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The Long-Term Prediction of Landslide Processes within the Precarpathian Depression of the Cernivtsi Region of Ukraine

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ABSTRACT

The purpose of this publication was the long-term forecasting of the landslide processes activation for the territory of the Precarpathian depression within the Chernivtsi region, taking into account the complex effect of natural factors. On the basis of statistical analysis and processing of long-term observations of landslide activation and natural time factors in particular solar activity, seismicity, groundwater levels, precipitation and air temperature, the relationship was analysed, the main periods of landslide activation were determined, the contribution of each time factor to the complex probability indicator of landslide development was estimated and long-term forecasting was carried out. An analysis of the influence of geomorphology on the landslide development was performed by using GIS MapInfo. By means of cross-correlation, Fourier spectral analysis, the periodicities were analysed and the relationships between the parameters were established. It was found that the energy of earthquakes precedes the activation of landslides by 1 year, which indicates the "preparatory" effect of earthquakes as a factor that reduces the stability of rocks. The main periodicities of the forecast parameters of 9–11, 19–21, 28–31 years were highlighted, which are consistent with the rhythms of solar activity. The forecasting was carried out using artificial neural networks and the prediction function of the Mathematical package Mathcad, based on the received data, the activation of landslides is expected in 2023–2026, 2030–2035, 2040–2044 with some short periods of calm. The main periods of the dynamics of the time series of landslides and natural factors for the territory of the Precarpathian depression within the Chernivtsi region were determined, and a long-term forecast of landslides was made. Taking into account the large areas of the spread of landslide processes, forecasting the likely activation is an important issue for this region, the constructed predictive time models make it possible to assess the danger of the geological environment for the purpose of early warning and making management decisions aimed at reducing the consequences of a natural disaster.

Keywords: engineering-geological areas; landslides; statistical methods; factors; time series; forecast.

INTRODUCTION

The problem of studying the natural factors of the landslide processes development and their forecasting in time is relevant for Ukraine, since these exogenous geological processes are one of the most common, occupy large areas, as well as cause irreparable damage to the environment, population, transport and energy communications. The regional forecast of geological processes assumes the establishment of the possibility of occurrence, development, intensity, scale and other parameters under the influence of mutually determined natural and man-made factors within a large area, a territory of the same type in terms of the geological structure, geomorphology, and hydrogeological conditions. With regional forecasts, it is usually not possible to indicate specific types, places and parameters of geological processes and phenomena, so their background characteristics with general patterns of development are provided by Kuzmenko et al. [2016].

Landslides are exogenous geological processes of rock destruction under the action of gravitational forces, characterized by significant areas of distribution and volumes of landslide masses.

According to the latest Information Annual Journal on the intensification of dangerous exogenous geological processes, according to, EGP (exogenous geological processes) monitoring data at the beginning of 2020, there are 22,937 landslides in Ukraine with an area of 2,140.9 km^2. The Chernivtsi region is one of the most affected by the mentioned processes – 1,467 units, with an area of 760.2 km^2 (Information, 2020).

At the state level, laws and information and analytical systems are being developed to prevent and reduce the impact of negative consequences from the spread of exogenous geological processes, in particular landslides. Currently, the law of Ukraine "National program for the development of the mineral and raw material base of Ukraine for the period until 2030" dated April 21, 2011, No. 3268-VI is in force, in which, among other tasks, the importance of "assessment of ecological and geological conditions and the possibility of occurrence of emergency situations of natural origin within a specific territory and the forecast of these phenomena for the future is highlighted; determination of features of the development and forecast of dangerous endogenous and exogenous geological processes and phenomena". Currently, the State Research and Production Enterprise "State Information Geological Fund of Ukraine" (SRPE "Geoinform of Ukraine") implements the state environmental monitoring system as part of the Government Information and Analytical System for Emergency Situations (GIAS ES) and uses the automated information system "Exogenous Geological processes" for processing information, analysing the state of exogenous geological processes and preparing the information on the possibility of emergency situations related to their development. According to the results of the completed works, based on the monitoring data of EGP, Information Annual Journals are created on the activation of dangerous exogenous geological processes on the territory of Ukraine.

