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The Impact of Landslides on Local Infrastructure and the Environment

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Abstract. Landslides are environmental processes that lead to natural disasters or technical failures, the effects of which usually threaten the life, health and property of people. In the classification of natural disasters and hazards that occur in the world, landslides are in fifth place, both in the number of casualties and material losses. Continuous surveillance and risk assessment is a very important issue in preventing the effects of natural disasters. The paper presents the causes of landslides, the classification of landslides, several examples of landslides and damage caused by landslides. Here, the occurrence of landslides as climatic events is given, as well as geological and anthropogenic factors of landslides. The paper indicates risk assessment methods in case of landslide hazard. The risk analysis developed here is presented for selected landslides from the Subcarpathian province.

Keywords: lanslides, geohazards, risk analysis.

Conference topic: Environmental protection.

Introduction

Landslides lead to the devastation of the infrastructure, including the destruction of buildings, and significant deformation of arable land and natural changes. They are among the most prevalent geohazards, often bearing the characteristics of a natural disaster. Nearly 9% of natural disasters in the world is related to landslides (Chalkias *et al.* 2014).

Both economic and functional losses triggered by landslides could be estimated, while the social and moral loss is almost impossible to evaluate. Although landslides are not the cause of such a large number of deaths as other catastrophic events, they contribute to many tragedies related to the destruction, in some cases, the entire life achievements. It makes risk prevention difficult to correct by psychological reasons, because what is often found in interviews with local residents – sudden landslides occur in larger time intervals than other natural disasters (e.g. flooding), and they are relatively easy removed from the intergenerational statements. So often new houses and roads are built in areas possibly predisposed to occurrence of mass movements. Meanwhile, the passage of time, vegetation, and erosion, and denudation processes may also conceal and erase the characteristic morphological features of landslides, so that the danger could only be detected by the expert-geologist highly field experienced. The movements on the mountain slopes, initially in the form of downhill creep, occurs at a slow pace, which is difficult to observe.

Over 95% of all landslides in Poland is located in the Polish Carpathians in the region of Lesser Poland, Subcarpathian and Silesian provinces (Rączkowski 2007). There are approximately of 2–3 landslides on average on 1 square km of area of the Carpathians, while of some Subcarpathian municipalities even up to 6–8 landslides on 1 square km. The Sudeten because of their geological structure (with igneous and metamorphic rocks) are relatively resistant to landslide processes. In the strip of the Polish highlands and lowlands landslides occur most frequently on the slopes of rivers, and the sea and waterfront areas covered by soils of aeolian origin (e.g. loess). The widespread occurrence of landslides in Subcarpathian province determines the presence of the substrate made of flysch. The susceplibility of the system of the slopes on landslides is mostly dependent on the varying slope internal conditions. Such properties as the angle of slope, the thickness of colluvium, the presence of older landslide activity, and also possible dislocations mostly determine the probability of landslides.

The general characteristics of landslides and the impact on the environment

Landslide is called a form created by the gravitational movement, causing by a sudden displacement of masses of soil or rock substrates downward the slope along the slip surface. The process of earth moving may be due to natural causes or anthropogenic activity (Table 1).

Table 1. Classification of landslides factors (source: Thiel 1989)

Passive factors (invariable)	**Active factors (variable)**
Lithology of substrate Structural (tectonic) Morphological (shape and slope angle)	Climate Hydrological Anthropogenic Tectonic movements Other

There are many classifications of landslides presented in the literature – e.g. global, regional, static and dynamic (Dikau *et al.*1996; Bober *et al.* 1997). Table 2 shows a division that seems to be significant due to the landslide risk analysis.

Table 2. The division of landslides due to their activity and size (source: own elaboration)

The division of landslides due to the activity	**The division of landslides due to the size**
Active (subsequent movements of soil recorded in the scale of one year) Hardly active (activated every few years) Inactive (frozen forms or artificially stabilized)	Large (area over 3000 m^2) Average (area between 1000–3000 m^2) Small (area smaller than 1000 m^2)

Landslides are subject to deform agricultural areas, and ecological and construction sites, as well as infrastructure both underground and over the ground. Landslide phenomena are also a source of negative impact on the natural environment resulting in:

- the natural landscape transformation,
- intensification of erosion processes,
- modification in the quality of the organic soil
- the loss of forests.

