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EVALUATION OF THE INFLUENCE OF CLIMATIC AND GEOMORPHOLOGICAL FACTORS ON LANDSLIDES DEVELOPMENT

Abstract. *The paper deals with the study of factors influencing the propagation of landslides in Ukraine. According to numerous monitoring studies, climate changes have significant impact on the stability of natural slopes and cause landslide processes. The topicality of the study is connected with the multifactor mechanism of landslides formation and complexity of this process development in space and time scales. Activation of landslides is registered on the territory of almost all administrative regions of Ukraine. The increasing dependence of the number of recorded landslides on annual precipitation and relief is established. For the most landslide-prone regions of Ukraine, the integral coefficients of the relief influence have been calculated, and the levels of potential landslide risk have been determined. Linear regression dependence between the amount of atmospheric precipitation and the number of landslides has been obtained, which allows predict landslide hazard in the regions of Ukraine. The results of the calculations are presented graphically in the form of a map.*

Key words: *exogenous geological processes, landslide, model of global circulation, integral coefficient of the relief influence, landslide risk.*

Introduction

Landslides are the most common exogenous geological processes (EGP), which create environmental and technogenic danger. The landslide processes of natural origin occur predominantly on the slopes of the river valleys, along the coastal shores and in the ravine-gully network of landscapes. Landslide of artificial or technogenic origin are observed in the slopes of the quarry faces as a result of technological operations while open cast mining, during construction and operation of geotechnical structures.

Natural landslides cause the greatest danger in the vicinity of settlements and in the areas with steep slopes, and usually followed with significant rainfalls or short-term seismic impacts.

Analysis of recent research and publications

Climate change and global warming are now the main environmental issue of the humanity. According to numerous monitoring and model studies, climatic changes significantly affect the stability of natural and engineering slopes and initiate landslide processes. Even now the mechanisms and intensity of this process in space and time is less clear, as well as the frequency of landslides in response to climate changes. In this sense, geoecological assessment is complicated by the search of interdependence between climatic factors, in particular atmospheric precipitation, and landslide processes in natural and artificial geosystems in spatial and temporal scales.

The study of the effects of climate change and the increase of atmospheric precipitation on intensification of landslides in Asia, South America and Africa was carried out on the basis of numerical simulation and back analysis of the landslides caused by climatic changes of temperature and precipitation, probabilistic landslide risk models at the regional level [1]. As a result of global warming, the frequency and intensity of precipitation, which is the main factor of rapid landslides, increases. These consequences of global warming and the development of EGP are difficult to predict and evaluate.

The landslides occur in the form of currents and slopes of the soil, the destruction of the surface geolayers, slides or shifts. Landslides have the characteristics of development and distribution for specific regions or even continents and play an important role in the evolution of landscapes. In many regions, they also pose a threat to local infrastructure and population [2].

Natural phenomena, including precipitation, melting of snow, temperature changes, earthquakes, volcanic activity, as well as anthropogenic activity are the dominant factors of the stability of slopes in the occurrence of landslides. The mechanisms by which climate change can affect landslides and reduce the stability of natural and engineering slopes are systematically studied through the evaluation of the impact of forecasted climatic changes on landslide processes [3]. Therefore, it is expected that in the future, climate change will continue to affect the stability of slopes at different time and geographical scales [4].

The study of the effects of climate on landslides is based on simulation results, empirical and combined approaches, long geomonitoring data, retrospective analysis of landslides, etc. The most commonly used is the empirical approach, which is based on the analysis of geographic and temporal context landslides, their conditions of occurrence, the frequency or speed of their development.

Many studies on the development of landslides are based on the use of the Global Circulation Model (GCM), which assesses the stability of the slopes, depending on the amount of rainfall. The model is mainly used for assessing shallow landslides in mountainous and hilly terrains [5]. Thus, the study of the intervals of repeatability of landslides in Spain and southern France during the 42-year period from 1971 in the hydro-geomechanical models of slope stability with allowance for precipitation revealed a significant decrease in the frequency of landslides due to a slight decrease in the average annual rainfall [6].

Similar results were obtained for mountainous areas in the northeast of Italy, where rainfall reduction and, accordingly, reduction of shear activity in spring periods. Studies in the south-east of England found that an increase of 11% of the average annual rainfall was predominantly in winter, as well as an increase by 13% in moisture evaporation, due to an increase in average annual temperature, altering soil moisture and reducing deviations in sloping slopes [7].

