GEOLOGIJA 49/2, 295–309, Ljubljana 2006
https://doi.org/10.5474/geologija.2006.022

Landslide susceptibility map of Slovenia at scale 1 : 250,000

Karta verjetnosti pojavljanja plazov v Sloveniji v merilu 1 : 250.000

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Keywords: landslides, susceptibility, influence factors, model, Slovenia
Ključne besede: plazovi, verjetnost pojavljanja, vplivni dejavniki, model, Slovenija

Abstract

Based on the extensive landslide database that was compiled and standardised at the national level, and analyses of landslide spatial occurrence, a Landslide susceptibility map of Slovenia at scale 1 : 250,000 was completed. Altogether more than 6,600 landslides were included in the national database, of which roughly half are on known locations. Of 3,257 landslides with known location, random but representative 65 % were selected and used for the univariate statistical analyses (χ^2) to analyse the landslide occurrence in relation to the spatio-temporal precondition factors (lithology, slope inclination, slope curvature, slope aspect, distance to geological boundaries, distance to structural elements, distance to surface waters, flowlength, and landcover type) and in relation to the triggering factors (maximum 24-h rainfall, average annual rainfall intensity, and peak ground acceleration). The analyses were conducted using GIS in raster format with the 25 × 25 m pixel size. Five groups of lithological units were defined, ranging from small to high landslide susceptibility. Also critical slopes for the landslide occurrence, other terrain properties and landcover types that are more susceptible to landsliding were defined. Among triggering factors critical rainfall and peak ground acceleration quantities were defined. These results were later used as a basis for the development of the weighted linear susceptibility model where several models with various factor weights variations based on previous research were developed. The rest of the landslide population (35 %) was used for the model validation. The results showed that relevant precondition spatio-temporal factors for landslide occurrence are (with their weight in linear model): lithology (0.3), slope inclination (0.25), landcover type (0.25), slope curvature (0.1), distance to structural elements (0.05), and slope aspect (0.05).

Izvleček

Na podlagi analize prostorskega pojavljanja plazov, ki so bili vključeni v obsežno bazo, je bila v merilu 1 : 250.000 izdelana karta verjetnosti pojavljanja plazov za območje Slovenije. V bazo so vključeni podatki o več kot 6600 plazovih, od teh pa jih ima le slaba polovica znano lokacijo. Izmed 3257 plazov z znano lokacijo je bilo za potrebe univariatne statistične analize (χ^2) naključno, a prostorsko reprezentativno izbranih 65 % plazov. Za izbrane plazove je bil analiziran vpliv prostorsko-časovnih *povzročiteljev* (pripravljalni dejavniki) (litologija, naklon, ukrivljenost in usmerjenost pobočja, oddaljenost od geoloških mej, oddaljenost od strukturnih elementov, oddaljenost od površinskih vod, dolžina toka površinske vode ter tip rabe tal) ter vpliv *sprožilnih* dejavnikov (maksimalne 24-urne padavine s 100-letno povratno dobo, količina povprečnih letnih padavin in objektni talni pospešek s 475-letno povratno dobo). Analize so bile izdelane s pomočjo GIS orodij na rastrskih podatkih s prostorsko ločljivostjo 25 × 25 metrov. Med litološkimi enotami se je oblikovalo pet skupin z različno verjetnostjo pojavljanja plazov, za vsako skupina pa je bil določen kritični kot pojavljanja plazov. Določene so bili tudi lastnosti terena in tipi rabe tal, na katerih je možnost pojavljanja plazov večja. Med sprožilnimi dejavniki so bile določene kritične vrednosti padavin in objektni talni pospešek, pri katerih se znantno poveča pojavljanje plazov. Rezultati analiz so bili uporabljeni za izdelavo več uteženih linearnih modelov verjetnosti pojavljanja z različnimi utežmi relevantnih dejavnikov, ostalih 35 % plazov pa je bilo uporabljenih za validacijo izdelanih modelov. Rezultati so pokazali, da imajo sledeči dejavniki vpliv na pojavljanje plazov (z vrednostjo uteži v linearnem modelu): litologija (0,3), naklon pobočja (0,25), tip rabe tal (0,25), ukrivljenost pobočja (0,1), oddaljenost od strukturnih elementov (0,05) in usmerjenost pobočja (0,05).

Introduction

Landslides are the most common local geohazard problem in Slovenia. A holistic national landslide protection approach is composed of several stages. At the first stage the collection of data is necessary, followed by analyses the available data. Based on the analytical results, the legislative stage has the responsibility to conclude the circle of protection approach. The approach does not stop at this point, but it is live, continuous process that improves with every repeated circle.

For the first time in Slovenia a huge landslide database, containing 6,602 landslides was collected in the frame of the project "Renewal and upgrading of landslide information system and its inclusion into the GIS_UJME database (in Slovene - *Novelacija in nadgradnja informacijskega sistema o zemeljskih plazovih in vključitev v bazo GIS_UJME*)" (Komac et al., 2005). The database, in which almost half of landslides (3,257) were geographically located, enabled the spatial and temporal analyses of landslide occurrence in relation to spatio-temporal factors. The analytical results represented a solid foundation for the production of the landslide susceptibility map at scale 1 : 250,000 for the area of Slovenia. All the analyses were conducted in the GIS with the 25 × 25 m pixel resolution and results were statistically analyses with univariate methods (χ^2). For the landslide susceptibility map a linear model of weighted spatial factors was used.

Study area and data used

The landslide susceptibility model was developed for the whole Slovenia, that is, for the area of approximately 21,000 square kilometers.

For the purpose of model development, the spatial factors' data that have already been proven to be relevant to the landslide susceptibility by many authors (Carrara, 1983; Carrara et al., 1991; Kojima et al., 2000; Fabbri et al., 2003; Crozier & Glade, 2005) were gathered. The landslide data were obtained from the renewed GIS_UJME landslide database. As mentioned the landslide population consisted of 3,257 landslides, of which approximately 2/3 (2,176) were randomly, but representatively for each engineering-geological unit, selected for the landslide susceptibility model training phase. The rest 1081 landslides or nearly 1/3 of the population was used for the model evaluation. Where less than 40 landslides occurred in a specific engineering-geological unit, the landslide occurrence served as an indication that helped the geologist to make the right classification decision of the landslide occurrence probability for the given unit. The digital elevation model (DEM) data were obtained from the national 25 m resolution InSAR DEM 25 (Survey and Mapping Administration, 2000). All the additional data on the terrain morphology (curvature, elevation, slope, aspect, basins, and primary slope-units) were derived from the DEM. The Geological Map of Slovenia at the scale of 1 : 250,000 (Buser, in print) served as a source for the geologic data and engineering geological data (Komac, 2005c and Komac et al., 2005). For the land use and the vegetation cover the CORINE land cover data were used (ARSO, 2004). The surface water data were obtained from ARSO (2005) and are at scale 1 : 25,000. The maximum 24-hour rainfall data with the return period of 100 years and the average annual rainfall data, based on a 30-years observation period were obtained from interpolated data for whole Slovenia with 100 m pixel resolution (ARSO, 2002). The peak ground acceleration data with the resolution of 0.25 g for the return period of 475 years were obtained from (Lapanje et al., 2001). The symbolical overview of the data used for the analyses is shown in Figure 1.

Methodology

To understand natural processes the influencing spatio-temporal factors on observed process have to be defined and their interaction has to be addressed. The most appropriate way to understand the »back-stage« of natural processes is to analyse the factors or their approximations. The better is the understanding, the better is the prediction of future events. The groups of influencing factors on landslide occurrence were selected based on the previous research (Komac, 2005a; 2005b; 2006a). At the first stage the analyses were conducted on the landslide population for all of the spatio-temporal factors for the whole of Slovenia, and in the next stage on the landslide population for all of the spatio-temporal factors for each of the 29 engineering-geological units.

