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4. Landslide Hazard Assessment Using Spatial Statistical Methods

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Abstract: The paper presents several commonly used statistical methods: bivariate analysis with weighting factor and multivariate conditional analysis with regard to the landslide hazard assessment within GIS environment. Complete methodology from selection of input factors, data collection and preparation of parametric maps as well as compilation of landslide hazard map is proposed. Finally, evaluation, advantages or disadvantages of both applied methods are compared in case study area nearby Hlohovec and Sereď (Slovak Republic) in detailed map scale.

Keywords: landslide hazard • landslide susceptibility map • spatial statistics • bivariate analysis with weighting • multivariate conditional analysis • parametric maps • Geographic Information Systems (GIS) • Hlohovec – Sereď area

4.1. Introduction and terminology

In the present time landslides pose a significant environmental threat with their unfavourable socio-economic impact in many regions of the world, including Slovakia. Therefore, the interest of many researchers is mainly focused on the defining factors of slope movements and making prognoses of landslides occurrence in the future with high probability. This effort has led to the development of many methods of landslide hazard assessment and prognosis. Among them, the quantitative methods have an important position, which includes also the statistical methods presented in this paper (Aleotti & Chowdhury, 1999). They are based on relation between relevant factors affecting the slope stability and registered slope deformations, with subsequent statistical processing.

Statistical methods have been gradually developed since the 70ies, when there were published a lot of papers presenting many different approaches to solve the above topic. A detailed overview of the methods from this period is contained in the studies of authors van Westen, 1993; Carrara et al., 1991.

In the natural sciences, which are mainly engaged in the examination of objects and phenomena, the real geographical space is closely related the use of geoinformation systems (GIS). The wider use of GIS technology in natural science disciplines has been started from the first half of the 90ies in connection with available personal computers. Thanks to use of available technology, which is needed for processing large statistical data files, development of statistical methods in the landslide hazard assessment was significantly shifted both in theory and in practice.

With respect to the fact that the statistical prognosis of the landslides occurrence is based on the assessment of the similarity of a set of conditions in the affected area, it followed the assumption that landslides will occur in the future under the same conditions as occurred in the past and occur at present. According to this assumption, the steps of assessment are: the detailed landslide inventory; the mapping of factors (parameters) associated with the landslides occurrence; the classification of set of factors, regarding a degree of landslide susceptibility in the area based on the statistical relation to the registered slope deformations; and the final synthesis and compilation of the resulting prognosis map.

The final prognosis maps divide the area into a defined number of landslide susceptibility zones. From these maps it is possible to determine critical areas, where occurrence of slope deformations can be expected in future, assuming the presence of appropriate trigger events. In Slovakia, three zones are defined: stable areas, conditionally stable and unstable areas in terms of methodology by Kováčik (1996) and Directive of MoE SR (1999). These maps were compiled predominantly in traditional way (empirical engineering geological and geotechnical approaches), but at present they could be significantly improved using statistical methods within GIS environment.

In the presented case-study the area between the Hlohovec and Sereď cities in western part of Slovakia was chosen. The area is intensively affected by the active landslides and has been continuously monitored since 1997 by the State Geological Survey (SGIDŠ, Iglárová et al., 2011).

4.1.1. Basic terms

Herein used terminology is based on the most commonly used terms, mainly from studies: Carrara (1983, 1988); van Westen (1993); van Westen et al. (1993) and Aleotti & Chowdhury (1999). The terminology of engineering geology, geological hazards and risks follows the study of Varnes (1984), the landslides classification (in the Slovak Republic) is according to Nemčok, Pašek and

Rybář (Nemčok et al., 1974) and Matula (1995), Ondrášik & Gajdoš (2001), Drdoš (1992), Minár & Tremboš (1994).

In this paper the *landslide susceptibility* term depends on the context and can be optionally replaced with the term *landslide hazard*.

In the scope of the landslide hazard assessment we can estimate the areas of the occurrence, the time and the intensity of this phenomenon with various degree of probability. The place of the occurrence can be predicted with a high probability based on the analysis of relevant factors by conventional models with low uncertainty. The models are based on the implementation of the spatial distribution of those factors, which are relevant to the occurrence of slope failures. The term *slope stability conditions* includes various external and internal factors that affect the stability of slopes, e.g. lithology, physico-mechanical properties of the rock environment, character of geological structures and setting, georelief (slope dip, slope length, aspect), hydrogeological conditions (rainfall and groundwater level), land cover, etc.

Most of the mentioned conditions and factors of slope movements can be quantified; i.e. expressed in numerical form (absolute or relative/semi-quantitative). Numerically expressed factor of slope deformations is called *index* or *parameter*.

Trigger factors directly cause landsliding in unfavourable conditions, for example by increasing the active forces acting on the slope (external causes), or reducing the shear strength of rocks inside the slope (internal causes). They are usually unexpected events that cannot be predicted by conventional deterministic models: e.g. earthquake, rapid rainfall, increasing of slope angle caused by lateral erosion during the storms and floods, various influences of anthropogenic activities (surcharge on slope with artificial fills, undercutting the slope toes, etc.). Trigger factors and events are not included in the presented methodology.

For solving of presented problems within GIS environment it is necessary to define each input parameter in a spatial form as *parametric map* (often termed as "index map"). The parametric map in digital form (vector or raster) represents a data coverage (theme) with polygon topology. In terms of vector graphics each polygon is given by a set of nodes (vertices) of border line, where the nodes are defined by pairs of coordinates (X, Y) in two-dimensional geographic space. For the methodology used in the present paper the raster format is more appropriate and recommended, which is the standard for using map algebra.

4.1.2. Review and progress of statistical methods in the landslide hazard assessment

Among the statistical methods, two groups of methods are the most important: bivariate and multivariate analyses. In the case of *bivariate analysis* each input parameter is compared separately with landslides inventory map. The advantage of the bivariate analysis is the possibility to weight each input parameter, calculated on the basis of the landslides density within each class of parameter. Weights for each input parameters are reflected in the final compilations of resulting maps.

The *multivariate analysis* considers mutual combination of several (or all) input parameters simultaneously with the landslide inventory map. The quasi-homogeneous *unique condition units (UCUs)* are created by combination of classes within each input parametric map. In this case the weights of individual parameters are not accepted, because the importance of each parameter is determined by its frequency and repeating the class of parameter in combinations within the UCU. The multivariate analysis also partially reflects the interaction and influences among different input factors.

The first case studies of statistical approach to landslide hazard assessment were published by Carrara (1983, 1988) and Carrara et al. (1990, 1991). Later on, several authors continued in this research, innovating and applying the issue of quantitative landslide hazard assessment using GIS in many areas (Atkinson & Massari, 1998; Guzzetti et al., 1999; Gupta & Joshi, 1990; Jäger & Wieczorek, 1994, etc.). The summary report of methodology of GIS application in the landslide hazard analysis is in the works of Carrara et al. (1995) and van Westen (1993). Van Westen (1993) discussed in detail basic principles of different approaches using bivariate (or univariate) analysis, as well as the multivariate analysis. Authors implemented the theoretical principles into the sophisticated program GISSIZ which practical manual was the second part of the publication (van Westen et al., 1993).

From practical point of view the following studies are notable: Irigaray & Chacón (1996); Clerici (2002); Süzen & Doyuran (2004); Joshi et al. (1997). Comprehensive summary of the landslide hazard assessment, short description and classification scheme of mostly used methods (including statistical methods) is presented in the work by Aleotti & Chowdhury (1999).

In Slovakia, except of a pioneer work by Vlčko et al. (1980), the application of exact quantitative methods of landslide hazard assessment was not systematically solved until early the turn of millennia. Since 2001 to 2012, several progressive works and studies as well as scientific publications dealing with the practical application of statistical methods in landslide hazard assessment have been created.

In the initial period, the studies were focused more in the theoretical principles of statistical methods and their practical application in selected areas predominantly in the scale 1:50,000 (Pauditš & Bednarik, 2002; Bednarik et al., 2005; Jurko et al., 2005; Pauditš et al., 2005, etc.). Later, the case studies and practical applications were focused in the landslide hazard maps creation in smaller areas in more detailed scales (Bednarik, 2007; Magulová, 2009; Petrýdesová, 2012).

At present, the attention is focused in specific theoretical and practical aspects of these methods (Bednarik & Pauditš, 2010) as well as a comprehensive assessment of larger areal units, including transboundary areas (Bednarik & Liščák, 2010; Holec et al., 2013).

The attention deserves a project titled "Engineering Geological Mapping of Slope Deformations in the Most Vulnerable Areas of the Flysch Zone" (Grman et al., 2011), in which the landslide hazard map of the north-west and north-eastern part of Slovakia with an area of 4,042.23 km^2, at a scale of 1:10,000 was created.

4.1.3. Terminology and principles of the raster data model and map algebra

Generally, the Geographic Information Systems (GIS) have been considered as a special type of IT systems where the most data have been fixed to spatially localized objects, phenomena or events (according to Clarke, 1999). One of the basic advantages of using GIS is the modelling and analysis of dynamic spatial processes by set of numerical and statistical methods (Tuček, 1998; Hofierka, 2003). In the case of raster data model the basic unit is presented by grid cell. Set of cells represents a regular numeric matrix in two-dimensional space *(grid)*. Each cell of raster is defined by a pair of coordinates in real two-dimensional geographic space and at least by one numeric attribute - quantifier, which represents the basic entry for mathematical operations.

The relation between the numerical values of cells in the grid can be continuous or discrete. In the case of continuous values smooth transitions exist between the neighbouring grid cells (e.g. continuously changed values of altitudes). Conversely, discrete data field has crisp boundaries between differently classified areas, without smooth transitions (it is not possible to present it in the form of isolines). The change in grid topology from continuous to discrete allows a *reclassification* process, by definition of intervals. On the other side, the *interpolation* process allows for calculating the empty space between the discrete input data (points or lines). In case of entry into the statistical analysis it is better to use the reclassified data fields (for example the slope angle divided into six intervals, the aspect into four quadrants, etc.).

The most frequently used analytical tool for processing of raster maps is *map algebra*. It provides the opportunities for manipulation of numeric values in the grid cells as elements of arithmetic expressions and functions. Programming procedures and calculations within the map algebra could be usually run using short scripts in command line environment. In the present paper utilization of map algebra environment of the *open source GIS GRASS* is recommended – the r.mapcalc package (Shapiro & Westervelt, 1992). In the past, the GRASS GIS environment was used in predicting landslide hazard and the creation of landslide susceptibility maps by Gupta & Joshi (1990); Jäger & Wieczorek (1994); Clerici (2002) and others. Statistical analyses were realized in GRASS system (r.stats package) connected with statistical software *R-statistical language* (Bivand, 2000).

4.2. Methodology overview

Methodical approach of landslide hazard maps creation by statistical methods in the Slovak Republic has been published repeatedly since 2002 and practically verified by several case studies. Development of the coherent methodology at the present time depends mainly on the relatively dynamic implementation of GIS technologies to geological practice. This trend is likely to influence also a development of related legislation, not only in Slovakia but also worldwide.

