# MINING

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# PREDICTING THE GEOFILTRATION PROCESSES WITHIN THE CLOSED QUARRY ZONE IN DIFFICULT TECHNOGENICALLY DISTURBED CONDITIONS

**Purpose.** The research purpose is a predictive assessment of the water content of the mined-out quarry cavity under conditions of simultaneous technogenic impact of active quarries and mines based on numerical modeling of geofiltration processes to determine the probability of contact and water saturation of the formed backfill mass over time.

**Methodology.** A numerical geofiltration model implemented in the MODFLOW software package is used to study the hydrodynamic regime of a specified site in the Kryvyi Rih region, where a closed quarry is located, planned for backfilling. The solution of inverse and prognostic problems is applied, in the course of which the adequacy of reflecting the hydrodynamic conditions of the studied area in the geofiltration model has been determined, as well as the predicted rates and nature of the level restoration at the mining site have been obtained.

**Findings.** A complex model of geofiltration processes has been developed and tested, taking into account the technogenic impact of operating quarry and mines, which makes it possible to assess the nature of groundwater level restoration in dynamics. It has been found that in the current situation of the hydrodynamic groundwater regime at the site, the greatest impact is caused by drainage dewatering of mines, which has led to the formation of depression cones and groundwater discharge in a large active quarry and a closed quarry planned for backfilling. It has been determined that if the drainage dewatering of all mining enterprises is completely stopped, which is unlikely, the groundwater level restoration in a closed quarry can occur no earlier than in 50 years, while the dependence of the groundwater level restoration over time is logarithmic.

**Originality.** Based on the modeling of geofiltration processes, an assessment of the groundwater level restoration in a closed quarry is provided during the development of various scenarios for the cessation of dewatering at mining enterprises that have a significant technogenic impact on the hydrodynamic regime. It has been proven that when backfilling the mined-out space of a closed quarry, a monolithic backfill mass will not be prone to a decrease in physical-mechanical characteristics from the influence of aquifers, which will ensure its long-term geomechanical reliability.

**Practical value.** A methodology has been developed for modeling geofiltration processes and restoring the groundwater level of a closed quarry, taking into account the difficult complex technogenic impact of various mining enterprises. The results obtained are important for the predictive assessment of the probability of water saturation of the backfill mass in the quarry cavity and planning of engineering-geological measures for its isolation.

**Keywords:** *quarry, geofiltration processes, groundwater, level restoration, depression cone, dewatering, backfill mass*

**Introduction.** Today, in the context of technological progress, humanity uses a variety of mineral resources on a large scale for infrastructure construction, military affairs, metallurgy, space technology, energy, medicine, etc. [1, 2]. Mining of mineral resources contributes to the economic development of many countries in the world, especially those with raw material-based economies, but at the same time is a source of significant damage to the natural environment. Open pit mining is currently considered the most efficient and cost-effective method due to its high level of productivity and lower initial capital costs for operation. However, it significantly disturbs the earth's surface with quarrying and accumulated waste (waste rock dumps and tailing dumps) [3, 4].

Upon completion of field exploitation, the legislation of many countries obliges subsoil users to reclaim disturbed land and return it to a state close to the natural one [5, 6]. Usually, subsoil users choose simple and inexpensive methods of reclamation from an economic point of view: flooding of quarries, levelling and terracing of quarry walls with subsequent reforestation or agricultural use in shallow quarries [7, 8]. However, in the case of mined-out quarry cavities that are deep and located in industrially developed regions or cities, traditional reclamation methods are inefficient in terms of losing valuable land areas and their possible potential for rational use. In favorable conditions, when there are sufficient and diverse reserves of potential backfill materials near the formed quarry cavities, and the earth's surface above the quarry is capable of bringing economic value to the region development, the use of technologies for the formation of a monolithic backfill mass of quarry cavities [9], characterized by better physical-mechanical properties, can be an innovative and very promising approach to reclamation.

One of the factors [10], that can influence the geotechnical stability and environmental safety of the formed backfill mass of quarry cavities is the influence of aquifers that have been opened and disturbed by quarrying since the beginning of field operation. Studying and predicting the hydrogeological situation during the reclamation of mined-out spaces of closed quarries is an important component of both ensuring the long-term geomechanical reliability of the backfill mass and further assessing of possible aquifer contamination with harmful substances.

The prediction of geofiltration processes in the studied quarry cavity is significantly complicated when there is an additional technogenic impact on the hydrogeological conditions of the site of other operating mining facilities (quarries and mines) [11], which is of scientific and practical value. The quarry cavity planned for backfilling may be in dry conditions due to the functioning of the drainage complexes of the influencing objects. However, over time, when mines and quarries close, drainage stops, allowing groundwater level to restore [12]. It is important to understand the dynamics and nature of the natural groundwater level restoration to predict the probability of their interaction with the backfill mass.

