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LANDSLIDE SUSCEPTIBILITY ZONATION: A CASE STUDY OF THE MUNICIPALITY OF BANJA LUKA (BOSNIA AND HERZEGOVINA)

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Infield or a landslide? Landslide in Banja Luka, April 2012.

Landslide susceptibility zonation: A case study of the Municipality of Banja Luka (Bosnia and Herzegovina)

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ABSTRACT: Along with flash floods, landslides are one of the most widespread and damaging natural hazards in Bosnia and Herzegovina. This paper determines areas susceptible to landslides in the Municipality of Banja Luka (Republika Srpska, northwest Bosnia and Herzegovina). Based on a terrain survey in a 55.4 km^2 area, 216 landslides were identified with a total area of 2.9 km^2 or 5.2% of the municipality. According to landslide susceptibility modeling, low susceptibility is present from one-quarter to one-half of the territory and very high susceptibility is present from several percentages up to one-third of the territory, depending on the model used. The results may support government mitigation programs and help in developing a landslide hazard and risk assessment model for the area.

KEYWORDS: landslides, landslide susceptibility, GIS, Banja Luka, Bosnia and Herzegovina

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1 Introduction

Landslides are recognized as an important »natural hazard« in many countries (e.g., Crozier and Glade 2005; Zorn and Komac 2007; Tošić et al. 2012). Along with flash floods, they are one of the most widespread and damaging natural hazards in Bosnia and Herzegovina. Population growth, increased urbanization, and expansion of urban and manmade structures into potentially hazardous areas leads to extensive damage that has dramatic effects on human life, infrastructure, and the environment (Luzi and Pergalani 1999; Zorn and Komac 2009; 2011; Komac et al. 2013). Determining the spatial and temporal extent of landslide hazard requires identifying areas that are, or could be, affected by landslides and assessing the probability of landslides occurring within a specified period of time. To reduce the risk from landslides, knowledge of landslide-prone areas is needed. This information is often described in the form of landslide susceptibility zonation (e.g., Aleotti and Chowdhury 1999; Guzzetti et al. 1999; Luzi and Pergalani 1999; Crozier and Glade 2005). A large number of studies on landslide susceptibility zonation have been carried out over the past 30 years (Crozier and Glade 2005). Overviews of various landslide susceptibility zonation techniques can be found in Carrara et al. (1991), van Westen et al. (1997), Guzzetti et al. (1999), and Zorn and Komac (2004; 2007). Many techniques use GIS and remote sensing to determine landslide-prone areas (e.g., Nagarajan et al. 1998; van Westen and Lulie Getahun 2003). With the help of GIS, it is possible to integrate different spatial data layers to determine landside-prone areas (e.g., van Westen 1994; Carrara et al. 1995; Aleotti and Chowdhury 1999). However, this type of research has not been applied in Bosnia and Herzegovina until now, and the investigation and study of landslides has been based only on the geo-technical approach (Perić et al. 1971).

In the Municipality of Banja Luka a large number of landslides in urban and peri-urban areas were triggered during the autumn of 2011 and spring of 2012. Because there is currently no landslide database (inventory) for the Municipality of Banja Luka, which is necessary for any land-use planning purpose, landslide susceptibility zonation was performed to determine landslide-prone areas. The creation of a landslide susceptibility map is the first important step for preventing and mitigating landslides in the study area.

The objective of this study is to assess the landslide susceptibility of urban and peri-urban areas of the Municipality of Banja Luka using various methods: the Index-Based Method (IBM), the Statistical Index Method (SIM), and Landslide Susceptibility Analysis (LSA).

2 Study area

The Municipality of Banja Luka is located in the northwestern part of Bosnia and Herzegovina (Figure 1). It occupies an area of 55.4 km^2, with around 226,450 inhabitants.

The entire area of the Municipality of Banja Luka belongs to the Pannonian region. According to morphostructural characteristics, the study area is a neotectonic depression whose formation begun during

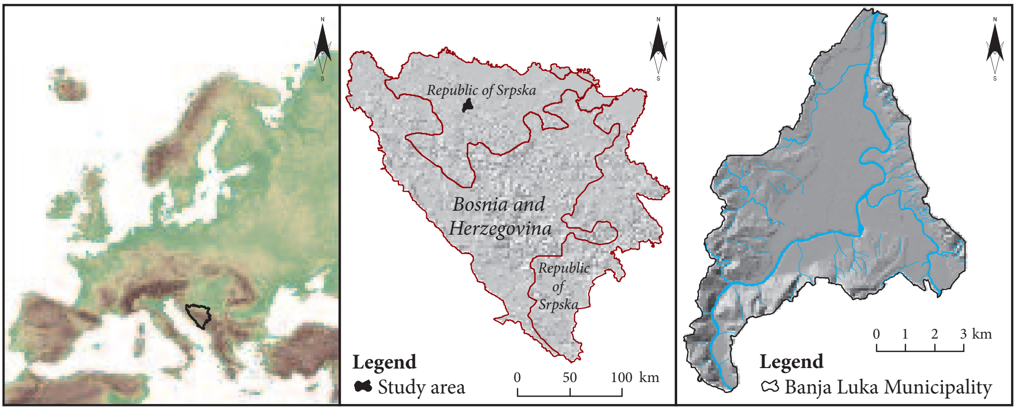


Figure 1: Location of the study.

