

# QUANTIFICATION OF THE NATURAL FACTORS' IMPACT EFFECTIVENESS ON ENVIRONMENTAL HAZARDS – SLOPE MOVEMENTS IN THE FLYSCH AREAS OF THE KYSUCE REGION

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## Abstract

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The flysch areas belong to the territories with highest occurrence of landslides in Slovakia. Almost 67% of all landslides in Slovakia take place within the Carpathian flysch. It is a type of slope deformation that responds sensitively to the quality of individual factors that form the landscape and to the change in natural conditions. The occurrence of various geodynamic phenomena can be understood as a geological barrier that reduces or inhibits the use of natural environment and negatively affects the life of society and territorial development. In this paper, we evaluate the statistical significance of selected natural factors of the landscape in relation to the occurrence of unstable slopes in the Kysuce region. In addition, we also evaluated the expansion of unstable slopes in individual landscape factors. Significant linkages between the variables' hydrogeological base\_sandstones with thin clay layers (HB\_s) and geological-substrate complex\_loamy wastes to loamy-stony debris on sandy conglomerates (GSC\_sc) ( $R = 0.95$ ,  $p = 0.002$ ) and secondary significant linkages between the variables soil type: Dystric Cambisols (S\_Cmd) and HB\_s ( $R = 0.40$ ,  $p = 0.002$ ) (Klokočov and Zákopčie cadastres) were observed. Significant correlation of variables within the areas with unstable slopes was also observed between hydrogeological base\_sandy flysch (HB\_sf) and geological-substrate complex\_loamy wastes on flysch stones (GSC\_fs) ( $R = 0.81$ ,  $p = 0.002$ ) (Nová Bystrica and Kysucké Nové Mesto cadastres). The most unstable slopes occur in Nová Bystrica cadastre (34.62% of the area) and in the Klokočov cadastre (28.25% of the area). The inclination of slopes (especially slopes above 12°) plays an important role within the unstable slopes. Slopes with steep inclination cover up to 81.45% of the cadastral area of Nová Bystrica, of which almost 1/3 are unstable slopes.

*Key words:* slope movements, statistical methods, flysch area, natural factors.

## Introduction

The Carpathian flysch region forms a contiguous belt at the outer edge of the Western Carpathian Mountains and extends through extensive spurs to the inner Carpathian Mountains. The rock complexes of the flysch formation have a dominant position, of which the most

widespread is the rhythmic-bedded clayey-sandstone flysch. The flysch territory belongs to the areas with the highest landslide occurrences in Slovakia. Almost 67% of all landslides in Slovakia take place within the Carpathian flysch. It is a type of slope deformation that responds sensitively to the quality of individual factors that make up the landscape and to the natural condition changes. The occurrence of various geodynamic phenomena can be understood as a geo-barrier that reduces or totally obviates the use of natural environment and negatively affects the life of society and territorial development.

Most of the territory in Kysuce region is built by Paleogene complexes of the fine-rhythmic flysch, which are a good prerequisite for forming of strong deluvial covers. These can activate slope movements under suitable hydrogeological conditions, after large-scale solifluction processes with the formation of shear surfaces with pre-Quaternary subbasement. Unstable slopes in Kysuce region cover almost 235 km<sup>2</sup>.

As reported by Húška (1981), the landslide occurrence is caused by the breach of balance between stabilizing forces (cohesion) and gravity. Changes in the balance can cause inclination change, surface load, slope base violation, increased content of soil water, increased amount of water and water leakage on the impermeable bedrock.

An important task in determining the causes of slope movements is the evaluation of conditions in which they happen and to test the selection of presumed correlating factors responsible for their occurrence. The geological, geomorphological, hydrogeological, hydrological and climatic conditions can be included among the factors responsible for the formation and development of slope movements. Factors that cause or affect changes in natural conditions (slope changes, changes in the slope height, changes in the water content, groundwater flow, frost activity, weathering, vegetation cover changes, etc.) have natural and anthropogenic character. Listed factors combine together, while water activity is always present and penetrates into the permeable slope layers, softens the soil and forms a sliding surface on the impermeable bedrock, on which the overlying layers slide with their own weight.

In some mountain areas, landslides are termed as dominant erosive processes influenced by human activities such as road construction and changes in the use of soil (Morgan, 2005; Preuth et al., 2010). Fine-grained sedimentary rocks (marl and clay shale) condition the genesis of soils with high erodibility, which are prone to landslides (Eberhardt et al., 2005). Ahmadi, Esfandarani (2002) reported that marls without a vegetation cover occurring in areas with 20-40° slope inclination were prone to landslips. Water retention in soil is strongly subordinated to the percentage content of clay, when the content of water in soil can be increased up to 210 mm/m in the soil profile (Hazelton, Murphy, 2007; Ondr et al., 2016). High stability of the soil aggregate protects the soil from erosion. On the contrary, low aggregation of soil particles is a characteristic feature of the soils with unstable structure, low permeability and low infiltration, which contributes to the occurrence of tubular pores in clay soils and these soils are more prone to the formation of slope deformations. Diaz et al. (2006) derived the inverse relationship between the stability of soil aggregate and the density of tubular structure in the clay soil. Soils with low aggregate stability are susceptible to erosion. When the stability of soil aggregate is reduced, soil erodibility can be increased (Blanco, Lal, 2008; Heshmati et al., 2011).

Geological structure (lithology, seismic-tectonic ratios and structural ratios), geomorphological conditions and the character of the georelief (morphometric characteristics, in

particular, the slope inclination), hydrogeological-climatic and related hydrological conditions of the area, as well as, anthropogenic factors represented by inappropriate use of the landscape (Skokanová et al., 2016; Špulerová et al., 2016) can be considered as relevant factors reflecting the favourable conditions for the occurrence of landslides.

The most important publications dealing with landslide hazards are Carrara et al. (1991, 1995), Klimeš (2007), Metelka, Kycl (2007), Havlín et al. (2009) and so on. In the Slovak Republic, the evaluation of landslide hazards has been recently dealt with by various authors, for example, Paudiš, Bednarik (2002, 2006), Bednarik et al. (2005), Magulová (2009) and so on. Paudiš et al. (2005) evaluated 11 input parameters derived from the geological conditions of the area, climatic and hydrological conditions, morphometry of the georelief and current landscape structure. The evaluation was processed by the bivariate method with the weight of the parameter as a whole.

In this paper, we evaluate the statistical significance of the selected natural factors of the landscape in relation to the occurrence of unstable slopes in the Kysuce region. We also evaluated the abundance of individual landscape factors and unstable slopes in selected cadastral areas.

