Mineralia Slovaca, 42 (2010), 193 – 204
ISSN 0369-2086

Landslide susceptibility assessment in Slovakia

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Abstract

The paper deals with a bivariate statistical landslide susceptibility assessment for the territory of Slovakia. The input data provided the Atlas of the slope stability maps of the Slovak Republic at a scale 1 : 50 000 and the digital map of Quaternary Genetical Types of Slovakia at a scale 1 : 500 000. Altogether 21 190 slope deformations covering the area of 2 575.912 km^2 registered in the Landslide Atlas pose either damage or the threat for 5.25 % of the area of the Slovak Republic, which equals to 49 036.30 km^2. The geological input created 19 Categories of both Quaternary cover and Pre-Quaternary bedrock retrieved through reclassifying of former 31 genetic types. Besides the parametric map which contains an information on the geological setting of Slovakia, the further input parametric maps in the process of bivariate statistical analysis are DEM (Digital Elevation Model) derivatives – slope angle and the slope aspect. The DEM was retrieved from the topography of Slovakia at a scale 1 : 10 000 with grid cell size 20 x 20 m. The output of this study is the prognostic map of landslides. The prognosis relates to spatial distribution only, the time-dependence of the susceptibility is not analysed due to the lack of relevant information of this kind.

Key words: slope failures, landslide susceptibility assessment, Quaternary cover, DEM, morphometric parameters, GIS, Slovakia

Introduction

Expected climate change is considered to be one of the most serious threats to sustainable development with the adverse impacts on the environment, human health, food supply safety, natural resources and the infrastructure. Occurrence of the extreme climate phenomena, droughts, floods, landslides, extremely high and low temperatures will be probably more frequent due to the global changes of the climate.

The landslide susceptibility assessment supported by statistical methods is based on assumption that mass movements will occur in analogical conditions as those ruling in the past or recently. The statistical approach is therefore based on a comparison of the set of conditions (factors) which stand for environment with spatial distribution of registered mass movements. Therefore, for the assessment it is necessary to select relevant parameters with the high level of credibility.

The geological setting of Slovakia is suitable for evolution of the slope failures. This has been confirmed by the great amount of slope deformations which were identified in two major inventory projects of the Slovak engineering geology.

The momentum for systematic research of the slope deformations in the former Czechoslovakia gave a catastrophic landslide in the town of Handlová, which in 1960/1961 destroyed 150 housing units, water pipeline, state road and electric line. The sliding volumes equalled to 20 mil. m^3 (Záruba and Mencl, 1969).

The case of the Handlová landslide and several others has shown that stabilization of the active slope deformations is far more expensive than preventive measures. Another important finding represents the fact that the slope movements are recurrent in the areas of old landslides, mainly.

In the light of the above stated the next logical step in the research into the slope deformations was their inventory; this effort has contributed to a development of prominent school of Czechoslovak engineering geologists dealing with landslides around Nemčok a. o. (for instance, Nemčok, 1982). The inventory project lasted over 30 years and the results of this stage were summed up in the paper by Modlitba and Klukanová (1996), estimating an amount of about 15 000 identified slope deformations throughout Slovakia.

The next important project of the "Atlas of slope stability maps of the Slovak Republic at 1 : 50 000 scale" (Landslide Atlas) covered a period from 1997 till 2006. It was based upon the previous inventory; nevertheless the number of the identified landslides increased significantly to 21 190 and the added value is also an estimation of the territory susceptibility to slope deformation (Kopecký et al., 2008). We have to note that the main susceptibility criteria were geology and the slope angle, but only in the sense of quality, without any quantification.

A new approach in the regional Slovak landslide school was brought by the studies of the slope stability, susceptibility and hazard/risk assessment of Pauditš and Bednarik (2002a, b), Bednarik et al. (2005), Pauditš (2005), Pauditš et al. (2005), Pauditš and Bednarik (2006), Bednarik (2007), Liščák, Bednarik and Feranec (2009) at the level of the landslide hazard and risk assessment. The methodology for the above studies was provided in numerous contributions by various authors. The first paper dealing with a statistical approach was published more 25 years ago by Carrara (1983, 1988), and later, the author modified his original methodology to the GIS environment (1990, 1991). The term "apparatus" for statistical evaluation of landslide hazards is well defined in both papers mentioned above, and also in Brabb (1985). A quantitative statistical approach in the world literature has been widely used since the early 1990s. Most interesting is Van Westen´s (1993) work dealing in details with univariate (bivariate) and multivariate statistical analysis as well as the landslide susceptibility analysis, the information value method and weight of evidence modelling. The landslide hazard assessment reached a high theoretical and practical level in the last decade (Irigaray and Chacón, 1996; Aleotti and Chowdhury, 1999; Dai et al., 2001; Dai et al., 2002; Donati and Turrini, 2002; Clerici, 2002; Clerici et al., 2006; Süzen and Doyuran, 2004; Castellanos and Van Westen, 2007; etc.).

The bivariate statistical analysis is based on the comparison between a landslide inventory map as a dependent variable and all the separate input parametric maps (lithology/landslides, slope angle/landslides, etc.). This approach allows calculation of weights for each input variable. Here-in, the weighting process is based on the methodology proposed by Vlčko et al. (1980). The weight value for each separate parameter is expressed as an entropy index.

The final prognostic landslide susceptibility map was created by a simple summation of the weighted multiplications of secondary reclassified parametric maps. The result of this summation is a continuous interval of values and it represents various levels of landslide susceptibility, generally divided into three or five conventional categories.

Input parametric maps

The landslide susceptibility assessment methodology solutions in a GIS environment are based upon suitable selection of those factors, which play a dominant role in the slope stability state. The evaluated input factors reflect geological conditions, climatic and hydrologic conditions, morphometric characteristics of the relief. The landslide susceptibility assessment statistical processing is outgoing from an axiom of actualism, so there is valid that the landslides in the future will occur under the same conditions like in the past. Selected factors are processed as parametric maps in the raster form with 20 x 20 m cell size for the morphometric characteristics and the landslide inventory map and in this form they enter in the statistical processing, underpinned by the map algebra in a GIS environment.

Lithology

To date, more than 90 % of Slovakian territory is covered by the basic geological maps at the scale of 1 : 50 000. However, for a better visualization of geological characteristics, these maps suppress the Quaternary cover (as a rule, complexes more than 5 m thick are depicted). Naturally, for the slope failure evolution, the Quaternary cover is of utmost importance, therefore we have used the brand-new map of the Quaternary cover (Maglay et al., 2009).