Landslide movements in the forests are most common on the slopes covered by the product of weathering. Slopes reinforced by the root systems of trees are not the subject of so sudden gravitational movements (Ji *et al.* 2012). The dynamics downhill creep is different than in the open space. However, curved trunks of beech forests testify downhill creep of top soil layer of the slope. The young cutting erosion beds are sensitive forms of landslides in the Carpathian forests. Moreover, landslides situated along riverbeds and creeks may block outflow of water and contribute to local flooding.

Polish legislation and the issue of mass movement

The surface of land is a concept legally defined in *the Act of April 27th, 2001 – Environmental protection law* (POŚ). Through the surface of land is understood the natural terrain, agricultural soil and located underneath the ground to a depth of anthropogenic impact. According to Article 101 of Environmental protection law (POŚ) protection of earth surface consists of:

1. ensuring the best possible quality (including natural shape transformation mitigation)
2. prevention of mass movements of soil and landslide negative effects.

Activities under paragraph 2 of Article 110a described by the Environmental protection law (POŚ) by the task of local authorities (municipalities) is the observation of areas at risk of mass movements and recording information about these areas. Particular aspects of this task have been defined in *the Regulation of the Ministry of the Environment of June 20th, 2007 on the information regarding the mass movements of soil.*

This regulation defines:

- how to determine the areas at risk of soil mass movements and the land on which the landslides exist,
- the methods, the scope and frequency of surveillance of landslide area,
- information that should contain a record of landslides,
- operating mode, form and system of registry.

The Act of March 27th, 2003 on spatial planning and management imposes an obligation by taking into account the occurrence of areas of natural hazards and environmental threats and to identify areas at risk of flooding and landslides of soil masses at the stage of urban planning of every single community.

System Guards Against Landslides (SOPO)

In 2006, the Polish National Institute of Geology commissioned by the Ministry of Environment started the implementation of the project SOPO – System Guards Against Landslides. The main objective of the project is to identify, document and present the Maps in the scale of 1:10,000 of Landslides and Mass Movement Endangered Areas (MOTZ) in Poland and the establishment of a system for downhole and surface monitoring for 100 selected landslides. As a result of work Landslides Registration Cards (KRO) and Registration Cards of Areas Threatened with Mass Movement (MOTZ) are developed and forming an example of a basic registration document for landslides collected by local authorities. All results in the form of landslide cards and landslide maps are currently stored in the SOPO database, accessible to Internet users (PIG 2017).

These maps are developed in the administrative organization – on municipal (as for Carpathians) and the county (for the remaining part of Poland) level. The maps are marked with boundaries of landslides, with crucial elements of the landslide (slopes, gaps, trenches, depressions), and the hydrographic conditions (blue color). Other colors applied are dedicated to landslides: red (active landslides), purple (landslides periodically active) and gray (inactive landslides), as well as orange (Areas Threatened with Mass Movement).

As far as monitoring of landslides is concerned accurate and reliable information is needed i.e. appropriate selection of measurement methods, appropriate distribution points and proper analysis of the results (Bibi *et al.* 2016). Accurate analysis of data obtained from downhole and surface monitoring, supported by information on the size of precipitation allows to take, in appropriate time, efforts to minimize losses.

Downhole monitoring relies on measurements performed by inclinometers located in boreholes at different depths and it is accompanied by measurements of the water table in the piezometric boreholes. The data collected on each landslide (mostly displacements on the surface and in the depth of the landslide) allow to develop a geological model of the landslide with slip surfaces (both active and inactive), thickness of colluvium and level of the water table. Surface monitoring is based on a number of surveying points located at the landslide, at which regular GPS based measurements are carried out. Other surface monitoring methods applied are as follows: remote sensing methods, including satellite interferometry, as well as ground-based and airborne laser scanning (Fanti *et al.* 2013).

The laser scanning and satellite interferometry photos are used to develop the Digital Terrain Model of Coating and Digital Terrain Model. The latter represents an area of land without vegetation cover and infrastructure, so it is possible precise analysis of the soil surface (with cracks and cavities), which may indicate the occurrence and degree of the dynamics of mass movements. Re-scan of area allows us to evaluate spread of the landslide, and significantly reduces the field tests.

