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5. A Large-Scale Landslide Hazard Assessment within the Flysch Formation in the Slovak Republic

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Abstract. The article presents the main results of the project "Engineering geological mapping of slope deformations in the most vulnerable areas within the Flysch Formation at a scale 1:10,000", consisting of three kinds of maps, data sheets (passports) of slope deformations and final report. The focus is on the methodology for the creation of landslide hazard maps and assessment of landslide hazard in the restricted area of Flysch Zone in the northern and northeastern part of Slovakia. The selected area is characterized by a high density of slope failures; it is periodically affected also by floods accompanied with the activation of slope deformations, particularly landslides and earth flows, due to impact of adverse climatic conditions.

***Key words*:** landslides, landslide hazard, Flysch Formation, Slovakia

5.1. Introduction

During the years 2005-2011 geological project "Engineering geological mapping of slope deformations in the most vulnerable areas within the Flysch Formation at a scale 1:10,000" was realized in Slovakia, ordered by the Ministry of Environment SR (MoE) (Grman et al., 2011). The project was solved by team of researchers from the following organizations: GEO Slovakia, Ltd., Košice, GEOTREND, Ltd., Žilina, Faculty of Natural Sciences, Comenius University in Bratislava, Slovak University of Technology in Bratislava, Technical University in Košice and SGIDŠ in Bratislava. The project was generated by the society-wide necessity in the context of increased negative consequences of repeated activation of slope deformations.

The main outputs are defined below:

- Specialized engineering geological map at scale 1:10,000
- Map of documentary points at scale 1:10,000
- Landslide hazard map at scale 1:10,000
- Data sheets (passports) of slope deformations.

This article is focused primarily on the landslide hazard maps that are pioneering work by their mapping scope and used methodology. In the area studied they represent a significant update of Atlas of Slope Stability of Slovakia at a Scale 1:50,000 (Šimeková et al., 2006) and also compensate deficiencies of "Atlas", resulting from used scale and follow the experience in creating maps of the landslide hazard in smaller scales (Liščák et al., 2009, Bednarik & Liščák, 2010).

The landslide hazard presents probability of occurrence of the landslide phenomenon within the space. The output of the project are prognosing landslide hazard maps, which now represent a suitable basis for spatial planning, or solution of the current slope stability situation. They have a recommendatory character and are intended to bring the investor, designer, statics to a decision what extent, type and method of engineering geological investigation is needed for a specific site (line, ground and underground) in terms of the occurrence of slope deformations. The incidence of geodynamic phenomena, in this paper mainly slope deformations, significantly affects and changes the view of the implementation of the engineering works. Landslide hazard maps generated on large scales (1:10,000 and larger) can significantly reduce direct and indirect damages resulting from landslide hazard.

5.2. Delimitation of the mapped area

The territory assessed covers an area of 4,042.23 square kilometres, in other terms, 17 map sheets at scale 1:50,000, or on 285 map sheets at scale 1:10,000.

The area is divided into western (Žilina Region) and eastern parts (Prešov Region) (Fig. 5.1), representing whole or partial cadastres of 50 municipalities in five districts of the Žilina Region (13 municipalities partially), 310 municipalities in 11 districts in the Prešov Region (of which 66 villages partially).

For map compilation predominantly area belonging to the Flysch Zone was chosen, in which the geological, hydrological and morphological conditions create favourable conditions for the slope deformations occurrence. In most districts of the area of interest the share of the registered slope deformations exceeds 10 % (Šimeková et al., 2014).

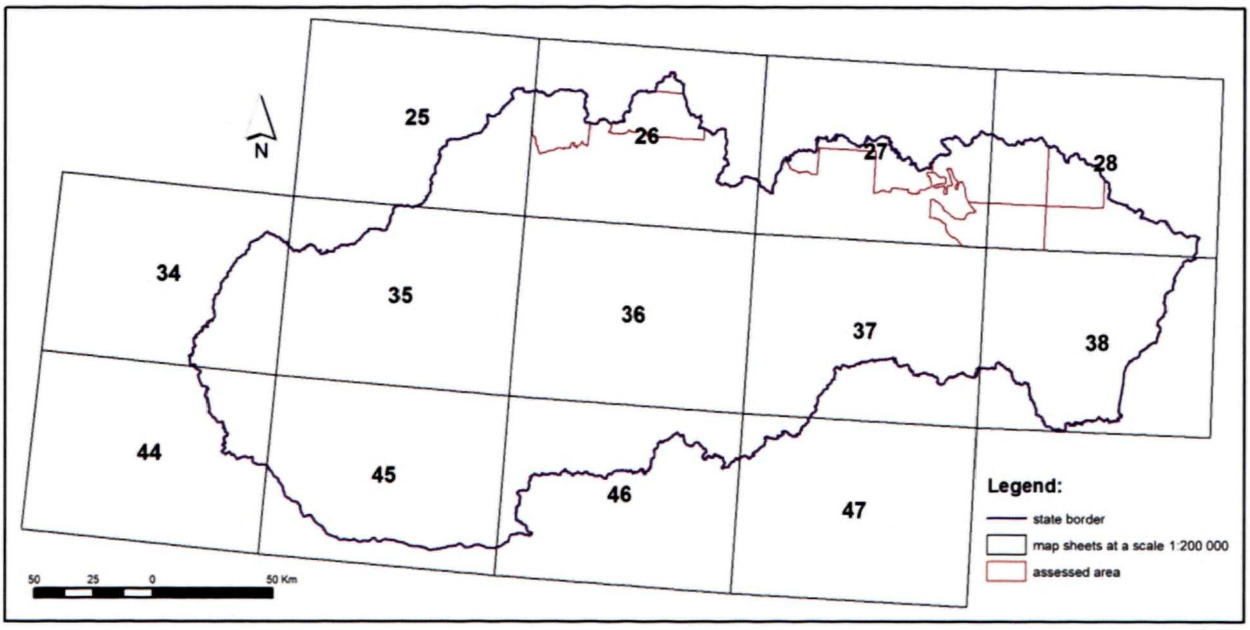

Fig. 5.1 General overview of the assessed area

According to engineering geological regional division of Slovakia (Matula & Pašek, 1986) the mapped area belongs mainly to the region of the Carpathian Flysch (areas of Flysch Uplands and Flysch Highlands), only in the eastern parts the study area extends into the region of Neogene Tectonic Depressions (Area of Intermountain Depressions) and to the region of Neogene Volcanics.

In the region of the Carpathian Flysch due differentiated tectonic conditions it is possible to distinguish:

- Sub-region of Outer Flysch Carpathians,
- Sub-region of Klippen Belt,
- Sub-region of Innner Flysch Carpathians.

5.3. The methodology of compilation of specialized engineering geological map

Specialized engineering geological map represented a fundamental starting basis for the compilation of the landslide hazard map. It is also self-use map with versatile application in the field of geology, building constructions and urban planning. The maps were constructed on the basis of archive data processing, re-compilation of existing maps and field mapping.

Specialized engineering geological map on topographic base at a scale 1:10,000 shows: rock environment, geodynamic phenomena, hydrogeological data, hydrological data and tectonic conditions.

Within the geological environment are displayed:

- Quaternary lithological complexes with thickness more than 1 m,
- Pre-Quaternary lithological complexes exposed at the surface (Quaternary cover less than 1 m).

Information on the rock environment are shown as coloured areas and the corresponding numerical indexes expressing the genesis and representing lithological types.

Basic lithological types represented within the assigned formations and complexes are generally reviewed in Tab. 5.1.

On the geological setting of the area predominantly rocks of the Flysch Formation are participating, in the area of the Klippen Belt the rocks of variegated Sandstone-Marlstone-Limestone Formation are abundant, and in comparison with the Flysch Formation are lithologically more heterogeneous, as well as from engineering geological properties points of view, and partly also Neovolcanites Formation is involved. The Pre-Quaternary rocks are irregularly distributed across the mapping area and incoherently covered by Quaternary sediments.

