Carpathian Journal of Earth and Environmental Sciences, February 2020, Vol. 15, No. 1, p. 157 - 166; DOI:10.26471/cjees/2020/015/118

THE PROBLEM OF LONG-TERM PREDICTION OF LANDSLIDE PROCESSES WITHIN THE TRANSCARPATHIAN INNER DEPRESSION OF THE CARPATHIAN REGION OF UKRAINE

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Abstract: Nowadays, within the Carpathian region (Ukraine), the main factor characteristics determining the temporal prediction shall be the sunspot activity (the Wolf number) and seismic activity (the total energy released in earthquakes). Engineering-geological zoning, as a method of representative analysis of geological data, is used as a spatial component, which includes the grouped structural-tectonic, geomorphological, morphometric and climatic features of a specific engineering-geological area. The article proposes a new approach to the temporal prediction within individual engineering-geological areas. For the selected study area, we have performed a statistical analysis of factor characteristics, which are a measure of factor determinability to choose the optimal model of long-standing temporal analysis within the engineering-geological areas of the Carpathian region of Ukraine. To substantiate the methodology of spatial-temporal analysis, we have patterned the data regarding the landslide activity, sunspot activity (the Wolf number), groundwater levels, an average of annual temperature, seismic activity (total energy released in earthquakes), an average of annual rainfall within the certain engineering-geological area of the Transcarpathian inner depression. Statistical analysis of data based on the consistent study of the factor characteristics. At the same time, we have performed the correlation analysis with the allocation of autocorrelation functions as a basis for considering temporal dynamic features of each of the factor characteristics. Based on them, we have drawn up the periodograms of main climatic factors such as an average of annual rainfall, an average of annual temperatures and an average of groundwater level. Under the spectral analysis, we distinguished the main periodicities by summarizing the data at the point of landslide manifestation and three points in the form of a function of the temporal series. There was a comparison of the temporal series based on PREDICT function of MathCad integrated mathematical package and neural network prediction. We determined that the basic frequency components of temporal activation dynamism of landslide processes for certain engineering-geological area of the Carpathian region of Ukraine can be divided into the cycles having a period of small and large activation. Under the long-term prediction, the main cycle of the landslide activity is 28 years. In particular, the neural network prediction distinguished the highest probability of the landslides in 2020-2021 of the first half cycle (2019-2023) and 2028-2030 of the second half cycle (2027-2032). The prediction based on Predict function highlighted the period of 2020 – 2030. Therefore, the next massive activation of the landslides will be in 2020-2023 and in 2028-2030.

Keywords: temporal prediction; factor characteristics; engineering-geological areas, landslides; the Transcarpathian inner depression, the Carpathian region

1. INTRODUCTION

A multifactorial structure is a basis for the approaches to the study of exogenous geological processes. The factors selected for the study area and the type of exogenous geological process shall be expressed as a factor characteristic, a measure of the factor determination.

The dynamism of the landslide process over time is perhaps the biggest scientific problem that needs a constant study. The factor approach to the study of landslides gave us the possibility to substantiate and, more to the point, to identify the group of factors that have dynamic changes and can be catalysts for their development. In scientific work by Kasiyanchuk et al., (2018), Pona et al., (2016), the authors first outlined in details the main approaches to choose the temporal prediction methods and mainly the factors initiating them.

However, while analysing the temporal model, the essence of the “prediction” somewhat loses one’s meaning as the environmental changes are too dynamic and the climate variations are fundamental in searching the new factors to adjust the prediction model. The analysis presented in the monograph by Kuzmenko et al., (2016) identifies such probabilistic changes arose due to the main dynamic climatic fluctuations. The temperature increase results in a change in atmospheric pressure, humidity and cloudiness. It can ultimately affect the accuracy of the prediction models. We should understand that dynamism is a basis to create a prediction. The changes with a cyclical nature, such as the Sun activity, provide the main sine curve to study landslides in their long-standing analysis.

Table 1 presents the main results by Kuzmenko et al., (2016) of the temporal prediction of the landslide processes with distinguishing the main periods of their possible activation.

Table 1. Main periods determined in the long-time prediction of the landslide processes (Kuzmenko et.al, 2016)

Factors determined the prediction	Area of the prediction performed	Determined periodicity, in years (highlighted main periodicities)	Years of activation according to the prediction
Activity of landslides	Transcarpathian region	**19-20** 9-13, 18-21, 27-30	2019-2021
Number of active landslides	The mountainous part of Peredcarpattia	4-6, **10**, 18-21, 30	2017, 2027

To evaluate the accuracy of the prediction model, we should analyse the existing approaches, where both the factors selected for analysis and the repetition of the process would be presented. The landslides, unlike the other exogenous geological processes, have a clear temporal dependence on the Wolf number and earthquakes. Such studies had a significant influence upon the option of additional factors, which may qualitatively describe the prediction model since the offset from peaks of the rise or fall of the Sun’s activity is unstable and conditional over time. It gives us prerequisites to consider the solar activity, which is expressed in the Wolf number, as a non-constant, not only a basic factor characteristic but its main dynamic change over time.

