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Time series analysis of karst breakdown development on the potassium salt deposit areas within Precarpathian region

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Abstract. The work is devoted to the analysis of karst breakdown development over time within the area of the Kalush-Golynske and Stebnytske potassium salt deposits. A study of the relationship between the development of karst breakdowns with the factors influencing their development in natural conditions and in the conditions of natural-technogenic systems is presented.

Time series of karst breakdowns in the Kalush-Golynske and Stebnytske deposits of potassium salt were selected for the investigation. The time series reflect the number of formed failures of the earth's surface due to karst processes. Climatic (average annual temperature and annual precipitation), heliophysical (solar activity), seismic (number and energy of earthquakes), hydrogeological (groundwater levels) were chosen as such factors. Breakdown phenomena, which are included in the time series of their long-term dynamics, are associated with different hydrodynamic zones of karst processes. For these zones, the indirectness degree of the influence of the selected for the analysis factors is different and the meteorological parameters are more effective in the supply zone, seismic factors work in all zones. Statistical methods such as correlation analysis, calculation of autocorrelation and cross-correlation functions, spectral analysis are used for the analysis of the time series. Statistical regularities in the series of karst breakdown development for Kalush-Golynske and Stebnytske potassium salt deposits and between the selected natural time factors and karst series have been established, which allows asserting the indirect influence of natural component of karst activation. The presence of periodic components in the long-term series of karst breakdowns should be associated with the natural factors that indirectly activate karst processes. These factors should be investigated and taken into account when creating temporal prognostic models for the development of karst breakdown processes within the deposits of potassium salt of Precarpathia.

Key words: karst, potassium salt deposits, time series, meteorological factors, time series analysis

Часовий аналіз розвитку карстопровальних процесів на родовищах калійної солі Передкарпаття

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Анотація. Роботу присвячено аналізу часового розвитку карстопровальних явищ, які інтенсивно проявляються у межах відпрацьованих родовищ калійної солі українського Передкарпаття (Калуш-Голинського та Стебницького родовищ калійної солі) і пов'язані з наявністю гірничих виробок та інтенсивними процесами розвитку соляного карсту за рахунок розчинення засолених порід при інфільтрації підземних вод. Виконано дослідження зв'язку розвитку провальньо-просадкових проявів карстових процесів із факторами, що впливають на їх розвиток у природніх умовах, та відповідно характеризують природну складову їх активізації, а в умовах природно-техногенних систем, якими є відпрацьовані соляні родовища можуть опосередковано визначати їх розвиток у часі. Такими факторами обрано кліматичні (середньорічна температура та річна кількість опадів), геліофізичні (сонячна активність), сейсмічні (кількість та енергія землетрусів), гідрогеологічні (рівні ґрунтових вод). Для аналізу часових рядів використано статистичні методи – кореляційний аналіз, розрахунок функцій автокореляції та функцій взаємної кореляції, спектральний аналіз. Встановлено статистичні закономірності у рядах розвитку провальньо-просадкових проявів карстових процесів для Калуш-Голинського та Стебницького родовищ калійної солі та між рядами обраних природних часових факторів та рядами карсту, що дозволяє стверджувати про опосередкований вплив природної складової активізації карсту. Встановлено, що у часових рядах карстової активності наявні періодичні складові, зокрема для Калуш-Голинського родовища часовий ряд має виразну періодику в 10-12 років. За результатами автокореляційного та спектрального аналізів, виконаних з метою визначення основних періодів гармонічних часових коливань в рядах часових факторів визначено основні

періодичності, зокрема для ряду сонячної активності періодичність складає приблизно 10-11 років, для річної кількості опадів чіткої періодичності не виявлено, незначні періодичні складові виявляються раз на 9-11 років, у ряді рівнів ґрунтових вод 15 та 17 років, в ряді середньорічної температури існує слабка періодичність у 8-10 років, у ряді логарифмів енергії землетрусів існує деяка періодичність у 8-11 років. Оцінено вплив та охарактеризовано закономірності впливу ініціюючих часових факторів на активізацію карстових процесів. Зокрема, аналіз кроскореляційних функцій показав, що між рядами кількості карстопроявів та річної кількості опадів суттєвої синфазності не спостерігається, кількості карстопроявів та середньорічної температури спостерігається слабка обернена кореляція, кількості карстопроявів та енергії землетрусів слабка пряма кореляційна залежність, для пари рядів «кількість карстопроявів – числа Вольфа» встановлено, що ці ряди знаходяться в протифазі, для ряду рівня ґрунтових вод спостерігається протифаза зі зміщенням на 1 рік. Зазначені фактори слід досліджувати та враховувати при створенні часових прогностичному моделей розвитку карстопроявних процесів у межах родовищ калійної солі Передкарпаття.

Ключові слова: карст, родовища калійної солі, часові ряди, метеорологічні фактори, аналіз часових рядів

Introduction. In Ukraine deposits of potassium salts are found in the Precarpathian Prefecture, which forms the Precarpathian Potassium Basin (Fig. 1). Deposits of potassium and potassium-magnesium salts of the Precarpathian potassium basin belong to the Kalush strata of the Stebnyk and Vorotyshenska neogene formation and lie in the form of layered and lenticular deposits of 3.0 – 120.0 m thickness. Much of these reserves are concentrated at the depth of 600-700 m. Most of the mined potassium salts in Ukraine were used to produce potassium mineral fertilizers. Potassium salts can also be used in the chemical industry to obtain more than ten kinds of chemical products, the main component of which is potassium (potassium sulfate, potassium-magnesium, potassium nitrate, caustic potash, etc.). State balance of mineral reserves of Ukraine accounted for 13 deposits of potassium-magnesium salts, of which two had been being exploited for quite a long time. These are the Kalush-Holynske deposit (JSC “Oriana”, Ivano-Frankivsk region) and the Stebnyk one (“Polimineral”), Lviv region. At present, both productions are stopped. Since 2007, due to the emergency condition of the mine №1 and the lack of funds for its reconstruction, mining works within the Stebnytske deposit have been discontinued. Extraction of potassium salts at the Dombrovsky quarry of The Kalush-Golynske deposit has also not been carried out since 2007, and production has been decommissioned (Mineral Resources, 2014).