Among the geodynamic phenomena are shown:

- slope deformations,
- erosion-accumulation phenomena.

Depending on the size, the slope deformations as resulting forms of slope movements, are shown spatial or point objects. By line colour and the marks inside slide polygon, or by mark colour (for point plotted slope deformations) activity of slope deformation is distinguished. The type of slope failure is differentiated by marks within the area of slope deformations, or by pictogram (in the case of small-size failures).

Within the mapping area in accordance with the classification of slope movements in Slovakia (Nemčok, 1982) committed basic groups and types of slope deformations were used (Tab. 5.2).

The most common type of slope movement in the study area is sliding. In flysch environment, there occur slip movements along a flat (planar) or complex (rotary-planar) slip surface. The slip surface of landslides tends to be mostly predisposed to interface among weathered and sound Pre-Quaternary, mainly flysch rocks, or to the boundary of the Quaternary slope sediments and basement rock. In deep landslides in their bodies

Tab. 5.1 Rock environment within the study area

Period	Formation	Lithological complex		Index within map	Basic lithotypes
Quaternary	Quaternary cover	anthropogenous		**1**	deposits, landfills
		slope sediments		**2**	clays, silts, debris
		proluvial	valley	**3**	gravels, clays, silts, debris
			terrace	**4**	gravels, clays, silts
		fluvial	alluvial	**5**	gravels, clays, silts, sands
			terrace	**6**	gravels, clays, silts
		glacifluvial		**7**	gravels, clays, sands
		organogenous		**8**	clays, sands
		organic		**9**	peat
		chemogenous		**10**	foamstones
Neogene	Neovolcanites	tuff		**11**	tuffs, conglomerates, sandstones
		extrusive andesites		**12**	andesites
		effusive andesites		**13**	andesites
	Molasse	siltstones-claystones siltstones-sandstones sandstones-conglomerates		**14**	claystones, siltstones, sandstones, conglomerates
Paleogene	Flysch	Flysch sandstones-conglomerates		**15**	sandstones, claystones, conglomerates, breccias
		Flysch with predominance of claystones		**16**	claystones, sandstones, siltstones
Paleogene-Cretaceous		Flysch with predominance of sandstones		**17**	sandstones, claystones, conglomerates
Paleogene		claystones		**18**	claystones
Paleogene-Cretaceous	Variegated sandstone-marlstone-limestone	Flysch marlstones-limestones		**19**	marlstones, claystones, sandstones, limestones, conglomerates
Cretaceous-Jurassic		limestones		**20**	limestones, sandstones
Jurassic				**21**	limestones, radiolarites
Triassic				**22**	limestones, dolomites

Tab. 5.2 Classification of slope deformation within the study area

Basic groups of slope deformations	Types of slope deformation	Slope deformation activity
Deep creep	- block deformations (block fields, block ridges)	stabilized, dormant
Surface creep	- surface creep movements of Quaternary sediments	dormant, active
Sliding	- different types - erosive slides	dormant, stabilized, active
Flowing	- flows - streams	dormant, stabilized, active
Falling	- debris cones, scree cones - stone seas	stabilized, dormant

there are also numerous individualized rock blocks, which are mostly characterized by a lower degree of disintegration.

A particular type of landslide, which often occurs in the area, but generally has smaller dimensions, is a waterside slump. This type is formed by sliding of bank of a watercourse or water reservoir into the bed, due to lateral erosion of a stream, or due to abrasion. Depending on their size, the accumulations of these landslides are usually transported by water flow immediately after the sliding. Deep creep deformations with character of block fields (block landslides) are concentrated in areas with a prevalence of Flysch sandstones overlying claystone formations, or formations with predominance of claystone with favourable bedding, or tectonic conditions. Quaternary slope sediments or colluvial-eluvial soils are affected by flows, mainly. Within the mapping area numerous earth and debris flows have been recorded. Special form of flow-type slope movement are ravines. These are usually of a small area, or linear, caused by abrupt erosion, torrential rainwater, or by intensive oversaturation of surface layers. Being soaked, a loss of strength starts in top layers (grass surface, topsoil) up to the depth usually 0.3-0.5 m, occasionally up to 1 m. They are frequent on the banks of watercourses, as a result of a sudden drop in water table level.

The group of falls within the mapping area includes the shedding of fragments of rocks that are gradually accumulated at the foot of rock walls and cliffs. The loose debris and fallen rocks combined with saltation and sliding down the slope form on its foot or directly below the rock walls different morphological forms - scree cones, debris cones, stone fields. Their occurrence in the mapping area is rare, they are significantly concentrated only in the Klippen Belt area, particularly in the geomorphological unit of Pieniny.

The slope failures (landslides of various stages of activity) in the territory occur mostly in the environment of deluvial complex and Flysch complex with a predominance of clays. The share of slope deformations atop identified lithological complexes is presented in the Tab. 5.3. Part of landslides extends over two, occasionally three lithological complexes simultaneously, which is also valid in terms of the depth of the reach of many landslides. The Quaternary soils and underlying Pre-Quaternary basement affected by landslide movement are characterized as sliding sediments. The slope deformations, where underlying lithological complexes are covered by original slope sediments or other Quaternary sediments with thickness greater than 1 m are included in the area of slope deformations on deluvial sediments complex, although by landsliding may be affected not only Quaternary sediments but also underlying rocks.

Tab. 5.3 Representation of lithological complexes and their disturbance by slope deformations

Formation	Lithological complex (LC)	Index within the map	Area of LC		Slope deformations (SD)			
					area	% from area of LC	% from total area of SD	% from the total area
			km^2	%	km^2	%	%	%
Quaternary cover	anthropogenous	1	0.62	0.02	0.04	5.8	0.01	0.00
	deluvial sediments	2	1,784.55	44.15	331.69	18.59	58.13	8. 21
	proluvial - Pleistocene	3	25.10	0.62	0.18	0.70	0.03	0.00
	proluvial	4	18.60	0.46	0.01	0.07	0.00	0.00
	fluvial - Pleistocene	5	362.16	8.96	2.23	0.61	0.39	0.06
	fluvial	6	54.26	1.34	2.18	4.02	0.38	0.05
	glacifluvial	7	15.79	0.39	0.13	0.83	0.02	0.00
	organogenous and organic	8, 9	0.38	0.01	0.00	0.00	0.00	0.00
	chemogenous	10	0.001	0.00	0.00	0.00	0.00	0.00
Pre-Quaternary formations	tuff	11	0.22	0.01	0.00	0.00	0.00	0.00
	andesite	12, 13	6.97	0.17	0.41	5.90	0.07	0.01
	Molasse Formation	14	4.85	0.12	0.53	10.92	0.09	0.01
	sandstones-conglomerates	15	301.13	7.45	28.40	9.43	4.98	0.70
	Flysch with predominance of claystones	16	844.24	20.89	131.95	15.63	23.12	3.26
	Flysch with predominance of sandstones	17	482.49	11.94	50.45	10.46	8.84	1.25
	claystones	18	1.81	0.04	0.09	5.10	0.02	0.00
	marlstones-limestones	19	85.49	2.12	21.07	24.65	3.69	0.52
	limestones	20-22	14.15	0.36	1.23	18.44	0.21	0.03
	Watercourses and reservoirs		39.41	0.97	0.01	0.03	0.00	0.00
	Total		4,042.22	100.0	570.59	14.12	100.0	14.12

Among the erosion phenomena on the maps are shown linear erosion on slopes (erosion gullies, potholes) and active erosion of watercourses as a line entity. On the banks of reservoirs places with an active abrasion are marked. For larger watercourses lateral erosion is more significant, in the smaller tributaries and mountain brooks with steep slopes lateral and streambed erosion are more often.

From the accumulation phenomena in the map proluvial cones are depicted.