There is no unique interpretation of how the Sun changes its activity. They mainly consider the short-term (10-11 years) and long-standing (22-30 years) cycles. But this raises the problem related to the long-time prediction, namely taking into account the changes in the magnetic field of the Sun and its influence over the Earth and landslide processes in particular.

The most complicated are tasks of the temporal prediction. One of the methods of studying exogenous geological processes for the long-term prediction is described in the scientific work by Sheko & Krupoderov (1984). It is noted, that, in the absence of the long-standing temporal series of observations, the regional temporal prediction of exogenous geological processes (EGP) is based on a detailed study of the conditions of the landslide development in interaction with the whole complex of existing factors.

Rudko in his scientific work (1991) presents the temporal prediction of active landslides for Peredcarpattia, based on the harmonic analysis. In this case, the author has considered the development of landslides-flow as an autocorrelation process characterized by a certain repeating pattern depending on the rainfall regime. It is specified that the periods of mass activation of the landslides begin in 2-3 years after the earthquake.

The idea that extreme rainfall values are a trigger for landslide processes has been developed in several publications. Thus, the scientific work by Guzzetti et al., (2007) based on the data on the amount and duration of rainfall has established that duration of rainfall is more important for landslide activation than its intensity in the regions with the temperate climate in the middle latitude, whereas in the mountainous areas, the intensity is more important than duration. Using the temporal series of rainfall, the scientific work by Ching & Liao (2006) has predicted the landslides on Taiwan’s mountain roads, in compliance with the Gaussian distribution model and discrimination analysis. The scientific work by Capparelli & Tiranti (2010) described the FLaIR hydrological model for monitoring and prediction of the landslide development depending on the previous rainfall effect.

The scientific work by Popov et al., (2018), which is devoted to the study of the trend of changes in air temperature, reveals that the warming trend is more noticeable in summer, afterwards in winter and spring, in Bosnia and Herzegovina.

An objective quantitative estimate is the calculation of a standard probability series. It is a task of establishing probabilistic regularity of the variability of the landslide development under the influence of temporal factors at the quantitative level.

The determinative factor in temporal and spatial analysis is the choice of reasonable model data analysis within a given zone. The general methodology of the regional engineering-geological zonation was developed by Ponomar (1969).

The engineering-geological zonation, as a way of probable representative submission of data, and mainly, of their accurate prediction models, is based on the estimate of geological-geomorphological conditions of landslide developments, degree of stability of slopes regarding the landslide developments and submitted at the level of areas and sub-areas. The areas are distinguished by the nature of deposits and the erosion base level. We can consider the ravine erosion as a regional factor, which, together with the rainfall, provokes the development of landslides through the close connection of these processes. The types of areas shall be determined by lithological rock composition of rocks, as it is the one that forms physical and mechanical properties of the rocks, determining the speed and mechanism of the development of landslides. As a result, we draw up a map of the engineering-geological zonation with contours of areas and regions. The following work is connected with a typing of slopes on certain features including the genetic type (erosion slopes, erosion-landslide slopes, and landslide slopes), the steepness of slope; a typing by height is acceptable for the slopes washed by the river (Klymchuk et al., 2008) (Fig.1).

