# Landslide susceptibility map of Liptovska kotlina basin using GIS

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**Abstract**: The aim of the study was to prepare a landslide susceptibility map of a region of about 500 km$^2$ between two of the most famous mountain areas in Slovakia, the High and Low Tatras, situated in the north-central part of Slovakia. The area of study, the Liptovska kotlina basin and adjacent slopes, represents the gateway to those touristically very attractive places. The area is formed of flysch highlands and inter-montane basins where a large density of landslides is concentrated. Hence, for further development of the area, it is vital to assess the probability of future landslide occurrence. For this purpose, the statistical approach (bivariate method) based on GIS (Geographical Information System), has been applied to assess the landslide hazard of that area. The bivariate method consists of a statistical comparison between landslide distribution as the dependant variable and a number of separate instability factors (input parameters). This approach makes it possible to calculate the 'weight' of an individual input parameter. The method is based on the assumption that landslides will always occur in the same geological, geomorphological, hydrogeological and climatic conditions as in the past and the procedure considers a number of environmental factors that are thought to be connected with landslide occurrence.

The following input parameters were compared and analysed: lithology, annual precipitation, slope angle, land-cover and total length of main scarps. The data layers, in which each factor was subdivided into a convenient number of classes, were separately overlain and statistically compared with the landslide inventory map. Subsequently, the landslide density was calculated and the weighted value was determined for each individual class. The final landslide susceptibility value was expressed as the sum of all parameter classes ranked according to the calculated landslide density for each class.

**Résumé**: Le but de l'étude était de préparer une carte de susceptibilité d'éboulement d'une région d'environ 500 km2 entre deux des secteurs de montagne les plus célèbres en Slovaquie, le haut et bas Tatras, situé dans la région du centre-nord de la Slovaquie. Le bassin de kotlina de Liptovska avec les pentes adjacentes, comme domaine d'étude, représente le passage à ces endroits touristically très attrayants. Le secteur entier est constitué des montagnes de flysch et des bassins entre montagnes où un grand nombre d'éboulements de Slovakian sont concentrés. Par conséquent, pour le développement ultérieur du secteur, il est essentiel d'évaluer la probabilité de la future occurrence d'éboulement. À cette fin, l'approche statistique (méthode bivariate) basée sur des GIS (système d'information géographique), a été appliquée pour évaluer le risque d'éboulement de ce secteur. La méthode bivariate se compose d'une comparaison statistique entre la distribution d'éboulement comme variable dépendente et un certain nombre de facteurs d'instabilité (paramètres d'entrée) séparément. Cette approche permet pour calculer le « poids » d'un paramètre individuel d'entrée. Fondamentalement, la méthode est fondée sur l'hypothèse que les éboulements se produiront toujours en mêmes conditions géologiques, géomorphologiques, hydrogéologiques et climatiques que dans le passé. Le procédé considère un certain nombre de facteurs environnementaux, qui sont pensés pour être reliés à l'occurrence d'éboulement.

Les paramètres suivants d'entrée ont été comparés et analysés : la lithologie, précipitation annuelle, angle de pente, terre-couvrent et se montent à la longueur des escarpements principaux. Les couches données, dans lesquelles chaque facteur a été subdivisé en nombre commode de classes, ont été séparément recouvertes et statistiquement comparées à la carte d'inventaire d'éboulement. Plus tard, la densité d'éboulement a été calculée et la valeur pesée a été déterminée pour chaque classe individuelle. La valeur finale de susceptibilité d'éboulement a été exprimée pendant que la somme de toutes les classes de paramètre se rangeait selon la densité calculée d'éboulement pour chaque classe.

**Keywords**: data analysis, engineering geology maps, geographic information systems, geological hazards, landslides

# INTRODUCTION

In recent years the international interest in landslide hazard, risk and susceptibility maps has extended widely. The reasons for the increasing international interest in landslides are twofold. Firstly it is the result of an increasing awareness of the socio-economic significance of landslides and secondly, there is the increased pressure of development and urbanization on the environment (Aleotti & Chowdhury 1999). Landslide hazard maps are widely used in resource, land use and development planning, and in the design of linear projects such as transportation routes. Among new technologies and approaches for predicting natural hazards and mitigating their impacts to a society, GIS (Geographical Information Systems) have played an important role in order to collect, store, analyze and display large sets of geographically referenced data. It has also facilitated development of new more reliable models which better simulate and reflect real sites. GIS has enhanced the possibilities of systematic mapping of large regions and increased significantly the productivity of mapping procedures. The purpose of most of the methodologies has been the identification and assessment of areas most favourable to landslides. In that respect, the aim of this study was to prepare a landslide susceptibility map of a region of about 500 km$^2$ between two of the most famous mountain ranges in Slovakia, The High and The Low Tatras, situated in the north-central part of Slovakia. The area of study, the Liptovska kotlina basin (Figure 1) and adjacent slopes, represents the gateway to those touristically very attractive places. The area comprises flysch highlands and intermountain basins, where the majority of landslides in Slovakia are concentrated and therefore with regard to further development of the area, it was vital to assess the probability of future landslide occurrence.