The development of potassium salt deposits in the territory of the Precarpathian region (Kalush-Golynske and Stebnytske deposits) by the underground method led to the creation of significant artificial cavities at depths of 100-400 m, the total volume of which is 35 mln m³. At present, most of the operating chambers have been eliminated by filling with saturated brines or waste products. The operation of the Kalush-Golynske deposit is completed and one of two mines at the Stebnytske deposit is filled with brines and the second one is temporarily suspended. The presence of underground cavities, which were

formed during the operation, led to the violation of mechanical equilibrium of the rock masses and, accordingly, to the violation of geological, hydrogeological, and geomorphological conditions. This led to the activation of dangerous geological processes, among which land subsidence and dips are the most widespread ones.

As noted in (Gaidin, 2016), the main cause of subsidence and failures on the territories with potassium salt deposits is the development of karst processes. Failures and deformations of the earth's surface are the final phase of this. The mechanism of karst processes development in the conditions of the fulfilled salt deposits is difficult, especially for conditions of mines which are in a stage of wet preservation (flooding by brines as on the Stebnytske deposit). It can be established only on the basis of water movement direction. However, in (Gaidin, 2016) it is noted that for the hydrodynamic system of karst formations there are areas of supply, transit and discharge. In the feeding area, salt rocks are intensively dissolved by fresh water, and the rate of their dissolution depends on its temperature and flow rate. In the transit section, the karst process fades, surface deformations are insignificant. The dissolution of salts intensifies at the place of discharge. Especially dangerous when discharge takes place in the mined space, which leads to the deformation of the earth's surface. The consequence of hydrodynamic processes in potassium salt deposits (especially now seen on the example of Stebnytske, mine №2 which is in the stage of flooding with brines) is the erosion of the ceiling of mines and interchamber pillars, and karst breakdowns. The term karst breakdown is employed in this paper to denote the totality of processes and phenomena of gravitational and/or hydrodynamic destruction of the ceiling of a karst cavity and of the overlying sediments, was adopted from (Klimchouk, 2005). This intensifies the formation of significant collapses (failures 30.09.2017 and 15.03.2020), and are directly related to geomechanical processes in the mines. In this article we will oversee just one type of karst manifestation - breakdowns.

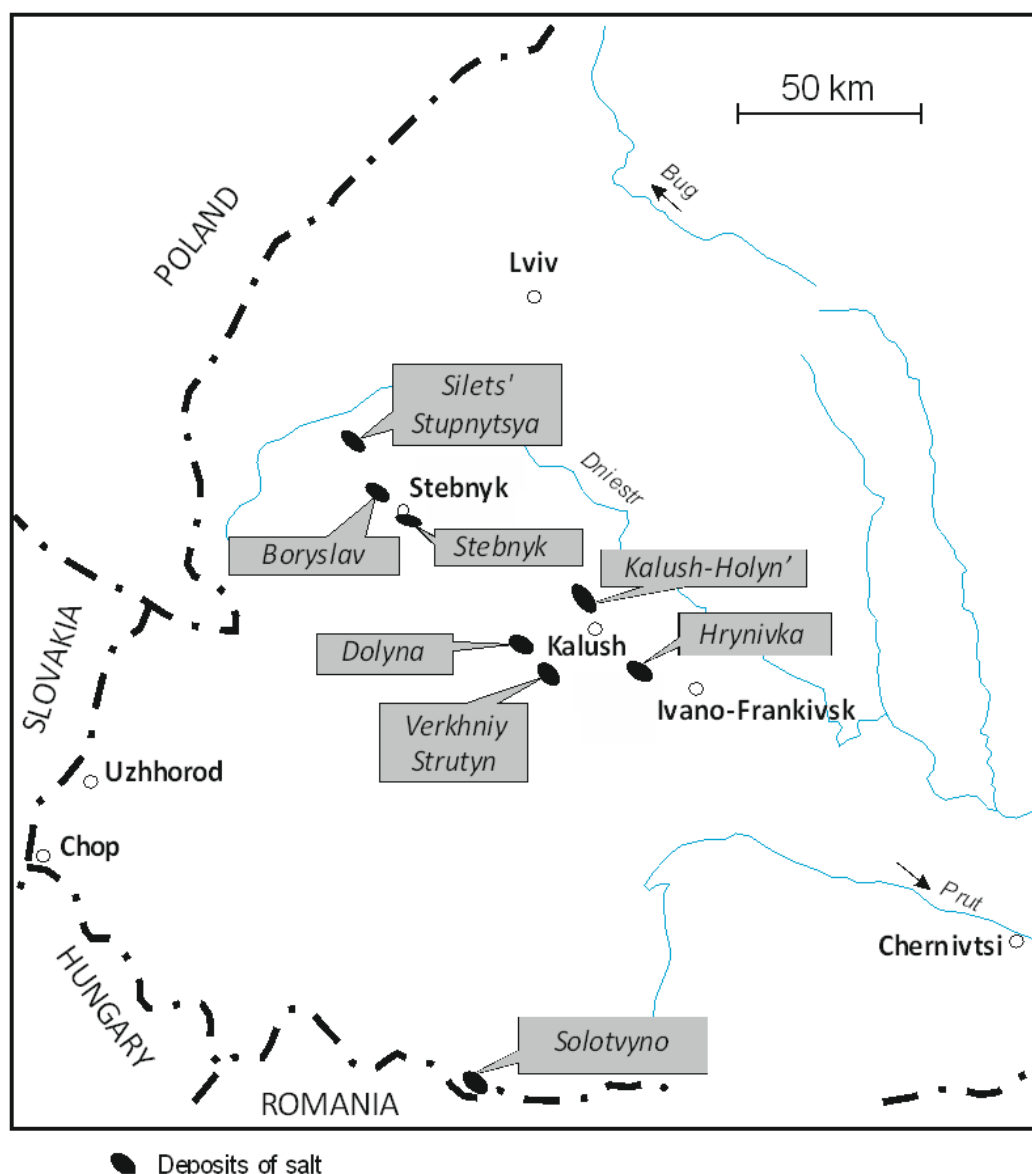


Fig. 1. Schematic image of location of salt deposits and manifestations in the western part of Ukraine

Our previous scientific studies on regional prognostic modeling allow us to state that the dynamics of any exogenous geological processes, including karst processes, is associated with the dynamics of such natural phenomena as climatic, heliophysical, seismic, and hydrogeological phenomena (Chepurnyi, 2018; Kuzmenko, 2017).