The methodology of statistical assessment and prognosis of landslide hazard is based on the appropriate selection of slope stability factors and their evaluation resting in a comparison with the occurrence of slope deformations in the study area. Based on the above, potential occurrence of landslides in future is expected in the same conditions as in the past, respectively at present. Set of factors, statistically assessed in GIS environment by comparison with the spatial distribution of registered landslides has been applied using the extrapolation to the field units in the whole assessed area, where it is also assumed the possibility of occurrence of slope deformations in analogical favourable conditions. A new prognostic map dividing the study area into the zones with different degrees of landslide susceptibility was created. The zones classified according to the statistical approach can be applied only in the area where the statistical assessment has been done, so the extrapolation has not a general application. Terrain units cannot be classified by the same way as in other areas where the conditions of landslide susceptibility can be different.

Based on the above, the main thesis and goals of this paper are:

- selection of the appropriate statistical methods for creating of landslide hazard map with regard to the implementation within GIS environment;
- proposal of methodology with respect to optimal possibilities of practical applications: data collection, statistical processing, final compilation of the resulting maps;
- practical verification of weighting calculations with subsequent determination of the relevance of various input parameters in the model area;
- practical application of the proposed methodology in the model area between Hlohovec and Sereď, creation of landslide hazard map of detailed scale (compatible with ZB GIS; Michalík, 2010), including all necessary attributes resulting from existing directives (Kováčik, 1996; Directive MoE SR, 1999);
- proposal of the most appropriate method for the practical use in future (with respect to data sources and data availability, legislation, geological conditions, landscape-ecological and urban aspects, etc.).

The progress of the works can be summarized as follows (Fig. 4.1):

Engineering geological mapping and landslides registration are required for statistical analysis and application of all mentioned methods. The landslides can be obtained from different types of data archives, maps or remote sensing images, etc. The field verification and supplementary mapping focused on the accurate position of entities is necessary.

Mapping of input parameters. Different natural and anthropogenic factors influencing the slope stability represent important input variables in the statistical analysis. Selection of the input factors is specific for each study area and widely depends on the individual assessment of conditions and professional experience of researcher. For example, the slope aspect more markedly influences the soil moisture in coastal areas with predominant winds in one direction (usually from the seaside), as in the inland where the wind direction does not influence so much. The weight of each factor in specific area can be exactly determined using methodology by Vlčko et al. (1980).

Implementation into GIS environment. Each input factor has to be quantified prior to entering the GIS and spatially expressed in the form of index map. At present sense of words, index map represents a system whose each component is represented by quantified parameter class.

Statistical analysis consists of comparing the index maps with landslides inventory map in GIS environment based on exact rules and statistical methods. In the presented study, the bivariate analysis with application of weighting of variables and conditional multivariate analysis were used. The result of the analysis represents the reclassification of input parameters according to susceptibility to landslides based on frequency of landslide occurrence in each parameter class.

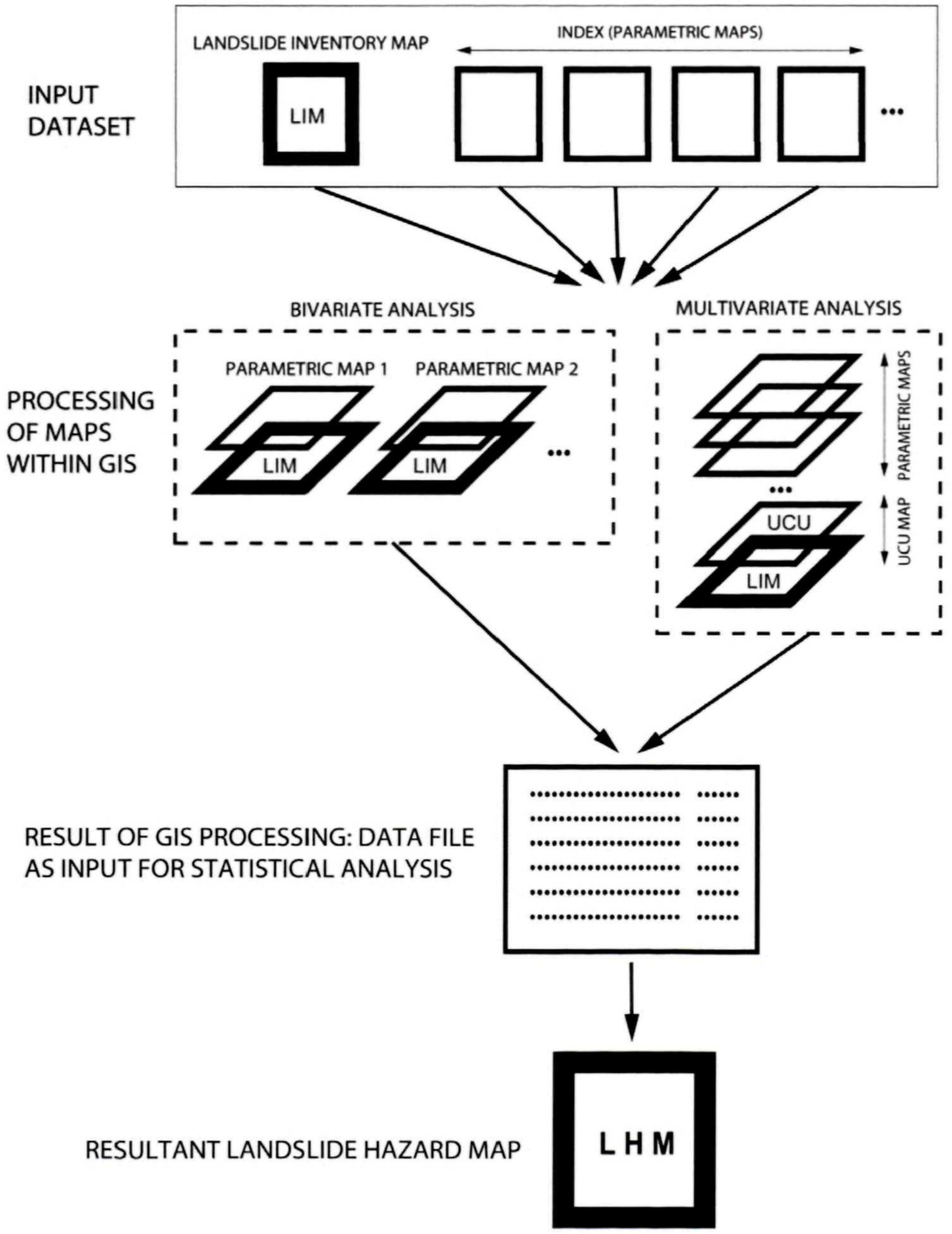

Fig. 4.1 Landslide hazard assessment schematic flowchart.

Compilation of the prognosis map is the final step of the whole methodology process. The distribution process and determination of the finite number of the zones in the map represents a creative and highly responsible part in terms of the final results, which depends on the individual approach of the investigator and used procedure.

4.2.1. Preparation of index maps

Technology of raster based GIS and map algebra assumes a precise preparation of the input index maps, often created by the conversion of primary vector data layers into raster format, which creates a basis for all statistical and mathematical operations.

Each index map in the GIS environment represents the spatial distribution of the parameter that enters into the statistical analysis. For the correct work with these maps in GIS environment, it is necessary to fulfil certain technical requirements. The basic requirement of each parametric map is its *positional accuracy*. Parametric maps are often derived from multiple sources: different thematic maps in various cartographic documents, digital vector maps in various projections, remote sensing data, satellite images, etc. Positional accuracy of such sources is often variable and results mainly from scale, method and precision of scanning and georeferencing.

In the Slovak Republic in the GIS environment most commonly used coordinate system is S-JTSK in Křovak cartographic reference. Despite the fact that its accuracy is being currently reevaluated, it is still officially supported coordinate system and most digital data (including topographic groundwork) are available within this system. For this reason, the cartographic data transformations among different coordinate systems are often necessary (e.g. from S-JTSK to UTM). This is usually connected with minor or major loss of positional accuracy.

In the former Czechoslovakia before the 1989, some public cartographic maps were deliberately distorted and deformed for strategic reasons. These distortions were strongly reflected mainly in the maps of small and medium scales. Later they were partially transferred also into digital map series (e.g. SVM 50 - seamless vector map 1:50,000) distributed by GKÚ SR, which currently cannot be considered as spatially accurate. Since 1989, all published map layers should contain correct positioning (in relation to the S-JTSK and its known position errors). Currently, the actual digital maps (e.g. ZB GIS; Michalík, 2010) have solved the problem of positional accuracy in detailed scales (so called "scaleless" map series).

Many thematic maps, which contain important information source for the input index maps were processed in the past and currently exist only in printed form. Therefore, for their entry into the GIS their digitization is needed. This includes for example: set of geological maps at a scale of 1:50,000, issued in SGIDŠ until the year 1992; synoptical engineering geological map of Slovakia from 1989 (PIGMAS, Matula et al., 1989) and many authors´ original manuscripts plotted on different topographic and elevation layouts. Some of these maps cannot be georeferenced with required precision and subsequently digitized, therefore, they are not considered as positionally accurate.

Despite the mentioned facts, for the correct subsequent processing the positional alignment of all input maps with topographic layouts (and also with each other) is necessary. Statistical methods require indispensable geographic accuracy and *correct superposition* of all input parametric maps. For mutual "superpositioning" of the digital maps derived from various sources serve different transformation algorithms (linear and polynomial transformation, *rubber-sheeting*), which are commonly implemented in GIS systems (e.g. the ADJUST in ESRI/ArcInfo^{TM}, i.rectify command in GRASS GIS, etc.).

Another important step, which is needed for conversion of vector layers into raster parametric maps, is the *topological correction,* which involves error corrections of polygon topology generated during digitization process and subsequent map editing. Among standard errors belong: snapping error and overshooting of lines to fitting point, missing fitting point, unclosed polygon, etc. Without correction of these seemingly minor technical errors the conversion to raster format would not be possible, which is the final stage of technical preparation of parametric maps. For topological correction, the BUILD and CLEAN commands are standard-used.

After the conversion to raster format, it is also necessary to adjust all input parametric maps in terms of the geometry of grid. This means that each parametric map must have the same grid geometry (same number of cells of the same size) within the assessed area; otherwise the results of statistical analyses could be highly distorted and unreliable. GRASS GIS system defines uniform geometry for all parametric maps already within the definition of the system variables (LOCATION/MAPSET) and these are fixed to all index maps of the same project.

The cell size is chosen based on the required precision and scale, eventually also depending on the required quality of the printed output. In general, for the data derived from maps of medium and large scales the cell size 10 x 10 m is adequate; more detailed grid with smaller cells takes inappropriate requirements on computing performance, but usually doesn't give higher information value in results.

In the model area in the present paper, the uniform defined grid of square cells of cell size 5 m is used, which in the whole area (89.40 km^2) represent 1,720 x 3,430 cells.