The activation of landslides is a problem for other parts of Ukraine and needed for ecological risk assessment researched by Kasiyanchuk et al. [2021]. In various countries of the world, programs for early warning of possible danger and overcoming the consequences of the activation of landslides are being developed and implemented. Such programs exist in the USA and Europe. The guidelines for landslide monitoring and early warning systems in Europe have been developed by the International Geohazards Center (Norwegian Geotechnical Institute, Oslo, Norway) with the aim of monitoring, analysing and prompting the occurrence of landslides. The Norwegian Landslide Prediction and Warning Service works in close cooperation with the Flood Forecasting Service. Hydrometeorological forecasting models are created on the basis of data from hydrological stations, weather stations, the historical series of activation of landslides, floods, and extreme values of precipitation. In order to reduce economic and human losses from a potential disaster, the service conducts a daily landslide hazard assessment at the regional level (for a county and/or a group of municipalities) by Krøgli et al. [2018]. In the USA, there is a National Landslide Program (LHP) to collect information, respond to emergency situations, and conduct scientific research. The US Geological Survey is developing and using a real-time and near-time landslide monitoring system to ensure timely operational response at the first signs of a catastrophic rockslide by Reid et al. [2012]. At the Fifth World Landslide Forum (WLF5) (5th World, 2021), which took place on November 2–6, 2021, Kyoto (Japan), the agreement "ISDR-ICL Sendai Partnership 2015–2025" on landslide risk reduction and the Kyoto Commitment were adopted Action Against Landslides 2020 (KLC2020) on the global promotion of understanding of the occurrence of landslides, in particular, through the improvement of technology for monitoring, analysis, and modelling of early warning of landslides taking into account natural aspects; investigating the impact of climate change on rain-induced landslides and developing effective rainfall forecasting models to provide early warning.

Taking into account the engineering and geological zoning of Ukraine [Demchishin, 1992], the patterns and relationships of the spread and development of landslide processes in the Precarpathian region within the Chernivtsi region were studied. The relevance of the research is related to the significant areas affected by landslides within this territory; therefore, the study of the conditions of their development is an important stage in the development of forecasting methods in order to reduce the negative consequences of landslides on the environment. The Cadastre of landslides in the Chernivtsi region is formded by SRPE "Geoinform of Ukraine". Data from literary and Internet sources on solar, seismic activity, groundwater levels, and climatic parameters at the Chernivtsi weather station during 1960–2021.

STUDY AREA

The geological, tectonic, and geomorphological structure are known to be constant factors in the development of landslide processes [Kasiyanchuk et al., Davybida et al., 2018; 2016; Shtohryn et al., 2021], as well as the seismic regime of the area and hydrogeological conditions. According to the scheme of regional-zonal engineering-geological zoning by Klymchuk et al., [2008], most of the territory of the Chernivtsi region belongs to the Carpathian mountain-fold system (Ж) [Ponomar, 1969], within which a significant area is occupied by the Precarpathian depression (Figure 1).

The Precarpathian depression is composed of a layer of Neogene sedimentary deposits, which are represented by a sandy-clay salt-bearing layer, marls, sandstones, conglomerates and shales. Rocks are dislocated. The Neogene is overlain by Quaternary alluvial and diluvial deposits, which accumulate in the Prut and Seret river valleys and are the environment for the development of landslide processes. In total, 744 units with an area of 352.26 km^2 have been registered, and the rate of damage by landslides is 7.8% [Herenchuk, 1978].