Quaternary genetical deposit types

Besides many common features with the older geological periods, the Quaternary witnessed some specifics, like global cyclic climatic changes in stages – the alternation of cooler and warmer periods (glacials and interglacials). The older part of the Quaternary with the glacials supremacy is termed as the Pleistocene and the younger one as the Holocene.

The dominant feature of the Quaternary was the continental and mountain glaciation of extensive areas of the Earth´s surface, which directly and indirectly influenced the deposition of the sedimentary rocks. The areas out of glaciation, so-called the periglacial ones, to which also the Slovak territory had belonged, manifest a specific climate and development of the Quaternary deposits. The dominant among sediments are the terrestrial ones, covering about two thirds of the territory. They are represented by the glacial and mainly fluvioglacial high mountains sediments, which fill up river valleys bottoms, depressions and Quaternary basins. The aeolian wind-blown deposits deposited in lowlands and uplands, the colluvial deposits developed on slopes. Other typical Quaternary sediments are travertines and calcareous tufas along springs, and peats. In the Quaternary the volcanic activity on the Slovak territory terminated, with lava basalt effusions and surges of gaseous explosions (maars) in the Southern Slovakia and in the Štiavnické vrchy Mts.

The Quaternary deposits evolved sometimes under very different geological conditions, depending on various exogenous and endogenous factors. This is why they are so variable. Their spatial distribution on the Slovak territory is illustrated on the Map of the Quaternary cover (Maglay et al., 2009), which distinguished 31 Quaternary and Pre-Quaternary genetic types in the geological setting of Slovakia. We reclassified them into 19 categories in order to simplify the statistical analysis of this input parameter (Fig. 1, Tab. 1).

Category 1: **The glacial sediments** are very important because of the role, which the repeated glaciation played in our region. In the territory of Slovakia only the manifestations of the mountain glaciers occur. This glaciation was genetically connected with the higher parts of the Slovak high mountains, with suitable climate conditions. The moraines are accumulations of chaotically deposited unsorted material of stony-blocky rough fragments, both fresh and weathered rock material, with local sandy admixture. Such moraines developed below the frontal parts of glaciers. The glacial sediments cover 102.4 km^2 (0.21 %) of the territory of Slovakia.

Category 2: Below the glaciers of the High and Low Tatras Mts. the waters from glaciers´ thawing deposited **glaciofluvial sediments**. The flat outwash cones of this type (sanders) are common in the Liptovská, Popradská and Oravská kotlina depressions, together with terraces and valleys bottom fills. The sediments are semi-rounded sandy gravels with boulders to blocks. Typical are the layers of placer sands, which originated from the weathered granites. The glaciofluvial sediments gradually transit into the river terraces and valleys´ bottom fills. The glaciofluvial sediments cover 405.12 km^2 (0.83 %) of the territory of Slovakia.

Category 3: **The river (fluvial) sediments** occur in mountain valleys, at the depressions and uplands valleys as well as in lowlands around Slovakia. They are represented by bottom accumulations including their alluvial cover or in the form of river terraces flanking the valleys. They were deposited by streams from tiny brooks to large rivers. The material was deposited either within the riverbed (alluvium) or within flood throughout the flood basin. Fluvial sediments are at places covered by aeolian sands; and rather frequently organogenic, fluvioorganic to palustrine sediments occur within them, mainly in the form of oxbow fills. Because these sediments are typical for the flats with minor occurrence of landslides, we joined them with the fluvial sediments in our reclassification – all-in-all they cover 8 415.95 km^2 (17.16 %) of the territory of Slovakia.

Category 4: **The river terrace deposits** are made of coarse and extensive accumulations of sandy gravels with small portion of sandy, silty and clayey lenses. The extensive terraces have been preserved along the depression sections of the rivers Váh, Turiec, Hron, Ipeľ, Rimava, Hornád, Poprad, Torysa, in the valleys of Orava and Kysuca and in the upland parts of lowlands along the rivers Váh, Nitra, Žitava and Hron. The terrace sediments cover 974.16 km^2 (1.99 %) of the territory of Slovakia.

Category 5: **The outwash sediments (proluvium)** are linked genetically with the solifluction slope deposits and slope debris. At the formation of proluvial sediments the relief, resistance of rocks against weathering, weathered volumes, territory tectonic regimen, climate, vegetation cover and other factors are important.

The most frequent are the small, but steep proluvial cones, spread around all Slovak mountains. We can see them at the mouth of gorges and the tributary dry valleys. They represent a product of the violent flushes of water, bearing solifluction deluvia. The material of such cones is rather chaotic, poorly graded and rough.

Not so numerous but frequently extensive and flat proluvial cones occur at foothills, at the rim of intra-mountains depressions and valleys of the main Slovak streams as well as in the transitional zones between mountains and uplands. The flat proluvial cones frequently conjoin into extensive zones, flanking mountains like, for instance, Malé Karpaty, Malá Fatra, Slanské vrchy and Vihorlat Mts. The sediments of proluvial cones come from various sources. The alternation is common also among clayey, sandy and stony fractions. At the periphery or in the distance from the mountains the proluvial cones transit into sandy-gravelly terraces and river bottom accumulations (alluvions). Frequently they are covered by aeolian sands or loess and loess-like loams. The proluvial sediments cover 1 664.86 km^2 (3.40 %) of the territory of Slovakia.

Category 6: **The aeolian sands** differ from the loess not only due to coarser grains, but also due to different deposition mode and smaller extent. Dunes are the characteristic feature of aeolian sands accumulation.

In the Slovak territory, the aeolian sands are common close to the river terraces and river flood plains, sometimes they form islands upon them. The largest extent they reach on the Záhorská nížina Lowland (Bor), in the south-eastern part of the Podunajská nížina and Východoslovenská nížina lowlands. The aeolian sands cover 640.59 km^2 (1.31 %) of the territory of Slovakia.

Category 7: **The loess** represents the wind-blown, partially cemented soil. The prevailed grain fraction is made of particles 0.01 – 0.05 mm in size, with tiny clayey and fine-sandy admixture. The greatest extent the loess reaches in the uplands of the Slovak lowlands: Chvojnická, Trnavská, Nitrianska, Žitavská, Hronská, Ipeľská and Východoslovenská pahorkatina uplands. Towards the intramountainous depressions, the loess transits into the loessy loams.