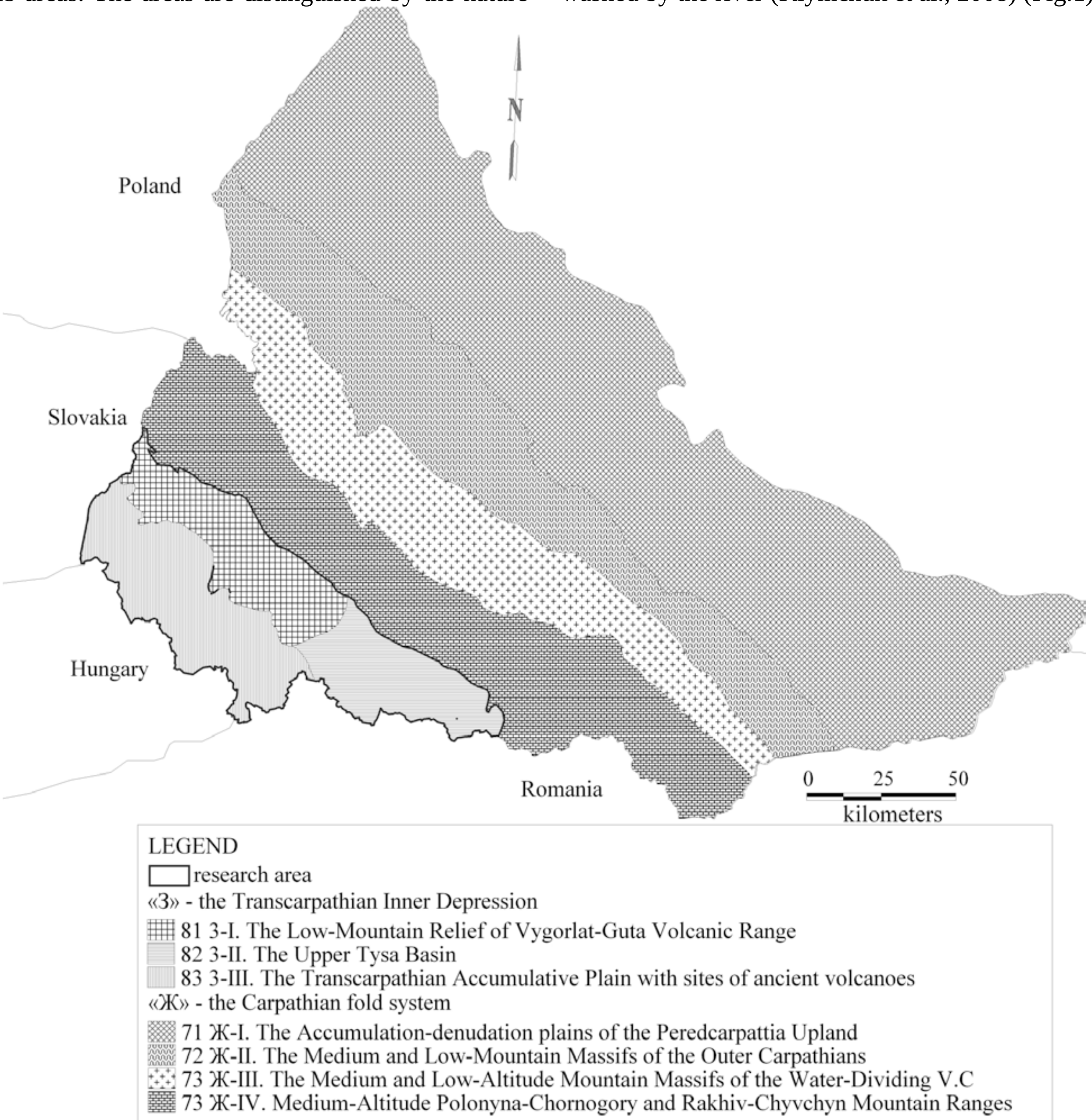


Figure 1. The map of the engineering-geological regions

2. STUDY AREA

The Carpathian area of Ukraine is significantly affected by various exogenous geological processes (EGP), including landslides that lead to changes in the surface and structure of the geological environment. According to Informative Yearbook (2019), on 01.01.2019, they registered 22958 landslides with an area of 2135.48 sq. km. In total, in the studied area, we have registered 4754 landslides (20.7% of the registered landslides in Ukraine) with a total area of 1145.4 sq. km, which is 53.6% (more than half of the total spread area of landslides in Ukraine).

In the geo-structural plan, the studied area consists of two main engineering-geological regions: «Ж» - the Carpathian fold systemand «З» - the Transcarpathian inner depression with the relevant separation into engineering-geological areas (Fig.1).

The Carpathian fold system belongs to the Alpine folding, which characterized by the change of the rocks in the indigenous base from flysch formations of Cretaceous and Palaeogene deposits in the mountainous part to Miocene formations overlain by Quaternary deposits in the foothills.

The region of the Transcarpathian inner depression is represented by Neogene deposits of different formations.

The geological structure is very complex, and it contributes to the active motion of the earth surface. Seismic fluctuation, caused mainly by the proximity to Vrancea zone (Romania) leads to the activation of all gravitational processes with an overlay of the other factors. The Transcarpathian area and the Carpathian fold system area are especially exposed to landslide activation due to high groundwater level, heavy irregular rainfall, etc.

The Transcarpathian inner depression (З) was shaping within the period from the end of the Palaeogene to the beginning of the Neogene. The mass of molasse sediments has accumulated due to destruction of the Carpathians and the raised Pannonian massif. Among the debris of the above sediments, the chemical deposits and volcanic formations of andesite-basalts and their volcanic ashes with the layer thickness from 100 m to 600 m in the individual areas have developed. At the foot of the Vygorlat-Guta range and in the Irshavaintermountain valley, they are overlaid by sedimentary deposits (Ruban & Nikolshyna et al., 2005).