One of the reasons for the development of landslides is the high density of the river network of 1.11 km/km^2. Mapinfo GIS tools were used to calculate distances to the nearest river, which shows that 374 landslides are located at a distance of up to 400 m from watercourses. Thus, their development is affected by the complex action of both river erosion during floods, when the lower part of the slope is washed away, and excessive wetting of the upper layer of rocks during intense, long-lasting precipitation. The absolute marks of the landslides vary within 138–715 m, the steepness of the longitudinal profile is 6–40°, and they are characterized by large dimensions – length up to 3500–5250 m, width 1300–2100 m, area 5–11 million m^2, the capacity of landslide masses from 4.0 to 15.0 m.

MATERIAL AND METHODS

Solar activity

To date, there is no unambiguous interpretation of the Sun's influence on the mechanism of the landslide process development. It can be assumed that it manifests itself indirectly, through the transfer of energy, as well as the effect on circulation processes in the troposphere. In particular, in [Laurenz et al., 2019], a study of the relationship between average monthly data on atmospheric precipitation and the number of sunspots in European countries was conducted and it was found that abnormal precipitation is delayed by 3–4 years relative to the sunspot minimum. In another publication byNazarevich et al. [2011], a connection was established between the times of occurrence of the Carpathian earthquakes with M>3 and cycles of solar activity. The well-known scientist Rudko H. I., having researched forecasting of landslide processes, noted that landslide processes occur cyclically and are controlled by solar activity [Rudko et al., 2021].

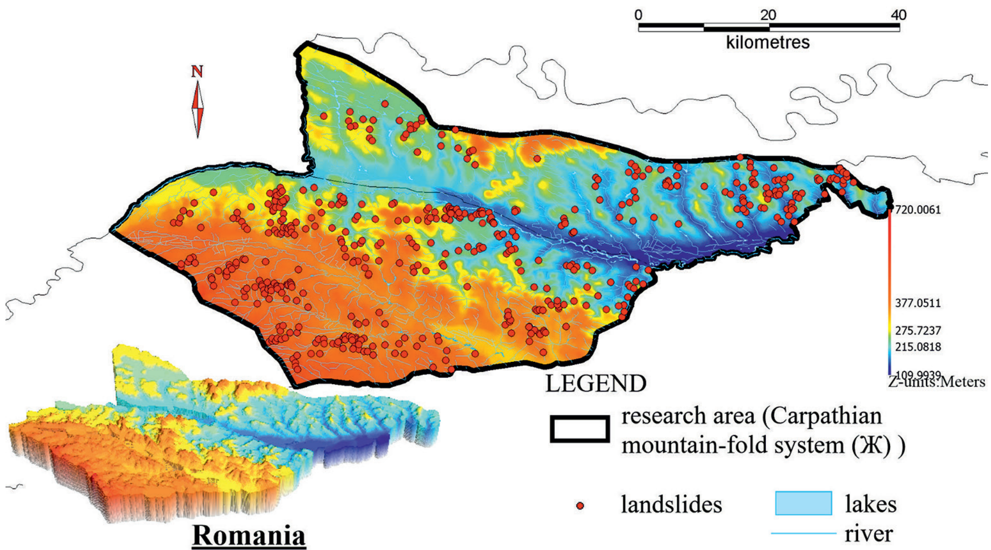

Figure 1. Methodology of analysis of hydrogeological data with gaps

Air temperature and atmospheric precipitation, affecting the upper layer of the geological environment, contribute to relief-forming processes such as weathering, erosion, and also form floods. The dynamics of precipitation and air temperature are illustrated in Figure 2.

In addition to the mutual influence of temperature and precipitation, it should be noted that there is no regularity in their correlation. Therefore, the temperature factor, as an independent factor, is taken into account when analysing the series of activation of landslides. From general physical considerations, this factor is additionally associated with the landslide activity in spring due to its influence on the condition of the snow cover, whereas in summer – on intensive evaporation, as well as on the weathering of rocks.

The processes of global warming are clearly highlighted on the graph of average annual temperatures. The revealed positive linear trend (Figure 3) indicates an increase in temperature by 0.4°C per decade or by 2.5°C over the whole period of the study. Such dynamics of air temperature growth accelerates the processes of rock weathering due to the formation of new cracks through which atmospheric precipitation infiltrates.