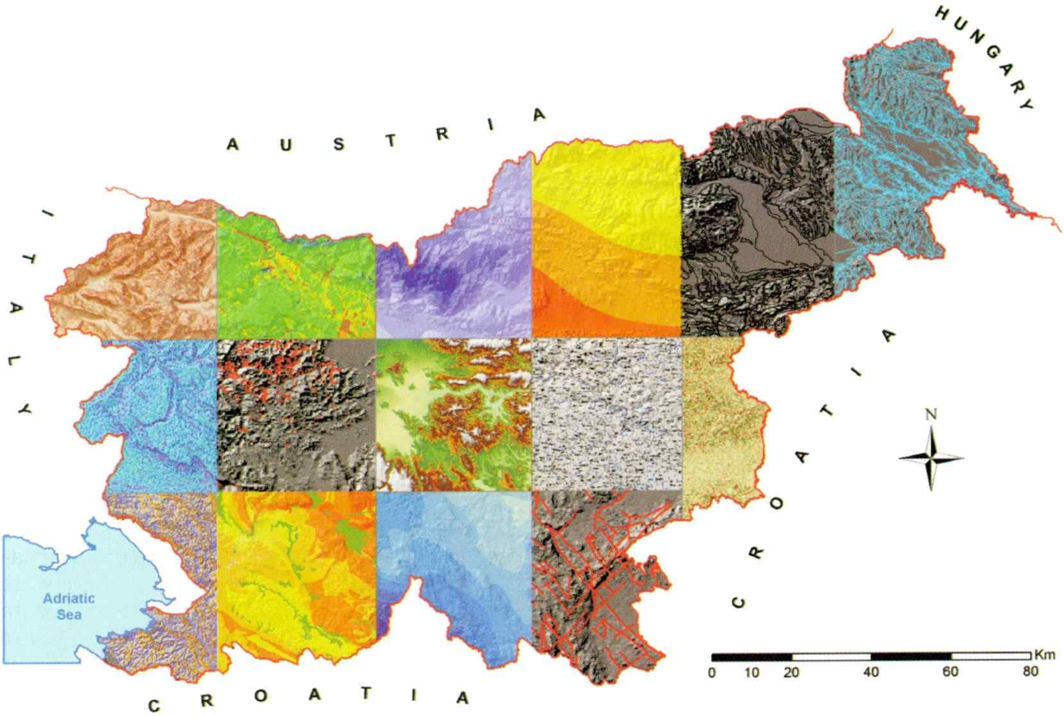

Figure 1. Symbolical overview of the data used for the analyses in order of appearance from NW: slope, landcover type, maximum 24-h rainfall intensity, peak ground acceleration, geological boundaries, surface waters, flowlength, landslide locations, DEM, topography, curvature, aspect, engineering-geological units, average annual rainfall, and structural elements.

Slika 1. Simbolični pregled podatkov, uporabljenih v analizah po zaporedju pojavljanja začenjši na SZ: naklon, raba tal, maksimalne 24-urne padavine, talni pospešek, geološke meje, površinske vode, dolžina toka površinske vode, lokacije plazov, DMV, topografija, ukrivljenost, usmerjenost, inženirsko-geološke enote, povprečne letne padavine in strukturni elementi.

Several authors (Stančič & Veljanovski, 1998, 2000a, 2000b; Veljanovski, 1999; Komac, 2005b) showed the applicability of the χ^2 (Chi-square) method for testing normally distributed categorical variables. The Chi-square method is based on the comparison of observed and expected frequencies of the phenomenon (Davis, 1986). For the purpose of the model development the categorical variables were transformed to numerical form on the basis of relative probability of phenomenon occurrence. In short, they were normalised but one has to consider that such an ordinal scale does not comply with the law of equal intervals between the classes or numbers.

Based on the results of the χ^2 univariate analyses the classes of each of the spatio-temporal factor were ordered according to the statistical landslide occurrence probability. Where obvious discrepancies of classes order occurred, the expert decision was made to correct the error. Before the inclusion of relevant factors into the model development, the values of each factor were normalised. It was a necessary step to equalise the different class numbers in factors with a goal that the weights in models represented the real influence of given factor. The normalisation was done using the Equation 1.

$$NVR = \frac{5*(RV - \min)}{\max - \min}, \qquad \text{Equation 1}$$

where *NVR* stands for a new, normalised value, *RV* represents the old (nominal) value, the difference between maximum (*max*) and minimum (*min*) is always one less than the original number of classes. The normalised values ranged from 0 to 5.

The normalised factors were used to develop the optimum landslide susceptibility model. The models were developed using the linear weighted sum (Voogd, 1983). The result is standardised landslide susceptibility, calculated from the Equation 2:

$$H = \sum_{j=1}^{n} w_j \times f_{ij}, \qquad \text{Equation 2}$$

where H represents the standardised relative landslide susceptibility (0–5), w_j represents the weight for the given factor and f_{ij} represents continuous or discrete variable. Values of weights for different factors were defined based on the previous research (Komac, 2005b) and modified or adapted to some extent. Altogether ten models for the whole Slovenia were calculated using different weight combination. In order to select the optimum one the comparison of models was necessary. The comparison based on the equal area method to avoid the differences between the models' values distributions. Every model was divided into 100 classes, 1 % of the area per one class. The criterion for the model effectiveness was the number of successive classes in which statistically significant proportion of landslides occur. Lower was the number of classes, which represented the landslide susceptible area, and higher was the proportion of landslides in the landslide susceptible area, better was the model.

Results and discussion

General results of analyses

Five groups of lithological/engineering-geological units were defined, ranging from small to high landslide susceptibility: The least susceptible to landsliding phenomenon were units located on flood plains, but it has to be stressed out at this point that these units were classified to this group merely due to their location and not due to their geomechanical properties. Second group was represented by carbonates (limestones, dolomites, and rocks consisted of the two) and resistant igneous rocks, followed by the third group of resistant metamorphic rocks (miccaschists and gneisses), less resistant igneous (intrusive and pyroclastic) rocks, carbonates with inclusion of less resistant rocks, and gravely soils located on slopes (gravels). The fourth group and second most susceptible to landsliding is composed of less resistant metamorphic rocks, resistant clastites, clayey rocks, conglomerates, limestones with marls and anthropogenic sediments, and the most susceptible group of lithologic units, where soils prevail, was formed by clayey and marly soils, gravel, less resistant clastites and combination of soils of different fractions.

Landslides occur significantly different from expected at slopes between 11° and 14° and between 23° and 26°, conditionally between 26° and 29°. The overall critical slopes for the landslide occurrence range from 11° to 29°.

The concave areas of slopes, related to pore water concentration proved to be critical for the landslide occurrence.

In terms of aspect, the southern slopes are the most susceptible to mass movements. This could be related to greater exposure of slopes to temperature variations, which are more dramatic on southern slopes.

Landslides occur with significance at distances ranging from 25 to 1100 meters from larger faults, included in the analyses at scale 1 : 250.000. These distances point to the fact that smaller fault systems, which were not included in the analyses, tend to have influence on landslide occurrence. Nevertheless, smaller fault systems are related to greater systems, resulting in dependence of landslide occurrence upon the distance to structural elements.

Among CLC 2000 landcover types, the following proved to have the influence on landslide occurrence: Discontinuous urban fabric (112), Vineyards (221), Pastures (231), Complex cultivation patterns (242), and Land principally occupied by agriculture, with significant areas of natural vegetation (243). Increased occurrence of landslides in the areas of discontinuous urban fabric is most probably the consequence of infrastructure placement over landslide susceptible areas. Vineyards are always located on southern slopes, where the natural vegetation was replaced by cultivated land with relatively poor root system. The shallow root system of pastures that lay on the steeper slopes, ranging from 21° to 33° (Vrišer, 1997) does not provide effective protection against mass movements. The negative influence is increased by pasturing. The prevention against landslide occurrence is not of great importance in the areas of land principally occupied by agriculture, with significant areas of natural vegetation, which is usually not of great economical significance.