The present research is intended to study geofiltration processes and assess possible water inrush over time, taking into account the complex technogenic impact of other mining facilities in one of the closed and unreclaimed iron ore quarries in the Kryvyi Rih region, which is very promising for construction reclamation using cemented paste backfilling technology.

**Literature review.** The need to maintain a satisfactory state of the earth's surface when mining mineral resources has led to the rapid development of technologies for backfilling underground cavities, which eliminate the negative deformation processes of subsidence of rock mass layers and significantly improve the natural environment by utilizing significant industrial waste volumes. However, the processes of restoring the earth's surface over mined-out quarry cavities using backfilling technologies have not yet become widespread and are not sufficiently studied, which is especially important for industrial regions where the allocation of new land areas is scarce. When using traditional technologies for reclamation of quarry cavities associated with filling with dump waste rock, further use of the restored surface is limited, as the mass is characterized by significant voidness, high filtration properties and subsequent long-term shrinkage over time [13, 14].

Cemented paste backfilling is a new innovative approach that allows utilizing significant volumes of beneficiation tailings and creating a solid and geomechanically stable monolithic mass in the quarry cavity, on the surface of which various infrastructure facilities can be built [15]. Despite its very low filtration properties with constant water inrush into the quarry cavities, the paste backfill mass will gradually become saturated with water, which can lead to a decrease in its strength and deformation properties over time. In such cases, it is important to understand the time period during which water inrush from aquifers may have an impact on the backfill mass, what physical-mechanical properties the backfill mass will achieve during this period of time, and how critical this will be for its stability.

Foreign scientists have experimentally studied the mechanical properties of cemented paste backfilling with water saturation from 0 to 100 %. The research results have shown that the water saturation of cemented paste backfill samples significantly influences the mechanical properties and the evolution of their damage [16]. The negative impact of water saturation is also confirmed by other studies that have proven that the interaction of paste backfill material with water leads to an exponential increase in the weakening coefficient with increasing hardening time and a linear decrease in strength at higher water content [17]. Today, numerous geofiltration models are successfully and reliably used to reproduce the natural and technogenic hydrogeological situation at mining sites [18, 19].

Among the analyzed scientific works, the most common are the studies of geofiltration processes in order to predict the formation of depression cones and the restoration of groundwater level after the completion of mining processes within the boundaries of both mine fields [20, 21], and quarries [22, 23]. In the existing studies, the groundwater level restoration after the completion of mining processes is studied mainly under the influence of a single technogenic object – a mine or a quarry. Thus, scientists have studied the level of spatial distribution of groundwater flow after the depletion of reserves of a large coal quarry, determined the duration of the restoration process, and proposed ways to intensify the restoration and conservation of water resources [24].

Other studies have used numerical groundwater modeling to understand how regional hydraulic gradients, aquifer properties, net evaporation rate, and quarry geometry determine the hydraulic evolution of groundwater-fed quarry lakes, which is of fundamental importance for quarry closure and post-mining land use planning [25]. Groundwater modeling was performed to understand the closure options and how they would result in the formation of quarry lakes, which determines how the landscape can be used after the completion of the mining process. The results show that the time to restore groundwater level after mining increases with a decrease in the aquifer permeability [12]. In [26], the author, based on many years of experience, presents the specifics of using groundwater flow modeling to study the processes of quarry drainage, their flooding and impact on the environment. Some scientists have used numerical modeling of geofiltration processes after backfilling quarries with industrial waste to predict possible migration of harmful substances in groundwater and to develop a system for assessing their impact [27, 28].

The above studies have made a significant contribution to the progress of numerical modeling of geofiltration processes, emphasizing the importance and wide range of problems to be solved related to the prediction of hydrodynamic groundwater regimes to formulate rational approaches to the development of effective measures in the "post-mining" period.

**Unsolved aspects of the problem.** Despite the wide range of problems to be solved in modeling geofiltration processes, the peculiarities of their development under conditions of complex technogenic influence caused by the simultaneous functioning of both quarries and mines in mining regions, where complex open-pit and underground mining is performed, are still insufficiently studied. Moreover, this technogenic impact was not considered in solving problems to further assess the probability of water inrush into the quarry cavity and contact of the hardened monolithic mass with the aquatic medium. The presented research is intended to make a scientific contribution and expand knowledge when solving complex problems in assessing the nature and long-term prediction of the impact of technogenically disturbed mass by operating enterprises on the restoration of the natural hydrological groundwater regime in a closed quarry for further assessment of the risks of groundwater impact on the state of the backfill mass.