## Study area

We have selected four regions, which characterize the diversity of abiotic and biotic components of the whole studied area. The selected areas are: Klokočov, Zákopčie, Nová Bystrica and Kysucké Nové Mesto (Fig. 1). Selected areas belong to three regions according to the

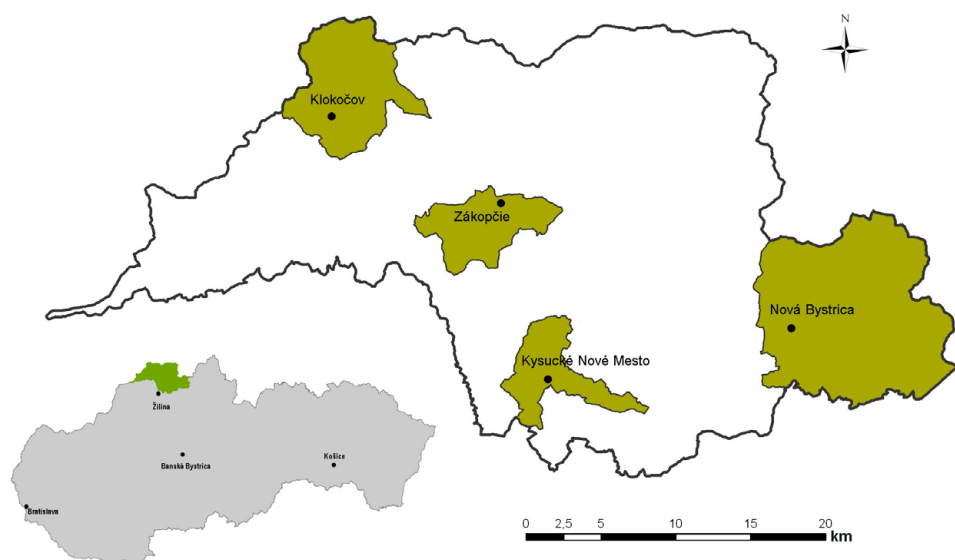


Fig. 1. Location of the study sites.

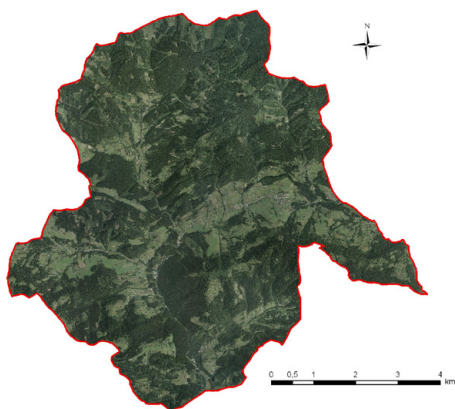


Fig. 2. Klokočov village.



Fig. 3. Nová Bystrica village.

geomorphological units of the Slovakia (Mazúr, Lukniš, 1986): Stredné Beskydy (units – Kysucká vrchovina highlands, Kysucké Beskydy Mts., Podbeskydská vrchovina highlands, Oravská Magura Mts. and Oravské Beskydy Mts.), Západné Beskydy (units – Moravsko-sliezske Beskydy Mts. and Turzovská vrchovina highlands) and Slovensko-moravské Karpaty (unit – Javorníky Mts.).

#### *Klokočov village*

The cadastre of Klokočov village (51 km<sup>2</sup>) (Figs 1 and 2) lies in the Turzovská vrchovina highlands (3,523 ha) and Moravsko-Sliezske Beskydy Mts. (1 588 ha), in the north-western part of Kysuce region. It has an upland to mountainous character with an altitude of 508 to 1,061 m a. s. l., with predominance of slopes with 12 to 17° (36.3% of the cadastral area). Slopes with inclination from 7 to 12° cover 28.9% of the area and slopes with inclination from 17 to 25° cover an area of 27.3%. The territory belongs to the Predmieranka river basin, which is an important inflow of the Kysuca river. The cadastre is built mainly by the Istebna Formation (quartzite-arcose and greywacke sandstones to conglomerates) and the sandy facies of the Ráztoky Member. Most of the soils are dystric cambisols (70.6% of the cadastral area) and skelly-eutric cambisols (10.9%). Coniferous forests cover 64% of cadastral area, meadows and pastures cover 14%, permanent crops 9% and arable land 1% and so on.

#### *Nová Bystrica village*

Cadastre of the Nová Bystrica village has an area of 125 km<sup>2</sup> (Figs 1 and 3). This village has been joined by the municipalities of Riečnica and Harvelka, which had been flooded due to the construction of a water tank for drinking water, and now belongs to the largest villages in Slovakia. The whole territory belongs to the Bystrica river basin. It is located in five geomorphological units. The largest area covers Kysucká vrchovina highlands (9 038 ha) and Kysucké Beskydy Mts. (2 463

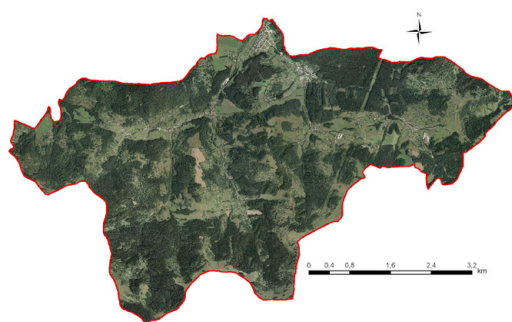


Fig. 4. Zákopčie village.

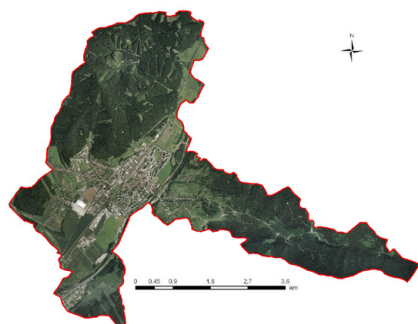


Fig. 5. Kysucké Nové Mesto city.

ha). Podbeskydská vrchovina highlands, Oravská Magura Mts. and Oravské Beskydy Mts. cover 1033 ha. The territory has an upland to mountainous character with an altitude of 490 m to 1226 m a.s.l. Slopes with inclination from 17 to 25° (42.1%) and from 12 to 17° (32.5%) cover most of the area. This area is built by sandstone flysch consisting mainly of Bystrica Member (Bystrica-type claystone, arkosic sandstones) and Kýčera Member (greywacke sandstones, locally shales). Eutric cambisol is the most widespread and covers 49.4% of the cadastral area and dystric cambisols cover 18.5% of the area. Coniferous forests cover most of the area with 58.4%. The meadows and pastures cover 16.3% of the area and the arable land only 1%.