Neogene tectonic activity (Vilovski 1970; Mojićević et al. 1976; Trkulja 1998). Figure 3 shows only major lithologic complexes, some of which have played a dominant role in the distribution of landslides: fluvial sediments, torrential sediments, slope material, flysch, Neogene sediments (sands, clays and marl), and Mesozoic rocks (limestone, dolomite and diabase-hornstone rock). The largest spatial distribution is that of fluvial sediments located in the center of the study area.

The terrain ranges from 137 to 432 meters above sea level. Alluvial plains with slopes less than 5° are dominant across the entire study area (within the Vrbas, Vrbanja, and Crkvena valleys; Figure 2). Hilly terrain encompasses the slightly rippled sides of peripheral parts of the Banja Luka depression. The northern and northwestern slopes have inclinations between 5 and 15° and only sporadically are there slopes with an inclination over 20°. Slopes with dominant inclinations over 20° are located in the southwestern and southern parts of the study area and intermittently in the southeast parts (Figure 3).

According to the dominant denudation process, the slopes of the southwestern and southern parts of the Banja Luka depression and river valley sides are subject to linear erosion. In higher parts of the slopes there are ravines, and torrents are frequent in the middle and lower parts. The northwestern parts of the study area, which are composed of Neogene sediments, do not experience extensive linear erosion processes, but frequently have landslides.

The climate has the characteristics of a moderate continental climate with an average annual temperature above 10 °C and annual rainfall of 1,050 mm (Tošić et al. 2013). In the study area there are two large rivers: the Vrbas and Vrbanja. The dominant soils are planosol (pseudogley), fluvisol, and gleysol (dystric, eutric, and mollic) (Burlica and Vukorep 1980).

3 Data and methodology

3.1 Data

The identification of influence factors for landslides is the basis of many methods of susceptibility assessment. These influence factors can be separated into three broad categories: topographic, geological, and environmental (Crozier and Glade 2005). In this study, ten influence factors were considered: lithology, land use, slope, aspect, relative relief, distance from faults, distance from streams, curvature (profile curvature), elevation, and seismic zone (Figure 3).

The data on elevation, slope, aspect, relative relief, and curvature (profile curvature) were derived from a digital elevation model (DEM) of the study area using the Surface Analyst tools in ArcGIS 10. Distance from streams was defined using the topographic database, the buffer was calculated at a value of 0 to 50 meters from a stream, and more than 50 meters from a stream. The lithology map was prepared from a 1 : 10,000 scale geological map (Vilovski 1970; Perić et al. 1971; Mojićević et al. 1976; Trkulja 1998).

Table 1: Spatial data layers used in the study.

Category	Layer	Data type
Digital elevation model (DEM; 5 meter resolution)	Elevation, slope, aspect, profile curvature, relative relief	Raster (grid)
Geological map; map of seismic micro-regionalization	Lithology, distance from faults, seismic zone	Vector (point and line)
Digital orthophoto Topographic database	Land use Distance from streams	Raster (grid) Vector (point and line)

The distances from faults were found using a geological map, the buffer was calculated at value of 0 to 50 meters from faults, and more than 50 meters from them (Vilovski 1970; Perić et al. 1971; Mojićević et al. 1976). The seismic map was prepared by using the map of seismic micro-regionalization of the Municipality Banja Luka (Trkulja 1998). Land use was determined according to CORINE Land Cover methodology (CORINE … 1994). Classification was generated from digital orthophotos of the Municipality of Banja Luka at a scale 1 : 1,000. After the data were collected, all vector data were converted to a raster grid with 5 × 5 meter cells (the resolution of the DEM used).

3.2 Methodology

There are two ways to approach landslide susceptibility zonation: qualitative and quantitative. Qualitative approaches (e.g., geomorphological mapping) were popular before the widespread use of information technologies. Quantitative approaches (statistical analysis, probabilistic approaches, fuzzy set–based approaches, and artificial neural networks) have become popular in recent decades thanks to the development of remote sensing and GIS (Aleotti and Chowdhury 1999; Guzzetti et al. 1999; Clerici et al. 2002; Santacana et al. 2003; Zorn and Komac 2004). GIS-based statistical approaches have become very popular in landslide susceptibility zonation due to their multiple advantages, such as effective data management, simultaneous use of several types of layers, graphic and attribute crossing of these layers, and providing accurate output data. In this study, the analysis of landslide susceptibility is based on quantitative methods, i.e. the application of an empirical method and two statistical methods.

The first step in our analysis was to create a landslide inventory map of active landslides in the study area. The landslide inventory map was completed using orthophoto images, topographic maps (1 : 1,000, 1 : 2,500, 1 : 5,000, and 1 : 10,000), and a terrain survey.

As mentioned, three methods were applied for landslide susceptibility zonation: the **Index-Based Method** (IBM), the **Statistical Index Method** (SIM), and **Landslide Susceptibility Analysis** (LSA).

