# STATISTICAL LANDSLIDE SUSCEPTIBILITY MODELING ON A NATIONAL SCALE: THE EXAMPLE OF SLOVENIA[1]

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**Statistische Modellierung der Erdrutschungsgefahr auf der nationaler Ebene: das Beispiel von Slowenien.** Zur Zeit, gibt es ungefähr 6,600 aufgezeichnete Erdrutschungen (ungef. 0,4 pro km$^2$) in Slowenien, aber man nimmt an dass es rund 10,000 aktive Erdrutschungen (ungef. 0,5 pro km$^2$) gebe. Allerdings, kaum ein Viertel dieser Erdrutschungen stellen eine Gefahr für die Infrastruktur und Gebäude dar. Erdrutschungen sind natürliche Prozesse die schwer aufzuhalten sind. Daher, geeignete Anpassung ist oft der größte begrenzende Faktor für städtische und wirtschaftliche Entwicklung. Im Durchschnitt, betragen die Schäden, die mit natürlichen Katastrophen in Slowenien zusammenhängen, jährlich zwei oder drei Prozente des slowenischen BIP, aber sie können im Falle von individuellen großen natürlichen Phänomenen viel höher sein. Wohlüberlegte Sicherheitsmaßnahmen würden höchstwahrscheinlich die Kosten der Wiederstabilisierung senken, aber es gibt noch keine gemeinsame Strategie und Regelungen um diese Ereignisse anzugehen. Naturgefahrenkarten stellen einen der wichtigsten Schritte gegen eine effektive Strategie dar, die Erdrutschungen sowie andere Massenbewegungen zu kontrollieren. Daher, haben wir drei Rutschungsgefahrenkarten für das Gebiet der Republik Slowenien angefertigt mit der Hilfe eines deterministischen Modells und zweier statistischer Modelle. Ein paar Vergleiche von Methoden und deren Ergebnissen werden in der Arbeit besprochen.

## INTRODUCTION

Slovenia is believed to have between 7,000 and 10,000 active landslides (Ribičič, Buser, Hoblaj, 1994), which indicates a density of approximately 0.4 landslide/km$^2$. A full quarter of these pose a threat to infrastructure and/or buildings. From 1994 to 2004, both landslides and avalanches caused nearly €90 million damages, not including cleanup costs and human lives lost (Komac, Zorn 2005; Komac *et al.*, 2008). Figures 1–3 show some recent landslides.

The main cause of landslides in Slovenia are the frequent heavy and intense precipitation. The minimum amount of precipitation to trigger landslides differs by lithostratigraphic units and is between 100 and 150 mm/24-hour precipitation, and between 130 and 180 mm/48-hour (Komac 2005a).

Elaboration of landslide hazard maps is one of the basic methods of landslide prevention. This article presents three such maps covering the entire territory of Slovenia. They were produced using geographical information systems, a digital elevation model with a 25 × 25 m grid resolution, several physical geographical landscape elements, and the National landslide database.

The landslide was triggered on 15 November 2000 across an area of approximately 25 ha, at an elevation of 1,300 to 1,700 m. The volume of the mass moved was approximately 2,500,000 m$^3$. On 17 November 2000, the landslide liquefied and a debris flow took seven lives, destroyed and damaged 18 houses on the way, finally depositing 700,000 m$^3$ of material over a 15 ha area in the form of a fan. The total damage was estimated at nearly €14 million (Zorn, Komac 2002).

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Fig. 1 - In September 2007, heavy rain in the Selška Sora Valley (western Slovenia) not only caused floods, but also triggered many landslides (photo by Matija Zorn).


Fig. 2 - The Stovžje Landslide (*1*), debris flow track (*2*), debris fan in the village of Log pod Mangartom (*3*; © Surveying and Mapping Authority of the Republic of Slovenia, 2005).

## LANDSLIDE HAZARD MODELING

Methods of landslide hazard modeling are divided into direct (qualitative or empirical) and indirect (quantitative) methods. The direct method most frequently used is (geomorphological) mapping. Its accuracy depends on the experience and expertise of cartographers, which is why the products demand a considerable amount of time to be completed; but, because of the fieldwork performed, they are more accurate (but also more expensive) than maps produced using indirect methods (van Westen, Seijmonsbergen, Mantovani 1999). The cartographic results of various authors may differ by 55 to 65% or even up to 80% (Ardizzone *et al.* 2002), which renders them extremely subjective.

Because one seeks to be as objective as possible in producing these kinds of maps, cheaper and faster indirect methods are often used. These are divided into deterministic, statistical, and probabilistic methods. Some authors (e.g. Komac 2005b) equate statistical methods with probabilistic ones, whereas here they are regarded as a special category because they combine both deterministic and probabilistic methods. However, it is true that due to this mixing in particular it is difficult to classify these methods into one of the categories above.

Nonetheless, deterministic methods are still characterized by subjectivity; in statistical methods this is reduced using statistics, whereas in probabilistic methods subjectivity is (almost) completely avoided (van Westen, Seijmonsbergen, Mantovani 1999).

Map production generally uses geographical information systems, and takes into account various contributing factors and various methods of calculating the significance of contributing factors for landsliding. These are used to solve the problem of comparing or combining various data layers. The data differ in terms of their presentation method, they can be vector- or raster-based, and they are often not homogeneous because they have been collected by various people or institutions that followed the rules or methods selected to varying extents. This can significantly reduce the model's accuracy. In deterministic methods only contributing factors are used, whereas in statistical and probabilistic methods contributing factors are combined with actual landslide occurrences.

For the landslide hazard maps used in this study, the National Landslide Database (*Nacionalna 2006*) was used to determine actual landslide occurrences (Fig. 3). This database was established in mid-2005. It contains information about 6,602 mass movements, of which 3,257 were precisely spatially located. The polygon vector data include information about relative (roads, buildings) and absolute (Gauss-Krüger coordinates) location, information about width, length and depth of landslides and information about their activity. It also includes information about sources of information and damage caused by landslides (Komac *et al.*, 2008). That this database is far from being perfect is shown by the fact that it does not include several thousand minor landslides (or slumps) that occurred in eastern Slovenia during the 1989 thunderstorms, for instance (Fig. 4; Natek 1989, Gabrovec 1990), or over 800 landslides that occurred in 1998 in the flysch Goriška brda Hills in western Slovenia (Ažman Momirski *et al.* 2008). Furthermore, it does not include several hundred landslides determined through previous geomorphological mapping (Radinja 1974, 1983). Another problem is that the database does not distinguish landslides from other slope processes and is therefore more of a database of slope processes than landslides *per se* (Komac *et al.* 2008), although landsliding processes do predominate among the entries.

## STATISTICAL METHODS

Simpler statistical methods generally involve a mathematical procedure or modeling that compares the effects of various factors on landslide frequency. In geographical information systems, this enables calculations using various data layers. The basic premise is that on the basis of past landslides one can establish where there is a greater or lesser possibility of their future occurrence. Various data are actually used to determine the relatedness of areas, on the basis of which conclusions about the landslide hazard in these areas are drawn. Based on this comparison, each factor can be ascribed a weight and a final landslide susceptibility map can then be prepared. Due to ascribing values to individual data layers, the method's subjectivity increases in this part of the procedure. We thus pass from statistical to deterministic methods.

Fig. 3 - After heavy precipitation in July 1989, several slumps were triggered in the Haloze Hills (photo by Milan Orožen Adamič).