In addition, the maps show: hydrogeological data (springs, waterlogged areas), hydrological data (watercourses, natural and artificial reservoirs), and tectonic data (observed and predicted tectonic lines and failures, bedding).

5.4. The methodology of creating landslide hazard maps

Landslide hazard assessment using statistical methods in GIS environment is based on the selection of the appropriate factors affecting the slope stability. Statistical analysis of the landslide hazard comes from the principle of actualism of geological phenomena and processes, according to which the landslides will occur in places where they have been in the past, or currently under similar conditions of activation. Selected factors affecting the genesis and development of slope movements are formulated in parametric maps and thus enter into the process of statistical evaluation using map algebra in GIS environment. According to the chosen statistical method, the comparison of parametric maps with landslide inventory map followed. The conclusions resulting from the statistical comparison were then extrapolated to the whole evaluated territory and the result is a prognostic map of hazard. Further, it is necessary to divide the landslide hazard map, based on the mathematical distribution (e.g. median, standard deviation and other), into three (low, medium, high degree of hazard) or five (very low, low, medium, high and very high degree of hazard) categories representing the degree of landslide hazard.

From the group of statistical methods for the landslide hazard assessment within GIS environment a bivariate statistical analysis was selected, which together with multivariate analysis is the most widely used method with high success rate of model (Pauditš & Bednarik, 2006).

This method presents a statistical combination of each parametric map with a map of registered landslides. Bivariate statistical analysis uses one dependent variable (landslide inventory map) and one independent variable (individual input parametric map). The result gives the total number of grid cells with landslides and without landslides in each class of input factors, calculated per unit area or percentages. The double combinations are stored in tabular form, where one of the numbers is a class in the parametric map and the second number represents the presence or absence of landslides (0 - false, 1 - true).

Based on this combination it is necessary to provide secondary reclassification for each parametric map. During this process to the existing classes within each parametric map new numerical values are assigned, representing statistically calculated probability to sliding. The highest numerical value is assigned to the class most susceptible to sliding and vice versa, a class with the lowest numerical value is the least susceptible to sliding.

Before the summing secondary reclassified parametric maps it is necessary to determine the weights of individual parameters. Here-in, weights are calculated based on entropy index according to mathematical procedure proposed by Vlčko et al. (1980).

Result of bivariate statistical analysis is a map of the landslide hazard, calculated as the weighted sum of the secondary reclassified parametric maps. The equation for the final sum has the form:

$$y = \sum_{i=1}^{n} C * W_i \qquad (5.1)$$

where:

y - the value of landslide hazard in the final map,
i - individual parametric maps,
C - class,
W_i - weight of the corresponding parameter.

The result of the weighted sum is then a continuous range of values representing the value of the landslide hazard degree in the model area. Continuous interval is necessary to interpret and divide into classes, reflecting the degree of the landslide hazard. Here-in, the five-point scale representing very low, low, medium, high and very high degree of landslide hazard was used.

5. 5. Landslide hazard assessment

5.5.1. Input parameters

Eight input factors are evaluated, which somehow affect slope stability. Each factor enters to the bivariate statistical analysis in the form of parametric map. Chosen parameters reflect the geological, climatic and hydrological conditions in the area, morphometric characteristics of the relief and current land-use.

The total processed area has an extent of 4,042.23 square kilometres, the area of registered slope deformations constitutes 570.59 km^2, thus, 14.12 % of the total area is affected by slope deformations.

Interpretation of geological conditions

Basis to obtain information about the geological setting of the study area provide specialized engineering geological maps at a scale of 1:10,000 in a vector form. These maps are one of the outputs of the project. The maps were scanned, georeferenced and then vectorized in a coordinate system S-JTSK. Parametric map in a vector form was converted to the raster format with a cell size of 10x10 m (Fig. 5.2). Legend to this parametric map is shown in tables 5.1 and 5.3.

Based on the statistical evaluation that was performed using map algebra within GIS environment, it was found a percentage of individual lithological complexes of the total area (Tab. 5.4). Index Ac represents the total area (acreage) of class expressed in km^2.

Tables 5.3 and 5.4 show that the largest area extent in the model area (1,784.55 km^2) have deluvial sediments; among the Quaternary sediments also fluvial sediments have significant representation. Paleogene Flysch sediments - classes 15, 16 and 17 occupy summary area of more than 1,600 km^2.

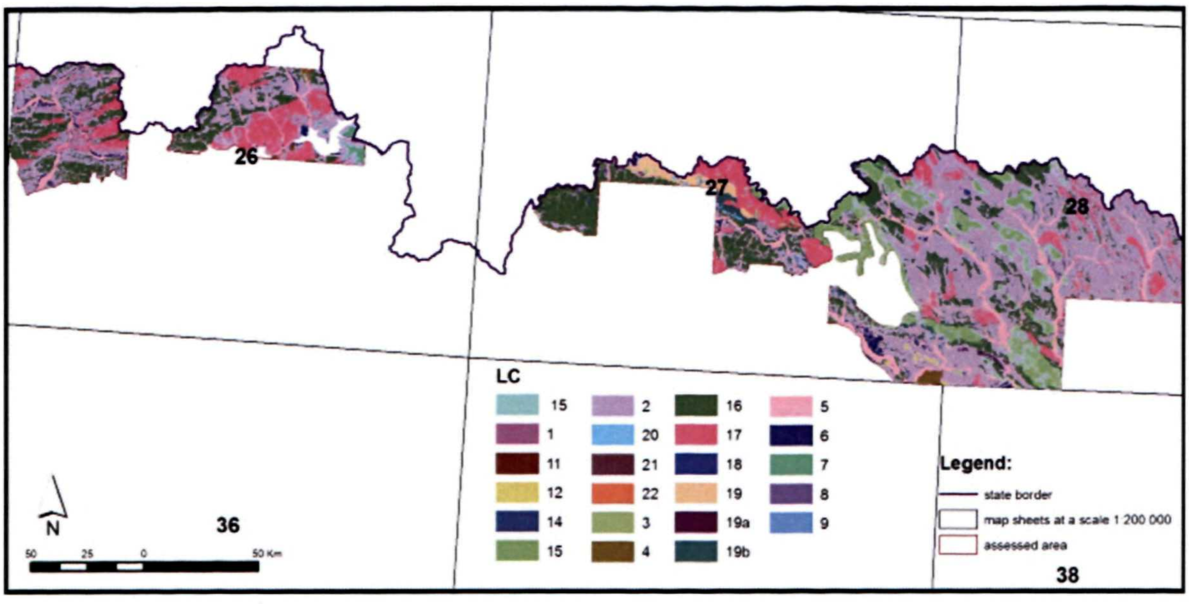

Fig. 5.2 Parametric map of engineering geological conditions in a raster form

Tab. 5.4 Spatial distribution of individual classes of lithological complexes

Class	Ac (km^2)	Class	Ac (km^2)
1	0.6204	13	0.001
2	1,784.5468	14	4.8546
3	25.1002	15	301.1265
4	18.6031	16	844.2422
5	362.1564	17	482.4918
6	54.2643	18	1.8052
7	15.7852	19	48.8389
8	0.0409	19a	4.5785
9	0.3416	19b	32.0758
10	0.001	20	9.1895
11	0.22	21	4.6789
12	6.9676	22	0.2829

Morphometric parameters of the relief

In the frame of this study following morphometric parameters were evaluated:

- hypsographic levels (levels of altitudes),
- slope angle,
- slope aspect,
- curvature of relief,
- slope length,
- contributing areas.

Morphometric parameters were derived from a digital elevation model (DEM - Fig. 5.3). The source of input data for the compilation and calculation of the DEM in the model area were contour lines and elevation points from topographic maps at a scale 1:10,000, which are distributed by Institute of Geodesy and Cartography. Areal extension of the categories is shown in Tab. 5.5.

More than 2,900 km^2 of the total area of the study area is located at altitudes 290-770 m a.s.l. (classes 2, 3 and 4). The height difference between the lowest and highest altitude represents 1,420 meters.

