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Geohazard map of the central Slovenia – the mathematical approach to landslide prediction

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Abstract

Issues connected with unwanted natural occurrences, such as landslides, floods or earthquakes, are a source of concern around the world and Slovenia is no exception. Landslides belong to the category of "manageable" natural disasters. Today, we cannot envisage spatial modelling and prediction of various events without the information technology. GIS is also used to analyse the landslide data and satellite images can serve as a support to the ground reconnaissance. Using the methods of univariate statistics, the influences of individual spatial factors on the different landslide types and on landslides generally were tested. Using multivariate statistical methods, the interactions between factors and landslide distribution, and defined the importance of individual factors on the landslide occurrence were tested. Having combined all the spatial data available, several models were developed. Those that produced best results were then used to determine and locate the potentially hazardous areas and to draw the map of landslide risk. The landslide risk-map permitted the assessment of the hazard to the inhabitants and infrastructure (roads) on the tested area.

Introduction

As a result of the recent natural disasters in Europe, like floods in 2002, the need for a better understanding of natural phenomena has arisen. Independently of whether these events result from human actions or are the work of nature, their prevention or mitigation is an important factor when the preservation of the modern man's environmental quality is at stake. Hence the need for better understanding of these phenomena, especially when their consequences can be to some measure controlled, like in the case of landslides. For this purpose, the statistical approach to analysing the influence factors and their contribution to landslide occurrence was chosen (Carrara, 1983; Carrara et al., 1991). For the study area, the central part of Slovenia, west of Ljubljana, was selected (Figure 1), covering approximately 35×35 km. A better understanding of the described relationships should enable a more precise and a more affordable identification of the landslide-prone areas. In order to determine the capacity of an accurate spatial prediction of landslides or landslide-prone areas, several linear prediction models, using AHP (Saaty, 1977), were developed. The applicability of the AHP (Analytical Hierarchy Process) method to landslide prediction has been shown before (Barredo et al., 2000; Mwasi, 2001; Nie et al., 2001).

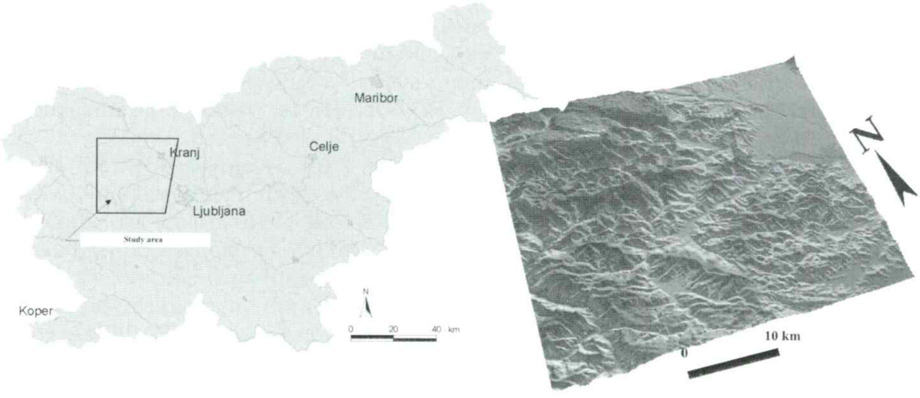

Figure 1. The study area

Data acquisition

To successful predict landslide occurrence and to produce the map of landslide-prone areas, relevant spatial data are needed. The data needed for this investigation were obtained from several sources. The landslide data were obtained from the landslide database that was constructed at Geological Survey of Slovenia. For the study area, it contains data on 614 landslides. Further, the digital elevation model (DEM) data were obtained from the national 25 m resolution DEM (InSAR DMV 25) (Survey and Mapping Administration, 2000). All the additional data on the terrain morphology (curvature, elevation, slope, aspect, basins, primary slope-units) were derived from the DEM. The Basic Geological Map of Yugoslavia at the scale of 1:100.000 served as a source for the geologic data of the area (Buser et al., 1967; Buser, 1973; Buser, 1986; Grad & Ferjančič, 1976). For the land use and the vegetation cover, satellite images from different sources were used and combined, using PCA (Principal Component Analysis) merging method. The multi-spectral part of the satellite data was obtained from the Landsat-5 TM images, and the high-resolution part was obtained from the Resurs-F2 MK-4 images. The topologic map in scale 1:50.000 was used as a source of the surface water net data (Survey and Mapping Administration, 1994). The population density data were obtained from National Office of Spatial Planning et al. (1997) and infrastructure data from Survey and Mapping Administration (2000).

Data analysis

The aim of the paper was to examine several topics, related to the landslide prediction in the central part of Slovenia, west of Ljubljana. One of the project's main goals was to study spatial factors that influence the occurrence of landslides, individually and conjointly, and to statistically establish the univariate and multivariate relations with the landslide distribution. A better understanding of the described relationships should enable a more precise and a more affordable identification of the landslide-prone areas. In order to determine the capacity of an accurate spatial prediction of landslides or landslide-prone areas, several linear prediction models, based on various methodologies were developed.

