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ORIGINAL PAPER

# Landslide hazard and risk assessment: a case study from the Hlohovec–Sered' landslide area in south-west Slovakia

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**Abstract** Landslide hazard or susceptibility assessment is based on the selection of relevant factors which play a role on the slope instability, and it is assumed that landslides will occur at similar conditions to those in the past. The selected statistical method compares parametric maps with the landslide inventory map, and results are then extrapolated to the entire evaluated territory with a final product of landslide hazard or susceptibility map. Elements at risk are defined and analyzed in relation with landslide hazard, and their vulnerability is thus established. The landslide risk map presents risk scenarios and expected financial losses caused by landslides, and it utilizes prognoses and analyses arising from the landslide hazard map. However, especially the risk scenarios for future in a selected area have a significant importance, the literature generally consists of the landslide susceptibility assessment and papers which attempt to assess and construct the map of the landslide risk are not prevail. In the paper presented herein, landslide hazard and risk assessment using bivariate statistical analysis was applied in the landslide area between Hlohovec and Sered' cities in the south-western Slovakia, and methodology for the risk assessment was explained in detail.

**Keywords** Landslide · Susceptibility · Hazard · Vulnerability · Risk · Slovakia

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## 1 Introduction

Landslide hazard problems can be solved by use of statistical methods in GIS (Geographical Information Systems) environment. A huge number of articles related to the landslide hazard and susceptibility assessment using the various statistical methods have been published, predominantly in last two decades (Aleotti and Chowdhury 1999; Bednarik et al. 2005, 2010; Bednarik and Pauditš 2010; Constantin et al. 2010; Cevik and Topal 2003; Clerici 2002; Dai et al. 2001, 2002; Donati and Turrini 2002; Fell 1994; Finlay 1996; Irigaray and Chacón 1996; Lee and Touch 2006; Nandi and Shakoor 2009; Pauditš and Bednarik 2002a, b; Süzen and Doyuran 2004; Van Westen 1993; Yilmaz 2009a, b; Yilmaz and Keskin 2009; Yilmaz 2010a, b; Akcapinar Sezer et al. 2011, etc.). However, landslide risk, in it strictest sense, is not a frequent topic in recent landslide literature. The main reason for this peculiarity is that there is still no common methodology for landslide risk assessment in medium to large scale (1: 10,000 and larger) in particular. Risk assessment has predominantly been limited with urbanized areas in connection with their socioeconomic development. Complex landslide risk assessment in an appropriate scale has a practical meaning not only for land use planning but also for municipalities, various state institutions, and insurance companies.

In this study, landslide hazard and risk assessment using bivariate statistical analysis was applied in the landslide area between Hlohovec and Sered' cities in south-western Slovakia (Fig. 1). Landslide risk assessment procedure in this article consists of two main phases such as; *landslide hazard or susceptibility assessment* and *vulnerability and risk assessment*. Landslide hazard or susceptibility assessment was based on the selection of relevant landslide contributing factors which play a role on the slope instability. In general, to predict landslides, it is necessary to assume that landslide occurrence is determined by landslide-related factors and that future landslides will occur under the same conditions as past landslides. Selected factors such as the influenced genesis and development of slope movements were processed in the form of parametric maps and statistically assessed using map algebra implemented in the GIS environment. Positional accuracy and superposition were required for all parametric maps, and here, the heterogeneity of various data sources was a serious problem.

Parametric maps were compared with the landslide inventory map by the selected statistical method, and results were then extrapolated to the entire study area as a final product of landslide hazard or susceptibility map. Statistical methods were based on an exact comparison of the spatial distribution of registered landslides, usually presented as the dichotomic variable of presence or absence, with the spatial distribution of individual parameters representing independent input variable factors.

In the second stage, elements at risk were defined and analyzed in relation with landslide hazard, and their vulnerability was thus established. Only material vulnerability such as direct costs established by the landslide hazard map was evaluated herein. However, indirect economic losses such as temporary interruptions to main roads and severed energy and water supplies affecting economical outcomes in regions affected by mass movements were not evaluated in this case study. Risk scenarios and expected financial losses caused by mass movements were presented by the landslide risk map which utilizes prognoses and analyses arising from the landslide hazard map.

**Fig. 1** The study area between towns Hlohovec (on the north) and Sered' (on the south)

## 2 Input parameters

Eight landslide contributing factors (lithology, elevation, slope angle, slope aspect, curvatures of the relief, slope length, contributing areas, actual land use) directly or indirectly related to the causes of landslide occurrence as inputs (Fig. 2) within the study area were

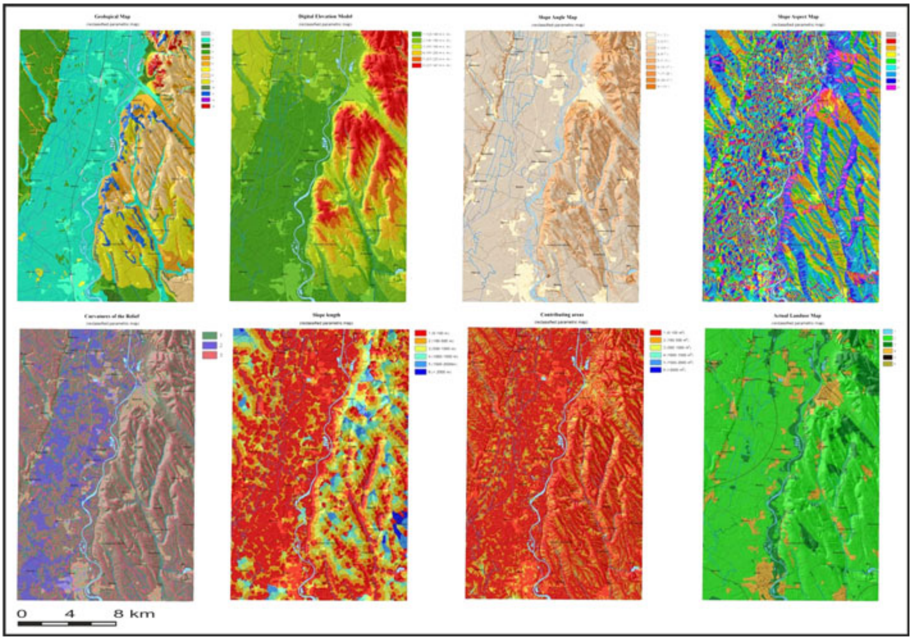


**Fig. 2** Input parametric maps

considered. Each factor was obtained as a parametric map in bivariate statistical analysis. These rated parameters reflect the geological, climatic and hydrological conditions in the area and the relief and morphometric characteristics of the current use of the landscape. Detailed explanation of the processing of input parameters in the form of parametric maps can be found in the paper published by Bednarik (2007).

## 2.1 Geological framework

Geological structure of the study area is one of the most important factor influencing the formation and evolution of slope deformations. Parametric map of lithological units is of the utmost importance in determining weights for each parametric map, and the physico—mechanical properties resulting from the lithological composition of the rock environment are important factors affecting slope stability.

1:50,000 scaled digital geological map containing the geological structure of the Hlohovec–Sered’ study area (Kácer et al. 2005) was used in the study. This map, in vector form and S-JTSK coordinate system, was modified and aligned in 1: 10,000 topographic scale. The original geological map contains 47 lithological units with the original identification number (ID) as assigned in the original map series. The modified geological map in vector form was then converted to raster format with a resolution of 1,687 rows and 2,404 columns having the cells size of 10 × 10 m.

Either bivariate or multivariate statistical processing of landslide hazards is usually necessary to reduce the original number of lithological units into fewer classes. This process is known as primary re-classification, and it simplifies the original map while preserving important information on landslide hazards. The physical and mechanical properties of rocks were the main criteria in most cases in the primary re-classification of the geological maps. The optimal number of lithological units following primary re-classification is from 8 to 15 classes. These intervals of the classes are typical for most works associated with statistical processing and assessment of landslide hazard in the GIS environment.

The original 47 lithological units were re-classified into 13 classes according to the similarities of the physico—mechanical properties of the rock environment. Re-classified lithological units are presented in Table 1, and re-classified parametric map of lithological units in the Hlohovec–Sered' study area is shown in Figure 2.

As can be seen in Table 1, Holocene fluvial sediments, where the landslide accumulation is frequently placed, outcrop in the largest area more than 46 % of the whole study area. The Pleistocene terraces (class 4) and the aeolian sediments consisting mostly of loess and loess loam (class 8 and 9) are distributed in an area larger than 10 % of the territory.

## 2.2 Morphological parameters of the relief

The shape of the relief is mostly affected by current activity of endogenous processes, exogenous geodynamic processes, and human activities. It is therefore necessary to prepare a realistic model of the relief in the GIS environment and to understand its morphometric characteristics which represent the geometric properties of terrains and influence processes in the country, including geodynamic phenomena (Hofierka 2003). Krcho (1990, 1999) defines relief as a continuous scalar field of altitudes which can be analyzed by differential geometry.

Here, the morphometric parameters such as hypsographic degrees denoting altitude levels, slope angle, slope aspect, curvature of relief, slope length, and contributing areas were assessed and analyzed. Evaluated morphometric parameters are secondarily derived from the digital elevation model (DEM) which reflects a set of numbers contained in computer memory signifying the spatial distribution of altitudes values, usually in the form of a two-dimensional matrix. Each number in the file represents a certain area (pixel) in the form of discrete presentations of relief. Thus, the prepared DEM is sufficiently coherent and appropriate to derive the above-mentioned morphometric parameters of the relief using raster GIS analytical tools (Hofierka 2003).

Input data source for the compilation and calculation of the DEM comprised contour lines from 1:10,000 scaled topographic maps distributed by the Geodetic and Cartographic Institute in Bratislava. For the study area of Hlohovec-Sered', this consisted of 18 raster images in *tiff* format, which were then geo-referenced to the S-JTSK coordinate system.

The calculated model can be re-classified into integer values—hypsographic degrees (Fig. 2). Aerial and percentual distributions of the categories were given in Table 1. More than 76 % of the whole study area is at altitudes ranging from 120 to 180 m a.s.l., and the difference between the lowest and highest altitude is only 221 meters.