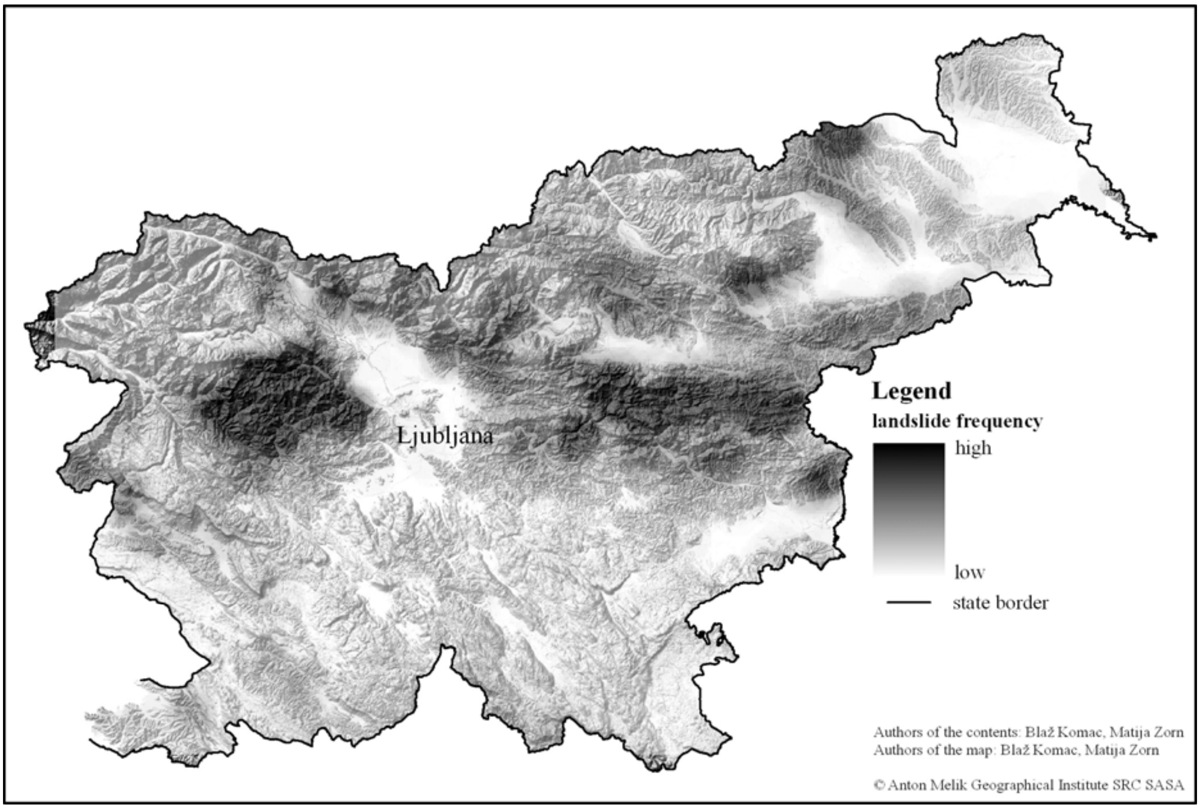


Fig. 4 - Frequency of landslide occurrence in Slovenia, calculated based on the National Landslide Database (Nacionalna, 2006).

Statistical methods are more reliable and less subjective when we do not return to weights. Univariate statistical analysis and multivariate analysis represent one such method. In univariate analysis, the frequency of landslides is calculated for each data layer used, and the data are then combined. Multivariate statistical (or discriminant) analysis is a more precise procedure, which takes into account a great number of contributing factors; in addition, regression and discriminant analyses are also more precise procedures. Recently, analyses using fuzzy statistical methods such as the Dempster-Shafer algorithm (Dempster 1968; Shafer 1990; Zorn, Komac 2007b, 2008a), fuzzy set theory (Staut, Kovačič, Ogrin 2007), the MYCIN model, and the application of neural networks (Binaghi *et al.* 1998) have frequently been used.

Despite the great accuracy of these analyses, errors can occur due to incorrect input data. These methods can thus only be used to simulate natural conditions. The methods and the final product (in our case, the landslide susceptibility map) are thus only used as aids for understanding natural processes better or for fieldwork, but cannot serve as a final explanation of the natural state and processes.

## THE LANDSLIDE INDEX METHOD

Landslide hazard in Slovenia was determined using two statistical methods. We first used the landslide index method (e.g., Ruff, Czurda 2008), which is based on comparing the map of actual landslides with maps of various contributing factors. The frequency or density of landslides is calculated for specific contributing factor values or classes and finally compared with the frequency or density of landslides in the entire area studied.

In the next step, maps are produced using weights that have been ascribed to each contributing factor class. The weights are calculated using the natural logarithm (ln) by dividing the landslide density logarithm in a particular class of a selected contributing factor with the landslide density logarithm in the area studied. The natural logarithms calculated have positive and negative values. Positive values are typical of areas with an above-average landslide density, and negative values are typical of areas with a below-average landslide density. Based on these data, a landslide susceptibility map is then made with individual landslide hazard categories. An arbitrary number of contributing factors may be used in making the maps. In this way, a partial map is made for each contributing factor, so that it shows the weights calculated for each contributing factor class. Partial maps are then combined into a map showing areas with greater and lesser probabilities of landslide occurrence.

## THE CERTAINTY FACTOR METHOD

The certainty factor method was also used. This method is one of the fuzzy statistical methods used as part of the MYCIN model (Shortliffe, Buchanan 1975).

Calculating the certainty factor is one of the favorability functions and makes it possible to compare and combine various or heterogeneous data (Chung, Fabbri 1993). According to the favorability theory, the favorability function $f_f$ is defined as follows:

$$f_f : \begin{cases} A \rightarrow [\min_f, \max_f] & \rightarrow [a, b] \\ A \rightarrow \{1, 2, 3 \ldots n_f\} & \rightarrow [a, b], \end{cases}$$

where $A$ is the area studied, $min_f$ and $max_f$ are the continuous values, numbers $1, 2, 3 \ldots n_f$ are discrete values, and $a$ and $b$ are the range of the favorability function in which all the values lie after transformation. The certainty factor was first used by Shortliffe and Buchanan (1975) and later on by Heckerman (1986). It has been used by Chung and Fabbri (1993, 1998), Binaghi *et al.* (1998), Luzi and Pergalani (1999), and Lan *et al.* (2004) to study landslides.

In order to use this function to calculate landslide hazard or other natural processes, one has to suppose, as with the landslide index method described above, that the landsliding probability can be defined based on the statistical relationship between past events and various data layers representing contributing factors (e.g., geological structure, surface inclination, land use, etc.).

The certainty factor is calculated as follows (Binaghi *et al.* 1998):

$$CF = \begin{cases} (cp_a - pp_s) : (cp_a(1 - pp_s), & \text{if } cp_a \geq pp_s, \\ (cp_a - pp_s) : (pp_s(1 - cp_a), & \text{if } cp_a < pp_s, \end{cases}$$

where $cp_a$ is the conditional probability of landslide occurrence in the area of class $a$ of a specific contributing factor, and $pp_s$ is the prior probability of landslide occurrence in the entire area studied (A). Positive values denote an increase in the probability of landslide occurrence, values close to zero denote that the conditional probability is very close to prior probability and thus the probability of landslide occurrence is difficult to estimate, and negative values denote a low probability of landslide occurrence.

The certainty factor is calculated by first calculating the probability of landslide occurrence in individual, previously defined data layer classes of the contributing factors. Thus, partial maps are produced and compared with the map showing all landslides.

## LANDSLIDING CONTRIBUTING FACTORS

In producing the landslide susceptibility maps, several contributing factors were taken into account: lithology, surface inclination, surface curvature, land use, maximum 24-hour precipitation, and surface aspect.

One of the more important factors for triggering landslides is lithology (Verbič 2001) because landslides frequently occur on some rock types, whereas on others they do not occur at all. A digital 1:100,000 lithological map and a 1:25,000 soil map were used.