The relief of the Transcarpathian inner depression in the south-west is determined by the Transcarpathian accumulative plain having the above sea levels of 120 m and formed by the valley of the Tysa River and its tributaries. The Vygorlat-Guta volcanic range with the highest altitudes of about 1000 m stretches from the north-west to the south-east. The area is one of the most humid with the precipitation levels ranging from 600 to 1100 mm per year. The relief is strongly dissected by the dense network of rivers (1.7 km/km^2), the main of which are: the Uzh, the Latorytsia, the Borzhava, the Rika, the Tereblia, and the Teresva – the tributaries of the Tysa River. The nourishment of the rivers is due to snow and rain. About 60% of annual rainfalls happen in the warm period. All the rivers of Transcarpathia have a high-water hydrological regime. Landslides develop on the river slopes during the abnormal humidity. Hydrogeological conditions of the Transcarpathian inner depression include water-bearing horizons and complexes related to the massive layer of sedimentary deposits and effusive formations.

The hydrogeological cross-section consists of deposit layers represented by pebble stones, alluvium, cobblestones with inclusions of sand-clay formations.

In the upper part of the section we can observe the loam soils, sandy-loam soils occasionally and the clay layers are less often. Water bearing rocks are underlain by sand-clay formations. The depth of groundwater occurrence is 3-5 m on average.

The nourishment of water-bearing horizons is mainly due to rainfall infiltration and filtration of surface water during the floods.

The Transcarpathian inner depression is one of the most earthquake-prone regions in Ukraine. The depression is bounded by the Transcarpathian deep-seated fault in the north-east and Prypannonian deep-seated fault in the south-west, where we may register the earthquakes with hypocentres of 2-17 km with the magnitude of 7-8 scores on MSK-64 scale. Subsurface crustal earthquakes are dangerous for the geological environment because they cause different secondary effects (movements, residual deformation in the soils, landslides) (Pronyshyn & Pustovitenko, 1982).

The total number of landslides is 821 units (Fig. 2) in the region of the Transcarpathian inner depression. The landslides are mainly in the form of bands within the structural and tectonic zones, which significantly impair the stability. The most developed are consequent landslides, which are common in the diluvial and colluvial Quaternary clay layers and loam soils. The consequent landslides are typical in the Vygorlat-Guta volcanic range, and they appear due to over humidity of the rocks. They have the following dimensions: the length is 120-750 m; the width is 200-950 m; the layer thicknessis 5-6 m. The Upper Tysabasinis characterized by small landslides that are common on the slopes of the river valleys. There are typical rock-falls and consequent landslides. The main deforming horizon is argillaceous and loam deposits (Velychko et al., 2019).

3. MATERIAL AND METHODS

A long-standing temporal prediction of the landslide activity in the Transcarpathian inner depression was performed in this scientific work. For analysis of the landslide processes, we have chosen the data on the sun activity, temperature, rainfalls, groundwater levels, earthquake energy and the number of the landslides during 1960 -2018. In general, we analyzed the information on the meteorological stations of Uzhgorod, Beregovo and Khust; regarding groundwater (Ruban & Nikolishyna, 2005), average of annual solar activity data under the information from Royal Observatory of Belgium Av; registered earthquakes (under seismological bulletins of USSR and Ukraine); the activation of landslides (Informative Yearbook, 2019).