**Purpose of this research** is to predict the water content of a mined-out quarry cavity under conditions of simultaneous technogenic impact of active quarries and mines based on numerical modeling of geofiltration processes to determine the probability of water saturation of the formed backfill mass. For the long-term development of the directions for backfilling the mined-out quarry cavities in order to restore the disturbed earth's surface, the study and understanding of the hydrological regime is of key importance for the geomechanical backfill mass stability.

**Methodological aspects of the research.** To solve the problem of predicting water content, a specific iron ore quarry of the former K. Liebknecht Ore Mining Administration on the western outskirts of the city of Kryvyi Rih (47°57′44.17″N, 33°24′3.85″E), closed in the 80s of the *20th* century, is studied, which is unreclaimed and identified as promising for cemented paste backfilling for the restoration and further rational use of the surface for infrastructure construction. Using Google Earth toolkit, the following parameters have been determined:

length – 500 m, width – 270 m, maximum depth – 60 m. The quarry mined martite ore from the Parallel Quarry No. 2 deposit of the sixth ferruginous horizon $k_2^{\,63}$, which outcropped to the earth's surface. As of today, according to satellite imagery, there is no quarry lake in the mined-out space, which indicates dry conditions and is probably associated with the technogenic impact of adjacent mining enterprises: Kryvorizka Mine, Pokrovska Mine, Frunze Mine and Hleiuvatskyi Quarry. Schematic location of the facilities is shown in Fig. 1.

To perform numerical modeling, the basic initial data are determined based on the study of hydrogeological materials of the reports from the mentioned fields (Fig. 1) in the library of the State Research and Development Enterprise "State Geological Information Fund of Ukraine" (Geoinform of Ukraine), which are open for use to citizens of Ukraine. If some of the data is outdated, the predictive data in the reports for the coming decades is taken into account. The hydrogeological situation of these fields in the Kryvyi Rih region has been sufficiently studied in many reports on geological exploration and reserve estimation and is not duplicated in this research.

To predict the water content of the closed quarry of the K. Liebknecht Ore Mining Administration, several scenarios are considered in the numerical modeling, taking into account the completeness of possible changes in the hydrodynamic regime of the research site:

- cessation of dewatering of all mining enterprises and restoration of groundwater level in the studied closed quarry;
- cessation of dewatering in the Pokrovska Mine and groundwater level restoration in the studied closed quarry;
- cessation of dewatering in the Kryvorizka Mine and groundwater level restoration in the studied closed quarry.

To study the hydrodynamic regime of the specified site, a numerical geofiltration model implemented in the MODFLOW 2009.1 software package is used, which is a model of three-dimensional groundwater flow of constant density in a porous medium and is described by the partial differential equation

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t}, \quad (1)$$

where $k_{xx}$, $k_{yy}$ and $k_{zz}$ – are hydraulic conductivities in the direction of coordinate axes $X$, $Y$ and $Z$; $(L/T)$; $h$ – is the searched head function $(L)$; $W$ – is a unit flow rate $(T^{-1})$: for the input flow $W > 0$, for the output flow – $W < 0$; $S_s$ – is the specific capacity of a porous medium $(L^{-1})$; $t$ – time $(T)$.

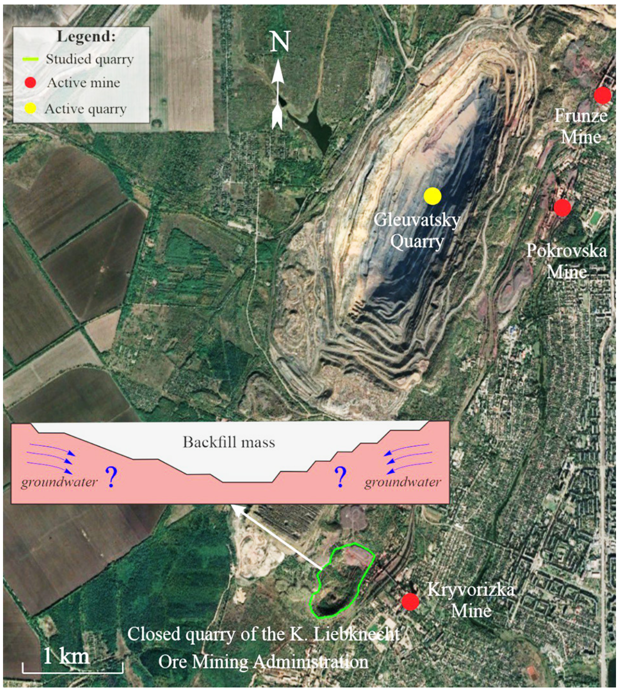


*Fig. 1. Schematic site location with the studied closed quarry and technogenic facilities influencing the hydrodynamic situation*

