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SPATIAL MODELING AND PREDICTION OF ENVIRONMENTAL SITUATION WHEN FILLING DOMBROWSKI QUARRY: GIS APPROACH

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ПРОСТОРОВЕ МОДЕЛЮВАННЯ ТА ПРОГНОЗУВАННЯ ЕКОЛОГІЧНОЇ СИТУАЦІЇ ПРИ НАПОВНЕННІ ДОМБРОВСЬКОГО КАР'ЄРУ: ГЕОІНФОРМАЦІЙНИЙ ПІДХІД

Purpose. The objective of this study consists in development of a digital model of the Dombrowski quarry and calculation of the parameters of the quarry filling dynamics with the brines on the basis of the geospatial data.

Methodology. The geoinformation analysis methods, as well as the mathematical and cartographic modeling on the basis of the GIS technologies, were used in order to achieve the stated objective.

Findings. The topical problem of elimination of the Kalush mining region operating results was considered. Temporal dynamics of water-filling and brine concentration increase in the Dombrowski quarry was analyzed. The dependencies, whose parameters are a basis for predicting the water balance of the object, were obtained. A digital model of the Dombrowski quarry relief, which is the spatial geoinformation basis for prediction and modeling of the filling dynamics, was developed when conducting the studies with the help of the GIS technologies.

Originality. A conception of the analytical GIS spatial modeling and prediction of the emergency situations that can arise within the territory of the Kalush mining region was developed.

Practical value. The absolute critical altitudes of the brine contact with the water-bearing gravel horizon were determined. A possible time of the brine surface rise to the water-bearing horizon and predicted value of the total mineral components concentration for this period were defined.

Keywords: *Dombrowski quarry, spatial modeling, prediction, brines, GIS*

Introduction and problem statement. The Dombrowski quarry, the only mining object in the world where salt extraction was carried out using the open-pit mining method, was put into operation in 1967. The operations in the quarry were conducted according to the transportation system of development with transportation of the stripping rocks into external and internal dumps, and ores – into the crushing department. The development was carried out by two districts – south and north ones. Shattering of the ore and stripping hard rocks was conducted with the help of the drilling-and-blasting method. The soft stripping rocks were developed by steps 10 m high with organization of the selective mining of the topsoil, clay loams, shingles, and gypsum-and-clay rocks. The stripping hard rocks and ore deposits were developed by steps up to 15 m high. Total volume of the developed area is equal to 52.5 mln m^3.

The quarry flooding started after the potassium ore extraction had been terminated. Mechanism of brines formation in the Dombrowski quarry is the result of interaction of the atmospheric precipitations and salt-bearing rocks. Volume of the brines in the quarry depends on the amount of precipitations and watershed area. The watershed area of atmospheric precipitations almost doubled due to drainage termination of the drain ditch and quarry in 2008. At present, it is equal to 360–380 ha. Taking into account the annual average amount of precipitations (700 mm) and evaporation, water inflow into the quarry is equal to approximately 2 mln m^3 per year only due to the atmospheric precipitations. Besides, the whole water inflow from the water-bearing gravel horizon gets into the quarry in the volume of 1 mln m^3 per year after termination of water drainage into external ponds. Thus, general water inflow into the quarry is equal to approximately 3 mln m^3 per year. The accelerated flooding of the Dombrowski quarry can result in inflow of toxic brines that have accumulated in the quarry into the water-bearing horizon that is the only source of domestic potable water supply within the boundaries of the Kalush industrial and urban agglomeration, as well as in anomalous flow pollution of the Limnytsia and Mlynivka Rivers that are tributaries of the transborder Dnister River. Penetration of the salt-saturated aggressive quarry waters into the salt-extraction "Novo-Holyn" and "Khotynska" mines leads to karst activation in the rock massif and destructive deformations within the boundaries of the adjacent settlements.

Analysis of recent research and publications. Taking into account the topicality of the stated problems, there have been conducted a significant number of different

studies [1–4] for the Dombrowski quarry and adjacent territories. They primarily referred to the ways of eliminating negative influence of the objects onto the environment.

