https://doi.org/10.33271/nvngu/2024-5/093

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ANALYSIS OF NATURAL AND MAN-MADE FACTORS OF LANDSLIDE DEVELOPMENT IN THE CARPATHIAN REGION USING GIS

Purpose. Determination of the dependencies of spatial relationships between landslides in the Carpathian region of Ukraine and the factors causing them, taking into account the differences in geomorphological, geological, climatic conditions and natural and geographical zoning according to the landscape principle.

Methodology. The morphometric analysis of the territory was carried out using QGIS tools to determine the slope angles and exposure; linear characteristics were calculated: distances to the river, road, and houses. Based on the image interpretation data, we calculated the total annual rainfall and average annual air temperature. The impact of the factors considered on landslide formation was assessed using multivariate statistical analysis: factor analysis and linear multiple regression.

Findings. Studies on the impact of natural and topographical conditions and anthropogenic activity on the development of landslide processes have been conducted. Orographic and climatic factors play the most important role. Construction of business facilities results in a decrease in the slope stability in 14–19 % of cases. The analysed independed factors showed good consistency between the distribution of existing landslides and the parameters under consideration: the share of the total variance of the factors under consideration is 71–76 %, the coefficient of determination of the regression model is 0.7. Based on the results of geoinformation and statistical analyses, it is proved that differences in geomorphological conditions and human activity (construction of roads, economic facilities) are dominant in the formation of landslides in different landscape zones.

Originality. It is established that there is a dynamic coherence between the spatial change in natural conditions and human settlement and activity, which interact with each other to create prerequisites for the development of landslides.

Practical value. This study is important from the point of view of understanding and mitigating the cause-and-effect relationship of landslide development for certain territories, and the results obtained can be useful in developing land use planning strategies, infrastructure development, and planning new construction works.

Keywords: *landslides, GIS, natural and anthropogenic factors, geoinformation analysis, factor and regression analyses*

Introduction. Landslide processes in Ukraine are some of the most widespread natural phenomena, covering large areas, producing large volumes of rock fall and causing significant material damage to human activity. According to published data [1], the western regions of Ukraine suffer the most from landslides: Zakarpattia – 3,297 (385.8 km^2), Ivano-Frankivsk – 805 (301 km^2), Lviv – 1,347 (292.6 km^2), Chernivtsi – 1,467 (760.2 km^2). In total, landslide areas in these oblasts cover 1,739.6 km^2, which is 81 % of the total landslide area in Ukraine (2,148.17 km^2). The last cases of local activation were observed in the summer of 2020 due to prolonged heavy rainfall [2, 3]. The differentiation of geological and tectonic conditions of formation and development of gravitational processes, which are the most studied, makes it necessary to find a new method of spatial analysis of landslides.

Literature review. The study of the influence of the natural conditions of the Carpathian region on the development of landslide processes and the division of the territory by engineering-geological and tectonic conditions for the study of the spatial factors of landslide development is reflected in a number of modern Ukrainian studies, in particular, by Demchyshyn M. G. [4], Kuzmenko E. D. [4, 5], Zhuravel O. M. [4, 5], Karpenko O. M. [4], Ivanik O. M. [6], Kasiyanchuk D. V. [7, 8]. The study of spatial and temporal correlations of landslide activation with the factors causing it is devoted to [9, 10]. By analysing geospatial data using GIS tools (topography, geology, hydrology, weather conditions and anthropogenic activities), the Landslide Vulnerability Index was determined [11, 12]. The publication [13] highlights the use of statistical methods to analyse differences in the leading factors based on geomorphological zoning. In recent years, artificial intelligence methods (regression, neural network analysis) have been widely used to model landslide susceptibility, taking into account the importance of each factor of the processes under study [13, 14].

In this publication, the conditions for the development of landslide processes are analysed on the basis of the homogeneity of the geomorphological, geological and climatic conditions of the area and on the basis of physical and geographical zoning.

General characteristics of the study area. Landslides in the Carpathian region are influenced by geological and tectonic structure, relief, climate and human activity. The triggering factors can be divided into two groups: permanent and rapidly changing ones. Permanent factors include geological and tectonic structure [15] and geomorphology [16], which remain relatively unchanged. These factors play a role in shaping the characteristics and intensity of landslides.