The loess is massive, without bedding, porous and calcareous. It has a coarse-columnar vertical jointing and preserved steep and vertical walls. At places with the greater time-span of loess accumulation, a complex loess formation developed with deluvial cover and buried (fossil) soils. The loess and loess-like sediments cover 4 558.73 km^2 (9.3 %) of the territory of Slovakia.

Category 8: **The eluvial and eluvial-deluvial wastes (eluvium, weathered rocks)** form the weathered mantle at their original position above their mother rocks (solid, partially lithified or even loose rocks). Rare occurrences of eluvium are limited to smaller ridges parts of mountains, intermountain ridges, plateaux and plains. The lithological content of the Quaternary eluvium depends upon the mother rocks, from which they evolved. Their grain composition consists of clasts of various sizes (fractions) from the coarsest ones to the finest clayey loams. The eluvia provide the material for colluvial sediments (deluvium). The eluvial sediments cover 175.24 km^2 (0.36 %) of the territory of Slovakia.

Category 9: **The slope deposits – colluvial and slope debris (deluvium)**, according their volume, area extent and occurrence, are the most frequent genetic type of the Quaternary terrestrial deposits. They occur almost

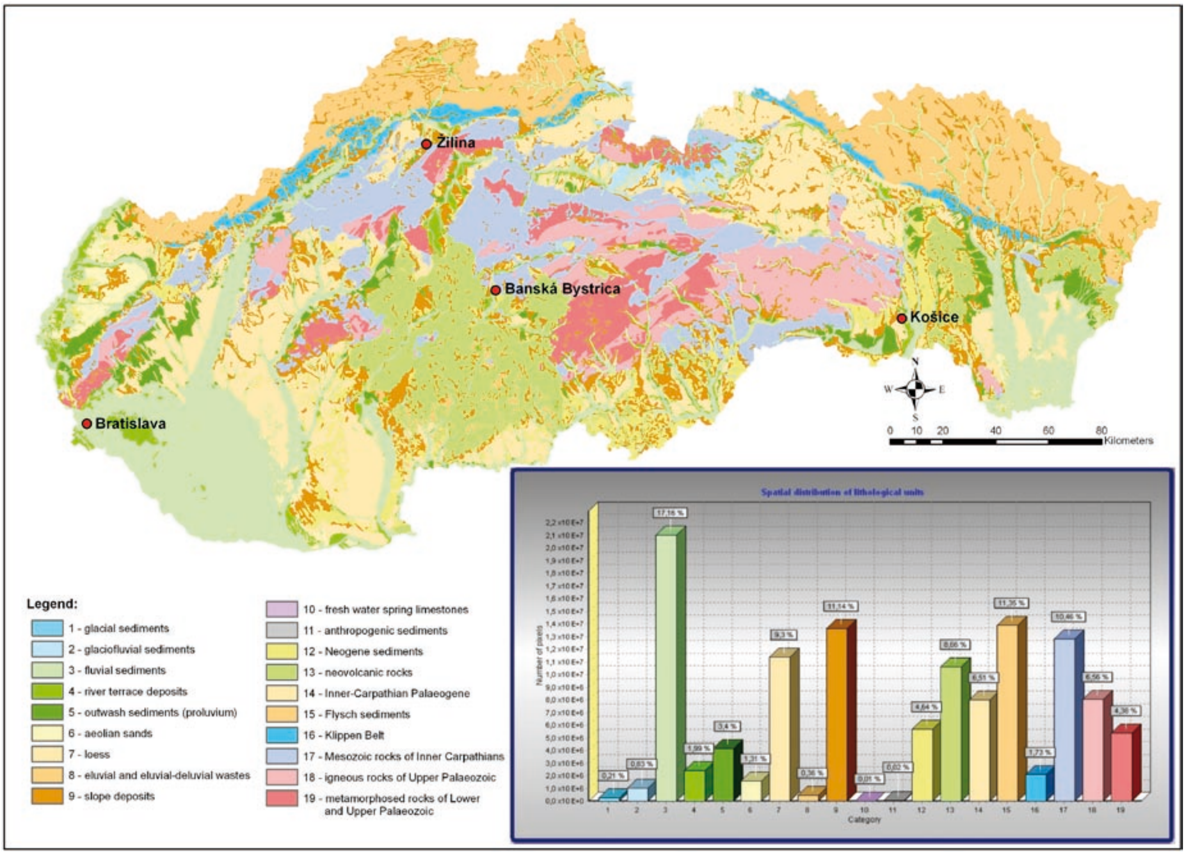

Fig. 1. Quaternary and Pre-Quaternary genetic types – reclassified parametric map.