Equation (1), together with boundary and initial conditions, describes a three-dimensional unsteady groundwater flow in heterogeneous and anisotropic medium, provided that the main directions of hydraulic conductivities coincide with the directions of the coordinate axes. To solve equation (1), the numerical model uses the finite difference method, for which the filtering area is discretized by a rectangular grid into separate calculation blocks. Within each block, there is only one point, called a node, for which the head value is calculated. In the structure of the numerical model, when using one package of internal flow parameters (hereinafter – the package), packages of flow rate characteristics are used, which include feeding within the modeled site and on its contours, infiltration feeding, operation of water intake and injection wells, linear and planar drainage structures, etc. Each package that contains different sources of feeding or discharge is called a flow rate characteristic package, with discharge treated as negative feeding. The package of area-distributed feeding is used to model groundwater recharge both due to infiltration feeding with atmospheric water and inrush to the groundwater surface from other sources of a planar nature. By default, the infiltration feeding in the flow rate package is applied to the uppermost active (water-saturated) layer of the model within each vertical column of the grid calculation blocks. The evaporation package reproduces the effect of plant transpiration, direct evaporation and seepage to the ground surface. The package operation requires information on the value of evapotranspiration and the depth of the groundwater level, below which evaporation is insignificant. The package is based on the following provisions: when the groundwater level is at or above the ground surface (in the upper part of layer *1*), the flow rate from groundwater evaporation occurs at the maximum set evaporation rate; when the groundwater level is below the depth of possible evaporation, or under layer *1*, there is no evaporation from the groundwater surface.

Given the impact of surface water bodies on groundwater, the numerical model uses a package that allows implementing a third-kind boundary condition in the calculation scheme of the modeled site. Surface water bodies can either contribute to the recharge of water reserves in the overall groundwater system without acting as discharge zones for the latter (depending on the hydraulic gradient between the water surface in rivers and the groundwater system), or act as groundwater drainage contours in the area of their hydraulic interconnection.

The modeling methodology provides for the solution of inverse and prognostic problems, in the course of which the adequacy of reflection in the geofiltration model of the research site hydrodynamic conditions has been determined, as well as the predicted velocities and nature of the mining site level restoration have been obtained. The adequacy of the geofiltration model to reflect the existing hydrogeological conditions is assessed by its compliance with the accepted hydrodynamic scheme, the balance components of the model in terms of the convergence of calculated and actual water inrush volumes to the mine workings, as well as the convergence of calculated and actual groundwater levels for the relevant calculation periods.

**Research results and discussion.** Hydrodynamic schematization of the site has been made in accordance with the geological structure peculiarities of the territory, the nature of the occurrence of aquifers and their hydraulic characteristics, filtration properties of water-bearing rocks, the presence of hydraulic interconnection between aquifers, the nature of feeding and discharge of aquifers in the area of their development and on external contours. In accordance with the main regime-forming factors, which in natural conditions are the area-distributed infiltration feeding and drainage impact of surface watercourses, and in technogenically disturbed conditions – the additional spatial location of the main objects of technogenic impact, the modeled site is defined in the contours of the main geomorphological elements, components of the hydrographic network and objects of mining enterprises.

Given the spatial location of these boundaries, the dimensions of the modeled site are defined by rectangular coordinates of 6,526,000 and 6,536,000 m in the latitudinal direction and 5,312,000 and 5,322,000 m in the meridional direction, with a total area of the modeled site of 100.00 km$^2$. The calculation blocks of the numerical model are assumed to be 100×100 m in size, which allows for sufficient detailing of the geometry of the modeled objects, the gypsometry of the surface of the calculation layers, the contours of internal and external hydrodynamic boundaries, as well as the groundwater surface. In accordance with the geological structure of the territory and the nature of the occurrence of aquifers developed within its boundaries, the model structure is reduced to a two-layer water-bearing stratum consisting of a sedimentary stratum and a crystalline mass disturbed by mining operations (Fig. 2).