The IBM uses a simple ranking and rating technique for landslide susceptibility zonation. The first step in this method is to select influence factors of slope instability in the study area. Each influence factor is then considered as a parameter map. The relative importance of each parameter map for slope instability is evaluated according to subjective experts' knowledge. On the basis of comparisons of different parameters, weight values are assigned to each parameter map. Subsequently, each parameter map is classified into several significant classes based on their relative influence on mass movements, and rating values are assigned to each class depending on their influence on slope instability. The rating values are also fixed according to expert opinions and estimates (e.g., Anbalagan 1992; Turrini and Visintainer 1998; Barredo et al. 2000; Zorn and Komac 2004). Finally, integration of the various factors and classes into a single landslide susceptibility index (LSI) is achieved by a procedure based on the weighted linear sum (Voogd 1983):

$$LSI = \sum_{j=1}^{n} \left(W_j \cdot W_{ij} \right) \tag{1}$$

in which LSI is the landslide susceptibility index, W_j is the weight value of parameter *j*, w_{ij} is the rating value or weight value of class *i* in parameter *j*, and *n* is the number of parameters. All LSI values were than separated into four classes using a natural breaks algorithm to present four categories (low, moderate, high, and very high) of the landslide susceptibility zone (LSZ). Similar techniques can be found in many studies (e.g., Barredo et al. 2000; Saha et al. 2002; Foumelis et al. 2004; Zorn and Komac 2004; Wati et al. 2010; Dragićević et al. 2012).

The SIM is a bivariate statistical analysis introduced by van Westen (1997) for landslide susceptibility analyses. A weight value for a parameter class (e.g., a certain lithological unit or a certain slope class) is defined as the natural logarithm of the landslide density in the class divided by the landslide density in the entire map. This method is based on the following formula (van Westen 1997):

$$W_{ij} = In\left(\frac{f_{ij}}{f} \right) = In\left(\frac{A_{ij}^{*}}{A_{ij}} \cdot \frac{A}{A^{*}} \right) = In\left(\frac{A_{ij}^{*}}{A^{*}} \cdot \frac{A}{A_{ij}} \right) \tag{2}$$

in which W_{ij} is the weight given to a certain class *i* of parameter *j*, f_{ij} is the landslide density within class *i* of parameter *j*, *f* is the landslide density within the entire map, A_{ij}^{*} is the area of landslides in a certain class *i* of parameter *j*, A_{ij} is the area of a certain class *i* of parameter *j*, A^{*} is the total area of landslides in the entire map, and *A* is the total area of the entire map. The SIM is based on statistical correlation of the landslide inventory map with attributes of various parameter maps. The W_{ij} value in Equation 2 is only calculated for classes that have landslide occurrences. In the case of no landslide occurrences in a parameter class, W_{ij} is valued as zero (e.g., van Westen 1997; Cevik and Topal 2003; Oztekin and Topal 2005; Magliulo et al. 2008; Zorn and Komac 2008).

In the study, every parameter map was crossed with the landslide inventory map, and the density value of the landslide in each class is calculated. Then these were summed up by Equation 3 to obtain the resulting LSI for the study area:

$$LSI = \sum_{j=1}^{n} W_{ij} \tag{3}$$

in which LSI is the landslide susceptibility index, W_{ij} is the weight of class i in parameter j, and n is the number of parameters. The same procedure as in the previous method was used for reclassifying the LSI values into different susceptibility zones and for map validation.

LSA is a simple bivariate method of analysis that aims to determine the importance of different variables for landslide occurrence. To evaluate the influence of each variable, weighting factors are determined, which compare the calculated density with the overall landslide density in the area (Süzen and Doyuran 2004) as follows:

$$W_{ij} = 1000\left(f_{ij} - f\right) = 1000\left(\frac{A_{ij}^{*}}{A_{ij}} \cdot \frac{A^{*}}{A}\right) \tag{4}$$

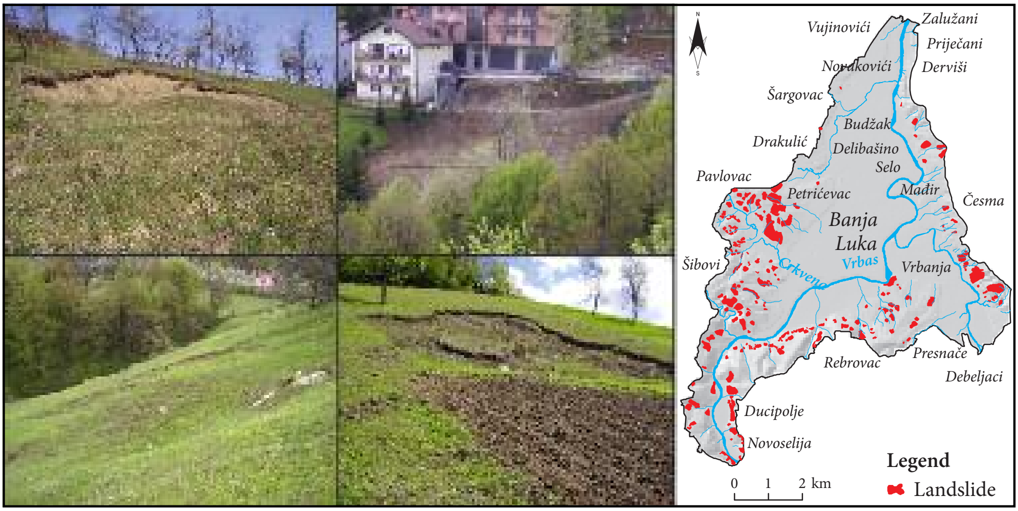
in which W_{ij} is the weight given to a certain class i of parameter j, f_{ij} is the landslide density within the class i of parameter j, f is the landslide density within the entire map, A_{ij}^{*} is the area of landslides in a certain class i of parameter j, A_{ij} is the area of a certain class i of parameter j, A^{*} is the total area of landslides in the entire map, and A is the total area of the entire map. In the next step, all weights are summed up as in Equation 3 in order to obtain a resulting LSI map for the study area. The same course of action as in the previous method is used for reclassifying the LSI values into different susceptibility zones and the map validation.