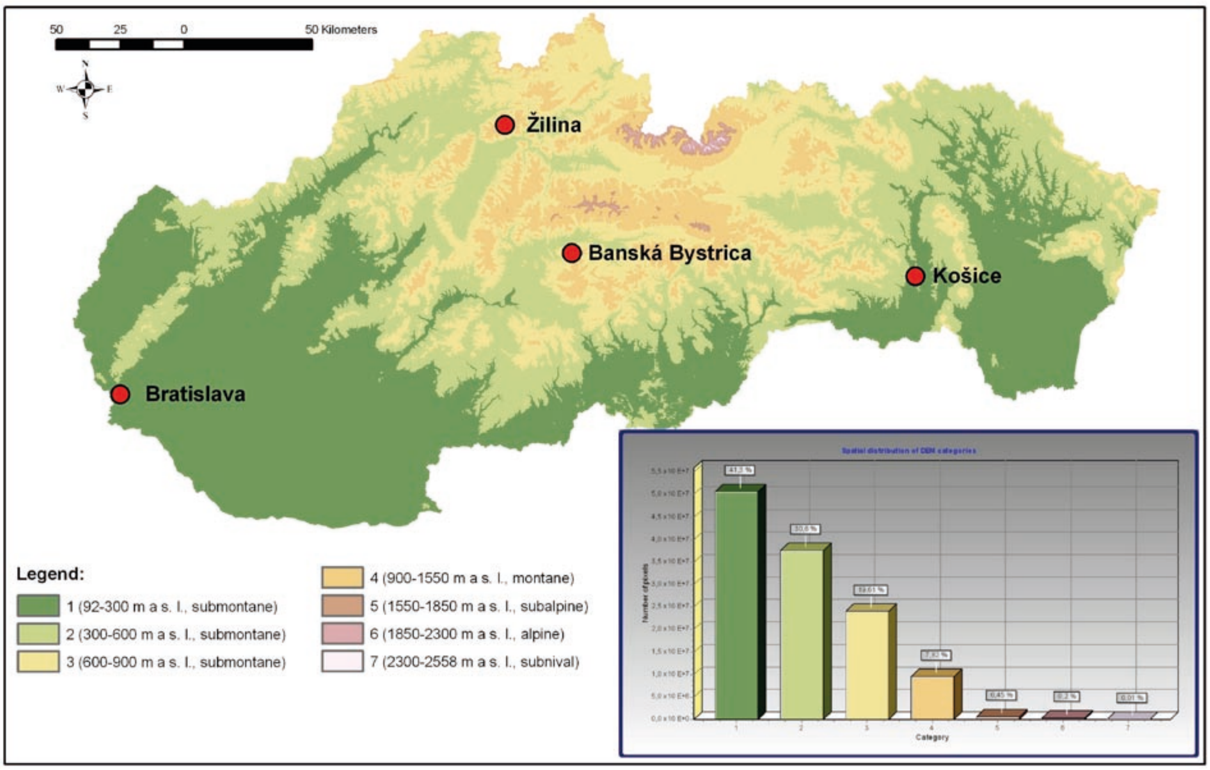

Fig. 2. DEM – reclassified parametric map.

atop of any type of the Pre-Quaternary basement, besides the sites of solid rocks exposures. They occur mainly on foothills, where they reach their greatest thicknesses.

The most frequent among the slope deposits are the loamy-stony, loamy-sandy to loamy soils. The other colluvial sediments of monomict composition, like colluvials from sandstones, differ from the above; they are exclusively made of pure sands with clayey admixture. The stony slope deposits, composed of the rock fragments with blocky fraction prevail, forming coherent felsenmeers. They are frequently a product of the rockfall, fragments falling or mechanical frost weathering and subsequent creeping of blocky jointed rocks. The purely gravitation slope deposits, mainly slope debris cones below cliffs, are derived from the mode of jointing of mother rocks and they can be stony to stony sandy ones. The slope deposits cover 5 460.24 km^2 (11.14 %) of the territory of Slovakia.

Category 10: **The fresh water spring limestones** represent the sediments, which precipitate from the water solutions at chemical processes with the assistance of organisms, like algae and higher plants. The springs with warmer waters coming from the greater depths form distinct valley and slope mounds and terraces, valley cascades and benches. They consist of sandstone and structural foam sinters, but the compact platy solid travertines are dominating. Typically, they are situated atop of the softer bedrock (Neogene, Paleogene); this structure results in their breaking up and creep of separated blocks downslope. The travertines cover 7.2 km^2 (0.01 %) of the territory of Slovakia.

Category 11: **The anthropogenic sediments** – although there have been registered over 9,000 waste disposals in Slovakia, the map depicts only seven largest polygons of anthropogenic sediments – spoil heaps and tailings left behind from the industrial boom in Slovakia. They cover 10.93 km^2 (0.02 %) of the territory of Slovakia.

Tab. 1
Reclassified Quaternary and Pre-Quaternary genetic types

Cat.	Description	Area (km^2)	Area (%)
1	Glacial sediments	102.44	0.21
2	Glaciofluvial sediments	405.12	0.83
3	River (fluvial) sediments	8 415.95	17.16
4	River terrace deposits	974.16	1.99
5	Outwash sediments (proluvium)	1 664.86	3.40
6	Aeolian sands	640.59	1.31
7	Loess	4 558.73	9.30
8	Eluvial and eluvial-deluvial wastes	175.24	0.36
9	Colluvial and slope debris	5 460.24	11.14
10	Fresh water spring limestones	7.20	0.01
11	Anthropogenic deposits	10.93	0.02
12	Neogene sediments	2 274.26	4.64
13	Neovolcanic rocks	4 245.66	8.66
14	Inner-Carpathian Paleogene	3 193.45	6.51
15	Flysch sediments	5 564.61	11.35
16	Klippen Belt	849.15	1.73
17	Mesozoic rocks of the Inner Carpathians	5 127.43	10.46
18	Igneous rocks of Upper Paleozoic	3 217.72	6.56
19	Metamorphosed rocks of Paleozoic	2 148.57	4.38

Tab. 2
Spatial distribution of reclassified Digital Elevation Model

Cat.	Interval (m a. s. l.)	Level	Area (km^2)	Area (%)
1	92 – 300		20 248.00	41.3
2	300 – 600	submontane	15 001.43	30.6
3	600 – 900		9 615.28	19.61
4	900 – 1 550	montane	3 832.88	7.82
5	1 550 – 1 850	subalpine	219.85	0.45
6	1 850 – 2 300	alpine	99.79	0.2
7	2 300 – 2 558	subnival	5.17	0.01

Pre-Quaternary bedrocks covered by the incoherent Quaternary cover

Category 12: In the region of the Western Carpathians **the Neogene sediments** filling up depression structures were deposited under the marine-continental conditions which often alternated (in geological record of time). The result of the sinking of sedimentary depocentres, of the uplift of surrounding mountain ranges and coeval volcanic activity, which supplied a heterogeneous material, are often huge (up to 8 000 m thick) accumulations of sediments. In the filling of the basins and depressions mainly clastic sediments predominate – gravels/conglomerates, sands/sandstones, silts/siltstones, clays/claystones – accompanied by the seams of coal and lignite, evaporites and carbonates (organogenic and/or freshwater limestone). The Neogene sediments cover 2 274.26 km^2 (4.64 %) of the territory of Slovakia.

Category 13: **The neovolcanic rocks** in Slovakia originated in the Neogene, some of them even in the Quaternary. The magmatic material originating from partial melting of metasomatically affected mantle with the following diapiric upwelling in the conditions of the back--arc extension provided the sources for andesite volcanic activity of the areal type in the territory of Central Slovakia (Bezák et al., 2008). The andesite volcanism was preceded by acid rhyodacite – rhyolite volcanism of the areal type. The alkaline basalt volcanism active during the Pannonian, Pliocene and Pleistocene periods represents the final stage of the volcanic activity on the territory of Slovakia.

The neovolcanites underwent massive degradation but they have been preserved in the Central and Eastern Slovakia in several mountain ranges. Typically, these volcanic sequences are situated atop softer sediments of Neogene and Paleogene age which gives a predisposition for their gravitative disintegration. The neovolcanic complexes cover 4 245.66 km^2 (8.66 %) of the territory of Slovakia.