Index maps originally obtained or generated in raster form: e.g. DEM and its derived morphometric parameters (slope angle, curvature, etc.) primarily represent the distribution of input factor in form of a continuous grid. Therefore, they must be transformed into grids with discrete values separated by crisp boundary. Conversion process of continuous values into discrete intervals is called *reclassification*. Rules for the reclassification of various parametric maps may be different; mostly they are not based on exact procedures, but on the author's opinion and character of given input parameter in the assessed area.

The objective of the first reclassification of parametric maps is to get the minimum number of categories (classes) in each parametric map, in order to obtain the minimum number of final quasi-homogeneous units (UCUs) in combination with each other in the case of multivariate analysis. Either the maps without primary reclassification or maps with a large number of classes (e.g. the original geological map with many units) are used, the number of final UCUs in multivariate analysis will be enormous (nonsensical proportions in principle) and very difficult for final processing. On the other side, in the case of bivariate analysis, the weighting process containing determination of correlation coefficient is preferable to work with a lot of data contained in original non-reclassified parametric maps.

4.3. Bivariate analysis with determination of the weight of input parameters

In the case of bivariate analysis each parametric map is statistically compared with landslide inventory map separately. In simplified term, it is a comparison of two input parameters where one (the landslide inventory map) presents a dichotomous variable as the binary map with numeric values: 1 (TRUE) or 0 (FALSE). The result is a table containing a double combination, in which one of the numbers is a class in the parametric map and the second number (0 or 1) means the presence or absence of the landslide in given category.

Having in mind that the landslides map is usually expressed in the form of sequences of grid cells representing a scarp zone of landslide as the line, the number of landslides cells in each class of parameter is decisive. The result of combination is to determine a total number of cells with and without landslide scarps in each class of parameters.

The next step is the calculation of *density* within each class of parametric maps. The density represents a number of cells contained in the area with landslides in each class in proportion to the total number of cells in the parameter's class.

The density calculation is in principle relatively simple, while the landslide inventory map is expressed by dichotomy form of binary grid (0/1). Provided the landslides in parametric map are presented in the form of scarp lines (main scarp upper edge - MSUE; Clerici, 2002), the number of cells can be converted to the length of scarp (e.g. based on the ratio of the basic cell size and the diagonal; Jurko, 2003) and intensity of landslide activity in the study area was expressed by total length of MSUE (in meters)/1 km^2 of area of the parameter class. In the case of presentation of landslides entities as raster polygons, the number of cells has to be converted to total area (in m^2) and intensity was expressed as the percentage or per mille (Bednarik & Pauditš, 2010).

These calculations are obviously loaded with systematic errors, resulting from the approximation of cell size, but generally the cell size doesn't significantly influence accuracy and reliability of the calculation result of density value. For instance, for the 5 x 5 km area, the difference in accuracy with cell size 10 x 10 m and 2 x 2 m is of order of tenths of a percent.

This way obtained density generally expresses a frequency of landslide events in the parameter class. For example, by comparing the lithology factor with landslides inventory map it can be found that statistically most affected areas per basic area unit fall within flysch formation with a predominance of clayey soils, etc.

This indicates that usually the output maps have been highly influenced by the inaccuracies and errors during the preparation process of parametric maps, especially by differences in positional accuracy and mutual superposition. Results from non-coincident, spatially inaccurate and geometrically different maps cannot be considered as representative and may be misleading.

Based on the calculated density of the landslide occurrence, each parametric map can be secondarily reclassified, where newly assigned numeric value (replacing the first one) represents statistically determined landslide susceptibility separately for each parameter class (see Tab. 4.1). The reclassified parametric map is created, in which the highest numerical value represents the class most susceptible to sliding and on the other hand, the class with the lowest numerical value presents the lowest landslide susceptibility hazard.

Tab. 4.1: Example of secondary reclassification of input parametric maps with assignment of weighted classes' values (by Bednarik, 2001: Pauditš & Bednarik, 2002).

	Lithology	Slope	Elevation
Primary classes	1 2 3 4 5 6 7 8 9 10 11	1 2 3 4 5 6	1 2 3 4 5 6
Secondary reclassified classes	4 11 9 1 1 2 3 3 10 8 1	5 6 4 3 2 1	6 5 4 3 2 1

An outcome of the bivariate analysis is the final map of landslide hazard resulting from the weighted summation of all secondary reclassified parametric maps. Prior to the final summation it is necessary to determine the weight of each input parameter.

Another necessary step prior to the final summary is the equalisation of the number of classes in each input parametric map according to the parametric map with the largest number of classes (parameter z/m_i - equation 4.1). If this equalisation is not applied before the final summation, parametric maps with fewer classes would enter into the summary with distorted (undervalued) values, and therefore partially depreciate the weight of each parameter.

The equation for the final summation in the bivariate statistical analysis for the calculation of the weighting parameter as a whole is as follows:

$$y = \sum_{i=1}^{n} C * \frac{z}{m_i} * W_i \qquad (4.1)$$

y – value contained in final landslide hazard map;
i – the number of the input parametric maps (1, 2.....n);
z – the number of categories in the parametric map with the highest number of categories;
m_i – the number of categories in the relevant parametric map;
C – the value of class in secondary reclassified parametric map;
W_i – the weight of the input parameter.

The result of such summation is a continuous interval of values limited by the equalised summary of the lowest and highest values in each of the parametric maps in the whole study area.

Finally, the interval of values should be divided into a final number of classes, representing the zones of landslide hazard map. Current Directive of the Ministry of Environment of Slovak Republic issued to produce the landslide susceptibility maps (Kováčik, 1996; Directive MoE SR, 1999) indentifies three degrees (zones) of stability of the area: zone of the unstable areas, zone of the conditionally unstable areas and zone of the stable areas. The ranges (intervals) are advisable to be selected based on either an equitable distribution of the result to three equal parts, or more exact methods application (Pauditš et al., 2005; Pauditš, 2006). In other cases, a five level scale could be used: low, moderate, medium, high and very high susceptibility, which describes zoning area in more detail (Bednarik & Liščák, 2010; Holec et al., 2013; Petrýdesová, 2012).

4.3.1 Determination of weight of the input parameters

The weight of each input parameter indicates its relevance in the landslide hazard analysis. It determines the degree of correlation of values in the parametric map data with a constant value of 1 (TRUE), representing the occurrence of landslides. If the degree is high, it can be stated clearly that the parameter has a significant impact on the formation and distribution of slope deformations within the study area.

The principle of weighting determines the possibility to use the weight of input parameter value in the bivariate analysis only when the weighted value enters into the final summation of the secondary reclassified parametric maps. In the case of the multivariate analysis the weighting of values in that sense of word cannot be used, because when compared with the landslide inventory, all parametric maps enter simultaneously. Nevertheless, the weight of a parameter is possible to determine as a partial result of multivariate analysis – matrix of values combination of the all input parametric maps, based on the analysis of frequency and probability distributions by any standard statistical processes (Student's t-test, χ^2 test, etc.). This way obtained weight can be used only in the process of the bivariate analysis.

The methods of determination of the weight of input parameters could be various: as a whole, including all classes (Vlčko et al., 1980) or individual for each class (category) within the parametric map (van Westen, 1993; Donati & Turrini, 2002; Süzen & Doyuran, 2004). Each of the methods has some specifics and different usability in a given area. For example, in areas, where the dependence of the occurrence of landslide on certain factor, which lacks any category having some impact on the landslide occurrence, has been observed (e.g. northern quadrant of aspect), the low weight of such parameter as whole could be set falsely, whereas all the remaining classes didn't show significant statistical correlation. Therefore it is necessary to apply always such a weighting method, which takes into account the specificities of the study area and also the character values within input parameter maps. There is recommended to calculate the weight of each parameter separately for specific monitored area, or to use a subjective weighting method for each area.

In order to obtain the most exact result of calculating the weighting parameter it is necessary to work with the maximum input data set. Therefore, it is preferable to calculate the weight parameter prior to primary reclassification of parameters into classes. For example, if the weight for slope angle factor is calculated (using any method), it is better to use the original input floating point values (calculated with step of 1°), and not just a small number of classes after the reclassification. Similarly, it is necessary to follow the same way in all cases where the original grid exists in the form of continuous (floating point) data field.

In this paper, the determination of the weight parameter as a whole based on the value of entropy and information coefficient has been used. Practical approach, especially within the GIS environment, the exact method of determining the relevance and calculating the weight of individual input parameters was suggested by Vlčko et al. (1980). The present approach is based on the principle of the bivariate analysis, which determines the intensity of slope deformations occurrence (p_{ij}) in the individual classes of input parameters. Within the model area between Hlohovec and Sereď cities, 6 parameters were used: lithology, digital elevation model, slope angle, curvature of the relief, distance to stream and current land use. The way of determining the weight parameter as a whole is based on the determination of entropy (H_j) and maximum entropy (H_{jmax}) of the system according to the following equations:

$$H_j = -\sum_{i=1}^{S_j} \left[p_{ij} * \log_2(p_{ij}) \right] \qquad (4.2)$$

H_j – entropy;
S_j – number of components in system – classes in parametric map (j = 1... n);
p_{ij} – probability of the landslide occurrence in class of parameter (i = 1 ... S_j).

$$H_{j\max} = \log_2 * S_j \qquad (4.3)$$

$H_{j\,max}$ – maximum entropy;

S_j – number of classes in the parametric map, j = 1... n.

The information coefficient I_j is defined according to equation, for j = 1, 2… n:

$$I_j = \frac{H_{j\max} - H_j}{H_{j\max}} \qquad (4.4)$$

The result will be in range [0, 1]. When the closer is a result to 1, the more destabilizes the input parameter the system. The weight of the parameter W_i is the product of the information coefficient I_j and the average probability p_j (represents the real probability values for each classes of all parameters), for $j = 1, 2 \ldots n$:

$$W_i = I_j * p_j \qquad (4.5)$$

Calculated weight value of each parameter can be entered into the equation (4.1) as the value W_i for the determination of the resulting categories of landslide susceptibility in the bivariate analysis.

4.4. Conditional analysis

Multivariate analysis, in broad terms, is based on a comparison of the input parameters simultaneously as independent variables with landslides inventory map. The landslide inventory map (dichotomous variable) does not take into account only the value 1 (TRUE), but also the value 0 (FALSE), which is equally important informative value.

In the case of *conditional analysis* (Carrara et al., 1995; Chung et al., 1995; Clerici, 2002), the extensive table containing all combinations of the classes in all input parametric maps, which are in mutual superposition, has been obtained by mutual simultaneous combination of all input parameters. The combination of all classes in parametric maps creates new areal elements in interim map, which represents quasi-homogeneous units, so-called Unique *Condition Units* – UCU (Clerici, 2002). For instance, if the class 6 (10° – 15°) is superimposed on the map of slope angle, class 4 (Pleistocene terraces) in the map of lithology and class 3 (forest) in the map of land use, the resulting quasi-homogeneous unit will consist of combination [4.6.3], etc.

When comparing with landslide inventory map in this combination [4.6.3] the main scarp edges attain a total length XY m ([6.4.3.1]) and combination without landslides occupies a total area of the XY m^2 ([6.4.3.0]). The final table includes the same number of records (rows) as the total number of mutual combinations of all classes contained in the all input parametric maps, landslide inventory map included. This number may reach the order of several thousands.