Average annual rainfall above 1000 mm proved to be a critical triggering factor for the landslide occurrence in more loose soils in eastern parts of Slovenia (Tertiary sediments) and annual amount of rainfall above 1600 mm influences the landslide triggering in less resistant rocks (Triassic and Permo-Carbonian rocks). Despite the indications there is a reasonable doubt that average annual rainfall intensities play an important triggering role in landslide occurrence.

On the contrary, maximum daily rainfall above 100 mm proved to be critical for landslide occurrence, especially in more loose soils and in less resistant rocks (Quaternary, Tertiary, Triassic, and Permo-Carbonian rocks) (Komac, 2005c). The trend is similar to the one of average annual rainfall. The results prove the assumption that for triggering of landslides in landslide susceptible soils and rocks, lower amounts of rainfall (around 130 mm/24 h, after Komac, 2005c) are enough.

The landslide occurrence positively correlates with the amplitude of peak ground acceleration (PGA). The value of the design ground acceleration that proved to be significant for the landslide occurrence is 0.15 g. This is mainly influenced by the relatively big number of landslides (124) in the area of one unit, which is classified among soft rocks. The lower number of landslides in the areas of PGA of 0.25 g is due to the fact that the majorities of these areas lay on flat plains or are consisted of solid rocks.

With growing distance from geological boundaries landslides begin to occur significantly in areas ranging form 25 to 150 meters. Due to the questionable relation of landslide occurrence and distance from geological boundaries, this factor was excluded from further analyses.

Since the landslides occur significantly different in the class of distance from surface waters ranging from 25 to 55 meters, the correlation between landslide occurrence and surface waters is of pure coincident.

Results of analyses for different engineering-geological units

Prior to representing the results of analyses of spatio-temporal factors that govern the landslide occurrence, it would be reasonable to overview the engineering-geological classification of rocks that are presented in the Geological Map of Slovenia at scale 1 : 250,000. The classification is shown in the Table 1.

In soils (S-FP in Figure 2) landslides start to occur at 5° and the critical slope angles range to 29° where it probably stops due to the fraction angle of material (EG unit 3). In case of soils located on slopes (S-SL in Figure 2; EG unit 5) and in case of rock-forming soils (S-RF in Figure 2; EG units 8 and 9) landslide occur at slope angles between 11° and 17°. Statistically significant triggering angle for soft rocks (R-SF in Figure 2; EG unit 11 and EG unit 13) is 14° and the upper angle is 26°. In clastites (CLA in Figure 2; EG unit 15) landslides occur with statistical significance at 17°, in carbonates (CAR in Figure 2; EG units 18, 20, 21, 22, and 23) the critical slope angles vary, which is probably related to the sequential alternation of carbonates with strata of less stable rocks (i.e. marl). When considering pure carbonates (EG units 20 and 21) the statistically significant triggering angle for limestones and dolomites is 26° and for dolomites 17°. All engineering-geological unit (EG unit) identification numbers were adopted after Komac (2005c). Figure 2 represents the statistically significant critical slope angles for different rock types. Inadequate landslide number occured in metamorphic and igneous rocks for statistically reiable evaluation and the determination of the significant

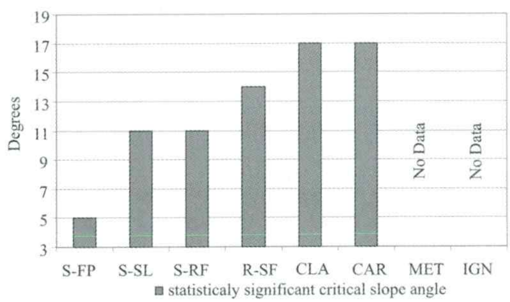

Figure 2. Statistically significant critical slope angles for different rock types. The explanation of labels is given in Table 1. Inadequate landslide number occured in metamorphic and igneous rocks for statistically reiable evaluation and the determination of the significant landslide triggering angles, hence the missing information for the two rock types.

Slika 2. Vrednosti najmanjših signifikativnih naklonov pobočij glede na tip kamnine. Oznake so obrazložene v Preglednici 1. Podatki o najmanjših signifikativnih naklonih v magmatskih in metamorfnih kamninah manjkajo, saj glede na omejeno število plazov na območju teh dveh tipov kamnin ni bilo možno izvesti zadovoljivega statističnega ovrednotenja.

Table 1. Classification of rocks from Geological Map of Slovenia at scale 1 : 250,000 into engineering-geological units (after Ribičič et al., 2003). Column "EG unit" represents identification number of "Rock type description" column where rocks, found on Geological Map are listed. "EG rock group" column represents the engineering-geological classification of descriptions in "Rock type" column, and "EG rock group description" describes the engineering-geological group of rocks.

Preglednica 1. Razdelitev kamnin, ki se pojavljajo na Geološki karti Slovenije v merilu 1 : 250.000 v inženirsko-geološke enote (po Ribičič et al., 2003). Stolpec "EG unit" predstavlja indetifikacijsko oznako za posamezno rubriko v stolpcu "Rock type description", v katerem so navedene kamnine z Geološke karte. Stolpec "EG rock group" prestavlja inženirsko-geološko klasifikacijo posameznih kamnin v stolpcu "Rock type", stolpec "EG rock group description" pa podaja razlago inženirsko-geoloških oznak.

EG unit	Rock type description	EG rock group	EG rock group description
1	mainly clayey soils	S-FP	Soils on flat plains
2	marls, lacustrine sediments (clay, peat, silt)	S-FP	
3	alternation of soils (gravel, sand, clay...), gravel and sandy gravel	S-FP	
4	clayey soils (deluvial, proluvial)	S-SL	Soils on slopes
5	gravely soils with clay component	S-SL	
6	scree deposits, glacigenic diamics	S-SL	
7	clayey rock-forming soils	S-RF	Rock-forming soils
8	alternation of fine- and coarse-grained rock-forming soils	S-RF	
9	gravely rock-forming soils	S-RF	
10	anthropogenic sediments	S-AN	Anthropogenic soils
11	clayey and marly soft rocks	R-SF	Soft rocks
12	clayey and marly soft rocks with carbonates	R-SF	
13	alternation of different soft rocks (marls, sandstones, conglomerates...)	R-SF	
14	conglomerates	R-SF	
15	shales with inclusions of other rocks	CLA	Clastites
16	marls and sandstones with inclusions of other rocks (flysch)	CLA	
17	sandstones and conglomerates with inclusions of other rocks	CLA	
18	layered and reef limestones	CAR	Carbonates
19	thin layered limestones	CAR	
20	limestones and dolomites	CAR	
21	dolomites	CAR	
22	limestones with marls	CAR	
23	limestones with inclusions of other rocks	CAR	
24	limestone conglomerates and breccias	CAR	
25	metamorphic slates and fillites	MET	Metamorphic rocks
26	micaschists and gneisses	MET	
27	trachyte (keratophyre), diabases, other igneous rocks with tuffs	IGN	Igneous rocks
28	amphibolites, serpentinites, diaphthorites	IGN	
28	amphibolites, serpentinites, diaphthorites	IGN	
29	tonalites, dacites, granodiorites	IGN	

* Obrazložitev angleških pojmov: S-FP – zemljine na ravnicah, S-SL – zemljine na pobočjih, S-RF – kamenotvorne zemljine, S-AN – zemljine antropogenega izvora, R-SF – polhribine, CLA – klastiti, CAR – karbonati, MET – metamorfne kamnine, IGN – magmatske kamnine.

landslide triggering angles, hence the missing information for the two rock types in the Figure2.

Statistically significant values of curvature, at which landslides start to occur are similar to all engineering-geological units where curvature was proved to be important (EG units 3, 15, 16, 17, 20, and 21). The areas that show to be of importance are concave shaped slope areas with values between – 2 and – 0.5. The only exception is EG unit 8, where landslides occur with significance also in the convex areas (values range from 0.5 to 1). Neglecting the exception, it is obvious that concentration of pore water in concave areas influence the landslide triggering.