The analysis of the total annual precipitation shows that for the period from 1960 to 2021 the average multi-year total annual precipitation is 640 mm, and the range of change varies from 379 mm (2015) to 890 mm (1974). The wettest season is the summer period from May to August, when half (331 mm) of annual precipitation falls. The dynamics of the precipitation regime during the studied period shows higher amplitude of abnormal rains for the period 1965–1980 than for the period 1988–2021, which confirms the climate change over the last thirty years (Fig. 1). When precipitation exceeded 640 mm by 15 per cent or more, a massive activation of landslides was registered (1965 – 825 mm, 1969 – 844 mm, 1970 – 832 mm, 1974 – 890 mm, 1980 – 806 mm, 1991 – 715 mm, 1998 – 747 mm, 2001 – 760 mm, 2005 – 831 mm, 2008 – 731 mm, 2010 – 840 mm), in 1991 there was also a massive activation of landslides, then in July, 321 mm of precipitation fell against the norm of 91 mm.

Groundwater. During abnormal rainfall, there is a strong fluctuation of groundwater. The rocks below the groundwater level are fully hydrated, have high pore pressure, and are a potential mirror of rock sliding [Davybida et al., 2018; Tymkiv, 2019]. Groundwater is confined to sandy, sandy-loamy rocks (in river valleys) and pebbly deposits with sandy and loamy aggregates, covered by loess loams and, directly, in loess loams. In the Prut valley and its tributaries, modern alluvial formations are represented mainly by fine- and medium-grained sands, pebbles, and rarely loams. The depth of these waters is from 0 to 11 m (more often – 3–4 m) [Ruban, Nikolishyna, 2005].

Seismic impact is manifested in the violation of slope stability due to the propagation of cracks of different directions and sizes, while the strength of rocks that are in a water-saturated state changes the most. Landslides, primarily landslides-currents, may occur in such rocks under seismic influence when the stability of the

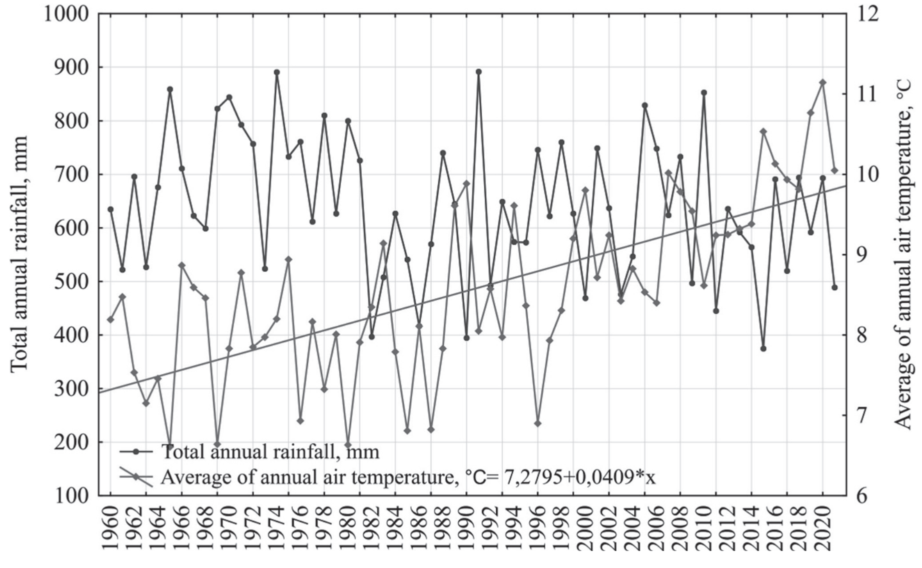

Figure 2. Graphs of the dynamics of weather parameters at the Chernivtsi weather station (1960–2021)

slope is disturbed. To take into account the influence of seismicity on the activation of landslide processes, a series of earthquakes in the Precarpathian depression, as well as adjacent territories (Romania, Hungary) were analysed. In general, the Precarpathian depression is characterized by sporadic and differentiated seismicity with earthquakes of relatively low magnitude (magnitude up to 3.5 points, shaking intensity up to 5–6 points) [Nazarevich, 2018]. The Prut and Seret rivers, on the banks of which landslides develop, flow in tectonic fault zones, which are the environment for the occurrence of earthquakes with epicentres at shallow depths.