**Figure 1.** Geographic location of Liptovska kotlina basin in the north – central part Slovakia

# APPROACH

There are various techniques evaluating landslide susceptibility (landslide hazard) although quantitative, mostly statistical methods are used (van Westen 1993; Aleotti & Chowdhury 1999). They are based on the comparison and subsequent statistical analysis of factors identified as influencing instability within the area affected by landslides. At present the statistical methods applied in landslide hazard assessment are distinguished into two groups: bivariate and multivariate (vanWesten 1993; Aleotti a Chowdhury 1999). To accomplish the aim of this study, the statistical approach (bivariate method) based on GIS, has been applied to assess the landslide hazard of that area. The multivariate method, which compares relationships between relevant environmental factors and the occurrence of landslides over a given study area, had been applied to evaluate landslide hazard (Jurko, Paudits & Vlcko 2005). The bivariate method consists of a statistical comparison between landslide distribution, as the dependant variable, and a number of separate instability factors (input parameters). The methods are based on the assumption that landslides will always occur in the same geological, geomorphological, hydrogeological and climatic conditions as in the past and the procedure considers a number of environmental factors thought to be connected with landslide occurrence. This approach makes it possible to calculate the 'weight' of an individual input parameter. Traditional ways for obtaining weighted values are based either on empirical methods or exact methods as have already been extensively published (e.g. van Westen 1993; Vl ko, Wagner & Rychlikova 1980). In our case, the weighted value used to categorize every parameter is expressed by the entropy index (2), maximum entropy index (3) and information coefficient of system instability (4) (Vlcko *et al.* 1980).

Although the applied procedure is particularly suited for GIS operations, it requires an intensive sequence of operations with an irregular data distribution. A fundamental condition to entering into GIS operations is precise and complex input data preparation. Aerial distribution of each evaluated parameter is in GRASS GIS (Neteler a Mitášová 2002), presented in the raster format parametric maps. The fundamental technical requirements to compile parametric maps are spatial and cartographic accuracy, correct mutual superposition and correct topology and grid geometry.

# INPUT DATA

Six parameters were compared and analyzed, lithology, annual precipitation, slope angle, land-cover and total length of main scarps. For the purpose of the statistical analysis, the total numbers of classes within the input parameters were desired in order to avoid difficulties with evaluating the statistical reports, as this may result in thousands of small, statistically meaningless units being generated during the statistical analysis itself. Most of them are the result of errors in data collection and digitization and can be cancelled out. Furthermore, it should be considered that numerous units resulting from statistical analysis may occupy small parts of the investigated area and so they can be neglected.

## *Geological setting*

As a source of the geological settings, the geological map of theLiptovska kotlina basin (Marsina, Gross and Halouzka 1996) was used. As there was the need to reduce the number of input classes for the various factors, the 46 original lithological units displayed in the input map were grouped into 9 classes with similar lithological and engineering properties. Table 1 shows partial statistical results representing territorial distribution of the lithological units. It is obvious that the study area is predominantly formed by Paleogene flysh-like rocks and Quaternary soils.

Table 1. Reclassification of the geological settings

| Class | Lithology | Area (%) | km$^2$ |
|---|---|---|---|
| 1. | Fluvial sediments | 24.53 | 121.8 |
| 2. | Proluvial sediments | 0.51 | 2.55 |
| 3. | Glacifluvial sediments | 17.28 | 85.8 |
| 4. | Organic sediments | 0.13 | 0.63 |
| 5. | Deluvial (slope) sediments | 22.19 | 110.13 |
| 6. | Flysh deposits (sandstone/claystone 1:1) | 18.68 | 98.75 |
| 7. | Flysh-predominance of claystones | 9.59 | 47.61 |
| 8. | Conglomerates | 2.34 | 11.62 |
| 9. | Mezozoic rocks | 4.75 | 23.6 |

## *Slope angle*

In order to evaluate the geomorphological conditions of the study area, only the angle of slopes with sufficient characteristics were considered and entered into the analysis. A Digital Elevation Model (DEM) was therefore created to derive slope angles. These were calculated from the DEM produced from the geographic map 1: 50 000 (SVM – 50), similar to Paudits and Bednarik (2002). Slope data, computed in 1-degree steps (floating points), were grouped into 6 classes after Hrašna (1986). The parametric map of slope angles produced contains values ranging from 0° to 40. 4°. Statistical evaluation of slope classes within the study area is given in Table 2.