When developing the measures for prevention of technogenic threats in the studied region, there arises a problem of spatial-and-time modeling and prediction of the situation evolvement in the region of the Dombrowski quarry location. Its effective solution requires continuous monitoring with the help of the GIS technologies. Modern GIS functional possibilities provide for integration of different type data that were obtained from various sources with the help of diverse methods in the form of a single database with the account of the geospatial binding and scale of the studies. This, in its turn, provides a possibility to conduct full assessment of the situation at all levels (from the local to national ones) and stages of the monitoring [5]. At present, the three-dimensional modeling is actively used for the needs of the geological and geoecological territory studies since it accelerates processing of considerable data volumes, increases the accuracy and velocity of the cartometric operations, and allows utilization of different visualization forms for more effective depiction of real objects [6]. The means of the three-dimensional modeling and visualization are an integral component of the modern GIS (particularly ArcGIS and MapInfo Professional) and software complexes for remote sounding data processing. Taking into account the abovestated, the primary objective of development of the geoinformation local-level monitoring software consists in creation of the digital elevation model (DEM) of the Dombrowski quarry as a spatial basis for further analytical studies.

Unsolved aspects of the problem. It is necessary to mention the existing attempts to create DEM of the Dombrowski quarry on the basis of the vectorized archival topographic plans [7–9]. However, as the authors themselves [8] stated, the developed models require addition of the situational component, field graphical and descriptive information, analytical and calculational apparatus for assessing not only factual but also predicted parameters of the quarry filling dynamics, as well as activation of the model using the data of remote sounding and laser scanning. The complex geoinformation approach and functional completeness of DEM creation determine their further utilization effectiveness. Undoubtedly, computer 3-D models provide a possibility to obtain realistic images of the studied objects and replicate the necessary graphical documents if required. However, if the Dombrowski quarry DEM is to be developed as a primary spatial component of the geoinformation system, such an approach will allow automating solutions of a wide range of engineering, geoecological, and hydrogeological problems: automated water balance control of an object, classification of the monitoring observation data concerning the levels of brines mineralization, assessment of the actual and predicted parameters of the quarry filling, modeling of the hydrogeochemical and geofiltrational processes, etc.

Objectives of the article. The purpose of this study is to create a reliable DEM of the Dombrowski quarry by means of the modern geoinformation systems and technologies, as well as to calculate the parameters of the quarry filling dynamics on the basis of the developed geospatial database.

Presentation of the main research. The materials of the "Kaliinyi Zavod" ("Potassium Plant") SE, particularly the topographic plans of the studied territory at the scales of 1 in 2 000 and 1 in 1 000, were used as input data for creation of the Dombrowski quarry DEM. Scanning and scaling of the bitmap images, as well as elimination of the distortions that emerged while scanning and during the period of the paper copies utilization, were carried out at the first stage of the paper maps processing. Correction of the bitmap images was conducted in the environment of the EasyTrace software complex in accordance with the available intersections of the coordinate grid that allowed obtaining minimum distortions.

After correction of the bitmap images had been completed, their vectorization was carried out. The cartographic image was divided into separate layers, in particular, into altitude marks, relief contour lines, renewed benchmarks of topographic survey, wells, roads, electricity transmission lines, technical facilities and objects. A structure of attributive data was also developed for each cartographic layer. The vectorization was conducted in the EasyTrace environment with the help of the authorized equipment in accordance with the corrected bitmap image with the concurrent introduction of the appropriate attributes. After the vectorization had been completed, verification and correction of the topology of the vector objects and introduced attributive data were carried out.

The next stage was to adjust the obtained cartographic images to a single map with minimum information value losses and provide continuous coverage of the Dombrowski quarry territory. Adjustment of the maps to a single system of coordinates was complicated by the use of the assumed and local systems of coordinates for the original cartographic materials. Consequently, the adjustment was carried out only in accordance with the distinguished landmark points that are clearly visualized on all maps. The accuracy of different objects locations corresponds to the accuracy of the paper copies for the resultant maps; probable error does not exceed ± 0.5 m.