### *2.2.1 Slope angle*

It can be generally assumed that slope angle is the most important morphological parameter. In digital form, the slope angle grid or raster presents a matrix of values of the scalar field of altitudes derived from the digital elevation model (Hofierka 2003). The angle of the slopes is presented in degrees ranging from 0 to 90° or as percentage. Together with

**Table 1** Re-classified factors and their spatial distributions

| | Category | Description | Area (km$^2$) | Area (%) |
|---|---|---|---|---|
| DEM (m n. m.) | 1 | 120–140 | 127.6 | 37.79 |
| | 2 | 140–160 | 82.6 | 24.47 |
| | 3 | 160–180 | 47.8 | 14.15 |
| | 4 | 180–200 | 26.8 | 7.94 |
| | 5 | 200–220 | 20 | 5.92 |
| | 6 | 220–341 | 32.8 | 9.72 |
| Lithological units | 1 | Anthropogenic sediments | 1.7 | 0.5 |
| | 2 | Holocene fluvial sediments | 155.4 | 46.02 |
| | 3 | Holocene proluvial sediments | 3.3 | 0.98 |
| | 4 | Pleistocene terraces | 41.9 | 12.41 |
| | 5 | Slope sediments | 18.2 | 5.38 |
| | 6 | Wash down sediments | 21 | 6.23 |
| | 7 | Eolian sediments—fine-grained sands | 1.1 | 0.32 |
| | 8 | Eolian sediments—loess | 43.6 | 12.92 |
| | 9 | Eolian sediments—loess loam | 35 | 10.35 |
| | 10 | Neogene sediments—predominantly gravels | 4.3 | 1.27 |
| | 11 | Neogene sediments—predominantly clays | 9.1 | 2.7 |
| | 12 | Neogene sediments—predominantly sandstones and conglomerates | 0.1 | 0.04 |
| | 13 | Mezozoic—Paleozoic subsoil | 3 | 0.88 |
| Slope angle (°) | 1 | $< 2$ | 214.5 | 63.52 |
| | 2 | 2–3 | 28.4 | 8.42 |
| | 3 | 3–5 | 35.3 | 10.44 |
| | 4 | 5–7 | 24.4 | 7.21 |
| | 5 | 7–11 | 23.9 | 7.1 |
| | 6 | 11–17 | 9 | 2.67 |
| | 7 | 17–20 | 1.1 | 0.34 |
| | 8 | 20–31 | 0.9 | 0.27 |
| | 9 | $> 31$ | 0.1 | 0.03 |
| Slope aspect | 1 | (−1) | 0.01 | 0.01 |
| | 2 | (0–22.5) (337.5–360) | 21.1 | 6.26 |
| | 3 | (22.5–67.5) | 41.9 | 12.39 |
| | 4 | (67.5–112.5) | 50.7 | 15.03 |
| | 5 | (112.5–157.5) | 40.1 | 11.87 |
| | 6 | (157.5–202.5) | 40.9 | 12.11 |
| | 7 | (202.5–247.5) | 66.5 | 19.69 |
| | 8 | (247.5–292.5) | 49.7 | 14.7 |
| | 9 | (292.5–337.5) | 26.8 | 7.94 |
| Curvature | 1 | Concave | 134.8 | 39.91 |
| | 2 | Linear | 62.6 | 18.53 |
| | 3 | Convex | 140.3 | 41.56 |

**Table 1** continued

| | Category | Description | Area (km$^2$) | Area (%) |
|---|---|---|---|---|
| Actual land use | 1 | River network | 47.1 | 1.4 |
| | 2 | Arable land | 261.5 | 77.44 |
| | 3 | Forests | 38.1 | 11.29 |
| | 4 | Settlement | 27.9 | 8.26 |
| | 5 | Road network | 4.7 | 1.39 |
| | 6 | Railway network | 0.8 | 0.23 |

other parameters, the slope angle significantly affects slope stability conditions. In this study, the slopes are divided into 9 categories (Table 1).

The total area of the re-classified categories of slope angle and their percentages can be seen from Table 1, and the re-classified parametric slope map for bivariate analysis is shown in Fig. 2. More than 60 % of the study area forms flat and very flat areas (class 1), while areas in classes 3, 4, 5, and 6 are occupying the larger area than 27 % of the study area where landslides are frequently observed.

### 2.2.2 *Slope aspect*

The parametric map of slope aspect presents a continuous data field which indicates the values from a certain angle of the cardinal points in a clockwise direction are recorded in degrees (Fig. 2). The slope aspect map is re-classified into 9 categories, where category 1 represents the planes without relationship to the cardinal points (Table 1). Table 1 shows that the study area is dominated by hills oriented in southern directions such as south-west (class 7), south (class 6), and south-east (class 5) covers more than 43 % of the total study area.

### 2.2.3 *Curvature of the relief*

Curvature of the relief represents the dynamics of surface water flow (deceleration, acceleration, convergence, and divergence) and is used in the assessment of the vulnerability of areas for various types of surface water and gully erosion (Mitášová et al. 1980). This parameter is rarely used in landslide susceptibility assessment (Irigaray and Chacón 1996; Pauditš 2005; Lee and Touch 2006). The curvature of relief for the model area Hlohovec–Sered' was also generated from the DEM. The resulting curvatures were re-classified into three categories such as convex (positive values), concave (negative values), and linear (inflection field values close to 0). The line connecting the inflection points has a curvature value of 0, and it indicates the isolines of zero curvature relief and the separate convex and concave forms essential for landslide susceptibility assessment (Pauditš 2005). The intervals; $<-0.00025$ (concave forms), from $-0.00025$ to 0.00025 (linear forms), $>0.00025$ (convex form) were used in the re-classification. Table 1 illustrates the aerial distributions of various forms of curvatures and the re-classified parametric map of curvature of the relief is shown in Fig. 2. The convex and concave relief forms are spread rather evenly in this model area, with a slight predominance of convex forms.

### 2.2.4 *Slope length and contributing areas*

Slope length (m) is expressed in the form of a continuous grid, in which each grid cell indicates the total length of the catchment (gradient) line from the highest point on the slope. The catchment curve also indicates the shortest trajectory of potential water flow direction down the slope, which is usually perpendicular to the contour course. Density gradient curves are usually expressed in terms of their direction, and when expressing upstream waters they indicate the so-called fall line grid density of contributing areas in m$^2$. Contributing areas reflect the total area of the micro-catchment from which water flows down the slope to the relevant point (Paudītš 2005).

The flow direction must be calculated from a hydrologically accurate digital elevation model to derive the above parameters. In this study, flow direction was calculated in the ArcGIS (2009) environment using the "flow direction" module. Slope lengths were generated from the parameter "flow down", and contributing areas can be obtained using the parameter "flow up". The resulting grids were then re-classified into 6 classes (Fig. 2).

Slope lengths up to 1 km totally dominate with more than 89 % and interval slopes up to 100 m form approximately a half of all slopes in the study area. Contributing areas up to 500 m$^2$ (categories 1 and 2) are dominant in the study area.

## 2.3 Actual land use

The current landscape structure reflects the current land use, including vegetation cover. This parameter is very dynamic, subject to relatively rapid changes over time, and therefore, it is necessary to use the latest data during in modeling. The most reliable sources are current aerial and satellite images delivering an orthophoto of the study area. The primary factors involved in dynamic changes in current land use are human intervention in agricultural, industrial and other activities, climate change and geodynamic phenomena. Vegetation cover particularly affects slope stability in the areas of retention of rainfall, having differential evaporation, distribution and depth range of the root system, soil resistance to erosion (Paudītš 2005).

The Hlohovec–Sered' model area is mainly used for agricultural activities due to its favorable climate and geomorphological conditions. Slope movements are started to be activated by the removal of vegetation and deforestation of slopes in adjacent parts of this territory. The following areas and percentage extensions of existing landscape structural elements are located here and depicted in Table 1: The River Network (class 1), arable land (class 2), forests (class 3), settlements (class 4), road networks (class 5), rail Networks (class 6). The spatial extents of arable land area cover more than 77 % of the total area, forests comprise more than 11 % and populated areas occupy approximately 28 km$^2$, accounting for about 8 % of the total land use.

## 2.4 Landslide inventory

The landslide inventory map is a dependent binary variable, and all input parametric maps are compared with the inventory in bivariate statistical analysis. The landslide binary grid or raster contains only the values 0 and 1 indicating false for landslide absence and true for landslide presence, respectively.

Engineering geological maps at different scales and register of slope deformations stored in the Slovak Geological Survey (Geofond) provide the most common source of information on landslide distribution in Slovakia. Modern methods of determination of the spatial distribution of landslides are based on remote sensing (including a stereographic interpretation of satellite and aerial images), laser scanning technology, the earth's surface (LIDAR), and photogrammetry. Results of these interpretations must be verified in the field especially in masked forms of landslide phenomena. Only spatial forecast of landslide events in Slovakia is possible in most cases because of the lack of archival records of recent landslide activation and landslide fossil dating.

Interpretation of landslides in the parametric map can vary depending on which of two perspectives are assessed for particular purposes: areas susceptible to landslides or landslide hazard assessment in individual studied areas (Bednarik and Pauditš 2010).

Otepka et al. (1983) provided the basis for compilation of landslide parametric maps for this Hlohovec–Sered' area, and these maps were processed in a detailed scale of 1: 5,000. "Paper" maps had to be scanned and geo-referenced to the S-JTSK coordinate system. After the vectorization of landslides in the ArcGIS environment, they were converted to raster form. Registered landslides in the study area cover an area approximately 6 km$^2$ (5,980,062 m$^2$). The resulting landslide inventory map (Fig. 3) was used in the bivariate statistical analysis.

## 3 Determination of the weight of each parameter

The weight of each input variable indicates its informational value in the landslide hazard analysis. The relevance of the parameter increases with the increment of the weight of the parameter. The weight of each input variable determines the degree of correlation between the values in the parametric map data and the constant value of 1, which stands for "True" and indicates the occurrence of landslides. When the degree of correlation values in the parametric map of the landslide occurrence is high, it can be concluded that the parameter has a significant impact on the creation and distribution of landslides in the study area (Pauditš 2005).

There are different approaches in determination of the weights of input parameters. Essentially, they can be divided into two major groups; first is a subjective approach based on expertly assigned weights to each parameter, and second is based on mathematical approach. This allows the determination of the scale parameter as a whole (Vlčko et al. 1980) or individual weight classes in the parametric maps (Van Westen 1993; Süzen and Doyuran 2004).

In this study, mathematical approach was used in determination of the weights of the parameter as suggested by Vlčko et al. (1980). This approach is based on the definition of entropy rate, which gives a measurement closer to the normal probability distribution ($p_{ij}$). Entropy is a measure of disorder and the degree of chaos, so that it expresses which components in the natural environment are most vulnerable in causing slope movements. The entire process of determination of weights is described by Bednarik et al. (2010) and Constantin et al. (2010), in detail.

Thus, the calculated weights of each parametric map present the value $W_i$ in the final equation for the sum for bivariate statistical analysis (Eq. 1). The principle of bivariate analysis with weight parameters is demonstrated in Fig. 4.

$$y = \sum_{i=1}^{n} C * W_i \tag{1}$$

where $y$ is value of landslide hazard in each pixel, $i$ is individual parametric maps, $C$ is class value, and $W_i$ is weight.