In the works [Kasiyanchuk et al., 2018; Shtohryn et al., 2020; Hablovska et al., 2022] detailed structured main approaches were used to select the methods of temporal forecasting of landslides and the factors that initiate them. As a theoretic basis for the analysis of factors that changes over time are the complex of classical statistical methods, special heuristic procedures and adaptive statistical methods, including:

- correlation-regression analysis;
- spectral analysis;
- analysis of integral curve anomalies;
- analysis within the 11-year solar cycle;
- adaptive models.

The prediction of the landslide activations within the Transcarpathian inner depression was performed under the following methodology [Kuzmenko et al., 2016]:

1) selection of natural temporal factors that influence on the development of landslides;
2) checking of temporal series for the presence of the trend, if the latter is significant it should be deleted;
3) normalization of data series to bring them to the non-dimensional values;
4) an auto-correlation function is calculated for the distinction of main periods for each series;
5) calculation of the cross-correlation function between sliding activity and factors that influence its development. The value of displacement of certain factors over time is estimated to achieve the phase synchronism while assuming the delay of landslide activations regarding the initiating factors;
6) confirmation of the correct choice of factors and determination of information capacity of each of them by means of correlation coefficients *Rnp* (1):

$$R_{np_j} = \frac{\sum \left| r_{i,j} \right|}{\sum_j \sum_i \left| r_{i,j} \right|} \cdot 100\% \quad (1)$$

where: $r_{i,j}$ – a coefficient of pair correlation between *i, j* variables in the matrix of coefficients of correlation of factor characteristic.

7) calculation of the integrated index, which takes into account the complex effect of all factors affecting the development of landslides (2):

$$\Phi_i = \sum_{j=1}^{m} X_{ij}^{norm} \quad (2)$$

where: *m* – number of temporal factors, *i* – a year of observation.

A long-standing temporal prediction is performed. Then, using the normalized Laplace function, the integral indicator was calculated into the value of the probability of landslide processes [Shtohryn et al., 2020] (3):

$$f(\Phi_{ij}) = \frac{1}{\sqrt{2\pi}} \cdot e^{-\frac{(x_{ij}^{норм})^2}{2}} \cdot \max(f(\Phi_{ij}))^{-1} \quad (3)$$

In order to reduce individual emissions, the time series of the complex integral indicator was adjusted at two points.

RESULTS AND DISCUSSION

Statistical processing of the series of landslide activation and the factors that provoke it begins with the determination of the theoretical law of distribution according to the Kolmogorov-Smirnov criterion. Almost all parameters obey the normal law (total annual precipitation, average annual air temperature, average annual groundwater levels). However, solar activity is distributed according to Weibull's law, and the total annual energy of earthquakes is subject to a lognormal distribution. In order to bring the distribution closer to normal, the values were logarithmized.

Landslide forecasting was carried out according to the algorithm described in the following sequence: identification of the trend component and transformation of the range of average annual air temperature, reduction of data to dimensionless values by standardization, determination of the rhythmicity of factors using the autocorrelation function. It resulted in the following main harmonics: activation of landslides 2, 10–11, 17, 19, 21–22, 32; solar activity 9–13, 20–23, 31–34; total annual precipitation 2–5, 9, 17, 25, 27, 29–32; average annual air temperature 7–8, 11, 15–18, 25, 26, 33; total annual energy of earthquakes 1–3, 14, 16–18, 30–32; groundwater level 1–4, 10, 11, 20–21, 25–29. Common periodicities of 2, 9–11, 17, 18, 25–29, 32 years are observed, which are multiples of the periods of activity of the Sun and the Moon (18.6 years) [Pona et al., 2016]. Cross-correlation analysis was used to assess the degree of displacement of the series of time factors compared to the series of landslide activation (Figure 3).