On the one hand, these characteristics form a separate group of time factors, which are associated with the karst activity, and, in addition, are imposed on the permanent spatial factors (geological, geophysical, landscape, geomorphological, hydrogeological, etc.).

Each of the above mentioned temporal or spatial factors can be evaluated by its quantitative factor characteristic.

Output data. Surface manifestations of karst are controlled by a number of natural and anthropogenic factors. The recognized definition of the basic

conditions for the karst formation is given in the work (Sokolov, 1962): “As a geological process, the karst is steadily developing where the four conditions exist simultaneously: solubility of rocks, their water permeability, presence of mobile waters, and their soluble ability”. The provided four conditions for the emergence and development of karst are indispensable, but the process of karst formation is associated with a number of accompanying natural processes and phenomena.

At present, one of the main directions of research of natural processes, and karst processes in particular, is a direction, which is based on the ideas about the regularities of repetition of the majority of natural phenomena for the separate territories or for the whole globe (Sheko, 1984; Trofimova, 1985; Sheko, 1999). Since the process of karst formation is a multifactorial system, it is manifested under the influence

of a certain number of natural and anthropogenic factors that have their own rhythmicity, it is expedient to reveal the time regularities of karst formation with the help of the theory of the rhythm of natural processes.

Time series of karst breakdowns in the Kalush-Golynske and Stebnytske deposits of potassium salt were selected for the study. The time series reflect the number of formed subsidence of the earth's surface due to karst processes. For the Kalush-Golynske deposit of potassium salt, the series is represented by 24 failures from 1975 to 2015, for the Stebnytske deposit of potassium salt - 21 failures from 1980 to 2016. The natural and technogenic process of karst formation in salt rocks has a significant rate of development over time and is characterized by a fairly high frequency of formation of new karst craters and dips, therefore, one should expect expressive time regularities in the development of the karst process and the factors that determine it, and on the other hand, these regularities can have a less expressed nature due to the influence of the technogenic component (Kuzmenko, 2017;

Chepurnyj, 2018). The technogenic component that significantly affects the development of karst in the salt deposits under consideration is the presence of artificial underground cavities and applied measures for wet conservation of mines, which significantly affected the stability of the territory.

In order to assess the conditions for the development of karst processes in terms of the impact on this process of natural factors, (which were discussed above), consider the mine №2 of Stebnytske potassium salt deposit (Fig. 2). As can be seen from the figure, the development of karst processes within the mine №2 is dedicated to 3 cells. Consider them in more detail. The center of development of karst near by the valley of the river Vyshnytsia, is characterized by intensive development of karst processes and dedicated to the zone of supply and transit of groundwater. Karst processes have been developing here since 2000 and by 2016 there were 5 failures. Groundwater movement is directed towards drainage chambers (Gaidin, 2016; Kuzmenko, 2019). The depression funnel here