Significant classes of aspect that influence the landslide occurrence are southern (EG units 11, 18, and 21) and south-eastern faced slopes (EG units 6 and 22). The fact that there units are predominantly solid carbonates suggests that greater temperature oscillations influence the occurrence of mass movements on sun-exposed slopes. Also here an exception exists (EG unit 16) where landslides significantly occur on eastern faced slopes. Landsliding occurrence on flyschy eastern slopes may be connected to proximity to the surface waters that govern the orientation of slopes. EG unit 6 (scree deposits) is also a result of temperature oscillations in higher laying rock formations.

The proximity of geological boundaries seems to have an influence on landslide occurrence in soft rocks (EG unit 13) and in carbonates (EG unit 20 and 21). The vicinity of these units obviously sets ideal conditions for landslide triggering, since the significant classes range from 0 to 25 meters of distance. These two types of engineering-geological units are either a source of lower laying landslide susceptible deposits (scree deposits) as in the case of EG 20 and EG 21 or a possible source of groundwater, which triggers landslides at contacts with less permeable rocks as in the case of EG 13. In engineering-geological unit 3 (alternation of alluvial sediments) landslides occur with significance at distances between 25 and 55 meters from geological boundaries. This most probably due to the fact that alluvial sediments stretch right to the foot of slopes, where landslides occur. There is also one other engineering-geological unit (EG unit 22), in which landslides significantly occur in classes with distance from geological boundaries over 55 meters, but this influence is highly questionable.

Considering the proximity of the structural elements, landslides significantly occur at distances between 25 to 55 meters from elements in engineering-geological units 3, 15, 20, 23, and 27. In engineering-geological unit 21 (dolomites), landslides significantly occur very close to structural elements, which can be the consequence of fractured and mylonised dolomites. In the engineering-geological unit 16, landslides significantly occur between 55 and 150 meters, for the engineering-geological unit 22 (marls and limestones) landslides significantly occur at distances between 150 and 400 meters, and for the engineering-geological unit 26 (gneisses), landslides significantly occur at distances between 400 and 1100 meters from structural elements. The significant distances for the landslide occurrence indicate that side systems of structural elements to major faults, indicated on the Geological map of Slovenia at scale 1 : 250,000 (Buser, in print), or mylonite zones near faults influence the landsliding phenomenon.

Surface waters have very little influence on landslide occurrence on general, the two exceptions are engineering-geological unit 9 and 20. In first the landslides occur at a distance of 55 to 150 meters from riwer network, which could most probably be the consequence of landsliding of slopes between river terraces, while in the second case (EG unit 20) the proximity (0–55 meters) could be the consequence of steep slopes of carbonates that are subjected to water erosion where landslide phenomenon occurs.

In case of flowlength that represents recharge area of specific location, landslides occur with statistical significance in EG unit 3 at distances from 155 to 400 meters, in EG unit 9 at distances from 55 to 150 meters, in EG units 11 and 15 at distances from 155 to 1100 meters, and in EG unit 20 at distances from 400 to 3000 meters. Despite the fact that there is a noticeable trend of growing flowlength with growing stability of engineering-geological units, this relation is statistically not reliable.

Landcover types by the CLC 2000 classification show following influences on landslide occurrence. Discontinuous urban fabric (112) has influence on landslide occurrence in EG unit 13 and 16, which is most probably the result of linear infrastructure, i.e. roads, traversing less stable units. Vineyards (221) influence the landslide occurrence in EG unit 3 in NE part of Slovenia and in EG unit 16 in SW part of Slovenia. Vineyards are always located on southern slopes, where the natural vegetation was replaced by cultivated land with relatively poor root system. Pastures (231) influence the landslide occurrence in EG units11, 15, 16, and 21. The reason of landsliding in these units is the presence of poorly protected upper soil cover with root system. Areas of Complex cultivation patterns (242) are of to complex structure to analyse in detail the real reasons of influence of this landcover type on landslide occurrence in EG units 8, 9, 18, 20, 22, 26 and 27. The same could be stated for the influence of landcover type Land principally occupied by agriculture, with significant areas of natural vegetation (243) on landsliding in EG units 3, 5, 9, 11, 13, 14, 15, 16, 17, 20, 21, 22, 23, and 27. Broad-leaved forest (311) looses its protection role against landslide occurrence on soils, since statistically significant numbers of landslides occur on EG unit 3.

Average annual rainfall bimodally influences the landslide occurrence, first at intensities ranging from 1000 to 1300 mm/year and secondly at intensities ranging from 1600 to 2000 mm/year (Komac, 2005c). The first peak influences the landsliding in EG units 3, 8, 11, 13, 14, 18, 20, and 22, while the second peak influences the landsliding in EG units 3, 5, 13, 15, 16, 21, and 23. Results are discussed in more details by Komac (2005c).

Considering only analyses conducted in the frame of this research the factor of maximum 24-hour rainfall influences landslide occurrence differently indifferent EG units. The statistically proven triggering threshold for EG unit 14 is 100 mm/24h, for units 3, 5, 8, 13, 15, 21, 22, 23, and 26 is 150 mm/24h, for EG units 16 and 17 is 200mm/24h, and for EG unit 20 is 400 mm/24h. As already stated in the section General results of analyses, maximum 24-hour rainfall quantities have greater influence on landslide occurrence than average annual rainfall intensities. Komac (2005c) conducted more detailed analysis of influence of rainstorms as a triggering factor for landslide occurrence.

Peak ground acceleration influences the occurrence of landslides with statistical significance. In EG units18 and 22 the triggering PGA is less than 0.1 g, in EG unit 26 the triggering PGA is 0.1 g, in EG units 3, 11, and 13 the triggering PGA is 0.125 g, in EG units 8, 15, 16, 17, 20, 23, and 27 the triggering PGA is 0.175 g, and in EG unit 21 the triggering PGA is 0.2 g. Excluding the EG unit 3, the trend of landslide occurrence is correlated with the stability of EG units. With growing stability of units, greater PGA is needed to trigger landslides. This trend is very obvious when comparing triggering PGA for soft rocks (0.125 g) and for rocks (0.175 g). In the first exception, the EG unit 18, the landslide occurrence is the consequence of sandstone inclusions in the limestones, which cause the lower stability of the unit. In the second exception, the EG 22, the reason of landslide occurrence in the areas of lower PGA is probably due to the inclusions of marly components in the limestones.

Landslide susceptibility modelling

The logical next step from analyses is to transform the results into a prediction, in this case into prediction of landslide susceptibility for the whole of Slovenia. A mathematical model was developed and the results represented in a form of a GIS data set and its visualisation, a map. Landslide susceptibility map of Slovenia at scale 1 : 250,000 is a final product of linear mathematical modelling of spatio-temporal factors that govern the landslide occurrence and hence the landslide susceptibility. Based on the expert decision, the areas with slopes less than 5° were excluded from the modelling and the lowest possible susceptibility was assigned to them. In the areas with slopes less than 5°, where no landslides should occur, 55 or roughly 5 % of these phenomenon from the testing set are present. This error is due to the fact of generalisation of digital elevation model (possible generalisation of transitions between terraces) and due to the fact that analyses were conducted at scale 1 : 250,000. The error is present in all of the models. Table 2 represents the area distributions of the analysed area for all of ten models and cumulative distributions of landslides in each model by proportion of the area.