4 Results and discussions

Using the landslide inventory, we identified 216 landslides with a total area of 2.9 km^2 (5.2% of the municipality). Most landslides have depths between 1 and 10 meters. Their main characteristic is that landslides do not occur as isolated events, but rather as a group, mostly on the slopes of valleys and upper courses of streams. Terrain consisting of Neogene sediment has a high number of landslides. Landslides are also characteristic of flysch terrain (e.g., Zorn and Komac 2009); they mostly occur in regolith. This most often happens in the upper courses of streams and in lower slope areas where there are many slope deposits. Complex linear erosion features are most dominant on terrain consisting of diabase-hornstone rock, and landslides are related to regolith and slope material. Using analysis of the spatial distribution of landslides, it is possible to pinpoint several locations in the study area where landslides occur as a group, and also some locations where landslides occur as isolated events.

The area where landslides occur in groups is the settlement of Novoselija in the southwestern part of the study area. On the left side of the Vrbas Valley in that settlement, shallow landslides prevail on slope material. On the opposite side of the valley in this part of the settlement (the southeastern part of study area) a significant number of landslides have been recorded on flysch, slope material, and torrential sediments. The next area with a large number of landslides is in the eastern part of the study area, on slope material with 15 to 20° slopes. These landslides are up to 3 meters deep and sliding mass mostly rolls linearly. This means that the sliding plain is a unique, single surface between the rock mass and slope material. The third area that has a greater number of landslides is in the northeast part of the study area, where Neogene sands and clays are dominant. Rivers have cut their beds into these sediments and caused slope instability and landslides on the sides of the valley. Further north from this location, the slopes consist of diabase-hornstone series covered by slope material and clays. In this area there are also landslides mostly caused by cutting of slopes. Slopes in this location are unstable with a significant number of active landslides with depths ranging from 3 to 5 meters.

The fourth area is in the western part of the study area and is related to both sides of the Crkvena Valley. There are landslides on the left slopes related to terrace level and clay-like pebbles. These landslides



RADISLAV TOŠIĆ, MAY 2012

Figure 2: Some landslides in the study area (left, center) and the location of all landslides in the study area (right).

are deep (over 10 meters) because they expand not only into the slope material but also degrade Neogene sediments and clays. Hence, these are complex landslides, temporarily on hold, but their activity should not be questioned when bearing in mind numerous morphological indicators of landslide processes. Moreover, there are a significant number of smaller active landslides in the complex; the »body« of large landslides and these landslides are mostly related to the claylike slope material with pebbles reaching 5 meters in depth. Landslides located on the right side of the Crkvena Valley developed in Neogene sediments, consisting of slightly calcareous mudstones and sand covered by a thin layer of slope material up to 5 meters thick.

The fifth area, in the northwestern part of the study area, contains a smaller number of mostly isolated landslides. These landslides are related to slope material that is layered over Neogene sediments. The depth of these landslides is up to 10 meters. Currently active landslides on this location develop in gravel and other slope material (Figure 2).

After mapping landslides and creating a GIS database, maps of influence factors were developed. The selected landslide influence factors for the study area were carefully considered based on relevance, availability, and scale attributes. Consequently, we considered ten influence factors (Figure 3; Table 2): lithology, land cover / land use, slope, aspect, relative relief, distance from faults or line (lineaments), distance from streams, curvature (profile curvature), elevation, and seismic zones. Several studies considered elevation as an indirect factor related to other factors such as rainfall, temperature, soil development, and so on. In the study area, the elevation varies between 137 and 432 meters above sea level. This factor is not as favorable for instability as in mountainous areas, which often experience larger volumes of precipitation, both in rain and snow. The relation between aspect and landslide has been investigated for a long time, but no general agreement exists on aspect (e.g., Carara et al. 1991; Nagarajan et al. 1998). There is also no consensus about the influence of distances from structural elements (faults) on the occurrence of landslides. As a result, different distances are used with respect to structural elements (e.g., Anbalagan 1992; Luzi and Pergalani 1999). Table 2 shows the weights for each influence factor for all three methods.