#### *Zákopčie village*

The cadastre of Zákopčie village (29.6 km<sup>2</sup>) extends in the north-eastern part of the Javorníky Mts. (Figs 1 and 4). Javorníky are one of the geomorphological units of this territory. The territory has an upland character with an altitude of 470 to 875 m a.s.l. Slopes with inclination of 12 to 17° cover half of the territory (50.3%). The territory is drained by the Zákopčeiánsky and Rakovský creeks. The area is predominantly built by a normal flysch, which is formed by Vsetín Member (Bystrica-type claystones, sandstone with glauconite, arkosic sandstones and conglomerates) and Zlín Formation (claystones, sandstones, sandstone with glauconite). The most widespread soil subtype is cambisol, which occurs on 40.4% of the territory, and 38.2% of the territory cover skeli-eutric cambisols. Almost 42% of the territory is covered by coniferous forests. Meadows and pastures cover 23% and arable land only 0.8% of the area.

#### *Kysucké Nové Mesto city*

Kysucké Nové Mesto cadastre (26.4 km<sup>2</sup>) is situated in Javorníky Mts. (2 022 ha) and Kysucká vrchovina Mts. (620 ha) (Figs 1 and 5). The territory has upland and partly mountainous character with an altitude from 340 to 999 m a.s.l. Slopes ranging from 12 to 17° and from 17 to 25° cover equal sizes of the area (22.5% of the cadastral area). The territory is drained by the Povinský creek and the Kysuca river. In this area, sandstone flysch prevails (44.9% of

the territory) and is formed by Bystrica Member (44.9% of the area). Floodplains and terraces formed by sandstones and sandy gravel cover 18.6% of the area and the Klippen belt (Posidonia and Supra-Posidonia beds, and Pieniny Limestone Formation) extends to the territory with 10.2%. The most widespread is the eutric cambisol (32.2%), then stagnic cambisol (29.4%) and eutric fluvisol (25.2%). Coniferous forests cover the largest area (39.2%), meadows and pastures following with (14.8%). Arable land has a 7.5% representation.

### Material and methods

We proceeded from the database of Landscape Ecological Complexes (LEC types), which are vector representation of synthetic units expressing relevant properties of the abiotic elements of the landscape together with the landscape cover elements. We compiled a data matrix from the selected presumed correlation parameters that are in the form of vector layers. Data matrix was evaluated using the multidimensional statistical method in program CANOCO.

We obtained altogether 52 054 samples of LEC and unstable slopes occurrence from the area of Kysuce region (Žabková et al., 2003; Šimeková et al., 2006). For purpose of our analysis, we chose four most characteristic cadastres, which gave us the final number of 12 716 samples for our analysis (Klokočov – 2680, Kysucké Nové Mesto – 1074, Nová Bystrica – 7608, Zákopčie – 1354). Analysis and final graphs were made in program CANOCO 5.0 (ter Braak, Šmilauer, 2012). The indirect gradient analysis – PCA (principal component analysis) was used to see the variation in landscape factors. The RDA (redundancy analysis) with the forward selection command was used to evaluate the interaction between individual factors and to determine the landscape parameters that best explain the variance of the data set (Annex 1). We used 499 permutations for the RDA analysis to calculate the correlation coefficients (p = 0.002). The parameters listed in Tables 1–5 were used as categorical variables. Parameters –slope inclination, depth of groundwater levels, depth of soil, and soil skeleton are semi-quantitative and were transformed using corresponding ordinal levels (Šmilauer, Lepš, 2014). In the output ordination graph, we can interpret the proximity of two points (co-ordinates of individual factors).

Overview of selected parameters in the form of LEC vector layers:

- **Morphographic-morphometric types of relief** – the layer was created by digitizing the underlying layers with respect to the morphographic types and positional forms of the relief and so called elementary forms of georelief – morphotopes were bounded (Table 1).
- **Slope inclination (in degrees)** – represents a continuous field of altitude gradients, it is a key morphometric parameter determining the instant intensity of gravitational geomorphological processes. The slope inclination was divided into the following categories: **1** - (0-1>, **2** - (1-3>, **3** - (3-7>, **4** - (7-12>, **5** - (12-17>, **6** - (17-25>, **7** - (25-35>, **8** - (35-90>.
- **Hydrogeological base (HB)** – a hydrogeological complex with a rocky character (Malík et al., 2007), (Table 2).
- **Geological-substrate complex (GSC)** – a layer of basic genetic types of quaternary sediments (quaternary deposits typology) (Table 3).
- **Depth of groundwater levels below the surface (DGL)** – data on groundwater levels were obtained from hydrogeological borehole. A correlation of data with morphometric relief characteristics was performed for the outlying areas. In

Table 1. Morphographic-morphometric types of relief (MM).

Legend	Definition
MM_ft	flat top
MM_ct	cupola top
MM_r	ridge
MM_wf	wide river-floodplain
MM_nf	narrow floodplain of mountain streams
MM_ac	alluvial cone
MM_ds	downward slope
MM_s	saddle
MM_bwb	bottom of the water basin
MM_d	dell
MM_bsv	bottom of slope valley
MM_sv	slope valley
MM_ts	transport slope
MM_p	plateau
MM_g	gully to ravine

areas affected by hydrogeological research, values were extrapolated by interpolation algorithm (Malík et al., 2007). The groundwater levels were divided into the following categories (in m): up to 1; 1.0 – 1.5; 1.5 – 2.0; 2.0 – 3.0; 3.0 – 4.0; 4.0 – 6.0; 6.0 – 8.0; 8.0 – 10.0; 10.0 – 12.0; 12.0 – 15.0; 15.0 – 20.0; 20.0 – 25.0; 25.0 – 30.0; 30.0 – 50.0; 50.0 – 100.0.

- **Soil subtype (S)** – a complex of soil units in terms of the soil subtype, according to the Societas pedologica slovacica, (2014), (Table 4).
- **Grain Size (GS)** – a soil grain layer was created on the basis of input data contained in soil probes (grain fractions – sand, silt, clay) and maps of forest soils. Multiple linear regression and interpolation in a geographically homogeneous environment with sufficient density of the input dot field was used. The grain size was divided into the following categories: **Gs\_sc** (sandy-clay), **Gs\_l** (loamy), **Gs\_sl** (silty-loam), **Gs\_scl** (sandy-clayey-loamy) and **Gs\_cl** (clayey-loam).
- **Depth of soil** (in m) – divided into categories: **up to 0.3 m** (shallow soils), **0.3–0.6 m** (medium deep soils) and more than **0.6 m** (deep soils).
- **Soil skeleton** (in %) – divided into categories: **up to 10%** (skeleton-free), **10–25%** (low skeletal soils), **25–50%** (medium skeletal soils) and **over 50%** (heavily skeletal soils).
- **Landscape cover (LC)** – represents a materialized projection of natural spatial characteristics as well as the current use of the landscape; its presence on the surface of Earth is mainly differentiated by its appearance and morpho-structural properties (Table 5).
- **Unstable slopes** (Fig. 6) – data were processed on the basis of outputs in Žabková et al. (2003) and Šimeková et al. (2006), which are based on the databases and field mapping.