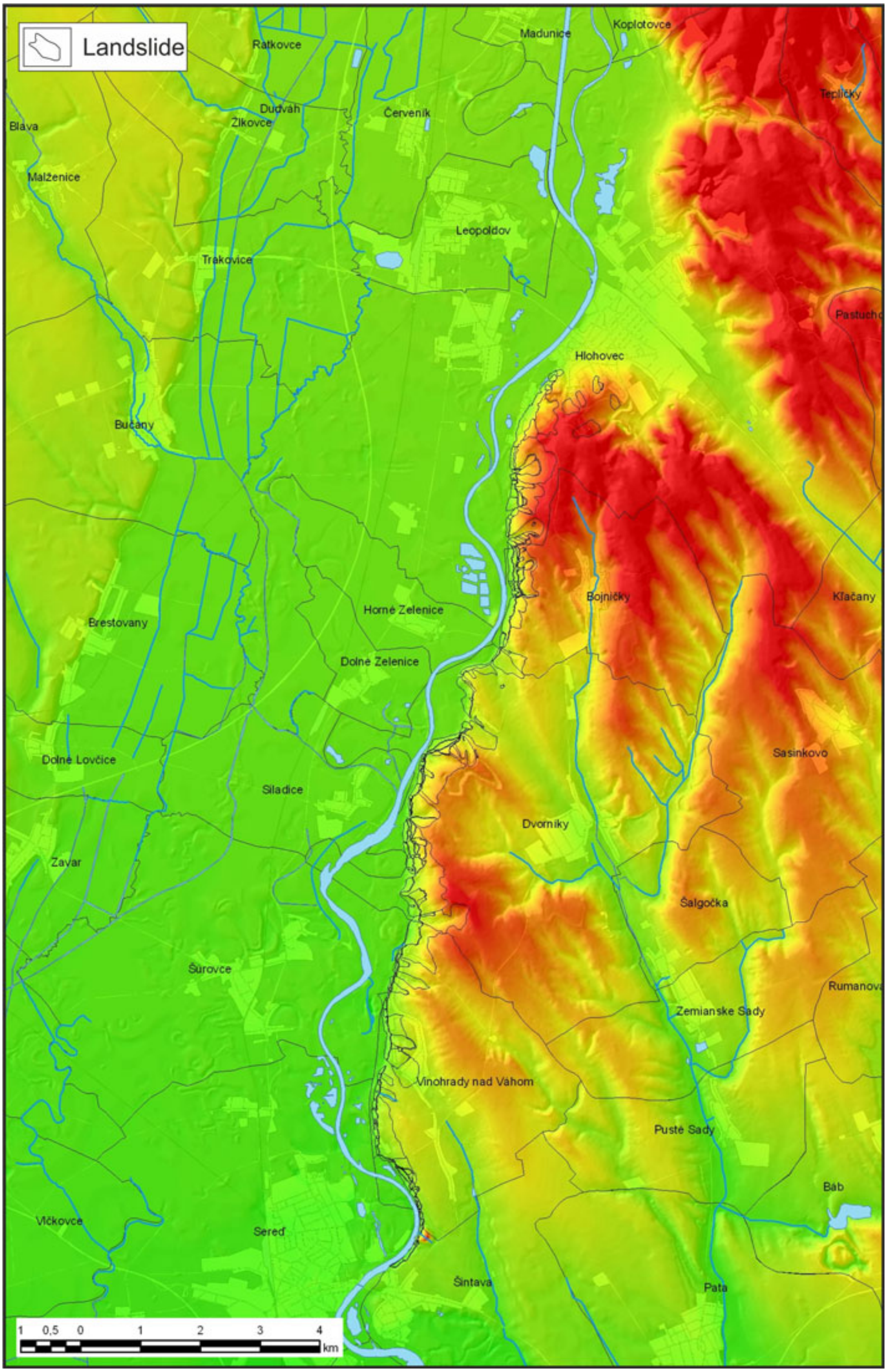


Fig. 3 Landslide inventory map

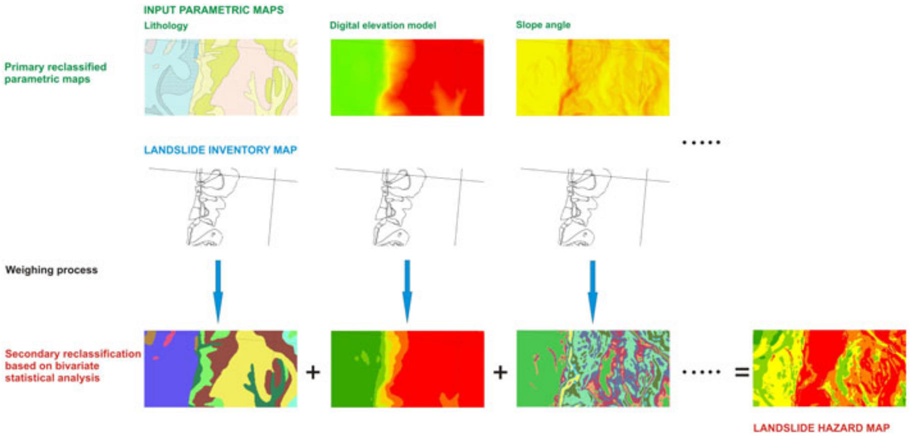


**Fig. 4** The principle of bivariate statistical analysis

## 4 Bivariate statistical analysis with determination of the weight of each parameter

This method is a statistical combination of each input parametric maps with a landslide inventory map. Bivariate statistical analysis works with one dependent variable (landslides inventory map) and one independent variable (individual input parametric maps). The result is a combination of the determined total number of grid cells with landslides and without landslides in each class of parameters, calculated per unit area or percent. Double combinations are stored in tabular form, where one of the numbers represents a class of the parametric map and the second number represents the presence or absence of landslide (0—false, 1—true).

The differences in positional accuracy, superposition, and grid geometry have an important influence on the outcome of the consistency of the technical preparation of the parametric maps. Based on this combination, each parametric map should be secondarily re-classified. Within the secondarily re-classification of the existing classes in each parametric map, new numeric values representing the statistically determined probability of landslides are assigned. The highest numerical value is assigned to the class most prone to landsliding, and the class with the lowest numerical value is least prone to landsliding. The result of bivariate statistical analysis is a map of landslide hazard resulting from the weighted sum of the secondarily re-classified parametric maps.

Weighted sum of the continuous range of values represents the value of the degree of landslide hazard in the model. This continuous interval is necessary for interpretation and division into classes which reflect the degree of landslide hazard. As mentioned above, intervals were determined on the basis of equitable division into equal parts and also by using more accurate approaches including statistical median and standard deviation. The adopted landslide hazard scale contains a classification divided into five categories: *very low*, *low*, *medium*, *high*, and *very high* degree of landslide hazard (Bednarik 2007, 2010, Constantin et al. 2010).

The comparison of the parametric maps (lithology, elevation, slope angle, slope aspect, curvatures of the relief, slope length, contributing areas, actual land use) with the landslide distribution in the study area is given below.

1. A comparison of parametric map of lithological units with that of landslides shows that the most affected areas are composed of deluvial and Neogene sediments, and mainly clay in character. Although these two classes represent only 8 % of the total area of the studied territory, 30 % of the total area of landslides occurs in these two categories. More than 10 % of landslides as a cause of deluvial wash down sediments in the territory are observed in 6.23 % of the total area.
2. The model area does not show a distinct dissection in morphology, where the difference between the lowest and highest altitudes is 221 meters.
3. The most critical slopes are those within the slope angle range of 3°–17° in 80 % of the total area of landslides. However, the range 7°–11° in *class 5* with 30 % of landslides is more critical than the *class 6* having the range of 11°–17°, which covers for the area more than 20 % of the total landslide area.
4. 80 % of landslides fall within the western quadrants (SW, W and NW) represented in categories 7, 8, and 9, respectively.
5. Comparison of relief curvature with the landslide inventory map shows a balanced landslide distribution relative to the concave and convex relief forms.
6. 47, 42, and 10 of the landslides are, respectively, distributed in the slope length categories 1 (100 m), 2 (100–500 m), and 3 (500–1,000 m). Landslides in other categories of this parameter are relatively insignificant.
7. Most of the landslides were generally activated in small micro-catchments, and the respective distributions of the landslides in the categories 1 ($< 100\ \mathrm{m}^2$) and 2 ($100$–$500\ \mathrm{m}^2$) are 60 and 30 %.
8. As can be seen in Table 2, landslides mainly affect the arable lands (category 2), which cover more than 77 % of the total area. The proportion of landslide area in this category is higher than 56 % of the total area of landslides. 32 % of the wooded areas (category 2), which cover 11 % of the total area, are affected by the landslides. The line structures such as roads, railway, and river networks are not affected yet by registered slope deformations.

After the interpretation of results obtained from bivariate statistical analysis, the process of weighting followed. From the calculated parameter weights (column $W_j$), it follows that the dominant effect upon landslide generation and development within the model area Hlohovec–Sered' is posed by lithological composition and slope angle parameters. The parameters of current land use (current landscape structure), slope length, slope aspect, curvature of the relief, contributing areas, and hypsographic degrees are less important. The complete calculation of weight determination for individual parameters is presented in Table 2.

Based on the calculated probability and probability density ($P_{ij}$), each entry parametric map was secondarily reclassified (recl_2 column in Table 2). The classes were assigned with a new numeric value (integer) for each grid cell (grid), which represents in given parameter the degree of susceptibility of individual class to landsliding.