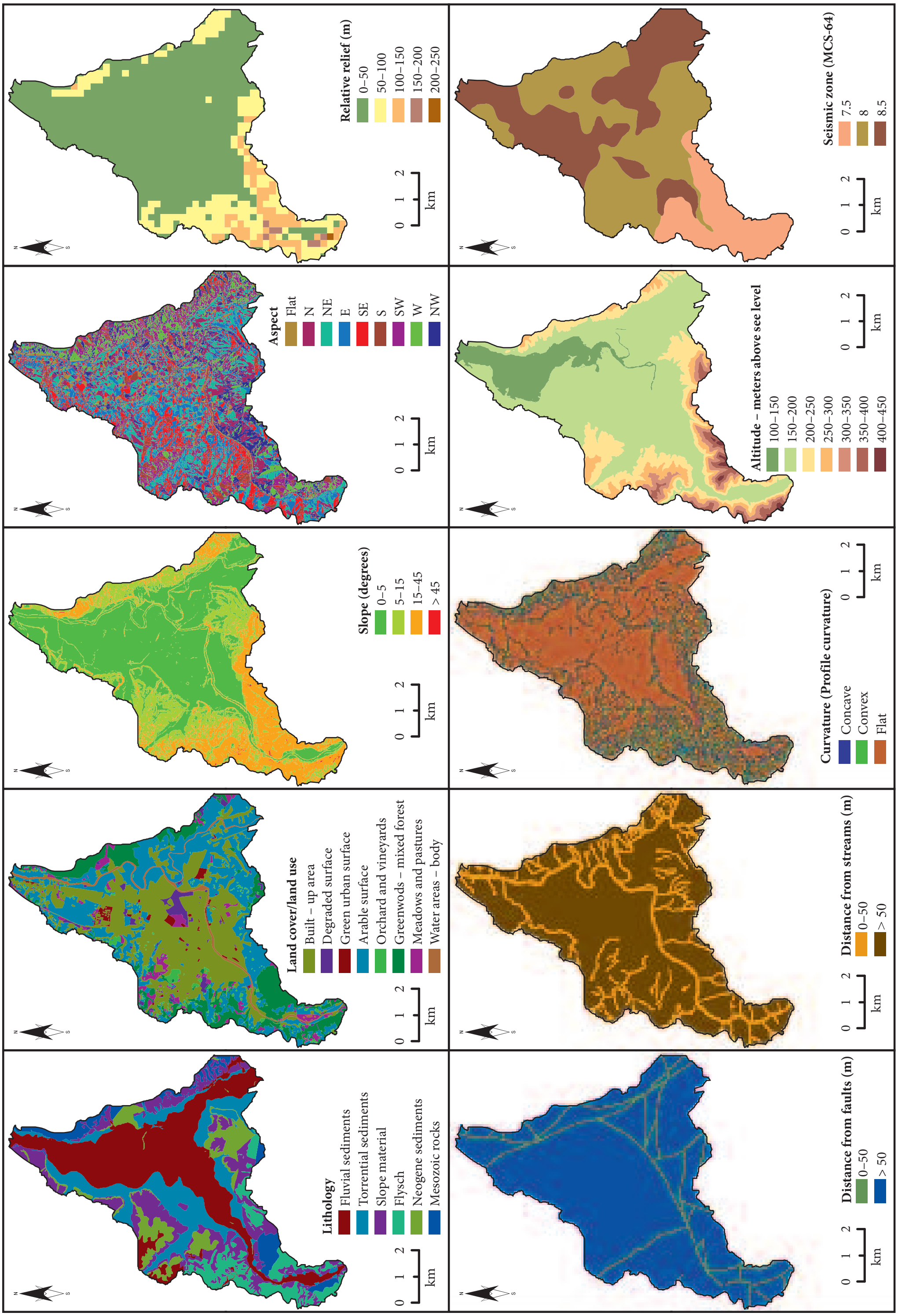
All three methods used are based on the calculation of weighting values for each selected influence factor's class. If the total weight is positive, the factor is considered to be favorable for the occurrence of landslides, and if it is negative the factor is not favorable for instability.

According to lithology, the highest W_{ij} were obtained for slope material and Neogene sediments. According to land use, positive W_{ij} were obtained for meadows, pastures, orchard, and vineyards. Positive W_{ij} were obtained for most slope angle classes, except for the classes 0–5° and > 45°. Among the relative relief classes, the highest W_{ij} were obtained for the classes 50–100 and 100–150 m. Significantly lower total weights were obtained for certain classes of other influence factors as a result of the small number of occurrences

Table 2: Influence factors and their total weights for methods used.