Tab. 5.5 Spatial distribution of reclassified DEM

Class	Interval [m a. s. l.]	Ac (km^2)
1	130-290	408.8894
2	291-450	907.917
3	451-610	1,204.765
4	611-770	813.4838
5	771-930	409.9881
6	931-1,090	183.1551
7	1,091-1,250	80.6844
8	1,251-1,410	28.0409
9	1,411-1,550	5.2991

Slope angle

Slope angle is indicated in degrees (range 0-90 degrees) or as a percentage (or per mille). Parametric map of slope angle (Fig. 5.4) is reclassified according to Hrašna (1980, in Matula et al., 1983), which is commonly used in the engineering geological mapping (Tab. 5.6). Slopes are divided into 9 categories.

Tab. 5.6 Classification of slope angle

Class	Slope angle [%]	Slope angle [°] (class)
I. Flat (with small slope angle)	< 3	< 2 (1)
	3-5	2- 3 (2)
	5-9	3-5 (3)
II. Slightly (with a moderate slope angle)	9-2	5- 7 (4)
	12-20	7- 11 (5)
	20-30	11-17 (6)
III. Steep (with a large slope angle)	30-36	17-20 (7)
	36-60	20-31 (8)
	> 60	> 31 (9)

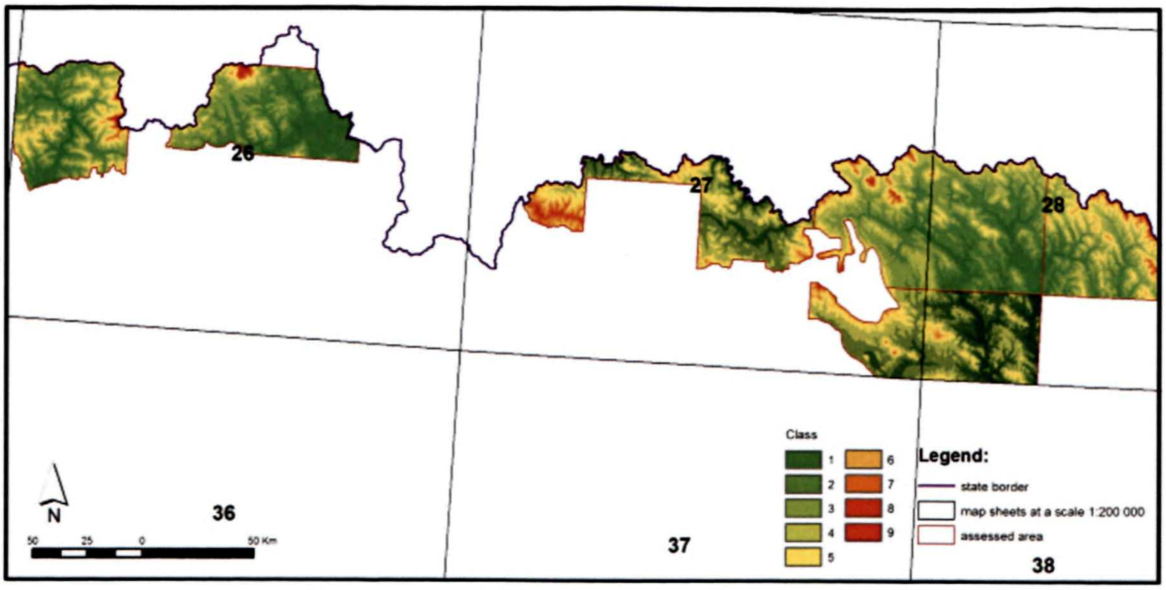

Fig. 5.3 Parametric map of digital elevation model in a raster form

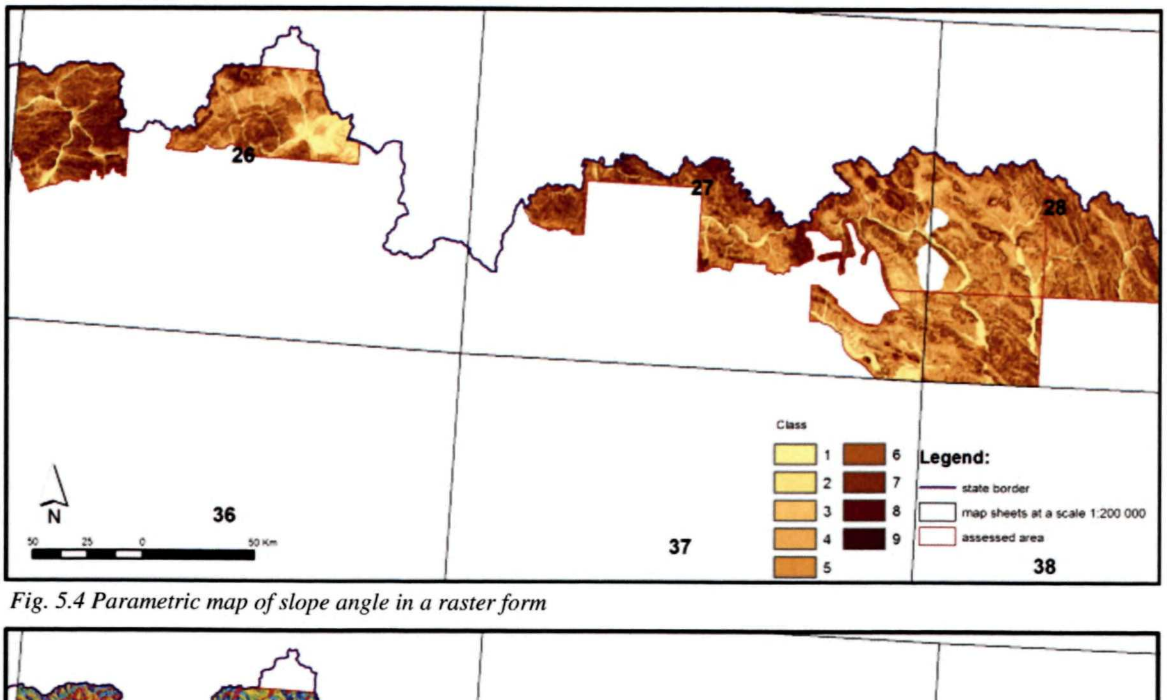

Fig. 5.4 Parametric map of slope angle in a raster form

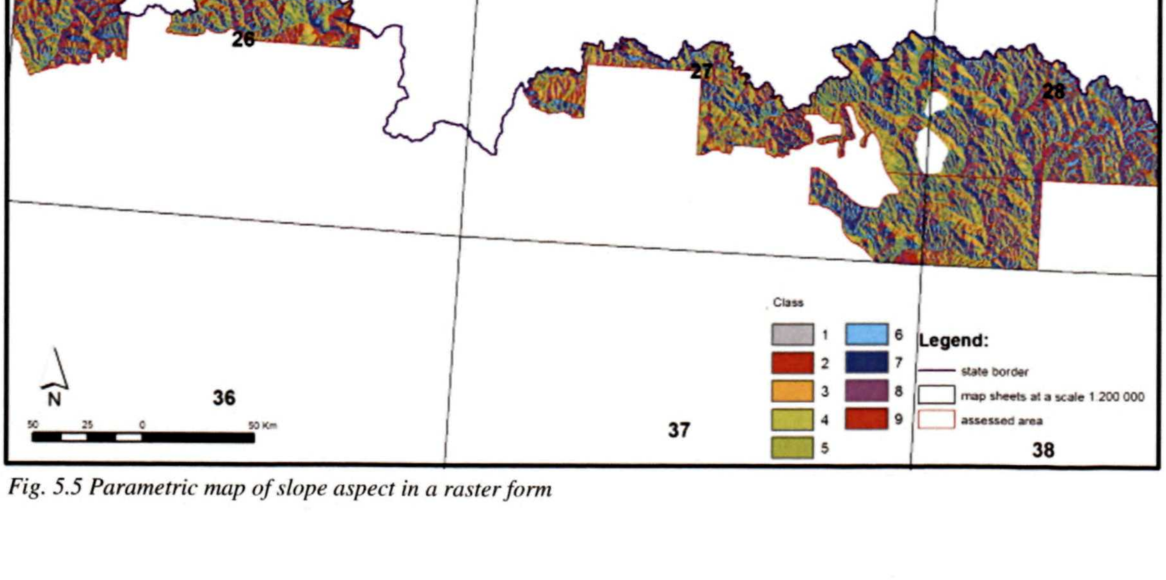

Fig. 5.5 Parametric map of slope aspect in a raster form

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The total area of the reclassified categories of slope angle is shown in Tab. 5.7. The largest area have the slopes with a moderate slope angle of 11-17° (class 6) and slopes of 7-11° (class 5). Other classes are approximately equally distributed, except class 9 (steep slopes), which occupies just over 14 km^2.