**Table 2.** Reclassification of slope angles

| Class | Angle | Area %) | km$^2$ |
|---|---|---|---|
| 1. | 0 - 2 ° | 24.53 | 121.8 |
| 2. | 3 - 6 ° | 0.51 | 2.55 |
| 3. | 7 - 10 ° | 17.28 | 85.8 |
| 4. | 11 - 14 ° | 0.13 | 0.63 |
| 5. | 15 - 19 ° | 22.19 | 110.13 |
| 6. | > 19 ° | 18.68 | 92.75 |

## *Land use*

The land use input data presenting vegetation cover of the study area were adopted from the CORINE – Landcover map (Feranec a O ahel 1996). Based on the same condition as described above, 17 original units found in the input map were reclassified into 8 classes (land use units) with similar properties. Table 3 indicates aerial distribution of the reclassified land use units.

**Table 3.** Reclassification of land use

| Class | Land use | Area %) | km$^2$ |
|---|---|---|---|
| 1. | Settlements and industrial estates | 9.75 | 48.42 |
| 2. | Meadows and pastures | 37.39 | 185.66 |
| 3. | Greenwoods | 0.55 | 2.67 |
| 4. | Conifer forest | 7.58 | 37.64 |
| 5. | Mixed forest | 0.53 | 2.66 |
| 6. | Fields and plantations | 39.12 | 194.23 |
| 7. | Transition forest – bush area | 0.89 | 4.4 |
| 8. | Water areas | 4.19 | 20.81 |

## *Precipitation*

Rainfall data were incorporated into the evaluation procedure as an important condition of landslide origin not as a triggering factor. 3D interpolation of mean rainfall data, gained by long term monitoring from the whole territory of Slovakia, was utilized to interpret spatial distribution of precipitation (Hofierka *et al.* 2002). Authors of this model considered series of precipitation from 435 meteorological stations throughout Slovakia during the years 1976 - 1995. The precipitation data were reclassified into 5 classes (Table. 4), while each class threshold was defined by a 10 % increase of the upper limit of the previous class interval.

**Table 4.** Reclassification of precipitation

| Class | Precipitation | Area %) | km2 |
|---|---|---|---|
| 1. | 600-660 | 22.57 | 112.4 |
| 2. | 661-720 | 37.65 | 186.34 |
| 3. | 721-790 | 35.59 | 177.01 |
| 4. | 791-870 | 3.79 | 18.74 |
| 5. | >871 | 0.41 | 2.01 |

### *Landslide inventory map*

As a source of data representing an important and significant input parameter, the map of relative landslide susceptibility from the region Ružomberok – Liptovský Mikuláš at 1: 50 000 scale (Baliak *et al.* 1997) was used. All landslides were digitalized regardless of their activity and type etc. and no other detailed classification was considered. It should be noted that landslides as the dependent variable were entered into the analysis and were presented by the main scarp upper edge (MSUE). Since the method claims to identify the conditions where the landslides originated, the upper edge of the landslide main scarp was assumed as the slope failure and therefore the landslides origin (Clerici 2002). It is commonly known, that in a landslide it is possible to identify two different zones, the upper part or depletion zone, where a landslide is generated, and a lower part or accumulation zone, which is affected by material transported from the upper zone. Assuming the main scarp upper edge as the place of landslide origin allows us to acquire more accurate and reliable statistical information considering the landslide body area. In such a cases when displaced material within accumulation zone is covering one type (class) of environment (factor), and the main scarp is located in a different environment, statistical analysis methods may lead to statistical inaccuracy.

## BIVARIATE ANALYSIS

The procedure including data import, production of the parametric maps, reclassification, spatial and statistical analysis, was carried out using GIS GRASS environment. Prepared input parameters were entered into the analysis in the form of parametric maps, where the factors were subdivided into the convenient number of classes as mentioned above. All the parametric maps present spatial distribution of the factors being considered and were incorporated into statistical analysis separately in to be combined with the dependent variable (the landslide distribution map represented by main scarp upper edge). The ratio of the number of grid cells representing the main scarp to the overall area of a class defines the landslide density within each class of a parameter (Figure 2).