## 5 Landslide hazard map

According to the guidelines for landslide susceptibility, hazard and risk zoning published by the JTC-1 Joint TechnicalCommittee on Landslides and Engineered Slopes (Fell et al. 2008), landslide susceptibility is defined as a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or

**Table 2** Weight calculation based on entropy index

| Factors | Category | $P_{ij}$ | $(P_{ij})$ | $H_j$ | $H_{j\ \max}$ | Average $P_{ij}$ | $I_j$ | $W_j$ | recl_2 |
|---|---|---|---|---|---|---|---|---|---|
| Lithological units | 1 | 0.006479 | 0.014579 | 2.065593 | 3.70044 | 0.034184 | 0.441798 | 0.015102 | 1 |
| | 2 | 0.002277 | 0.005123 | | | | | | 7 |
| | 3 | 0 | 0 | | | | | | 0 |
| | 4 | 0.00317 | 0.007133 | | | | | | 1 |
| | 5 | 0.122159 | 0.274888 | | | | | | 12 |
| | 6 | 0.030017 | 0.067545 | | | | | | 10 |
| | 7 | 0 | 0 | | | | | | 0 |
| | 8 | 0.005541 | 0.012468 | | | | | | 8 |
| | 9 | 0.008018 | 0.018042 | | | | | | 9 |
| | 10 | 0.066603 | 0.149874 | | | | | | 11 |
| | 11 | 0.200132 | 0.450348 | | | | | | 13 |
| | 12 | 0 | 0 | | | | | | 0 |
| | 13 | 0 | 0 | | | | | | 0 |
| Actual land use | 1 | 0 | 0 | 1.228211 | 2.584963 | 0.016136 | 0.524863 | 0.008469 | 0 |
| | 2 | 0.012894 | 0.133184 | | | | | | 4 |
| | 3 | 0.05093 | 0.526064 | | | | | | 6 |
| | 4 | 0.02212 | 0.228477 | | | | | | 5 |
| | 5 | 0.01087 | 0.112275 | | | | | | 3 |
| | 6 | 0 | 0 | | | | | | 0 |
| Slope aspect | 1 | 0 | 0 | 2.450986 | 3.321928 | 0.017776 | 0.26218 | 0.004661 | 0 |
| | 2 | 0.046468 | 0.26141 | | | | | | 7 |
| | 3 | 0.007849 | 0.044157 | | | | | | 5 |
| | 4 | 0.000701 | 0.003945 | | | | | | 1 |
| | 5 | 0.000866 | 0.00487 | | | | | | 1 |
| | 6 | 0.00248 | 0.013953 | | | | | | 4 |
| | 7 | 0.015255 | 0.085819 | | | | | | 6 |
| | 8 | 0.052116 | 0.29318 | | | | | | 9 |
| | 9 | 0.052024 | 0.292664 | | | | | | 8 |
| Slope angle | 1 | 0.000769 | 0.000776 | 2.401597 | 3.169925 | 0.1102 | 0.24238 | 0.02671 | 1 |
| | 2 | 0.007004 | 0.007062 | | | | | | 2 |
| | 3 | 0.020115 | 0.020281 | | | | | | 3 |
| | 4 | 0.040027 | 0.040358 | | | | | | 4 |
| | 5 | 0.082819 | 0.083504 | | | | | | 6 |
| | 6 | 0.147082 | 0.148298 | | | | | | 7 |
| | 7 | 0.262527 | 0.264698 | | | | | | 8 |
| | 8 | 0.349667 | 0.352559 | | | | | | 9 |
| | 9 | 0.081788 | 0.082465 | | | | | | 5 |
| Curvature | 1 | 0.024407 | 0.554609 | 1.097365 | 1.584963 | 0.014669 | 0.30764 | 0.004513 | 3 |
| | 2 | 0.000766 | 0.017397 | | | | | | 1 |
| | 3 | 0.018835 | 0.427994 | | | | | | 2 |
| Slope length | 1 | 0.01691 | 0.290651 | 1.176712 | 2.584963 | 0.009697 | 0.544786 | 0.005283 | 5 |
| | 2 | 0.026929 | 0.462869 | | | | | | 6 |
| | 3 | 0.012715 | 0.218547 | | | | | | 4 |
| | 4 | 0.001625 | 0.027933 | | | | | | 3 |
| | 5 | 0 | 0 | | | | | | 0 |
| | 6 | 0 | 0 | | | | | | 0 |

**Table 2** continued

| Factors | Category | $P_{ij}$ | $(P_{ij})$ | $H_j$ | $H_{j\ \max}$ | Average $P_{ij}$ | $I_j$ | $W_j$ | recl_2 |
|---|---|---|---|---|---|---|---|---|---|
| Contributing areas | 1 | 0.015023 | 0.161511 | 2.152879 | 2.584963 | 0.015503 | 0.167153 | 0.002591 | 3 |
| | 2 | 0.025007 | 0.268844 | | | | | | 5 |
| | 3 | 0.02813 | 0.302427 | | | | | | 6 |
| | 4 | 0.020108 | 0.216179 | | | | | | 4 |
| | 5 | 0.004748 | 0.05104 | | | | | | 2 |
| | 6 | 0 | 0 | | | | | | 0 |
| Altitude | 1 | 0.005488 | 0.038942 | 2.411335 | 2.584963 | 0.023487 | 0.067168 | 0.001578 | 1 |
| | 2 | 0.021443 | 0.152163 | | | | | | 3 |
| | 3 | 0.02837 | 0.201318 | | | | | | 4 |
| | 4 | 0.035128 | 0.24927 | | | | | | 6 |
| | 5 | 0.034847 | 0.247276 | | | | | | 5 |
| | 6 | 0.015647 | 0.111031 | | | | | | 2 |

potentially may occur in an area. Fell et al. (2008) also stated that landslide susceptibility may also include a description of the velocity and intensity of the existing or potential failure. However, it is well known that the time frame of the event is not taken into account in the landslide susceptibility concept (Fell et al. 2008). The time frame or in other words the probability of a potentially damaging event occurring in unit time is evaluated in the landslide hazard concept (Crozier and Glade 2005). Landslide hazard evaluation methods could be classified under two main headings: (1) techniques based on landslide inventory and (2) applications based on the responsible triggering factor (Nefeslioglu et al. 2011). Particularly, considering the occurrence probability of the critical threshold value for the responsible triggering, a concept—the effective return period for hazard evaluation—was introduced by Nefeslioglu and Gokceoglu (2011). According to the researchers, the probability of spatial occurrence—landslide susceptibility is able to be defined as the probability of temporal occurrence—landslide hazard in case the evaluation time interval is over the effective return period for the critical threshold value for the responsible triggering. Therefore, it could be suggested that landslide susceptibility results are able be defined as landslide hazard and directly evaluated in landslide risk calculations.

Landslide hazard map was constructed based on a simple summation of the secondary re-classified parametric maps multiplied by calculated weights against the Table 2. The equation used to develop landslide hazard maps for the model area has the following form:

$$\begin{aligned} y = {} & /\text{slope\_recl2}/ * 0.02671 + /\text{aspect\_recl2}/ * 0.004661 + /\text{land use\_recl2}/ * 0.008469 \\ & + /\text{geol\_recl2}/ * 0.015102 + /\text{curvat\_recl2}/ * 0.004513 + /\text{flowdown\_recl2}/ \\ & * 0.005283 \quad + /\text{flowup\_recl2}/ * 0.002591 + /\text{dem\_recl2}/ * 0.001578 \end{aligned} \tag{2}$$

The result of the summation is a continuous interval of values from 0.119 to 0.604, representing varying degrees of landslide hazard. This interval is necessary to re-classify into three or five conventional classes. Although there are quite numbers of classification methods, the easiest way is to regularly divide into equal intervals, and sophisticated methods of classification are based on different mathematical distributions.

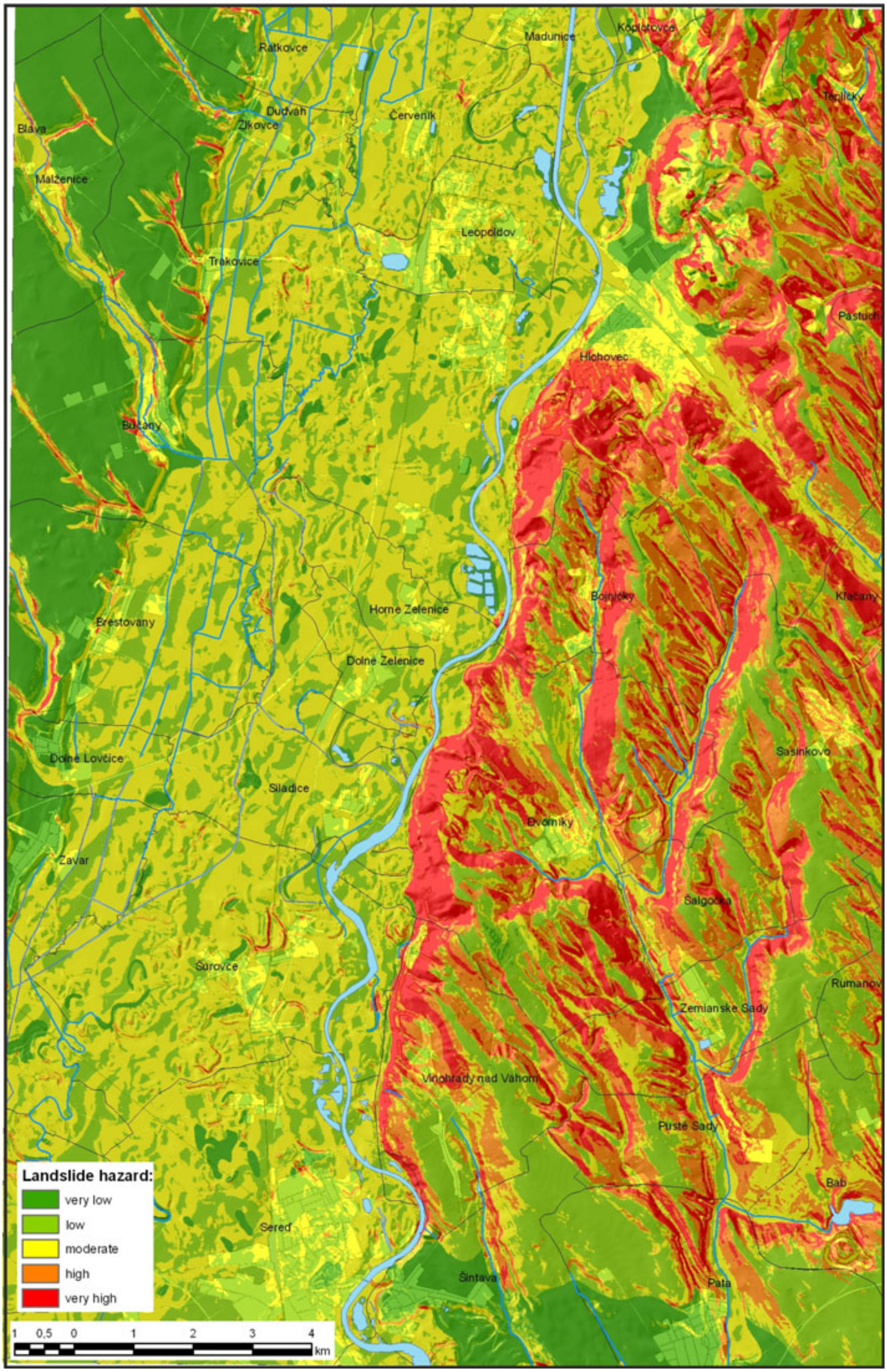


**Fig. 5** Landslide hazard map

Classification used to allocate this interval is based on natural boundaries (natural breaks) and devotes five classes of landslide hazard. This method divides the dataset into classes by comparing the sum of the squares of the differences based on the median class. The bottom line is sorted in ascending values, following the sum of squares difference (SRS) to determine the earliest boundaries and other boundaries calculation.