Neither secondary reclassification nor weighting of parameters is necessary before entering the multivariate analysis. In this case, the weight of parameter (or class of parameter) is determined on the basis of certain value repeating in each parametric map. Frequency of repeating values in matrices of categories can be determined exactly by known statistical methods (e.g. χ^2). However, for the conditional multivariate analysis (Clerici, 2002) determination of weight (in above mentioned sense of word) is not substantiated.

As in the case of bivariate analysis, the final combination with landslides existence (value 1 in the landslide inventory map) has been set according to calculated intensity occurrence as a ratio between the number of UCU cells with landslides and the total area of UCUs. Results ordered in the upper rows of the table represent combinations of classes of the input parametric maps, which we may consider in terms of landslide susceptibility as the most dangerous.

In the position of the last rows are UCUs that contain a very small number of cells of the scarps. These can be caused by systematic errors during the parametric maps creation. Determination of the number of "error" cells must be done empirically, individually for each project, based on the quality of source data.

In the case of using a larger number of input parameters the UCUs may be affected by landslides in a very high share (up 100%), although their area is negligible (often 1 or 2 cells from several millions).Value of the intensity of landslides in such UCU is very high and moves such UCU to the highest ranking position in the statistical susceptibility assessment. Such cases cannot be avoided, but for example the UCU where the total number of grid cells is less than 50 can be ignored in the process of assessment.

Process of final categorization area to a specified number of zones can be based on the following principles (Jurko, 2003):

- calculation of the mean intensity of landslides (M_d - *mean density*) in the study area within the UCU, which is affected by landslides (MSUE value 1 in the landslide inventory map) based on the ratio of the total number of cells in a given area and the summary number of cells of the scarp zones. The average intensity of affected UCUs represents the mean value of the middle interval calculated in ‰:

$$M_d = \frac{N_{pix} MSUE}{N_{pix} total} * 1000 \qquad (4.6)$$

- the searched range of the interval of the landslides occurrence intensities in each combination (C_i - class interval) can be determined from the equation:

$$C_i = \frac{M_d * 2}{N_{inrervals}} \qquad (4.7)$$

- subsequently, total number of combinations in the areas affected by slope deformations were divided into a specified number of zones on the basis of the calculated interval range: 0 – C_i; (C_i +1) – (C_i * 2); [(C_i * 2) + 1] – (C_i * 3); ...etc. In the present paper, where the value of M_d = 3.307, the following five intervals were defined: **1.** 0 – 1.322, **2.** 1.322 – 2.646, **3.** 2.646 – 3.966, **4.** 3.966 – 5.288, **5.** >5.288 corresponding to 5 degrees of landslide hazard.

For the final classification of all existing combinations (UCU) into final landslide hazard zones (degrees), program in map algebra environment can be used (shell script; Clerici, 2002; Bednarik et al., 2005), or a spatial database environment with the use of SQL language. In the case of using the SQL relational database an extensive table, which contains the coordinates of the grid cells (or spatial extension), combinations values and new assigned categories of landslide susceptibility are processed. Number of rows (records in the table) can increase to millions, depending on the size of the reference area and raster resolution (cell size).

Processing of such amount of data is quite time-consuming and requires the high performance computing, even with the current availability of IT. Other technical way is to export an extensive table to an external database, allowing processing of spatial data in real geographic coordinates (e.g. PostGIS spatial database). Operations of exports and backward reloading the result into the GIS system are also time-consuming.

4.5. Compilation of resulting hazard map

In terms of methodology based on the "Directive of the Ministry of Environment of Slovak Republic" issued to compilation of the geofactors maps is the final map entitled: "Map of relative susceptibility of region to landsliding" prepared by the compilation of the following topics:

- coloured area zonation (zones and subzones);
- lithology (the class of lithological units shown by hatching);
- borderlines of landslide bodies;
- deformations caused by the undermining;
- elements of water erosion;
- tectonic features;
- hydrological and hydrogeological conditions;
- topographic groundwork.

Area zonation in final map is highlighted in coloured zones using the standard "semaphore" scale presenting the zone of stable areas (green), conditionally stable areas (yellow) and unstable areas (red). For better visualization, the colours can be highlighted using the hill-shade effect, as the map will have more "plastic" character and allows better orientation in map with respect to morphology.

Schematic lithology in the map is represented by transparent hatches, overlaying the basic colour zones. Hatches identify the typology of Pre-Quaternary rocks and Quaternary cover. Lithological classes are formed by merging classes of the original geological, respectively engineering geological maps and their number can be varied.

Special item in the map legend are *geodynamic phenomena*, which are divided into active (red), temporarily stabilized (purple) and stabilized (black). Slope deformations are classified into 6 groups: A. falling and toppling, B. earth flows, C. landslides in soils, D. creep deformations of rocks, E. block fields and rifts, F. creep deformation of soils (slope deposits). In each group more types of slope deformations are selected marked by individual symbols. Tectonic faults are shown in the form of lines different for Pre-Quaternary and for neotectonic active failures. Elements of water erosion (rills, gullies, etc.) are represented by red line entities.

4.6. Input index maps

The six input parameters have been evaluated in the present case study Hlohovec – Sereď, specifically: lithology, DEM, slope angle, curvature of the relief, distance to stream and current land use. DEM, slope angle and curvature of relief are the geomorphological factors. Each input parameter enters the statistical analyses in the form of raster index map, which technical preparation requires a precise approach (see above).

The positional accuracy of maps is adapted to binding topographic groundwork in the Slovak Republic - ZB GIS (Primary Base of Geographic Information Systems), applicable to a scale 1:10,000 and higher (up to detailed cadastral maps).

4.6.1. Lithology

In the term of presented methodology, the factor of geology converted into the index map of lithological units, has been considered as one of the most important assessed factors. Besides the character of lithology, in the landslide susceptibility assessment there has to be taken into account a structural characteristic of rock environment as a complex unit. Spatial distribution of lithological types significantly controls the formation and evolution of slope deformations in the study area. The main factors influencing the slope stability are engineering geological properties of rocks: physical properties (bulk density, permeability) and strength characteristics expressed by cohesion and angle of internal friction.

The map of lithological units in assessed area was primarily derived from digital geological map at 1:50,000 scale (Káčer et al., 2005), which has been subsequently modified and adjusted to 1:10,000 topography, mainly water streams in alluvial basins and valleys. The original 20 lithological units contained in the source geological map were reduced to 9 classes (primary reclassification) based on the similarity of the engineering geological properties (Fig. 4.2, Tab. 4.2). The largest spatial distribution in the selected area occupy the aeolian sediments represented by loess and loess loam (class 7), which are distributed in more than 46% of the whole area.

4.6.2. Geomorphology

Morphological parameters of georelief (slope angle and curvature of the relief) present secondary derivative obtained from digital elevation model (DEM) created in ArcGIS environment using the interpolation tool (Topo to Raster), that interpolates a hydrologically correct raster surface from point, line and polygon data. As an input data source for DEM creation the contour lines from 1:10,000 scaled topographic maps were used which have been geo-referenced to S-JTSK coordinate system. The final raster of DEM (cell size 5 x 5 m) represents a matrix of associated values of altitude with floating point, which was reclassified to integer values (discrete intervals) - *hypsographic levels*. Digital elevation model was reclassified into five classes and their spatial distribution is given in Fig. 4.2 and Tab. 4.3. The differences in altitudes are relatively small, only 180 m, and a bit more than 45% of the study area falls within the second class ranging from 140 to 180 m a. s. l.

Tab. 4.2 List of reclassified lithological units with ID number contained in origin geological map.

Class	Description
1	anthropogenic and organic-fluvial sediments (3, 38)
2	Holocene fluvial sediments (1, 24, 25)
3	Holocene proluvial sediments (26)
4	Pleistocene terraces (4, 5, 11, 28)
5	slope sediments (18, 20, 40)
6	outwash sediments (14, 124)
7	eolian sediments - loess and loess loam (16, 681)
8	Neogene sediments - predominantly gravels (22, 1721)
9	Neogene sediments - predominantly clays (23)

Slope angle belongs to the most important geomorphological factors, which significantly influences the slope stability. Each slope has a threshold value of slope angle, beyond which the slope begins to be unstable. In the digital form, the slope angle grid represents a matrix of values of angles in degrees. In the present study, the values of slope angle derived from DEM were reclassified into 9 classes (Tab. 4.3, Fig. 4.2) in terms of the methodology LANDEP (Miklós & Izakovičová, 1997). Tab. 4.3 shows that in the studied area dominates first class of very flat slopes (slope angle is less than 2°) which occupies more than 33% of the whole area. This class is characterized by the alluvial plain of the river Váh and the area isn't prone to sliding. Nevertheless, this class is relatively important in relation to accumulation zones of landslides. The areas, where the landslides are more frequent, take more than 53% (classes 5 and 6). Slopes with the angle value over the 17° (classes 7, 8, 9) occupy very small part - only 1.12% of the assessed area.

Curvature of the relief is the another geomorphologic factor derived from DEM. Curvature factor substantially affects the dynamics of the surface water flow over the relief (acceleration, convergence and divergence) and often is used in assessment of the vulnerability of areas to surface water erosion (Hofierka, 2003). Within GIS environment is possible to calculate several types of curvature (profile, tangential, mean, etc.). The most widely used type of curvature which was applied in this study is combination of curvature - combination of profile and plan form curvature. While the profile curvature affects the flow acceleration (influences on erosion and deposition), the plan curvature influences convergence and divergence of flow. Considering both kinds of curvatures together allows to understand more accurately the flow across a surface (www.esri.com, 2014). The resulting raster map of curvature of the relief (Fig. 4.2) was reclassified into three classes according to Pauditš (2005) and Bednarik (2007): convex (positive values), concave (negative values) and linear (values close to 0 – inflection points). During the reclassification process the following intervals were used (Pauditš, 2005): less than -0.00025 (concave forms); from -0.00025 to 0.00025 (linear forms) and values more than 0.00025 (convex form). The concave and convex relief forms were relatively evenly distributed in the assessed area with a slight predominance of convex forms (Tab. 4.3).

4.6.3. Distance to streams

Lateral erosion of stream may affect the stability of slopes undercutting the landslide toe, reducing the passive forces acting contra the sliding. At the same time the vicinity of a stream leads to increased water saturation of the rock environment.

The distance from the streams determined in the GIS environment can be realized using various distance analyses. The simplest way is to determine the two-dimensional space using Euclidean distance based on the straight-line distance. The Euclidean distance output raster contains the measured distance from every cell to the nearest source - streams. The distances are measured as the crow flies (Euclidean distance) in the projection units of the raster, such as feet or meters, and are computed from cell centre to cell centre.

The map is represented by grid distance of landslides from streams and rills. As a basis for compilation of parametric map distances to streams, detailed vector map of the river network was used. The final raster map was reclassified into 8 classes. In Tab. 4.3 the interval of the distance distribution area of streams is listed, as well as the spatial distribution of individual classes and cumulative expression of the distance area.