93% of Slovenia consists of sedimentary rocks, and the remaining 7% is made us of igneous and metamorphic rocks. However, there are great differences among individual types of sedimentary rocks in terms of landslide hazard. According to the National Landslide Database (*Nacionalna 2006*), landslides are common on clastic rocks, such as sandstone, flysch, and especially argillite and marl, as well as clay, sand, silt, and gravel if slopes are made of these sediments. They also occur on volcanoclastic rocks (tuff) – Fig. 5. Practically no landslides occur on some types of limestone and dolomite, and on igneous rocks and marsh sediments, because the latter are obviously only found in flatlands. Landslides also seem to be common on fractured dolomite and bedded limestone. This is the result of a non-uniform database concept, which indicates that in setting up the database on the distribution of phenomena, rockfalls and rockslides were also classified under landslides in the narrow sense.

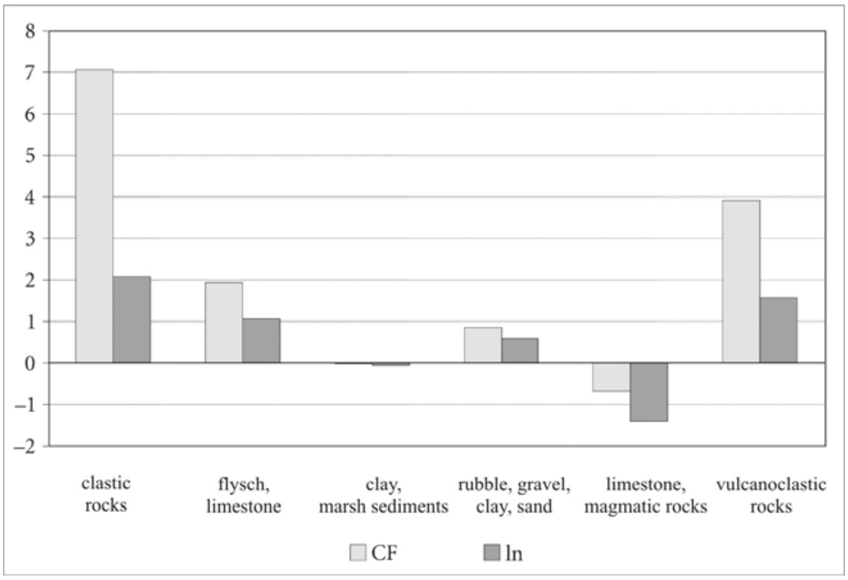


Fig. 5 - Impact of lithology on landslides calculated using the landslide index (*ln*) and certainty factor (*CF*) methods.

Surface inclination is also closely connected with geomorphic processes. In Slovenia, these processes are most common in Alpine regions (with an average inclination of 18°), whereas they are less common in Dinaric (11°) and Mediterranean (10°) regions. Inclination is also closely connected with elevation because it usually increases with elevation. Approximately 8% of Slovenia's surface consists of flatland with an inclination close to 0°, and nearly a quarter of its surface is composed of areas with an inclination between 12 and 20°. A good fifth of Slovenia's surface has an inclination between 6 and 12°, and a good sixth between 20 and 30° (Perko 2001).

In order to produce the landslide susceptibility maps, a digital elevation model with a 25 × 25 m grid resolution was used. According to the National Landslide Database (*Nacionalna 2006*), landslides are most frequent in areas with 20° to 30° inclination. They are very frequent in areas with 10° to 20° inclination, and less frequent in areas with 30° to 40° inclination. They are extremely rare in areas with an inclination below 10° or over 50°, and also rare between 40 and 50° (Fig. 6). Because data on landslides or slope processes in areas with low and high inclinations are scant in the database, we decided to eliminate inclinations below 2° and above 45° in the final calculation in order to avoid the problem described in the introduction – that is, that the National Landslide Database is actually a database of slope processes. Therefore, these areas account for the susceptibility class zero and they were added to other – as defined by models – values in zero category. The reason for eliminating greater inclinations is the fact that an inclination of approximately 32° is a natural angle of repose. Above this inclination, processes of falling and tipping thus predominate. Because of experiences with landslides that occurred even at inclinations up to 40°, the upper threshold was set at 45°.

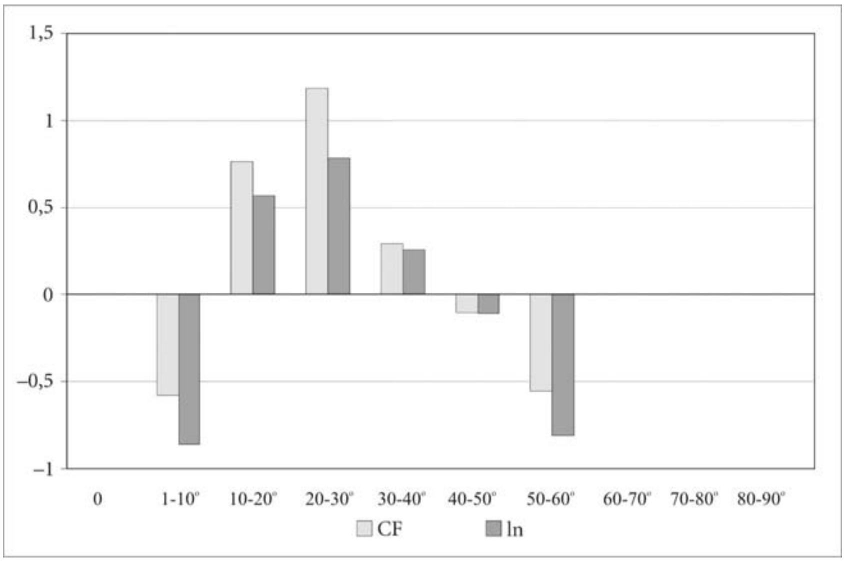


Fig. 6 - Impact of inclination on landslides calculated using the landslide index (*ln*) and certainty factor (*CF*) methods.

Landslide hazard is also affected by the curvature of the surface or the spatial differences in surface inclination or exposure (Hrvatin, Perko 2002; Perko 2007).

Horizontal curvature of the surface – that is, curvature in relation to the vertical plane, denoting the degree of change in the surface aspect – is also especially important for landslide hazard. Horizontal surface curvature marks areas where rainwater converges on slopes. These areas are important because, with an extremely great amount of precipitation, water can accumulate on the surface and in the sediment, thus burdening the slope. 53% of landslides occurred in concave parts of slopes (Fig. 7).

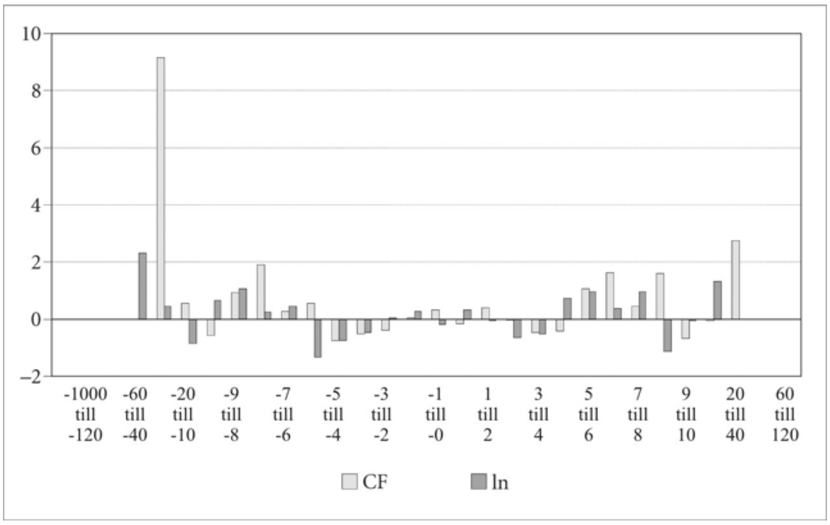


Fig. 7 - Impact of surface curvature on landslides calculated using the landslide index (*ln*) and certainty factors (*CF*) methods.