As the lower boundary of the model, taking into account the achieved depth of mining operations in mines, a conditional surface in an undisturbed crystalline mass at an absolute level of –1,000.0 m is taken. Given that, according to previous studies, the aquifers of sedimentary covering deposits at this site are drained, distributed locally and do not significantly influence water exchange in the zone of influence of the study objects, the sedimentary stratum in the model is represented by a common layer with averaged permeability parameters. According to the specified structure of the modeled site, the permeable layers in the numerical model are represented as follows:

*1 ayer* – water permeable, represented by sedimentary deposits of Quaternary, Neogene and Paleogene age, where groundwater is not widespread due to drainage as a result of the impact of mining operations and is found sporadically; rock thickness varies from 0.0 m in the areas of pinching-out to 100.0 m and more within watershed areas; filtration properties of rocks, determined based on experimental research data, are characterized by filtration coefficient values from 0.00001 to 10.0 m/day;

*2–3 layers* – represented by granites and magnetite quartzites of the crystalline mass; within the modeled stratum, the calculated thickness of crystalline mass disturbed by mining operations reaches 1,100.0 m; filtration coefficients of ore-bearing stratum for undisturbed mass are 0.00001–0.2 m/day; in the zone of location, there is a separate productive stratum, actively mined by various enterprises over the past century, which has a high degree of disturbance and, accordingly, increased water permeability.

As hydrodynamic boundaries on the external contours of the model, remote contours with a supplied feeding ($Q = f(H)$) are taken, determined in accordance with the general hydrodynamic scheme of the studied area. The values of heads at the external boundaries of the model for aquifers of the water-bearing stratum are taken in accordance with the averaged values of water levels and heads within the modeled site, which is due to the determining influence on their hydrodynamic regime of the geomorphological structure and relief fragmentation, as well as the formed regional technogenic impact. The water conductivity at the external boundaries of the model calculation layers is determined from the averaged values of their hydraulic conductivity within the modeled site contours. The values of water conductivity and absolute groundwater levels at the modeled site boundaries for the calculation layers are given in Table 1.

The filtration parameters of the calculation layers are specified according to the data of research performed at various stages of field exploration and engineering surveys for the construction of mining complex facilities. The values of filtration coefficients, elastic and gravity water return are taken for calculation in accordance with the ranges of values given in Table 2.

In the absence of a distinct zonation of hydraulic characteristics within individual calculation layers, their values are set by averaged values over the entire area of distribution of water-bearing deposits with the identification of a zone with increased technogenic disturbance due to mineral mining and, accordingly, increased water exchange and increased values of permeability parameters. The accepted values of the calculated hydraulic characteristics and parameters of the hydrodynamic boundaries of the modeled site are further estimated based on the results of solving inverse problems in a non-stationary setting (Fig. 3).

Infiltration feeding over the model area is specified at the level of 15.0 mm/year, that is about 5.0 % of the total amount of atmospheric precipitation, which, according to the data of the Kryvyi Rih State Geophysical Enterprise UKRCHERMETGEOLOGY for 2018, is 423.0 mm/year (in 2015 – 531.4 mm/year, 2016 – 663.7 mm/year, 2017 – 401.8 mm/year) with an average multi-year norm of 410.0 mm/year. In assessing the natural infiltration feeding, data from surveys conducted at

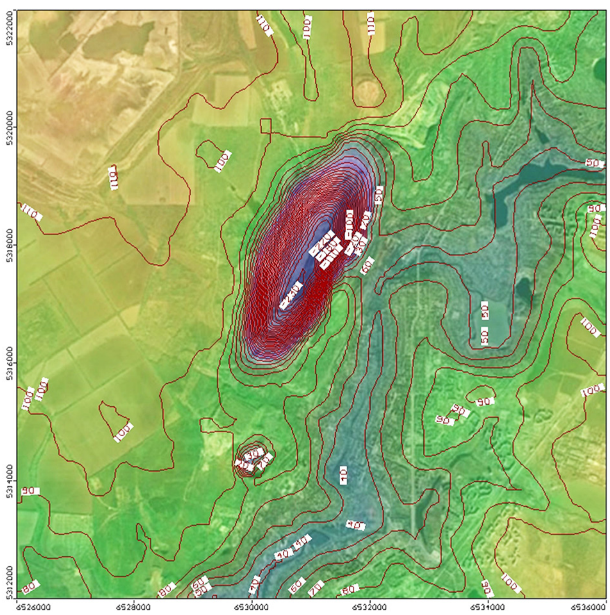

*Fig. 2. Modeled site in the plan*

*Table 1*

Parameters of hydrodynamic boundaries on the modeled site contours

| Hydrodynamic boundary | Absolute level marks, m | Water conductivity, m$^2$/day |
|---|---|---|
| Eastern and western contours | 20.0–15.0 | 0.025–0.5 |
| Northern and southern contours (drainage zone) | –250.0 | 10.0–100.0 |

