the percentage the lower the susceptibility level.

In contrast to AHP method, FR method requires a training data set to compute the weights for each factor and its classes. Training sets as well as test sets were generated as descrided above. The FR model was applied to define weights for each factor, using the ratio of the percentage of landslides in a class of the selected factor to the percentage of the area of this class in the study area. Finally, the Landslide Susceptibility Index was used for landslide susceptibility mapping based on the weights were derived from the bivariate statistical analysis (Figure 2b and Figure 3b). Here, the LSI_{FR} for Corfu island ranges between 1.7 to 16.2 while in Evritania region between 2.2 to 18.

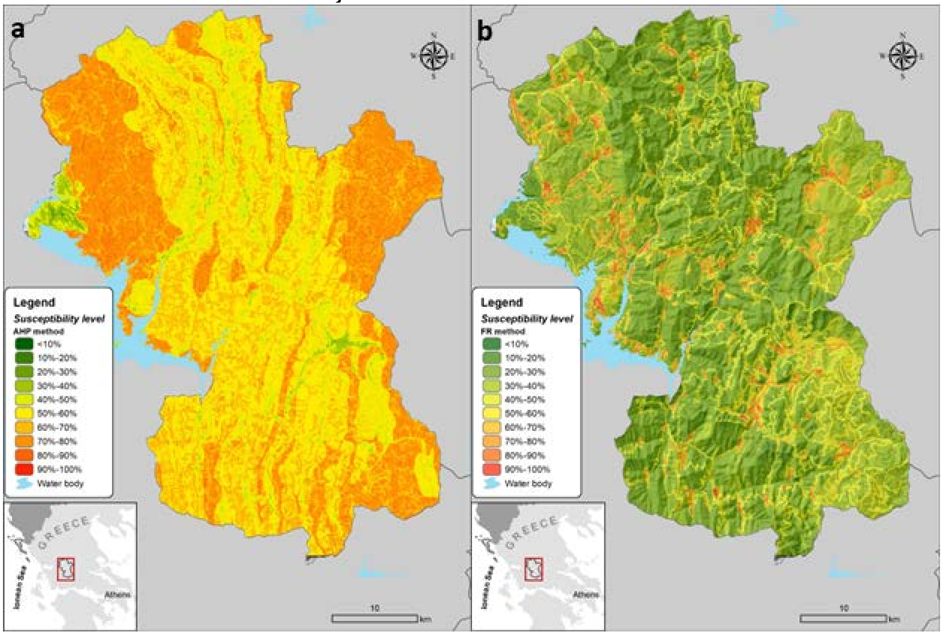

Figure 3 Landslide susceptibility map of Evritania region a) AHP method and b) FR method

Model validation and evaluation

An important stage on landslide susceptibility assessemnet is to evaluate the effectivenes of the produced landslide susceptibility map. For this purpose, receiver operating characteristic (ROC) curves are used, firstly for checking the reliability of the proposed model (success rate curves) as well as to check the ability of the model to pinpoint landslide-prone areas (prediction rate curves).

The accuracy of the model is checked for each area, using the the training set and an equal number random set of points free of landslides. This was repeated for the validation set of landslides in order to find if these independent landslide occurences were correctly adapted in different suscectible areas.

Based on these, comparing the methods, the landslide susceptibility maps of Corfu island gives AUC=0.737, std=0.026 for AHP method and AUC=0.893, std=0.017 for FR method (Figure 4a). Interestingly, the prediction rate for FR method is characterized by AUC=0,906 while for AHP method the results are similar as before with AUC=0,706 (Figure 4b).

In Evritania region, the success rate results showed that the AUC was 0,499 (std=0.023) for AHP method and 0,872 (std=0,014) for FR method (Figure 5a). Furthermore, the prediction rate results were 0.429 and 0.874 respectively (Figure 5b).

Discussion

The landslide susceptibility analysis at the regional level defines areas with high susceptibility and allows the focus for a detailed local research and urban and regulation plans for areas of interest.

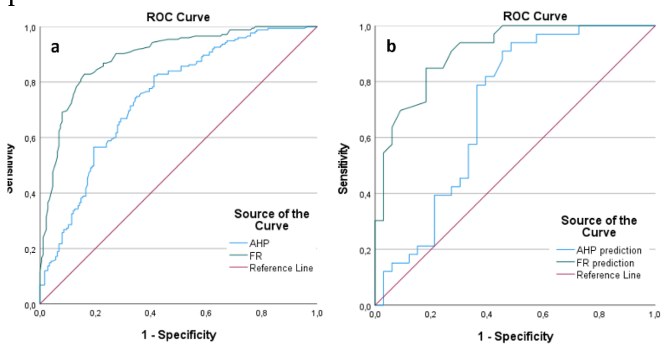

Figure 4 ROC curves for Corfu Island a) Success rate b) Prediction rate

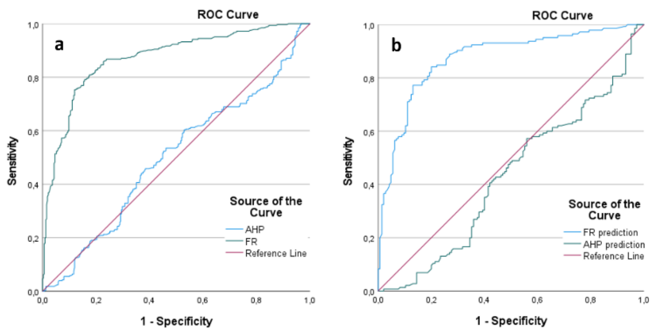

Figure 5 ROC curves for Evritania region a) Success rate b) Prediction rate

According to the ROC analysis, it is seen that both the success rate and prediction rate curve show almost similar result in any case. However, FR model seems to have better performance than AHP model. A comparison of the two susceptibility maps of Corfu island reveals that both highlight the most susceptible areas such as the central and the western part of the island, where annually suffer by landslides. On the other hand, landslide susceptibility analysis with AHP and FR methods in Evritania region differs a lot. Comparing the relevant ROC curves , the AHP method with AUC<0.7 is not able to sufficiently determine susceptibility levels. However, the FR model showed reasonably good accuracy in predicting the landslide susceptibility of the road section and the settlements. Nevertheless, in Evritania region the results are vague has to do maybe with the fact that, a) the majority of landslides in database are recorded along the road and into settlements, b) large mountainous areas into the region is difficult to access and c) the experts were based mainly on an geological point of view to suggest the factors weights.

Acknowledgements

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