Land use is also an important landslide triggering factor, reflecting complicated relationships between natural and socioeconomic factors. The impact of land use is especially evident in the effect of flora on the water balance, and thus the amount of groundwater or ground saturation, which influence the stability of earth masses. It is difficult to define the impact of land use on the occurrence of landslides with precision because the significance of flora at middle latitudes also changes with the seasons, for example (Natek 1990).

The Use of Agricultural Land map by the Ministry of Agriculture, Forestry, and Food (Dejanska, 2004) was aimed at obtaining the information on land use. According to the National Landslide Database (*Nacionalna 2006*), landslides most commonly occur in orchards and vineyards. They are also frequent in meadows and pastures, intensive orchards, forests, and built-up land. Landslides do not or only rarely occur in hop fields, olive groves and other areas with permanent crops, and on boggy and barren land[2] (Fig. 8).

As already mentioned above, precipitation significantly increases the frequency of landslides. Both the amount and intensity of precipitation are important factors in this case. The occurrence of landslides is not so much affected by differences in the average annual precipitation as it is by differences in the maximum amount of precipitation that may occur in a specific area within a specific time interval. This factor is usually expressed by the maximum amount of precipitation that may occur in one day (in 12 or 24 hours). This is referred to as the maximum 24-hour precipitation. The Map of Maximum 24-Hour Precipitation was used to produce the landslide hazard maps (Maksimalne 1995) – (Fig. 9).

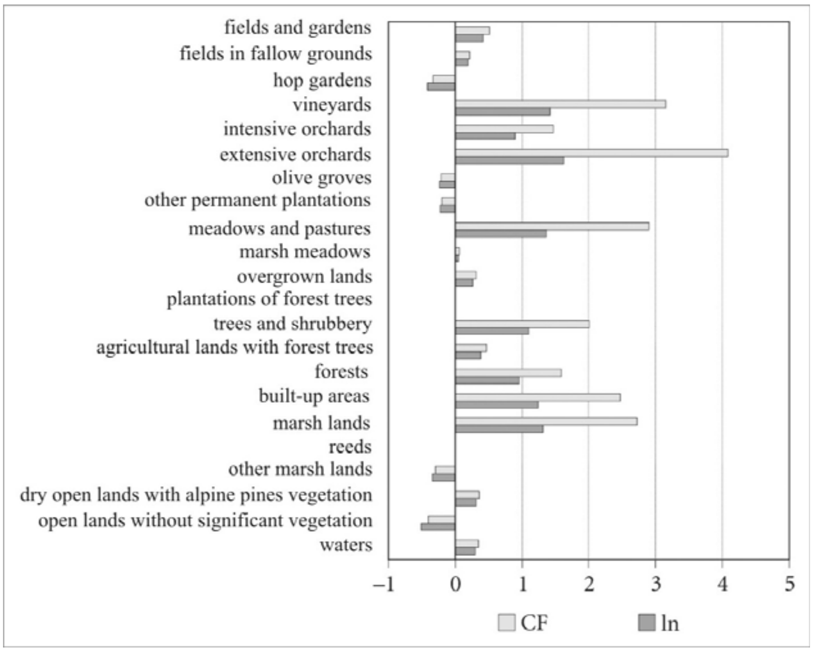


Fig. 8 - Impact of land use on landslides calculated using the landslide index (*ln*) and certainty factor (*CF*) methods.

Landsliding is also influenced by surface direction or aspect, although only indirectly, and through insolation, which affects the humidity of slopes. In Slovenia, landsides are most common on slopes with a southeast, south, and southwest exposure (Fig. 10), whereas the impact of aspect on landsliding for other exposures is difficult to determine or is extremely vague. Because landslide-prone exposures are also those with most sun exposure – that is, they are also arid – it can be presumed that landslide hazard is also indirectly influenced by the potential different average inclination of slopes facing various directions (north and south).

[2] High values of marsh vegetation influence on landsliding (Fig. 8) are due to the differences in the extent of marsh sediments on the map of lithology (Verbič 2001; Fig. 5) comparing to much higher marsh vegetation as shown on the land use map (Dejanska 2006).

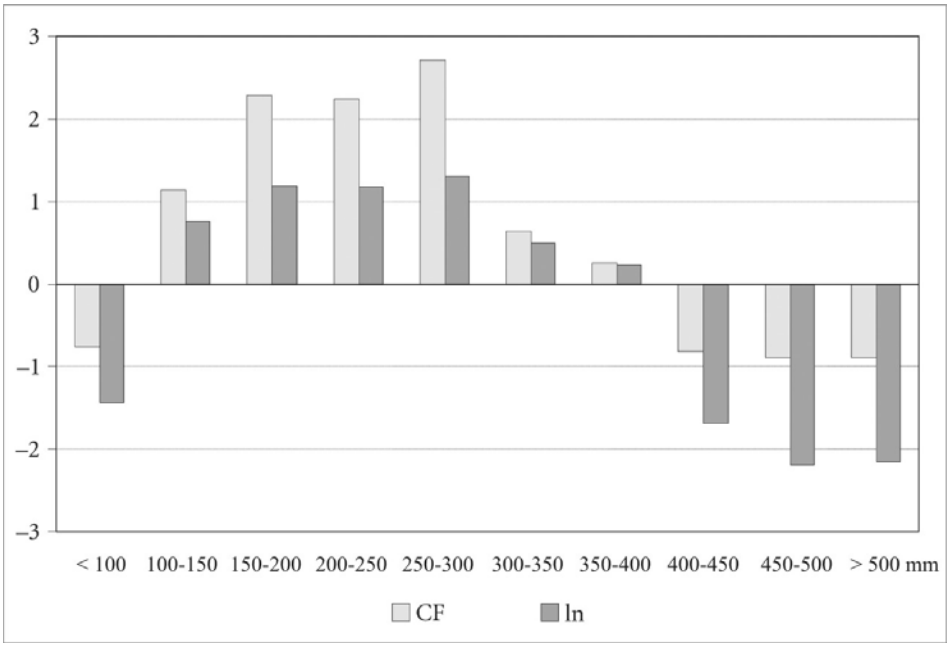

Fig. 9 - Impact of maximum 24-hour precipitation on landslides calculated using the landslide index (*ln*) and certainty factor (*CF*) methods.

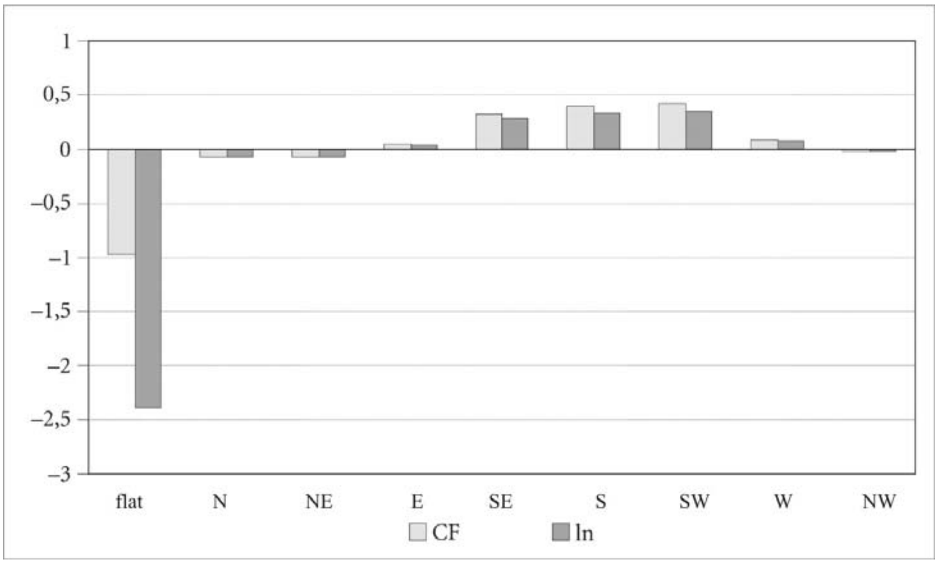

Fig. 10 - Impact of surface direction or exposure on landslides calculated using the landslide index (*ln*) and certainty factor (*CF*) methods.