Geotechnical analysis to predict the future behavior of active landslide processes in the Basento valley (Southern Italy) using different climatic scenarios has shown that, with a decrease in average daily rainfall of 2.4% and an increase in average daily temperature by 0.04% for every ten years for the period 1965–2100 will reduce the level of groundwater by 8 mm and decrease the displacement of soil by 77–86 cm.

Thus, according to the results of the analysis, the expected changes in climate are not significant, but affect the dynamics of the landslide process in the consequence of a modest decrease in the number of annual precipitation and temperature rise [8].

In the study of expected landslides in the area of Orvieto (Umbria, Central Italy), it was established that the decrease in precipitation will slow down sloping processes in the slopes [9]. In [10], the worst scenario for the development of Taiwan's mountainous terrain was estimated, and it was found that with an increase in the amount of precipitation by 15% in the average annual maximum for the study period from 1960 to 2008 and for the period 2010–2099, the average intensity of the landslides will increase by 12%.

Summarizing, we note that provided above analysis of modern studies just briefly describes the complex dependence of the influence of various factors on the development of natural landslides that increase an interest to forecast of landslide danger also for selected regions in Ukraine.

Selection of previously unresolved problems

As a result of the analysis of diverse litrerature and research sources about natural landslides, we can assume that these exogenous geological processes are due to a number of factors, both natural and technogenic. However, in the vast majority of cases, soil landslide, in the role of a trigger factor, along with possible seismic influences, is the moisture of an massif of soils or rocks, which is due to the intensity of precipitation, raising the level of groundwater, melting snow, etc. Thus, the study of these EGPs requires careful analysis of statistical data on the intensity of precipitation in the studied areas, taking into account the terrain. These data are necessary for constructing an adequate mathematical model for forecasting the number of landslides.

The *objective* of this paper is to assess the natural and climatic conditions and predict landslide hazard in the the most landslide-prone regions of Ukraine taking into consideration geomorphological factors.

Presenting main material

Landslides are widely propagated on the territory of Ukraine. The main natural factors of the activation of landslides are meteorological, hydrological, hydrogeological, seismic, and the like. The influence of technogenic activity on the development of landslides is associated with external loads, trimming slopes during construction, additional landslide of landslides, caused by excessive irrigation, and the creation of dynamic loads. The development of the landslide process causes the failure and deformation of many industrial, engineering, residential and public buildings. The activation of landslides that develop on slopes of different genesis is often accompanied by erosion or abrasion, which are considered as factors of strengthening the main process.

According to the data of the State Research and Development Enterprise “Geoinform Ukraine”, there are 22,943 landslides were registered on the territory of Ukraine. Their number is constantly changed due to liquidation, merging of some close displaced forms or as a result of further formation of new ones. Activation of landslides is observed on the territory of almost all administrative regions, except of Volynska and Rivnenska regions, the territories that have no initial conditions for the development of landslide processes. The landslides are the most common on slopes and coastal areas, which are composed of soft rocks and soilos with the ability to deform. On the slopes of the river valleys, these processes develop with the deepening of the valley line and increasing the relief potential energy. The unilateral displacement of watercourses forms the asymmetry of river valleys. The development of mountainous landslides is due to the high elevation and steepness of the slopes, the presence of a thick layer of heavily rocks on them, and the intensive dismemberment of the relief. The most extensive development of landslides was recorded along the Black Sea coastal territories within the Odeska, Mykolaivska oblasts and Crimea regions, Azov Sea coast and in the basin of the most important Ukrainian rivers like Seversky Donets (Donetska oblast), the right bank of the Dnipro river and its right tributaries, in the basins of Uzh, Tisza rivers, Latoritsa, Rika, Tereblya, Teresva (Zakarpatska oblast) and the basins of Dniester, Prut, Cheremosh, Syrets, Stryi, Vyshnia rivers (Lvivska, Ivano-Frankivska, Chernivetska oblasts) [11].

The Fig. 1 and 2 present the dynamics of the number of landslides and total amount of precipitation in the most landslide-prone regions of Ukraine for the period 1982–2016.