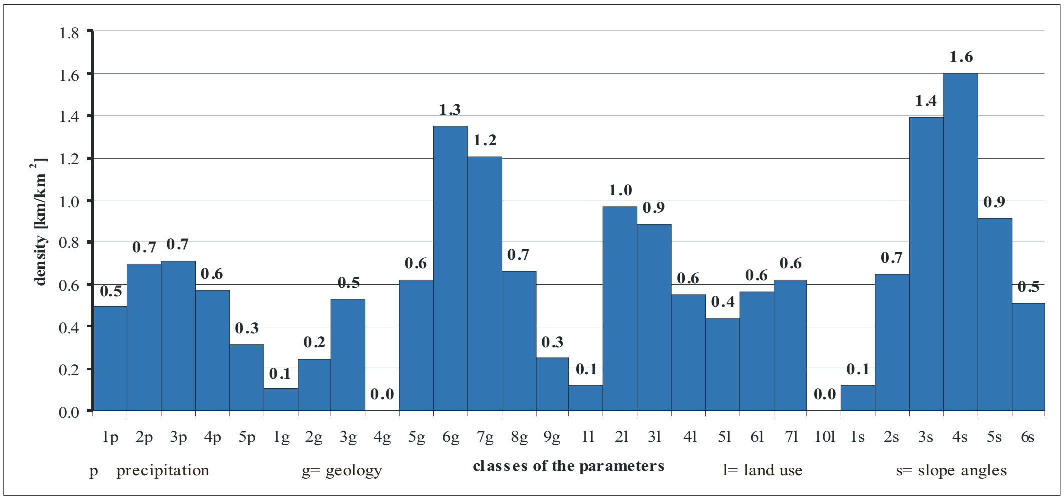


**Figure 2.** Landslide density within each class of analysed parameters

The landslide density was obtained by dividing the total length of the main scarp upper edge (in km) by the area (in $km^2$) of the particular class. In this way the computed landslide density corresponds to the intensity of landslide activity for a particular class of a parameter. Based on the landslide density secondary classification was performed, which resulted in assigning a new category for each class of all the parameters (Table 5). New categories were sorted in descending order, which reflects decreasing degree of the potential for future landslide occurrence. All classes of all parameters were examined and consequently reclassified and sorted

**Table 5.** Based on the landslide density reclassified lithological units

| Class | Lithology | Area (%) | $km^2$ | Landslide density | Secondary class category |
|---|---|---|---|---|---|
| 1. | Fluvial sediments | 24.53 | 121.8 | 0.10 | 2 |
| 2. | Proluvial sediments | 0.51 | 2.55 | 0.24 | 3 |
| 3. | Glacifluvial sediments | 17.28 | 85.8 | 0.53 | 5 |
| 4. | Organic sediments | 0.13 | 0.63 | 0 | 1 |
| 5. | Deluvial (slope) sediments | 22.19 | 110.13 | 0.62 | 6 |
| 6. | Flysh deposits (sandstone/claystone 1:1) | 18.68 | 98.75 | 1.35 | 9 |
| 7. | Flysh-predominance of claystones | 9.59 | 47.61 | 1.20 | 8 |
| 8. | Conglomerates | 2.34 | 11.62 | 0.66 | 7 |
| 9. | Mezozoic rocks | 4.75 | 23.6 | 0.25 | 4 |

The final susceptibility value (1) is expressed by the sum of all parameter classes, ranked according to the calculated landslide density for each class:

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

Where ***y*** is the sum of all the classes; ***i*** is the number of particular parametric map (1,2, ...n); ***z*** is the number of classes within parametric map with the greatest number of classes; $\boldsymbol{m_i}$ is the number of classes within particular parametric map; ***C*** is the value of the class after secondary classification and $\boldsymbol{W}_i$ is the weight of a parameter.