The aerospace images were first downloaded from the tile BingMaps service and the distinguished points that can be identified in the bitmap images, space image, and in-situ were determined in order to solve the problem of adjustment of the cartographic materials to the system of coordinates Pulkovo – 1942. Thereafter, the coordinates of the identified distinguished points were determined in-situ with the help of the GPS survey method. Spatial binding of the created bitmap coverage on the basis of the space image was concurrently carried out together with determination of the points coordinates in Pulkovo – 1942 in the GIS environment MapInfo. Utilization of the specific projection and tile service system of coordinates is a shortcoming of such system. It is necessary to re-register into the system of coordinates Pulkovo – 1942 in accordance with the geodetic survey field data after the initial registration of the bitmap image.

The next stage is to import the vectorized cartographic materials into the GIS MapInfo environment and develop a digital elevation model in accordance with the conventional methodology using the MapInfoDiscover software package. In general, when developing a DEM for the territory with the area of 2.75 km^2, there were used 20 000 dots with fixed values of absolute height that corresponded to the conditional requirements for the survey at the scale of 1 in 1000. Average density was one dot per 12 m^2. The density of dots was equal to approximately one dot per 25 m^2 for the areas with rugged relief. The main distortions for the digital elevation model were obtained from the dots that corresponded to absolute altitudes of wells since the wells plotted on the map had absolute wellhead altitudes as of the date of their construction and the initial relief was changed considerably during the Dombrowski quarry life time. Identification of such data is done through visual study of the three-dimensional surface. When refining a DEM, such points were then excluded from the input data.

The developed Dombrowski quarry DEM (Fig. 1) was created in the form of a regular grid and it can be used in different software complexes that provide for similar type data handling.

The obtained DEM together with the geological and hydrogeological vector terrain maps, as well as the results of the hydrodynamic, geochemical, and geophysical observations, are used as a basis for creation of the analytical geoinformation complex for spatial modeling and prediction of an ecological situation in the process of the quarry filling at different scenarios of events development.

Dynamics of water inflows into the quarry and volume increase of the brines can be described to a high precision by the exponential dependencies whose parameters are a basis for prediction of the quarry water balance.

The dynamics analysis of the Dombrowski quarry water balance allows distinguishing two time periods when operating it. The first one was from the beginning of operation (1967) (altitude +175 m at the south district) to the flooding in 2008 when the levels of the south and north districts became equal (altitude +255.4 m). At this period, the quarry filling was restrained with the help of artificial interception of water inflows, water drainage from the circular drain ditch, injection of brines into the quarries, etc. The second period started after the flooding in 2008 when the south and north quarry fields were connected in a hydraulic way and it has lasted up to now. At this period, the measures for interception of water inflows turned out to be ineffective due to destruction and loss of drainage capacity of the circular drain ditch, increase of watershed area, infiltration recharge as a result of erosion loosening of the overlying rocks, and, probably, production stimulation from sludge and tailings pits. Drainage of brines from the quarry influenced the process of the quarry filling insignificantly. It is natural that during both periods there can be observed a decrease in the rate of growth of the absolute altitudes of the brines surface that is connected with the quarry widening.

In order to make the calculations, the DEM was divided into two parts – north and south districts. The division of the areas was conducted along the barrier in the central quarry part with minimal absolute altitudes that were approximately equal to 253.5 m. When considering the modeling results, it should be taken into account that the north and south districts were connected in 2008. The modeling results are shown in Fig. 2. These are actual volumes before the actual altitude of +276 and after the altitude +277 – predicted filling volumes. The results of the calculations conducted in an automatic mode on the basis of the developed DEM allowed determining the actual filling volume of the quarry as of the end of 2015 that corresponds to the absolute altitude of the brines +276 and is equal to 20.48 mln m^3.

The absolute altitudes dynamics of the brine surface in each of the distinguished time periods of the quarry existence can be quite accurately approximated by the curve

$$H = H_0 + H_1 \cdot (1 - e^{k_H t}),$$

where H_0 is initial absolute altitude for each period, *m*; $H_0 + H_1$ is maximum absolute altitude of the brine surface for each period when the quarry filling rate remains the same, *m*; k_H is rate constant of increase of the absolute altitudes of the brine surface, *year*$^{-1}$; *t* is time, *years* (with zero reference point for each period).