As already mentioned above, the resulting landslide hazard interval was re-classified into five classes representing the degree of landslide hazard in the model area:

1. very low degree of landslide hazard (interval 0.119–0.256)
2. low degree of landslide hazard (interval 0.256–0.332)
3. medium degree of landslide hazard (interval 0.332–0.395)
4. high degree of landslide hazard (interval 0.395–0.480)
5. very high degree of landslide hazard (interval 0.480–0.604).

The resulting prognostic landslide hazard map is presented in Fig. 5. The obtained hazard map model was validated by using ROC curve by means of landslide affected area corresponding to hazard classes. Other mathematical methods of success calculation were also applied. Validation results showed that the obtained prognostic model is good adjusted. Prognostic map revealed a number of new potentially unstable areas. This is particularly true in the slopes of the municipalities Hlohovec Dvorníky, Vinohrady nad Váhom, Bojničky, Sasinkovo, Pusté Sady, Zemianske Sady, and Šalgočka. While the area of mapped (registered) landslides in the landslide inventory map is 5,980,062 $m^2$, very high degree of hazard in prognostic map covers an area of 33,362,400 $m^2$.

## 6 Landslide risk assessment

Risk assessment is especially important in urban areas or in areas included in development plans with land use for socioeconomic, technological, and other means. Vulnerability is an essential component in assessment of landslide risk (Leone et al. 1996) and evaluated with respect to each element at risk. Population, buildings, economic activities, public services, infrastructure, etc. are accepted as important elements at risk.

### 6.1 Vulnerability assessment

Vulnerability assessment of the individual elements at risk is an essential part of landslide risk assessment and helps to understand the interaction between landslide event and the damaged risk elements. Elements at risk are defined from parametric maps of the actual land use (Fig. 2). Individual polygon and line entities in the parametric map were delineated by cadastral borders of individual villages. Following elements at risk were allocated from land use parametric map: river network, arable land, forests, settlement (built-up areas), road network, rail network.

Elements at risk were evaluated in terms of their physical vulnerability, which was considered only with direct landslide losses. Indirect losses that may occur in a period of time after activation of the hazard, such as disruption of infrastructure and hence economic activity, for example, because of slip roads, were not calculated for obvious reasons. Calculation and modeling of indirect losses cannot be completed without an expert in economy.

There are 37 municipalities in the study area and elements at risk are expressed in Table 3 in the form of their spatial distributions. After identification of the elements at risk, necessary

**Table 3** Identification of elements at risk

| Cadaster | River network ($m^2$) | Arable land ($m^2$) | Forests ($m^2$) | Settlement ($m^2$) | Road network ($m^2$) | Rail network($m^2$) |
|---|---|---|---|---|---|---|
| Madunice | 141,600 | 1,314,100 | 459,100 | 350,400 | 45,500 | 0 |
| Jaslovské Bohunice | 0 | 918,000 | 0 | 0 | 1,400 | 0 |
| Ratkovce | 51,800 | 3,652,100 | 778,200 | 125,500 | 96,200 | 0 |
| Koplotovce | 23,400 | 304,700 | 445,700 | 146,900 | 22,000 | 0 |
| Červeník | 81,500 | 6,596,800 | 825,800 | 526,400 | 148,600 | 30,300 |
| Horné Trhovište | 0 | 489,400 | 90,400 | 40,600 | 8,900 | 0 |
| Tepličky | 0 | 3,377,700 | 481,200 | 219,300 | 36,400 | 0 |
| Žlkovce | 16,500 | 6,900,200 | 465,100 | 260,600 | 167,800 | 0 |
| Malženice | 12,400 | 6,387,500 | 599,800 | 358,600 | 90,000 | 0 |
| Trakovice | 1,400 | 10,428,600 | 422,400 | 548,200 | 232,100 | 0 |
| Leopoldov | 205,500 | 2,916,000 | 388,300 | 1,811,900 | 170,000 | 158,300 |
| Hlohovec | 1,517,500 | 39,713,200 | 16,230,700 | 6,534,500 | 1,099,800 | 166,600 |
| Bučany | 13,800 | 12,924,900 | 306,100 | 1,021,900 | 153,300 | 11,600 |
| Pastuchov | 0 | 922,000 | 827,600 | 0 | 6,000 | 0 |
| Brestovany | 16,900 | 11,974,800 | 632,400 | 844,000 | 98,200 | 53,800 |
| Horné Zelenice | 105,300 | 3,503,500 | 215,800 | 330,600 | 69,600 | 13,500 |
| Bojničky | 3,700 | 7,891,100 | 748,700 | 551,100 | 83,800 | 0 |
| Kl’ačany | 0 | 2,893,900 | 220,200 | 0 | 23,600 | 7,400 |
| Dolné Zelenice | 27,300 | 2,121,100 | 286,400 | 372,400 | 69,600 | 16,600 |
| Dolné Lovčice | 10,300 | 2,859,300 | 133,800 | 362,200 | 76,000 | 5,900 |
| Zavar | 95,900 | 4,373,400 | 6,800 | 692,900 | 82,300 | 0 |
| Sasinkovo | 0 | 9,910,400 | 1,077,300 | 617,400 | 53,700 | 0 |
| Dvorníky | 260,500 | 20,784,200 | 3,032,600 | 1,070,200 | 149,500 | 0 |
| Siladice | 315,700 | 6,281,500 | 375,900 | 434,000 | 128,600 | 81,700 |
| Šúrovce | 447,200 | 16,149,100 | 1,930,400 | 1,160,800 | 162,900 | 47,600 |
| Rumanová | 0 | 2,808,100 | 0 | 14,100 | 0 | 0 |
| Križovany nad Dudváhom | 38,000 | 3,471,800 | 71,400 | 0 | 19,200 | 6,900 |
| Šalgočka | 15,300 | 4,333,300 | 170,800 | 213,900 | 35,100 | 0 |
| Zemianske Sady | 31,500 | 7,530,300 | 191,900 | 512,500 | 44,700 | 0 |
| Vlčkovce | 0 | 5,746,100 | 0 | 21,400 | 85,200 | 0 |
| Vinohrady nad Váhom | 6,900 | 7,572,400 | 2,130,400 | 885,400 | 122,400 | 0 |
| Pusté Sady | 0 | 7,230,700 | 106,900 | 500,600 | 41,400 | 0 |
| Báb | 170,500 | 5,250,600 | 312,700 | 204,200 | 21,500 | 0 |
| Šintava | 243,000 | 7,779,800 | 649,900 | 839,200 | 132,400 | 0 |
| Sered’ | 777,000 | 13,695,400 | 2,725,600 | 5,084,600 | 722,700 | 163,500 |
| Pata | 0 | 10,497,900 | 553,600 | 1,121,100 | 191,200 | 0 |
| Dolná Streda | 81,400 | 0 | 215,600 | 107,200 | 9,500 | 0 |

and logical next step is their financial estimation which will serve as a basis for calculation of the vulnerability. Financial estimation is processed only in terms of official prices, the market price when the individual elements at risk vary depending on market demand. The identified elements at risk were remunerated arable land, built-up areas, and forests. River, road, and rail networks were not assessed for two reasons: the first is the relatively small risks resulting from the prognostic hazard map and the second is a rather complicated expression of their physical vulnerability (pricing per unit area in regional terms).

Official prices (Table 4) were established on the basis of existing legislation, which were used in the following laws and decrees.

- Act. 582/2004 Z. z. on local taxes and local fees for municipal waste and small construction wastes (Annex. 1, which gives a figure of arable land and permanent grassland—SKK/m$^2$ for individual cadastral areas in Slovakia and Annex. 2 of the value of building land, gardens, built-up areas and other areas by population, in SKK/m$^2$),
- Decree no. 492/2004 Z. z. establishing the general value of assets (appendix no. 14, which determines the fundamental value of forest land in SKK/ha),
- Ministry of Agriculture Decree No. 38/2005 Z. z. determining the value of land and plantations of them for the purpose of land consolidation (Annex. 1, which determines the value of land which is agricultural land and other surface as creditworthy soil ecological units SKK/m$^2$).

Vulnerability is a simple multiplication of spatial distribution of elements at risk and the price thus reflects the amount of potential damage which can be caused by activation of the assessed landslide hazard. Calculated vulnerabilities for the 5th (very high) level of landslide hazard were summarized in Table 5.

The procedure for calculation of the physical vulnerability based on the official price is given below.

a. Well-arranged ordering of elements at risk to individual cadastres presented by the code. The code is composed of 2 or 3 numbers, first number is the value of 2, 3, and 4 (which is rated the risk component: 2—Arable land, 3—forests, 4—built-up areas) and second and third numbers are the identification number of municipality (values from 1 to 37)—for example, Code 21 is a component of the risk of arable land in Madunice, etc.
b. Assigning spatial distribution of elements at risk contained in the 5th degree of landslide hazard, SH 5 (SH—hazard level).
c. Calculation of vulnerability expressed in SKK and corresponding sum €, as the product of the price risk component and its spatial distribution within the selected degrees of landslide hazard.
d. Comparison of the total area of each component of risk and the percentage proportion of the total surface area of the component risk elements of risk delimited 5th degree of landslide hazard.
e. Graphical representation of percentages of the components of vulnerability and risk for each cadastre municipality.

Table 5 shows that the most vulnerable components of risk are in the municipalities Hlohovec, Dvorníky, Vinohrady nad Váhom, Bojničky, Sasinkovo, Pusté Pole, Zemianske Sady and Šalgočka.

### 6.2 Map of risk assessment: regional risk scenarios

Landslide risk map reflects the expected financial losses due to landslides and uses the results of forecasts and analysis based on the assessment of landslide hazard. Landslide risk is defined as a simple multiplication of landslide hazard and vulnerability.