Category 14: **The sediments of the Inner-Carpathian Paleogene** – are formed by several Flysch complexes in the lower part consisting of transgressive breccia, conglomerates, carbonate and polymict sandstones to siltstones, and in the upper part of organodetrical an organogenic limestones, occasionally of marlstones. Upwards the sequence contains occasional claystones

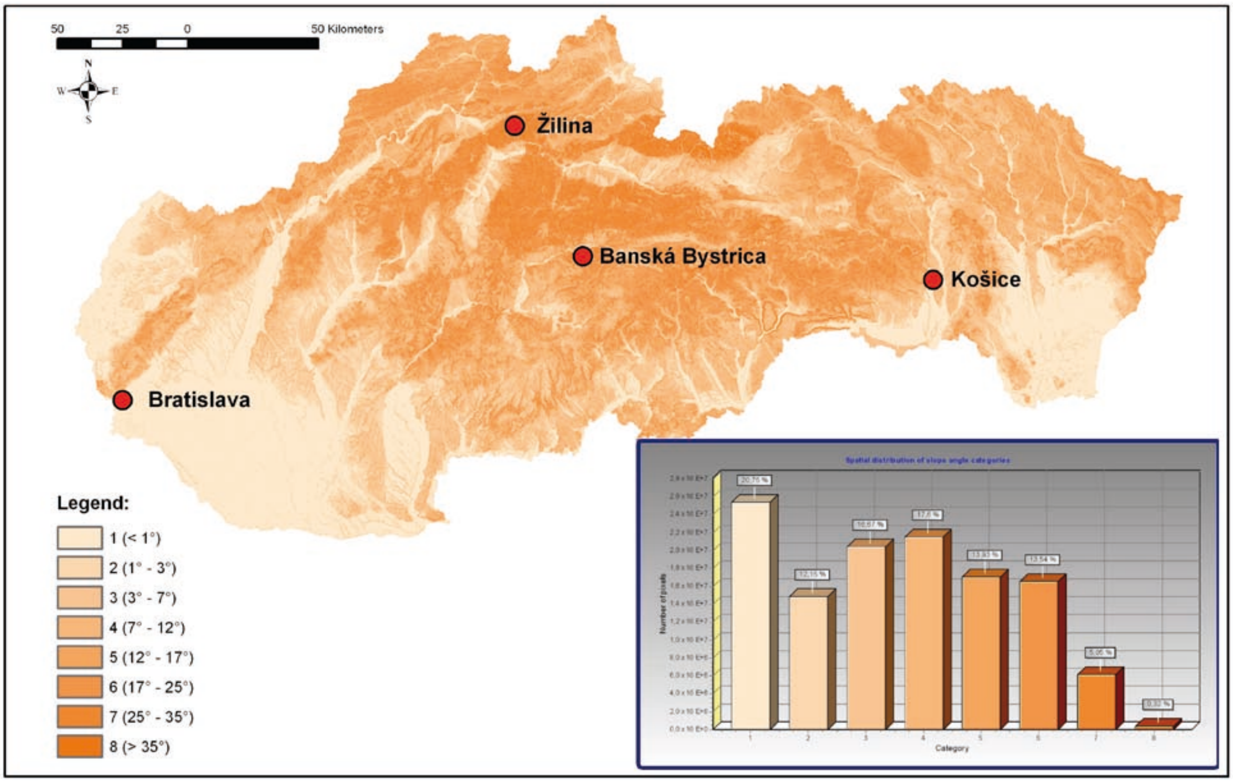

Fig. 3. Slope angle – reclassified parametric map.

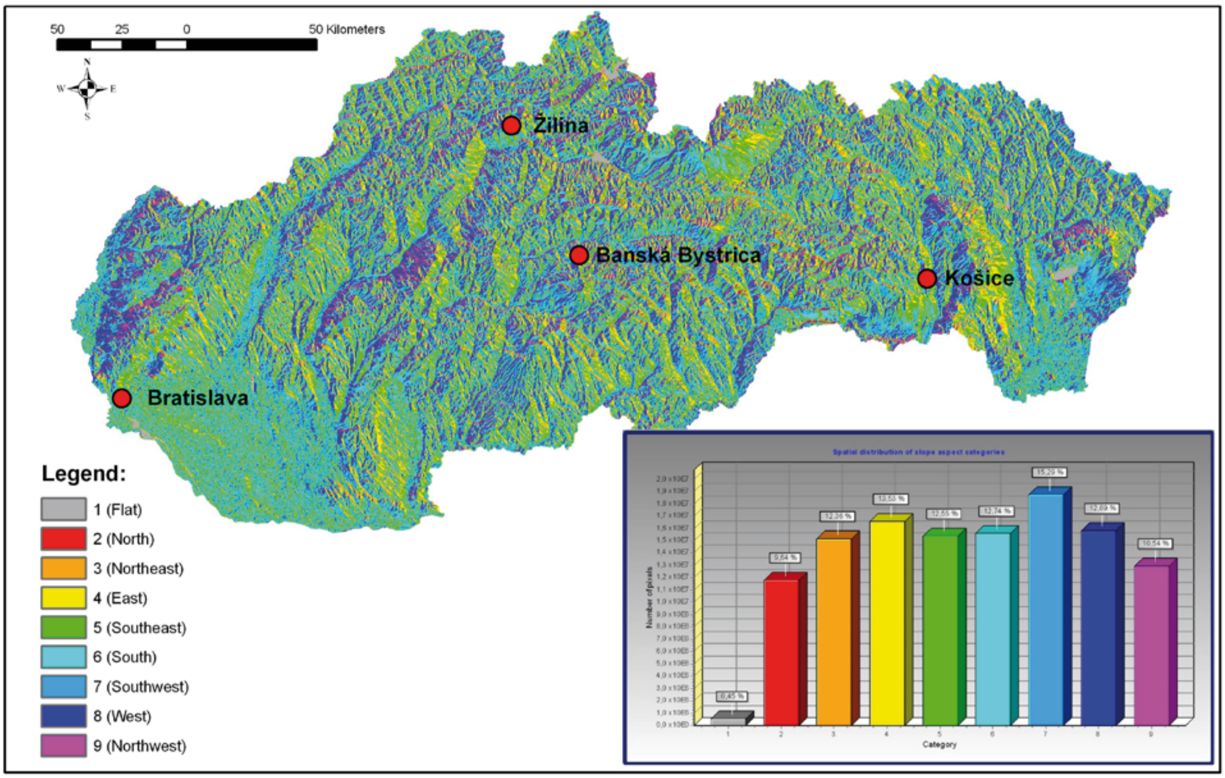

Fig. 4. Slope aspect – reclassified parametric map.

of the menilite type, the main mass being variably composed of calcareous, partly of non-calcareous claystones with sporadical sandstone banks, fine-grained conglomerates and Paleocarbonates. The uppermost part consists of typical flysch sequences characterized by repeated, more or less regular alternation of sandstones and claystones, scarce conglomerates and Paleocarbonates. Typically, the strata are sloping towards depression centre, which creates a precondition for the planar slope failures evolution. The Inner Carpathian Paleogene sediments cover 3 193.45 km^2 (6.51 %) of the territory of Slovakia.