Factor	Class	Method		
		IBM (weight)	SIM (weight)	LSA (weight)
Lithology	Fluvial sediments	8	–2.0931	–45.8778
	Torrential sediments	16	–2.9685	–49.6415
	Slope material	48	0.8982	76.1437
	Flysch	32	0.1634	9.2904
	Neogene sediments (sands, clays and marl)	48	1.0309	94.3779
	Mesozoic rocks (limestone, dolomite and diabase-hornstone rock)	8	0.0180	0.9520
Land cover / land use	Built-up area	18	–2.2699	–46.9237
	Degraded surface	18	–0.5753	–22.8933
	Green urban surface	18	0.0000	–52.3303
	Arable surface	18	0.2961	18.0339
	Orchard and vineyards	54	1.4348	167.3904
	Deciduous-coniferous, mixed forest	9	0.3088	18.9361
	Meadows and pastures	27	1.4394	168.3982
	Water areas	0	0.0000	–52.3303
Slope (°)	0–5	10	–2.5878	–48.3959
	5–15	40	0.6827	51.2448
	15–45	30	0.7990	64.0188
	>45	20	–0.7458	–27.5076
Aspect	Flat	3	0.0000	–52.1821
	N	3	–0.2967	–13.4332
	NE	6	–0.3552	–15.6449
	E	3	–0.4195	–17.9294
	SE	9	0.0916	5.0174
	S	9	0.6529	48.2031
	SW	9	0.5071	34.5626
	W	9	0.2545	15.1636
	NW	3	–0.0034	–0.1750
Relative relief (m)	0–50	16	–0.6465	–24.9169
	50–100	20	0.8462	69.6348
	100–150	12	0.8647	71.9157
	150–200	8	0.0000	–36.5691
	200–250	4	0.0000	–52.3303
Distance from faults (m)	0–50	3	0.1014	5.5834
	>50	6	–0.0122	–0.6341
Distance from streams (m)	0–50	3	0.1116	6.1782
	>50	6	–0.0333	–1.7136
Curvature (profile curvature)	Convex	8	0.4078	26.3475
	Concave	12	0.4725	31.6107
	Flat	4	–0.0931	–4.6532
Elevation: meters (m)	100–150	2	0.0000	–52.3303
	150–200	2	–0.8977	–31.0047
	200–250	6	1.1264	109.0864
	250–300	4	1.0017	90.1619
	300–350	4	0.3205	19.7734
	350–400	2	0.0000	–29.4239
	400–450	2	0.0000	–52.3303
Seismic zone (MCS–64)	7.5	6	0.6989	52.9379
	8	9	0.1199	6.6685
	8.5	3	–0.9694	–32.4804

Figure 3: Thematic maps of influence factors used for creating landslide susceptibility maps. ➤


Lithology
Fluvial sediments
Torrential sediments
Slope material
Flysch
Neogene sediments
Mesozoic rocks
Land cover/land use
Built – up area
Degraded surface
Green urban surface
Arable surface
Orchard and vineyards
Greenwods – mixed forest
Meadows and pastures
Water areas – body
Slope (degrees)
0–5
5–15
15–45
> 45
Aspect
Flat
N
NE
E
SE
S
SW
W
NW
Relative relief (m)
0–50
50–100
100–150
150–200
200–250
Distance from faults (m)
0–50
> 50
Distance from streams (m)
0–50
> 50
Curvature (Profile curvature)
Concave
Convex
Flat
Altitude – meters above see level
100–150
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7.5
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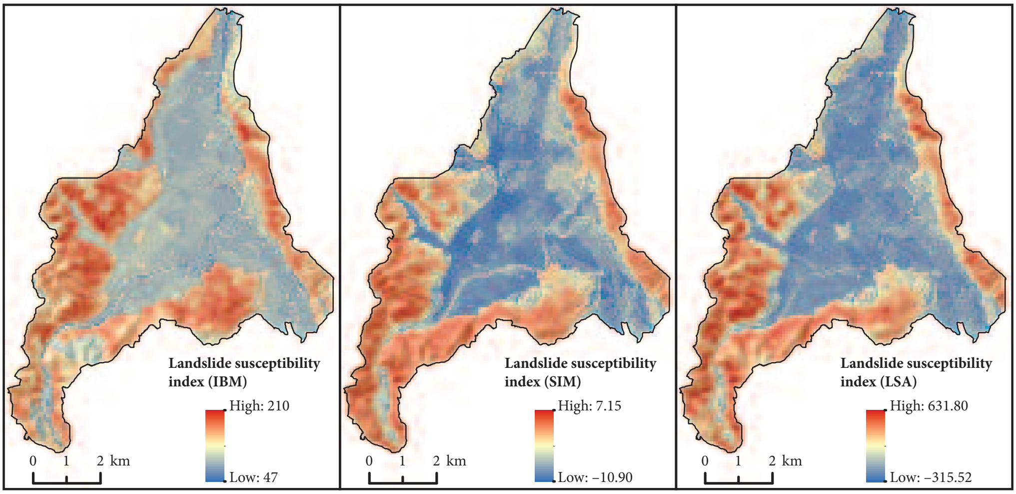

Figure 4: Landslide susceptibility index maps of the study area obtained with Index-Based Method (IBM), Statistical Index Method (SIM), and Landslide Susceptibility Analysis (LSA).