## LANDSLIDE SUSCEPTIBILITY MAPS OF SLOVENIA

### THE WEIGHT-OF-EVIDENCE METHOD

In addition to the statistical methods described above, a comparable landslide susceptibility map was also made using a deterministic weight-of-evidence method (Zorn, Komac 2004). Based on the values of logarithms and certainty factors, the values of the contributing factors were appropriately ranked. Taking into account experience to date (e.g., Zorn, Komac 2005, 2007a, 2007b; Komac, Zorn 2007) and literature (Komac 2005b; Komac, Ribičič 2008), weights were used to produce the map. These weights are presented in Table 1. The weighted values were transformed into categories on the basis of frequency distribution. Tresholds were defined at 2$^{nd}$, 3$^{th}$, 5$^{th}$, 6$^{th}$ and 7$^{th}$ deciles.

Table 1 - Weights used to produce the landslide susceptibility map by the weight-of-evidence method.

| Contributing factor | Weight |
|---|---|
| Lithology | 0.30 |
| Land use | 0.25 |
| Inclination | 0.25 |
| Horizontal surface curvature | 0.10 |
| 24-hour maximum precipitation | 0.05 |
| Surface aspect | 0.05 |

The landslide susceptibility map produced using the weight-of-evidence method presents the areas with landslide hazard relatively well; however, its disadvantage is that the weights or significance of individual factors are defined arbitrarily. Areas in the highest landslide hazard category make up 1.1% of the surface area, but only 4.5% of landslides occur there (Fig. 11); the situation is similar with the second-highest landslide hazard category, which makes up 4.2% of the surface area and in which 12.3% of landslides occur. Areas that are not threatened by landslides cover 28.0% of the surface area, with only 5.0% of landslides. Only one-sixth of all landslides thus occur in the two highest categories, which cover 5% of the territory.

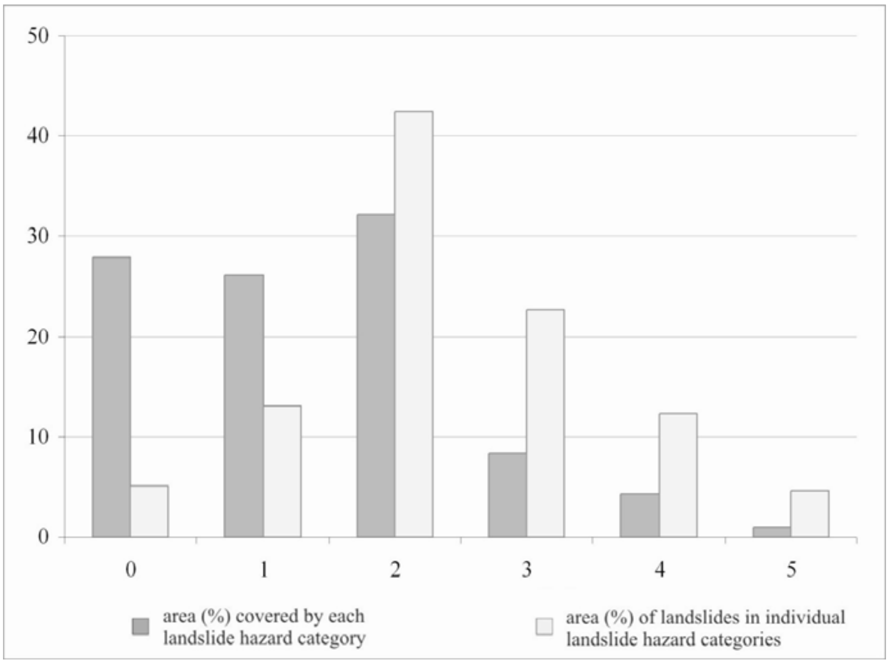


Fig. 11 - Percentages of surface area covered by each landslide hazard category and percentage of landslides in individual categories.

Only 38% of the landslide-prone areas calculated using the weight-of-evidence method coincide with the areas in which landslides have already occurred in the past. Nonetheless, the map correctly shows that in Slovenia alpine mountains (see Fig. 17, sub-macroregion 1.2) are the most susceptible to landslide hazards (Fig. 12). The Karavanken Mountains and the hills of eastern Slovenia are also landslide-prone. On this map, the landslide-prone areas are not continuous.

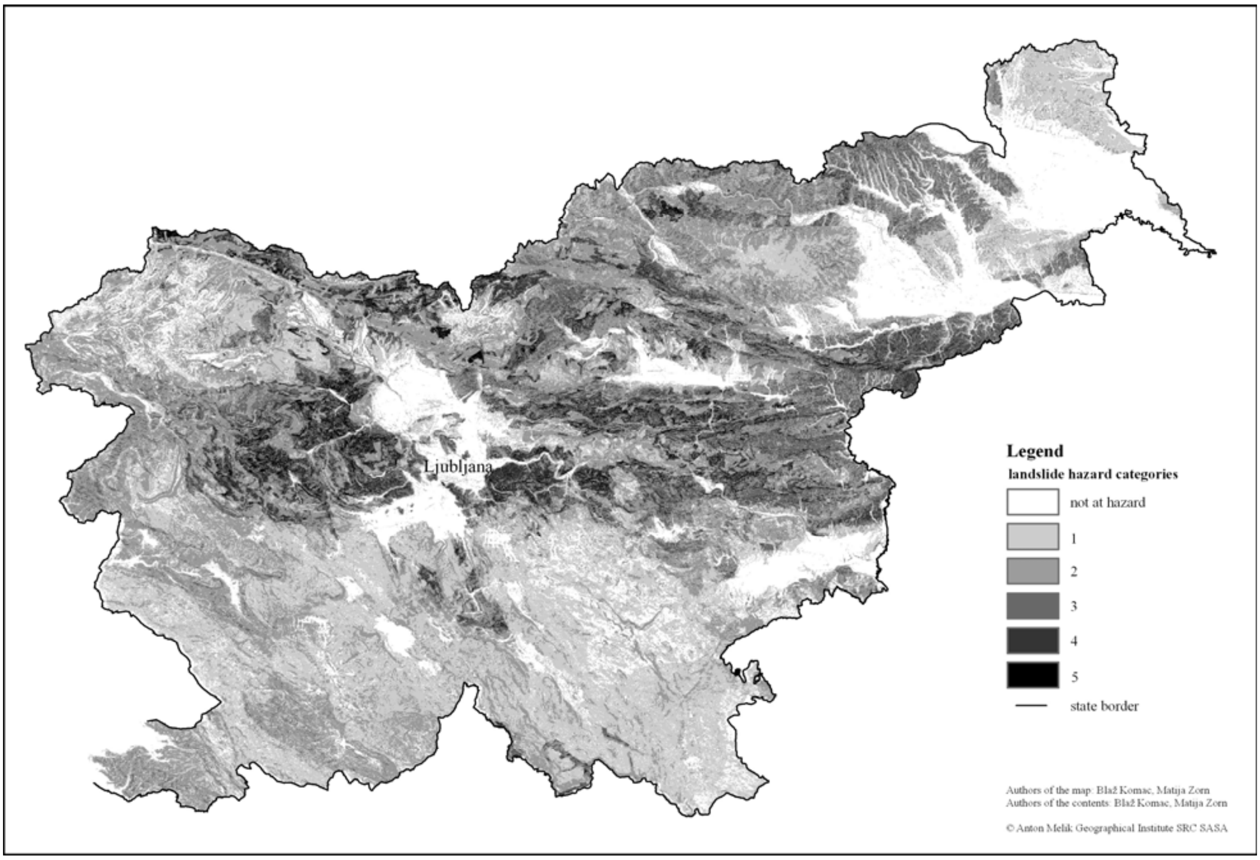


Fig. 12 - Landslide susceptibility map produced using the weight-of-evidence method.