Univarate statistical analysis

Using methods of univariate statistics, the influences of individual spatial factors on the different landslide types and on landslides generally were tested. For the categorical variables, Kolmogorov-Smirnov and $\div^{2}$ test were used, where actual frequency of the landslide occurrence was compared to the expected frequency. Bigger difference represents stronger influence of the observed factor. Continuous variables were also tested with Student's *t* test. On the basis of these results the stability characteristics of the individual classes of the observed factors were assessed. The factors that proved to have played an important role are shown in the following table (Table 1). The steepness and the curvature of the slopes,

Table 1. Factors that play an important role in landslide occurrence (univariate statistical methods)

Variable	*All landslides*		*LS_type1*		*LS_type2*		*LS_type3*		*LS_type4*	
	χ^2	**K-S**	χ^2	**K-S**	χ^2	**K-S**	χ^2	**K-S**	χ^2	**K-S**
Slope	**0,0**	**0,01**	**0,0003**	**0,01**	**0,0**	**0,01**	**0,039**	**0,01**	0,28	**0,01**
Elevation	**0,0**	**0,01**	0,107	**0,01**	**0,0**	**0,01**	0,124	**0,01**	0,2515	**0,05**
Aspect	**0,001**	0,2	0,088	n.s.	**0,008**	n.s.	0,886	n.s.	**0,008**	**0,01**
Curvature	**0,0**	**0,01**	0,18	**0,01**	**0,0**	**0,01**	0,38	**0,05**	**0,011**	**0,01**
Lithology	**0,0**	**0,01**	**0,0**	**0,01**	**0,0**	**0,01**	**0,002**	**0,01**	**0,005**	**0,01**
Dist_geo_bound	**0,0**	**0,01**	**0,0164**	**0,01**	**0,0**	**0,01**	**0,002**	**0,05**	0,327	**0,05**
Dist_structures	**0,01**	**0,01**	0,282	**0,05**	0,2569	**0,05**	0,869	n.s.	0,067	n.s.
Dist_waternet	**0,0**	**0,01**	**0,0**	**0,01**	**0,0**	**0,01**	**0,001**	**0,01**	**0,0**	**0,01**
n		614		68		413		57		60

the distance to the geological borders, the distance to the rivers, lithology, and the type of vegetation proved to play an important role in landslide occurrence. LS_type1 stands for fossil landslides, LS_type2 for dormant landslides, LS_type3 for creeping, and LS_type4 for slides. Confidence limits for means were set to 95 %. Significant variables (statistical significance is higher than 95 %) are shown in bold text in the Table 1.

Satellite images

Prior to analysis, the multi-spectral satellite data, obtained from the Landsat-5 TM images, were merged with the high-resolution satellite data, obtained from the Resurs-F2 MK-4 images,. The merging of the two was done using the PCA joining method, where first principal component of the multi-spectral satellite data is replaced with the first principal component of the high-resolution satellite data (Cliché et al., 1985; Chavez et al., 1991; Sanjeevi et al., 2001; Vani et al., 2001). A part of the images were transferred from RGB colour model to the CIE L*a*b* (CIE, 1986) colour model (Figure 2). All images were than classified according to landslide prediction rate (areas or land-types where more landslides occurred have higher possibility of future landslide occurrence) using unsupervised classification and advanced RGB clustering method (ERDAS, 1999). The best results gave the image that was the composite of channels 3, 4 and 5, transformed with the CIE L*a*b* model. The landslide prediction error was 12,6 % (portion of the area that was classified as non-landslide, but where current landslides do occur) and the non-landslide area prediction error was 8,1 % (portion of the area that was classified as landslide-prone, but where no landslides can be found).

Multivarate statistical analysis

Using multivariate statistical methods (factor analysis and multiple regression analysis), the interactions between factors and landslide distribution were tested, and the importance of individual factors on the

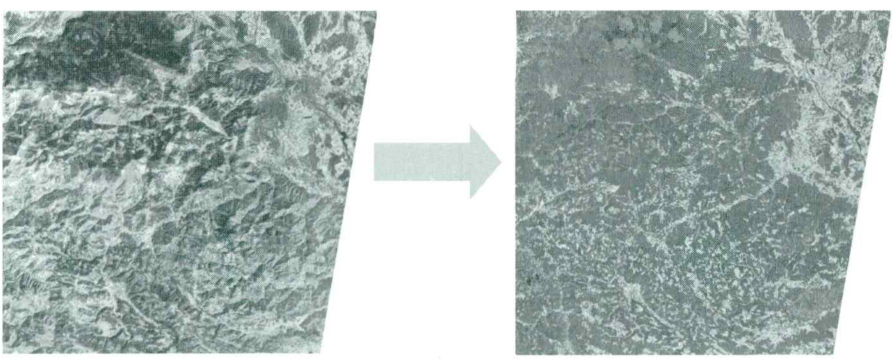

Figure 2. RGB to CIE L*a*b* transformation

Table 2. Portions of the variance, explained by factors with loaded variables (factor analysis)