In particular, the geological structure and lithological composition of the rocks influence the level of rock stability and the intensity of landslide processes. The study area includes large mountain ranges and plains of different structure and age. Landslides are associated with areas dominated by two-component flysch (composed of alternating argillites and siltstones), clays, loams, marls and other water-resistant rocks. Various clay formations act as ‘sliding mirrors’ for the overlying rocks.

The rapidly changing factors category combines meteorological aspects (such as rainfall and air temperature), seismic events (earthquakes) and anthropogenic impacts (deforestation, slope cutting, construction). These factors act as ‘triggers’ for the activation of landslide processes. They act indirectly through surface runoff, moisture, porosity, temperature and the mechanical properties of the rock. In addition, some exogenous processes also influence the development of landslides, in particular the erosion of permanent and temporary watercourses.

Summary of the main material. Considering that natural and landscape conditions are stable in time and at the same time different for different territories, this study aims to identify and study patterns in the factors of landslide development. The physical and geographical zoning of Ukraine is based on the identification of relatively homogeneous regions in terms of natural conditions, which differ in their landscape structure. The classification takes into account the spatial position of landscapes (in the plains, in the mountains), the relationship between climate, vegetation, relief, moisture conditions and the degree of influence of human activity on them. The spatial structure of landscapes has a zonal character (Fig. 1).

According to the natural and geographical zoning, the north-eastern and south-western parts of the administrative regions under consideration (Fig. 1) belong to the plain landscapes (Roztotsko-Opilska upland region, Prut-Dnister upland region, Precarpathian upland region, Zakarpatska lowland region), the rest of the territory belongs to the mountainous landscapes (External Carpathian region, Verkhovyna watershed region, Polonyna-Chornohora region, Marmaroshska region, Volcanic-intermountain basin region) [17]. Thus, the study area can be divided into two classes according to landscape characteristics: plain and mountainous.

The initial data for the spatial location of landslides and their absolute heights were the landslide cadastres of Geoinform SO in the region of Zakarpattia, Ivano-Frankivsk, Chernivtsi and Lviv. The development of landslide processes is influenced by a complex of factors, both natural and human. Based on the experience of similar studies [4, 10], geomorphological, anthropogenic and climatic factors were considered: data on precipitation, air temperature, road network, construction objects were obtained from the website WorldClim and the cadastre.

Research methods. Considering that different areas of the Carpathian region have different physical and geographical conditions, it is advisable to study landslide factors by geographical zoning, carrying out geographical information analysis using QGIS (calculation of slope angles and exposure, linear characteristics: distance to the river, to the road, to the houses). On the basis of the data obtained, we analysed the spatial variability and determined its impact on the development of landslide processes.

Fig. 2 shows the distribution of the considered factors for plains and mountainous areas (the ordinate axis shows the number of landslides, the abscissa – the values of the parameters).

Absolute landslide heights. The height of the relief affects the instability of the slope. Since the territory is divided into two areas with significant differences in relief – plain and mountainous – it is natural that there are significant differences in the absolute heights of recorded landslides. In the plains, the lowest elevation is 121 m (Prut-Dnister Upland) and the highest is 555 m (Precarpathian Upland), with the vast majority of landslides occurring at the 300 m mark. Mountainous areas are characterised by greater differences in elevation, ranging from a minimum of 125 m (Volcanic-Intermountainous Hollow region) to a maximum of 1,572 m (Verkhovyna watershed region), with most landslides occurring at absolute elevations of up to 800 m.

The slope angle also affects the instability of slopes: the steeper the slope, the greater the stress on the rock, and it also affects the run-off of precipitation and the moisture content of the rock. In flat areas, most landslides (84 %) occur on gentle slopes 5–10°, in mountainous areas – on moderate slopes up to 25°, with most landslides (78 %) occurring on slopes from 5 to 20°. As the slope angle increases, the number of landslides decreases (Fig. 2).

Slope exposure affects air temperature, moisture evaporation rate and rock weathering processes. The range of exposure is divided into 8 directions: north, north-east, east, south-east, south, south-west, west and north-west. It should be noted that landslides have been recorded on the slopes in all directions, which does not allow us to interpret the effect of exposure unambiguously. However, there is a certain tendency towards an increase in landslides on slopes facing south-east and south for mountainous areas (38 % – 646 landslides).