Based on the relation of k_H during the corresponding periods, it can be concluded that, at present, rise of the brines surface absolute altitudes goes five times faster than in the previous period (1967–2008) (Table 1).

The altitude of +278 m that corresponds to the lowest altitude of the water-bearing gravel horizon bottom can be achieved in 2018 if the conditions for preservation of the present structure and balance of water inflows are met. After this, the stratum of brines will create a hydraulic head for the underground horizon fresh waters that will determine the change of the conditions of the water balance of the object and the beginning of the third conditional period of the quazistable quarry filling. The possibility of relative stabilization of the brines surface at insignificant elevation above the oversalt horizon bottom will be the main characteristic feature of this period. The maximum calculated rise of the brine surface absolute altitudes is equal to +281–+288 m in accordance with the analyzed data. Flattening of the curve of the absolute altitudes increase rate (Fig. 3) leads to an assumption that the quarry will not be filled up to the critical altitude of +298 m at the current increase rates of the brine surface absolute altitudes. Instead, there will occur the discharge of the quarry filling fluid body into the stratum of the water-bearing gravel horizon, filling of karst caverns, washing out of slopes, increase of the quarry area and drainage area size of underground waters of the alluvial gravel-and-sand deposits of the Sivka and Limnytsia Rivers.

Two periods can be also distinguished in a similar way if the increase rates of the quarry brine volumes are considered [3]. The experimental and calculated data analysis gives grounds for their approximation with the help of the equation

$$\lg V = V_0 + V_1 \cdot (1 - e^{k_V t}),$$

where V_0 is initial brines volume for each period, m^3; $V_0 + V_1$ is maximum brines volumes for each period

