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Application of the index statistical method to analyze the landslide susceptibility of a selected area in the Podkarpackie Voivodeship

Zastosowanie indeksowej metody statystycznej do analizy podatności osuwiskowej wybranego obszaru z terenu województwa podkarpackiego

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Abstract. Landslides are among the most dangerous and common geohazards in Poland. A very important role in minimizing losses has a proper spatial planning based on accurate landslide susceptibility maps of the area, which are the basis ofthe process of determining the threat and then estimating the risk. The purpose of this article is to develop a landslide susceptibility map of a selected area of the Dynowskie Foothills in terms of landslide hazard assessment. The final landslide susceptibility map of the study area was developed on a local scale using the Index Statistical Method. The individual maps of factors affecting landslides were based on several thematic sections: slope; exposure; proximity to watercourses; geology.

Keywords: landslides; index statistical method; susceptibility map; Dynowskie Foothills; reliability assessment.

Streszczenie. Osuwiska należą do najniebezpieczniejszych i najczęściej występujących geozagrożeń na terenie Polski. Bardzo ważną rolę w minimalizowaniu strat ma odpowiednie planowanie przestrzenne bazujące na dokładnych mapach podatności osuwiskowej terenu, które stanowią podstawę procesu określania zagrożenia, a następnie szacowania ryzyka. Celem artykułu jest pokazanie metody opracowania mapy podatności osuwiskowej wybranego obszaru Pogórza Dynowskiego pod kątem oceny zagrożenia osuwiskowego. Finalna mapa podatności na osuwanie obszaru badań została opracowana w skali lokalnej z wykorzystaniem indeksowej metody statystycznej. Poszczególne mapy czynników mających wpływ na osuwanie terenu uwzględniają: nachylenie zbocza; ekspozycję; bliskość cieków wodnych; geologię.

Słowa kluczowe: osuwiska; indeksowa metoda statystyczna; mapa podatności; Pogórze Dynowskie; ocena niezawodności.

At present, various methods of prevention, including mapping methods, are used for proper land use and landslide risk management. In Poland, legal regulations, introduced after the „landslide disasters" of 1997, 2000 and 2010, obliged local government administrative authorities to observe areas at risk of mass movements and collect this information in the form of a database. Landslide maps and documentation sheets of landslides and areas at risk have been compiled since 2008 as part of the implementation of the state-wide Landslide Protection System – SOPO project. One of the resultant products of this project is the „Map of Landslides and Areas at Risk" (MOTZ) at a scale of 1: 10000. The combination of the information contained in the MOTZ with other complementary digital data that are the determinants of landslide activity make it possible to perform precise multi-criteria GIS analyses, allowing the assessment of landslide susceptibility, landslide hazards and landslide risk assessments of the studied areas. Estimation of landslide susceptibility, or landslide risk, is considered in numerous publications in the world literature, e.g. [1 – 6]. In Poland, geo-information analyses mainly concern the southern part of Poland [7 – 13].

Many techniques and computational methods are used in landslide susceptibility studies including empirical, statistical, or deterministic approaches used at large scales in engineering geology [1 – 3]. Vulnerability or risk map methods describe the phenomenon under consideration only qualitatively, so supplementing such analyses with verification by reliability methods makes it possible to present the state of hazards in a quantitative manner that is more accessible to foundation

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engineers. It should be emphasized that qualitative research helps to understand the problem under consideration, while quantitative research helps to describe the phenomenon using statistical data. The best solution is the synergy of these methods. Two methods were used to analyze the landslide susceptibility of a selected area from the Podkarpackie province: a qualitative statistical index method (WoE – Weights of Evidence), developed by Van Westen, and a quantitative fully probabilistic method, used for reliability analyses of building structures.

visualized in the form of maps were used in the analyses (Figure 1). These are: geological structure; slope; altitude; exposure; watercourses; and land cover. Directly from the digital elevation model, such topographic attributes as slope and exposure were calculated.

Topographic attributes calculated directly from the digital elevation model represent continuous variables, so they were converted to interval (categorized) form. In order to determine the regularity of landslide formation, selected vector layers were generalized. The geological map was developed based on the reinterpretation of earlier geological maps of the area.