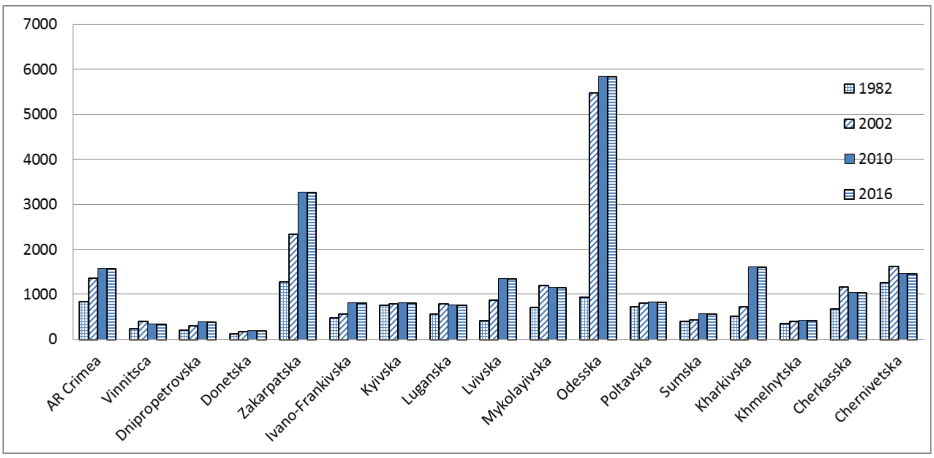

Fig. 1 – The number of landslides in the most landslide-prone regions of Ukraine (1982–2016)

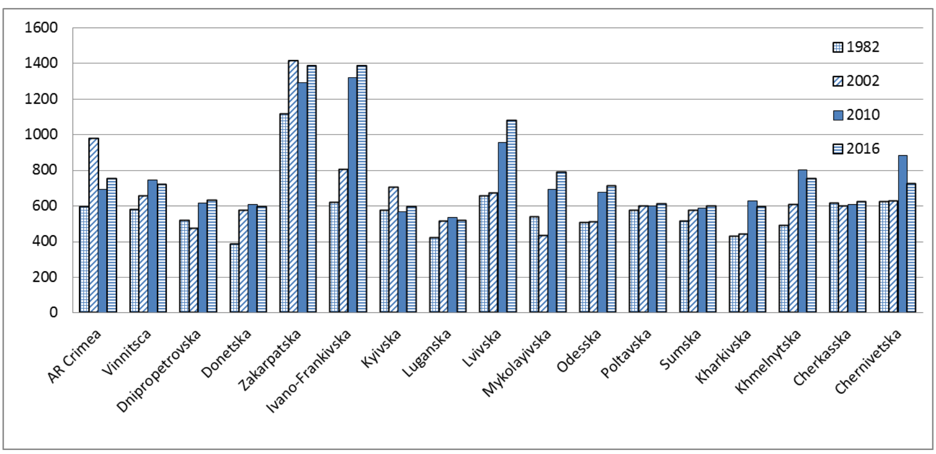

Fig. 2 – Dynamics of total rainfall in the most landslide-prone regions of Ukraine, mm/year (1982–2016)

The preliminary comparison of the above diagrams does not reveal a direct correlation between the amount of precipitation and the number of landslides in the regions of Ukraine. In addition, the landslide danger of the region, obviously, depends on the nature of the relief of the territory, so this factor should also be taken into consideration for a reliable forecast of the development of landslides along with precipitation.

It is known that excessive soil moisture occurs mainly due to atmospheric precipitation, which in the last 10 to 20 years has tended to increase due to global and regional climate change. This factor is mainly considered as a trigger in the development of the landslide process. Therefore, to determine the numerical characteristics of the influence of atmospheric precipitation on the number of displacements, the authors carried out a more detailed analysis of these indicators with the ultimate objective to identify a regression relationship between them.

Data on the number of landslides in the regions of Ukraine for the period from 1982–2016 were obtained on the basis of long-term observations of SRDE "Geoinform Ukraine" [11, 12]. In this case, the absolute values of the number of landslides were re-calculated to a specific value, which characterizes the number of landslides per 1000 km^2 of the area in a certain region of Ukraine. Data on the average annual rainfalls for the period 1982–2016 were obtained from the materials of the Hydrometeorological Center of Ukraine.

The correlation field for these indicators is shown in Fig. 3.