Subcarpathian province as area of study

Subcarpathian province is situated on two tectonic areas – the Outer Carpathians in the south and the Carpathian Foredeep in the north (Fig. 1). The structure of the Outer Carpathians is very diverse and strongly favours the landslide movements. The largest part of the Outer Carpathians is occupied by Skolska and Silesian tectonic units; a smaller part belongs to Dukielska and Magurska units (Żelaźniewicz *et al.* 2011). In the Carpathian Foredeep landslides appear very often. These are mostly plateau loess landslides occurring latitudinally on border with Skolska unit (over Dębica-Rzeszów-Jarosław-Przemyśl line) and river slopes (near Tarnobrzeg).

In some municipalities of Subcarpathian province approximately up to 30–40% of the area is occupied by landslides (Fig. 2). A vast number of landslides is the result of transport service. On average, one landslide occurs at the 1 km of public roads and 10 km of railway lines. Stabilization of landslides requires huge financial investments.

Among the primary factors, which determine the landslide susceptibility one may find lithological, hydro-meteorological and geometry parameters of the slopes (Długosz 2011). As far as secondary factors are concerned one may distinguish the elevation, the exposure to the slopes, land use and cover parameters, or local seismicity.

The activity of landslides associated with hydro-meteorological conditions is reasonably well understood in comparison to other factors owing to natural conditions. Threshold values of rainfall initiating earth mass movements are not the same in different parts of the Carpathians (Rączkowski 2007). The process and the type of landslide movement is dependent on the intensity and duration of precipitation. The activity of landslides in the Subcarpathian province is closely associated with the occurrence of flood conditions in the area. Since the late nineties of the 20th century it has been found a significant increase in flood risk. In 2014, the Subcarpathian province has been faced 648 local threats, associated with the increase in water level of rivers and 2979 related to heavy rainfalls, which is about 12.5% and 11.2% of the national threats, respectively (Podkarpackie 2017). Following catastrophic rains and flooding in the summer 1997 it has been activated more than 20 000 landslides in the Carpathians.

In Subcarpathians most favorable conditions for landslide exist on the slopes of the northern exposure and the angle of inclination 7–15° and 15–22° (Kamiński 2012). The increase of farmland forestation in the province in recent years, due to obtaining subsidies from European structural funds has got presumably positive impact on slope stability. Mining activities carried out more than 100 years in Subcarpathians, i.e. oil and gas exploration, as well as geothermal energy sources exploration, weakens the structure of the substrate and changes the hydrogeological conditions. These actions may cause uncontrolled local soil settlements and activate earth mass movements.

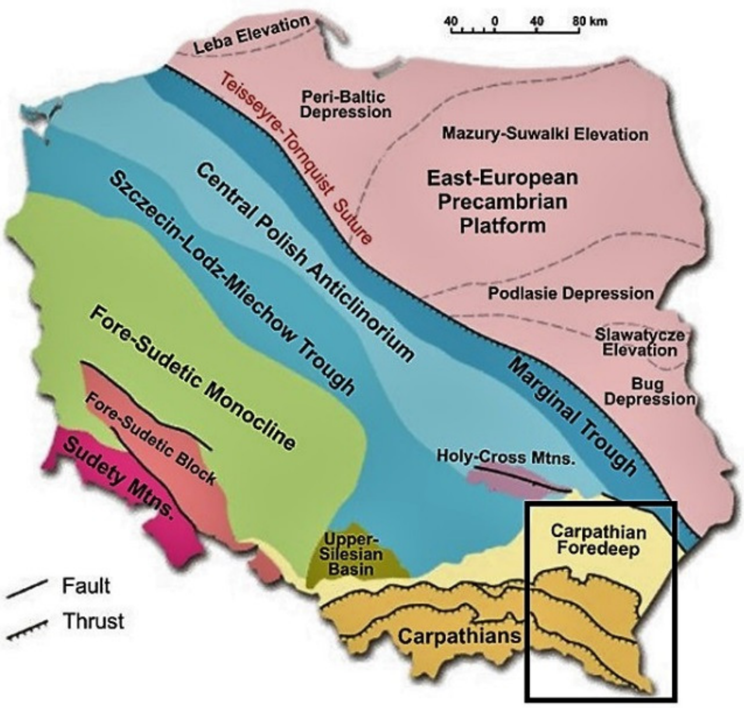

Fig. 1. The Subcarpathian province on the principal tectonic units of Poland
(source: modified from Redstone exploration services 2017)