Tab. 5.7 Spatial distribution of reclassified slope angles

Class	Interval	Ac (km^2)
1	< 2°	304.6084
2	2-3°	142.2787
3	3-5°	327.4622
4	5-7°	428.0142
5	7-11°	967.6527
6	11-17°	1,134.34
7	17-20°	342.5587
8	20-31°	381.1609
9	> 31°	14.147

Slope aspect

The resulting parametric map is in degrees; in raster form with cell size of 10x10 m is shown in Fig. 5.5. The slopes are reclassified into 9 categories, where category 1 presents a flat area without relation to the cardinal points (Tab. 5.8).

Within the study area slopes in terms of orientation to cardinals are approximately equally distributed. The largest spatial representation have slopes with South-West orientation - class 7.

Tab. 5.8 Spatial distribution of slope aspect

Class	Interval (°)	Ac (km^2)
1 (flat)	(-1)	34.3354
2 (N)	(0-22.5), (337.5-360)	417.0316
3 (NE)	(22.5-67.5)	565.114
4 (E)	(67.5-112.5)	549.594
5 (SE)	(112.5-157.5)	479.8359
6 (S)	(157.5-202.5)	535.2548
7 (SW)	(202.5-247.5)	651.2452
8 (W)	(247.5-292.5)	472.633
9 (NW)	(292.5-337.5)	337.1812

Curvature of the relief

The resulting curvature (Fig. 5.6) was reclassified into three categories - convex (positive values), concave (negative values) and linear (inflection field values close to 0). Tab. 5.9 presents spatial extension of the individual forms of relief curvature in the study area. Convex and concave relief forms are spread rather evenly with a slight predominance of concave forms.

Tab. 5.9 Spatial distribution of reclassified forms of relief curvature

Class	Interval	Form	Ac (km^2)
1	< -0.00025	Concave	1,427.502
2	- 0.00025 to 0.00025	Linear	1,516,017
3	> 0.00025	Convex	1,098.704

Slope length and contributing areas

To derive the slope length and contributing area parameters, flow direction of hydrologically correct digital elevation model should be calculated firstly. Direction of water flow was calculated in ArcGIS using the module "flow direction" and the output is a grid cell with the cell size 10x10 m. From it, slope lengths - using the "flow down" and using the "flow up" modulus contributing areas grids were generated in the model area. The resulting grids were reclassified into 6 classes (Figs. 5.7 and 5.8), and their area extension is shown in Tabs. 5.10 and 5.11.

Tab. 5.10 Spatial distribution of reclassified slope length

Class	Interval [m]	Ac (km^2)
1	0-100	133.0903
2	100-500	952.147
3	500-1000	1,111.89
4	1000-1500	786.299
5	1500-2000	481.8508
6	> 2000	576.9448

Tab. 5.11 Spatial distribution of reclassified contributing areas

Class	Interval [m^2]	Ac (km^2)
1	0-100	2,030.095
2	100-500	1,822.137
3	500-1,000	152.5688
4	1,000-1,500	22.0251
5	1,500-2,000	8.0694
6	> 2,000	7.3288

From the parametric maps of reclassified slope lengths is clear that they are evenly distributed throughout the model area except of class 1, which represents the slopes with a length of up to 100 m.

In contributing areas parameter classes 1 and 2 (up to 500 m^2) dominate, which correspond to the small contributing areas. Classes with a large surface area (class 6) occur in the model territory only over an area of 7.3 km^2.

The actual land-use

Parametric map of the actual land-use was vectorized from raster topographic images and is shown in Fig. 5.9. The spatial distribution of individual elements of the cur-