**Table 4** Financial evaluation of elements at risk (1 € ≅ 30 SKK)

| Cadaster | Inhabitants (to 31.12.2,004) | Arable land (SKK/m$^2$) | Pastures (SKK/m$^2$) | Building land (SKK/m$^2$) | Forests (SKK/m$^2$) |
|---|---|---|---|---|---|
| Madunice | 2,040 | 27.41 | 7.50 | 560 | 0.40 |
| Jaslovské Bohunice | 1,848 | 25.89 | 0.00 | 560 | 0.40 |
| Ratkovce | 288 | 25.09 | 0.00 | 400 | 0.40 |
| Koplotovce | 580 | 10.90 | 2.28 | 400 | 0.40 |
| Červeník | 1,495 | 25.89 | 6.97 | 560 | 0.40 |
| Horné Trhovište | 548 | 9.23 | 0.87 | 400 | 0.40 |
| Tepličky | 275 | 11.85 | 1.07 | 400 | 0.40 |
| Žlkovce | 648 | 28.50 | 0.00 | 400 | 0.40 |
| Malženice | 1,266 | 27.50 | 7.35 | 560 | 0.40 |
| Trakovice | 1,321 | 27.22 | 7.50 | 560 | 0.40 |
| Leopoldov | 4,092 | 13.84 | 3.38 | 560 | 0.40 |
| Hlohovec | 23,151 | 13.74 | 3.28 | 800 | 0.40 |
| Bučany | 2,157 | 25.43 | 4.41 | 560 | 0.40 |
| Pastuchov | 982 | 12.20 | 2.58 | 400 | 0.40 |
| Brestovany | 2,015 | 29.96 | 0.00 | 560 | 0.40 |
| Horné Zelenice | 655 | 29.27 | 7.23 | 400 | 0.40 |
| Bojničky | 1,291 | 13.66 | 3.57 | 560 | 0.40 |
| Kl'ačany | 976 | 15.63 | 0.00 | 400 | 0.40 |
| Dolné Zelenice | 534 | 30.56 | 7.85 | 400 | 0.40 |
| Dolné Lovčice | 704 | 24.59 | 3.60 | 400 | 0.40 |
| Zavar | 1,755 | 26.22 | 0.00 | 560 | 0.40 |
| Sasinkovo | 872 | 15.86 | 3.35 | 400 | 0.40 |
| Dvorníky | 2,017 | 16.16 | 3.78 | 560 | 0.40 |
| Siladice | 620 | 26.99 | 4.51 | 400 | 0.40 |
| Šúrovce | 2,213 | 27.97 | 7.23 | 560 | 0.40 |
| Rumanová | 772 | 18.57 | 7.42 | 400 | 0.40 |
| Križovany nad Dudváhom | 1,758 | 28.26 | 4.04 | 560 | 0.40 |
| Šalgočka | 444 | 23.46 | 7.35 | 400 | 0.40 |
| Zemianske Sady | 880 | 20.40 | 5.68 | 400 | 0.40 |
| Vlčkovce | 1,151 | 28.39 | 2.89 | 560 | 0.40 |
| Vinohrady nad Váhom | 1,515 | 20.04 | 0.00 | 560 | 0.40 |
| Pusté Sady | 662 | 15.11 | 3.52 | 400 | 0.40 |
| Báb | 960 | 26.91 | 7.99 | 400 | 0.40 |
| Šintava | 1,719 | 25.07 | 0.00 | 560 | 0.40 |
| Sered' | 17,286 | 26.74 | 3.45 | 800 | 0.40 |
| Pata | 3,051 | 18.88 | 7.99 | 560 | 0.40 |
| Dolná Streda | 1,374 | 33.36 | 2.93 | 560 | 0.40 |

$$r = h * v \tag{3}$$

where $r$ is value of landslide risk (expressed in € per pixel—10 × 10 m), $h$ is the degree of landslide hazard (according to prognostic maps of landslide hazard), $v$ is the vulnerability of the elements at risk (calculated per pixel).

**Table 5** Vulnerability assessment for 5th level of landslide hazard (1 € ≅ 30 SKK)

| Cadaster | Code | Hazard ($m^2$) | Price (SKK/$m^2$) | Vulnerability (SKK) | Area ($m^2$) | % |
|---|---|---|---|---|---|---|
| Madunice | 21 | 1,000 | 27.41 | 27,410 | 1,314,100 | 0.08 |
| | 31 | 0 | 0.40 | 0 | 459,100 | 0.00 |
| | 41 | 0 | 560.00 | 0 | 350,400 | 0.00 |
| Jaslovské Bohunice | 22 | 0 | 25.89 | 0 | 918,000 | 0.00 |
| | 32 | 0 | 0 | 0 | 0 | 0 |
| | 42 | 0 | 0 | 0 | 0 | 0 |
| Ratkovce | 23 | 21,300 | 25.09 | 534,417 | 3,652,100 | 0.58 |
| | 33 | 0 | 0.40 | 0 | 778,200 | 0.00 |
| | 43 | 2,800 | 400.00 | 1,120,000 | 125,500 | 2.23 |
| Koplotovce | 24 | 102,700 | 10.90 | 1,119,430 | 304,700 | 33.71 |
| | 34 | 39,200 | 0.40 | 15,680 | 445,700 | 8.80 |
| | 44 | 36,900 | 400.00 | 14,760,000 | 146,900 | 25.12 |
| Červeník | 25 | 15,400 | 25.89 | 398,706 | 6,596,800 | 0.23 |
| | 35 | 600 | 0.40 | 240 | 825,800 | 0.07 |
| | 45 | 1,000 | 560.00 | 560,000 | 526,400 | 0.19 |
| Horné Trhovište | 26 | 124,500 | 9.23 | 1,149,135 | 489,400 | 25.44 |
| | 36 | 15,800 | 0.40 | 6,320 | 90,400 | 17.48 |
| | 46 | 400 | 400.00 | 160,000 | 40,600 | 0.99 |
| Tepličky | 27 | 1,754,500 | 11.85 | 20,790,825 | 3,377,700 | 51.94 |
| | 37 | 110,400 | 0.40 | 44,160 | 481,200 | 22.94 |
| | 47 | 10,000 | 400.00 | 4,000,000 | 219,300 | 4.56 |
| Žlkovce | 28 | 36,800 | 28.50 | 1,048,800 | 6,900,200 | 0.53 |
| | 38 | 1,400 | 0.40 | 560 | 465,100 | 0.30 |
| | 48 | 1,600 | 400.00 | 640,000 | 260,600 | 0.61 |
| Malženice | 29 | 41,400 | 27.50 | 1,138,500 | 6,387,500 | 0.65 |
| | 39 | 3,400 | 0.40 | 1,360 | 599,800 | 0.57 |
| | 49 | 500 | 560.00 | 280,000 | 358,600 | 0.14 |
| Trakovice | 210 | 115,400 | 27.22 | 3,141,188 | 10,428,600 | 1.11 |
| | 310 | 8,200 | 0.40 | 3,280 | 422,400 | 1.94 |
| | 410 | 7,400 | 560.00 | 4,144,000 | 548,200 | 1.35 |
| Leopoldov | 211 | 400 | 13.84 | 5,536 | 2,916,000 | 0.01 |
| | 311 | 0 | 0.40 | 0 | 388,300 | 0.00 |
| | 411 | 0 | 560.00 | 0 | 1,811,900 | 0.00 |
| Hlohovec | 212 | 5,615,900 | 13.74 | 77,162,466 | 39,713,200 | 14.14 |
| | 312 | 3,520,600 | 0.40 | 1,408,240 | 16,230,700 | 21.69 |
| | 412 | 1,000,400 | 800.00 | 800,320,000 | 6,534,500 | 15.31 |
| Bučany | 213 | 100,400 | 25.43 | 2,553,172 | 12,924,900 | 0.78 |
| | 313 | 0 | 0.40 | 0 | 306,100 | 0.00 |
| | 413 | 23,700 | 560.00 | 13,272,000 | 1,021,900 | 2.32 |
| Pastuchov | 214 | 285,000 | 12.20 | 3,477,000 | 922,000 | 30.91 |
| | 314 | 445,300 | 0.40 | 178,120 | 827,600 | 53.81 |
| | 414 | 0 | 0 | 0 | 0 | 0 |

**Table 5** continued

| Cadaster | Code | Hazard ($m^2$) | Price (SKK/$m^2$) | Vulnerability (SKK) | Area ($m^2$) | % |
|---|---|---|---|---|---|---|
| Brestovany | 215 | 91,100 | 29.96 | 2,729,356 | 11,974,800 | 0.76 |
| | 315 | 0 | 0.40 | 0 | 632,400 | 0.00 |
| | 415 | 5,700 | 560.00 | 3,192,000 | 844,000 | 0.68 |
| Horné Zelenice | 216 | 0 | 29.27 | 0 | 3,503,500 | 0.00 |
| | 316 | 0 | 0.40 | 0 | 215,800 | 0.00 |
| | 416 | 0 | 400.00 | 0 | 330,600 | 0.00 |
| Bojničky | 217 | 2,122,800 | 13.66 | 28,997,448 | 7,891,100 | 26.90 |
| | 317 | 161,400 | 0.40 | 64,560 | 748,700 | 21.56 |
| | 417 | 105,600 | 560.00 | 59,136,000 | 551,100 | 19.16 |
| Kl’ačany | 218 | 634,700 | 15.63 | 9,920,361 | 2,893,900 | 21.93 |
| | 318 | 189,500 | 0.40 | 75,800 | 220,200 | 86.06 |
| | 418 | 0 | 0 | 0 | 0 | 0 |
| Dolné Zelenice | 219 | 100 | 30.56 | 3,056 | 2,121,100 | 0.00 |
| | 319 | 0 | 0.40 | 0 | 286,400 | 0.00 |
| | 419 | 0 | 400.00 | 0 | 372,400 | 0.00 |
| Dolné Lovčice | 220 | 8,700 | 24.59 | 213,933 | 2,859,300 | 0.30 |
| | 320 | 0 | 0.40 | 0 | 133,800 | 0.00 |
| | 420 | 0 | 400.00 | 0 | 362,200 | 0.00 |
| Zavar | 221 | 0 | 26.22 | 0 | 4,373,400 | 0.00 |
| | 321 | 0 | 0 | 0 | 0 | 0 |
| | 421 | 600 | 560.00 | 336,000 | 692,900 | 0.09 |
| Sasinkovo | 222 | 1,618,100 | 15.86 | 25,663,066 | 9,910,400 | 16.33 |
| | 322 | 516,500 | 0.40 | 206,600 | 1,077,300 | 47.94 |
| | 422 | 18,700 | 400.00 | 7,480,000 | 617,400 | 3.03 |
| Dvorníky | 223 | 6,057,600 | 16.16 | 97,890,816 | 20,784,200 | 29.15 |
| | 323 | 1,180,400 | 0.40 | 472,160 | 3,032,600 | 38.92 |
| | 423 | 106,800 | 560.00 | 59,808,000 | 1,070,200 | 9.98 |
| Siladice | 224 | 0 | 26.99 | 0 | 6,281,500 | 0.00 |
| | 324 | 0 | 0.40 | 0 | 375,900 | 0.00 |
| | 424 | 0 | 400.00 | 0 | 434,000 | 0.00 |
| Šúrovce | 225 | 68,200 | 27.97 | 1,907,554 | 16,149,100 | 0.42 |
| | 325 | 34,300 | 0.40 | 13,720 | 1,930,400 | 1.78 |
| | 425 | 0 | 560.00 | 0 | 1,160,800 | 0.00 |
| Rumanová | 226 | 142,500 | 18.57 | 2,646,225 | 2,808,100 | 5.07 |
| | 326 | 0 | 0 | 0 | 0 | 0 |
| | 426 | 2,500 | 400.00 | 1,000,000 | 14,100 | 17.73 |
| Križovany nad Dudváho | 227 | 300 | 28.26 | 8,478 | 3,471,800 | 0.01 |
| | 327 | 0 | 0.40 | 0 | 71,400 | 0.00 |
| | 427 | 0 | 0 | 0 | 0 | 0 |
| Šalgočka | 228 | 575,100 | 23.46 | 13,491,846 | 4,333,300 | 13.27 |
| | 328 | 107,000 | 0.40 | 42,800 | 170,800 | 62.65 |
| | 428 | 16,400 | 400.00 | 6,560,000 | 213,900 | 7.67 |