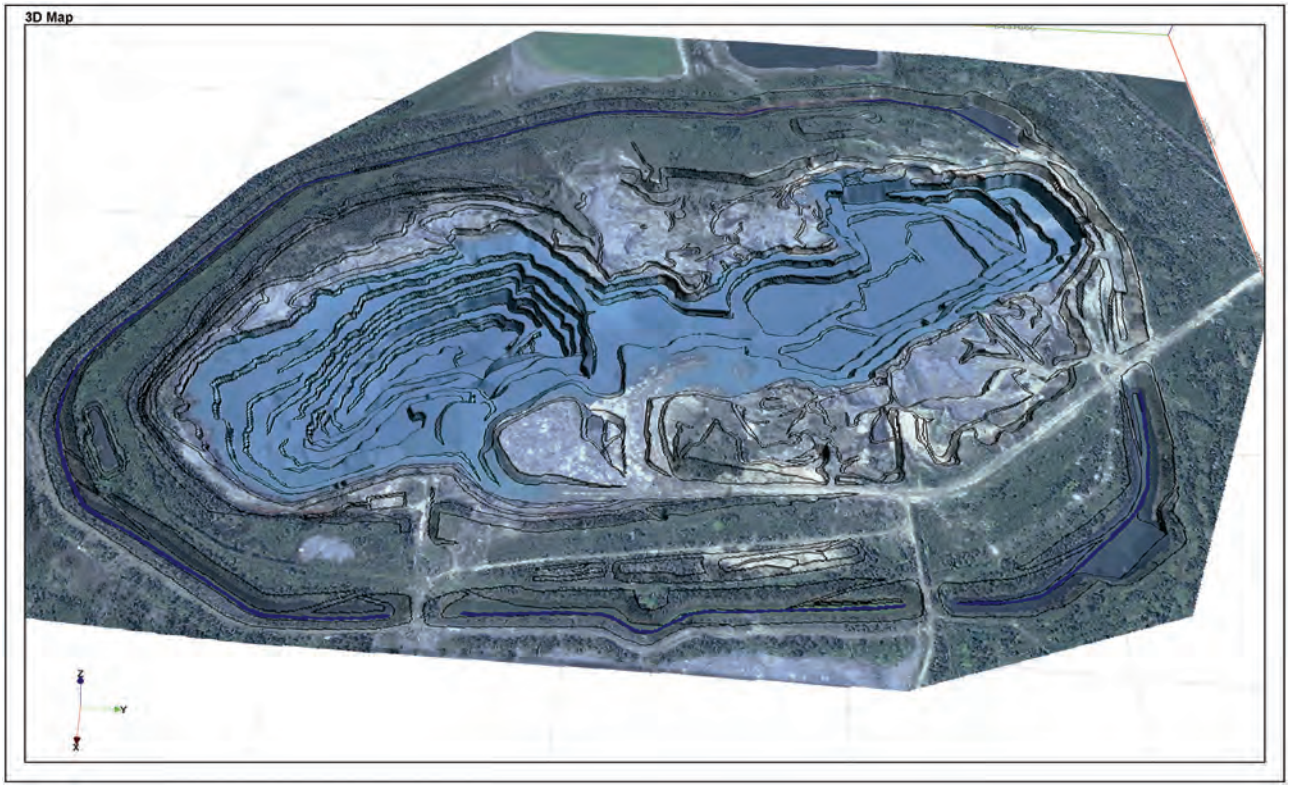

Fig. 1. The three-dimensional DEM of the Dombrowski quarry

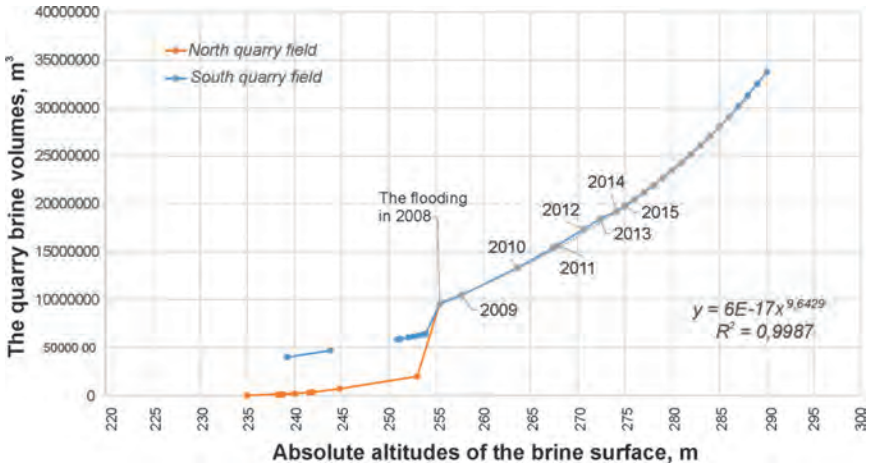

Fig. 2. The prediction curve of the Dombrowski quarry filling

when the quarry filling rate remains the same; k_V is rate constant of the quarry filling with brines, *year*$^{-1}$; t is time, *years* (with zero reference point for each period).

The k_V value for the current period is two times higher than for the period of 1967–2008, correspondingly, the quarry filling rates increased (Table 2). The estimated maximum filling volumes in different periods that were calculated on the basis of the formula

$$V_{\max} = 10^{V_0+V_1},$$

are equal to 11.9–33.1 mln m^3.

Table 1

Calculated dynamics parameters of the absolute altitudes of brine surface

Periods, years	H_0, m	H_1, m	$H_0 + H_1$	k_H, *year*$^{-1}$
1967–2008	175	106	281	0.0346
after 2008	254	34,0	288	0.162

The current conditional period of the Dombrowski quarry existence that started after the flooding in 2008 is characterized by an exponential concentration decrease of the brines surface layer. Lack of data on the brine mineralization and its chemical composition in 2009–2013 does not allow making some definite conclusions; however, the observed tendency to decrease in the brines surface layer mineralization during the time and when their volumes increase can be described with high precision ($R^2 \approx 0.9$) by such exponential dependency