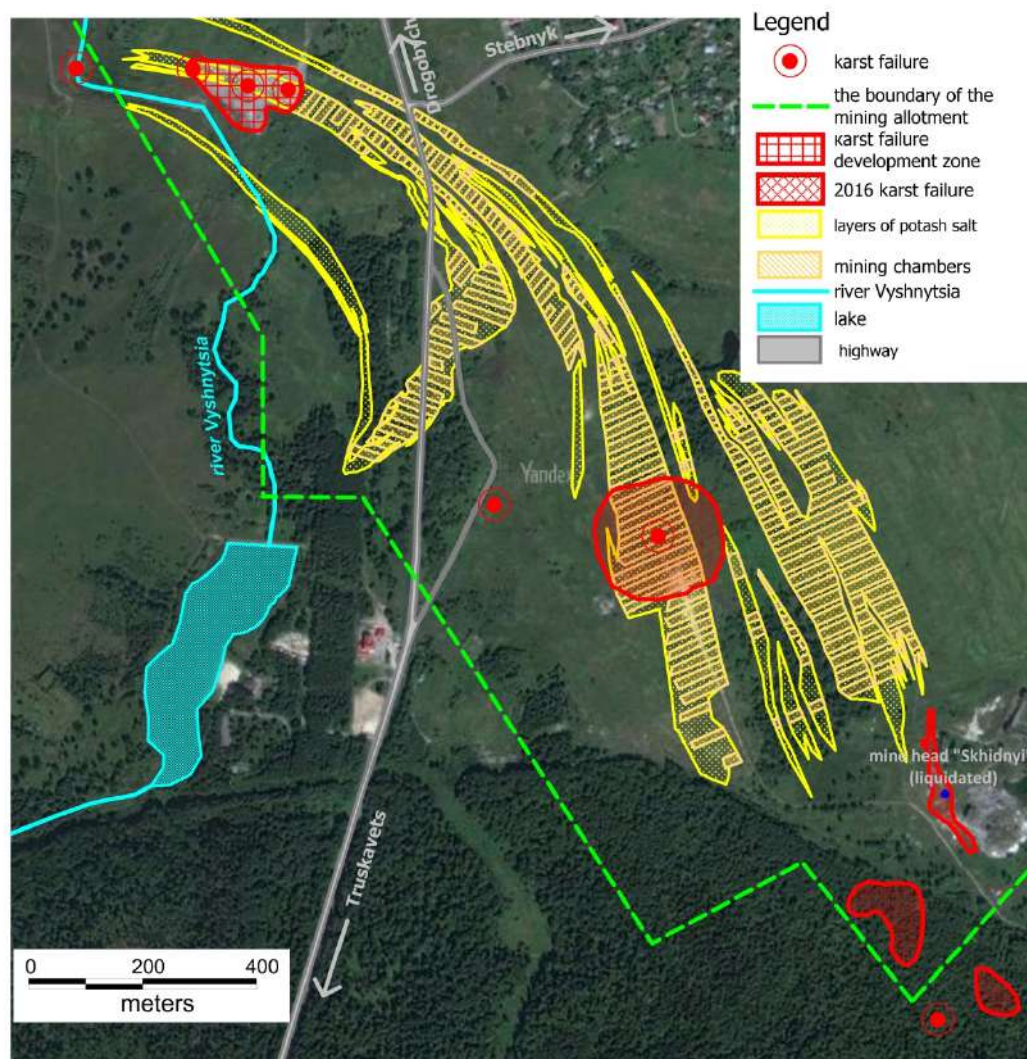


Fig. 2. Map of the distribution of karst failures within the mine №2 of the Stebnytske deposit of potassium salt

stretches west towards the Vyshnytsia river valley and southwest towards the lake. Another center of development of karst is the zone of the mine shaft «East» of the mine №2 (Fig. 1 - south-eastern part), where the intensive development of karst failures led to its elimination. South of this area there is a center for the spread of breakdown karst phenomena, which is associated with the groundwater supply zone (Gaidin, 2016; Kuzmenko, 2019) - previously present stream Kolpetskaya beam. There were 10 intensifications of the development of failure-subsidence phenomena of karst from 1982 to 1999. In recent years, there has been a significant intensification of this phenomena over the extraction chambers - the catastrophic failure of 2016 (Kuzmenko, 2019). It was dedicated to the zone of groundwater discharge.

Breakdown phenomena, which are included in the time series of their long-term dynamics, are associated with different hydrodynamic zones of karst processes. For these zones, the indirectness degree of the influence of the selected for analysis factors will be different, it is obvious that the meteorological parameters are more effective in the supply zone, seismic factors work in all zones. As we have seen in the example of karst breakdowns at the mine №2 of Stebnytske potassium deposit, most of them are dedicated to the hydrodynamic supply zone. The intensity of the inflow of aggressive fresh water into which depends on natural meteorological factors. Failures of the earth's surface, which are associated with the stability of the ceiling of the chambers and interchamber pillars are intensifying recently. Obviously, this is due to erosion processes during the flooding of mine №2. When the underground cavities of the mine №2 are flooded and groundwater levels stabilize, the hydrodynamic conditions will change accordingly, which will lead to a change in the intensity of karst breakdowns. The main purpose of this study is to assess the degree of indirect influence of natural time factors in the long term in order to be able to use them in prognostic models of karst processes development at the local and regional level.

The relationship between exogenous geological processes (EGP) with factors such as annual precipitation, average annual temperature, solar activity (a sequence of Wolf numbers), earthquake energy, groundwater level are outlined in general terms by the authors of (Sheko, 1984; Trofimova, 1985; Sheko, 1999; Panagopoulos, 2006). According to the solubility of rocks and, first of all, salt rocks, its correlation with the precipitation does not need any comments. The relationship between the solubility of salt rocks and temperature of the groundwater is also indicated in literature, in particular in (Gaidin, 2016). The lat-

ter factor correlates with the air temperature. Logic dictates that seismic processes are involved in the transition of the covered karst into the open one, i. e. they contribute to the failure phenomena, disrupting the equilibrium of the mountain mass due to the oscillations of the layer of rocks of the near-surface zone. This is obvious therefore we chose seismicity as one of the factors. So, there are already four long-term karstinification factors: the amount of precipitation, groundwater level, air temperature, and earthquake energy. A separate issue is the Wolf number, which characterizes the solar activity. In the literature, starting from the well-known monograph by A. Chizhevskyi (Chizhevskyi, 1976) and till now, the relationship of solar activity with natural processes that occur on the Earth surface is indicated. There are all reasons to believe that solar activity is associated with the EGP activity and with the factors that initiate them. In particular, this is indicated in works (Sheko, 1984; Trofimova, 1985; Sheko, 1999) and in many others. The relationship of solar activity with meteorological factors at the quantitative level has been thoroughly investigated in work (Herman, 1978), and the relationship of solar activity with landslides and earthquakes in works (Kuzmenko, 2004; Goshovskiy, 2004; Kuzmenko, 2007). However, given the external relations, the nature of such relations remains unclear, although there is a number of a hypothesis regarding these causes. Moreover, there is also no close universal connection between solar activity and any EGP factor: there is a correlation with a certain sign that corresponds to physical representations of the process, but this correlation is not always essential. Therefore, we propose to consider solar activity as one of the equal factors of the EGP, which is valid for the factors mentioned above.

The main task of this investigation is the establishment of possible time regularities in karst formation processes development in the potassium deposits within the territory of Precarpathian.

We have developed the methodological basis for the assessment of the complex effect of a combination of natural temporal factors on the processes of karst formation, which are displayed in the value of the complex integral factor indicator with the subsequent determination of the probability distribution of this indicator over time, extrapolation of which is considered as the predicted probability distribution of karst and mudflow activation (Kuzmenko, 2012; Chepurna, 2017).

The sequence of studies that allow us to analyze the time series of the development of karst breakdowns and their indirect natural factors is as follows:

- creation of the database of time annual series of

formation of the surface karst breakdowns in accordance with the existing catalogs and climatic, heliophysical, seismic, hydrogeological factors;

- calculation and development of autocorrelation functions of time series of karst breakdowns and each factor for the estimation of its rhythmicity;

- calculation and development of the mutual correlation functions of time series for the selected factors with a series of karst formations for the assessment and justification of the shifting of the series of factors in time in relation to a number of karst formations;

- spectral analysis of time series in order to identify the main rhythmic components.