T a b l e 2. Hydrogeological base (HB).

Legend	Definition
HB_sd	slope debris
HB_tc	debris cones and talus cones
HB_ld	loamy-stony and bouldery deposits of landslides deposition
HB_dc	loamy-stony debris cones
HB_ac	loamy, sandy, gravelly alluvial cones
HB_t	sand, sandy gravel, gravel floodplains and terraces
HB_llc	clay, limy clay and marl
HB_if	clayey flysch (with predominance of clay, silt, marl)
HB_nf	normal flysch (clay/marl, silt, sandstones)
HB_sf	sandy flysch (prevalence of sandstones)
HB_cf	conglomerate flysch (prevalence of conglomerates)
HB_s	sandstones with thin clay layers
HB_l	limestones (siliceous, marlaceous, sandy, etc.), radiolarites

T a b l e 3. Geological-substrate complex (GSC).

Legend	Definition
GSC_as	loamy-gravelly to gravelly alluvial sediments
GSC_ts	loamy-gravelly terrace sediments
GSC_ps	loamy-gravelly to gravelly proluvial sediments
GSC_ds	loamy-gravelly deluvial sediments
GSC_cs	gravelly-boulder colluvial sediments
GSC_l	landslides
GSC_css	loamy wastes on consolidated clayey-silty stones
GSC_fs	loamy wastes on flysch stones
GSC_sc	loamy wastes to loamy-stony debris on sandy conglomerates

T a b l e 4. Soil subtype (S).

Legend	Definition
S_LPe	Eutric Leptosols
S_LPk	Rendzic Leptosols
S_CMe	Eutric Cambisols
S_CMs	Skeli-Eutric Cambisols
S_CMd	Dystric Cambisol
S_CMj	Stagnic Cambisols
S_PZh	Haplic Podzol
S_GLe	Eutric Gleysols
S_FLe	Eutric Fluvisol

T a b l e 5. Landscape cover (LC).

Legend	Definition
LC_r	residential area
LC_ia	industrial, commercial and transport areas
LC_al	arable land
LC_pc	permanent cultures
LC_mp	meadows and pastures
LC_df	deciduous forests
LC_mf	mixed forests
LC_cf	coniferous forests
LC_f	other forests
LC_asv	areas with sparse vegetation
LC_wa	water areas

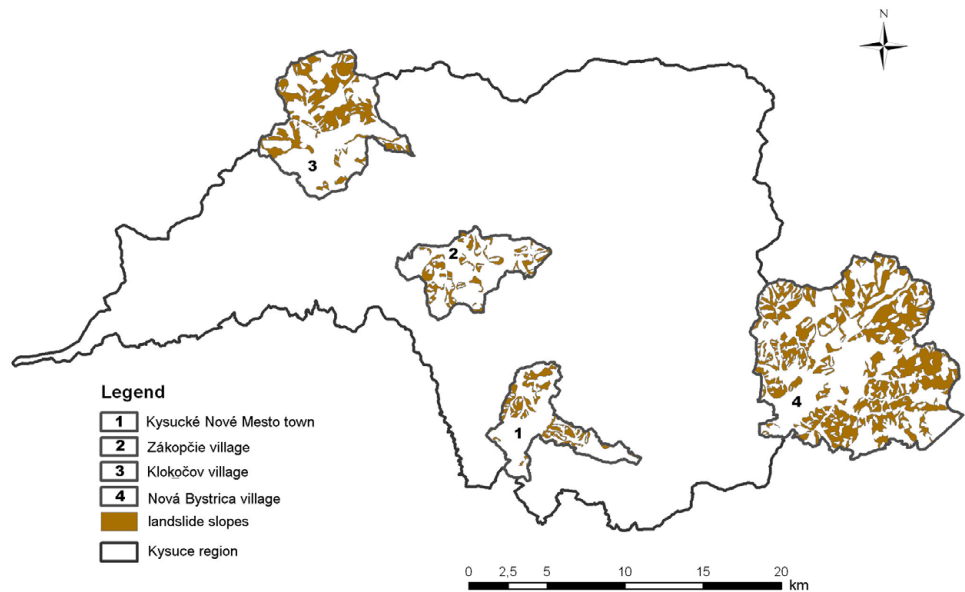


Fig. 6. Occurrence of unstable slopes in the individual cadastral areas.

Results and discussion

*a) Assessment of the correlation linkages between selected landscape factors and unstable slopes*

Significant linkages between the variables HB\_s and GSC\_sc ( $R = 0.95$ ,  $p = 0.002$ ) and secondarily significant linkages between the variables S\_CMd and HB\_s ( $R = 0.40$ ,  $p = 0.002$ ) were con-



firmed (Fig. 7). Sandstones with thin clay layers, which form loamy wastes with dystric cambisol occur in most areas with unstable slopes in the Klokočov cadastre and partly in Zákopce cadastral area. Significant correlation of variables in areas with unstable slopes was also observed between HB\_sf and GSC\_fs ( $R = 0.81$ ,  $p = 0.002$ ) (Fig. 7). It is mainly the area built by the sandstone flysch, which makes loamy wastes with typical cambisol. These are mainly territories in the cadastral areas of Nová Bystrica and Kysucké Nové Mesto. The rock complex in sandstone development is the main collector of groundwater, characterized by crack-intergrain permeability and the drainage of this complex is considerably variable. These complexes are made by rocks with low permeability. Unlike this complex, rocks in sandstone-clay development are characterized by rhythmic alternation of sandstones and clay (or prevalence of sandstones in some parts of the formation), that is, rocks with aquiferous properties with isolators that limit the groundwater circulation in the complex. The clayey substrate is poorly permeable and the most precipitation water flows over the surface, following with more intensive erosion development (especially in deforested areas) with subsequent formation of landslips.