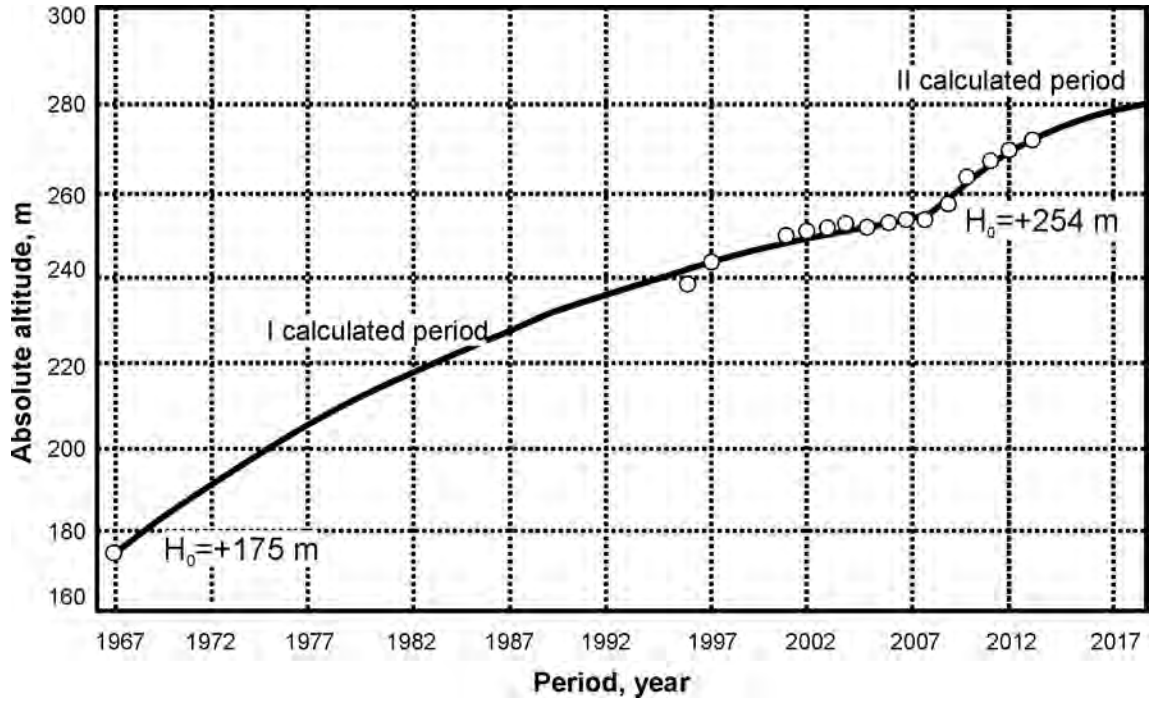

Fig 3. The absolute altitudes dynamics of the brine surface of the Dombrowski quarry

$$S = a \cdot e^{-k(t,\,V)},$$

where S is brine mineralization, g/dm^3; $k(t, V)$ is the constant that characterizes dynamics of the chemical composition formation process during some time or when brine volume increases and has a corresponding dimension *year*$^{-1}$ or m^{-3}.

According to the modeling data, the rise of the brine surface up to the altitude of +278 m (the lowest altitude of the water-bearing horizon bottom corresponds to the brines volume of 21.92 mln m^3 in accordance with the digital model) is predicted to occur in 2018. The calculated prediction also shows that the total predicted concentration of mineral components will be equal to 50–60 g/dm^3 in the period when the altitude of the water-bearing horizon bottom is the highest and if the balance of water inflows is preserved. This fact will determine the beginning of the third conditional period, in which the structure of the quarry water balance will change and, correspondingly, the predicted parameters will require significant correction on the basis of the monitoring observations and experimental determination of the hydraulic (near-slope zone) and filtration (lateral zone of the underground waters flow) parameters of the water-bearing gravel horizon. The authors consider the developed geoinformation system to be an instrument for integration of the monitoring results that will allow automating data processing for assessment and prediction of the state of the quarry and adjacent territories, as well as developing recommendations for the new cycle of observations and preventive measures.

Table 2

Calculated parameters of brine volume dynamics

Periods, years	V_0	V_1	$V_0 + V_1$	k_V, *year*$^{-1}$
1967–2008	0	7.077	7.077	0.0906
After 2008	6.795	0.725	7.52	0.175

Conclusions and prospects for further studies. The problem of elimination of the Kalush mining region operating results is topical for Ukraine. In order to create effective instruments for its solution, there was conducted vectorization of the cartographic materials that allowed obtaining electronic terrain maps and initial data for DEM development. The Dombrowski quarry 3-D model developed in the GIS environment is the basic element for calculating the main parameters of the dynamic, kinetic, and diffusion quarry model that provides a possibility to conduct spatial modeling, its filling, and prediction of emergency situations that can emerge within the territory of the Kalush mining region.