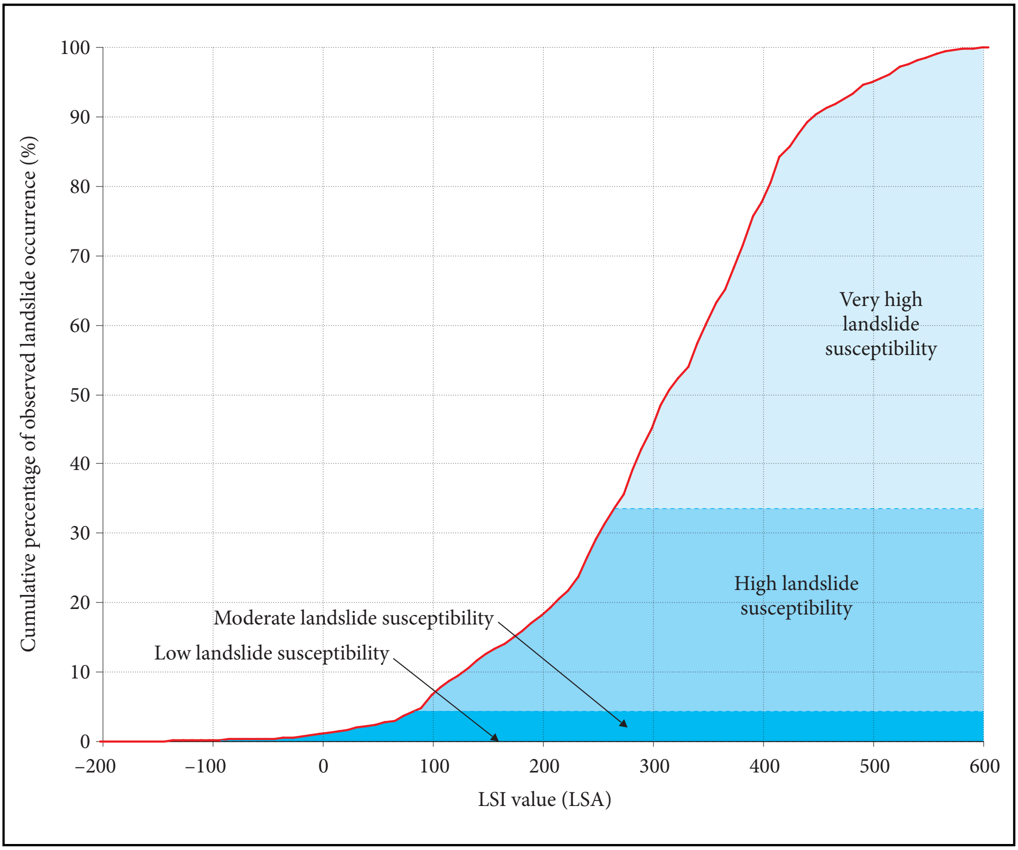

Figure 5: Cumulative percentage of observed landslides versus ranked LSI values resulting from the Index-Based Method (IBM), the Statistical Index Method (SIM), and Landslide Susceptibility Analysis (LSA).

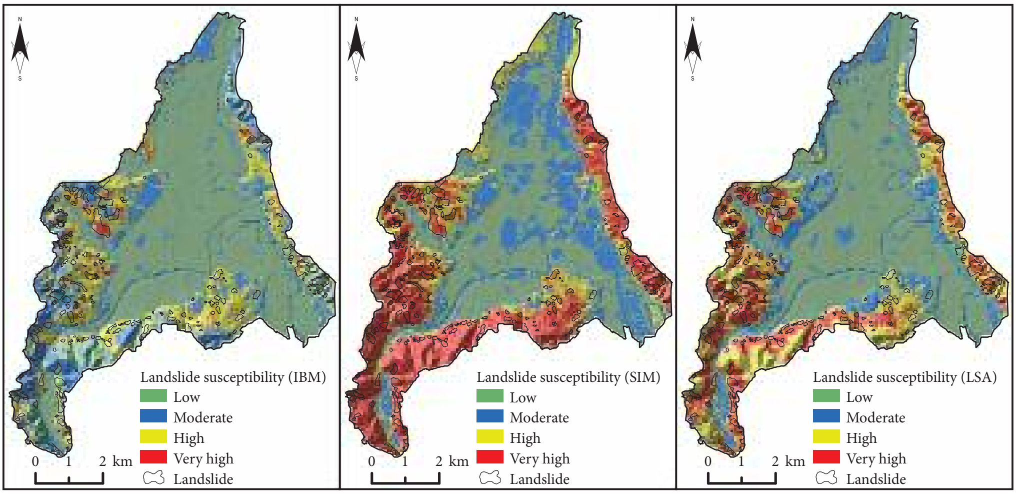

Figure 6: Landslide susceptibility zonation maps based on the Index-Based Method (IBM), Statistical Index Method (SIM), and Landslide Susceptibility Analysis (LSA).

of landslides in these classes. According to the relative importance (expressed in total weight), the main instability factors are lithology, land cover / land use, slope, and relative relief.

After calculating the weights for all influence factors, the weights were applied to create the landslide susceptibility index maps (LSI) for every method used (Figure 4). The integration of various influence factors and classes in a single LSI is accomplished using a procedure based on the weighted linear sum, Equation 3.

The LSI maps were compared to the landslide inventory map and the cumulative percentage of observed landslide values versus ranked LSI values were calculated (Figure 5). Three cut-off (»threshold«) percentages of observed landslides in the cumulative curve were used to identify the LSI scale value and four landslide susceptibility classes: low, moderate, high, and very high (Figure 6).