The results show that relative to the series of landslide activation, the average annual air temperature is behind by 1 year, and the total annual energy of earthquakes is ahead by 1 year (indicating a previous effect on the development of cracking and stress in rocks). The rest of the parameters are correlated without changes. After accounting for displacements, correlation coefficients were additionally determined (Table 1).

Correlation analysis confirms a close relationship between the development of landslides and anomalous quantity of precipitation (0.44). All factors have a direct correlation with the series of landslide activity of the Precarpathian region with more or less uniform influence (0.17–0.26). The contribution of each factor to the integral indicator: Wolf number 12.9%; total annual rainfall 32.9%; average annual temperature 19.3%; average annual levels of groundwater 18.3%; the total energy of earthquakes is 16.5%. In general, the weight coefficients show an even contribution. The most significant periodicities of the complex indicator of landslide hazard were revealed: 9–11, 19–21, 28–31 years, which are multiples of cycles of solar activity and are confirmed by the

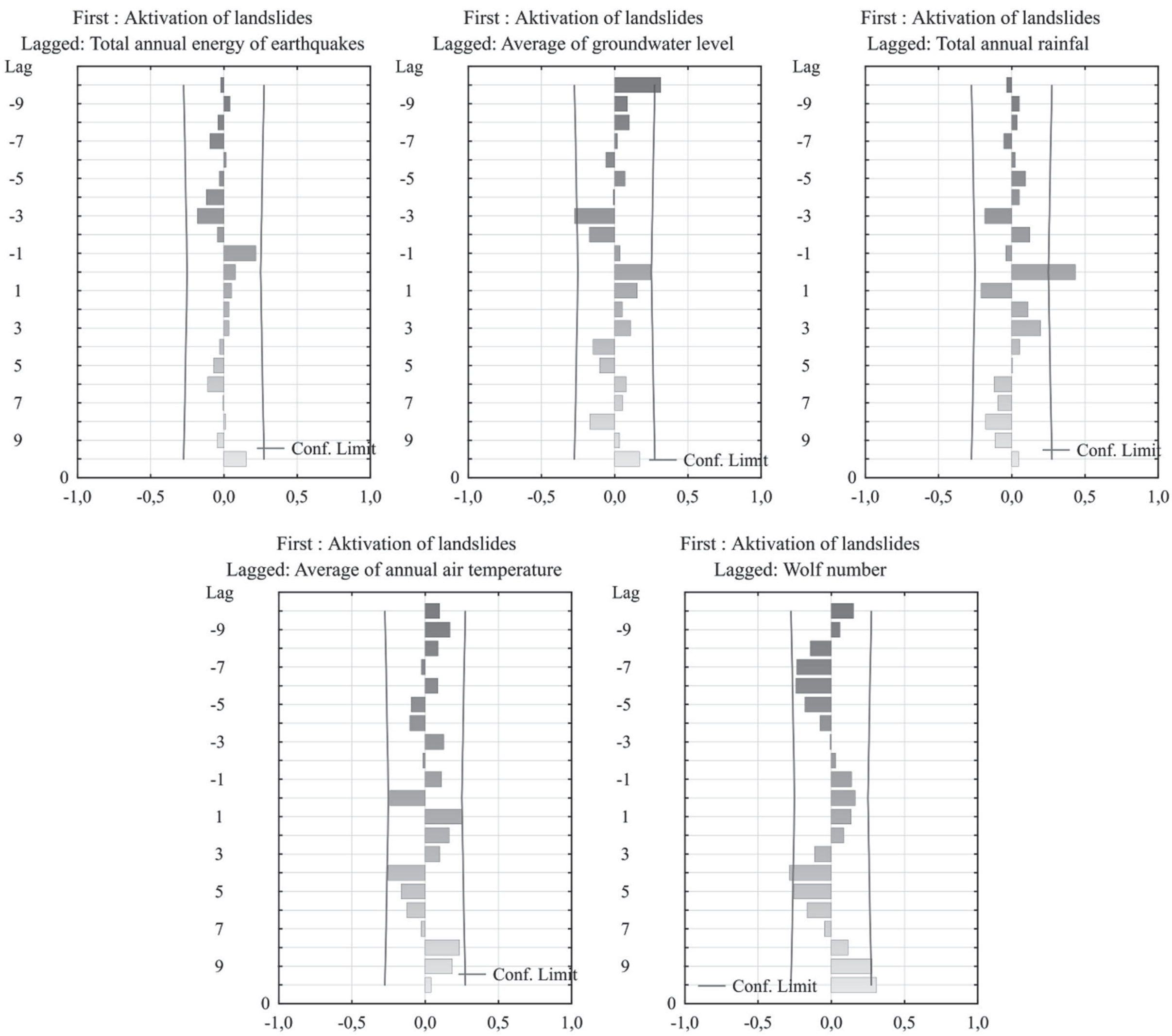

Figure 3. Cross-correlation functions between activation of landslides and influence factors

Table 1. Correlation matrix of shifted factors regarding the activation of the landslides