The results represented in the Table 2 and in the Figure 3 as anticipated indicate that the worst results were given by models, where engineering-geological properties (M_07) or landcover type were excluded (M_08). Slightly better results were achieved with the model M_06, where all of the factors were assigned equal weights. Next by performance was model M_09, where distance to structural elements was given an impor-

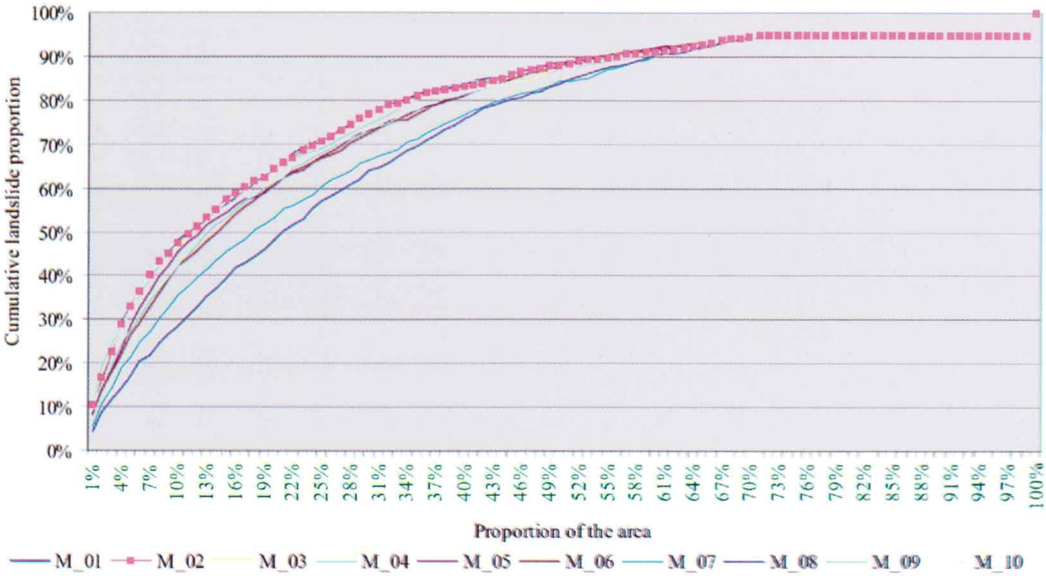

Figure 3. Cumulative distribution of landslides according to area proportion. Legend at the bottom represents labels for each of the linear models, explained in the Table 2.

Slika 3. Vsota porazdelitev deležev plazov glede na površino terena. Legenda na dnu slike predstavlja št. linearnega obteženega modela, katerega lastnosti so podane na začetku Preglednice 2.

tant role and the role of the landcover type was minimised. With model M_05 the landcover type was given very important role and the rest was split among other factors. The success rates of the rest (models M_01, M_02, M_04, M_10) were very similar.

For the most successful and suitable landslide susceptibility model the model M_02 was chosen based on good landslide to area ratio and based on the expert knowledge (and logic) of importance of spatio-temporal factors. On only 18 % of the area, 61.5 % of landslides occur, and on less than 1/3 of the area (29 %), 76 % of landslides occur. Split in half, to landslide susceptible and landslide »safe« areas, in landslide susceptible areas 88.2 % of landslides occur. Table 3 represents the basic characteristics of the model M_02, and Figure 4 represents the area distribution of landslide susceptibility classes for Slovenia. The reclassification of model M_02 values into landslide susceptibility classes, which are represented in the form of Landslide susceptibility map of Slovenia at scale 1 : 250,000 (Figure 5), based on actual landslide occurrences compared to expected ones. In the class of the highest landslide susceptibility, the areas where six times more landslides occurred than expected, were classified. The class represents top 7 % of area arranged by landslide susceptibility, and comprises 43.3 % of landslides. In the class of high landslide susceptibility, all areas where the proportion of landslides to proportion of area ratio is greater than one. In the area of 17 %, 27 % of landslides were located. The class of medium landslide susceptibility comprises areas where the proportion of landslides to proportion of area ratio is near or equal to one. In this class, which spreads over 10 % area, 10.5 % of landslides occurred. In the areas with low landslide susceptibility that spreads over 21 % of the area, 8.5 % of landslides occur, and on the areas with very low, but still some landslide susceptibility, which covers 17 % of the Slovenian area 4.9 % landslides occur. The rest of the area belongs to the "landslide safe" zone. Here 5.1 % of landslides occur. This error is, as already presented, due to the fact of digital elevation model generalisation (possible generalisation of transitions between terraces) and due to the fact that analyses were conducted at scale 1 : 250,000. Cumulatively in the first class 43.3 %, in the first two 70 %, in the first three 80 %, and in the upper four susceptibility classes 90 % of landslides occur. In each of the lowest landslide susceptible classes 5 % of landslides occur.

Table 2. Area distributions for different models. At the beginning of the table the weights for factors included in the models are given, followed by the cumulative proportions of landslides at every percent of the area. With red the areas where the proportion added is statistically significant for the last time are marked. After the 72nd percentage in the "Cumulative proportions of the area" column the success rate is the same for all models.

Preglednica 2. Porazdelitev deležev površin terena po modelih. Na začetku preglednice so podane uteži prostorskih dejavnikov za vsak model, v nadaljevanju pa so podani kumulativni deleži plazov po enakih deležih površine terena (po 1 %). Z rdečo so označeni deleži, pri katerih je dodatek h kumulativnemu deležu plazov zadnjič statistično značilen. Po 72. odstotku v stolpcu delež površin ("Cumulative proportions of the area") je uspešnost vseh modelov enaka.

MODEL	**M_01**	**M_02**	**M_03**	**M_04**	**M_05**	**M_06**	**M_07**	**M_08**	**M_09**	**M_10**
Weights of spatio-temporal factors by models										
Engineering-geological properties	0.3	0.3	0.25	0.4	0.1	0.1666	0	0.2	0.3	0.3
Slope inclination	0.2	0.25	0.25	0.2	0.1	0.1666	0.2	0.2	0.25	0.3
Slope curvature	0.1	0.1	0.05	0.05	0.1	0.1666	0.2	0.2	0.1	0.05
Slope aspect	0.05	0.05	0.05	0.05	0.1	0.1666	0.2	0.2	0.05	0.05
Landcover type	0.3	0.25	0.35	0.25	0.5	0.1666	0.2	0	0.1	0.25
Distance to struct. elements	0.05	0.05	0.05	0.05	0.1	0.1666	0.2	0.2	0.2	0.05
Cumulative proportions of the area	Cumulative proportions of landslides									
1 %	10.69%	10.41%	10.32%	11.06%	7.99%	8.18%	5.58%	4.28%	8.55%	10.78%
2 %	16.08%	16.54%	17.01%	19.42%	13.57%	13.66%	10.59%	8.74%	14.68%	17.75%
3 %	22.58%	22.58%	23.23%	24.81%	18.31%	17.94%	14.68%	11.90%	19.98%	23.79%
4 %	29.09%	28.81%	28.44%	28.25%	22.68%	21.84%	19.05%	14.31%	24.44%	27.97%
5 %	32.90%	32.81%	32.34%	32.43%	28.35%	26.21%	21.56%	16.82%	27.42%	32.34%
6 %	36.43%	36.43%	36.34%	36.15%	32.62%	29.18%	25.00%	20.35%	30.86%	36.80%
7 %	40.15%	40.24%	40.61%	39.78%	36.43%	32.90%	27.23%	21.93%	34.57%	40.06%
8 %	43.12%	43.31%	43.03%	42.94%	39.78%	36.15%	30.39%	24.72%	37.17%	43.49%
9 %	44.89%	45.07%	45.26%	45.91%	42.38%	39.13%	32.99%	26.77%	39.50%	45.07%
10 %	48.14%	47.49%	46.84%	47.68%	45.26%	42.29%	35.69%	28.44%	42.10%	47.40%
11 %	49.72%	49.44%	48.88%	49.63%	47.58%	43.96%	37.64%	30.67%	44.98%	49.26%
12 %	51.12%	51.12%	51.67%	51.30%	49.16%	45.72%	39.68%	32.71%	47.40%	50.56%
13 %	52.97%	53.16%	53.44%	53.16%	51.49%	47.77%	41.54%	35.22%	50.00%	52.14%
14 %	54.93%	55.02%	55.20%	54.83%	53.07%	49.54%	43.49%	37.08%	51.95%	54.09%
15 %	56.23%	57.43%	56.69%	56.60%	54.46%	51.77%	45.63%	39.59%	53.25%	55.67%
16 %	57.62%	58.92%	58.74%	58.18%	55.95%	54.00%	47.21%	41.91%	55.20%	57.53%
17 %	59.29%	60.13%	60.22%	59.76%	57.34%	55.58%	48.51%	42.84%	57.06%	59.11%
18 %	61.34%	61.52%	61.71%	61.62%	57.62%	57.25%	50.37%	44.33%	58.27%	61.99%
19 %	62.73%	62.45%	62.92%	62.92%	58.83%	59.20%	51.95%	45.91%	60.04%	63.29%
20 %	64.78%	64.41%	64.78%	64.68%	60.69%	60.59%	53.44%	48.23%	61.15%	64.13%
21 %	65.80%	65.61%	66.17%	65.80%	62.17%	62.17%	55.30%	50.19%	62.45%	65.71%
22 %	67.66%	66.64%	67.38%	66.73%	63.57%	63.20%	56.13%	51.67%	64.68%	67.47%
23 %	69.14%	68.40%	68.96%	67.75%	64.68%	64.13%	57.43%	53.07%	65.80%	68.77%
24 %	70.35%	69.52%	69.98%	68.49%	65.61%	65.61%	58.64%	55.48%	67.19%	70.45%
25 %	71.75%	70.45%	71.28%	69.24%	67.29%	66.64%	60.50%	57.25%	68.12%	71.75%
26 %	72.21%	71.47%	72.40%	70.26%	68.31%	67.57%	62.08%	58.27%	69.24%	72.49%
27 %	73.23%	73.05%	73.61%	71.47%	69.52%	68.49%	63.10%	59.67%	70.26%	74.16%
28 %	74.91%	74.54%	75.19%	72.58%	71.28%	70.26%	64.03%	60.97%	71.38%	74.81%