Distance to the river. The Carpathian region is characterised by the densest river network in Ukraine, with an average of 1.7 km/km^2 [18]. Such a system of watercourses causes vertical and lateral erosion, and during floods and high tides, large areas of the coastal zone are inundated. The width of the flood zone is the first few hundred metres. The factor of 'distance to the river' has been divided into intervals of 200 m. Considering that landslides can be hundreds of metres long and wide, the 'distance to the river' parameter is one of the most important factors in the formation of landslides. As shown in Fig. 2, a quarter of the landslides were recorded at the closest distance of 200 m (340 in the plain, 644 in the mountainous area). The number of landslides decreases with increasing distance from the river network.

The distance from roads is one of the main factors of anthropogenic influence [12, 13], as road construction cuts the slope, which increases the stress state, and also changes the direction of surface groundwater flow, which leads to a decrease in slope stability. This is confirmed by the location of landslides in relation to roads: more than half of them are lo-

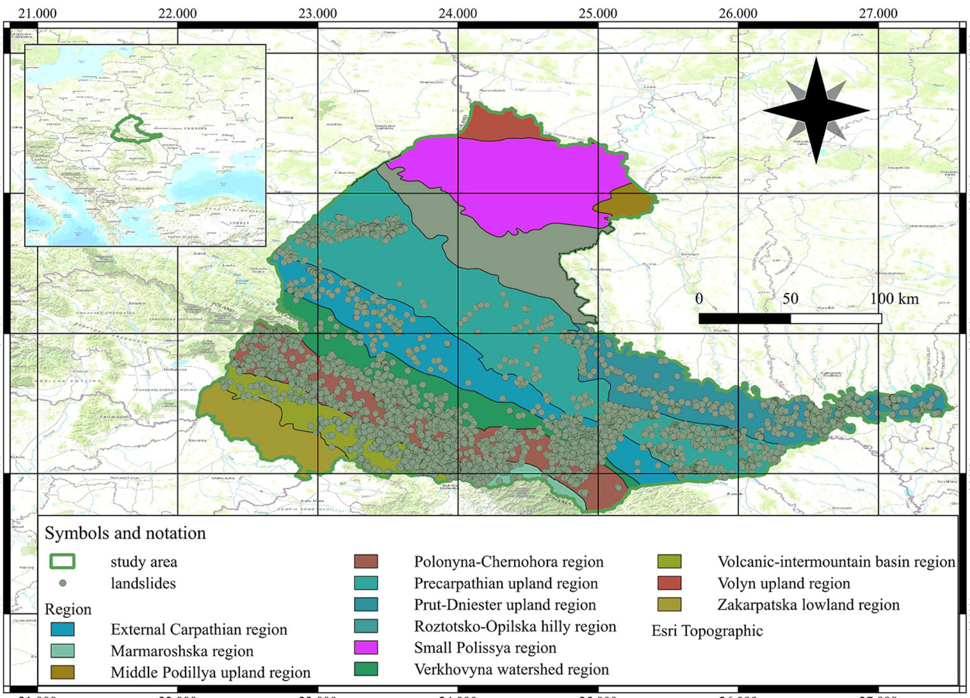

Fig. 1. Physical and geographical zoning of the study area

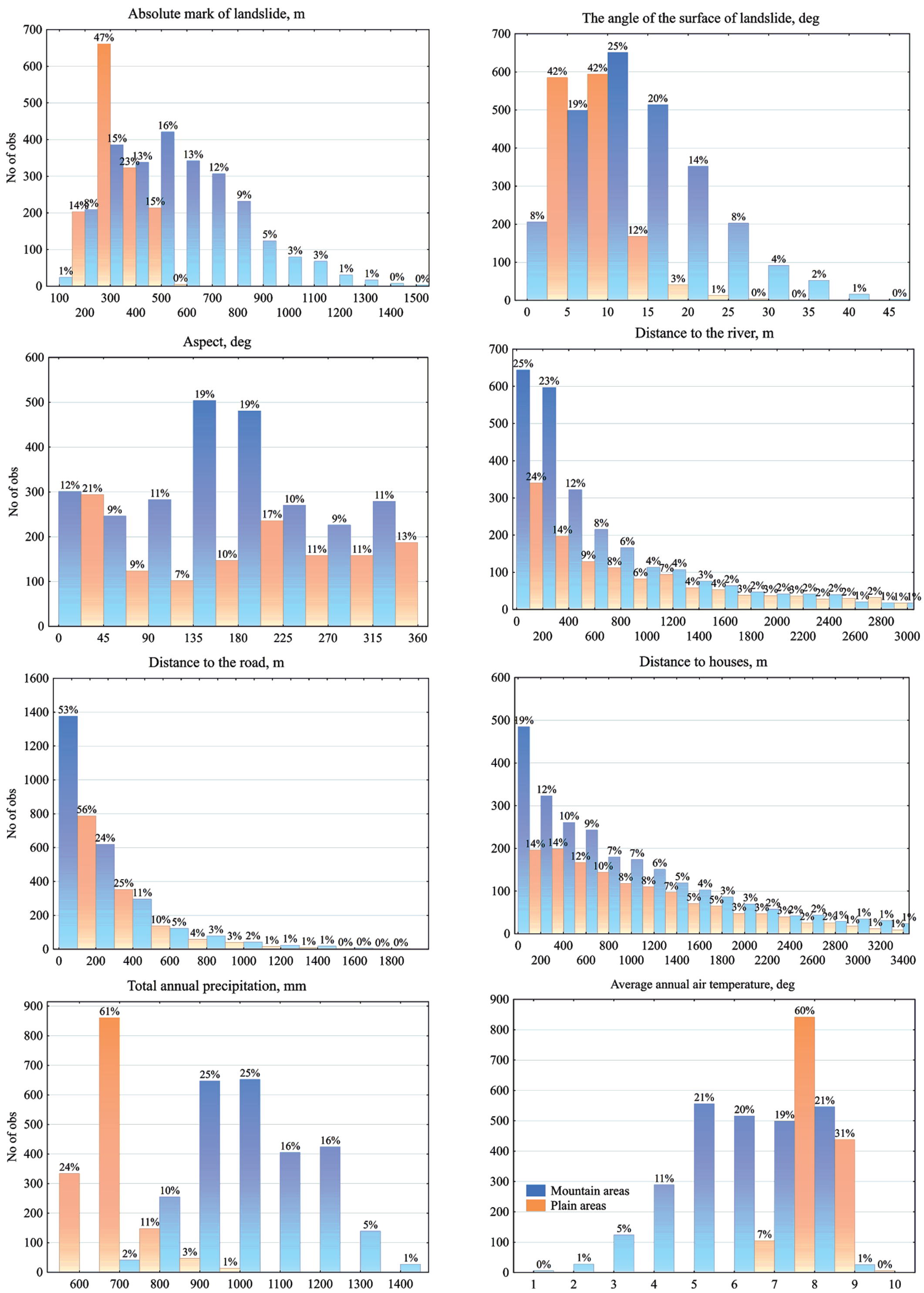

Fig. 2. Distribution of spatial characteristics of landslide factors

cated within 200 m of roads 787 (56 %) on flat land, 1,376 (53 %) on mountainous land). This pattern indicates a strong link with the development of landslides.