Application of the statistical index method

Spatial analysis was carried out using ArcGIS v.10.2 software. The study area is the village of Gwoździanka in the municipality of Niebylec, located in the Dynowskie Foothills, in southeastern Poland. The area has a hilly and mountainous character, typical of the landform of the Carpathian Foothills. The landslides occurring here, which pose a significant threat to the local road network, gas pipeline and buildings. The study area is completely contained within the Skolska Nappe, which is the outermost tectonic element of the Carpathians here. In the cartographic image, it is a series of scale and fold elements with a mainly NW-SE course. Fault zones play an important role in the study area, reflected in the morphology. Lithologically, the area is very diverse. In addition to Quaternary formations, its lithological structure consists of numerous lithological complexes of the Skolska Nappe flysch.

In the study area, three landslides were inventoried, including one periodically active, with a total area of 16,23 km^2. The calculated landslide index was 9,49%, and the landslide density factor was 1,316. Landslide colluvia are developed as clays, sandy and silty clays, sometimes clays with rocky debris of sandstones and rocky boulders, and sometimes with packets of flysch formations. The thickness of colluvium varies from a few to several meters [13].

The base source of information in the analysis and subsequent validation of the data is the MOTZ at a scale of 1:10000. In the case under consideration, the geo-information analysis covered all landslides. In the first stage of the study, thematic maps of factors affecting landslides were collected and subjected to selection. Finally, 6 passive factors