## THE CERTAINTY FACTOR METHOD

The data layers of the contributing factors were compared with the landslide layer, and the frequency of landslides in various categories of individual data layers was then calculated. By comparing the cell number of landslides in an individual data layer category and the number of landslide cells in the entire area studied, we were able to establish which contributing factor values have the highest landslide hazard probability (Table 2). Partial maps were produced in this way.

Table 2 - Agreed-upon division of certainty factor values into categories.

| Value | Description |
|---|---|
| below −0.09 | Extremely low probability |
| −0.09 to 0.09 | Unknown probability |
| 0.09 to 0.20 | Low probability |
| 0.20 to 0.50 | Medium probability |
| 0.50 to 0.80 | High probability |
| above 1.00 | Extremely high probability |

The certainty factor values calculated for individual data layers or partial maps were finally combined and the final certainty factor was calculated. The calculation was made by first comparing two partial maps, then comparing this combined partial map with the third partial map, and so on, as proposed by Binaghi *et al.* (1998). In order to show the final certainty factor values on the map more easily, they were divided into categories.

Areas in the highest landslide hazard category cover 9.1% of the surface area, although 33.0% of landslides occur there; the situation is similar with areas in the second-highest landslide hazard category, which cover 6.9% of the surface area and in which 17.9% of landslides occur. In the two highest categories, which cover 16.1% of the territory, just over half of all landslides (i.e., 51.0%) thus occur. Areas not threatened by landslides cover 17.7% of the surface, with 2.0% of landslides (Figs. 13, 14).

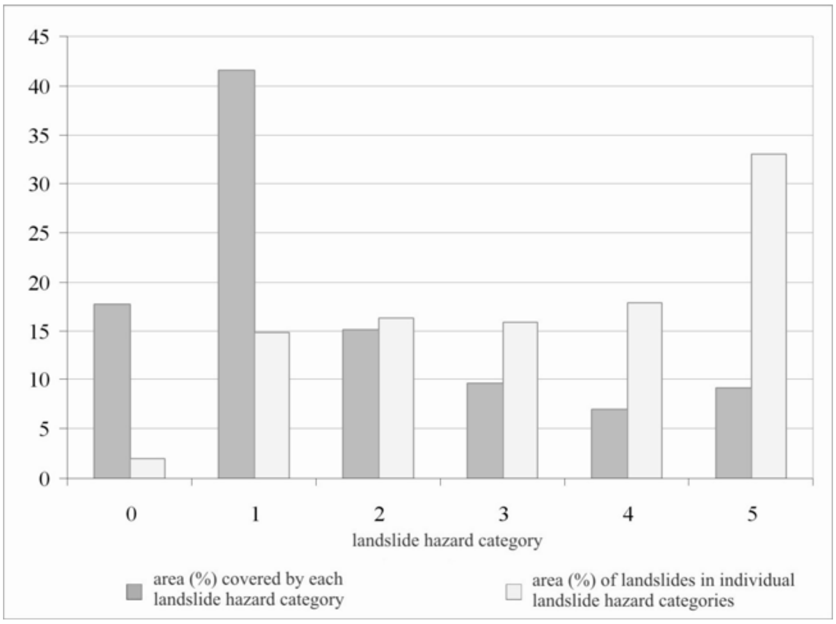

Fig. 13 - Percentages of surface area covered by each landslide hazard category and percentage of landslides in individual categories.

THE LANDSLIDE INDEX METHOD

This method is based on crossing a landslide map with maps of different parameters, used to calculate the density of landslides per parameter class. For each parameter class, a weight value is calculated. The weight value is defined as the natural logarithm of the landslide density in the class divided by the landslide density in the entire map. The weight values are negative when the landslide density is lower than usual, and positive when it is higher than usual.

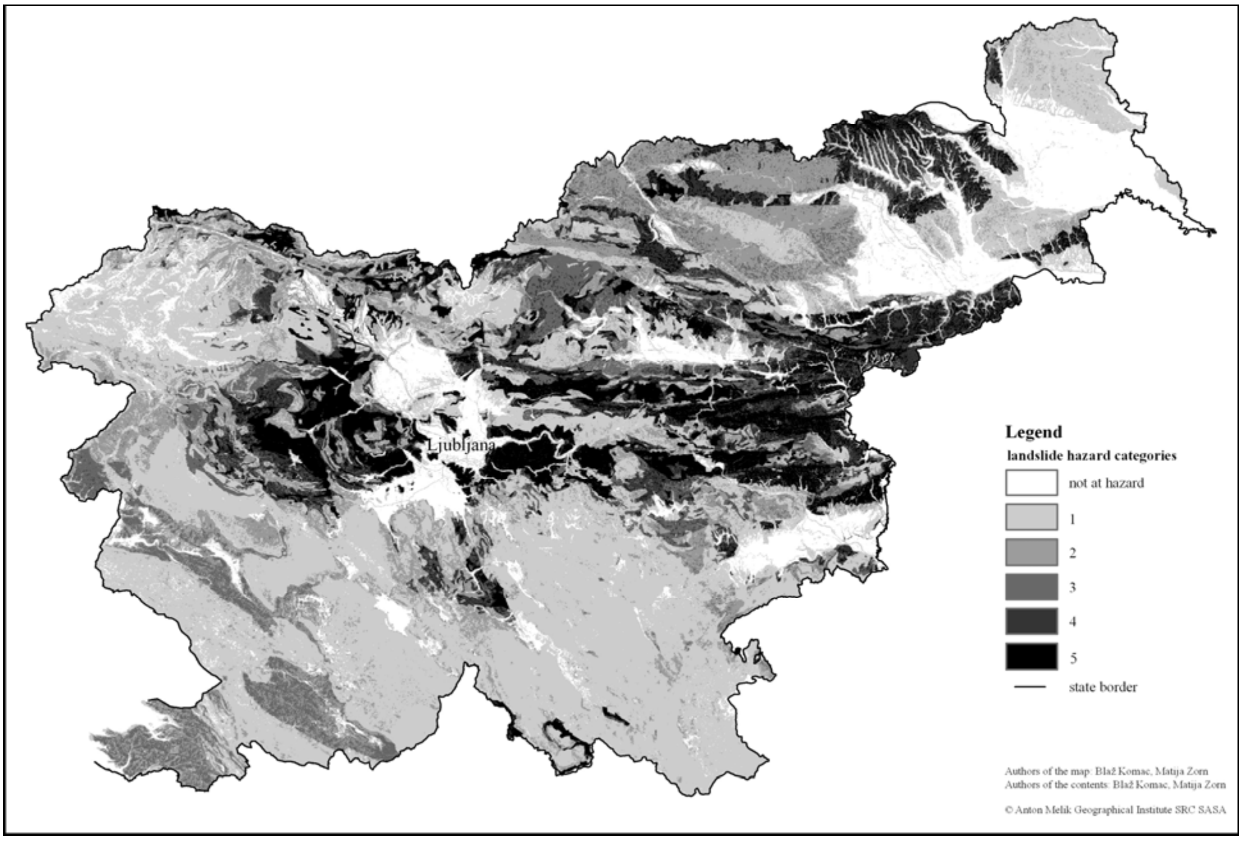

Fig. 14 - Landslide susceptibility map produced using the certainty factor method.