The obtained results will reflect the formal statistical relationship between the time series of karst breakdowns series and natural factors. And its cardinality is unlikely to be significant, but it will allow us to follow the general trend - to assess the degree of influence of the natural component in the formation of

dips in the earth's surface. It will also make it possible to correlate between the time series of the development of karst breakdowns for different deposits. Will assess the possibility of using natural time factors in creating prognostic time models at the local level. Of course, the geomechanical parameters of mines are important in predicting the spatial development of karst breakdowns at the object level, but they change over time under the influence of hydrodynamic factors, which are indirectly influenced by natural factors that are not decisive. The influence of natural factors can be manifested under conditions of their significant variation - extreme manifestations that can be predicted by modeling.

Results of experimental studies. Time series of karst breakdowns in the Kalush-Golynske and Stebnytske deposits of potassium salt for the period from 1975 to 2016 were selected for the experimental studies to determine the regularities for its development and initiating factors (Fig. 3). The developed

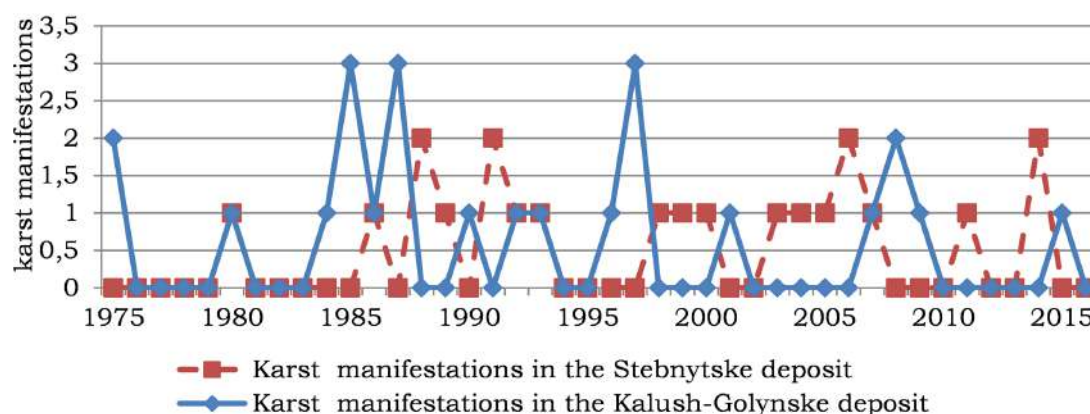


Fig. 3. Time series of karst breakdowns of surface in the Kalush-Golynske and Stebnytske deposits of potassium salt (units)

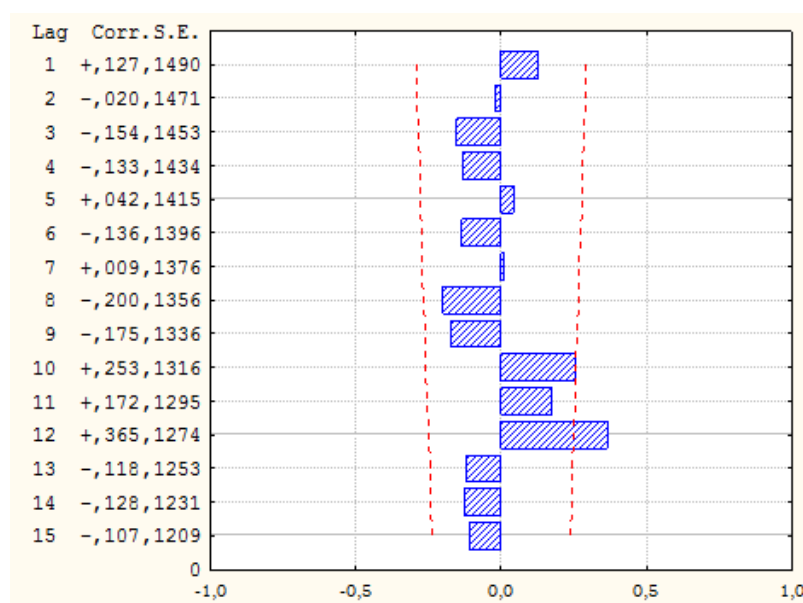


Fig. 4. Diagram of the autocorrelation function for the karst breakdowns in the Kalush-Golynske deposit of potassium salt