Factors	1	2	3	4	5	6
Activation of landslides (1)	1.00	0.17	0.44	0.26	0.22	0.24
Wolf number (2)	0.17	1.00	0.05	-0.02	-0.03	0.16
Total annual rainfall (3)	0.44	0.05	1.00	-0.01	-0.10	0.21
Average of annual air temperature (4)	0.26	-0.02	-0.01	1.00	-0.07	0.10
Total annual energy of earthquakes (5)	0.22	-0.03	-0.10	-0.07	1.00	-0.14
Average of groundwater level (6)	0.24	0.16	0.21	0.10	-0.14	1.00

autocorrelation function as well as Fourier spectral analysis (Figure 4). Forecasting was carried out in two ways: the 1st method is a neural network with a multilayer perceptron architecture, which creates connections between the time series of the calculated complex landslide hazard indicator and the required forecast at the output with the help of learning when the weight coefficients for each connection between neurons are taken into account so that the model can best recognize the temporal dynamics of the data (periodicity of multi-year activation of landslides is 28–31 years) and predict its behaviour in the future. The 2nd method is the Predict function of the MathCad integrated mathematical package, which is used when forecasting periodic data (Figure 5).

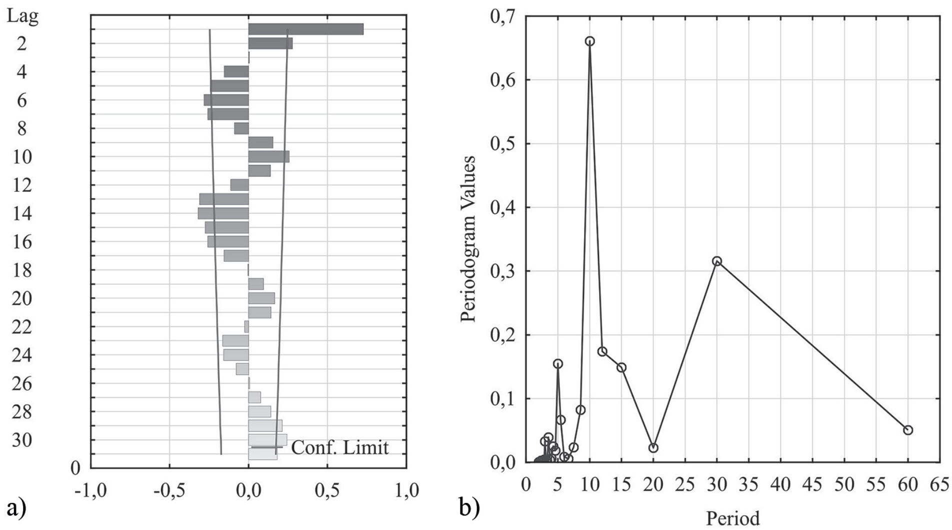

Figure 4. (a) Autocorrelation function of a complex index of long standing activation of landslides; (b) spectral analysis of a complex index of long standing activation of landslides