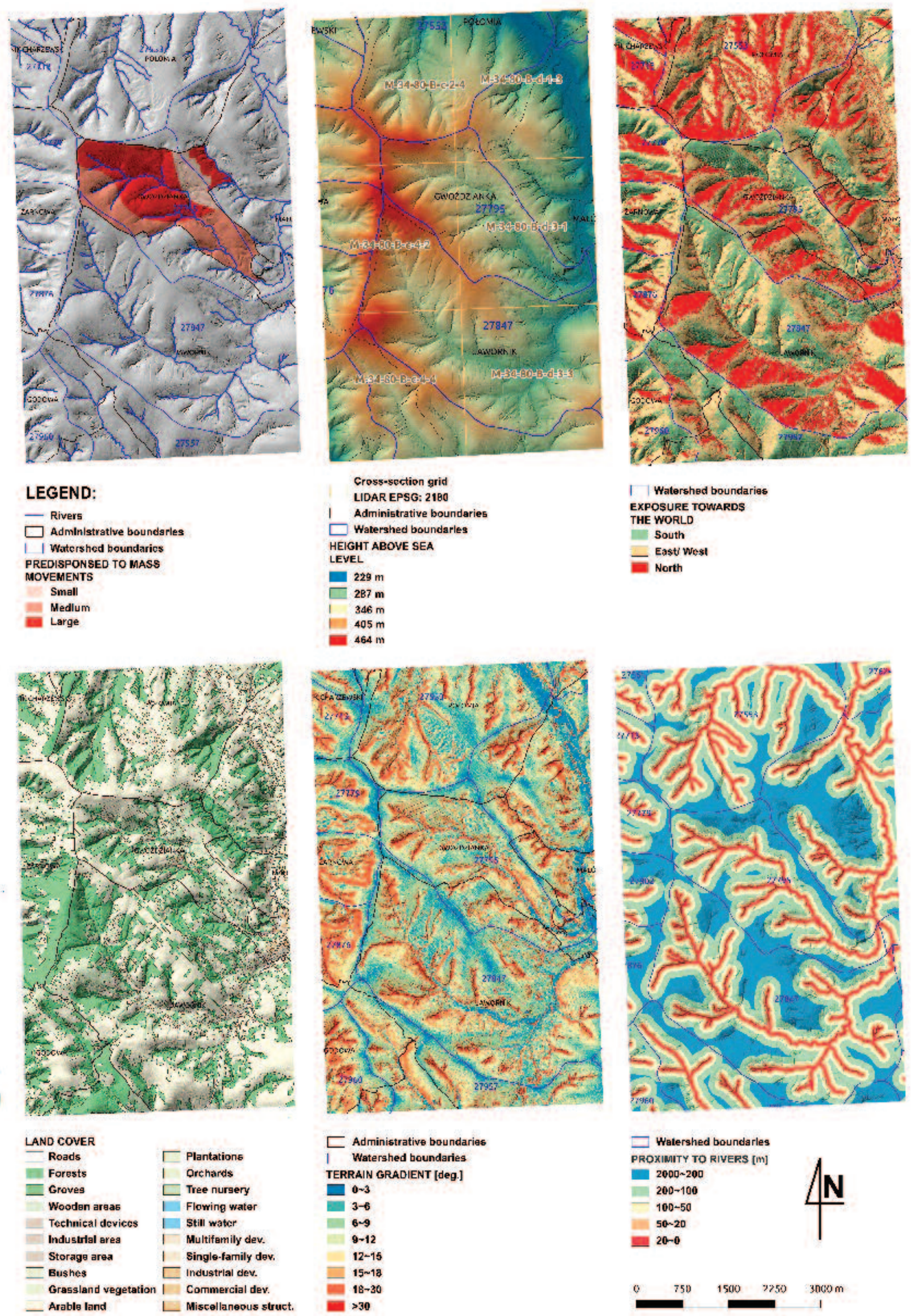

Fig. 1. Thematic maps for 6 passive factors
Rys. 1. Mapy tematyczne sześciu czynników pasywnych

It primarily shows the complexes forming the Carpathian flysch, with the distinction of three lithostratigraphic units. The data acquired during the field work (MOTZ) and 6 maps visualizing environmental-geological factors were used to make a landslide susceptibility map on a scale of 1 : 10000 by means of the index statistical method (WoE – Weights of Evidence) [1 - 2] using formula (1):

$$W_i = \ln\left(\frac{\text{Dens clas}}{\text{Dens map}}\right) = \ln\left(\frac{\frac{Npix(S_i)}{Npix(N_i)}}{\frac{\sum Npix(S_1)}{\sum Npix(N_1)}}\right) \qquad (1)$$

where:

W_i – landslide susceptibility coefficient assigned to a given class of thematic map;
Dens clas – landslide density in a given class of thematic map;
Dens map – landslide density covered by the map;
$Npix(S_i)$ – number of raster cells with landslides within a given class of thematic map;
$Npix(N_i)$ – number of raster cells within a given class of thematic map.

After summing the calculated indicators for all passive factors, a landslide susceptibility map of the Gwoździanka village area was obtained (Figure 2), with intervals selected by analyzing the histogram showing the density of index values [11]. The obtained landslide susceptibility indexes enable the construction of a hazard map, which is qualitative in nature, facilitating the classification of the considered area into sub-areas in terms of their susceptibility to landslide hazards. We can classify the index statistical method as a qualitative method of the so-called soft methods. Unfortunately, their application does not quantify the probability of damage to a structure located in a landslide-prone area. Therefore, we proposed to use in the next step the analysis according to a fully probabilistic method, which allows for this type of assessment. The calculation of the reliability index was performed using FREeT software. Based on the reliability calculations, the obtained landslide hazard map was verified and supplemented with the calculated values of the reliability index.