The highest percentage occupies the area remote from streams in range of 500 to 1,000 m (27.5 km^2). As already mentioned the largest influence on the formation and activation of landslides has the lateral erosion of streams and then the most important is the area closest to streams. All-in-all, within 250 m from streams is almost 25% of the study area, from which only 3% is up to 50 m.

4.6.4. Landcover

The parameter expresses the current land use, with focus on the character of the *vegetation cover*. The vegetation cover affects the slope stability mainly in terms of retention of rainfall, different ability of evapotranspiration and also the distribution and depth range of the root system. The state of vegetation cover also affects the resistance against erosion, which also partially affects the slope stability. The question of the vegetation cover and slope stability is thoroughly reviewed in the study of Greenway (1987).

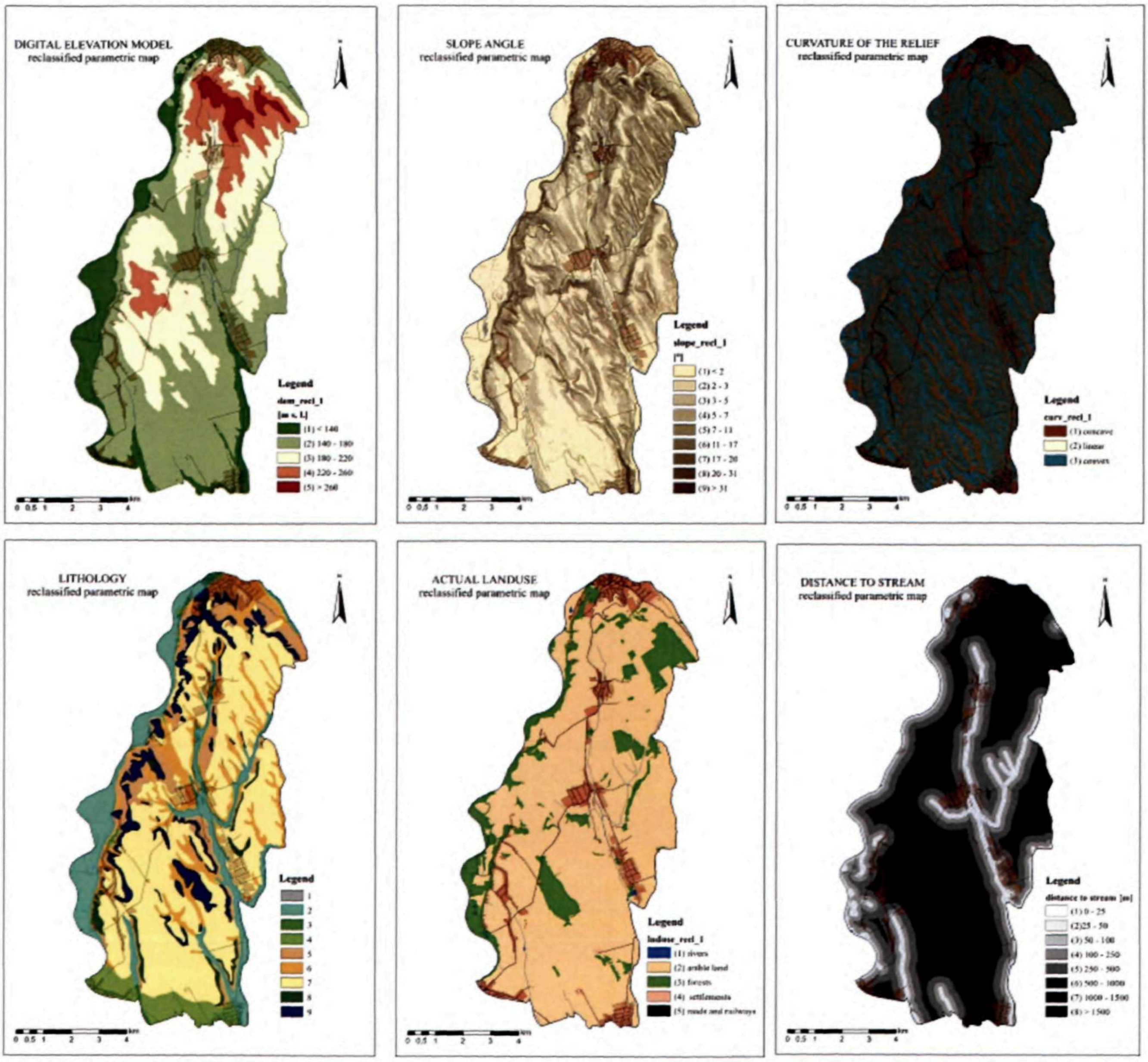

Fig. 4.2 Reclassified input parametric maps.

The map of actual land use was compiled from topographic raster images (scale 1: 10,000) provided by GKÚ in Bratislava. The map of current land use was divided into polygon features representing the elements of landscape structure and converted to raster format with cell size 5 x 5 m (Fig. 4.2). Spatial distribution of current land use classes is shown in Tab. 4.3. The case study area between Hlohovec and Sereď cities is predominantly exploited for agricultural purposes and therefore the most share represent the arable lands; up to 77.5% of the territory. Slope deformations, however, pose the greatest threat to the existing settlement and infrastructure, which together occupy 8.19% of the total assessed area.

4.6.5. Landslide inventory map

The landslide inventory map (Fig. 4.3) represents the most important input variable in statistical processing of landslide hazard analysis, which is compared with all parametric maps. It is presented as raster map containing dichotomous variable in binary grid form (0/1).

Within this study the interpretation of landslides in the form of lines presenting the main scarp zones (MSUE) was applied (Clerici, 2002; Bednarik & Pauditš, 2010). Using this form the landslide inventory is better interpreted as the entry of the entire landslide bodies including the accumulation zones. If the accumulation zones were included into the analysis, which often interfere to stable parts (e.g. alluvial plain), the final results would be significantly distorted and unreliable (Bednarik & Pauditš, 2010).

Overall, the slope deformations cover the area of 5.98 km^2 (597.98 ha) of the total area 89.4 km^2, so it constitutes 6.68% of the whole assessed area. However, the main scarp zones occupy markedly smaller part of the area, only 0.29 km^2 (0.32% of total area). The landslide occurrence in individual classes of input parameters is processed and presented in the following sections.

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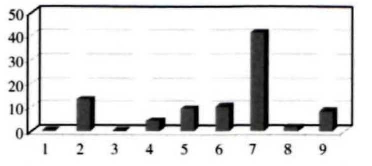
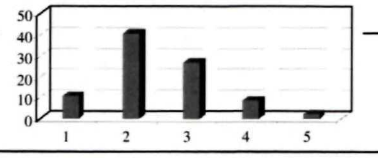
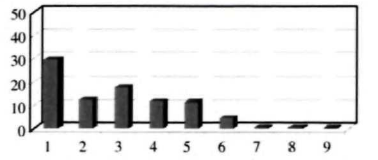
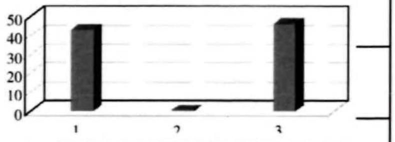
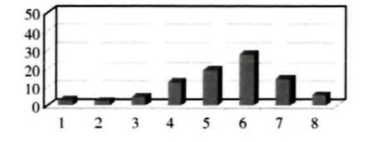
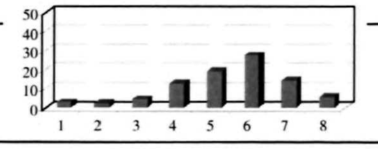
Tab. 4.3 Spatial distribution of input parameters.

Factor	Class	Description	Spatial distribution of classes		
			area S_t [km^2]	area S_t [%]	graphic visualization
lithology	1	anthropogenic and organic-fluvial sediments	0.1413	0,158	
	2	Holocene fluvial sediments	13,282	14,856	
	3	Holocene proluvial sediments	0,170	0,190	
	4	Pleistocene terraces	4,286	4,794	
	5	slope sediments	9,553	10,685	
	6	outwash sediments	10,240	11,453	
	7	eolian sediments - loess and loess loam	41,622	46,555	
	8	Neogene sediments - predominantly gravels	1,644	1,838	
	9	Neogene sediments - predominantly clays	8,467	9,471	
digital elevation model [m s. l.]	1	< 140	10,777	12,054	
	2	140 - 180	40,487	45,286	
	3	180 - 220	27,176	30,397	
	4	220 - 260	8,718	9,751	
	5	> 260	2,247	2,513	
slope angle [°]	1	< 2	29,636	33,148	
	2	2 – 3	12,502	13,984	
	3	3 – 5	17,747	19,851	
	4	5 – 7	11,644	13,024	
	5	7 – 11	11,470	12,830	
	6	11 – 17	4,658	5,210	
	7	17 – 20	0,739	0,827	
	8	20 – 31	0,799	0,893	
	9	> 31	0,209	0,234	
curvature	1	concave	42,928	48,015	
	2	linear	0,213	0,238	
	3	convex	46,264	51,747	
Euclidean distance to stream [m]	1	0 - 25	2,746	3,072	
	2	25 - 50	2,329	2,605	
	3	50 - 100	4,539	5,076	
	4	100 - 250	12,854	14,378	
	5	250 - 500	19,303	21,590	
	6	500 - 1000	27,508	30,769	
	7	1000 - 1500	14,342	16,041	
	8	> 1500	5,783	6,469	
actual land use	1	river network	0,132	0,147	
	2	arable land	69,369	77,591	
	3	forests	12,574	14,064	
	4	settlements	6,405	7,165	
	5	road and railway network	0,924	1,033	

4.7. Results

4.7.1. Bivariate analysis with weighted parameter as a whole

In terms of the methodology presented above, the all input parametric maps were analysed separately by statistical comparison with the landslides inventory map: lithology vs. landslides; slope angle vs. landslides, etc. Fig. 4.4 and Tab. 4.4 show the spatial distribution of landslides within classes of each parametric map. The mutual comparison resulted in the following findings:

- The landslides were the most abundant in slope sediments and Neogene clay sediments, where almost 70% of all scarp zones fall. These lithological units covered 20% of the whole assessed area. The Neogene sediments of clay character are generally considered as the sediments susceptible to sliding and to activation of slope deformations and landslide spatial distribution in study area has confirmed this definitely. More than 25% of the landslides were in the outwash sediments and aeolian sediments which covered almost 60% of study area.
- The occurrence of slope deformations is not significantly influenced by altitude and they are mostly concentrated in lower elevations (up to 220 m). This is mainly due to action of streams affecting the slope stability by lateral erosion in the past. Most of the landslides - 70% are in the class within the interval 140-180 m a. s. l. which occupies more than 45% of the whole area. Above 220 m a. s. l. (12% of the area) occur only less than 9% of all registered landslides.
- From a statistical comparison with the map of slope angle results that the most critical slopes are in the interval from 7° to 17°, where 53% of all landslides are located. Maximum occurrence, equalling to 28.6%, is in the 6th class with an interval of 11° to 17°. According to the classification by Hrašna (1980, in Matula et al., 1983) the landslides occurrence is concentrated in the class of gentle slopes with moderate slope angle (5° to 17°) where more than 61% of landslides are recorded. Steep slopes (>17°) occupy only 1.9% of the area but there are recorded up to 32.2% of the all scarp zones within this class.
- Although the relief curvature specifically affects the flow of masses on relief, spatial distribution of landslides occurrence in the concave and convex forms of curvature is nearly the same. Slightly prevalent are the convex forms of relief.
- The landslides occurrence depending on the distance to streams has been documented mainly in a range from 250 to 1,000 m, where 62% of the landslides are situated. The landslide occurrence in such a relatively