The distance to the houses not only poses a direct threat to human life, but also causes significant material damage. The construction of houses disrupts the natural stability of slopes and interferes with the drainage system of surface groundwater. Data show that between 14 % (137) and 19 % (420) of landslides in the plains and mountains occur at a dangerous distance from houses. Such close proximity can cause cracks in building foundations and walls, leading to destruction.

Total annual rainfall. Intense, prolonged rainfall is known to contribute to excessive moisture in the upper layer of rock, which shifts when in contact with clayey rock. This is one of the main driving forces for landslide activation [19]. A very high number of landslides (1,195, 85 %) were recorded in flat areas with precipitation up to 700 mm/year. The mountainous areas are characterised by a maximum of landslide events (1,959, 92 %) within the precipitation intervals of 800–1,200 mm/year [20].

Mean annual air temperature. Air temperature affects the rate of evaporation of moisture and the circulation processes in the atmosphere; it also accelerates the weathering of rocks and the number of landslides increases with increasing temperature. The amplitude of the average annual temperature varies from 1 to 9°, with an average of 7.8° for the plains and 6.5° for the mountains.

Methods. The use of statistical methods is based on the study of functional relationships between the phenomenon under study and the factors that determine it. To determine the significance and influence of each of the factors under consideration, multivariate statistical methods were used, in particular, factor and regression analyses [21, 22].