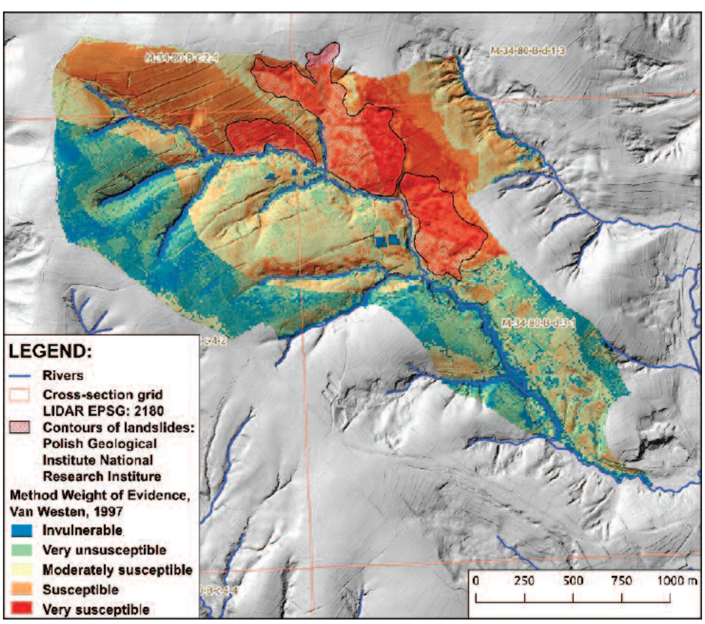

Fig. 2. Landslide susceptibility map for the village of Gwoździanka
Rys. 2. Mapa podatności osuwiskowej dotyczącej wsi Gwoździanka

Results of the study

Analyses carried out using the WoE method authorized the division of the morphodynamic study area into five susceptibility categories: invulnerable; very unsusceptible; moderately susceptible; susceptible and very susceptible (Figure 2).

In order to verify the validity of the developed landslide susceptibility map, methods based on the reliability of building structures were used, and geotechnical reliability levels were proposed. Using the probabilistic approach (IV level method of structural reliability analysis), the safety of building structures, including foundations, can be verified. According to [14], the values of reliability indexes for most structures and geotechnical objects are 1,0 – 5,0 (Table 1), which corresponds to a probability of failure of about 0,16 to 3 x 10^{-7}.

Table 1. The range of geotechnical reliability index β [14]
Tabela 1. Zakres geotechnicznego wskaźnika niezawodności β [14]

Reliability index β	Probability of failure P_f	Expected level of reliability	The level of reliability/scope of vulnerabilities proposed by the authors
1,0	0,16	very susceptible	very susceptible
1,5	0,07	susceptible	susceptible
2,0	0,023	moderately susceptible	moderately susceptible
2,5	0,006	below average	moderately susceptible
3,0	0,001	very unsusceptible	very unsusceptible
4,0	0,00003	invulnerable	invulnerable
5,0 or more	0,0000003 or less		

Reliability analyses were carried out for the bearing capacity of the subsoil beneath the foundation footing. The ultimate limit state condition was assumed in the form (2):

$$Z = R - E = c \cdot N_c + p_0 \cdot N_q + (B/2) \cdot \gamma \cdot N_\gamma - q \qquad (2)$$

where:

q – applied external load;
c – cohesion of the soil;
p_0 – effective stress from the overlap at the level of the foundation base;
B – width of the foundation;
γ – effective volume weight of soil below the foundation level;
N_c, N_q and N_γ – are dimensionless coefficients for bearing capacity, which are fixed functions of the internal friction angle ϕ of the soil (formulas 3 – 5):

$$N_q = e^{\pi \tan\phi} \cdot \tan^2(45 + \phi/2) \qquad (3)$$

$$N_c = (N_q - 1) \cdot \cot(\phi) \qquad (4)$$

$$N_\gamma = 2(N_q + 1) \cdot \tan(\phi) \qquad (5)$$

Several formulas for N_γ are used in the literature. In this case, the formula proposed by Vesic was used. Probabilistic analyses were carried out in FREeT software. Parameters for the analyses were adopted on the basis of a search of available geotechnical opinions and geotechnical and geological-engineering documentation of the area under consideration. Parameters were defined as random variables and determined quantities, and their values are shown in Table 2. The correlation of c and φ was assumed to be 0,5. An example of a frequency plot for the boundary condition function, obtained from the analyses conducted in FREeT software, is shown in Figure 3.

Based on the conducted analyses, it was concluded that the adopted categories of landslide susceptibility of the analyzed area are correct. The obtained values of failure probability (reliability index) for the conducted analyses showed consistency with the defined categories of landslide susceptibility of the studied area. High and very high landslide susceptibility is characterized by its northeastern part (Figure 4).