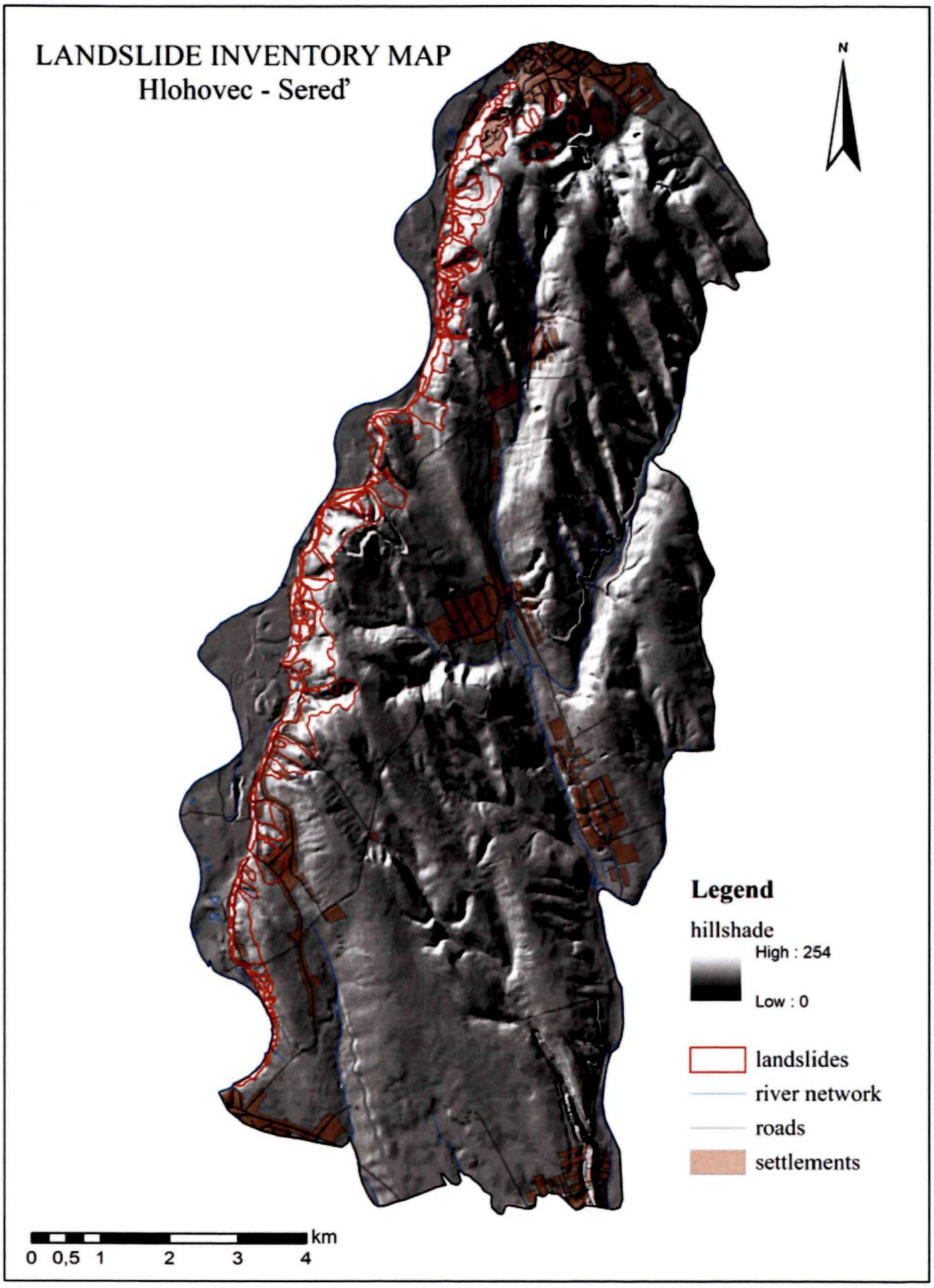


Fig.4.3 Landslide inventory map.

large distance from the stream is given by the width of the alluvial plain of the river Váh. Locally this width has been reduced (depending on the meandering of the river Váh) and within the distance 250 m occur 37% of the landslides.

- The study region is exploited mainly for the agricultural activities. The arable land together with forests occupies more than 90% of the study area and the landslides predominantly exist in these classes – 96%. Even though landslides affect also the settlements, roads and railways in relatively high percentage - 4%.

Based on the landslide density comparison, new numerical values for each class of parameter were assigned (secondary reclassification). The highest numerical value is given to class which is the most susceptible to landslides and the lowest value represents the class with the least tendency to sliding.

Subsequently the weight of each parameter was calculated according to the above mentioned methodology by Vlčko et al. (1980). The results are presented in Tab. 4.4, where the values of calculated weights (W_i) are shown and subsequently the partial results, sorted by the descen-

Tab. 4.4 Spatial distribution of classes, landslide occurrence within classes and partial calculations determining the weight of input parameters.

Input factor	Class	Spatial distribution of classes		Spatial distribution of landslides within the classes		p_{ij}	(p_{ij})	H_j	$H_{j\,(max)}$	$H_{j(max)}$-H_j	avgp_{ij}	I_j	W_i	recl_2
		S_t [km^2]	S_t [%]	S_z [km^2]	S_z [%]									
slope angle	1	29.636	33.148	0.003	1.015	0.0001	0.0006	2.117	3.170	1.053	0.020	0.332	0.006584	1
	2	12.502	13.984	0.003	0.930	0.0002	0.0012							2
	3	17.747	19.851	0.013	4.278	0.0007	0.0040							3
	4	11.644	13.024	0.023	7.913	0.0020	0.0113							4
	5	11.470	12.830	0.074	24.882	0.0064	0.0360							5
	6	4.658	5.210	0.085	28.686	0.0182	0.1021							6
	7	0.739	0.827	0.029	9.900	0.0396	0.2220							8
	8	0.799	0.893	0.058	19.699	0.0729	0.4089							9
	9	0.209	0.234	0.008	2.697	0.0382	0.2140							7
actual land use	1	0.132	0.147	0.000	0.000	0.000	0.000	1.355	2.322	0.967	0.004	0.417	0.001723	0
	2	69.369	77.591	0.106	35.974	0.002	0.074							3
	3	12.574	14.064	0.177	59.976	0.014	0.682							5
	4	6.405	7.165	0.009	2.891	0.001	0.065							2
	5	0.924	1.033	0.003	1.158	0.004	0.179							4
lithology	1	0.141	0.158	0.000	0.000	0.000	0.000	1.980	3.170	1.189	0.003	0.375	0.001293	0
	2	13.282	14.856	0.000	0.000	0.000	0.000							0
	3	0.170	0.190	0.000	0.000	0.000	0.000							0
	4	4.286	4.794	0.012	4.202	0.003	0.094							6
	5	9.553	10.685	0.152	51.319	0.016	0.512							9
	6	10.240	11.453	0.038	12.893	0.004	0.120							7
	7	41.622	46.555	0.037	12.597	0.001	0.029							4
	8	1.644	1.838	0.002	0.668	0.001	0.039							5
	9	8.467	9.471	0.054	18.321	0.006	0.206							8
distance to stream	1	2.746	3.072	0.001	0.499	0.001	0.024	2.341	3.000	0.659	0.003	0.220	0.000609	3
	2	2.329	2.605	0.005	1.666	0.002	0.095							4
	3	4.539	5.076	0.022	7.567	0.005	0.222							6
	4	12.854	14.378	0.082	27.866	0.006	0.289							8
	5	19.303	21.590	0.096	32.322	0.005	0.223							7
	6	27.508	30.769	0.089	30.081	0.003	0.146							5
	7	14.342	16.041	0.000	0.000	0.000	0.000							0
	8	5.783	6.469	0.000	0.000	0.000	0.000							0
curvature	1	42.928	48.015	0.127	42.780	0.003	0.431	1.173	1.585	0.412	0.002	0.260	0.000592	2
	2	0.213	0.238	0.000	0.017	0.000	0.034							1
	3	46.264	51.747	0.169	57.203	0.004	0.535							3
DEM	1	10.777	12.054	0.036	12.242	0.0034	0.3105	1.691	2.322	0.631	0.002	0.272	0.000588	4
	2	40.487	45.286	0.208	70.477	0.0051	0.4758							5
	3	27.176	30.397	0.046	15.413	0.0017	0.1550							3
	4	8.718	9.751	0.006	1.868	0.0006	0.0586							2
	5	2.247	2.513	0.000	0.000	0.0000	0.0000							0

ding weight value. The most significant effect on the formation and activation of slope deformations in the assessed area have the slope angle, actual land use and geological conditions.

The result of bivariate statistical analysis is the Landslide hazard map (Fig. 4.5) outgoing from the weighted summation of secondary reclassified maps. In GIS the equation (4.1) has the following form (4.8):

y = "dem_recl_2" * 1.8 * 0.000588312 + "slope_recl_2" * 1 * 0.006583607 + "curv_recl_2" * 3 * 0.000591835 + "gl_recl_2" * 1 * 0.001292551 + "vvt_recl_2" * 1.125 * 0.000608825 + "lnduse_recl_2" * 1.8 * 0.001723118 (4.8)

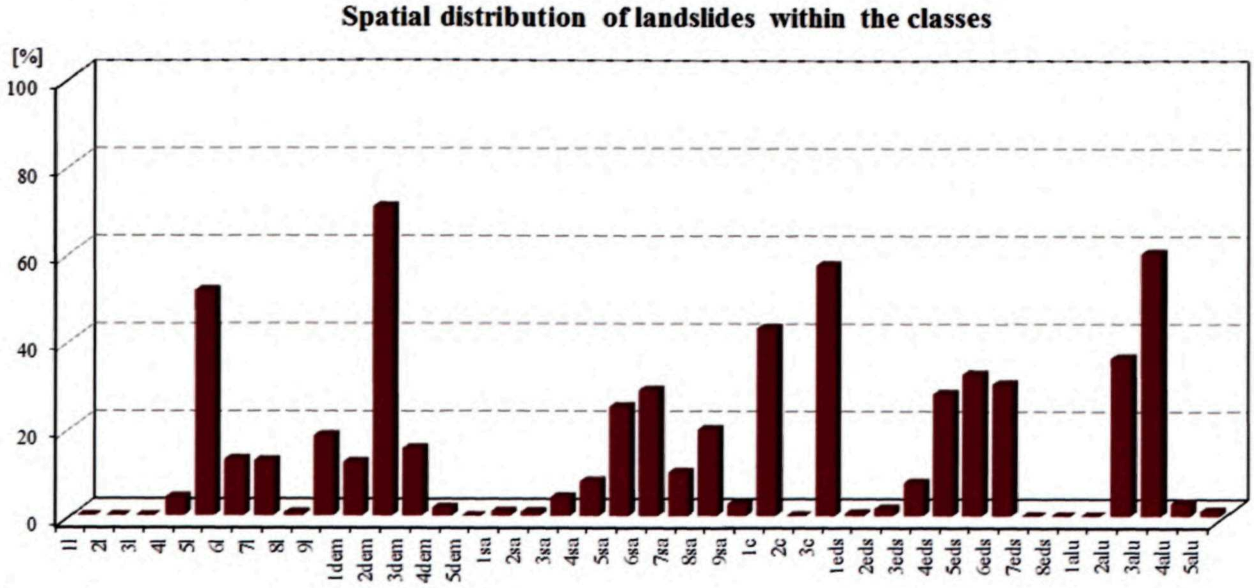


Fig. 4.4 Graphical view of spatial distribution of landslides within the classes, where: 1l - 9l means classes in lithological parametric map; 1dem - 5dem means classes in map of digital elevation model; 1sa – 9sa are classes in parametric map of slope angle; 1c - 3c means curvature of relief; 1eds - 7eds are classes of Euclidean distance to stream and 1alu - 5alu are classes of actual land use.