**Table 5** continued

| Cadaster | Code | Hazard ($m^2$) | Price ($SKK/m^2$) | Vulnerability (SKK) | Area ($m^2$) | % |
|---|---|---|---|---|---|---|
| Zemianske Sady | 229 | 1,363,100 | 20.40 | 27,807,240 | 7,530,300 | 18.10 |
| | 329 | 60,200 | 0.40 | 24,080 | 191,900 | 31.37 |
| | 429 | 9,300 | 400.00 | 3,720,000 | 512,500 | 1.81 |
| Vlčkovce | 230 | 2,500 | 28.39 | 70,975 | 5,746,100 | 0.04 |
| | 330 | 0 | 0 | 0 | 0 | 0 |
| | 430 | 0 | 560.00 | 0 | 21,400 | 0.00 |
| Vinohrady nad Váhom | 231 | 1,181,500 | 20.04 | 23,677,260 | 7,572,400 | 15.60 |
| | 331 | 563,400 | 0.40 | 225,360 | 2,130,400 | 26.45 |
| | 431 | 197,000 | 560.00 | 110,320,000 | 885,400 | 22.25 |
| Pusté Sady | 232 | 767,900 | 15.11 | 11,602,969 | 7,230,700 | 10.62 |
| | 332 | 46,300 | 0.40 | 18,520 | 106,900 | 43.31 |
| | 432 | 114,500 | 400.00 | 45,800,000 | 500,600 | 22.87 |
| Báb | 233 | 533,800 | 26.91 | 14,364,558 | 5,250,600 | 10.17 |
| | 333 | 126,400 | 0.40 | 50,560 | 312,700 | 40.42 |
| | 433 | 34,200 | 400.00 | 13,680,000 | 204,200 | 16.75 |
| Šintava | 234 | 121,400 | 25.07 | 3,043,498 | 7,779,800 | 1.56 |
| | 334 | 87,800 | 0.40 | 35,120 | 649,900 | 13.51 |
| | 434 | 1,200 | 560.00 | 672,000 | 839,200 | 0.14 |
| Sered’ | 235 | 8,500 | 26.74 | 227,290 | 13,695,400 | 0.06 |
| | 335 | 7,500 | 0.40 | 3,000 | 2,725,600 | 0.28 |
| | 435 | 2,800 | 800.00 | 2,240,000 | 5,084,600 | 0.06 |
| Pata | 236 | 447,000 | 18.88 | 8,439,360 | 10,497,900 | 4.26 |
| | 336 | 264,800 | 0.40 | 105,920 | 553,600 | 47.83 |
| | 436 | 1,300 | 560.00 | 728,000 | 1,121,100 | 0.12 |
| Dolná Streda | 237 | 0 | 0.40 | 0 | 215,600 | 0.00 |
| | 337 | 0 | 560.00 | 0 | 107,200 | 0.00 |
| | 437 | 0 | 0 | 0 | 0 | 0 |

For the model area Hlohovec–Sered’, two risk scenarios were evaluated based on Eq. 3. While Risk Scenario 1 was evaluated by considering alternative landslide hazard having 4th and 5th degrees, Risk Scenario 2 was estimated by taking into account only fifth degree of landslide hazard. The result is a “crown–pixel” map, reflecting the landslide risk in the model area (Figs. 6, 7).

The values of landslide risk in maps were divided into 5 categories:

- Category 0—represents zero risk of landslide risk per pixel
- Category 1–1,000 (33 €) to 3,000 (100 €) SKK/pixel
- Category 2–40,000 (1,333 €) SKK/pixel
- Category 3–56,000 (1,866 €) SKK/pixel
- Category 4–80,000 (2,666 €) SKK/pixel.

Category 0 represents areas that are not exposed to landslide hazard. Vulnerability of these territories is defined, but has a zero landslide risk. Category 1 represents the value of landslide risk on arable land and forested parts of the model area. Elements at risk in category 1 are exposed to 4th and 5th degree of landslide hazard. Categories 2, 3, and 4 represent the landslide risk in built-up areas (thus sharp boundary values, resulting from physical vulnerability values for built-up areas). They are also exposed to 4th and 5th degree of landslide hazard which arises from the above-mentioned prognostic maps of landslide hazard.

From the landslide risk map (in both scenarios) results that the municipalities with high landslide risk in terms of built-up areas (category 2, 3, 4) are Hlohovec Bojničky, Sasinkovo, Dvorníky, Zemianske Sady, Vinohrady nad Váhom, Pusté Sady a Teplička. First category, arable land and wooded areas of landslide risk affect a large part of the slopes on the left side of River Váh, in both scenarios.

Thus, compiled maps of risk scenarios should preferably serve as one of the bases for optimization of the planning of towns and villages and further development across land territory in the monitored area.

## 7 Verification process

After the establishment of prognostic maps, it is necessary to evaluate its explanatory value. In eighties, at the time, when the first landslide susceptibility maps were realized using map algebra implemented in the GIS environment, these were verified by visually comparing the prognostic maps with the landslide inventory map.

The most important criterion in evaluation of the quality of prognostic maps is the construction of a model of success, which assesses the relationship between the forecast and landslide inventory map. Model of success in general compares the density of landslides in the landslide inventory map (presence or absence of slope deformation, binary raster 1/0) with varying degrees of susceptibility in prognostic map. In the literature, several verification techniques of prognostic maps can be found. Procedures are generally verified by the methods of statistical success and ROC curves (Receiver Operating Characteristic curves).

Three contingency tables with size 2 × 2 were designed for two categories present/absence of registered landslides and stable/unstable areas in prognostic map. 59,805 randomly selected pixels from raster registered landslides and 59,805 pixels of raster forecast of landslide hazard were used. Thresholds were chosen by the degree of probability 0.4, 0.6, and 0.8.

Size of area under the curve was calculated as 0.912, which together with the steepness of the curve demonstrates the success of prognostic model stemming based on bivariate statistical analysis (Fig. 8).

Several authors also use the method by overlaying the raster maps of registered landslides with prognostic map as an easiest way in the verification (Bednarik 2001, 2007; Nandi and Shakoor 2009; Constantin et al. 2010). The percentages of registered landslides (number of pixels) in various degrees of landslide hazard bivariate model can be seen in Fig. 9. The figure shows that the success of the model is 92.5 % for the 4th and 5th degree of hazards (high and very high degree of landslide hazards), and this result is similar with the AUC value 91.2 % obtained from the ROC curve.

## 8 Conclusions

The principle of statistical methods is relatively simple, but their application requires a relatively good experience and contributions of the other disciplines such as engineering