MODEL	M_01	M_02	M_03	M_04	M_05	M_06	M_07	M_08	M_09	M_10
29 %	75.93%	75.93%	76.12%	73.70%	72.40%	71.38%	65.61%	62.08%	72.12%	75.74%
30 %	76.67%	76.77%	76.95%	74.81%	73.14%	72.30%	66.54%	63.94%	73.33%	76.95%
31 %	77.88%	77.88%	77.88%	75.84%	73.88%	73.61%	67.38%	64.68%	73.88%	77.88%
32 %	78.81%	78.72%	78.62%	76.77%	75.19%	74.63%	68.12%	65.89%	74.63%	78.44%
33 %	79.74%	79.28%	79.09%	78.35%	75.84%	75.28%	68.96%	67.10%	75.93%	78.90%
34 %	80.39%	79.93%	79.46%	79.55%	76.58%	75.56%	70.54%	68.49%	77.04%	79.28%
35 %	81.23%	80.95%	80.11%	80.48%	77.88%	76.86%	71.38%	69.61%	77.88%	80.48%
36 %	81.88%	81.51%	80.58%	81.23%	78.62%	77.97%	72.58%	70.91%	78.90%	80.76%
37 %	81.97%	81.88%	80.95%	82.25%	79.00%	79.37%	73.79%	71.84%	79.37%	81.04%
38 %	82.53%	82.34%	81.60%	83.27%	79.65%	80.02%	74.91%	73.33%	80.30%	81.41%
39 %	82.90%	82.62%	82.06%	83.36%	80.20%	80.67%	75.74%	74.44%	80.76%	81.88%
40 %	83.27%	83.09%	82.62%	84.11%	81.13%	81.32%	76.95%	75.93%	81.41%	82.06%
41 %	84.48%	83.27%	82.90%	84.48%	81.88%	81.97%	77.70%	76.67%	81.88%	82.34%
42 %	84.94%	83.83%	83.46%	84.57%	82.62%	82.62%	78.44%	78.25%	82.62%	82.53%
43 %	85.13%	84.29%	83.46%	85.13%	83.27%	83.27%	79.55%	78.81%	83.46%	83.36%
44 %	85.13%	84.85%	84.01%	85.50%	84.11%	83.92%	80.20%	79.46%	84.48%	83.74%
45 %	85.69%	85.78%	84.29%	85.69%	84.76%	84.94%	80.95%	80.11%	85.22%	84.20%
46 %	86.34%	86.52%	84.39%	86.06%	85.69%	85.41%	81.51%	80.67%	85.87%	84.67%
47 %	87.17%	86.99%	84.94%	86.06%	86.06%	86.34%	82.06%	81.51%	86.52%	85.13%
48 %	87.64%	87.36%	85.59%	86.34%	86.43%	86.62%	82.53%	81.97%	87.17%	85.97%
49 %	88.29%	87.83%	86.34%	86.52%	86.90%	86.99%	83.55%	83.09%	87.45%	86.80%
50 %	88.48%	87.83%	87.45%	87.08%	87.73%	87.83%	84.39%	83.74%	87.73%	87.27%
51 %	**88.75%**	**88.20%**	**87.73%**	**87.55%**	**88.38%**	**88.29%**	**84.57%**	**84.76%**	**87.92%**	**87.55%**
52 %	89.03%	89.03%	88.38%	88.01%	88.94%	88.94%	84.94%	85.59%	88.48%	88.20%
53 %	89.03%	89.22%	88.66%	88.20%	89.59%	89.22%	85.22%	86.25%	89.03%	88.57%
54 %	89.50%	89.41%	89.03%	88.57%	89.96%	89.87%	86.25%	86.99%	89.31%	89.03%
55 %	89.78%	89.68%	89.41%	89.03%	90.33%	90.15%	87.08%	87.55%	89.78%	89.31%
56 %	90.06%	89.96%	89.87%	89.41%	90.71%	90.71%	87.55%	88.01%	89.96%	89.68%
57 %	90.61%	90.52%	90.24%	89.78%	90.99%	91.17%	88.20%	88.29%	90.06%	89.96%
58 %	90.80%	90.71%	90.52%	90.15%	91.36%	91.17%	88.85%	88.85%	90.24%	90.24%
59 %	90.99%	90.89%	90.80%	90.43%	91.73%	91.36%	89.41%	89.50%	90.52%	90.52%
60 %	91.36%	91.17%	91.17%	90.89%	91.91%	91.73%	90.15%	90.24%	90.99%	90.99%
61 %	91.54%	91.45%	91.45%	91.08%	92.29%	92.01%	90.89%	90.52%	91.26%	91.36%
62 %	92.10%	91.82%	91.64%	91.26%	92.47%	92.47%	91.54%	90.61%	91.45%	91.54%
63 %	92.38%	92.19%	91.91%	91.73%	92.47%	92.75%	91.91%	91.08%	91.64%	91.91%
64 %	92.57%	92.47%	92.19%	92.29%	92.94%	92.94%	92.19%	91.64%	92.29%	92.29%
65 %	92.84%	92.84%	93.12%	92.57%	93.12%	93.22%	92.47%	92.19%	92.75%	93.12%
66 %	92.94%	93.22%	93.40%	93.03%	93.31%	93.31%	92.57%	92.47%	93.22%	93.49%
67 %	93.31%	93.77%	93.77%	93.68%	93.31%	93.40%	93.31%	93.12%	93.68%	93.77%
68 %	93.87%	93.96%	93.96%	93.96%	94.05%	93.68%	93.87%	93.77%	94.14%	93.87%
69 %	94.14%	94.24%	94.33%	94.05%	94.24%	94.33%	93.96%	93.77%	94.33%	94.33%
70 %	94.33%	94.33%	94.52%	94.24%	94.52%	94.42%	94.14%	94.33%	94.52%	94.52%
71 %	94.70%	94.70%	94.70%	94.61%	94.80%	94.70%	94.70%	94.70%	94.80%	94.70%
72 % – 99 %	94.89%	94.89%	94.89%	94.89%	94.80%	94.89%	94.89%	94.89%	94.89%	94.89%
100 %	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table 3. Distribution of landslide susceptibility classes' areas for the model M_02. Column "A" represents the proportion of the area, covered by given class (column "Class"). "Reclassified classes by area proportion" represents the area proportion of landslide susceptibility classes, column "Model values" represents the range of model values for a given class in model M_02, "Landslide susceptibility" defines the description of susceptibility, and "Landslide proportion" states the proportion of landslides in a given class.