Areas in the highest landslide hazard category cover 5.8% of the surface area, but 24.4% of landslides occur there; the situation is similar with areas in the second-highest landslide hazard category, which cover 14.8% of the surface area and in which a third (i.e., 33.3%) of all landslides occur. In the two highest categories, which cover one fifth (20.6%) of the territory, a full 57.7% of all landslides occur. Areas not threatened by landslides cover 16.9% of the surface area with only 1.9% of landslides occurring in these areas (Figs. 15, 16). Compared to the weight-of-evidence method, the landslide index method shows the landslide-prone areas more accurately and contiguously in space, and according to the reliability analysis (cf. Lan *et al.*, 2004) it is more reliable than the methods described above.

This map also shows that alpine mountains are the most susceptible to landslide hazard in Slovenia; in addition, landslide-prone areas also include the Karavanken Mountains and the tertiary hills of eastern Slovenia. The map does not show the flysch regions of western Slovenia as susceptible to landslide hazards, although there are several landslide-prone areas in this region (cf. Zorn, Komac 2007a, 2007b; Ažman Momirski *et al.* 2008). This is probably the result of insufficient input data from this region.

84% of the landslide-prone areas calculated using the landslide index method coincide with the areas in which landslides have already occurred. The landslide index method proved to be the most appropriate among all the methods used.

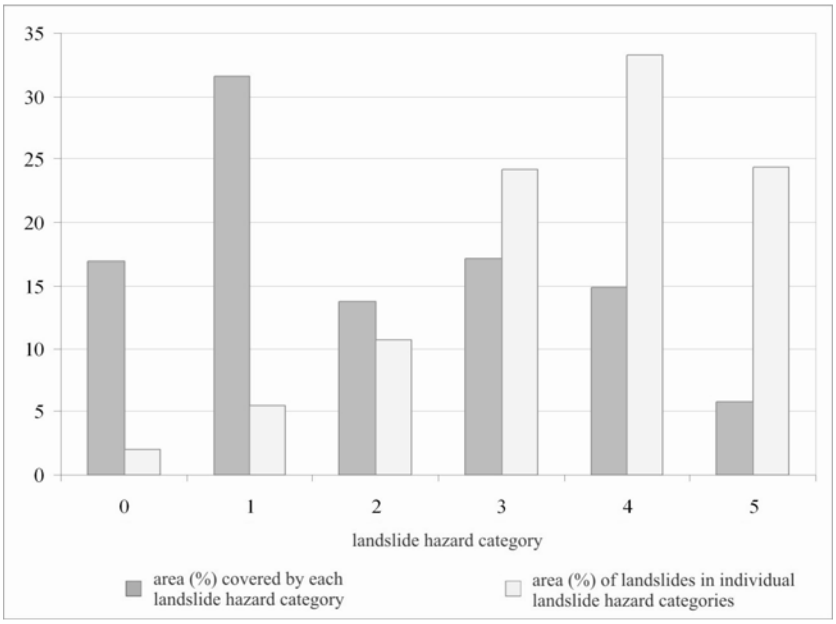


Fig. 15 - Percentages of surface area covered by each landslide hazard category and percentage of landslides in individual categories.

## LANDSLIDE HAZARD ACROSS SLOVENIAN REGIONS

In order to determine the landslide hazard of Slovenian regions, the landslide hazard index (Zorn, Komac 2008b) was calculated on the basis of the relative surface areas with the highest and second-highest degree of landslide hazard in an individual region. The index was calculated for individual Slovenian macro- and sub-macroregions (Perko, Kladnik 1998).

On average, the landslide hazard is the greatest in Slovenian alpine regions, where the areas most susceptible to landslides (hazard categories 4 and 5) cover 21% of the entire region's surface area. Among the sub-macroregions, the landslide hazard is the greatest in alpine mountains, where the areas most susceptible to landslides cover almost a third (i.e., 30.9%) of the surface area. Here, the Cerkno, Škofja Loka, and Polhov Gradec Mountains (with 48.3% of their surface area prone to landslides) and the Posavje Mountains (39.4%) are the most outstanding ones. In addition, there is considerable landslide hazard in the Ložnica and Hudinja hills (29.3%), and the Velenje and Slovenske Konjice hills (23.8%). Among the Alpine regions, the Western (34.3%) and Eastern Karavanken Mountains (24.6%) and the Kamnik-Savinja Alps (21.9%) are most prone to landslides.

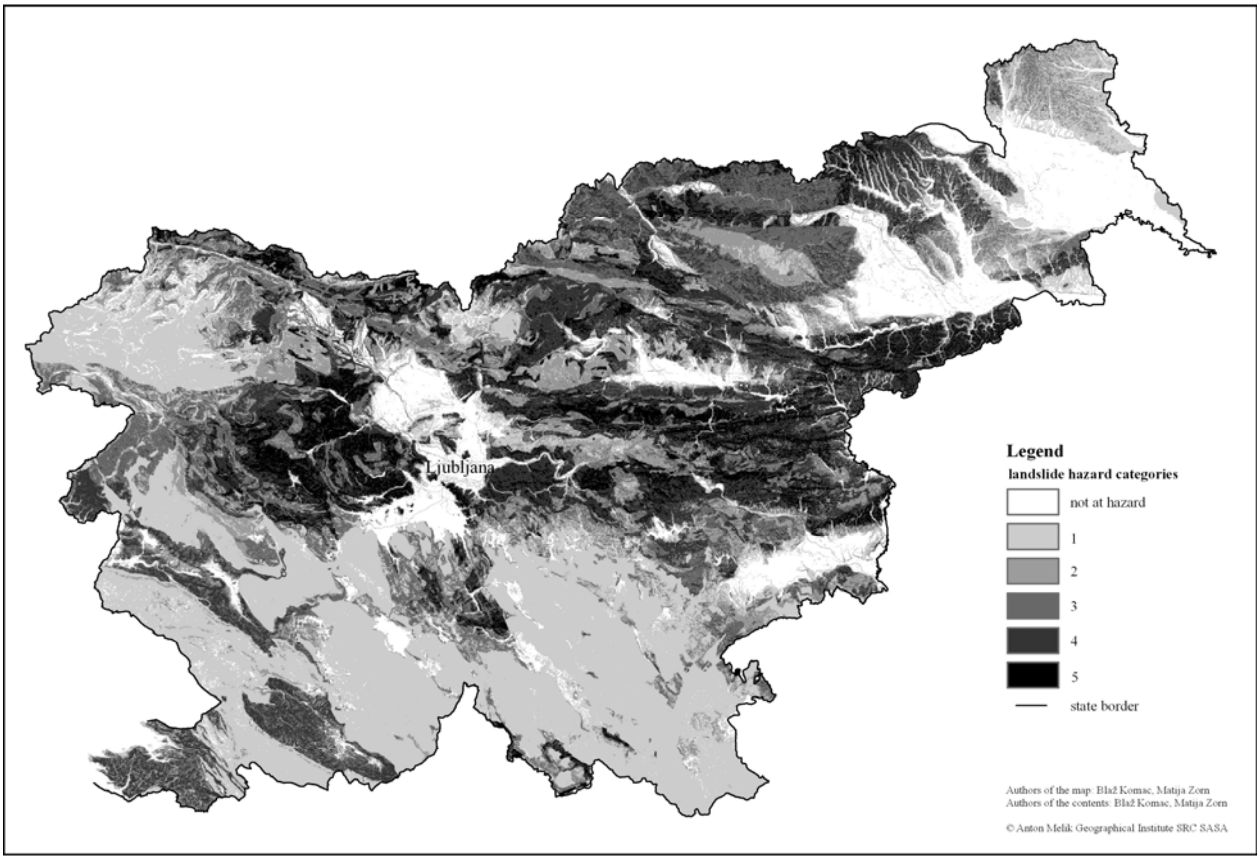


Fig. 16 - Landslide susceptibility map produced using the landslide index method.