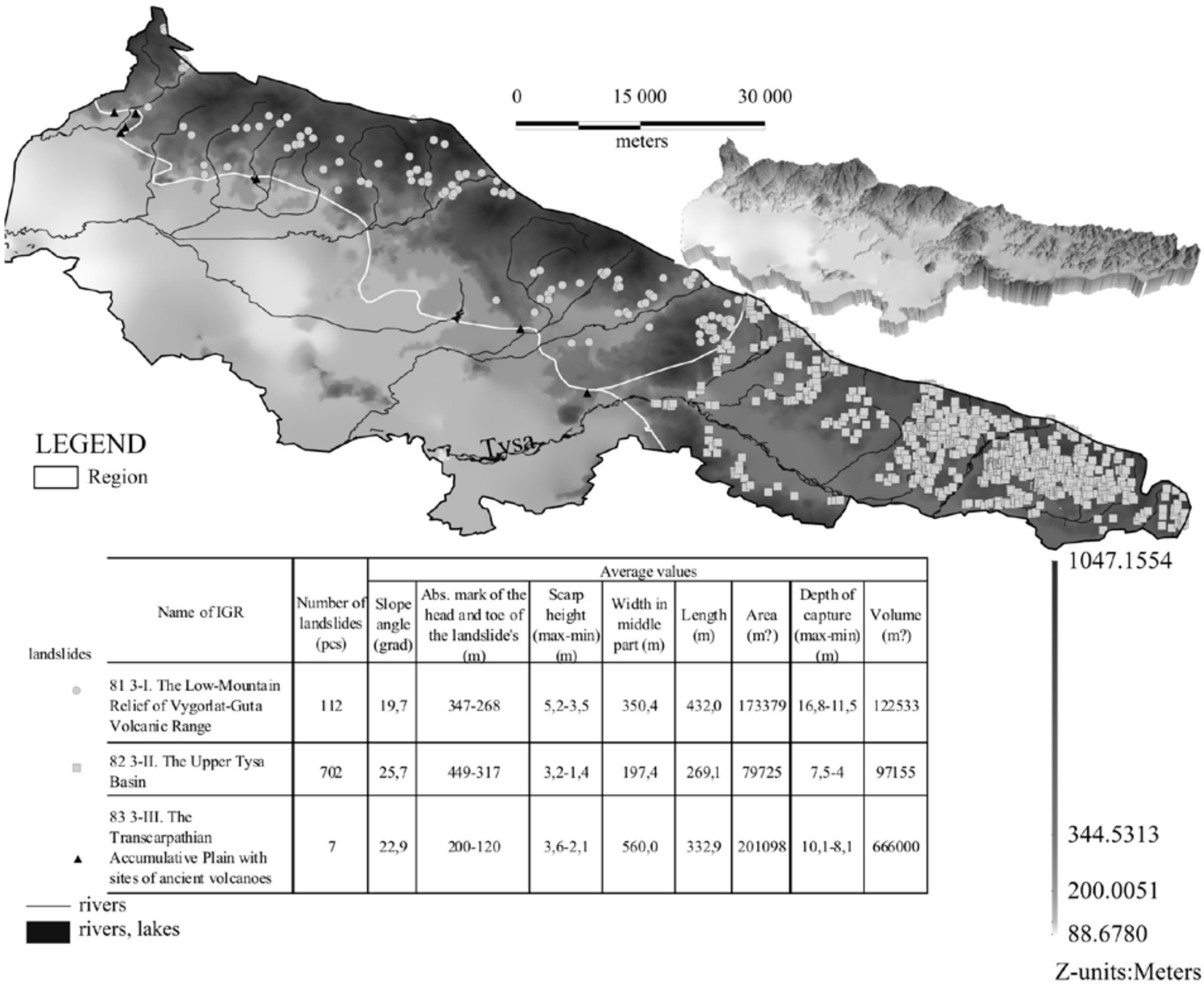
As a theoretic basis for the analysis of factors that changes over time, we propose in (Sheko & Krupoderov, 1984) the complex of classical statistical methods, special heuristic procedures and adaptive statistical methods:

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

Methodical recommendations for long-standing regional predictions of exogenous geological processes in the system of state monitoring of geological environment.

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;



landslides	Name of IGR	Number of landslides (pcs)	Average values							
			Slope angle (grad)	Abs. mark of the head and toe of the landslide's (m)	Scarp height (max-min) (m)	Width in middle part (m)	Length (m)	Area (m?)	Depth of capture (max-min) (m)	Volume (m?)
●	81 3-I. The Low-Mountain Relief of Vygorlat-Guta Volcanic Range	112	19,7	347-268	5,2-3,5	350,4	432,0	173379	16,8-11,5	122533
■	82 3-II. The Upper Tysa Basin	702	25,7	449-317	3,2-1,4	197,4	269,1	79725	7,5-4	97155
▲	83 3-III. The Transcarpathian Accumulative Plain with sites of ancient volcanoes	7	22,9	200-120	3,6-2,1	560,0	332,9	201098	10,1-8,1	666000

Figure 2. The map of the landslide activities of the Transcarpathian inner depression (relief and its 3D model)

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 function of cross-correlation between sliding activity and factors that influence its development. We estimate the value of displacement of certain factors over time 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*:

$$R_{np_j} = \frac{\sum |r_{i,j}|}{\sum_j \sum_i |r_{i,j}|} \cdot 100\%,$$

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 is taking into account the complex effect of all factors affecting the development of landslides:

$$\Phi_i = \sum_{j=1}^{m} X_{ij}^{norm},$$

where *m*– number of temporal factors, *i* – a year of observation. performing a long-standing temporal prediction.