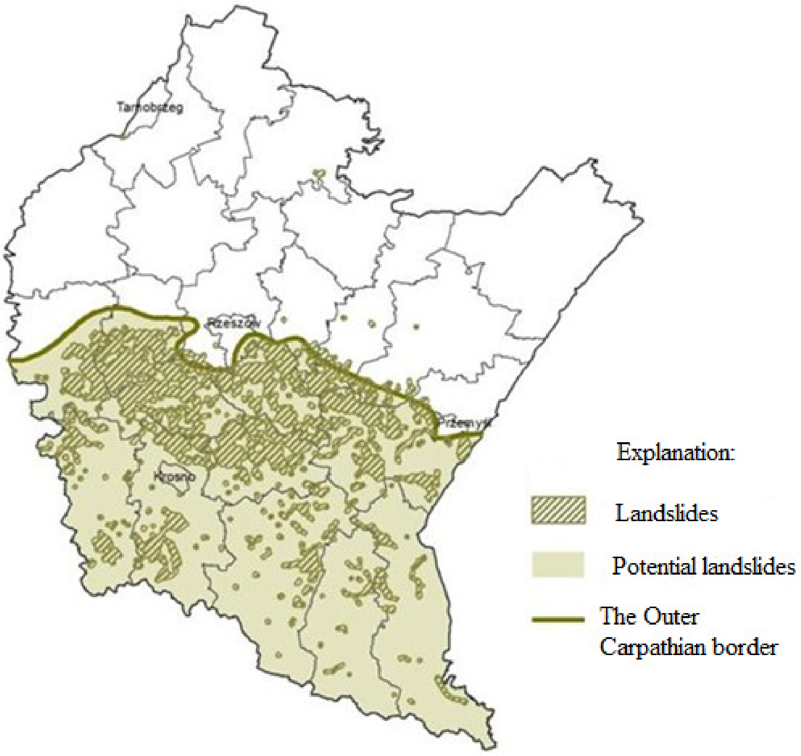

Fig. 2. Map of landslides in the Subcarpathian province (source: Podkarpackie 2017)

The risk assessment on the example of the village Zaborów

According to a commonly used definition of risk, it can be named as a measure of hazard or threat and usually it is defined as the Cartesian product of the probability and negative consequences of specified hazardous or undesirable event. The threat E_i is the possibility of an event causing the loss of life, health and/or social as well as physical and ecological losses. In the case of the random nature of threats E_i, they are considered as random events and the risk R is determined or random quantity. The total risk R may be estimated then as:

$$R = \sum_{i=1}^{n} p(E_i) \cdot D_i, \tag{1}$$

where: $p(E_i)$ – the probability of occurrence of a threat E_i, which is a random event; D_i – means the loss related to the occurrence of this event.

Losses D_i are also linked to the loss of human life or health, measured at most commonly in monetary units.

Hazard identification and determination of possible scenarios of destruction and assessment of the probability of damage and risk consequences may result to the work dedicated to risk analysis. Natural hazards are associated with random effects of loading acted on buildings, random building material properties, parameters adopted or geometric dimensions. The anthropogenic threat, human factor is directly related to the construction process, due to the unintentional or intentional derogation from the principles and construction rules (errors and omissions made by people) (Woliński 2006). In case of landslide risk assessment one deals with both natural and anthropogenic threats.

If the available knowledge on the consequences of the risks is imprecise, incomplete, subjective and/or R is qualitative risk defined by the formula (1), it can be considered as a fuzzy parameter and estimated using formula (2) as:

$$\tilde{R} = \sum_{i=1}^{n} \tilde{E}_i \cdot \tilde{D}_i, \tag{2}$$

where: $\tilde{E}_i$ – is imprecise occurrence associated with the occurrence of hazards; $\tilde{D}_i$ – is imprecisely defined, fuzzy loss caused by a hazard.

Qualitative determination of risk – $\tilde{R}$, and the occurrence of a hazard – $\tilde{E}_i$ and losses – $\tilde{D}_i$ due to the occurrence of landslides, may be expressed in the form of linguistic variables, which are described by fuzzy sets or special subsets of fuzzy numbers.