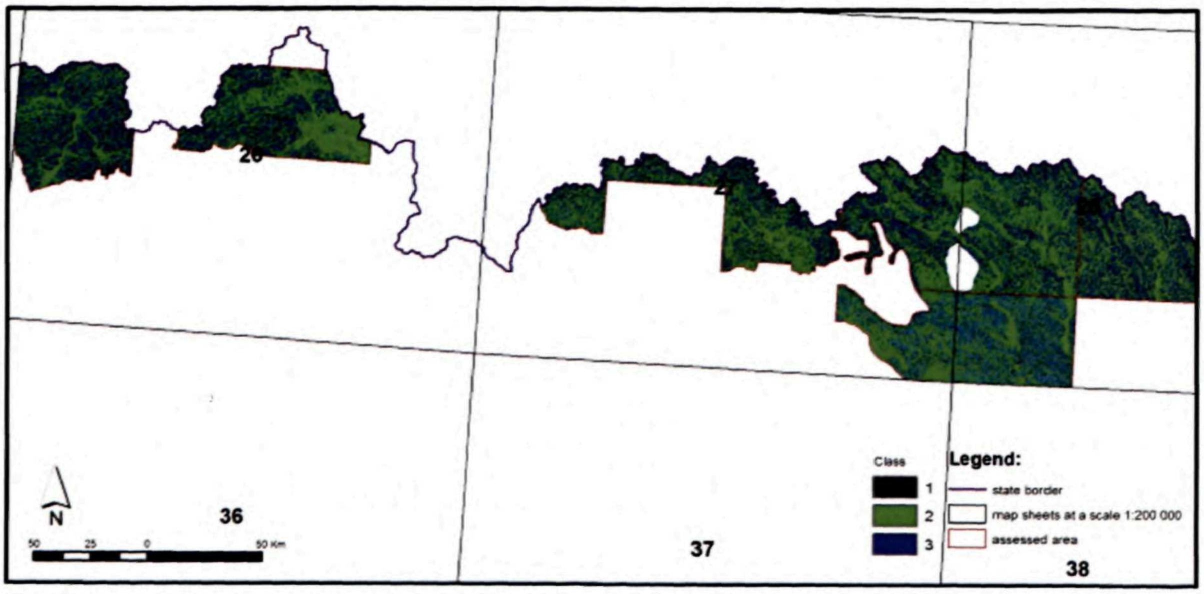

Fig. 5.6 Parametric map of relief curvature in a raster form

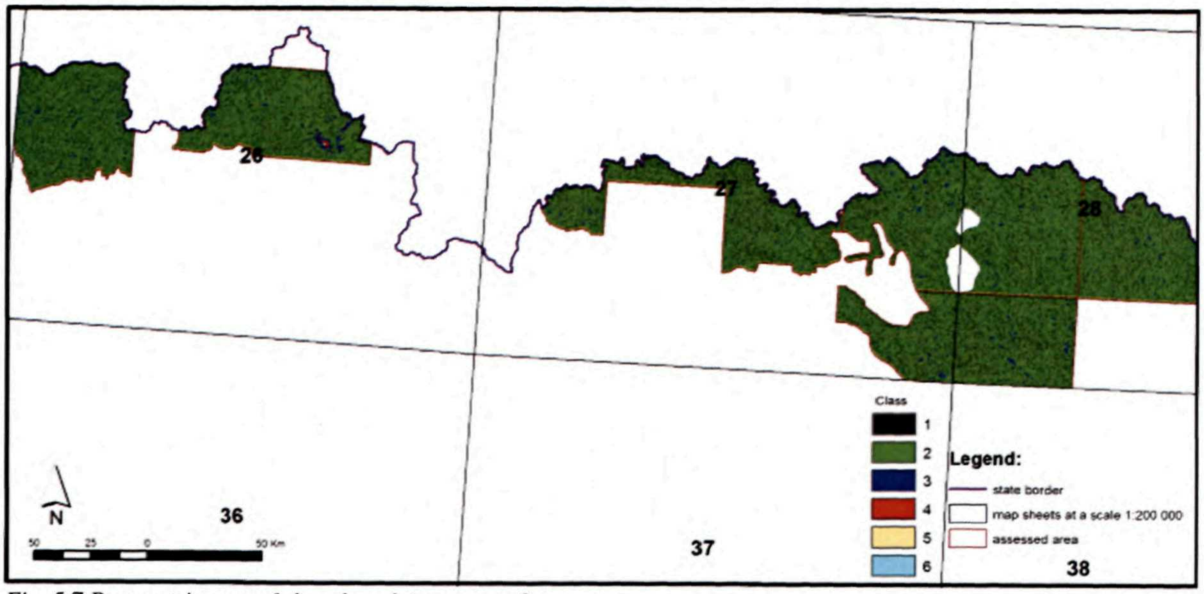

Fig. 5.7 Parametric map of slope length in a raster form

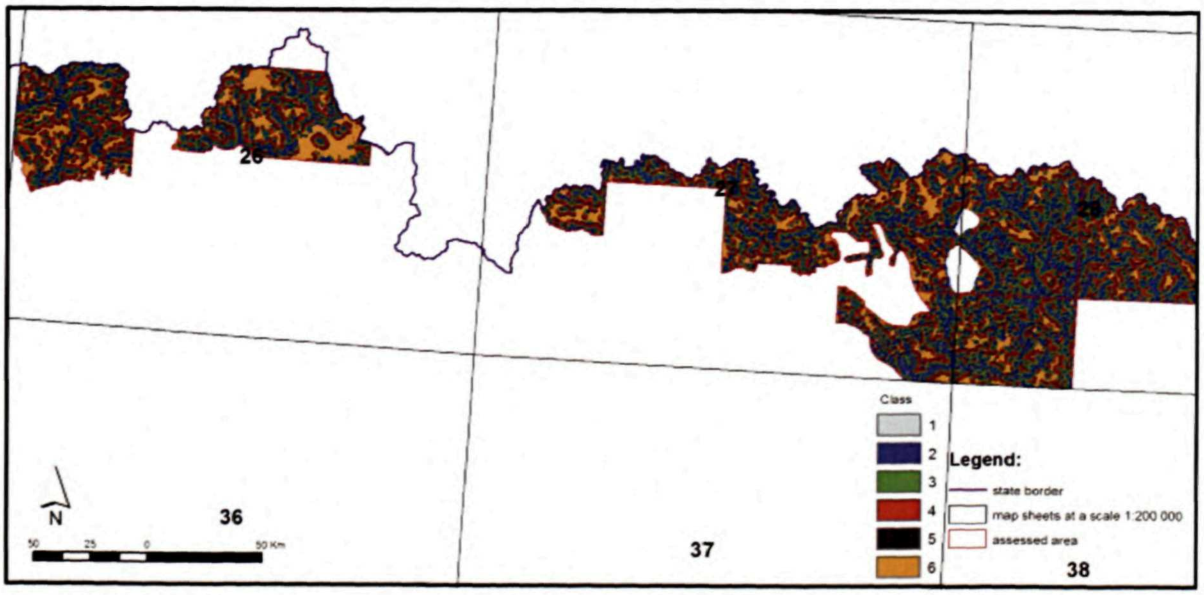

Fig. 5.8 Parametric map of contributing areas in a raster form

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rent land-use (Tab. 5.12) shows that the area is mostly afforested, class 5 (2,197.2 km^2), urban environment (class 2) covers an area over 124 km^2.

Tab. 5.12 Spatial distribution of elements of actual land-use

Class	Interval	Ac (km^2)
1	Road network	28.2893
2	Settlement	124.7727
3	Pastures	491.451
4	Arable land	1,066.1914
5	Forests	2,197.181
6	Meadows and gardens	90.5386
7	Watercourse network	41.5557
8	Railway network	1.7278
9	Quarries	0.4626

Interpretation of slope deformations

As a basis of preparation of the parametric map of landslides the study areas were revised and newly registered slope deformations were assessed in the maps of engineering geological conditions, as well as 372 landslides registered within the project "Registration and evaluation of newly evolved slope failures in 2010 in Prešov and Košice regions" (Liščák et al., 2010).

As was already mentioned, the registered landslides in the study area cover an area of 570.59 km^2 of the total area 4,042.23 km^2. This means that 14.12 % of the total area is directly affected by slope failures. The resulting parametric map of landslides as entry to the bivariate statistical analysis is shown in Fig. 5.10.