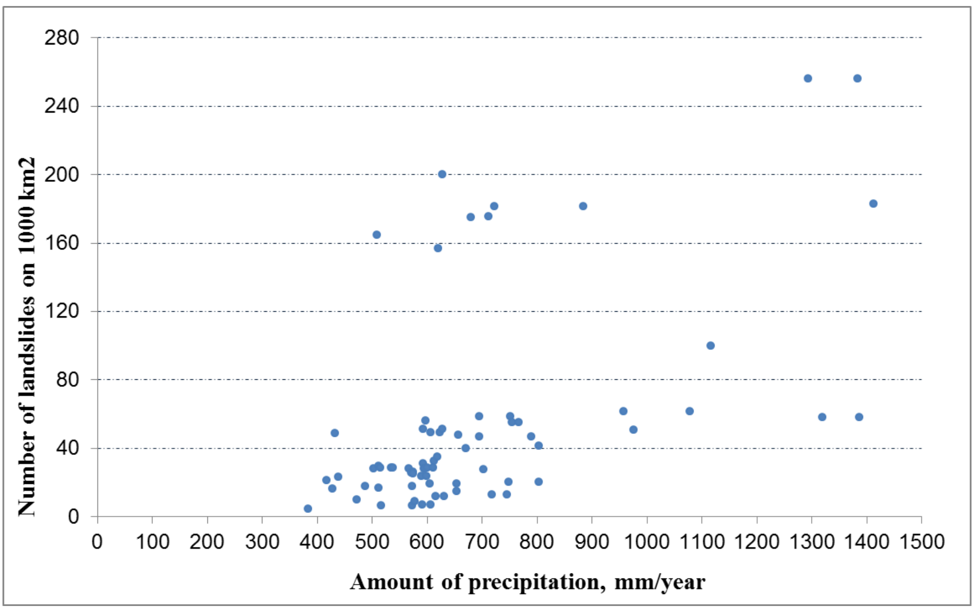

Fig. 3 – Field of the correlation for specific number of landslides from precipitation in the regions of Ukraine for the period 1982–2016

The obtained diagram shows a rather unequivocal increasing dependence of the number of recorded landslides on annual precipitation, although the vast majority of statistical data is distributed within the limits of precipitation values from 400 to 800 mm/year, and accordingly the number of landslides from 10 to 60 per 1000 km^2 of area characteristic of the most regions in Ukraine. In addition, there is some data striping observed, in particular a number of points grouped in the upper part of the field (150–250 landslides per 1000 km^2), while maintaining the tendency of increasing number of landslides from precipitation. This indicates a sufficiently influential factor which affects significantly on the number of landslides.

In the course of further analysis it was established that the overwhelming majority of the indicated data correspond to the regions for which the complex relief has characteristic features like significant elevation difference in mountain regions, terrain crossings etc. It plays a role of additional factor that not only affects the development and intensification of landslide processes but also serves as its precondition.

To eliminate the influence of this factor on the results of modeling the dependence of landslides on atmospheric precipitation, some possible components of this coefficient were identified, namely: the *altitude coefficient* (K_{alt}), the *relief density coefficient* (K_{dens}), and the *relief depth coefficient* (K_{depth}). Each of these coefficients varies from 1 to 3. The altitude coefficient is determined on the basis of zonal-statistical analysis of the distribution of the area of the studied region by the values of absolute heights (from sea level) and increases from 1 to 3 in accordance with the increase of the absolute alevation of the investigated area. The coefficient of relief density calculated in kilometers (km) characterizes the average width of the elementary object of the relief (hill, ravine, slope), and indicates the complexity of the relief and the area intersection. This indicator decreases from 3 to 1, respectively to increasing of the width of of the relief elementary object. The relief depth coefficient characterizes the excess of reservoirs level above the valley or ravine lines (in meters). This indicator increases from 1 to 3 respectively, due to increase of the height difference between the levels of ravines and reservoirs. Input data for calculation of the above mentioned coefficients were obtained from cartographic materials replaced on the geo-ecological web resource [13]. As a result of the zonal-statistical analysis of the above mapping materials, the averaged values of the relief effect coefficients were obtained for the number of landslides for each selected region of Ukraine.

Based on the averaged values of the three indicated coefficients, an integral coefficient of relief for each region is calculated. Since the role or significance of each of the given coefficients is difficult to determine at once, the integral coefficient of the relief influence (K_{int}) is defined as the product of three coefficients mentioned above, using the following formula (1):

$$K_{int} = K_{alt} \cdot K_{dens} \cdot K_{depth} \tag{1}$$

The value of the the integral coefficient of the relief influence and its components is given in the Table 1. According to the data obtained, the integral coefficient of influence of the relief varies from approximately 3 to almost 11.