In case of a risk assessment both the probability and material losses caused by the landslide is easier to express and evaluate in a qualitative way. Therefore, a risk analysis is carried out employing fuzzy risk matrix. An original fuzzy risk matrix has been developed on the basis of defined fuzzy functions (Moller, Beer 2004), the occurrence of hazards and consequences of risk and created base of rules (see Fig. 3).

Risk quantification is carried out for landslides located in Subcarpathian province in Zaborów (Czudec municipality, Strzyżów county). Landslide analysed here is located in the south-eastern part of Polish flysch Carpathians on Dynowskie Foothills in Skole tectonic unit. Landslide is consistent, resulting from the movement of the detritus and deluvial masses on the surface of the bedrock lying on the slope of the Wisłok valley. The area of the landslide is about 30 ha. It has activated in 1978, then in 1981/82, and the subsequent displacements were observed in 1997, 2000 and 2010 (Grabowski *et al.* 2012). In frame of the SOPO project a constant monitoring of landslide activity is carried out in Zaborów, due to the fact that there is a direct threat to the residential buildings and to the provincial road DW 988. The area analysed here is covered by landslide with varying degrees of activity. The northern part of the hill remains inactive, or periodically active, while the southern part of the landslide is still active. The area of the landslide covers almost the entire slope. The maximum height (this is also the top edge of the niche) is 343 m above sea level. The scarp angle is equal to 7°, at the bottom of the slope it reaches a height of 230 m above the sea level (the lower toe edge). The length of the landslide is 965 m, while a width of 490 m. The main slope of the landslide has a height of 8 m and the inclination of 45°. The initials cracks are not distinguished on the area of landslide, but three secondary slopes with a height not exceeding 2 m are visible. The estimated thickness of colluvium reaches 20 m here (Grabowski *et al.* 2012). The substrate of landslide mainly consists of sandstones and claystones. They form a transition layer between menilit and upper layer (Malata, Zimnal 2009). The border of layer is not clear, and the main feature is the predominance of sandstone over the claystone. Claystones are found during drilling already at a depth of 18 meters. The surface of the slope is made of Quaternary detritus soil. A large part of the area of the landslide is covered by silts and clays of different origin. The detritus also contains particles of bedrock. The number and size of particles increase with depth, until a bedrock is reached. One may find thick-bedded sandstones, claystones, cornea and marl (in menilit layers) (Rączkowski *et al.* 1992). This region is characterized by the presence Cretaceous and Paleogene flysch, with water in pores and cracks at depths not exceeding tens of meters. The aquifer is found in Neogene layers. The depth of groundwater layers in the area ranges from 3–5 m up to 20 m (Chowaniec *et al.* 1985). Precipitation from the period between 1931 and 1960 classified landslide of Zaborów zone with an average annual rainfall of 650 mm/m^2 (data from the Polish Institute of Meteorology and Water Management).

When determining the occurrence of landslide hazards into account several characteristics are taken into account: physiographic, tectonic (dislocations, faults, folds), hydrological (max. depth of groundwater: 20 m below the surface level, the average mean precipitation equal to 650 mm, water in cracks and pores), lithological (primary landslide), morphometric parameters (total surface of 30 ha, angle of 7°, length – 965 m, bright – 490 m., max/min height –

343/230 m a.s.l.), detailed morphometrics (main scarp of landslide): the height of the slope – 8 m, the angle of inclination of 45°, the number of secondary slopes – 3), colluvium foot (average thickness of 20 m), and geotechnical (safety factor, determined using the Plaxis software – 0,5).

Based on data mentioned above, the threat of landslide in the examined area is defined as *high*. The area is also highly urbanized region, so that the consequences of landslide occurrence also determined as *high*, so as the risk is defined as *high* (see Fig. 3).