The result of the summation is a continuous interval of values <0.0146497; 0.102494>, which represents different degrees of landslide hazard. Generally, the final landslide hazard can be reclassified using various methods into three or five conventional classes. The final map was classified based on the method of *"Natural breaks – Jenks"* implemented in GIS into 5 classes with the following intervals:

1. Very low degree <0.014649742; 0.03807494>;
2. Low degree <0.03807494; 0.048754074>;
3. Moderate degree <0.048754074; 0.059777696>;
4. High degree <0.059777696; 0.075968641> ;
5. Very high degree <0.075968641; 0.102494232>.

The natural breaks classes are based on natural grouping inherent in the data and normal Gauss distribution according the mean values. The features are divided into classes whose thresholds are set according to relatively biggest difference in the data values (www.esri.com, 2014).

Spatial distribution of the landslide hazard classes is shown in Tab. 4.5. Very high degree of landslide susceptibility covered almost 3% and together with the class of high degree they occupy almost 17% of the assessed area. From simple verification, which consisted of comparing the areas of existing landslides and classes of very high and high degree of the landslide hazard (Tab. 4.5) was calculated, that in these two classes exist more than 90% of the landslides.

4.7.2. Multivariate conditional analysis

As already mentioned, the principle of conditional analysis is based on the simultaneous comparison of all input parameters as independent variables with a landslide inventory map. The output of the analysis of statistical processing in GIS environment represents the 6,648 possible combinations of input parameters, the quasi-homogenous units (UCUs). After the statistical comparison with landslides, 655 of UCUs were affected by landslides and the rest 5,993 combinations, the landslides have not been present.

Tab 4.6 shows an example of the output of the statistical combinations. The numbers within the first column represent the classes of input parameters in the following order: lithology – actual land use – distance to stream – curvature of relief – slope angle – digital elevation model. The second column of the table contains the number of cells (count) of the UCUs (N_{pix}) and in the third column are the cells of the UCUs containing the landslides N_{pix}(MSUE). The fourth column represents the density of the landslides (D) for each UCU calculated based on the ratio of the UCU count containing landslides and count of the total number of cells expressed in per mille (‰).

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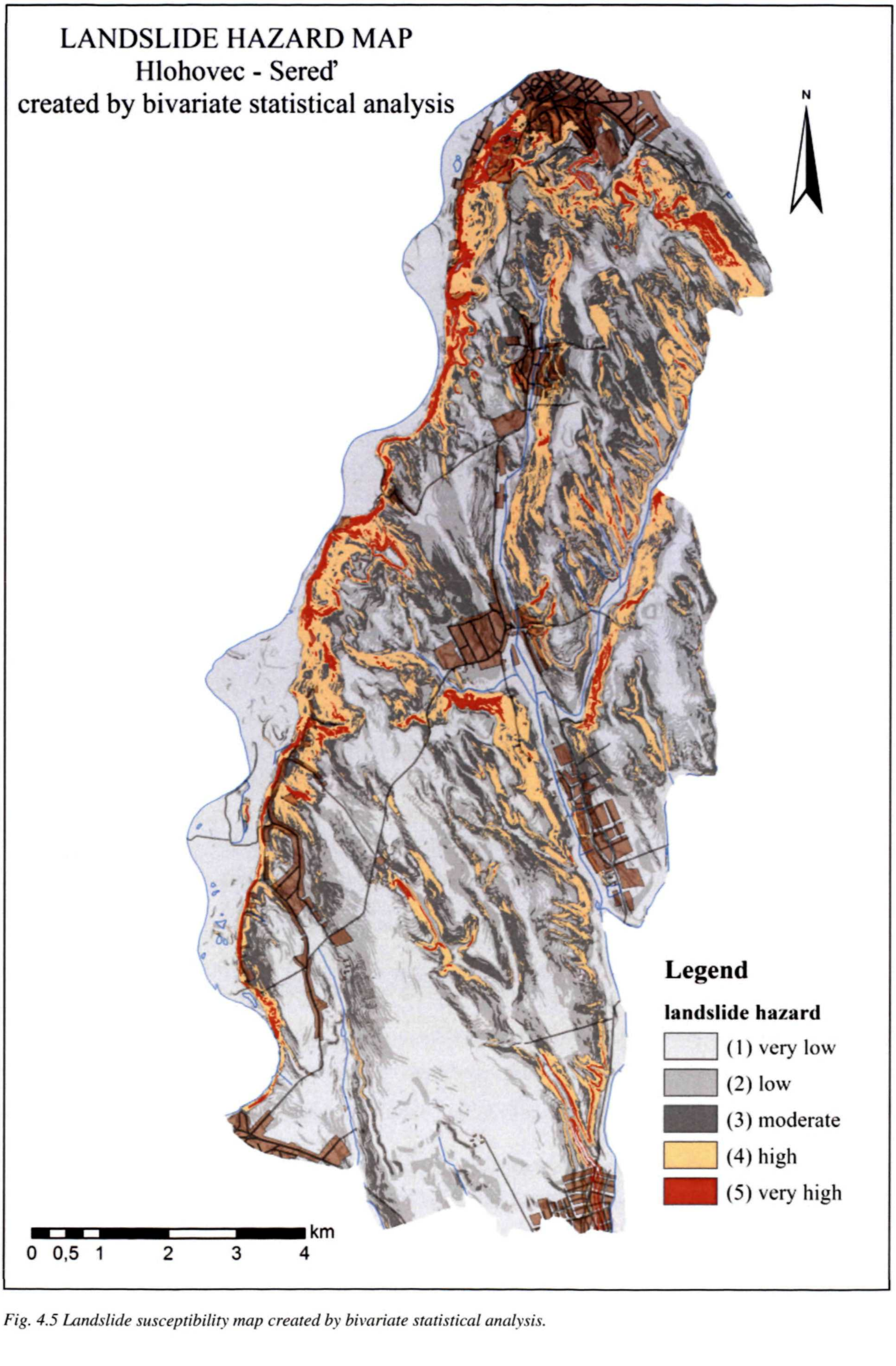

Fig. 4.5 Landslide susceptibility map created by bivariate statistical analysis.

The last column (susc.5) gives the degree of landslide susceptibility of the individual UCU. The comparison of the count of the UCUs with landslides in the whole study area and count of these MSUEs which are only contained within the 5th class of the landslide hazard, are given in Tab. 4.7.

Based on the Tab. 4.6 and Tab. 4.7 the following facts have resulted. The landslides occur mainly in the formation of slope sediments where there were recorded 231 combinations with landslides (from the overall 655) and the second class with the relative high frequency of landslides is linked to the class of the Neogene clay deposits. It means that these categories are mostly affected by sliding, which is in accord with the results of the bivariate analysis. The classes of the Holocene fluvial and proluvial sediments (2 and 3) are not influenced by landslides.

The second place in the first column belongs to the actual land use. Regarding the agriculture exploitation of the study region the most affected areas are the forests and arable land.

Tab. 4.5 Spatial distribution of classes of the landslide hazard and spatial distribution of landslides within the landslide hazard classes.

Class	Landslide hazard degree	Spatial distribution of classes		Spatial distribution of landslides within the classes [%]
		[km^2]	[%]	
1	very low	30.83	34.48	0.74
2	low	23.39	26.16	2.544
3	moderate	20.02	22.39	6.334
4	**high**	**12.74**	**14.25**	**31.25**
5	**very high**	**2.44**	**2.72**	**59.14**

Tab. 4.6 An example of multivariate statistical analysis results.

UCU	N_{pix}	N_{pix}(MSUE)	D	susc. 5
9.3.3.3.6.2	39	25	641.03	5
5.3.5.1.9.2	191	48	251.31	5
9.3.5.3.5.3	780	12	15.38	5
5.2.6.1.5.2	2884	38	13.18	4
9.2.6.1.5.3	7301	94	12.87	4
9.4.5.1.6.2	196	2	10.20	4
5.2.6.1.6.3	2486	25	10.06	4
9.3.4.1.5.2	101	1	9.90	3
9.2.6.3.5.4	4563	45	9.86	3
5.2.6.3.6.4	411	4	9.73	3
7.2.6.3.3.2	18982	76	4.00	2
9.2.5.1.2.3	259	1	3.86	2
9.3.3.3.8.2	261	1	3.83	2
9.2.6.3.4.4	1836	6	3.27	1
5.2.6.3.3.3	7645	24	3.14	1
9.2.6.1.2.4	340	1	2.94	1
5.2.6.1.1.3	2055	1	0	1
9.2.5.1.3.2	2634	1	0	1
9.2.5.1.5.2	2762	1	0	1

Tab. 4.7 The comparison of the count of the UCUs with landslides in the whole area and count of the UCUs with landslides contained only within the 5th class of the landslide hazard.

Parameter	Class	Count N_{pix}(MSUE)	Count N_{pix}(MSUE) in 5th class of landslide hazard
	1	0	0
	2	0	0
	3	0	0
	4	57	52
lithology	5	**231**	**171**
	6	144	122
	7	84	55
	8	13	6
	9	126	75
	1	0	0
	2	209	85
land use	3	**354**	**315**
	4	56	47
	5	36	34
	1	23	23
	2	43	41
	3	83	76
distance to stream	4	133	108
	5	**209**	**146**
	6	164	87
	7	0	0
	8	0	0
	1	**351**	208
curvature	2	2	2
	3	302	**271**
	1	18	9
	2	23	8
	3	50	22
	4	86	45
slope angle	5	**154**	111
	6	143	**116**
	7	86	81
	8	74	70
	9	21	19
	1	148	140
	2	**394**	**298**
DEM	3	86	39
	4	27	4
	5	0	0

Another important factor influencing the slope stability is the slope angle. From statistical combination results that the dominating are the slopes with angles from 7° to 17°, predominantly in combination with lithological classes 5 and 9. These results are very similar to those of the bivariate analysis. The final map (Fig. 4.6) was divided into 5 classes with the following intervals:

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Fig. 4.6 Landslide hazard map created by multivariate conditional statistical analysis.