*Table 2*

Estimated filtration parameters of numerical model

| Calculation layer | Filtration parameters | | |
|---|---|---|---|
| | Filtration coefficient, $k$ ($k_x = k_y/k_z$), m/day | Gravity water return coefficient, μ, unit fraction | Elastic water return coefficient, μ*, unit fraction |
| Layer 1 | 0.1–0.2/0.1–0.2 | 0.10 | $1.0 \cdot 10^{-4}$ |
| Layer 2 | 0.001–0.01/0.001–0.01 | 0.02–0.08 | $1.0 \cdot 10^{-4}$–$1.0 \cdot 10^{-5}$ |
| Layer 3 | 0.001/0.001 | 0.02 | $1.0 \cdot 10^{-5}$ |

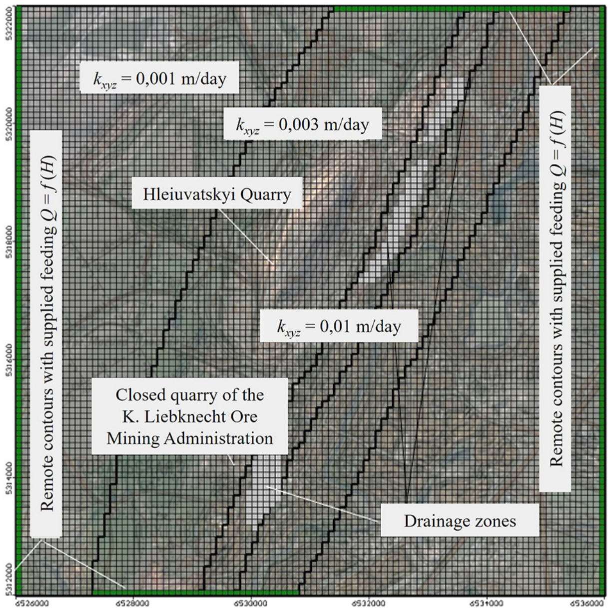


*Fig. 3. Zonation of hydrodynamic characteristics and internal hydrodynamic boundaries*

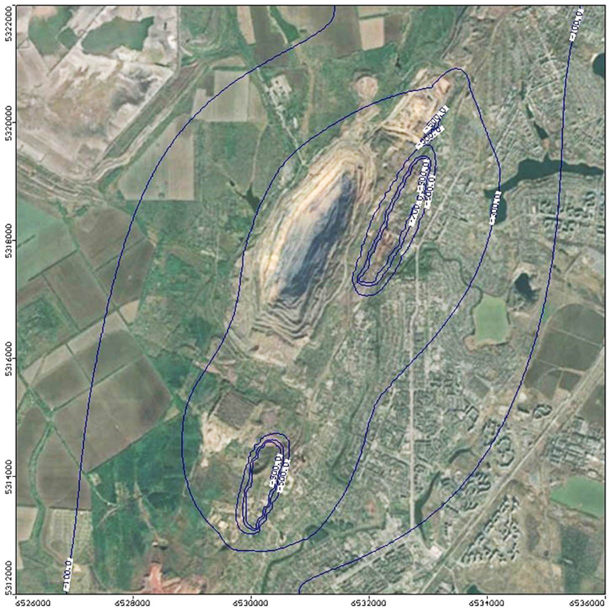

*Fig. 4. Estimated groundwater surface in the conditions of operating mine dewatering of adjacent mine administrations*

the balance stations of Prychornomorskyi artesian basin (Askaniiska, Inhuletska, Shkodohirska, Kazanska) are taken into account.

According to these data, the groundwater recharge rate of the Prychornomoria region, which is confined to loess-like loams, varies from 3.0 to 60.0 mm/year, and the infiltration rate corresponding to this range within the assessed area ranges from 13.0 to 42.0 mm/year. Within the studied territory, areas with significantly different feeding conditions have been identified from intensive impact of mining operations, where surface runoff is disturbed in the conditions of changed landscape – an increase in infiltration rate is due to additional feeding in areas of failures and shears, waste rock dumps, and quarry sites – the averaged increased infiltration rate is up to 60.0 mm/year.

In solving inverse problems and verifying the geofiltration model, data on the groundwater level regime and water inrush volumes to mine workings over the period of operation of mining enterprises are used. The research site represents the location and hydrodynamic interaction of water drainage of many enterprises and is characterised by the existence of a permanent depression zone formed as a result of the complex impact of dewatering, especially from the influence of mines. The inverse problem is solved in a stationary setting under the operating conditions of drainage mine dewatering. The nature of the groundwater level surface for the specified site obtained from the results of solving the inverse problem is shown in Fig. 4.

Analysis of Fig. 4 shows that in the structure of a complex hydrodynamic situation caused by the technogenic complex impact of ore mining, the large Hleiuvatskyi Quarry does not influence the hydrological regime of the studied closed K. Liebknecht Quarry, since it is in temporarily dry conditions from the action of mine dewatering. The main impact is caused by the depression cone of Kryvorizka Mine and partially by the depression cone from the dewatering of Pokrovska and Frunze mines. The Hleiuvatskyi Quarry is able to influence the hydrodynamic regime of the studied quarry provided that all mines stop dewatering. The balance components of the model show the correspondence of the total water drainage at the modelled site to the full-scale data and the predominant role of the contour feeding component (Table 3).