The next step was to rate the number of shifts relative to the integral coefficient of influence of the relief Kr, which was performed by dividing the actual specific number of shifts into the corresponding integral coefficient of influence of the relief of the region. The relative (normalized) number of landslides associated with terrain topography is obtained. Such a relative indicator, in our opinion, should offset the effect of terrain on the formation of landslides under the influence of precipitation.

After the normalization of the input data for the number of landslides, the stratification of the normalized indicators by the height of the correlation field has been practically disappeared, and the dependence of the growth of these indicators on the size of precipitation became more apparent.

Table 1 – Integral coefficient of the relief influence (K_{int}) and its components for landslide-prone regions of Ukraine

The name of the administrative area (oblasts)	Altitude coefficient, K_{alt}	Relief density coefficient, K_{dens}	Relief depth coefficient, K_{depth}	Integral coefficient of the relief influence, K_p
AR Crimea	1.71	2.16	1.70	6.26
Vinnitsca	1.76	2.40	1.56	6.62
Dnipropetrovska	1.42	2.03	1.43	4.13
Donetska	1.49	2.16	1.57	5.02
Zakarpatska	2.18	2.19	1.95	9.28
Ivano-Frankivska	2.32	2.45	1.71	9.75
Kyivska	1.50	2.00	1.38	4.15
Luganska	1.57	2.13	1.68	5.61
Lvivska	2.10	2.26	1.73	8.19
Mykolayivska	1.32	2.01	1.46	3.87
Odesska	1.29	2.21	1.47	4.19
Poltavska	1.39	1.95	1.39	3.77
Sumska	1.46	1.96	1.55	4.43
Kharkivska	1.45	1.97	1.55	4.40
Khmelnytska	1.94	2.39	1.46	6.80
Cherkasska	1.62	2.16	1.43	4.98
Chernivetska	2.27	2.47	1.93	10.84

This allowed to start finding a certain regressive dependence between the indicated values. At the same time, in order to reduce the dispersion of normalized parameters, they were initially grouped at intervals of precipitation values with a step of 150 mm/year. Then, the mean values in these intervals were determined, reducing the correlation field to 5 points. Their location allowed to put forward the hypothesis about linear regression dependence. As a result, the trend is plotted in the form of a straight line. The data conversion procedure is presented in the diagram (Fig. 4).

So, the dependence of the number of landslides normalized by the integral coefficient of the relief influence, after averaging is well approximated by the linear regression equation $Y = 0.011\,X$ at a high determination coefficient of $R^2 > 0.97$. Characteristically, the regression line begins with a zero point of coordinates, which confirms the physical representation of landslides from amount of atmospheric precipitation, and further indicates the reliability of the detected dependence of landslides number on the amount of precipitation taking into consideration the relief of a particular region. Reliability or accuracy of the model is greatest in the range from 300 to 1500 mm/year. This rainfall range covers almost the entire territory of Ukraine, with the exception of arid areas where landslides occur rarely.

By replacing Y and X with the corresponding values in the resulting model, we obtain a regression dependence in the form:

$$N_{ls}/\,K_{int} = 0.011\,W, \tag{2}$$

where K_{int} – integral coefficient of the relief influence in a certain region; N_{ls} – the number of landslides in the region; W – amount of annual precipitation, mm/year.