1. Very low degree <0.0; 1.322 >;
2. Low degree <1.322; 2.646>;
3. Moderate degree <2.646; 3.966>;
4. High degree <3.966; 5.288> ;
5. Very high degree > 5.288.

The average intensity of the landslide occurrence M_d in the study area is 3.307‰ and based on the equation 4.7 the class interval C_i is 1.322. Due to elimination of random and technical errors the first interval was assigned to the UCUs without registered landslides – very low degree (5 993 UCUs). Spatial distribution of the landslide hazard classes is given in Tab. 4.8 along with the comparison of the areas of the existing landslides and classes of very high and high degree of the landslide hazard. In these two classes are almost 90% of the existing landslides.

Tab. 4.8 Spatial distribution of classes in the landslide hazard and spatial distribution of landslides within the landslide hazard classes.

Class	Landslide susceptibility degree	Spatial distribution of classes		Spatial distribution of landslides within the classes [%]
		[km^2]	[%]	
1	very low	80.85	90.43	3.66
2	low	2.52	2.81	3.97
3	moderate	1.05	1.17	2.98
4	**high**	**1.50**	**1.68**	**5.91**
5	**very high**	**3.49**	**3.90**	**83.48**

4.7.3. Comparison of the results of multivariate and bivariate analyses

From the results of both used statistical analyses (multivariate conditional and bivariate) the most unfavourable conditions of slope movements have been identified. The landslides occur mostly in the slope and Neogene clays sediments in forests and arable land with slope angle 7°-17° at an altitude 140-180 m a. s. l. The comprehensive assessment of the most and the least susceptibility categories of each parameter of study area is given in Tab. 4.9.

The most stable areas are in the Holocene fluvial and proluvial sediments which are situated close to streams (alluvial planes). Although the least susceptible categories of parameters distance to streams and digital elevation model are just in the areas where these lithological units are absent, this has been confirmed by the interpretation of the landslide geometry which entered to the process of statistical assessment. To the process of susceptibility assessment only the main scarp zones of landslides have been considered. There were not assessed the whole landslide bodies, because their accumulation parts interfere with these areas, which are stable in term of landslides activation; otherwise the results would be distorted.

Comparison of the spatial distribution of the landslide hazard classes created by different statistical methods is shown in Tab. 4.10 where the spatial distribution of landslides within the classes is also presented. Differences in the values represent various approaches in the used methodologies; any of them does not vary so much to identify result as diametrically different. The most reliable is considered the result of conditional multivariate analysis.

Within the verification process, the very high and high levels of landslide hazard are compared with the registered landslides. According to this assumption it can be stated that the difference between the multivariate and bivariate statistical analyses is only 1%. In the case of multivariate statistical analysis the 5th class is almost 25% higher than the 5th class of the bivariate analysis. First three classes are evenly distributed in both cases.

4.8. Discussion

All the mentioned procedures are time-consuming. In order to achieve the highest quality and most accurate results, the most time should be paid to preparation of the input parameter maps. This phase is the most sensitive to generate errors in the whole process, because these kinds of errors would be transmitted to the next steps of the assessment and negatively affect the result. Reliability of the results depends mainly on the precise approach to the preparation of input data.

4.8.1. Results comparison obtained from presented statistical methods

Based on the results obtained from both presented statistical methods it can be concluded that the mutual comparison shows a small advantage of multivariate conditional method compared to bivariate analysis with the application of weights, where some corrections are necessary and they are affected by high subjectivity and experience of the researcher.

Preference of conditional multivariate analysis rests in the principle of simultaneous use of all input parameters. The method works primarily with larger data set (more complex data file) and reflects the interactions between input parameters more sensitively. It is also more appropriate, because it better reflects the degree of influence of the main factors on the landslide hazard (geological setting, lithology, morphometric parameters). The map created by the multivariate analysis divides the area in more detail and the borders between zones are more sensitive to local spatial changes in natural conditions of the area, as in the case of the bivariate analysis. The sensitivity threshold follows from the character of the multivariate analysis (working with a quantity and variability of mutual combinations of parametric maps), but also depends on the precise approach to the final susceptibility zoning.

Another advantage of the multivariate method is relatively less-demanding on technical and time-consuming computers operations. The exception is the final reclassification into five susceptibility zones associated with the operation in relational databases and subsequent backward import of the result into the GIS environment. The intensity of operations depends on size of processed area that is directly proportional to the number of cells in the

Tab. 4.9 The assessment of the most and the least susceptible classes of each parameter.

Input parameter	The most susceptible category	The least susceptible category
slope angle	5, 6 (7°-17°)	1, 2 (< 2°)
actual land use	2, 3 (arable land; forests)	1 (rivers)
lithology	5, 9 (slope sediments; Neogene clays)	1, 2, 3 (anthropogenic; Holocene sediments)
distance to stream	5 (250-500 m)	7, 8 (>1000 m)
curvature	1 (concave)	2 (linear)
DEM	2 (140-180 m a. s. l.)	5 (> 260 m a. s. l.)

Tab. 4.10 The comparison of results of multivariate and bivariate analysis.

Class	Landslide hazard degree	Spatial distribution of classes		Spatial distribution of landslides within the classes	
		bivariate analysis [%]	multivariate analysis [%]	bivariate analysis [%]	multivariate analysis [%]
1	very low	34.48	90.44	0.74	3.66
2	low	26.16	2.81	2.54	3.97
3	moderate	22.39	1.17	6.33	2.98
4	**high**	**14.25**	**1.68**	**31.25**	**5.91**
5	**very high**	**2.72**	**3.90**	**59.14**	**83.48**

area, which determines number of records in a database table. These time-consuming operations are not automatic, the interactive input of a project researcher is not required, and therefore the process is less prone to the creating of random errors, in contrast to the lengthy and laborious calculation of the weights by the bivariate analysis.

In the case of the bivariate analysis the major problem is the calculation of weights. The paper presents a method based on the degree of entropy of the system, represented by the parametric map, where the components of the system are represented by calculated value of intensity of landslide occurrence in each class of parametric maps. Despite complying with the methodology, the result does not sufficiently reflect objective reality and the susceptibility map compiled by the bivariate analysis without subsequent subjective modification of weights is not possible to recommend in future.

For future processing with statistical methods for landslide susceptibility assessment in GIS environment, we recommend the use of *conditional multivariate analysis*. This sophisticated methodology could be also binding in the future and included in the wording of the amended Directive for the compilation of landslide susceptibility maps of the Slovak Republic, as one of the possible and useful exact methods of the landslide hazard assessment.

4.8.2. Comparison of the presented methodology with existing empirical approaches

Regarding the assessment of principal advantages (or disadvantages) of statistical methods of the landslide hazard analysis using GIS compared to commonly used empirical methods, the following facts can be clearly stated:

- advantage of quantitative statistical approaches compared to the geotechnical model, for example, based on the analysis on physico-mechanical properties, is better availability of input data. Their obtaining is not so technically and financially demanding as for the required amount of physical parameters; this fact exactly favours the use of statistical methods in wide areas in regional scales;
- providing that the all of the above mentioned principles and rules will be adopted, the statistical methods allow for more complex results in GIS. This way, in the landslide hazard analysis those exact parameters could be included that have not been assessed only visually and empirically within standard approach (e.g. slope angle), respectively they have not been rated at all (average rainfall, slope length, etc.);
- vulnerability of both statistical methods is mainly in the accuracy of the input data: maps of varying quality from different sources, scales and coordinate systems, transformation and correlation issues, and as already mentioned a subjective approach to the precision within the preparation of parametric maps; all of these items highly influence the final results;
- despite the comprehensive approach to the data preparation, the mentioned processes are susceptible to the random and systematic errors generated mainly due to their complexity;
- the possibility of a subjective approach of these methods shall be limited to the selection of input parameters, selection rules for the first reclassification of parametric maps, selection of statistical methods and finally, the control and correction of partial results (especially in bivariate analysis), compared to the classical heuristic method, where the individual approach and expertise of researcher has been applied more significantly especially within the compilation of final maps.

4.8.3. Evaluation of the usability of presented methods and perspective of its utilization in future

The perspectives of the use of the presented methods for predicting landslide hazard are quite promising. In Slovakia, the creation of landslide susceptibility maps at a scale of 1:50,000 is part of the set of "Maps of the Environmental Geofactors" (Directive of MoE SR, 1999). After a successful pilot project of detailed landslide mapping and landslide hazard assessment at detailed scale realized in the Flysch Formation (Grman et al., 2011) real assumption of the project extension to the other part of Slovakia is arising. Therefore, it is necessary to prepare the binding methodology for creating these maps supported by the use of modern information technologies based on GIS.

Currently, the use of GIS technology has been more intensely applied in geological practice in Slovakia. Legislative and technical aspects of the use of GIS are regulated mainly by several directives of INSPIRE, as well as outdated Directive of MoE SR published in 2000, which obliges the researchers of geo-environmental projects to submit the resultant data in digital form in the GIS format.

4.9. Conclusions

In the paper the compilation of the landslide hazard map using statistical methods in GIS and implementation of these methods in the model area Hlohovec - Sereď is presented. Two, in the world most widely used quantitative statistical methods are used: the bivariate method using the weights of input variables and the multivariate conditional analysis. The weighting method takes into account the weights of input parameters as a whole based on the entropy of the system where individual components are represented by parameter classes (categories).

Statistical approaches are based on the assumption that landslides will occur preferably under the same conditions, as they occurred in the past and at present. The processed results are based on a statistical comparison of input parameter maps, representing relevant input factors, with a landslides inventory map.

Based on the evaluation of methodology and results obtained in the present study, the application of the conditional multivariate analysis has been recommended for the future reference and for its implementation in the binding methodology. The advantages are mainly in considering the interactions between input factors; a lower degree of subjectivity (as well as lower susceptibility to generation of random errors) in the assessment of input factors, working with the complex data sets and a higher sensitivity of the final map to local changes in conditions in the study area. Despite the possibility of the weighting of each input parameter in the process of bivariate analysis (compared with multivariate analysis) the disadvantages represent mainly the impossibility of interactions correction between input parameters and their calculated weights as well as improper modification of partial results. On the other hand, the possibility of correction of partial results allows better application of individual approach and the researcher's expertise.

Presented methods are conceptually simple; but their application is quite complicated and requires a lot of experience, especially with the use of computer technology and geo-informatics. Compared with previously used empirical processes, the applied methods are more exact and generally less burdened by subjective approach.

Application of the present methodology and techniques in the landslide hazard assessment in standard practice is promising. However, some improvements are necessary, especially in to current legislation, which should respond to the implementation of geoinformation technologies in professional practice.

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