The final 1 : 10,000 susceptibility map is a raster grid with 5 × 5 meter cells. According to the methods used, the high and very high susceptibility classes range (together) from 25.06 to 48.07% of the study area. Areas with these classes are distributed in the peripheral part of the study area. Low and moderate susceptibility classes range from 51.93 to 74.94% (Table 3).

Table 3: Comparison of different landslide susceptibility zonation methods.

INDEX-BASED METHOD (IBM)

LSI-classes	LSI scale value	Area (km^2)	Area (%)
Low susceptibility	47 to 101	28.08	50.37
Moderate susceptibility	101 to 135	13.69	24.57
High susceptibility	135 to 165	12.27	22.01
Very high susceptibility	165 to 210	1.70	3.05

STATISTICAL INDEX METHOD (SIM)

LSI-classes	LSI scale value	Area (km^2)	Area (%)
Low susceptibility	–10.90 to –7.78	15.32	27.48
Moderate susceptibility	–7.78 to –3.96	13.63	24.45
High susceptibility	–3.96 to 0.71	9.81	17.61
Very high susceptibility	0.71 to 7.15	16.98	30.46

LANDSLIDE SUSCEPTIBILITY ANALYSIS (LSA)

LSI-classes	LSI scale value	Area (km^2)	Area (%)
Low susceptibility	–315.52 to –114.91	24.92	44.71
Moderate susceptibility	–114.91 to 81.98	9.75	17.50
High susceptibility	81.98 to 264.02	11.96	21.46
Very high susceptibility	264.02 to 631.80	9.10	16.33

Table 4: Summary of the prediction accuracy of the final landslide susceptibility zonation maps.

Method	Number of landslides observed				Area of landslides observed			
	Good		Bad		Good		Bad	
	Number	%	Number	%	km^2	%	km^2	%
IBM	173	80.09	43	19.91	2.1785	74.67	0.7392	25.33
SIM	216	100.00	0	0.00	2.9041	99.53	0.0136	0.47
LSA	207	95.83	9	4.17	2.7893	95.60	0.1284	4.40

Susceptibility maps can be validated through comparison with the data obtained from a terrain survey. The quality of the landslide susceptibility method can be ascertained using the same landslide data used for the estimate, or by using independent landslide information that was not used for the assessment (e.g., Irigaray 1999; Remondo et al. 2003; Guzzeti et al. 2006; Zorn and Komac 2007). In order to select the final map of landslide susceptibility zonation, a cross validation technique was used to compare known landslide location data with the landslide susceptibility zonation map. In the study, we considered landslide prediction to be »good« if at least part of the landslide is in a »high« or »very high« susceptibility zone, and landslide prediction to be »bad« if at least part of the landslide is in a »low« or »moderate« susceptibility zone. Using SIM, all of the 216 landslides observed had good prediction, whereas using LSA 209 of the 216 landslides observed had good prediction, and only nine had bad prediction (Table 4).

Furthermore, using the IBM method 74.67% area of the landslides observed belong to the »high« and »very high« susceptibility class, whereas using the SIM and LSA methods 99.53% and 95.60% area of the landslides observed belong to the »high« and »very high« susceptibility class (Table 4).

The validation of our susceptibility assessment suggests that the application of a relatively simple methodology like IBM yields results that are quite different from those based on statistical methods. Although the input data were the same, it was shown that the use of IBM yields less reliable results, which is basically related to the subjectivity of the analysis, especially in defining weight coefficients for individual influence factors (e.g., van Westen et al. 1999; Fernández et al. 1999; Remondo et al. 2003; Guzzetti et al. 2006; Zorn and Komac 2008). The validation of the two statistical methods showed that they provide more accurate results. However, it should not be forgotten that the validation was carried out with the same set of landslide data that were used for the calculation and that the best way to check the accuracy of our final landslide susceptibility zonation maps would be using independent landslide data.

5 Conclusion

In the Municipality of Banja Luka, instable areas have significantly increased due to urbanization in landslide-prone areas. The study identified 216 landslides with a total area of 2.92 km^2 (5.2% of the municipality). In the study, three methods for landslide susceptibility zonation (IBM, SIM, and LSA) were applied to study the interrelations among the landslides observed and landslide influence factors.

Crucial factors for landslide susceptibility in the study area are lithology, land cover / land use, slope, and relative relief. According to lithology, two units are the most important: slope and Neogene sediments. The most important topographic factor is slope angle, especially from 5 to 15°. Land use has a significant impact on instability, especially in orchards, vineyards, meadows, and pastures, as a result of direct or indirect human activity. Other factors are of less importance, as indicated by the value of the total weight of these factors, or the weight of individual classes within the influence factors.

The results obtained show that statistical methods are important for creating landslide susceptibility maps and that an empirical method (IBM) can provide less accurate results, but can be useful when available data are limited (as in Bosnia and Herzegovina).

These study results can be used for better urban planning and landslide assessment purposes in Bosnia and Herzegovina, although they can be less useful at the site-specific scale (or microscale), where a geo-technical approach has some preference.

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