4. RESULTS AND DISCUSSION

We analyzed the temporal series, using the following algorithm. First, we checked the temporal series for the presence of a trend; if there was a significant trend, we deleted it. Thus, we found the linear trend (8.96 0.032·x) for an average of annual temperature. The trend is caused by global warming (an average of an annual increase in air temperature is 0.032°C). During the observation period, the temperature increased on average by 1.9°C. All this testifies of importance and dynamics this factor in time. A change in ±1°C leads to significant fluctuations for all other factor characteristics such as rainfall, groundwater level.

Then we normalized the series to reduce them to non-dimensional values. An autocorrelation function was calculated for each series to distinguish the basic periodicities. The results of the autocorrelation function (Table 2) allow us to evaluate the first periodicities for each factor characteristic.

They showed periodicities the most accurately for rainfall – about 10 years, for temperature – about 6 – 7, 11 years, for groundwater levels – 21-22 years, for total annual energy of earthquakes – 9-10, 27 years, for activation of landslides – 9-10, 21, 28-30 years.

Table 2. Main periodicities of factor characteristics

Factors	Period
Wolf number	9-12
Total annual rainfall	2, 10, 21-25, 28-30
Average of annual air temperature	5-8, 11
Average of ground-water level	2-6, 21-30
Total annual energy of earthquakes	4-6, 9-10, 23-24, 27
Activation of landslides	2-3, 9-10, 12, 18, 21, 28, 30

Figure 3 presents the results of the temporal series analyzed by pairs that allow us to distinguish the basic periodicities of the processes of development and activation of landslide processes concerning the factors initiating them.

While considering the cross-correlation functions, it should be noted that the air temperature did not reach the confidence interval limit. It underlines the presence of slowly varying interrelationship. We must understand the various natural constituent of the temperature changes. Significant fluctuations lead to complexity in using the data in prediction models but strengthen them through the mutual influence of temperature factor with solar activity and rainfall.

Cross-correlation functions show that there is a synchronous relationship for most of the factors (total annual rainfall, an average of annual air temperature, groundwater level), but the solar activity is shifted 1 year forward regarding the activation of landslides. This fact can be explained by the advancing effect of the solar cycles on the circulation processes of the Earth's atmosphere.

We can trace the correlation of series of the total annual energy of earthquakes if shifted 5 years forward (half of the period of solar activity) relative to the activation of landslides, which may be explained by preparatory actions of seismic factors (increase in fracture density of rocks, growth of stressed-deformed state), which through the years lead to development of landslide processes.