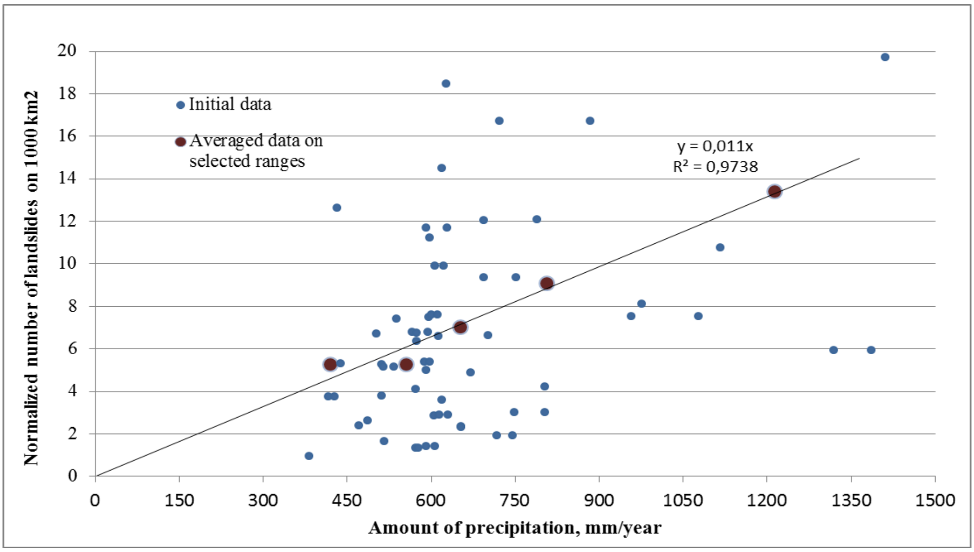

Fig. 4 – Correlation field for a specific number of landslides normalized by the integral coefficient of the relief influence from precipitation in regions of Ukraine

Note that the coefficient of the equation is 0.011, has a dimension of 1/(mm/year). To predict the number of landslides after precipitation it is worthwhile to rewrite the equation (2) in the form:

$$N_{ls} / W = 0.011\, K_{int}. \tag{3}$$

As we can see, the specific number of landslides per precipitation unit in the selected region of Ukraine with the corresponding K_{int} is a certain constant value that characterizes the potential landslide danger in a particular region and may be reflected on the map. At the same time, the forecast of the specific amount of precipitation (per 1000 km^2), depending on their actual number, for example after a heavy rainfall, can be estimated through the formula:

$$N_{ls} = 0.011\, K_{int}\, W \tag{4}$$

The results of determining the indicators of potential landslide hazard in the regions of Ukraine are summarized in the Table 2. It should be noted that the table includes just those regions of Ukraine in which landslide create real problem for environmental and technogenic danger at the regional level. According to the given data, the least value of the potential landslide hazard is pertinent to Poltavska oblast (24.65 landslides per 1000 km^2), the largest value for the Zakarpatska region (132.88 landslides per 1000 km^2).

Graphically, the results of the forecast of landslide danger in the regions of Ukraine are presented in the form of a map in Fig. 5. The ranges of potential landslides hazardousness are divided into 5 probationary intervals of landslides (landslides on 1000 km^2): extraordinary (more than 120), high (80–120), average (40–80), moderate (20–40), low (less than 20).

Table 2 – Results of determining the potential landslide hazard

The name of the administrative area (oblasts)	Precipitations on the regions *W*, mm/year*	Integral coefficient of the relief influence K_{int}, dimensionless	Regional potential landslide danger on preciptation ($N_{ls}/W = 0.011\ K_{int}$), landslides on 1000 km^2
AR Crimea	753.75	6.26	51.90
Vinnitsca	673.75	6.62	49.07
Dnipropetrovska	558.50	4.13	25.35
Donetska	538.50	5.02	29.76
Zakarpatska	1301.25	9.28	132.88
Ivano-Frankivska	1032.25	9.75	110.73
Kyivska	609.25	4.15	27.80
Luganska	494.50	5.61	30.52
Lvivska	840.25	8.19	75.71
Mykolayivska	613.50	3.87	26.12
Odesska	600.25	4.19	27.68
Poltavska	595.25	3.76	24.65
Sumska	568.00	4.43	27.65
Kharkivska	521.50	4.40	25.23
Khmelnytska	661.00	6.80	49.43
Cherkasska	610.00	4.98	33.44
Chernivetska	713.25	10.84	85.04