A procedure described by Vlcko *et al.* (1980) was applied to obtain weighted values for each of the parameters. The method is based on the principle of bivariate analysis, where the density of slope failures within a certain parameter is determined. The way in which the weight of the whole parameter is acquired, starts from calculating the entropy index (2), the maximum entropy index (3) and information coefficient of system instability (4) in accordance with the sequence of the equation (Rao 1978):

$$H_j = \sum_{i=1}^{S_j} (p_{ij}) * \log_2 (p_{ij}) \qquad (2)$$

Where $H_j$ is entropy index, $S_j$ is the number of categories (classes) in a parametric map (j = 1,... n), $p_{ij}$ is a slope failure probability within each class (weight of a class), (i =1,... $S_j$).

$$H_{j\max} \max = \log_2 s_j \qquad (3)$$

Where $H_{jmax}$ is maximum entropy, $S_j$ is the number of categories (classes) in a parametric map (j = 1,... n).

$$I_j = \frac{H_{j\max} - H_j}{H_{j\max}} \qquad (4)$$

Where $I_j$ is an information coefficient of system instability for (j = 1,... n).

The result varies from 0 – 1. The closer the value is to the number 1, the greater the instability is. Subsequently, the unknown weight of a parameter is defined as:

$$W_i = I_j * p_j$$

Where $I_j$ is an information coefficient of system instability for (j = 1,... n) and $p_j$ is a slope failure probability for (j =1,... n).

## RESULTS

The landslide density was calculated for each class resulting from the statistical comparison. The obtained landslide density provided an input attribute for calculating the weights of each whole parameter as mentioned above. Adopting this procedure (Vlcko *et al.* 1980) the obtained weight for each parameter was as a follows:

| | |
|---|---|
| Lithological | units |
| Slope | angles |
| Land | use |
| Precipitation | |

According to our results, the most important parameter that affects landslide occurrence is the lithology. The most irrelevant appeared to be the annual precipitation. Considering the assumption that "the past and present are keys to the future" (Carrara et. al. 1995) landslide density may provide some indication on the probability of future landslide occurrence. In addition, newly categorized and sorted classes (Table 5) were entered into the final summation (1), where the greatest value was assigned to the class with the most favorable conditions for landslide origin. In our case the equation (1) acquired followed the form:

$$y = \frac{9}{9} * \text{lk\_geology} * 2.05 + \frac{9}{8} * \text{lk\_landuse} * 0.61 + \frac{9}{6} * \text{lk\_slope} * 0.94 + \frac{9}{5} * \text{lk\_precipitation} * 0.13$$

After the final summation, a range of values within the range 5.67 – 33.57 was determined. The interval was subsequently subdivided into 3 classes of landslide susceptibility and a new landslide susceptibility map was compiled. The interval from 5 – 15 represents the zone of low landslide susceptibility, the interval from 16 – 24 the zone of medium landslide susceptibility and the interval from 25 – 34 represents the zone of high landslide susceptibility (Figure 3).

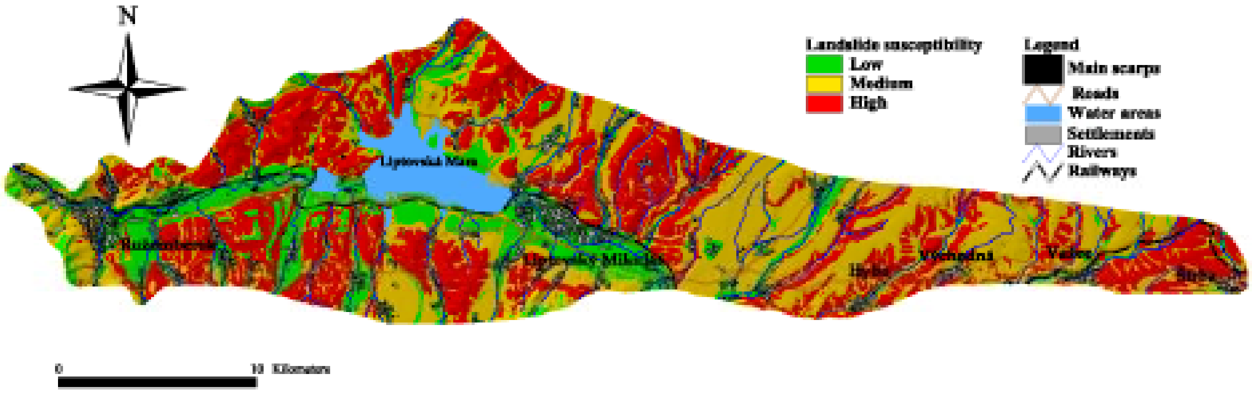


**Figure 3.** Landslide susceptibility map

## CONCLUSIONS

Applying the bivariate statistical method the most favourable conditions for landslide origin were found to be in the territory formed by flysh- like rocks, where sandstones and claystones are in ratio 1: 1 (class 6), with a slope angle of 11 – 14° (class 4), a mean annual rainfall of 721 – 790 mm (class 3) and where meadows and pastures (class 2) form the land cover. The landslide densities of another combination consisting of flysh - with claystone dominancy (class 7), slopes varying from 7 – 10° (class 3) and covered by greenwoods (class 3), with a mean annual precipitation of 661 – 720 mm (class 2) are distinct from the other classes of the parameters. The wide varieties of these classes tend to identify the most landslide prone areas.