Significant linkage was also calculated between the variables GSC\_cs and HB\_tc ( $R = 0.90$ ,  $p = 0.002$ ). It is a significant interconnection of the occurrence of gravel-boulder colluvial sediments with periglacial stony-sandstone blocks of debris cones and streams with high occurrence of rock falls and stone seas. Significant correlation coefficient  $R = 0.89$ ,  $p = 0.002$  was recorded between variables GSC\_as and HB\_t. These are mainly gravelly-loam and gravel alluvial deposits with sand, sandy gravel and fine to rough alluvial beds and low terraces covered with floodplain clayey loam, sandy loam, loamy sands and loamy gravels. These are rocks and pedogenic substrates which have high groundwater levels in their profile. Due to groundwater flow and climatic factor such as frost, unfavourable geodynamic phenomena arise in these areas as well. This is also confirmed by significant linkages between GSC\_as and S\_FLe ( $R = 0.78$ ,  $p = 0.002$ ). It is a connection of gravelly loam and gravel alluvial deposits with sand and sandy gravel with occurrence of fluvisols. There is a high groundwater level with a high retention capacity and possible occurrence of geodynamic phenomena. The weathering of flysch rocks is inhomogeneous and results from the lithological units' character. Lute and considerable part of the bedrock are carried away from the weathering layer of sandstones by weathering, making them more porous and more susceptible to disintegration. Claystones are more durable in resisting aerial alteration, and they are mostly weathered by the influence of repeated soaking and drying. The different degrees of resistance of flysch complexes to erosion depends on the substance inhomogeneity and the different behaviour of rocks in the weathering process. The sandstone and clay layers' alternation leads to selective erosion and therefore to significant terrain modelling. Sandstone complexes fairly resist erosion and form ridges. Formations with a lutaceous content and especially a finer rhythmicity form depression zones. Stronger tectonic deformation of the formation also conduces the erosion.

A moderately significant correlation with unstable slopes was noticed in the variables of the slope and GSC\_fs ( $R = 0.29$ ,  $p = 0.002$ ), which play an important role in the landslide areas. Slopes above  $12^\circ$  predominate within all disasters, which is also a prerequisite for increased landslides. However, we observed a negative correlation between the slope and S\_FLe variables, where the correlation coefficient has values ( $R = -0.42$ ,  $p = 0.002$ ). The recorded correlation confirms the occurrence of unfavourable geodynamic processes in the regions with luvisols

that formed on sands, sandy gravel and fine to rough gravel of the accumulation floodplain bottom or terraces and river floodplains. Based on our work, we can determine the order of significance of the observed factors. The geological substrate complex (GSC) and hydrogeological bedrock (HB) that condition the formation of unstable slopes are significant for the analysed area. Secondary impacts have morphography-morphometric types of relief (MM). The soil subtype (S) is at the border of significance. The impact of anthropogenic activities has not been confirmed because no significant human activity has been mapped in the concerned area. This is also confirmed by the analysis of the landscape cover (LC), where continuous forest stands, meadows and pastures dominate the monitored area.

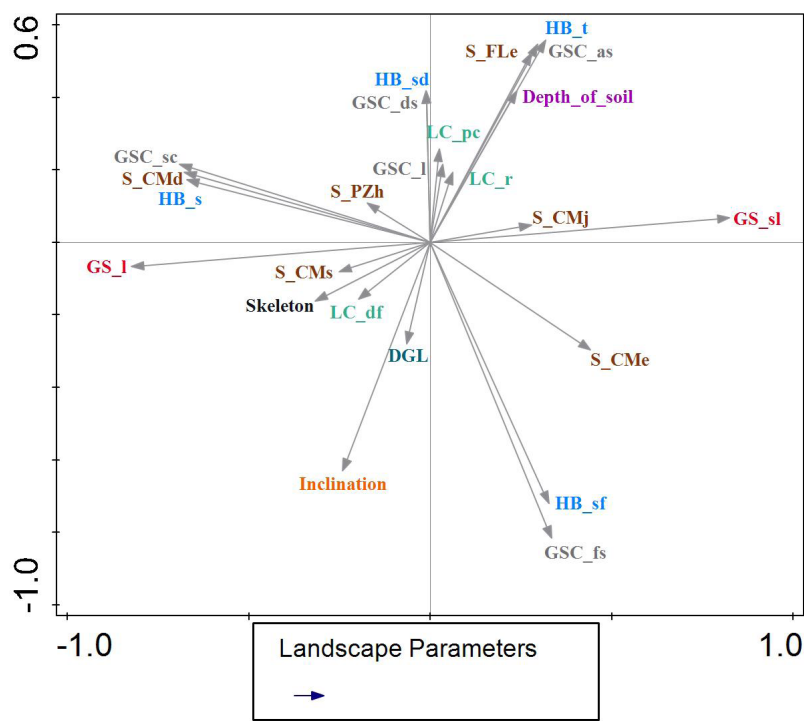


Fig. 7. Ordinal graph showing the dependence of selected landscape factors on selected cadastral areas with unstable slopes.

*b) Evaluation of superposition of the selected landscape factors and unstable slopes*

For the assessment, we proceeded from the extension of the given natural factor in the cadastre and from the extension of the unstable slopes occurrence within the area (Table 7). The largest area covered by unstable slopes is in the cadastral areas of Nová Bystrica (34.62%) and Klokočov (28.25%). Less coverage is in the cadastral areas of Kysucké Nové Mesto (19.03%) and Zákopčie

(16.87%). We only took into account the factors of the country with the highest occurrence of unstable slopes. The largest representation of the type of relief (MM) factor has the category of transport slope (MM\_ts). Within the transport slope category, the most unstable slopes occur in the cadastral areas of Klokočov (29.31% of the slippery surface within MM\_ts), Nová Bystrica (36.16% of the slippery surface within MM\_ts) and Kysucké Nové Mesto (26.11% of the slip surface within MM\_ts). From the total area of cadastral areas, the unstable slopes cover the largest area (21.74%) in Nová Bystrica cadastre, in Klokočov cadastre (17.05%), in Zákopčie cadastre (12.59%) and in Kysucké Nové Mesto cadastre (10.75%) (Fig. 8). In Zákopčie cadastre, there are very unstable gullies and ravens (MM\_g), which cover a small area of the cadastre, but the occurrence of unstable slopes on these types of relief is up to 67% (however, this area is negligible as compared to the total area, only 0.04%).

The instability of the area was also evaluated on the basis of slope inclination factor. The inclination of slope plays an important role in unstable slopes. Unstable slopes with inclination between 12 to 17° prevailed in three cadastral areas (Table 6). It was Klokočov cadastre, which has 28.04% of the unstable slopes in this category (it is 10.17% from the total cadastral area). Zákopčie cadastre has unstable slopes on an area of 17.11% (they represent 8.61% from the whole cadastral area) and Kysucké Nové Mesto cadastre has unstable slopes on the area of 35.99% (it is 8.14% from the total area of cadastre) (Fig. 8). In the cadastral area of Nová Bystrica there are also slopes with inclination above 35° and their instability is recorded on 50% of the area, which is only 0.01% of the whole territory. This cadastre has the most unstable slopes in the category from 17 to 25°, covering 38.78% of the territory (15.01% of the whole cadastral area). Slopes above 12° cover most of the monitored areas, in Nová Bystrica it is up to 81.45% of the area, in Zákopčie it is 72.67% of the area, in cadastral area of Klokočov it is 64.25% of the area and in the cadastral area of Kysucké Nové Mesto it is 53.00% of the area. The most unstable slopes in this category are represented in the Nová Bystrica cadastre (29.80% of the area) and in the cadastral area of Klokočov (18.52% of the area).