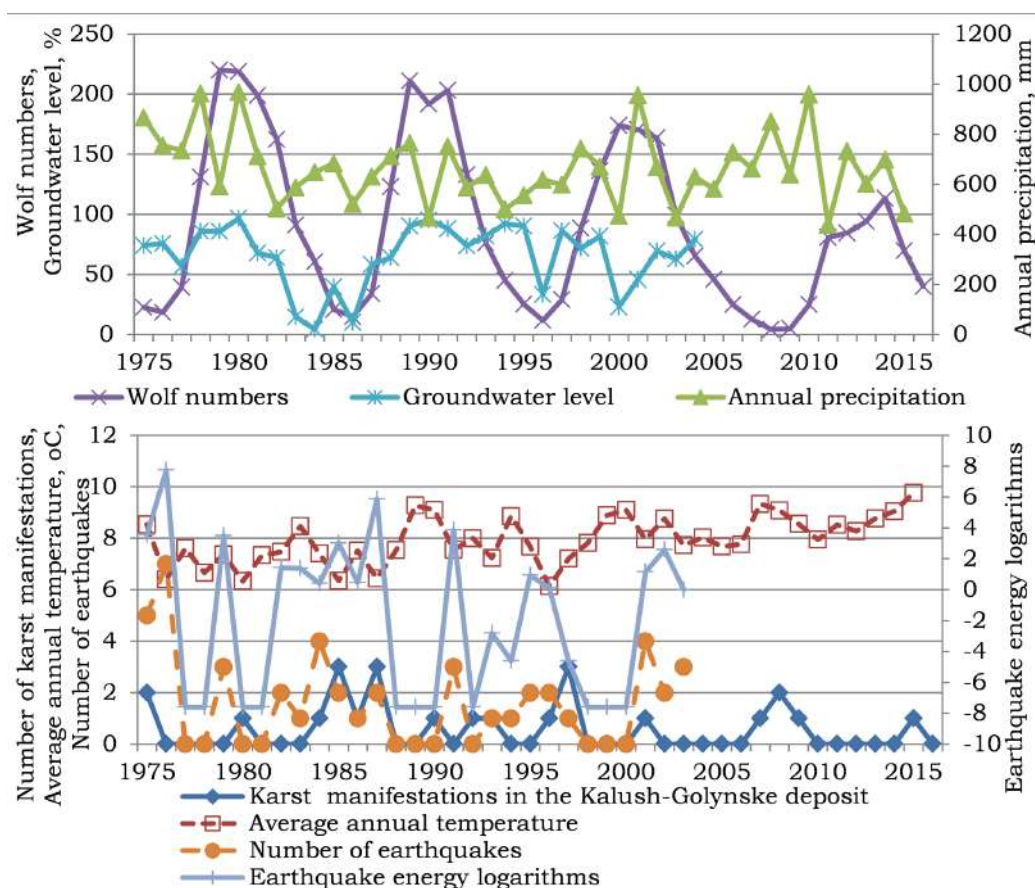


Fig. 5. Time series of karst manifestations in the Kalush-Golynske deposit and factors of karst activation

autocorrelation functions for these series indicate the presence of periodic components in the time of formation of karst dips on the surface. The further analysis is made for the Kalush-Golynske deposit, where the time series have the periodic of 10-12 years (Fig. 4).

Fig. 4 shows the observational time distribution of karst breakdowns and natural factors for the karst formation manifestations in the Kalush-Golynske deposit of potassium salt in the corresponding physical quantities.

Fig. 5 presents the results of autocorrelation analysis that was performed in order to determine the main periods of harmonic time fluctuations of karst breakdown activity and factors for its activation. It was noted that the main periods for a series of karst breakdowns are 10-12 years, for a series of solar activity – about 10-11 years, for the annual amount of precipitation – no regular periodicity is determined (insignificant periodic components appear every 9, 11 and 13 years). Regular periodicity appears every 15 and 17 years in the series of groundwater levels. In the series of the average annual temperatures there is a low periodicity of 8 years. There is a certain periodicity of 8, 11 and 17 years in the series of earthquake energy (logarithms).

Fig. 6 shows the periodograms for the studied time series, which allow us to confirm and clarify the conclusions made during the analysis of the ACF. As it can be seen from the figure, 5 and 10 year those periodic components are clearly distinguished for a series of activities of the karst breakdowns manifestation. For a series of Wolf numbers, the harmonics of 10 years is dominant, a series of the annual precipitation rate – 5 and 10 years. The greatest contribution into a series of logarithms of the earthquake energy is made by the periodic components of 9 years, in a series of groundwater levels – 15 years. There are harmonics with periods of 8 years for series of the average annual temperatures.

Fig. 7 shows the diagrams of the distribution of the cross-correlation function between the series of karst breakdown activity and natural time factors. Based on the analysis of figures, it is possible to make a conclusion about the displacement in time of the series of individual factors with respect to a series of karst activity. Thus, a significant in-phase operation of series is not observed for the series of the annual precipitation amounts. A low inverse correlation (antiphase) is observed with a series of average annual temperatures, and a low direct correlation dependence is observed for a series of earthquake energy. The value of the cross-correlation function for a pair of