The application of weighting to parameters as well as the subjectivity and experience of the researcher in the decision process (classifying and grouping input parameters), along with capabilities to fully exploit GIS tools for data acquisition, processing and analysis, make the adopted method reliable and relevant in evaluating landslide hazard. However, by anticipating the most reliable results using GIS tools, it requires skilful users who should be able to fully exploit the capabilities of GIS and who are familiar with the phenomena and processes under study.

Another aspect affecting landslide hazard assessment is uncertainty of input data. Input data are always affected by errors that cannot be commonly evaluated or omitted and the process requires time consuming treatment of data.

It can be concluded that the cooperation of multidisciplinary approaches where experienced landslide investigators, GIS experts and statisticians cooperate together, the result in a reliable hazard assessment being achieved.

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# REFERENCES

ALEOTTI, P. & CHOWDHURY, R., 1999. Landslide hazard assesment : summary review and new perspectives. In: *Bull. of Engineering geology and Environment*. Vol. **58**, No. 1, p. 21 – 44.

BALIAK, F., MALGOT, J. *et al.*, 1996. Map of relative slope failure susceptibility In: Pramuka, S. *et al.*, *Set of The Regional maps of environment geofactors of The High Tatras and Ružomberok – Liptovský Mikuláš in scale 1 : 50 000*, Bratislava

CARRARA A., CARDINALI, M., GUZZETTI, F. & REICHENBACH, P., 1995, GIS-based techniques for mapping landslide hazard. (electronic publication http://deis158.deis.unibo.it).

CLERICI, A., 2002. A GRASS GIS based Shell script for Landslide Susceptibility Zonation by the Conditional Analysis method. *Proccedings of the open source GIS – GRASS users conference 2002 – Trento*, Italy.

FERANEC, J., O AHEL, J., 1996. CORINE - landcover. Bratislava: Geographical Institute, SAV.

HOFIERKA, J., PARAJKA, J., MITAŠOVÁ, H. & MITÁŠ, L., 2002, Multivariate Interpolation of Precipitatio using Regularized Spline with Tension. In: WILSON, JP., FOTHERINGHAM, AS. & HUNTER, GJ. (ED.). *Transactions in GIS*. Los Angeles: University of Southern California, **6**(2), p. 135 – 150.

HRAŠNA, M., 1986, Map of Engineering Geological Zoning. Zborník referátov z vedeckej konferencie: *Progresívne smery v inžinierskogeologickom výskume*, Bratislava, PRIF UK, ss. 68 – 82 (in Slovak).

JURKO, J., PAUDITS, P., VLCKO, J. 2005. Landslide Susceptibility Zonation using GIS – statistical approach, *International symposium on latest natural disasters*, Sofia, on CD.

MARSINA, K.(ED.), GROSS, P., HALOUZKA, R., 1996. Geological Map. In: Pramuka, S. *et al.*, *Set of The Regional maps of environment geofactors of The High Tatras and Ružomberok – Liptovský Mikuláš in scale 1 : 50 000*, Bratislava.

NETELER, M., MITÁŠOVÁ, H., 2002. *Open source GIS : A GRASS GIS approach*. USA: Kluvert Academic Publisher, 435 s.

PAUDITŠ, P., BEDNARIK, M., 2002. Using Grass in evaluation of landslide susceptibility in Handlovská kotlina basin. *Proccedings of the open source GIS – GRASS users conference 2002 – Trento*, Italy.

RAO, R.C. 1978. *Lineární metody statistické indukce a jejich aplikace*. Praha, Academia. 666 s (in Czech)

VAN WESTEN, C.J. 1993. GISSIZ. Training Package for Geographic Information Systems in Slope Instability Zonation. Part 1: Theory. UNESCO – ITC Project on „Geo-Information for Environmentally Sound Management of Natural Resources“. Enschede, Netherlands.

VL KO, J., WAGNER, P. & RYCHLÍKOVÁ, Z. 1980. Spôsob hodnotenia stability svahov vä ších územných celkov. *Mineralia Slovaca*, **12**, (3), ss. 275-283, (in Slovak).