Another factor – hydrogeological base (Table 6) – has the largest representation in Klokočov cadastral area in HB\_s (sandstone with thin clay layers), which covers up to 56.40% of the cadastral area. Unstable slopes cover 31.39% of this area (which is 17.70% of the whole area). Most of the Zákopčie cadastre is built by normal flysch (HB\_nf), which occupies 39.07% of the territory, unstable slopes are on 14.56% (5.9% of the whole area). Nová Bystrica and Kysucké Nové Mesto cadastral areas are mainly built by sandstone flysch (HB\_sf), which covers 71.96% of the Nová Bystrica area with 36.40% of the unstable slopes (26.13% of the total cadastral area) and 44.89% of the Kysucké Nové Mesto area, of which unstable slopes are on 30.32% (13.61% from the total area of the cadastre) (Fig. 8).

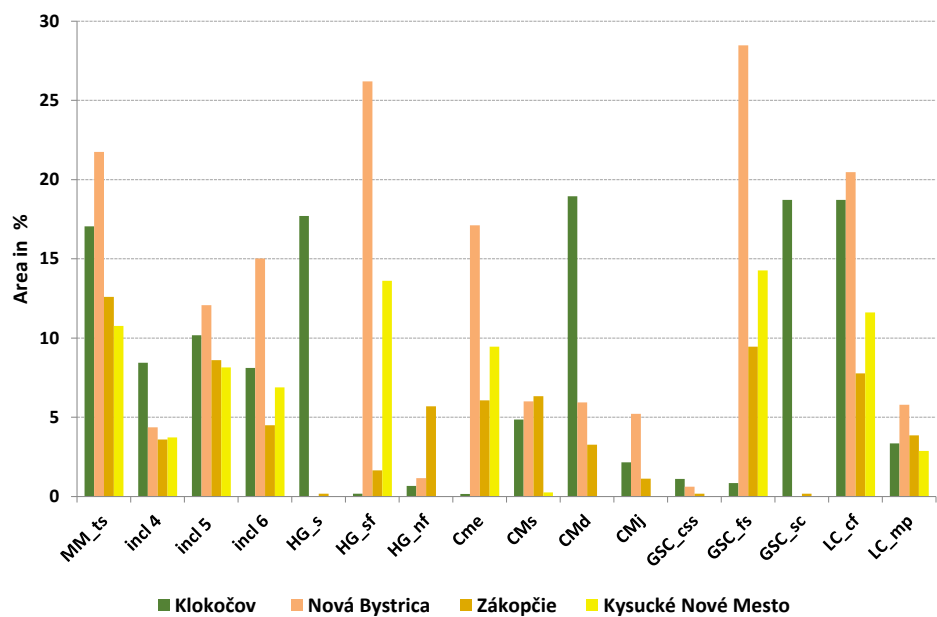
Dystric cambisol (CMD) is the most widespread soil subtype in the cadastral area of Klokočov, where this soil subtype covers 70.68% of the area (Table 6), unstable slopes are on 26.79% of the area, which is 18.94% of the total cadastral area. Eutric leptosol (LPe) covers only 0.93% of the area, but unstable slopes occur on 62.34% (only 0.57% of the total area). In Nová Bystrica cadastre, the most of the slippery slopes is on the eutric cambisol (CMe) – 49.19% and the skeli-eutric cambisol (CMs) – 13.75%. The slippery slopes are on 17.11% (CMe) and 6.00% (CMs) of the total cadastral area. Similar to Nová Bystrica cadastre, Zákopčie also has the largest representation of unstable slopes on eutric cambisol (CMe) and skeli-eutric cambisol (CMs), which cover 6.06%

and 6.32%, respectively, of the total cadastral area. Eutric cambisol (CMe) and stagnic cambisol (CMj) are the main soil subtypes in the cadastral area of Kysucké Nové Mesto, where most of the unstable slopes are located. Unstable slopes cover 29.37% on the CMe (9.45% of the total area) and 31.24% on CMj (9.17% of the total area) (Fig. 8).

GSC is represented by quaternary sediments. Cadastral areas of Nová Bystrica, Zákopčie and Kysucké Nové Mesto consist mainly of loamy wastes on flysch rocks (GSC\_fs). They cover up to 76.38% in Nová Bystrica cadastrate (unstable slopes within the cadastrate are on 28.47% of the area), in Zákopčie they cover 65.82% (unstable slopes cover 9.45% within the cadastral area) and in cadastral area of Kysucké Nové Mesto they cover 57.94% of the territory (the unstable slopes within the cadastrate cover 14.27%). Loamy wastes on sandstone conglomerates (GSC\_sc) form a substantial part of the Klokočov cadastrate (58.37%). Unstable slopes cover 32.07% of the area (Table 6), which represents 18.71% of the total cadastral area (Fig. 8).

Coniferous forests (LC\_cf) form a substantial part of the landscape cover in all cadastral areas, where the largest areas of unstable slopes are (Table 6). In the Klokočov cadastrate, 29.22% of unstable slopes is in coniferous forests, which represent 18.72% of the cadastral area. (Fig. 8). In the cadastral area of Nová Bystrica, it is 35.05% of unstable slopes in coniferous forests (20.47% of the cadastral area); in Zákopčie cadastrate, it is 18.47% (7.76% of the cadastral area); and in the Kysucké Nové Mesto cadastrate, it is 29.62% (11.61% of the cadastral area). An important finding is that in the cadastral area of Klokočov, there is 1/3 of the residential area (LC\_r) built on unstable slopes. In Nová Bystrica cadastrate, there is 35.41% of deciduous forests, which are on unstable slopes.

Fig. 8. Occurrence of unstable slopes on selected landscape factors within cadastral areas.



T a b l e 6. Occurrence of unstable slopes in individual cadastral areas.