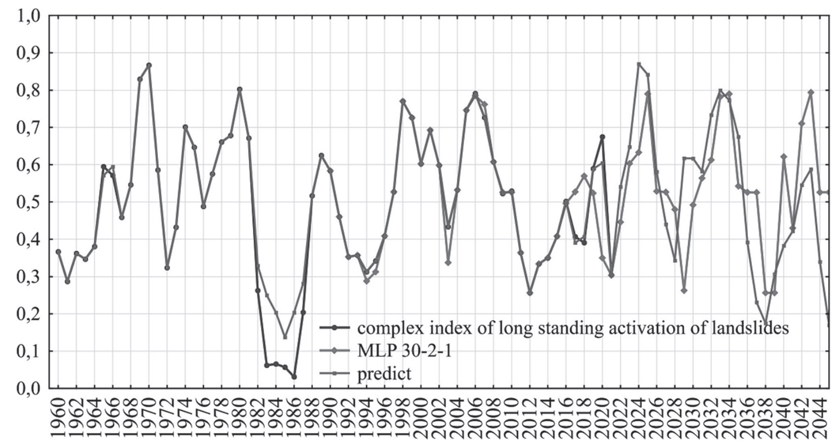

Figure 5. The graph of the complex index

The forecast time is equal to a third of the size of the original series. The degree of reliability was determined through the correlation coefficient of forecast periods (0.76). A comparison of the MLP and Predict models shows that the two methods generally synchronously reflect the main trends of the series. The forecast by the multilayer perceptron model with two hidden neurons highlighted the increased possible probability of occurrence of landslides equal to 0.6 and higher for the period 2023–2026, 2030–2035, 2040–2044. The predict function generally repeats the periods of the previous forecast with a shift of the maximum probability by 1–2 years.

It was determined that the main periods of dynamism of the time series of landslides and natural factors of their activation and based on these data a long-term forecast of landslides was made for the Precarpathian area within the limits of the Chernivtsi region. The constructed forecast time model allows predicting the probable development of landslide processes, taking into account the peculiarities of the natural conditions of the Precarpathian area in the territory of the Chernivtsi region. The forecasting results can be used for a timely warning about the likely activation of landslide processes in the territories with related structural-geological, hydrological, and seismic conditions.

CONCLUSIONS

Climate changes are almost the main factor determining the activation of landslide processes. This requires finding and improving the structure of temporal data analysis. Complex geological conditions, anthropogenic load initiate the development of landslide processes more and more.

Thus, as a result of the conducted research, it can be noted that the development of most landslides is influenced by erosion. It was proven that the main catalyst for the landslide development in the region is abnormal precipitation, the total annual energy of earthquakes is ahead of the time series of landslides by 1 year, which indicates the “preparatory” effect of earthquakes as a factor that reduces the stability of rocks. Based on autocorrelation, cross-correlation, and Fourier spectral analysis, the main periodicities of time factors are highlighted – 9–11, 19–21, 28–31 years, which is consistent with the rhythms of solar activity. The dynamics of the long-term forecast shows a probability of 0.6 and more of the occurrence of landslides for the period 2023–2026, 2030–2035, and 2040–2044. As a logical continuation of the long-term analysis of landslide activity within the Carpathian region of Ukraine, it is proposed to separate forecasting zones in the form of engineering-geological areas. It was proven that the change in engineering and geological conditions, temperature, groundwater level, precipitation significantly affects the time component of the sinusoid – Solar activity (Wolf number). The time difference in periodicities between individual areas forces to review the existing methods of forecasting landslides at the global level. This requires the unification of the territory according to its hydrogeological and climatic features, which serves as the subject of further research.

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