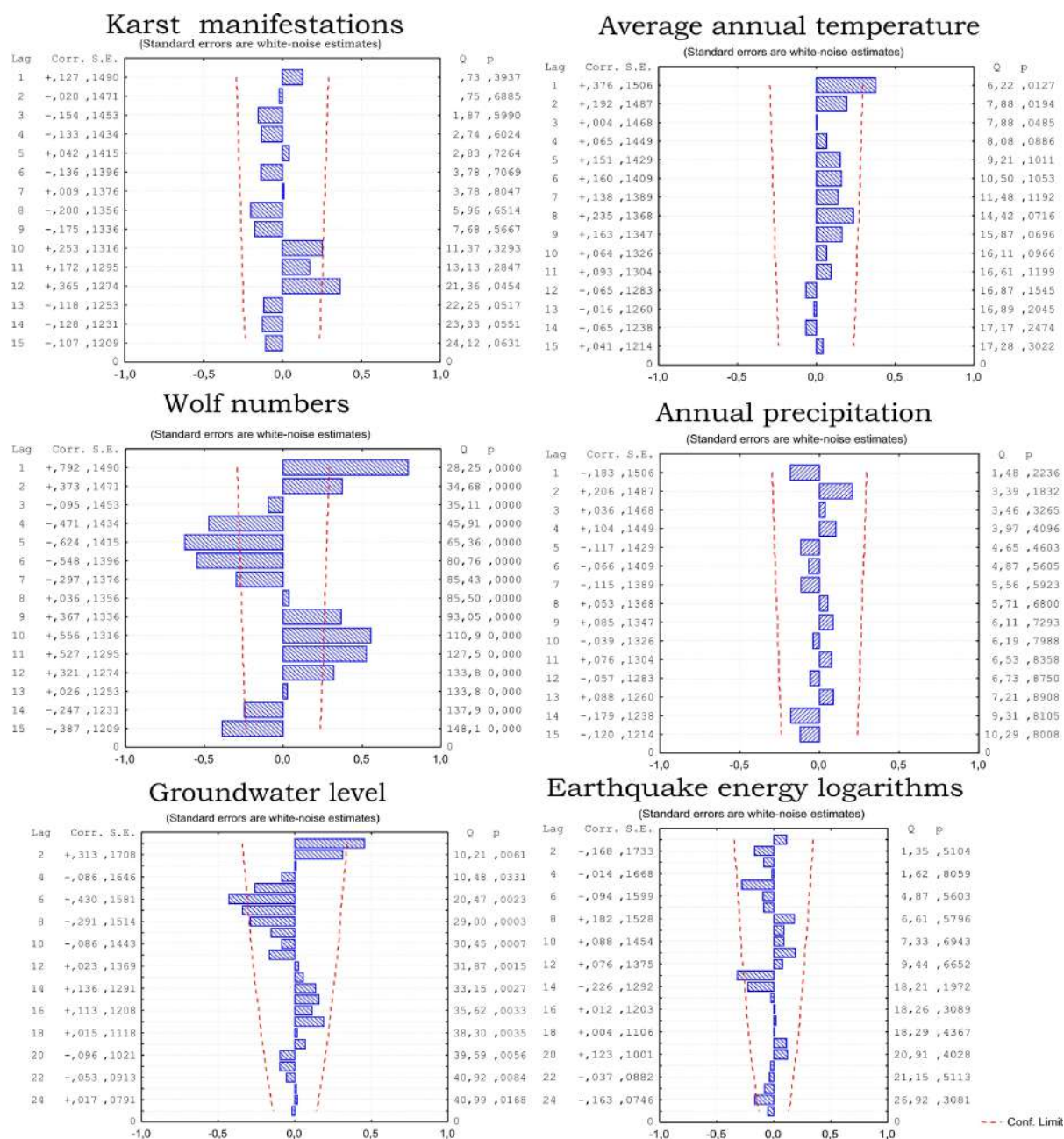


Fig. 6. Diagram of the autocorrelation function for the karst breakdown manifestations in the Kalush-Golynske deposits of potassium salt and natural factors of karst activation

Table 1. The main parameters of the periodicity indications in the time series for the Kalush-Golynske deposit

Time series	Determined periods and displacement, years		
	According to autocorrelation function	According to the Fourier spectral analysis	According to the function of the mutual correlation
Activity of karst manifestation	10-12	5, 10	-
Annual precipitation amount	9, 11, 13	10, 4	-1
Average annual temperature	8	8, 5	0 (reversed)
Wolf numbers	10-11	10	0 (reversed)
Groundwater level	15, 17	15, 10, 4	+1 (reversed)
Logarithm of the earthquake energy	8, 11	9, 4	0 (low)

rows in the number of karst manifestations – the Wolf numbers show that these series are in the antiphase,

and for a series of groundwater levels, the antiphase with a reduction of 1 year is observed.

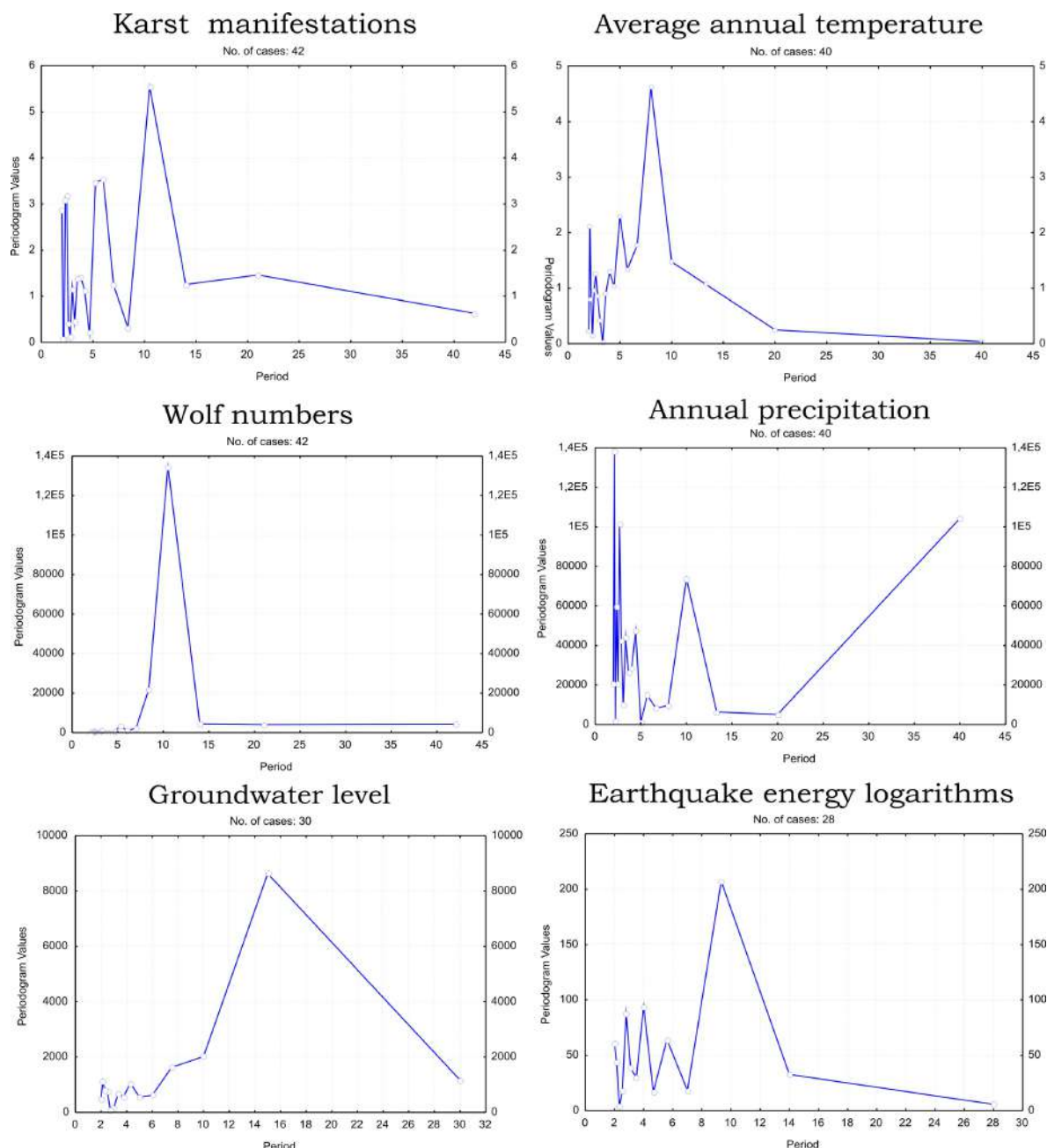


Fig. 7. Periodograms for the karst breakdown manifestations in the Kalush-Golynske deposits of potassium salt and factors of karst activation

Similar developments are made for the karst formation of the Stebnytske deposit.