Landscape element	Klokočov				Nová Bystřice				Zákopčie				Kysucké Nové Město			
	WA <sup>(1)</sup> (km <sup>2</sup> )	WA <sup>(2)</sup> (km <sup>2</sup> )	WA <sup>(3)</sup> (%)	SA <sup>(4)</sup> (%)	WA <sup>(1)</sup> (km <sup>2</sup> )	SA <sup>(2)</sup> (km <sup>2</sup> )	WA <sup>(3)</sup> (%)	SA <sup>(4)</sup> (%)	WA <sup>(1)</sup> (km <sup>2</sup> )	SA <sup>(2)</sup> (km <sup>2</sup> )	WA <sup>(3)</sup> (%)	SA <sup>(4)</sup> (%)	WA <sup>(1)</sup> (km <sup>2</sup> )	SA <sup>(2)</sup> (km <sup>2</sup> )	WA <sup>(3)</sup> (%)	SA <sup>(4)</sup> (%)
<b>MM_r</b>	10.27	2.86	20.09	27.88	22.98	8.99	18.35	39.15	4.38	0.41	14.78	9.52	4.49	1.17	16.99	25.96
<b>bvv</b>	4.96	1.48	9.70	29.90	9.66	3.48	7.74	36.06	2.34	0.53	7.89	22.56	1.55	0.51	5.87	33.22
<b>sv</b>	3.41	0.98	6.66	29.01	8.57	2.68	6.87	31.24	1.13	0.25	4.45	18.86	1.56	0.44	5.94	28.57
<b>ts</b>	29.75	8.72	<b>58.20</b>	<b>29.31</b>	75.40	27.27	<b>60.14</b>	<b>36.16</b>	19.80	3.73	<b>66.84</b>	<b>18.84</b>	10.88	2.84	<b>41.19</b>	<b>26.11</b>
<b>p</b>	0.55	0.19	1.08	35.77	1.40	0.35	1.11	25.64	0.29	0.04	0.90	1.76	0.19	0.01	0.72	6.26
<b>g</b>	0.03	0	0.07	1.32	0.02	-	0.01	-	0.01	0.01	<b>0.05</b>	<b>67.19</b>	0	-	0.01	-
<b>MM other</b>	2.12	0.18	4.20	8.78	7.25	0.62	5.78	8.56	1.51	0.05	5.09	3.97	7.73	0.04	29.28	0.64
<b>Incl. 3</b>	2.38	0.63	4.65	29.60	2.33	0.31	1.87	13.32	0.31	0.01	1.05	5.21	1.11	0.02	4.19	2.05
<b>4</b>	14.81	4.31	28.95	29.14	17.30	5.44	13.79	31.42	6.93	1.07	23.38	15.42	4.72	0.98	17.85	20.82
<b>5</b>	18.55	5.20	<b>36.25</b>	<b>28.04</b>	40.73	15.13	32.49	37.15	14.91	2.55	<b>50.33</b>	<b>17.11</b>	5.98	2.15	<b>22.65</b>	<b>35.99</b>
<b>6</b>	13.95	4.15	27.26	29.75	52.80	18.82	<b>42.15</b>	<b>38.78</b>	6.62	1.33	22.34	20.10	5.90	1.82	22.35	30.85
<b>7</b>	0.37	0.10	0.74	27.10	8.49	3.29	6.79	38.78	-	-	-	-	0.21	0.01	7.99	0.74
<b>8</b>	-	-	-	-	0.02	0.01	<b>0.02</b>	<b>50.73</b>	-	-	-	-	-	-	-	-
<b>Incl. 1+2</b>	1.09	0.05	2.14	4.85	3.64	0.40	2.89	11.00	0.86	0.03	2.90	3.85	6.59	0.03	24.97	0.56
<b>HB_sd</b>	11.41	2.87	22.31	25.14	5.74	2.34	4.59	40.65	8.67	2.03	29.27	23.43	2.18	0.68	8.26	31.37
<b>lc</b>	0.27	0.01	0.53	4.04	3.21	1.04	2.57	32.57	2.67	-	0.90	-	-	-	-	-
<b>l</b>	3.69	0.90	7.23	24.39	11.34	2.85	9.06	25.15	0.04	0.02	0.14	68.80	1.41	0.50	5.35	35.99
<b>clc</b>	2.26	0.56	4.42	25.41	2.44	0.79	1.94	32.69	0.18	0.05	0.63	28.11	-	-	-	-
<b>cf</b>	-	-	-	-	2.47	1.40	1.98	56.66	4.54	0.63	15.33	13.80	0.73	0.15	2.79	21.06
<b>nf</b>	2.20	0.34	4.30	15.62	3.07	1.46	2.44	47.40	11.57	1.68	<b>39.07</b>	<b>14.56</b>	-	-	-	-
<b>sf</b>	0.15	0.09	0.32	59.71	90.21	32.85	<b>71.96</b>	<b>36.40</b>	3.39	0.49	11.43	14.43	11.85	3.59	<b>44.89</b>	<b>30.32</b>
<b>cf</b>	1.00	0.52	1.96	51.53	-	-	-	-	-	-	-	-	-	-	-	-
<b>s</b>	28.85	9.06	<b>56.40</b>	<b>31.39</b>	-	-	-	-	-	-	-	-	-	-	-	-
<b>HB other</b>	1.29	0.09	2.53	7.47	6.82	0.67	5.46	9.91	0.86	0.03	2.90	3.85	10.23	0.06	38.71	0.66
<b>S_LPe</b>	0.47	0.29	<b>0.93</b>	<b>62.34</b>	-	-	-	-	-	-	-	-	-	-	-	-
<b>CMe</b>	1.01	0.08	1.98	8.15	62.06	21.46	<b>49.49</b>	<b>34.57</b>	11.95	1.79	<b>40.36</b>	<b>15.02</b>	8.50	2.50	<b>32.19</b>	<b>29.37</b>
<b>CMS</b>	5.58	2.49	44.55	17.19	7.53	13.75	<b>43.77</b>	11.29	1.87	<b>38.12</b>	<b>16.57</b>	0.66	0.07	2.48	10.35	-
<b>CMD</b>	36.16	9.69	<b>70.68</b>	<b>26.79</b>	23.28	7.45	18.58	31.99	3.68	0.96	12.42	26.26	-	-	-	-
<b>CMf</b>	4.65	1.10	9.09	23.81	17.19	6.55	13.72	38.05	1.84	0.33	6.20	18.10	7.76	2.42	<b>29.37</b>	<b>31.24</b>
<b>Pzh</b>	1.94	0.65	3.79	33.99	-	-	-	-	-	-	-	-	-	-	-	-
<b>S other</b>	1.33	0.14	2.59	10.31	5.59	0.43	4.46	7.73	0.86	0.03	2.90	3.85	9.50	0.04	35.96	0.45

Table 6. Continued.