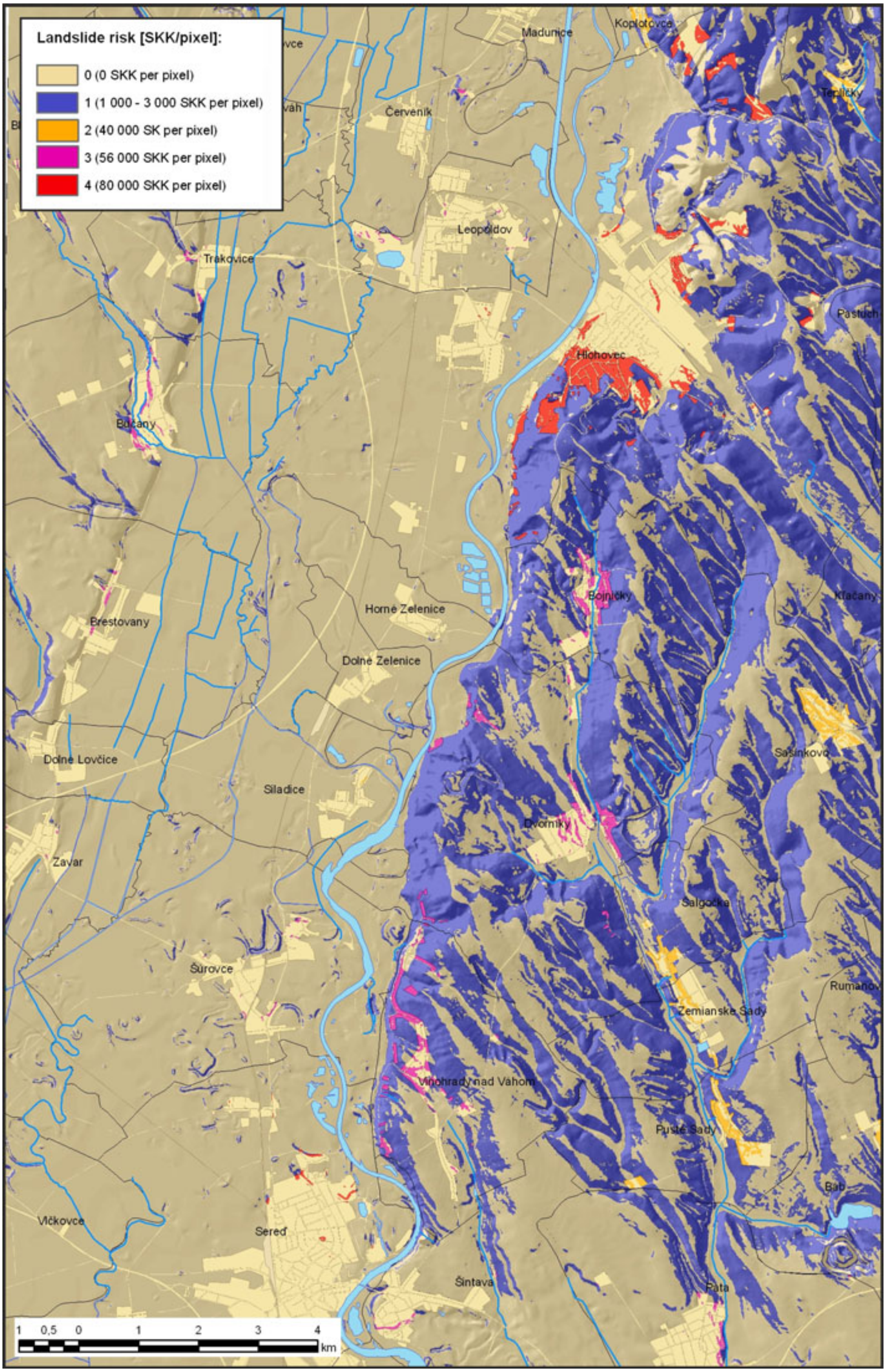


**Fig. 6** Landslide risk map—risk scenario 1

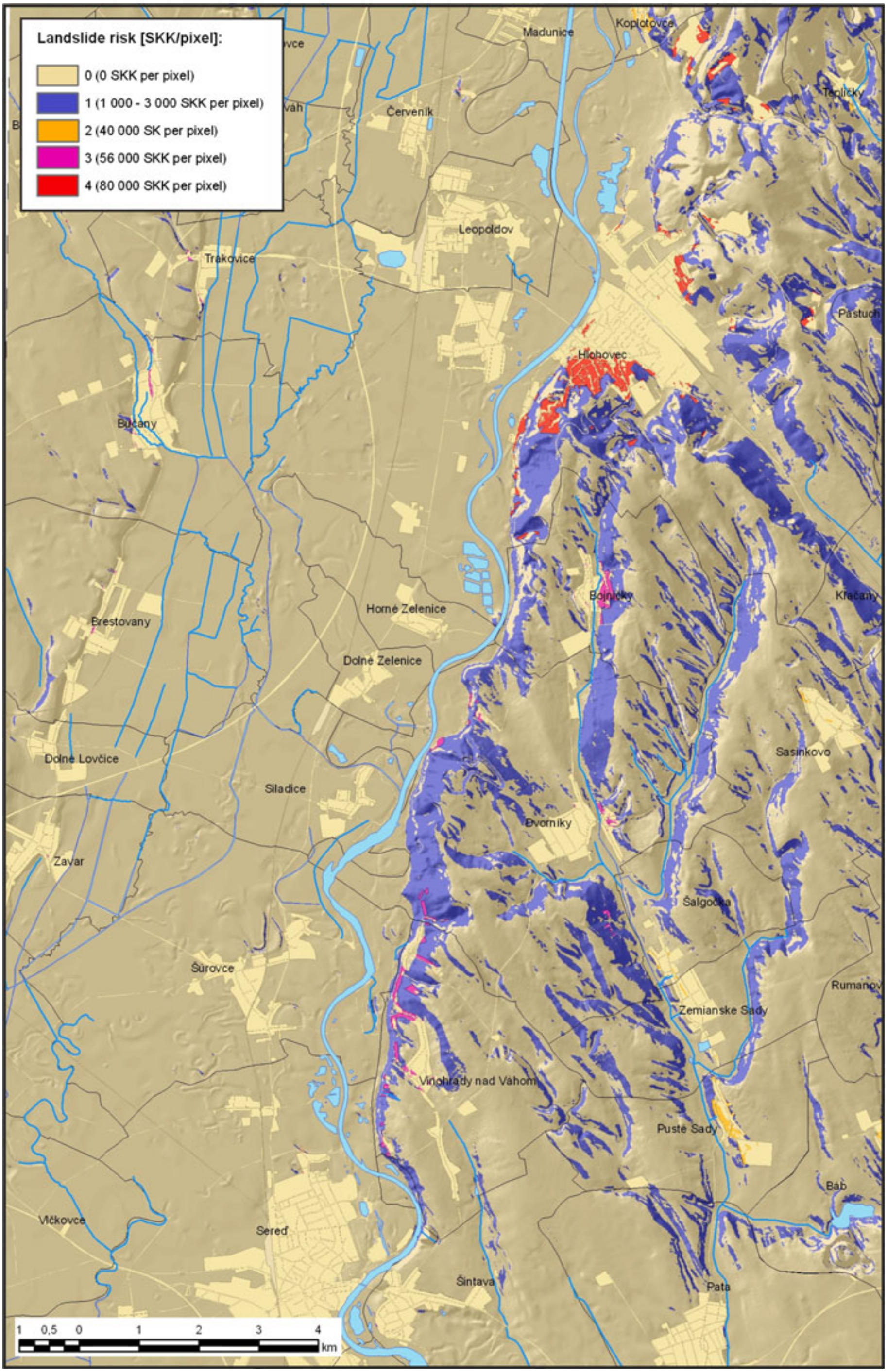
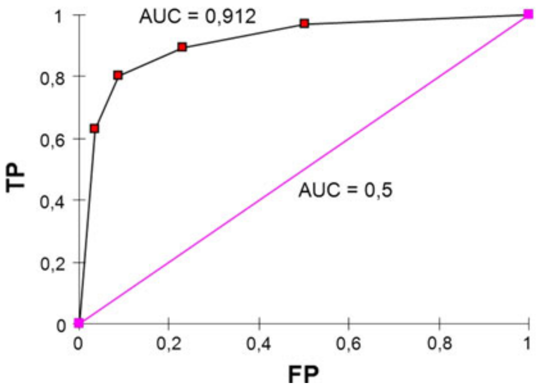


Fig. 7 Landslide risk map—risk scenario 2

**Fig. 8** ROC curve with AUC calculation



geology, theoretical and practical knowledge of GIS, statistics, computer science, and of course, geomorphology. In assessment of landslide hazard and risk, it is necessary to consider the following stages of the process solutions:

a. Choosing the appropriate methods for assessing landslide hazard from a group of statistical methods in view of the possibility of its use in a GIS environment: Based on the survey of knowledge about the use of statistical methods in evaluation of landslide hazard as well as its own multi-experience, the most used and proven methods are bivariate and multivariate statistical analysis. Both methods are accepted by experts as a method which provides reliable results of the forecasting of landslide hazard.
b. Draft methodology with the implementation of data processing in GIS environment, selection of an appropriate scale and depending on the derivation of collection methodology and existing data available, together with an application process of

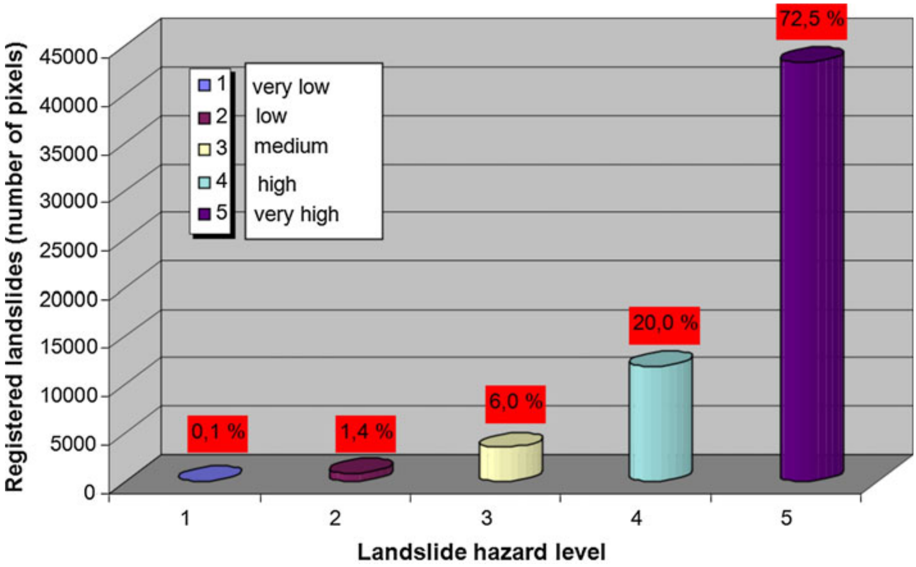


**Fig. 9** Comparison of registered landslides within different levels of landslide hazard

databases: If the output prognostic hazard and risk map will serve as a basis for land use planning, or for other uses (e.g., insurance), must be processed in large (detailed) scales (1: 10,000 and more detailed). Medium (basic) and small (clear) scales are not suitable for this purpose.

c. Practical application of knowledge to selected model area: Use of statistical methods in GIS environment can be applied only to areas providing several conditions:

    - occurrence of geohazards in the territory in sufficient quantities,
    - territory which is characterized by current anthropogenic activity,
    - well-researched territory (in terms of geological, engineering, hydrogeological, and other knowledge).

d. Verification of the prognosis: After the establishment of prognostic maps, it is necessary to evaluate its explanatory value by means of their validations. In the presented paper, a sophisticated method of verification of prognostic maps with statistical methods for success (ROC curves) and comparison of the percentage representation of registered landslides in various stages of prognostic landslide hazard was used. All methods confirmed good “adjustment” of statistical model.
e. Vulnerability assessment and delineation of the elements at risk: Vulnerability of individual elements is essential information in assessment of landslide risk. Identification of elements at risk is also relatively simple process carried out mostly on the basis of parametric maps of the actual land use or using recent aerial photography, respectively, orthophoto maps. Problem is the financial estimation of elements at risk. In this study, they were assessed on the basis of official prices, resulting from the current legislative documents. Determination of their market values is especially difficult in large areas where the market price varies depending on current demand. Vulnerability presenting the official price is therefore considerably underestimated. Another important problem is the determination of the indirect losses caused by activation of landslide phenomenon. Objective solutions of this problem would require the direct cooperation with experts in economy. Therefore, for obvious reasons, only the direct losses were rated in this paper.
f. Creation of landslide risk map: Map of landslide risk is a product of simple multiplication of landslide hazard and vulnerability. Risk scenarios, however, reflect the state of risk derives from the official financial assessment of vulnerability. Thus, the degree of risk is underestimated, but it is sufficient for purposes of land use planning documentation.

Landslide risk prediction is one of the most prerequisite for human being to provide livable conditions in environments threaten by landslides. Construction of landslide risk map is important for implementation of the principles related with the risk definition. Here, the most crucial question is, who will decide the level of risk and the proportion of acceptable risk, state law or local governments? This peculiarity is primarily related with market price of territories which are included among the areas with higher risk. This situation causes the limitation of future development in these territories. The results of risk assessments should be one of the basic documents for territorial planning process as well as insurance and development of regional units.

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