* Averaged values for the period 1982–2016

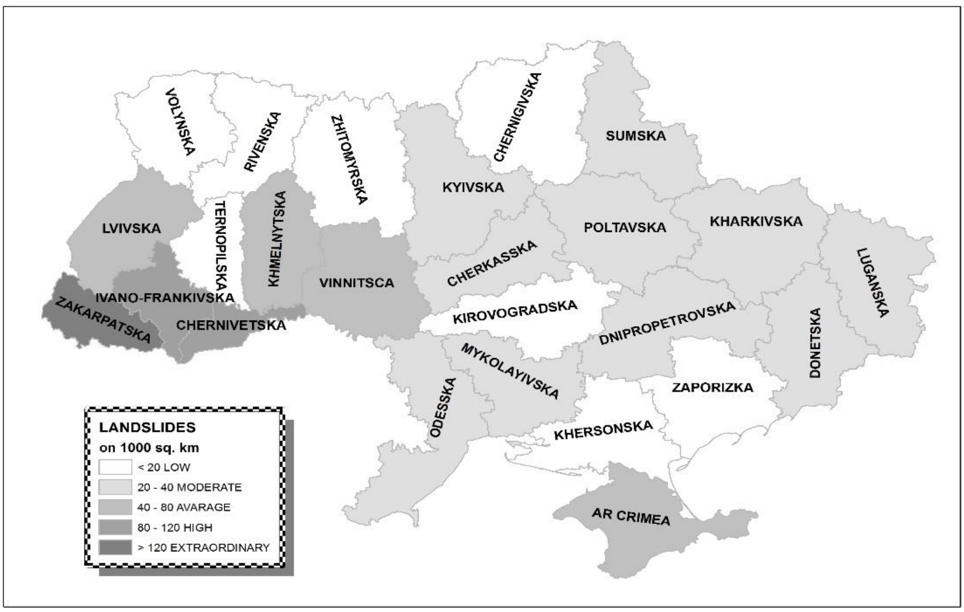

Fig. 5 – Results of the landslide hazard forecast in the regions of Ukraine

Thus, the most vulnerable territories in the development of landslide processes are Zakarpatska, Chernivetska, Ivano-Frankivska, Lvivska, Khmelnytska, Vinnytska oblasts and Autonomic Republic Crimea.

Conclusions

In this work, the forecast of landslide danger in the regions of Ukraine is carried out taking into consideration the climatic indicators and relief of the territory. The integral coefficient of the relief influence K_{int}, which is the product of the averaged coefficients of altitude (K_{alt}), relief density (K_{dens}), and the relief depth (K_{depth}) is suggested for estimation of landslide danger for regions of Ukraine. The K_{int} values vary in the range from 3 to almost 11. A linear regressive dependence of the specific number of landslides on the amount of precipitation is obtained. It determines the potential landslide hazard of a certain region of Ukraine presented graphically in the form of a map, and also allows prognose specific number of landslides (per 1000 km^2) in the region on the amount of actual precipitation.

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ОЦІНКА ВПЛИВУ КЛІМАТИЧНИХ І ГЕОМОРФОЛОГІЧНИХ ФАКТОРІВ НА РОЗВИТОК ЗСУВІВ

Анотація. Стаття присвячена дослідженню факторів, що впливають на поширення зсувів в Україні. За численними моніторинговими дослідженнями, зміни клімату суттєво впливають на стійкість природних схилів і спричиняють зсувні процеси. Актуальність роботи обумовлена багатофакторністю механізму утворення зсувів та складністю розвитку цього процесу у просторі та часі. Активізація зсувів відмічається на території майже всіх адміністративних областей України. В роботі встановлено зростаючу залежність кількості зафіксованих зсувів від річних опадів та рельєфу місцевості. Для найбільш зсувонебезпечних областей України розраховано інтегральні коефіцієнти впливу рельєфу та визначено рівні потенційної зсувонебезпечності. Отримано лінійну регресійну залежність між кількістю атмосферних опадів та чисельністю зсувів, яка дозволяє прогнозувати зсувонебезпечність по регіонах України. Результати прогнозу зсувонебезпечності представлено графічно у вигляді карти.

Ключові слова: екзогенні геологічні процеси, зсув, модель глобальної циркуляції, інтегральний коефіцієнт впливу рельєфу, зсувонебезпечність.

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У роботі встановлено зростаючу залежність кількості зафіксованих зсувів від річних опадів та рельєфу місцевості. Для найбільш зсувонебезпечних областей України розраховано інтегральні коефіцієнти впливу рельєфу та визначено рівні потенційної зсувонебезпечності. Отримано лінійну регресійну залежність між кількістю атмосферних опадів та чисельністю зсувів, яка дозволяє прогнозувати зсувонебезпечність по регіонах України. Результати прогнозу зсувонебезпечності представлено графічно у вигляді карти.

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Kovrov O., Kolesnik V., Buchavyi Yu. **Evaluation of the influence of climatic and geomorphological factors on landslides development** // Environmental safety and natural resources. – 2018. – Issue 1 (25). – P. 52–63.

The increasing dependence of the number of recorded landslides on annual precipitation and relief is established. For the most landslide-prone regions of Ukraine, the integral coefficients of the relief influence have been calculated, and the levels of potential landslide risk have been determined. Linear regression dependence between the amount of atmospheric precipitation and the number of landslides has been obtained, which allows predict landslide hazard in the regions of Ukraine. The results of the calculations are presented graphically in the form of a map.

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