Category 15: **The Flysch sediments** of the Outer Western Carpathians were folded and overthrusted over each other and over the European platform in the form of nappes. The disintegration of the Flysch complexes was completed by the Neogene fault tectonics. The lithological character is rather monotonous with dominating rhythmical claystone-sandstone. Flysch complexes covering 5 564.61 km^2 (11.35 %) of the territory of Slovakia. About 50 % of registered slope failures are known from the flysch region.

Category 16: From the Inner Carpathians the Outer Carpathians are separated by a narrow tectonic belt, which manifests the most remarkable signs of an oblique shift and in which there are squeezed out the units within the contact zone between both blocks. Thanks to the tectonic segmentation, this zone has been designated as **Klippen Belt**. Due to disharmonic folding a disturbance of the continuity of rigid limestone-sandstone strata of variegated marlstone formation occurred as well as their forcing into more plastic marlstone Cretaceous complexes in the form of "tectonic megabreccias" which in the present relief rise morphologically actively as conspicuous klippes. The Klippen Belt complexes cover 849.15 km^2 (1.73 %) of the territory of Slovakia.

Tab. 3
Spatial distribution of reclassified slope angles

Cat.	Interval (°)	Area (km^2)	Area (%)
1	<1	10 170.9052	20.75
2	1 – 3	5 954.9864	12.15
3	3 – 7	8 170.2792	16.67
4	7 – 12	8 626.7684	17.6
5	12 – 17	6 828.7432	13.93
6	17 – 25	6 636.284	13.54
7	25 – 35	2 476.7372	5.05
8	>35	157.7056	0.32

Tab. 4
Spatial distribution of reclassified slope aspect

Cat.	Interval	Area (km^2)	Area (%)
1	flat	220.0728	0.45
2	N	4 728.2064	9.64
3	NE	6 058.704	12.36
4	E	6 632.9324	13.53
5	SE	6 152.024	12.55
6	S	6 247.5312	12.74
7	SW	7 494.5744	15.29
8	W	6 319.6664	12.89
9	NW	5 168.6964	10.54

Category 17: **The Mesozoic rocks** of the Inner Carpathians represent the essential tectonic units, which build up the Central and Inner Western Carpathians. From the north to the south they are cropping out in the Klippen Belt, the Tatricum, Veporicum, Hronicum, Silicicum, Meliaticum and Turnaicum units.

The Triassic period started with sedimentation of detrital deposits (quartzites, sandstones, siltstones and shales). In the course of the Middle and Upper Triassic the shallow-marine environment carbonates were dominantly deposited (limestones and dolomites). In the southern zones, which were positioned in the continental shelf and bathyal parts of the sedimentary space, the deposition of turbidites and nodular cherty limestones took place. Within the southernmost zones the gradual rifting (extension) occurred, even at oceanic conditions, which resulted in formation of the ophiolite suite, radiolarites and other bathyal sediments.

The Jurassic sedimentation is represented by prevailingly bathyal deposits like mottled marlstones, cherty limestones and radiolarites.

In the Cretaceous period the deposition took place under variable conditions, which were affected by significant tectonic processes. They led to the formation of nappes, which have become a typical feature of the Carpathians Mts. The Mesozoic complexes cover 5 127.43 km^2 (10.46 %) of the territory of Slovakia.

Categories 18 and 19: During the oldest tectonic phase the crystalline basement of the Inner Carpathian block was formed. This crystalline basement is composed of Lower and Upper Paleozoic **metamorphosed rocks** (gneisses, mica schists, amphibolites – Category 19) and **igneous rocks** of Upper Paleozoic (different types of granitoids – Category 18). They were formed during the Paleozoic within the deep crust environment in quite a distant space from to date occurrence. They were a component of the massive Hercynian mountains of Europe, which arose from the collision of two continents of Gondwana and Laurasia, and microplates between them as well. In the course of these orogenic processes, deep in the crust the sediments underwent metamorphism leading to formation of crystalline schists and even to melting – the ascent of magma and its solidifying caused the origin of granitoid massifs. During the Upper Paleozoic these rocks were exposed to denudation and they have become a core of the crust of the Inner Western Carpathians. The Paleozoic metamorphic complexes cover 2 148.57 km^2 (4.38 %) of the territory of Slovakia, the granitoids cover 3 217.72 km^2 (6.56 %).

Digital Elevation Model (DEM)

DEM was constructed on the topography at the scale of 1 : 10 000 with a grid of 20 x 20 m (Esprit Ltd.). Taking into account the landuse of Slovakia (agriculture and forest) we