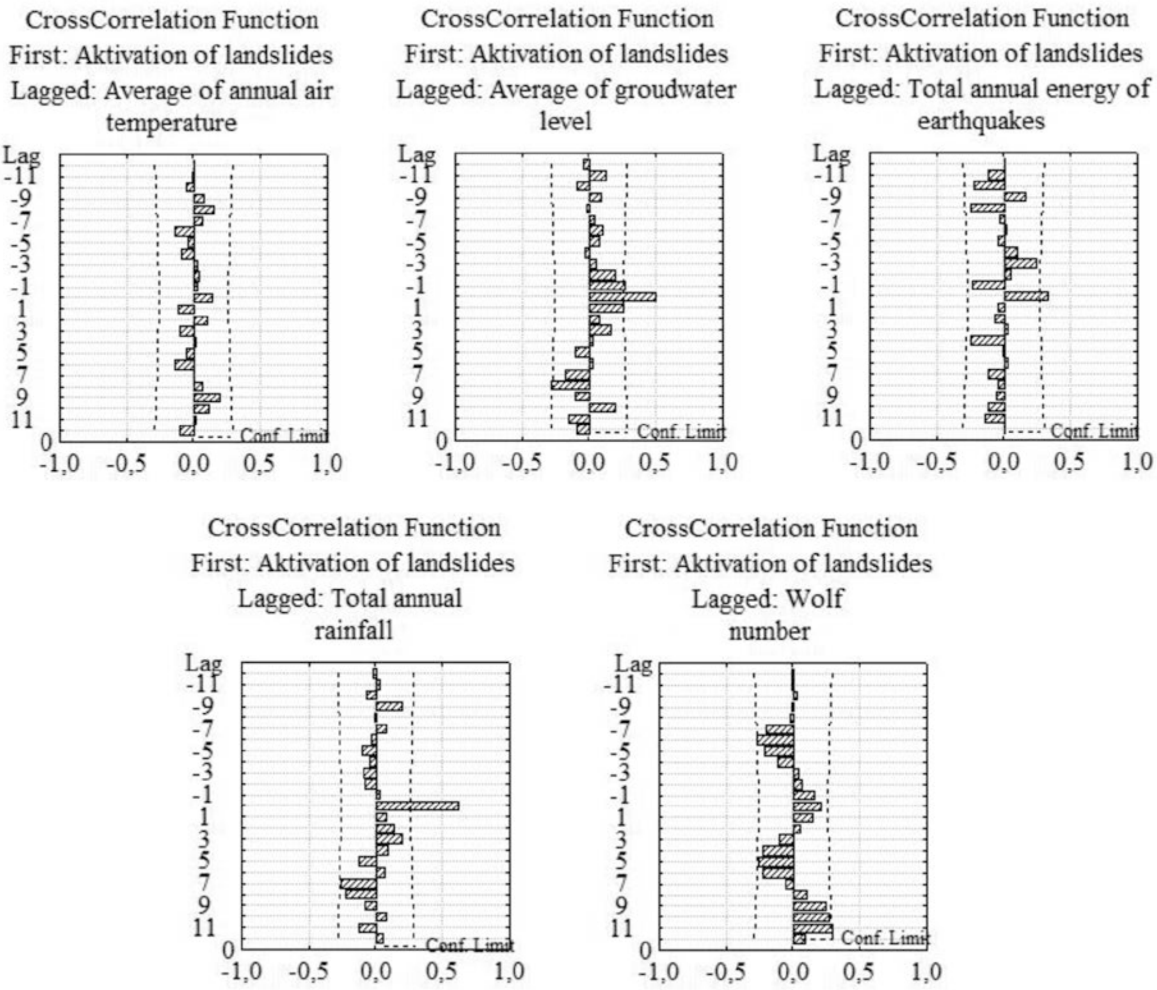


Figure 3. Cross-correlation functions between activation of landslides and influence factors

There are common periodicities of 9-11 years for the solar activity, rainfall, temperature, total annual energy of earthquakes, and activation of landslides. The rainfall, groundwater level, and total annual energy of earthquakes have a common periodicity of 21-25, 28-30 years with their inherent peaks within the cycle.

Taking into account the shift of the temporal series of the solar activity, total annual energy of earthquakes, we have performed a correlation analysis between the factor characteristics (table 3).

By considering the correlation relationships, we may evaluate an understanding of whether there is a close relationship between the analyzing factor characteristics.

Analysis of the incoming data indicates that rainfall and groundwater level are most closely related to data of activation of landslides. This fact shows and confirms that the main factors of development of landslides are rainfall, which contributes to the increase in groundwater level, creating a basis for wetting the soil in contact with the prevailing sandy shale formations and development of landslides.

Table 3. Correlation matrix of shifted factors regarding the activation of the landslides

Factors	1	2	3	4	5	6
Wolf number (1)	1.00	0.20	0.12	0.19	0.01	0.20
Total annual rainfall (2)	0.20	1.00	0.02	***0.64***	***0.29***	***0.63***
Average of annual air temperature (3)	0.12	0.02	1.00	-0.17	-0.04	0.17
Average of groundwater level (4)	0.19	***0.64***	-0.17	1.00	0.10	***0.49***
Total annual energy of earthquakes (5)	0.01	***0.29***	-0.04	0.10	1.00	***0.31***
Activation of landslides (6)	0.20	***0.63***	0.17	***0.49***	***0.31***	1.00

Almost all factor characteristics have a direct connection, except for the pairs: temperature – total annual energy of earthquakes and temperature – groundwater level. We can explain the first case by the different nature of the physics processes describing them. The second case can be explained by the fact that at the increase in temperature, the processes of evaporation in the surface layers of rocks increase, which helps to reduce the level of groundwater.

After a comprehensive statistical analysis, we have calculated the integrated index (1)

The series of the predicted activation of landslides shall be performed using the Laplace function based on the calculated data of the integrated index.

We carried out the prediction in two ways: by the neural network, which is a multilayer perceptron model with six hidden neurons and by the PREDICT function of the MathCad integrated mathematical package. The degree of reliability of the projection periods was determined through a correlation coefficient that is 0.8.

The sequence of study involves the construction of the autocorrelation graph and spectral analysis of integral index (Fig. 4).

As we can see from Figure 4, the function of the complex index average of three points describes the temporal dynamics better. The function value more clearly defines the confidence interval of the function. But this fact is not shown in the dynamics. The spectral analysis identifies three main periodicities for 11, 19, 28 years, cycles 19 and 28 are common to both graphs.

We converted the integral index to the value of the probability of landslide processes by the method described by Kuzmenko et al., (2016).

The temporal harmonics can most accurately describe the process of probable landslide activation. In particular, they allow not only performing the interpolation of the temporal series for the base period but also checking the accuracy of the model in the extrapolation component of the harmonic.