Table 2. Basic variables for probabilistic analysis

Tabela 2. Podstawowe zmienne przyjęte do analiz probabilistycznych

Random variable	Distribution	Average value	Standard deviation
c [°]	N	13	5
ϕ [kPa]	LN	14	2
N_q [m²]	zdet	3,804	–
N_C [m]	zdet	10,74	–
$N_γ$ [m]	zdet	2,507	–
Q_v [MNm]	zdet	200	–
q [MNm]	zdet q = Qv/B	166,7	–
B [m]	zdet	1,2	–
γ [kN/m³]	zdet	20	–
p_0 [m]	zdet	18	–

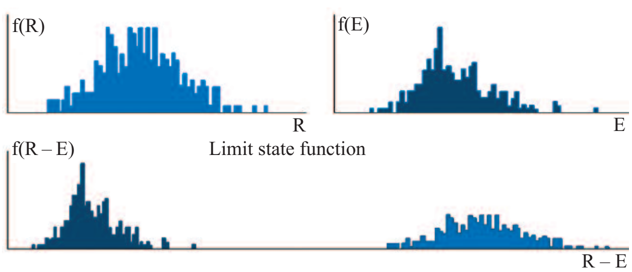

Fig. 3. Histogram for limit state function

Rys. 3. Histogram funkcji stanu granicznego

The use of an index statistical method makes it possible to determine the importance of individual geoenvironmental factors. Table 3 shows the landslide susceptibility index of the study area, estimated at 0,18, as well as the weighting values for each thematic map included in the final analysis. Analyzing the digital elevation model, it was found that areas with slopes of 3 – 12° and 12 – 30° had the largestshare. As the slope

Table 3. Landslide susceptibility weights for defined classes for individual thematic maps

Tabela 3. Zestawienie podatności na osuwanie w przypadku poszczególnych map tematycznych

Category	[A] Areas of landslides in category and subcategory [m²]	[B] Total areas in category and subcategory [m²]	[A]/[B]	W_i
Terrain gradient [deg]				
0 – 3	20385	136608	0,149	-0,172
3 – 6	81196	491200	0,165	-0,070
6 – 9	119824	764827	0,157	-0,123
9 – 12	120743	711508	0,170	-0,044
12 – 15	95241	504258	0,189	0,064
15 – 18	64935	307985	0,211	0,174
18 – 30	92003	404223	0,228	0,250
> 30	17223	127906	0,135	-0,275
Exposure towards the world				
North	73826	670474	0,110	-0,476
South	294986	1049197	0,281	0,461
East/West	242723	1728795	0,140	-0,233
Proximity to rivers [m]				
0 – 20	30899	345683	0,089	-0,685
20 – 50	90396	479529	0,189	0,062
50 – 100	147596	711111	0,208	0,158
100 – 200	196198	1128987	0,174	-0,020
200 – 1000	146704	783988	0,187	0,054
Land cover				
forests	700188	1044500	0,670	1,330
technical devices	0	1179	0,0008	-5,342
grassland vegetation	828581	1157714	0,716	1,396
arable land	613493	1014413	0,605	1,227
plantations	1785	1785	1,000	1,730
orchards	20908	44349	0,471	0,978
flowing water	0	393	0,0025	-4,244
multifamily development	77388	172460	0,449	0,929
miscellaneous structure	0	7224	0,0001	-7,155
Geology/Predisposed to mass movements				
G1	335999	1703814	0,197	0,107
G2	125592	1418012	0,089	-0,694
G3	148410	347180	0,427	0,880
Total area [m²]	3444009,305			
Landslide area [m²]	610438			
Landslide susceptibility	0,177246327			