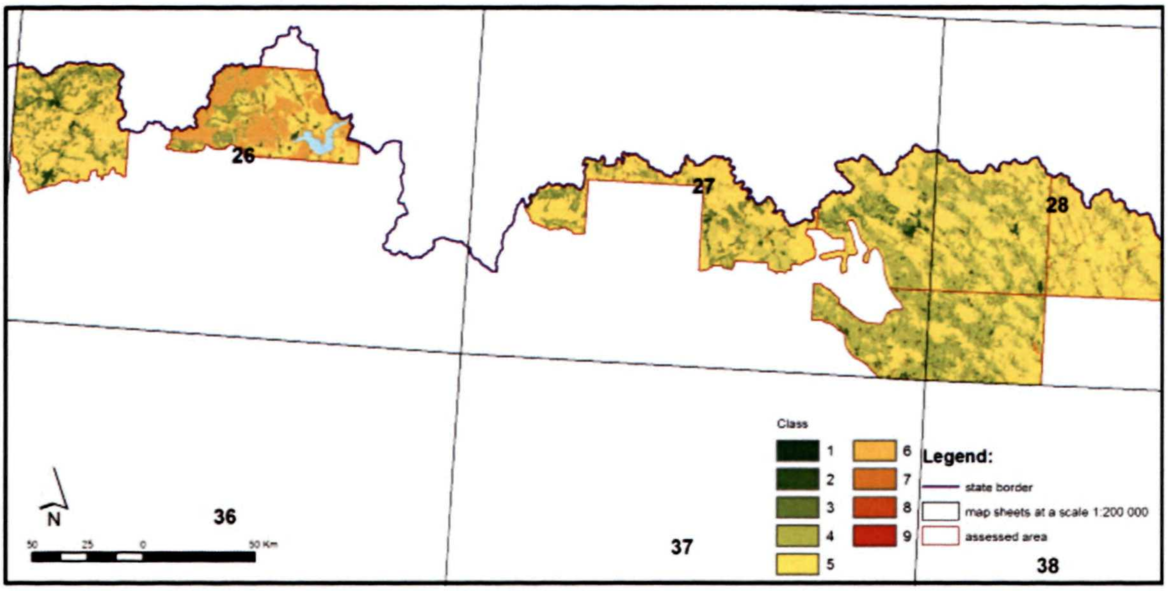

Fig. 5.9 Parametric map of actual land-use in a raster form

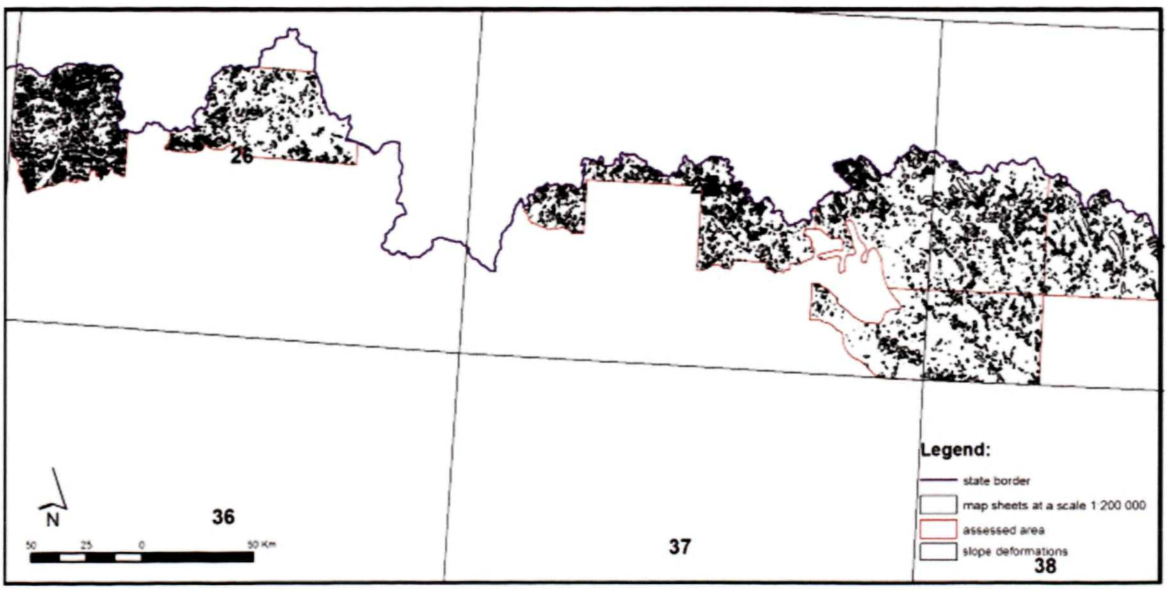

Fig. 5.10 Parametric map of slope deformations in a raster form

5.5.2. Results of bivariate statistical analysis

Table 5.13 shows the results derived from bivariate statistical analysis. Ac represents the area of classes after first reclassification; Asd is the area of landslides within the individual class of each parameter.

From the comparison of parametric map of lithological complexes with the landslide inventory parametric map follows that the most disturbed areas are built by deluvial sediments (class 2); 58% of all registered landslides can be found in this class. They are followed by class 16, Flysch with a predominance of claystones - 23%, and Flysch with a predominance of sandstones - 9% (class 17).

Most slope deformations are located at altitudes 450-610 m a. s. l. (class 3) - 31%, followed by the altitude interval 291-450 m a. s. l. with 26% (class 2) and the interval 611-770 m n. m. with 19% (class 4). The highest parts of the territory are affected by slope failures only marginally.

Almost 86% of the total area of landslides occur on slopes between 5° and 20°. The comparison shows that the most critical slopes are within the range 11° to 17° (class 6, more than 35% of landslides) and slopes within the range 7° to 11° (class 5, with more than 31% of the total area of landslides). They are classified as gentle slopes with moderate slope angle.

The slope aspects are evenly distributed in the model area, and similarly, the distribution of slope deformations in each class of slope aspect is evenly distributed, as well. This implies that the slope aspect parameter does not have a big impact on slope movements, as is evidenced also by the weight of this factor.

Tab. 5.13 Results of bivariate statistical analysis

	Class	Ac (km^2)	Asd (km^2)		Class	Ac (km^2)	Asd (km^2)		Class	Ac (km^2)	Asd (km^2)
Lithological complexes/landslides	1	0.6204	0.036	Slope angle/landslides	1	304.6084	1.8899	Land-use/landslides	5	8.069	0.7568
	2	1784.547	331.6866		2	142.2787	3.415		6	7.329	0.3624
	3	25.1002	0.1759		3	327.4622	20.7147		1	28.29	2.8498
	4	18.6031	0.0126		4	428.0142	54.6141		2	124.8	8.6659
	5	362.1564	2.2258		5	967.6527	176.5365		3	491.5	112.7914
	6	54.2643	2.1797		6	1134.34	204.9129		4	1,066	126.2962
	7	15.7852	0.1309		7	342.5587	54.7507		5	2,197	308.8293
	8	0.0409	0		8	381.1609	52.2858		6	90.54	10.9618
	9	0.3416	0		9	14.147	1.471		7	41.56	0.1369
	10	0	0	Slope aspect/landslides	1	34.3354	4.304		8	1.728	0.0428
	11	0.22	0		2	417.0316	60.7515		9	0.463	0.0134
	12	6.9676	0.4108		3	565.114	89.3241				
	13	0	0		4	549.594	77.5357				
	14	4.8546	0.53		5	479.8359	68.9181				
	15	301.1265	28.3958		6	535.2548	77.9717				
	16	844.2422	131.9468		7	651.2452	85.8633				
	17	482.4918	50.4527		8	472.633	61.4855				
	18	1.8052	0.0921		9	337.1812	44.4367				
	19	85.4932	21.0749	Curvature /landslides	1	1,427.502	282.5809				
	20	9.1895	0.7436		2	1,516.017	183.6193				
	21	4.6789	0.4844		3	1,098.704	104.3904				
	22	0.2829	0	Slope length/landslides	1	133.0903	13.7496				
Altitude/landslides	1	408.8894	40.7149		2	952.147	147.7797				
	2	907.917	150.5895		3	1,111.89	166.4366				
	3	1204.765	172.7775		4	786.299	112.1667				
	4	813.4838	109.626		5	481.8508	63.75				
	5	409.9881	56.45		6	576.9448	66.708				
	6	183.1551	25.4881	Contribution area/landslides	1	2,030.095	201.31				
	7	80.6844	10.8608		2	1,822.137	326.2965				
	8	28.0409	3.6112		3	152.5688	38.2747				
	9	5.2991	0.4726		4	22.0251	3.5902				

Comparison of parametric maps of curvature of the relief with the parametric map of landslides indicates that the slides occur more on concave relief forms (50%, class 1). To convex forms 32% of registered slope deformations are fixed. Accumulation parts of slope deformations are bound to linear forms of curvature.

Landslides are mostly located on the slopes with a length of 500-1,000 m (class 3, more than 29% of slides), as well as on the slopes with a length in the range of 100 to 500 m (class 2, more than 26% of landslides). 20% of landslides occur on slopes with a length of 1,000-1,500 m (class 4).

Most landslides occur in small contributing areas of the class 2 (up to 500 m^2, more than 57% of the total share of landslides) and in this regard class 1 is also interesting (up to 100 m^2), which encompasses 35% of landslides.

Forests are most affected by slope failures within the study area, 54% of registered deformations are in this class (class 5), 22% of slope deformations are in class 4 – arable land and 20% in pastures (class 3). More than 8 km^2 of landslides affect the built-up area (class 2). Road and rail networks are affected by slope failures in area of almost 3 km^2 (classes 7 and 8).

The evaluation of bivariate results was followed by determining the weights of individual parameters according to the methodology set out in the work by Vlčko et al. (1980). Calculated weights show that the greatest impact on the formation and development of landslides in the model area have slope angle and lithology of the area. Much lower impact have further parameters in the following order - the length of slopes, slope aspect, curvature of the relief, contributing area and hypsographic levels - altitude.

Based on the calculated probability P_{ij} and probability density (P_{ij}) each input parametric map was secondarily reclassified. To each class new numeric value was assigned (integer) for each grid cell, to represent the degree of landslide susceptibility of a given parameter class.