Factor analysis takes into account the correlations between a large number of variables in order to determine the structural relationships between the process under study, in our case shifts, and a set of independent variables whose combined effect creates the conditions for its development. Given the different nature of the factors under consideration, the data were first standardised. The test for normal distribution of the factors studied showed that all the parameters follow a lognormal, exponential or Weibull law, except for the parameters: slope angle, slope exposure and average annual air temperature. This distribution of factor characteristics can be explained as follows: 1) slope angle and slope exposure are natural factors for areas where landscapes are least exposed to human influence; 2) the dynamics of mean annual temperature change has, in addition to global time harmonics, intermediate periods of 'cooling' and 'warming', which form natural cycles in modern conditions; 3) precipitation is the most dynamic factor; 4) precipitation is the most dynamic component and depends on changes in temperature, surface heating and air movement, which is consistent with a lognormal distribution; 5) the absolute height of the landslide and the distance to water bodies in areas of medium altitude where active economic activity is carried out are unconditionally consistent due to human influence on the landscape conditions of the territory. To make the distribution more normal, logarithmisation was applied.

The optimal factor loadings are determined by rotating the axes using the orthogonal varimax method, which is used to analyse a specific general process (shifts). The significant contribution of each parameter is described by factor loadings equal to or greater than ±0.7 [21] (Table 1).

The results of the analysis show that the first factor explains more variables than the rest. Three factors can be distinguished: the first, with the highest variance, combines absolute heights and climatic conditions; the second groups linear parameters: distance to the river, road and houses; the third combines parameters that characterise the slope: slope angle and exposure.

The formation of landslides in the plain area occurs at lower gipsometric altitudes (–0.918), gentler slopes (–0.670), southern and south-western exposure (0.305), with lower annual precipitation (–0.886), higher average annual air temperature (0.950) and close to rivers (–0.617), roads (–0.752) but far from houses (0.790).

As for mountainous areas, landslides occur at high altitudes (0.895), near rivers (–0.682), on steep slopes (0.514), on eastern, southern and western exposures (0.719), with higher precipitation (0.663) and lower average annual air temperature (–0.874). The anthropogenic factor also plays an important role – More landslides were recorded near roads (–0.745) and houses (–0.643).

Thus, we observe differences in the influence of natural factors – absolute heights, climatic indicators – in different landscape zones, but the unifying factor is the anthropogenic impact. In total, the three factors explain 76.1 and 71.3 % of the total variance for plains and mountains respectively. The remaining percentage of unexplained variance can be attributed to the influence of geology, tectonic structure and seismicity.

The results of the factor analysis indicate the importance of considering geographical conditions as an important step in understanding the causal relationship between global climate change and building code compliance. The simplest geographical division of the territory is altitude, as it reflects changes in natural conditions and hence the geography of settlement.

In order to confirm the identified relationships between the considered factors and landslides, a multiple regression analysis was performed [20, 21] for one of the most representative physical and geographical areas in terms of the number of registered landslides in the flat landscape – the Prut-Dniester highland region (498 landslides). The multiple regression analysis is based on the functional relationship between the dependent variable (landslides) and several independent variables (considered factors)

$$y(i) = b_0 + b_i \cdot x(i), \tag{1}$$

where $x(i)$ – are the independent variables; b_0 – the free term; b_i – the angular regression coefficients.

In the equation, the regression coefficients represent the contributions of each independent factor to the outcome variable (displacements). The reliability of the regression model is determined by the multiple correlation coefficient (R), the coefficient of determination (R^2) and the normal distribution of the residuals (the difference between the actual data of the factors considered and the theoretical values of the regression equation). For the selected Prut-Dniester highland area, the multiple correlation coefficient is 0.837, which characterises the density of the relationship between landslides and the independent variables considered. The coefficient of determination characterises the degree of dispersion around the mean value of the dependent variable (landslides) described by the regression. In our case, $R^2 = 0.70$, i.e. 70 % of the causes of landslides are explained by the factors included in the equation. The columns of the table 'Coefficients of the regression model' contain the following information: b^* – standardised regression coefficients; Std.Err. – of b^* – standard error of b^*; b – coefficients of the regression equation; Std.Err. of b – standard error of the coefficients of the regression equation. Intercept is the free term in the regression equation. The value of $t(479)$ is the Student's t-test (t(number of degrees of freedom)) used to test the null hypothesis that the coefficients of the equation are equal to '0'; the p-value is the significance level for the null hypothesis. As can