	All landslides	Fossile landslides	Dormant landslides	Creeping	Slides
F1	Slope & terrain roughness (22%)	Lithological properties & slope variation (26%)	Slope & terrain roughness (24%)	Lithological properties (23%)	Slope & terrain roughness (27%)
F2	Lithological properties (15%)	Slope & terrain roughness (19%)	Avrg. dist. waters & cover type diversity (14%)	Slope & terrain roughness (19%)	Lithologic diversity, curvature type & avrg. dist. geol. boundaries (16%)
F3	Average curvature & avrg. dist. waters (12%)	Cover type diversity & avrg. curvature (12%)	Cover type & orientation (12%)	Avrg. dist. waters & avrg. curvature (15%)	Lithological properties (14%)
F4	Cover type & orientation (10%)	Lithologic diversity & avrg. dist. tectonic elements (9%)	Lithological properties (10%)	Cover type & orientation (12%)	Cover type (10%)
F5	Lithologic & cover type diversity (7,5%)	Cover type (8%)	Avrg. dist. tectonic elements (8%)	Lithologic diversity & avrg. dist. tectonic elements (6,5%)	Avrg. curvature (7,5%)
F6	Avrg. dist. tectonic elements (6%)	Avrg. dist. waters (7%)	Curvature type (6%)	Curvature type (5,5%)	Avrg. dist. tectonic elements (6%)
F7	Curvature type (5,5%)	-	Lithologic diversity & avrg. dist. geol. boundaries (5,5%)-	-	-
Sum	**78,3%**	**80,2%**	**79,2%**	**80,4%**	**80,5%**

landslide occurrence were defined. For the purpose of multivariate analysis, the area was subdivided into 78365 slope units, for which additional 24 statistical variables were calculated. In comparison with other multivariate statistical methods used, the factor analysis proved to be the most appropriate and reliable method for the landslide prediction. Table 2 is showing the portions of the variance, explained by various factors, that are represented by one or more variables. At the bottom, the total explained variance is shown.

After having combined all the spatial data, numerous models were developed, using the AHP method, with error ranging from 47 % to 3 %. Those that produced best results were then used to determine and locate the potentially hazardous areas and to draw the map of landslide risk. Figure 3 is showing the values of the weights of spatial factors in the most suitable models. The landslide risk-map was then used for assessment of hazard to the inhabitants and infrastructure (roads) on the tested area.

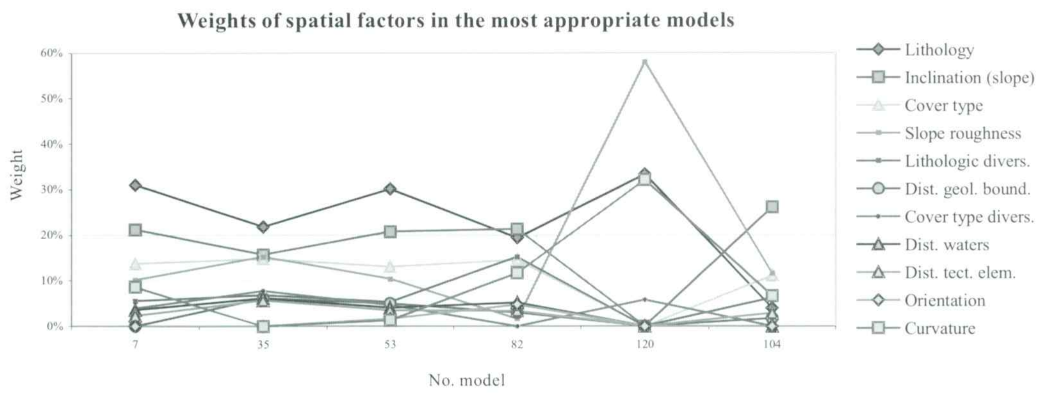

Figure 3. Weights of spatial factors in the most suitable models

Conclusions

Regarding the results of the univariate statistics, the following influencing factors proved to have played an important role in landslide occurence: the steepness and the curvature of the slopes, the distance to the geological borders, the distance to the rivers, lithology, and the type of vegetation. It was shown that high-resolution multi-spectral satellite images could be successfully used for the spatial landslide prediction. The multivariate statistical methods, which take into account several spatial factors, showed better prediction power compared to the results of the individual factor prediction. They indicated in the case of landslide occurrence the primary role of slope, terrain roughness and lithology. Of importance are also the type of the land use, cover type and terrain curvature. Other spatial factors have smaller impact on landslide occurrence. In the study area, a relatively small percentage of the population (less than 3 %) inhabit the high risk areas. 20 – 25 % of the population live in areas considered to be landslide-prone. The creeping and sudden landslides (slides) represent the biggest threat to inhabitants. More than half of the roads cross the areas subjected to ground mass movement and 3 % of all roads cross the high-risk areas.

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