Due to the varying volume of reserves within mine fields and different economic situations, premature closure of mining enterprises may occur. For this purpose, the following options are explored: either a complete cessation of dewatering of all mines or separately in each mine.

The predictive numerical calculations are performed under conditions of unsteady filtration regime, and the time intervals correspond to different periods after the cessation of the water drainage system operation: 365; 730; 1,095; 1,824; 3,650; 10,000 and 20,000 days, respectively, 1, 2, 3, 5, 10, 25 and 50 years. The resulting predicted profiles of groundwater level transformation for 1, 10, 25 and 50 years are illustrated in Fig. 5. Fig. 5 analysis shows a change in the groundwater regime over time, characterized by the gradual disappearance of the depression cone from the action of mine dewatering and the natural groundwater level restoration in the Hleiuvatskyi Quarry and the closed K. Liebknecht Quarry. The dynamics of groundwater level restoration determined based on the results of predictive modelling (Fig. 5) indicates that the level restoration in the first 10 years after the cessation of water drainage in the mines occurs in the immediate vicinity to the depression cone centre.

Based on the results of the determined groundwater levels in different periods of time in the conditions of the closed K. Liebknecht Quarry, the dependences of changes in their dynamics under different scenarios for the cessation of drainage water drainage are presented in Fig. 6.

Fig. 6 analysis shows that with the cessation of water drainage at all mining enterprises, the natural level in the closed K. Liebknecht Quarry can be restored in at least 50 years according to the logarithmic type of dependence. Under the scenario of water drainage cessation at Kryvorizka Mine, located

*Table 3*

Balance components of the modelled site based on the results of solving the inverse problem

| Balance components | Feeding, $m^3$/day | Discharge, $m^3$/day |
|---|---|---|
| Infiltration feeding | 3,907.951 | – |
| Contour loss | 18,554.77 | – |
| Mine water drainage | – | 22,460.15 |
| Total | 22,462.72 | 22,460.15 |
| Error | 2.574 | |
| Discrepancy, % | 0.01 | |