The article presents the results of the geoinformation modeling of the Dombrowski quarry filling with brines on the basis of the actual and predicted data. In particular, the absolute critical altitudes of the brine contact with the water-bearing gravel horizon were determined. The modeling results made it possible to determine the actual quarry filling volume that is equal to 20.48 mln m^3.

The altitude of +278 m (the lowest altitude of the water-bearing gravel horizon bottom) can be achieved in 2018 if the conditions for preservation of the present structure and balance of water inflows are met. After this critical altitude is reached, the stratum of brines will create a hydraulic head for underground fresh waters that will cause filling of karst caverns, washing out of slopes, increase of the quarry area and drainage area size of underground waters of the alluvial gravel-and-sand deposits of the Sivka and Limnytsia Rivers. The volume of the quarry brine, at which outflow of the brines into the water-bearing horizon will begin will be equal to 21.92 mln m^3. At this time, the total concentration of mineral components

in the near-surface zone will be approximately equal to 50–60 g/dm^3. It should also be noted that elevation above the critical level will result in the change of the quarry water balance structure and, thus, in order to develop adequate models and predict parameters of the quarry filling, it will be necessary to conduct additional monitoring observations. The main element of the monitoring system should be the GIS. This will allow performing three-dimensional modeling and actualization of the observed object state on the basis of the obtained information.

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Мета. Створення цифрової моделі Домбровського кар'єру та розрахунок параметрів динаміки заповнення кар'єру розсолами на основі геопросторових даних.

Методика. Для досягнення поставленої мети застосовано геоінформаційні методи аналізу, математичне та картографічне моделювання на основі ГІС-технологій.

Результати. Розглянута актуальна проблема ліквідації наслідків діяльності Калуського гірничопромислового регіону. Проаналізована часова динаміка водонаповнення та зростання концентрації розсолів Домбровського кар'єру. Отримані залежності, параметри яких є основою для прогнозування водного балансу об'єкту. У ході досліджень засобами ГІС-технологій створена цифрова модель рельєфу Домбровського кар'єру, що виступає просторовою геоінформаційною основою прогнозу та моделювання динаміки наповнення.

Наукова новизна. Запропонована концепція аналітичної ГІС просторового моделювання та прогнозування надзвичайних ситуацій, що можуть виникнути на території Калуського гірничопромислового регіону.

Практична значимість. Встановлені критичні абсолютні відмітки контакту розсолів із водоносним гравійно-гальковим горизонтом. Визначено ймовірний час підняття дзеркала поверхні розсолу до водоносного горизонту та прогнозне значення сумарної концентрації мінеральних компонентів на цей період.

Ключові слова: *Домбровський кар'єр, просторове моделювання, прогноз, розсоли, ГІС*

Цель. Создание цифровой модели Домбровского карьера и расчет параметров динамики заполнения карьера рассолами на основе геопространственных данных.

Методика. Для достижения поставленной цели использованы геоинформационные методы анализа, математическое и картографическое моделирование на основе ГИС-технологий.

Результаты. Рассмотрена актуальная проблема ликвидации последствий деятельности Калушского горнопромышленного региона. Проанализированы временная динамика водонаполнения и роста концентрации рассолов Домбровского карьера. Получены зависимости, параметры которых являются основой для прогнозирования водного баланса обьекта. В ходе исследований средствами ГИС-технологий создана цифровая модель рельефа Домбровского карьера, которая выступает пространственной геоинформационной основой прогноза и моделирования динамики наполнения.

Научная новизна. Предложена концепция аналитической ГИС пространственного моделирования и прогнозирования чрезвычайных ситуаций, которые могут возникнуть на территории Калушского горнопромышленного региона.

Практическая значимость. Установлены критические абсолютные отметки контакта рассолов с водоносным гравийно-галечным горизонтом. Определено вероятное время поднятия зеркала поверхности рассола до водоносного горизонта и прогнозное значение суммарной концентрации минеральных компонентов на этот период.

Ключевые слова: *Домбровский карьер, пространственное моделирование, прогноз, рассолы, ГИС*

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