Landscape element	Klokočov			Nová Bystřice			Žákopčie			Kysucké Nové Město		
	WA <sup>(1)</sup> (km <sup>2</sup> )	SA <sup>(2)</sup> (km <sup>2</sup> )	WA <sup>(3)</sup> (%)	SA <sup>(4)</sup> (%)	WA <sup>(1)</sup> (km <sup>2</sup> )	SA <sup>(2)</sup> (km <sup>2</sup> )	WA <sup>(3)</sup> (%)	SA <sup>(4)</sup> (%)	WA <sup>(1)</sup> (km <sup>2</sup> )	SA <sup>(2)</sup> (km <sup>2</sup> )	WA <sup>(3)</sup> (%)	SA <sup>(4)</sup> (%)
GSC ts	-	-	-	-	0.47	0.15	0.38	32.18	-	-	-	-
ps	0.23	0.05	0.47	20.28	0.25	0.02	0.25	7.52	-	-	-	-
ds	11.41	2.87	22.31	25.14	5.74	2.34	4.58	40.65	8.67	2.03	29.27	23.43
cs	0.27	0.01	0.53	4.04	3.57	1.10	2.84	30.93	0.27	-	0.90	-
I	3.69	0.90	7.22	24.39	11.35	2.85	9.06	25.15	0.04	0.03	0.15	68.81
cs	2.26	0.56	4.42	25.07	2.44	0.78	1.94	31.87	0.19	0.05	0.63	28.12
fs	2.35	0.44	4.61	18.54	95.76	35.70	<b>76.38</b>	<b>37.28</b>	19.50	2.80	<b>65.82</b>	<b>14.36</b>
sc	29.86	9.57	<b>58.37</b>	<b>32.07</b>	-	-	-	-	0.09	0.05	0.33	53.29
GSC other	1.06	0.05	2.07	4.65	5.74	0.45	4.57	7.79	0.86	0.03	2.90	3.85
LC s	1.56	0.45	<b>3.06</b>	<b>29.18</b>	1.18	0.20	0.96	17.66	0.81	0.09	2.72	11.95
ia	0.00	-	0.01	-	0.17	0.04	0.13	22.69	0.06	0.03	0.23	57.81
al	0.49	0.01	0.97	2.23	1.29	0.60	1.04	46.26	0.25	0.02	0.86	11.00
pc	4.48	1.45	8.76	32.32	4.50	1.19	3.59	26.46	2.67	0.37	9.00	14.09
mp	7.38	1.71	14.44	23.15	20.48	7.25	16.35	35.41	6.74	1.14	22.77	16.94
df	0.54	0.11	1.06	21.24	4.21	1.63	3.36	38.70	0.40	0.05	1.36	13.42
mf	0.72	0.35	1.42	47.82	4.51	1.37	3.59	30.43	0.70	0.09	2.34	14.06
cf	32.79	9.58	<b>64.09</b>	<b>29.22</b>	73.23	25.67	<b>58.42</b>	<b>35.05</b>	12.44	2.30	42.00	18.47
f	3.14	0.79	6.14	25.04	13.83	5.31	11.03	38.40	5.54	0.86	18.70	15.64
asv	0.02	0.00	0.04	16.96	0.17	0.09	0.15	54.42	0.00	-	-	-
LC other	0.00	-	0.01	-	1.73	0.03	1.38	2.26	0.00	0.00	0.02	9.49
											0.25	0.98
											0.02	-
											0.98	0.19

Notes: (1) – whole area (WA) of the landscape factor in km<sup>2</sup>, (2) – slippery area (SA) of the landscape factor in km, (3) – % of the whole area of the landscape factor, (4) – % slippery area of the landscape factor.

## Conclusion

In order for the stabilization works to be effective, it is necessary to fully know and understand the causes of the development and process of the landslide, to think about the subsequent steps of regulation and to propose a set of measures for permanent territorial protection. The presented work is focused on the quantification of the significance of individual features of the landscape or their combinations, which condition the formation of slope deformations in individual territories and which are to be known before the remediation works start. This knowledge is the starting point before the remediation works, with a logical order of operations according to the urgency. However, each territory is specific with regard to natural or anthropogenic conditions and it is necessary to carry out similar assessment for each territory before the remediation works begin. For areas characteristic by a high occurrence of unstable slopes, it is necessary to quantify their impact on natural factors, thus avoiding the undesirable effects that landslides may have in the area.

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Annex 1. Significant landscape parameters ( $p = 0.002$ ) within the data set of unstable slopes according to the RDA analysis (manual forward selection, 499 permutations).

Name	Explained variance (%)	pseudo-F	P
GSC_fs	6.2	840	0.002
Zr_prh	5.9	852	0.002
HB_t	5.1	786	0.002
GSC_l	4.2	679	0.002
HB_l	4.2	679	0.002
GSC_ds	4.1	690	0.002
HB_sd	4.1	690	0.002
GSC_cs	3.8	672	0.002
HB_clc	3.8	710	0.002
GSC_css	3.8	710	0.002
HB_ac	3.7	730	0.002
GSC_sc	3.7	730	0.002



Annex 1. Continued.

Name	Explained variance (%)	pseudo-F	P
GSC_ps	3.7	730	0.002
Skeleton	3.0	619	0.002
LC_cf	2.6	564	0.002
S_CMe	2.4	546	0.002
LC_mp	2.3	559	0.002
HB_sf	2.3	561	0.002
GSC_as	2.2	574	0.002
GSC_ts	2.2	574	0.002
LC_f	2.1	561	0.002
HB_l	2.0	579	0.002
S_CMs	2.0	592	0.002
S_CMj	1.9	588	0.002
Soil depth	1.9	615	0.002
LC_pc	1.9	641	0.002
HB_cf	1.9	672	0.002
HB_nf	1.9	672	0.002
LC_mf	1.9	708	0.002
Zr_h	1.8	742	0.002
LC_op	1.8	786	0.002
LC_df	1.8	834	0.002
LC_ia	1.8	890	0.002
Zr_pih	1.8	957	0.002
LC_wa	1.8	1035	0.002
HB_dc	1.8	1126	0.002
HB_tc	1.8	1126	0.002
LC_asv	1.8	1232	0.002
LC_r	1.8	1232	0.002
S_CMs	1.8	1365	0.002
HB_cf	1.8	1528	0.002
HB_s	1.8	1528	0.002
S_CMe	1.8	1717	0.002
Zr_ih	1.8	1980	0.002
Zr_ph	1.8	1980	0.002
S_FLe	1.8	2315	0.002
S_GLe	1.7	2686	0.002
S_LPk	1.6	3222	0.002
S_LPe	1.6	4214	0.002
DGL	1.5	5873	0.002
S_CMj	1.1	6449	0.002
Inclination	1.0	10966	0.002
S_CMd	0.7	21180	0.002
S_PZh	0.4	15352	0.002