Preglednica 3. Porazdelitev površine razredov verjetnosti pojavljanja plazov v Sloveniji za najprimernejši model (št. 2). Stolpec "A" predstavlja delež površine razreda ("Class"), "Reclassified classes by area proportion" podaja razpon novih razredov verjetnosti pojavljanja plazov glede na deleže površine terena, "Model values" podajajo razpon vrednosti modela št. 2, ki se raztezajo med 0 in 10, "Landslide susceptibility" podaja verjetnost pojavljanja plazov in "Landslide proportion" delež plazov v razredu verjetnosti pojavljanja.

Class	A (%)	Reclassified classes by area proportion	Model values	Landslide susceptibility	Landslide proportion
1	28.00 %	0 - 28	0 - 0.57	None	5.1 %
2	17.03 %	28 - 45	0.57 - 3.19	Very low	5.5 %
3	20.99 %	45 - 66	3.19 - 4.59	Low	8.5 %
4	10.00 %	66 - 76	4.59 - 5.42	Medium	11.4 %
5	17.00 %	76 - 93	5.42 - 7.16	High	26.2 %
6	6.97 %	93 - 100	7.17 - 9.88	Very high	43.3 %

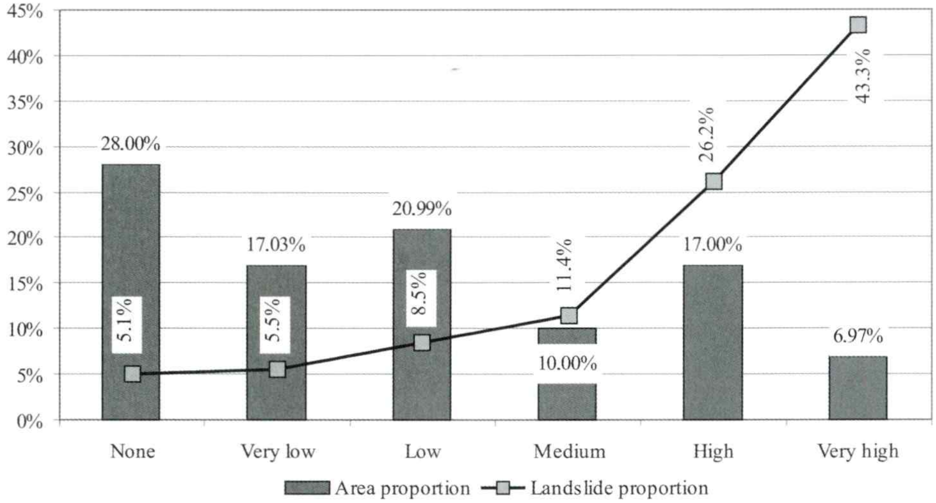

Figure 4. Area and landslides distribution for landslide susceptibility classes for model M_02 and for Landslide susceptibility map of Slovenia at scale 1 : 250,000.

Slika 4. Porazdelitev površine in deležev plazov glede na razrede verjetnosti pojavljanja plazov za model št. 2 in za Karto verjetnosti pojavljanja plazov v Sloveniji v merilu 1 : 250.000.

Concluding remarks

The results of analyses indicated one particular characteristic, an importance of three spatio-temporal factors, lithological or engineering-geological characteristics of rocks and soils, slope inclination, and landcover type. Using only these three factors models would not achieve such prediction performances as in the cases presented above since the prediction would be of lower details, but the results would still be satisfactory. The success rate analyses for these three factors showed that the error for the ideal combination of factors (lithology, 0.41; slope inclination, 0.26; landcover, 0.33) is 12.3 %, while in the chosen model M_02 the prediction error is 10.6 %. The "ideal" weights values of the three factors were determined as the average of the best ten weight values for each of the factors. This approach was selected to reduce potential extreme va-

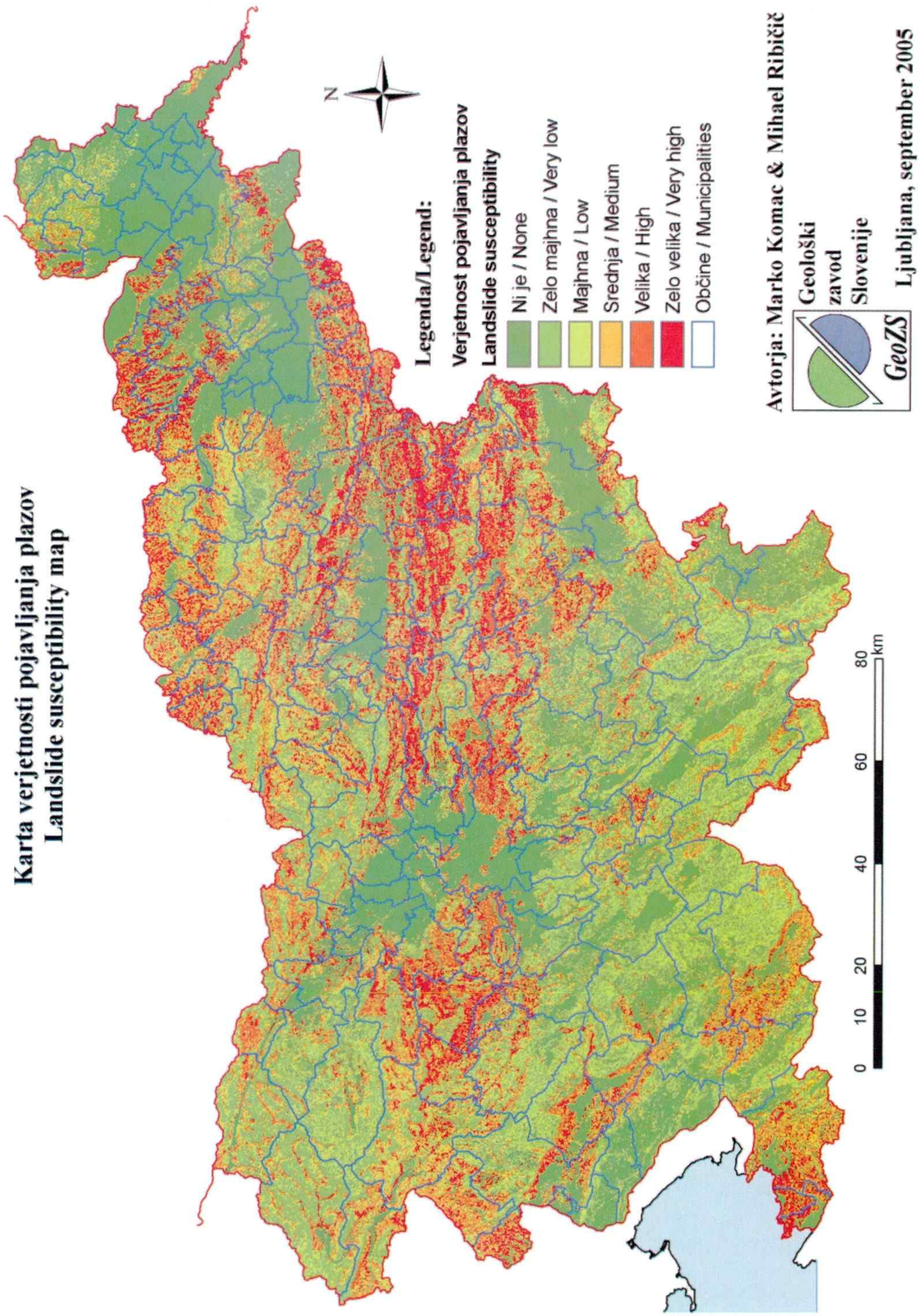

Figure 5. Landslide susceptibility map of Slovenia, based on the model M_02.
Slika 5. Karta verjetnosti pojavljanja plazov v Sloveniji po modelu št. 2.

riations caused by different factor weights. The comparison between the model M_02 and the model derived from only three most important factors poses a reasonable question of developing complex landslide susceptibility models. This question of course has no solid foundations, since the quality of models is augmented with inclusion of reasonable higher number of spatio-temporal factors. And, when the safety of inhabitants or the property is concerned every percent counts.