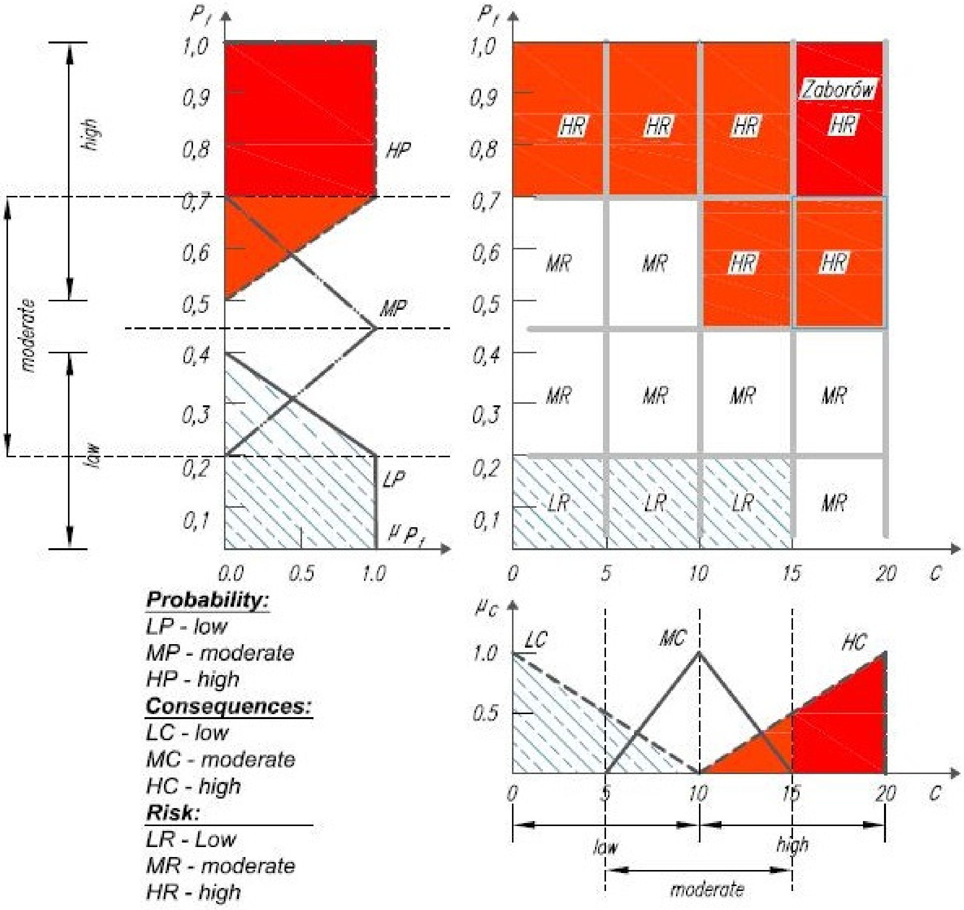

Fig 3. Risk matrix developed for the Subcarpathian province at risk of landslides (source: own elaboration)

The risk assessment is associated with the determination of acceptable damage probability, the number of potential casualties and the consequences of the financial, social, environmental and other origin. A particularly difficult issue here is assessment of the landslide impact. Evaluation in monetary units raise many objections, it is associated with the adopted scale of reference for individual person, community, district or region where the effects will be more or less perceived. The assessment of the social life of potential casualties is also difficult. Bearing in mind economic and/or social reasons, the appropriate assessment is easier to formulate in the form of linguistic variables. These are expressed as fuzzy parameters e.g. fuzzy numbers. On the other hand, material losses caused by the landslide are easier to express and evaluate in a qualitative way.

Conclusions

A very chaotic and intensive development of Subcarpathian hills and valleys in recent decades contributes to increasing losses in the real-estate values. In the nearest future residential and industrial structures, as well as the infrastructure should be located outside the landslide hazard zones. The location of these objects, and sometimes the whole housing estates on landslide-prone slopes is becoming more important anthropogenic factor initiating earth mass movements. The subsoil, additionally burdened with buildings, and cut by a network of roads and underground infrastructure loses its original strength resistance. Moreover, at certain water conditions it is more and more exposed for earth mass movements. So, the adequate drainage of the area plays an important role here and needs proper attention in the future investments. This is a very important role in minimizing losses is adequate planning based on maps of landslides and areas endangered by earth mass movements. The tasks implemented under the SOPO project will assist local authorities in the effective management of the risk of landslide, and also will reduce significantly the effects of damage caused by the development through the omission of investments, including road construction and housing within landslides. The results of the SOPO project will have a significant impact on the optimization of land use planning in areas at risk of the occurrence of earth mass movements.

A continuous update of maps and registration cards for landslides as the primary source of data for the process of risk assessment and risk management is particularly important. The methodology, which is based on the fuzzy set theory is an approach that allows to determine the risk arising from the threat of landslide phenomena. The risk assessment of landslide hazard is an integral part of the strategy on how to prevent and counteract the effects of natural disasters in the Subcarpathian province and sustainable development of the region.

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