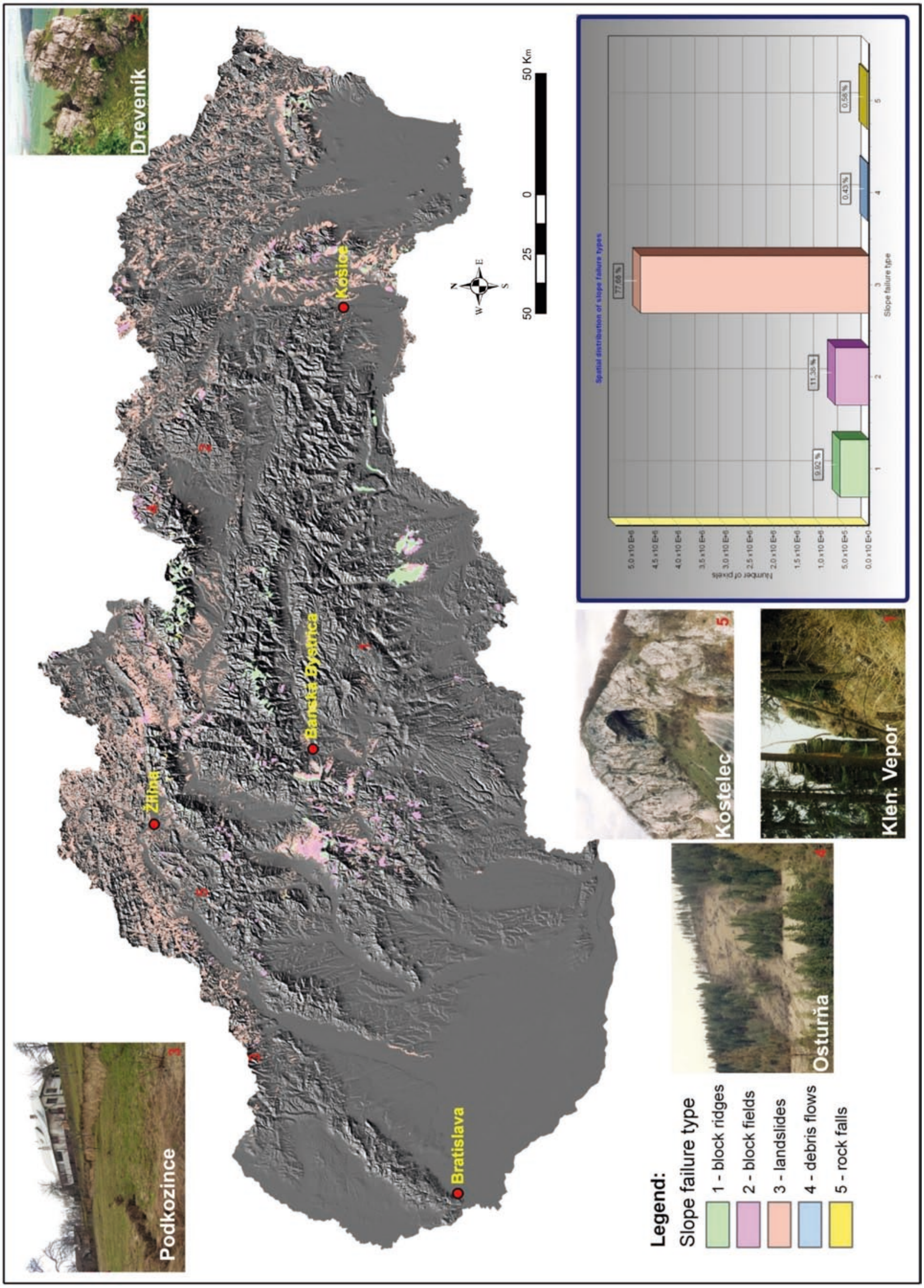

Fig. 5. Slope failures – reclassified parametric map.

distinguished 7 altitudinal categories; the Table 2 and Fig. 2 illustrate their share in the morphology of Slovakia. More than 90 % of the study area falls in an elevation interval from 92 to 900 m a. s. l.

Slope angle

The original slope angle grid spans values from 0° to 90°, and these were reclassified into nine categories in accord with the Landslide Atlas (Kopecký et al., 2008). We distinguished 8 categories of the slope angle; the Table 3 and Fig. 3 illustrate their share in the morphology of Slovakia.

Slope aspect

The slope aspect parameter is usually in the close relationship with climatic conditions. Spatial distribution of slopes into individual categories is almost uniform. We distinguished 9 categories of the slope aspect; the Table 4 and Fig. 4 illustrate their share in the morphology of Slovakia.

Slope failures

Spatial information on the slope failures is the most important input factor in the process of landslide susceptibility assessment; it was retrieved from the Atlas of the slope stability maps of the Slovak Republic at the scale 1 : 50 000. Altogether there were identified 21 190 slope failures covering 2 575.912 km^2, which means about 5.25 % of the territory of Slovakia (Kopecký et al., 2008). We have to note that in the Atlas database only so-called large scale failures are included, reaching a number of 16 212 and an area of 2 477.7846 km^2. The rest of 4 978 so-called small-scale failures are not included in the database, they cover an area of 98.1274 km^2.

The former attributes table of the Atlas distinguished 22 types and combinations of the slope failures; we reclassified them into 5 categories, which we present in the Table 5 and Fig. 5.

The slope failure inventory parametric map presents a binary dependent (dichotomic) variable which is compared with all input parametric maps in the process of bivariate statistical analysis. The binary grid (raster) includes the values 0 and 1 only (True/False), where a value of 1 indicates the presence of a slope failure in a cell, and the value 0 denotes its absence.

Tab. 5
Slope failures (reclassified) and their area in total

Slope failure type	Area (km^2)	Area (%)
Block ridges	245.9152	9.92
Block fields	282.1528	11.38
Landslides	1 925.0244	77.68
Debris flows	10.5404	0.43
Rock falls	14.4848	0.58

The interpretation of slope failures in the parametric inventory maps may vary, but it is generally based on a task specification – assessment of slope failure susceptibility and assessment of a slope failure hazard or risk. For the purpose of the slope failures presentation in the inventory map and for statistical assessment the area of landslide body including accumulation zone was accounted. This is a simple representation of the whole landslide body projected on the map in the form of an aerial entity.

Prognostic map of landslide susceptibility

Landslides area constitutes 77.68 % of slope failures, which equals to 1 925.02 km^2 (Tab. 5); they occur on the piedmont flanks of mountain ranges, mainly along the rims of intramountainous depressions and valley. The landslides represent a final stage of the slope failure evolution.

Equation used for constructing of the landslide susceptibility map has the following form:

y = /slope_L/*0.008 + /aspect_L/*0.00156 + /litho_L/*0.0763 + /dem_L/*0.00806 (1)

The result of this summation is a continuous interval of the values from 0.04094 to 0.27943 and these represent the various levels of the landslide susceptibility. Since this interval should be divided into three or five conventional categories, here, natural breaks classification method was used to divide the interval into five categories based on the equation (2) below:

$$\text{SSDi...j} = \sum_{n=i}^{j} (A[n] - median)^2 \qquad (2)$$

where:
SSD – the sum of the squared differences,
A – data set (in ascending order).

Level of the landslides susceptibility zoning according to equation (2):
very low (interval 0.04094 – 0.09893),
low (interval 0.09893 – 0.14662),
medium (interval 0.14662 – 0.19713),
high (interval 0.19713 – 0.23454),
very high (interval 0.23454 – 0.27943).