An important contribution to the quality of the landslide susceptibility prediction would be the inclusion of factor synchronism of geological strata dipping with slope orientation and inclination (Bavec et al., 2005; Komac, 2005d; Komac, 2006b), but modelling and interpolation of geological strata dipping data on national scale still represents a big challenge for geologists, GIS and computer capability.

Additional problem that arises when modelling natural phenomena is the independency of factors. There is always some overlapping of variables (factors), i.e. to a certain extent the lithology governs the slope inclination and the slope inclination governs the land use and hence the landcover type. But, the landcover type can influence the landslide occurrence significantly on the same type of rock and at similar slope inclinations. For example, landslides will occur with higher probability on pastures than in forests as a result of the different root systems. The balancing between the inclusion or exclusion of a specific spatio-temporal factor in the model is a complex procedure, based on the expert decision and logic.

The development of landslide susceptibility models and later landslide risk and landslide hazard models as upgrades of first, represents a live cycle, which is ameliorated with every new discovery, every new (set of) data, with every improvement of statistical approaches. A model of high quality serves as a basis for a sound spatial planning regardless of the scale, on national or on local level. It is better, wiser and cheaper to prevent than to cure. Even in the landsliding domain.

Acknowledgments

The authors would like to thank Ministry for the defence and the Ministry for the higher education, science and technology, which enabled the research through the financing of the CRP Novelacija in nadgradnja informacijskega sistema o zemeljskih plazovih in vključitev v bazo GIS_UJME = Renewal and upgrading of landslide information system and its inclusion into the GIS_UJME database, and the colleagues at Geological Survey of Slovenia for the support at the project.

References

ARSO 2002: Podatki o dnevnih padavinah.- arhiv.- Agencija RS za okolje, Urad za meteorologijo Ministrstva za okolje, prostor in energijo, Ljubljana.
(http://eionet-si.arso.gov.si/Dokumenti/GIS/splosno, 2005)

ARSO, 2004: Pokrovnost tal CORINE Land Cover Slovenija 2000.- Agencija Republike Slovenije za okolje, Ministrstvo za okolje in prostor, Ljubljana.

ARSO, 2005: Evropsko okoljsko informacijsko in opazovalno omrežje.- Agencija Republike Slovenije za okolje, Ministrstvo za okolje in prostor, Ljubljana.
(http://eionet.elsis.si/Dokumenti/GIS/splosno, 2005)

Bavec, M., Budkovič, T., Komac, M. 2005: Geohazard - geološko pogojena nevarnost zaradi procesov pobočnega premikanja. Primer občine Bovec = Estimation of geohazard induced by mass movement processes. The Bovec municipality case study. - Geologija, *48/2*, 303-310, Ljubljana.

Buser, S. in print: Geological Map of Slovenia at scale 1 : 250.000.

Carrara, A. 1983: Multivariate models for landslide hazard evaluation. - Mathematical Geology, *15*, 403–426.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V. & Reichenbach, P. 1991: GIS techniques and statistical models in evaluating landslide hazard.- Earth Surface Processes and Landforms, *16*, 427–445.

Crozier, M.J. & Glade, T. 2005: Landslide hazard and risk: Issues, concepts and approach.- In Glade, T., Anderson, M.G., Crozier, M.J., eds., Landslide Hazard and Risk, John Wiley & Sons, p. 1–40, New York.

Davis, J. C. 1986: Statistics and data analysis in geology. - John Wiley & Sons, pp. 646, New York.

Fabbri, A.G., Chung, C.F., Cendreo, A. & Remondo, J. 2003: Is Prediction of Future Landslides Possible with a GIS? - Natural Hazards, *30*, 287-499.

Kojima, H., Chung, C.F. & Van Westen, C.J. 2000: Strategy on the landslide type analysis based on the expert knowledge and the quantitative prediction model. - International Archives of Photogrammetry & Remote Sensing, *33/Part-B7*, 701-708.

Komac, M. 2005a: Verjetnostni model napovedi nevarnih območij glede na premike pobočnih mas - primer občine Bovec = Probabilistic model of slope mass movement susceptibility - a case study of Bovec municipality, Slovenia. - Geologija, *48/2*, 311-340, Ljubljana.

Komac, M. 2005b: Napoved verjetnosti pojavljanja plazov z analizo satelitskih in drugih prostorskih podatkov = Landslide occurrence probability prediction with analysis of satellite images and other spatial data. - Geološki zavod Slovenije, 284 p., Ljubljana.

Komac, M. 2005c: Intenzivne padavine kot sprožilni dejavnik pri pojavljanju plazov v Sloveniji = Rainstorms as a landslide-triggering factor in Slovenia. - Geologija, *48/2*, 263-279, Ljubljana.

Komac, M. 2005d: Verjetnostni model napovedi nevarnih območij glede na premike pobočnih mas - primer občine Bovec = Probabilistic model of slope mass movement susceptibility - a case study of Bovec municipality, Slovenia. - Geologija, 48/2, 311-340, Ljubljana.

Komac, M., Šinigoj, J., Krivic, M., Kumelj, Š., Hribernik, K. & Vehovec, A. 2005: Pregled in analiza podatkov v obstoječih bazah plazov za novelacijo baze GIS_UJME. - Geološki zavod Slovenije, 51 str., Ljubljana.

Komac, M. 2006a: A landslide susceptibility model using the analytical hierarchy process method and multivariate statistics in perialpine Slovenia. - Geomorphology (Amst.), [Print ed.], *74*, iss. 1/4, 17-28, Amsterdam.

Komac, M. 2006b: Application of a perialpine landslide susceptibility model in the Alpine region (Slovenia) = Uporabnost predalpskega modela verjetnosti pojavljanja plazov na alpskem območju. - Geologija, 49/1, 141-150, Ljubljana.

Lapanje, J., Šket Motnikar, B. & Zupančič, P. 2001: Potresna nevarnost Sloveije – Projektni pospešek tal.- Agencija Republike Slovenije za okolje – Uprava RS za geofiziko, Ministrstvo za okolje in prostor, Ljubljana. (http://www.arso.gov.si/podrocja/potresi/podatki/projektni_pospesek_tal.html)

Ribičič, M., Šinigoj, J. & Komac, M. 2003: New general engineering geological map of Slovenia.- Geologija, *46/2*, 397 – 404, Ljubljana.

Stančič, Z. & Veljanovski, T. 1998: Arheološki napovedovalni modeli in GIS. - V: uredniki Marko Krevs Šet al.Ć Geografski informacijski sistemi v Sloveniji, Znanstvenoraziskovalni center Slovenske akademije znanosti in umetnosti, str. 175–185, Ljubljana.

Stančič, Z. & Veljanovski, T. 2000a: Understanding Roman settlement patterns through multivariate statistics and predictive modelling.- Beyond the map, edited by Gary Lock., IOS Press, p. 147–156, Washington.

Stančič, Z. & Veljanovski, T. 2000b: Understanding Roman settlement patterns through multivariate statistics and predictive modelling. - Geoarchaeology of the landscapes of classical antiquity, edited by Frank Vermeulen & Morgan De Dapper, Stichting Babesch, p. 179–187, Leiden.

Survey and Mapping Administration 2000: InSAR DMV 25 (Digitalni model višin) = InSAR DEM 25 (Digital Elevation Model).- Geodetska uprava Republike Slovenije, Ljubljana.

Veljanovski, T. 1999: Prostorsko modeliranje in napovedovanje lokacij arheoloških najdišč: diplomska naloga. - Fakulteta za gradbeništvo in geodezijo, Univerza v Ljubljani, 164 str., Ljubljana.

Voogd, H. 1983: Multicriteria evaluation for urban and regional planning. - Pion Ltd., London.

Vrišer, I. 1997: Metodologija ekonomske geografije: metode, viri in bibliografija na primeru Slovenije. - Filozofska fakulteta, Oddelek za geografijo, Univerza v Ljubljani, str. 25–26, Ljubljana.