5.5.3. Landslide hazard map

Landslide hazard map was created based on a simple weighted sum of the multiplication of secondary reclassified parametric maps and weights of individual parameters. The equation used for the creation of landslide hazard map for the model area has the following form:

y = /slope_recl2/*0.011363 + /aspect_recl2/*0.001014 + /land-use_recl2/*0.010321 + /geology_recl2/*0.010515+ /curvat_recl2/*0.008359 + /flowleng_recl2/*0.001137 + /flowmic_recl2/*0.006903 + /dem_recl2/*0.00687 (5.2)

where:

y - represents the value of landslide hazard in the resulting map,

/slope_recl2/ - value in the each cell of grid of secondary reclassified parametric map of slope angle,

/aspect_recl2/ - value in the each cell of grid of secondary reclassified parametric map of slope aspect,

/land-use_recl2/ - value in the each cell of grid of secondary reclassified parametric map of the current land-use,

/geol_recl2/ - value in the each cell of grid of secondary reclassified parametric map of lithological complexes,

/curvat_recl2/ - value in the each cell of grid of secondary reclassified parametric map of curvature of the relief,

/flowleng_recl2/ - value in the each cell of grid of secondary reclassified parametric map of slope lengths,

/flowmic_recl2/ - value in the each cell of grid of secondary reclassified parametric map of contributing areas,

/dem_recl2/ - value in the each cell of grid of secondary reclassified parametric map of altitudes.

The result of this sum is a continuous range of values representing the varying degree of landslide hazard. The resulting landslide hazard interval was reclassified into five classes representing the degree of landslide hazard in the model area:

1. very low degree of landslide hazard,
2. low degree of landslide hazard,
3. moderate degree of landslide hazard,
4. high degree of landslide hazard,
5. very high degree of landslide hazard.

The resulting landslide hazard map is presented in Fig. 5.11. To check the degree of success of the hazard map, as the easiest way of verification a comparison with the parametric map of landslides was used. The verification compares the area of landslides which occupies a very high degree of landslide hazard (class 5) in the prognostic map. From this simple comparison came out percentage of 84.2%, which means that when exposed to a significant trigger factor over 80% assumed of slope failures can be mobilized according to the landslide hazard map.

5.6. Conclusions

Within the project frame 285 map sheets at a scale of 1:10,000 were processed in GIS. The result represents an original and unique solution not only in Slovakia. Vectorization, statistical analysis as well as visualization were carried out using the softwares ArcGIS, ESRI Ltd., which belong to the largest and most comprehensive commercial GIS softwares.

The map outputs were processed in the form of vector and raster data models in a coordinate system S-JTSK. Vector maps include also the database in the form of attribute tables. In raster models the cell size of 10 m was set out.

The main outcomes of the project are maps that cover an area of 4,042.43 km^2 (8.24% of the total area of Slovakia). The territory is almost exclusively built of the Flysch Formation with significant Quaternary cover. Three types of maps were created:

1. Specialized engineering geological map,
2. Map of documentary points,
3. Landslide hazard and flood hazard maps (flood hazard is not discussed in this paper).

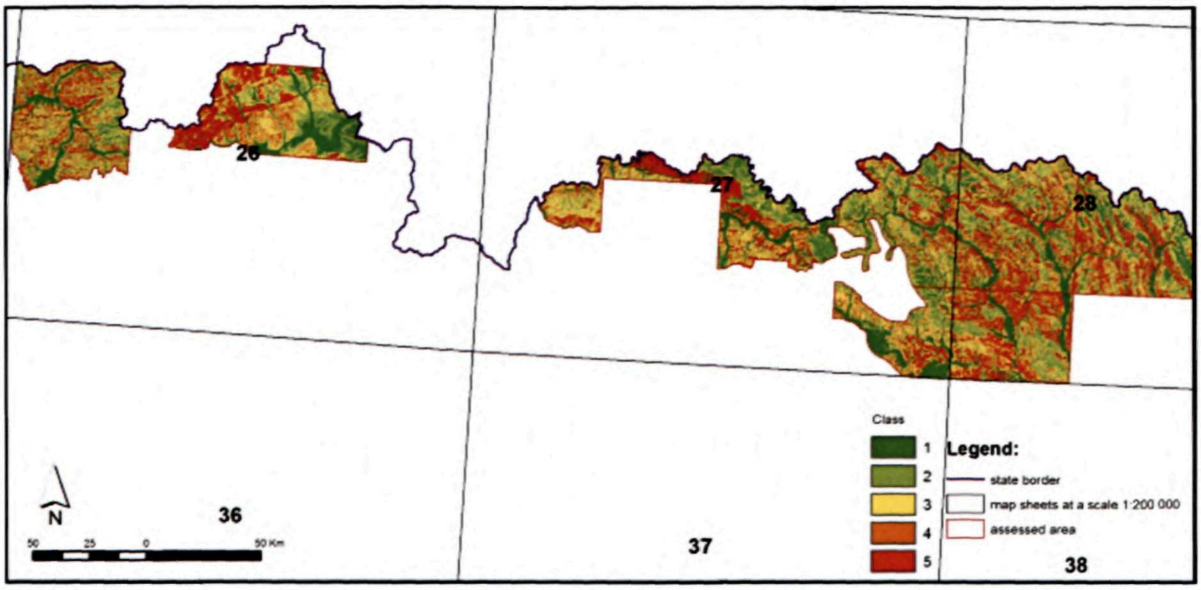

Fig. 5.11 Landslide hazard map

Specialized engineering geological map presents a base for the creation of the landslide hazard map, and provides a separate map series showing the geological setting of the area and geodynamic phenomena with emphasis on slope deformations, which significantly affect land-use. The slope deformations represented mostly by landslides in various stages of activity cover an area over 570.59 km^2; it equals to 14.12% of the total study area. This is several times higher compared to the average slope instability in Slovakia, which is 5.25% (Šimeková et al., 2014).

Landslide hazard maps currently represent a suitable basis for spatial planning. They have a recommendatory character – they enable to make qualified decisions of investors, engineers and contractors about the extent, type and method of engineering geological investigation required for the particular type of construction (lined, ground and underground) in terms of the probability of slope deformations occurrence. The occurrence of these geodynamic phenomena greatly affects and changes the view of the implementation of the works. Landslide hazard maps were generated on large scales (1:10,000) and are also suitable for design and implementation of remediation works that can largely avoid direct and indirect losses resulting from the landslide hazard.

Eight input factors, which in certain way affect the stability of slopes, are evaluated. Selected factors reflect the geological, climatic and hydrological conditions in the study area, morphometric characteristics of the relief and current land-use. In terms of calculated weights determined by the entropy (a measure of chaos in natural systems), different factors in the area have the influence on the stability of slopes in following order:

- Slope angle,
- Lithology,
- Land use.
- Much lower impact on slope stability have:
- Curvature of the relief,
- Contributing areas,
- Altitudes,
- The length of slopes,
- Slope aspect.

Landslide hazard maps are drawn in "traffic light" manner. The territory classified in the high and very high degree of landslide hazard (red colour) includes both multiple combinations of factors adversely affecting the stability of slopes, e.g. combination of unfavourable geological setting, together with the dangerous slope angle and inappropriate land-use. This should be an objective basis for the recommendation of the necessity of carrying out a comprehensive detailed engineering geological investigation focused primarily on evaluation of the stability conditions and the resulting assessment of the feasibility of a particular investment project itself, and also the feasibility of wide range of preventive remediation measures restricting the emergence of possible damage to area and constructed parts and measures providing definitive stability of the object.

The moderate degree of landslide hazard (orange colour) is a combination of two unfavourable factors, and there should be recommended at least preliminary engineering geological investigation and the consequent adequate designing and realization update – prior to a building plan implementation.

Low degree of landslide hazard (green colour) represents areas that have long been predicted as stable, in terms of the stability conditions is not necessary to carry out engineering geological investigation. This does not preclude assessment for the potential flooding area, the bearing capacity of foundation soil, aggressive rock environment and erosion.

Important component of this geological project was the development of record sheets (passports) of selected sites where there is damage or serious risk to various objects due to landslides or erosion processes. These sites were documented in detail and evaluated from the aspect of the needs and possibilities for remediation, with a proposal for necessary geological reconnaissance work preceding the actual remediation. A total of 212 passports were produced in 11 districts of Žilina and Prešov regions.

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