Figure 5 presents the temporal graphs of the probability of landslides in an average of values based on three points and the prediction using the MathCad integrated mathematical package and neural networks.

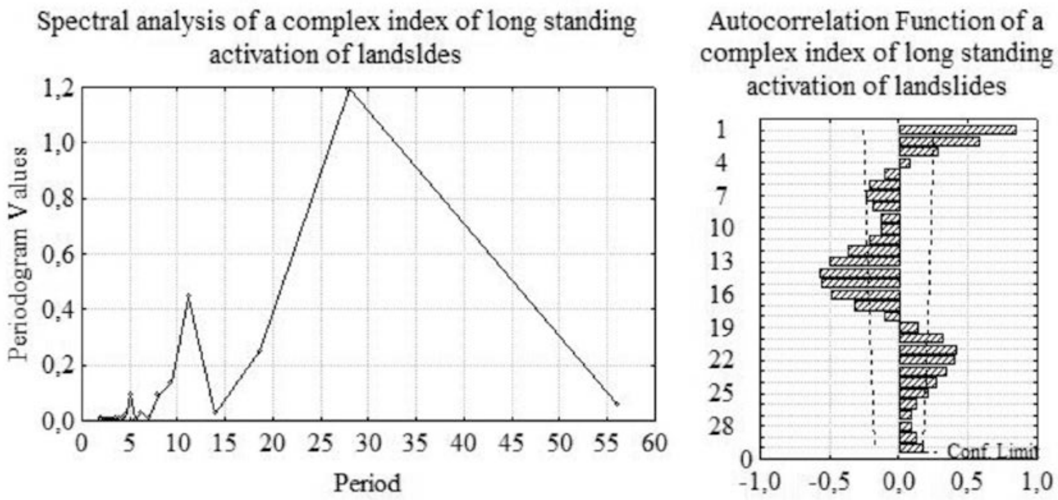


Figure 4. Spectral and autocorrelation analysis of complex index

Figure 5. The graph of the complex index

Analyzing the graph of the complex index, it should be noted that there is a clear periodicity of 28 years. We can consider the main period as a large cycle, which includes two smaller half-cycles having their oscillation with the peak values of activation of landslides. The temporal limits of half-cycles are 9,7 and 19 years.

The neural network prediction identified the probability of landslides in 2020 – 2021 of the first half-cycle (2019-2023) and 2028 -2030 of the second half-cycle (2027-2032). Prediction for the sum of the fundamental harmonics of the Fourier series showed a shift of the maximum probability by 1-2 years forward in 2022-2023 and 2029-2031. Such accuracy shall be acceptable taking into account the discrete in those years when the complex error is ±1 year. Therefore, the following mass activation of the landslide processes will be observed in 2021-2022 and 20229-2030 on average of.

5. CONCLUSION

Dynamic changes in the geological environment require the search for new factors to describe more accurately the prediction model of landslide processes.

The development of a logic structure of landslide analysis allowed us to identify the main groups of factors with their clear classification regarding the probable influence upon the processes of development and activation of gravitational processes.

Long-standing analysis of landslide activity for the Transcarpathian inner depression of the Carpathian region gave us the possibility to distinguish the periodicities of activation of slide processes based on auto-correlation graphs, cross-correlation graphs, spectral and network analysis. To detail our prediction, we have chosen the rainfall, temperature, the groundwater level, in addition to the main factors as solar activity and number of earthquakes. This enabled us, in conjunction with the information on the activation of landslides, to identify such factors as rainfall, number of earthquakes and groundwater level.

So, we note that:

1) the dynamic climatic factors should be used for long-standing prediction;

2) the spectral analysis of main components shows the availability of temporal dynamics at 5, 10, 28 years;

3) using such dynamic factors as an average of annual temperature, total annual rainfall, groundwater levels allowed us to step back from the main periodicity giving by the solar activity (the accuracy of prediction increases in that time);

4) the activation of landslide processes can be seen in long-standing cycles, more than 20 years, within which the cycle has two peaks of development, with half cycles in 8-10 years;

5) the neural network prediction highlights 2019-2032 as the following cycle of activation of landslide development with small peaks in 2020-2021 of the first half cycle (2019-2023) and the peak in 2029 of the second half cycle (2027-2032).

Long-term temporal prediction for some universal zones, by the example of engineering and geological zoning, provides prerequisites for further study within the entire Carpathian region where landslide activity is one of the greatest geological problems that threaten the environment and a human being as a whole.

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Received at: 24. 12. 2019
Revised at: 07. 02. 2020
Accepted for publication at: 09. 02. 2020
Published online at: 13. 02. 2020