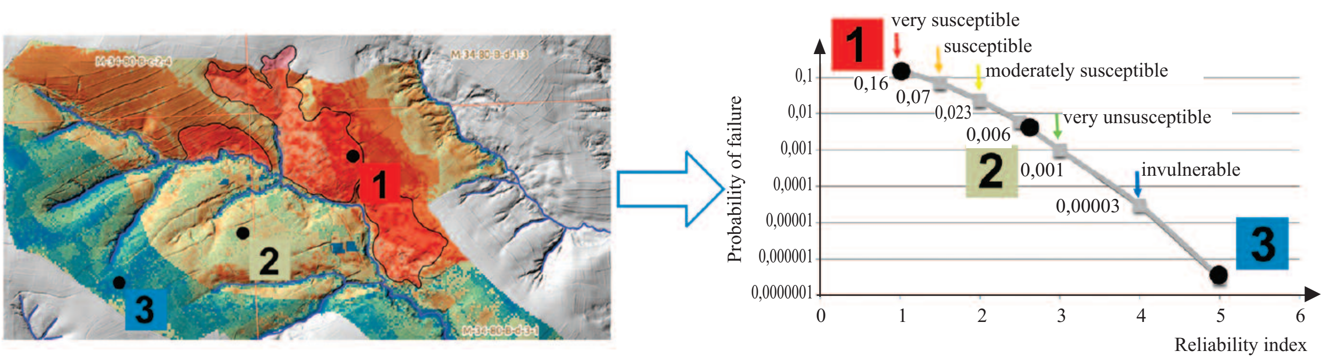

Fig. 4. Verification of vulnerability map by probabilistic methods

Rys. 4. Weryfikacja mapy podatności metodami probabilistycznymi increases, the values of the landslide susceptibility factor increase. The obtained results are consistent with the results of similar GIS analyses performed in the Low Beskidin the Carpathian Mountains, where the highest susceptibility was observed on slopes of 9 – 14°. An important factor determining the formation of mass movements is the geological structure, and above all the lithological differentiation of the layers. The highest susceptibility to landslides are clays (0,88) and silty clays that are easily dispersed (0,11). Hydrological and hydrogeological conditions are another factor controlling mass movements. Slopes near (up to 20 m) watercourses and reservoirs are particularly at risk (W_i = 0,68). This is primarily due to the large role played by fluvial erosion and the drainage function in mass movements. The N and NW exposures should also be associated with hydrometeorological conditions. The northern slopes have longer snow cover and there is increased infiltration of rainwater and snowmelt, hence the higher values of the landslide susceptibility factor are for the northern exposure (0,48 generated in GIS). The influence of other passive factors on landslide susceptibility, such as the first aquifer, would also need to be tested. Vulnerability modeling should still be carried out with other statistical methods, such as neural networks, to verify the results obtained with the WoE method.

Summary

The developed landslide susceptibility map shows the spatial distribution of areas with varying degrees of landslide susceptibility. In the range of very high risk included roads, residential buildings and forests. The analysis of landslide susceptibility showed a relationship between the occurrence of landslides and passive factors such as geological structure, slope, exposure of slopes, distance from watercourses and reservoirs, and land use. It was shown that the potential area for landslides is the northeastern and eastern parts of the study area. Geomorphological factors have the greatest influence on the formation of landslides.

Based on the elaborated maps, it was found that there is a clear correlation between the susceptibility map and the geological map and the map of slopes and watercourses. These passive factors have the highest landslide susceptibility coefficients (W_i). The conducted research has shown a high susceptibility to landslides of slopes of 6 – 18° and N, NW and NE exposures, built of sediments showing lithological diversity and characterized by the presence of various clays and rock interbeds.

Hydrological conditions, including the close proximity of surface water (0 – 20 m), are factors strongly determining landslide processes. Areas predisposed to the occurrence of mass movements are also associated with land use. As a result of the quantitative analyses carried out for the assessment of the reliability of the bearing capacity of the soil, the correctness of the adopted categories of landslide susceptibility was found for the considered area.

The qualitative Weights of Evidence (WoE) method, applied to model landslide-prone areas in the municipality of Niebylec, opens up further opportunities for research, including the inclusion of other passive factors for modelling, such as the first aquifer. The obtained landslide susceptibility map is the basis for assessing landslide risk and developing the degree of landslide vulnerability. The degree of loss (vulnerability) refers to the damage caused by landslides. When assessing vulnerability, elements potentially subjected to the destructive process as well as economic data should be taken into account. The developed landslide vulnerability map of Gwoździanka village can be helpful for land use and planning purposes.

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