Table 1

Results of the factor analysis

	Plain areas			Mountain areas		
Factor characteristics	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Absolute displacement mark, m	–0.918	0.073	0.086	0.895	0.168	–0.077
Slope angle, degrees	0.127	0.091	–0.670	0.514	–0.121	0.132
Exposure of the slope, degrees	0.016	–0.135	–0.760	–0.065	–0.098	0.719
Total annual precipitation, mm	–0.886	0.097	0.065	0.663	–0.166	0.021
Average annual air temperature, degrees	0.950	0.034	–0.034	–0.874	–0.287	0.065
Distance to the river, m	0.053	–0.617	–0.416	0.212	–0.682	–0.098
Distance to the road, m	–0.156	–0.752	0.014	–0.310	–0.745	–0.066
Distance to houses, m	0.003	–0.791	0.152	–0.242	–0.643	0.055
The proportion of total variance	0.409	0.202	0.150	0.380	0.198	0.135

be seen from Table 2, the multiple regression equation takes into account all the factors involved, with the exception of the slope exposure parameter. The main role in the formation of landslides is played by precipitation, which acts as a ‘trigger’ for rocks that have undergone changes under the influence of other factors; absolute altitude; and anthropogenic factors (more landslides occur near built-up areas and roads).

Thus, the development of landslides in the Prut-Dniester highland region is described by the equation

$$\begin{aligned} y = 1392.96 + 0.9 \cdot \text{Total annual precipitation} - \\ - 0.228 \cdot \text{Absolute landslide elevation} + \\ + 0.106 \cdot \text{Distance to houses} - 0.081 \cdot \text{Distance to road} - \\ - 0.101 \cdot \text{Average annual air temperature} - \\ - 0.062 \cdot \text{Distance to river} - 0.042 \cdot \text{Slope angle}. \end{aligned} \quad (2)$$

The quality of the regression is assessed by comparing the residuals of the model with the normal law according to the histogram. The histogram of the residuals and the graph of the expected normal distribution confirm the adequacy of the accepted multiple regression model (Fig. 3). When the regression model is fitted, the points on the graph should lie along a straight line, indicating that the residuals follow a normal distribution law.

Based on this, the Carpathian region can be clearly classified as the main condition for the distribution of geographical conditions and dominant factors for different areas, in addition to the stratigraphic component. Mountainous – as such, where climatic conditions, and especially global climate change, are fundamental and directly interdependent. Areas with predominantly flat terrain, or areas where the difference in absolute altitude is not so great, clearly indicate that human impact on landscapes is a key issue in the study area and can be generally accepted for similar conditions.

The analysis of the distribution of independent factors plays an important role in understanding the nature of the influence of each of them on landslide formation.

Conclusions. It has been established that there is a dynamic interaction between spatial changes in natural conditions and human settlement and activities, which interact to create conditions for the development of landslide processes in the study area:

1) the geographical division of the area provides a clear spatial variation of natural conditions with human settlement as a factor in the development and intensification of landslide processes;

2) landslide processes, understood as exclusively landscape-dependent, have intensified their development in places with intensive anthropogenic activity in recent decades, determined by the peculiarity of settlement in accordance with the most favourable natural and topographical conditions;

3) topographic (altitude, slope, distance from the river) and climatic factors (precipitation, air temperature) have the greatest influence, which is clearly evident in the geo-analytical analysis based on the geo-information approach;

4) a common significant factor in the development of landslides in both landscape zones is the anthropogenic impact, which is manifested during road construction and construction of economic facilities by cutting slopes, which reduces the natural stability of the entire slope (the development of half of the landslides is caused by road construction, and 14–19 % of landslides were formed in the vicinity of construction sites);

5) the study of natural and geographical conditions is closely related to engineering and geological zoning, which outlines common landscape zones for the territory that have been formed and determines the areas of settlement.