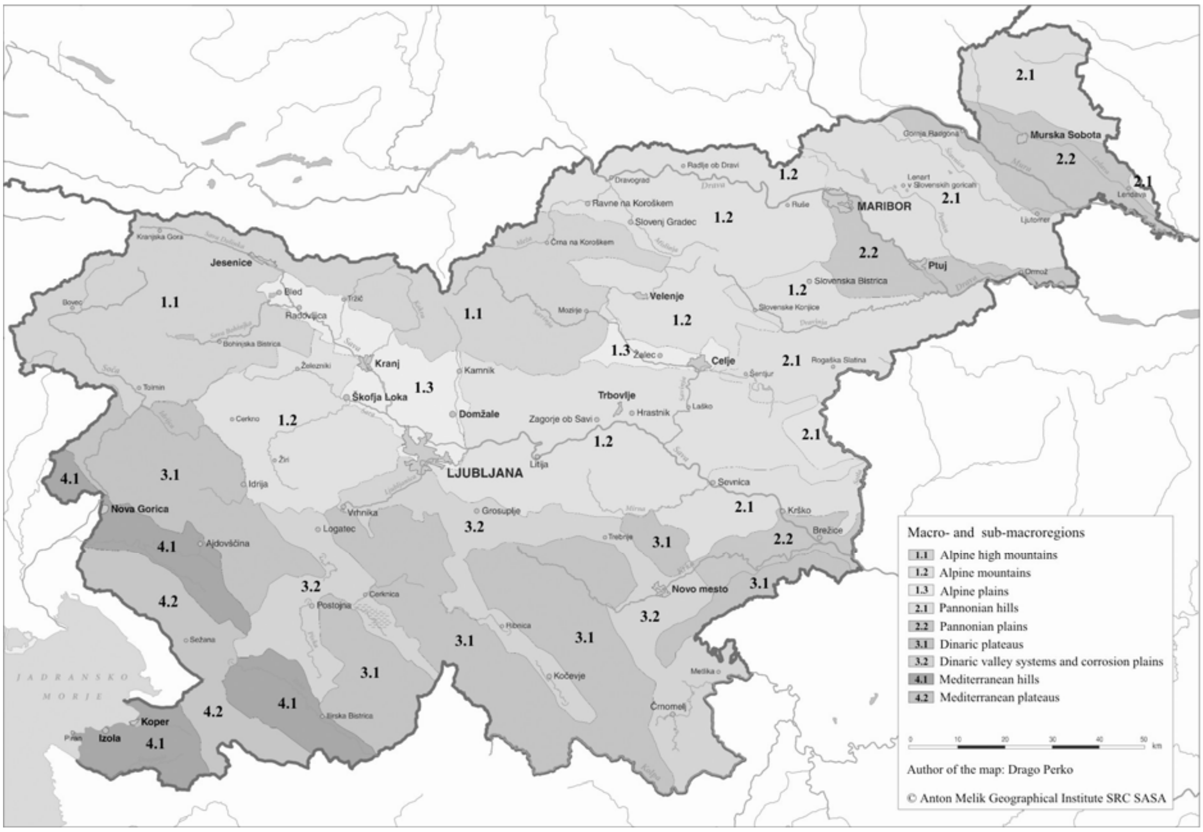


Fig. 17 - Slovenian macro- and sub-macroregions according to the geographical regionalization of Slovenia (Perko, Kladnik 1998).

In the Pannonian regions, landslide-prone areas cover 10.4% of the region's surface area. The hills, with 27.1% of landslide-prone surface areas, are the most susceptible to landslides. In certain ranges of hills, these areas cover even more than 50% of the entire surface area. In the Boč Mountain and in the Macelj Mountain, more than half of the land (i.e., 54%) is prone to landslides. Considerable landslide hazard is also typical of the Haloze Hills (50.3%), and the Voglajna and the Upper Sotla hills (43.4%). Areas less susceptible to landslides can be found in the Central Sotla Hills (37.4%), the Krško, Senovo, and Brežice hills (23.9%), as well as in the Slovenske gorice Hills, which cover one fifth of landslide-prone areas.

Mediterranean regions are less susceptible to landslides than the Pannonian regions, with areas most susceptible to landslides covering 8.4% of the region's surface area, and in some flysch areas even up to 17.1% (Goriška brda Hills). Areas that are the most susceptible to landslides also include the Brkini Hills (11.4%), the edges of the Vipava Valley (10.6%), and the Koper Hills (10.0%).

Areas least threatened by landslides are the (predominantly) limestone Dinaric regions where the areas most susceptible to landslides cover 7.2%. Among the Dinaric plateaus, the Idrija Hills (26.6%) are most susceptible to landslides, and among the Dinaric plains most susceptible are the Velike Lašče Region (36.0%) and the edges of the Ljubljana Marsh (21.2%).

In the landslide hazard findings presented above, one can see the influence of the database used, which also includes rockfalls and other slope processes in addition to landslides. Due to the non-uniform method of collecting data, the entire territory of Slovenia is not uniformly covered. For example, the flysch hills of Mediterranean Slovenia in the southwest (e.g., the Goriška brda Hills) and some Pannonian hills in the east (e.g., the Lendava Hills) stand out as areas a low landslide hazard, although exactly the opposite has been proven; for example, for the flysch hills in particular (cf. Zorn, Komac 2007a, 2007b; Ažman Momirski *et al.* 2008).

## CONCLUSIONS

The damage caused by landslides has been increasing in the last decades. In some places, this is truly the result of the greater frequency or intensity of natural processes; however, this can largely be ascribed to human encroachment into previously unsettled areas that are threatened by natural processes. Despite the constant threat, there is an extremely low level of awareness regarding this issue in society. It is thus alarming to see that in Slovenia, relief and geomorphic processes, including landslides, are not taken into account in land-use planning (Komac, Natek, Zorn 2008).

Traditional settlement should serve as a good example. In the past, people usually only built in areas that were not threatened by slope processes. Another step forward could be achieved by planning settlements in and directing them to safe areas, and protecting existing settlements by appropriate measures, if possible and as needed.

Landslide susceptibility maps provide a quick and effective way to determine the areas that people should not exploit or for which we know that any development would demand special construction and other measures. Our landslide susceptibility maps are small-scale maps. The most accurate data available at the national level were used to produce them.

The maps were produced by the weight-of-evidence method, the certainty factor method and the landslide index method. According to the weight-of-evidence method (certainty factor method; landslide index method) the highest landslide hazard category make up 1.1% (9.1%; 5.8%) of the surface area, but 4.5% (33.0%; 24.4%) of landslides occur there. In the second-highest landslide hazard category, 4.2% (6.9%; 14.8%) of the surface area and 12.3% (17.9%; 33.3%) of landslides occur in it. By comparing differences between proportions of hazard categories surface areas and areas with landslides for all the three methods we can conclude that the landslide index method is the most appropriate one, since the differences in proportions increase at the highest exponential rate.

It turned out that it is difficult to produce detailed maps using the existing data available at the national level; however, through the use of geographical information systems we can enrich and check the knowledge of landslide-prone areas. One of the great deficiencies of the maps presented, as well as of other such maps produced to date is that they do not include one of the key contributing factors of landsliding – that is, information on the depth of soil and regolith.

The maps presented are useful for planning land use at national and regional levels, but more detailed input data are required to also render them applicable at local level. Unfortunately, these data do not yet exist at national level. However, the methods used are also appropriate (given that appropriate input data are provided) for modeling landslide hazard at local level.

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