The prognostic map of the landslide susceptibility zoning is illustrated in Fig. 6.

Results

We are going to discuss the results of the bivariate statistical analyses. The landslides are the most abundant slope failures in Slovakia; they cover an area of 1 925.02 km^2 in total.

Landslides vs. lithology

The most affected is the category 15 – the Flysch sediments; 34.25 % of the landslides fall within this category.

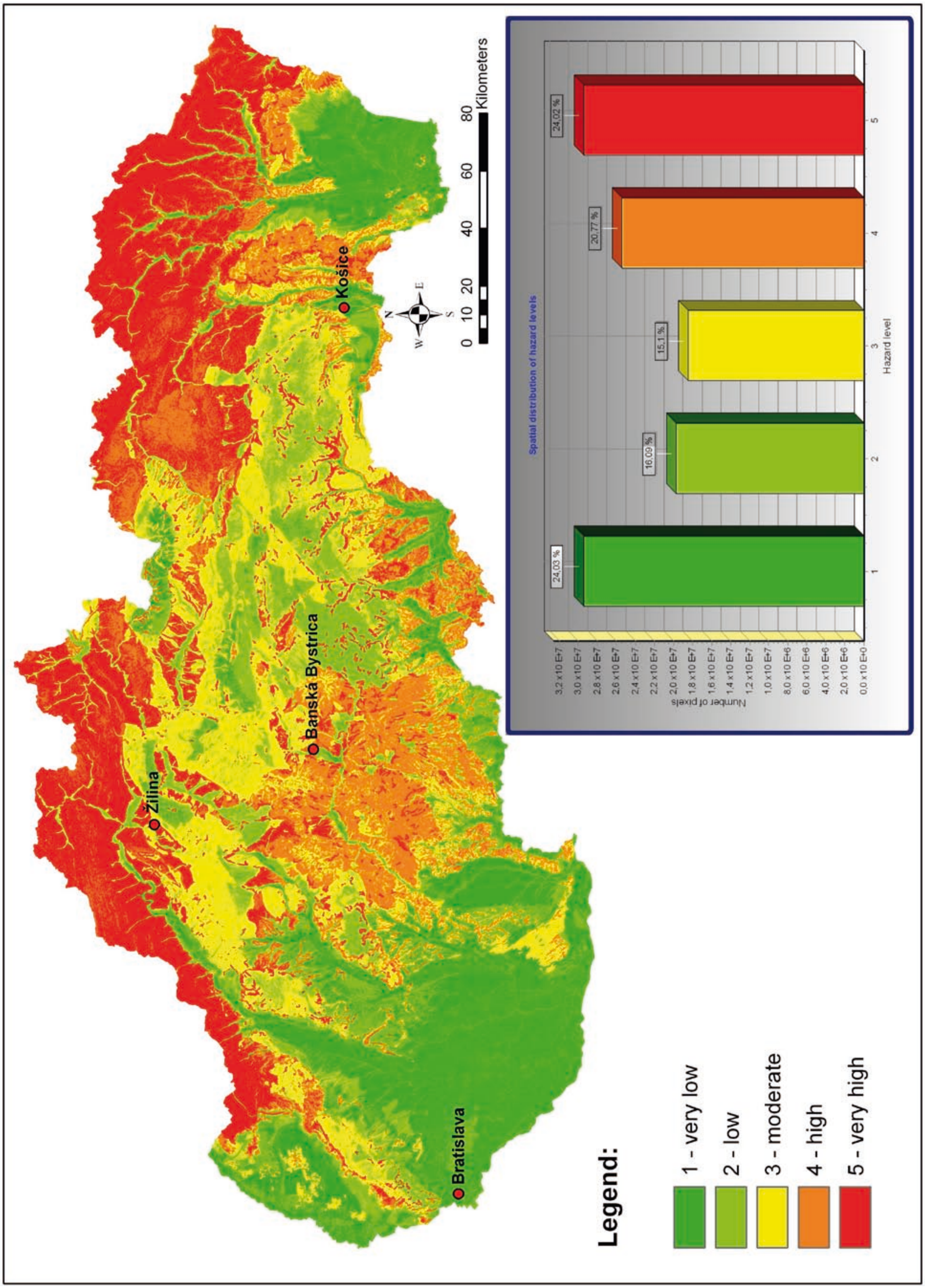

Fig. 6. Prognostic map of the landslide susceptibility zoning.

The second most affected is the category 9 – the slope deposits – colluvial and slope debris (deluvium); 23.9 % of the landslides fall within this category and the third category (14) are the sediments of the Inner-Carpathian Paleogene with 13.06 % coverage.

Landslides vs. DEM

49.93 % of the landslides are present in the category 2 (300 – 600 m a. s. l., submontane level); 28.45 % are present in the category 3 (600 – 900 m a. s. l., submontane level).

Landslides vs. slope angle

38.48 % of the landslides are present in the category 4 (7° – 12°) and 25.66 % in the category 5 (12° – 17°), 19.29 % in the category 3 (3° – 7°) and 13.45 % in the category 6 (17° – 25°).

Landslides vs. slope aspect

The landslides are distributed almost uniformly in all 9 categories.

Susceptibility prognosis

As it follows from the Fig. 6 the very high level of landslides susceptibility is attributed to the 24.02 % of the territory of Slovakia; the high level of susceptibility is interpreted for 20.77 % of the territory.

Conclusion

The slope failures are perceived as the most significant geodynamic phenomena which pose a threat for the environment of the Slovak Republic. This study presents a forecasted spatial distribution of landslides; however, it does not include the temporal frequency of their activation. The landslides are the most abundant type of slope failures in Slovakia.

In order to assess the landslide susceptibility we used bivariate statistical analysis, based on the comparison of individual slope failures retrieved from the inventory map with four parameters – lithology, DEM, slope angle and slope aspect. The grid resolution was 20 x 20 m. The application of statistical methods is generally based upon the actualism principle in geology. This means that in the case of landslides we presume that they will occur in the future in similar conditions to those we have previously or currently experienced.

Due to the scale of input data (1 : 500 000), except landslides dataset (1 : 50 000), and level of generalization, final prognostic map at the Fig. 6 reflects fully these facts. Level of generalization, especially in a case of simplicification (reclassification) process of geological conditions, has a dominant influence for final division of landslide susceptibility levels.

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Rukopis doručený 12. 3. 2010
Revidovaná verzia doručená 2. 8. 2010
Rukopis akceptovaný red. radou 7. 9. 2010