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Table 2

Regression model coefficients

Prut-Dniester highland region						
Regression Summary: $R = 0.83695875$ $R^2 = 0.70049995$ Adjusted $R^2 = 0.69612312$ $F(7.479) = 160.05$ p						
	b^*	Std.Err. – of b^*	b	Std.Err. – of b	$t(479)$	p-value
Intercept	–	–	1,392.96	30.952	45.004	0.0000
Average annual air temperature, degrees	0.900	0.046	1,117.39	57.342	19.486	0.0000
Absolute displacement mark, m	–0.228	0.051	–282.75	63.361	–4.463	0.0000
Distance to houses, m	0.106	0.028	129.99	34.334	3.786	0.0002
Distance to the road, m	–0.081	0.028	–99.76	34.722	–2.873	0.0042
Average annual air temperature, degrees	–0.101	0.053	–124.83	66.259	–1.884	0.0602
Distance to the river, m	–0.064	0.028	–52.30	34.653	–2.509	0.0319
Slope angle, degrees	–0.042	0.025	–51.58	31.008	–1.663	0.0969

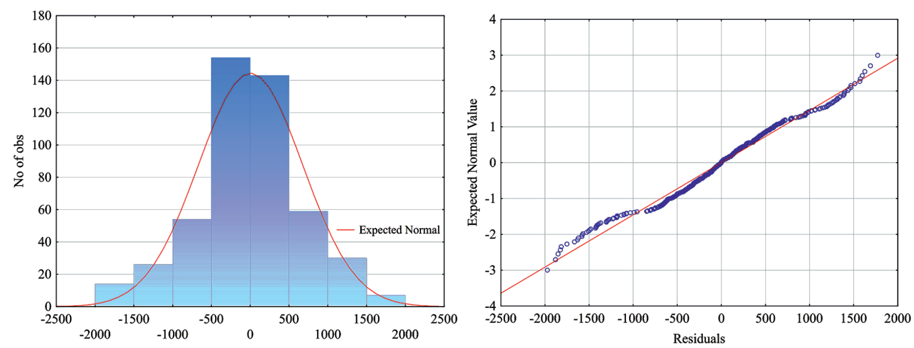

Fig. 3. Histogram and normal distribution curve of residuals

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Аналіз природно-техногенних чинників розвитку зсувів у Карпатському регіоні з використанням ГІС

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Мета. Визначення залежностей просторових взаємозв'язків між зсувами у Карпатському регіоні України й чинниками, що їх спричиняють, ураховуючи відмінності геоморфологічних, геологічних, кліматичних умов і природно-географічне районування за ландшафтним принципом.

Методика. За допомогою інструментів QGIS виконано морфометричний аналіз території для визначення кутів нахилу та експозиції схилу; обчислені лінійні характеристики: відстані до річки, доріг, будинків. На основі даних дешифрування знімків виконані розрахунки сумарної річної кількості опадів і середньорічної температури повітря. Оцінка впливу розглянутих чинників на процеси зсувоутворення виконана за допомогою багатофакторного статистичного аналізу: факторного й методом лінійної множинної регресії.

Результати. Виконані дослідження впливу природно-топографічних умов і антропогенної діяльності на розвиток зсувних процесів. Найвагомішу роль відіграють орографічні та кліматичні чинники. Будівництво об'єктів господарювання призводить до зменшення стійкості схилів у 14–19 % випадках. Проаналізовані незалежні чинники засвідчили гарну узгодженість між розподілом наявних зсувів і розглянутими параметрами: частка загальної дисперсії розглянутих чинників становить 71–76 %, коефіцієнт детермінації регресійної моделі 0,7. За підсумками геоінформаційного та статистичного аналізів доведено, що відмінності геоморфологічних умов і людська діяльність (будівництво доріг, об'єктів господарювання) є домінантними в утворенні зсувів для різних ландшафтних зон.

Наукова новизна. Встановлено, що існує динамічна узгодженість між просторовою зміною природних умов і розселенням і діяльністю людини, які, взаємодіючи між собою, створюють передумови для розвитку зсувів.

Практична значимість. Дане дослідження є важливим із точки зору розуміння й пом'якшення причинно-наслідкового зв'язку розвитку зсувних процесів для окремих територій, а отримані результати можуть бути корисними під час розроблення стратегій планування землекористування, розвитку інфраструктури, при плануванні нових будівельних робіт.

Ключові слова: *зсуви, ГІС, природні та антропогенні чинники, геоінформаційний аналіз, факторний і регресійний аналіз*

The manuscript was submitted 11.04.24.