In order to systematize the obtained data, a table with the main characteristics of time series was created (Table 1).

Conclusions. Within the territory of the abandoned deposits of potassium salt in the Ukrainian Precarpathian region, subsidence and surface dips, which are associated with the presence of mines (in total 35 mln m³), with the development of karst processes, which is caused by a complex hydrodynamic mechanism with the presence of zones of supply, transit and discharge, characterized by different intensity of the formation of karst. A

significant number of failures are associated with geomechanical processes in dedicated mines.

The subsidence of the earth's surface is of a plane nature and it complies with the mining works in time. The intensity of karst breakdowns occurrence on the surface (quantity in time) in the multiannual cycle contains the periodic component, which is expressed for the Kalush-Golynske deposit and is estimated by the correlation analysis every 10-12 years, and by Fourier spectral analysis – 5 and 10 years. For Stebnytske deposit, this component is less expressive and has periods of 8 and 15 years respectively, and also 4, 8 and 14 years. The reasons of the difference are probably consist on the technogenic component of the

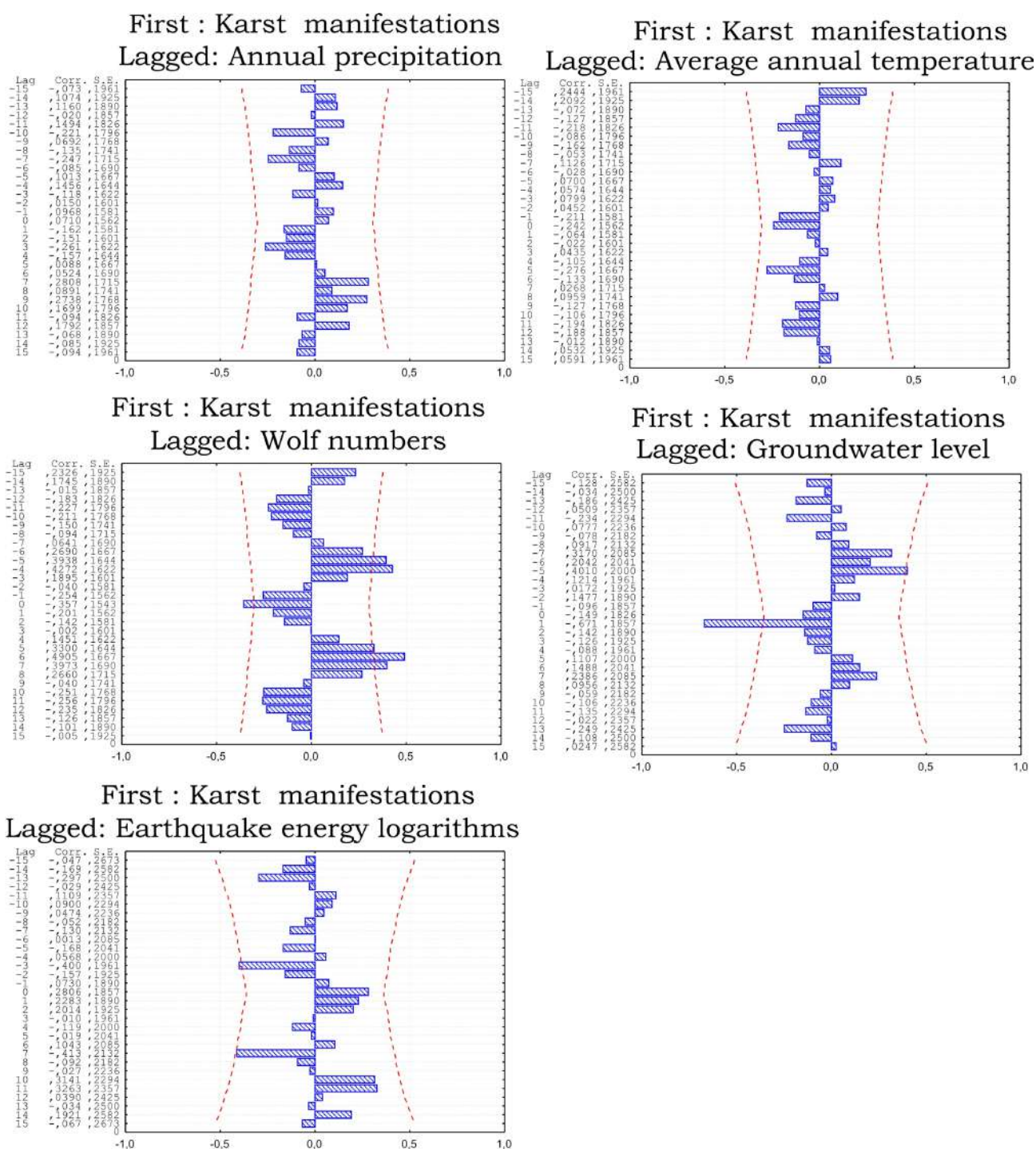


Fig. 8 Functions of mutual correlation for the karst breakdowns in the Kalush-Golynske potassium salt deposit and factors of karst activation

development of these processes, unknown at different stages of the process of wet conservation in these deposits.

The presence of periodic components in the long-term series of karst breakdowns should be associated with the natural factors that indirectly activate karst processes. Such factors are meteorological (precipitation, temperature), heliophysical (solar activity), hydrogeological (groundwater levels), seismological (earthquake energy).

A comparative analysis of the autocorrelation and cross correlation functions, as well as the spectral periodograms of the series of karst breakdowns manifestations and the factors indicated above, show some consistency in the presence of phase displacements.

In order to deepen the knowledge about the nature of karst breakdown processes and their connection with the natural factors, it should be considered expedient to continue research in this direction with the application of modern analysis methods. The

obtained results indicate the presence of a natural component in the development of breakdown manifestations of karst, the influence of which is formed indirectly by natural climatic, heliophysical, seismic, hydrogeological factors. In the future, the results obtained may become part of the prognostic spatio-temporal model of the emergence and activation of karst breakdown processes.

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