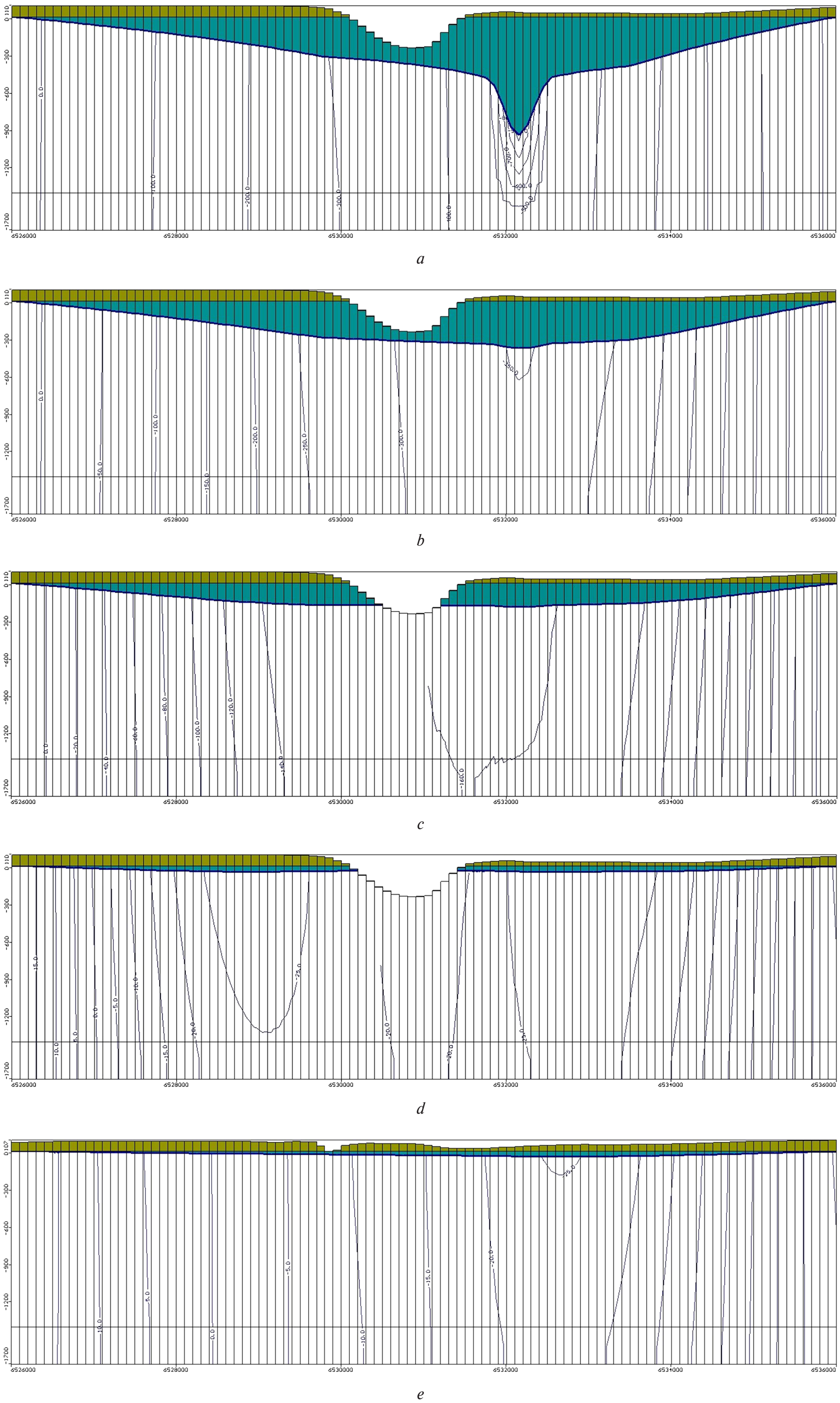


*Fig. 5. Estimated level surface in conditions of level restoration after conditional cessation of mine dewatering of adjacent mines: a – 1 year; b – 10 years; c – 25 years; d – 50 years; e – 50 years – K. Liebknecht Quarry area*

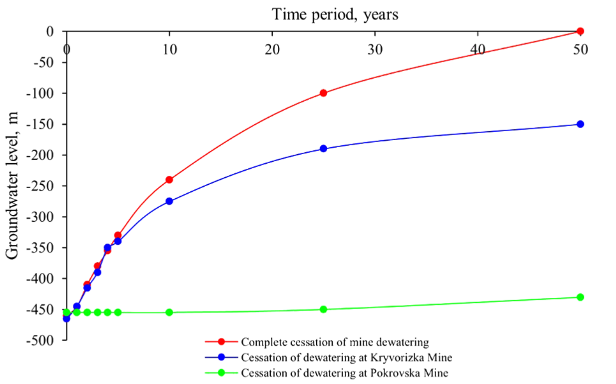


*Fig. 6. Patterns of groundwater level restoration under different scenarios of dewatering functioning at mining enterprises*

in close proximity to the closed quarry, the groundwater level changes from –460 to –150 m over 50 years according to a logarithmic type of dependence, and the mined-out space of the quarry is in dry conditions. Under the scenario of cessation of water drainage from the Pokrovska Mine located to the north, a minimal impact on the change in the natural water level of the closed quarry from –450 to –430 m is expected due to its exponential nature. In this case, water level restoration is slower, and the cessation of water drainage at the Pokrovska Mine has a more intense impact on the Hleiuvatskyi Quarry than on the K. Liebknecht Quarry, while the depression persists much longer and the complete flooding of the quarry does not occur even 50 years after the water drainage cessation. The scenario of complete water drainage cessation at all enterprises is unlikely, so the closed K. Liebknecht Quarry can be in dry conditions for quite a long time. Filling these quarry cavities with monolithic hardening backfill in the absence of water inrush and subsequent water saturation of the backfill mass are favourable conditions for the use of this type of construction reclamation of disturbed land.

For the research site, it is also of scientific interest to study the situations of only the impact of the Hleiuvatskyi Quarry dewatering on the closed K. Liebknecht Quarry in the conditions of complete absence of drainage impact of underground mining operations. The modelling is performed in a steady mode, drainage on the hydrodynamic model is implemented by drains – a hydrodynamic boundary ($Q = f(H)$) with absolute drainage levels of –300 m. The prognostic problem is solved for the same time intervals: 1–50 years, which makes it possible to determine the dynamics of changes in the level regime in the closed quarry zone under the influence of Hleiuvatskyi Quarry mining. It has been found that under these conditions, when the drainage operates, an ellipsoidal depression cone is formed due to the zonality of the disturbed zone permeability with a radius of influence of 2.0–3.5 km. Thus, the small quarry is located on the edge of the zone of depression cone influence from the Hleiuvatskyi Quarry when the covering Cenozoic deposits are drained. Thus, when the Velykohleiuvatskyi Quarry operation is stopped, the closed quarry begins to flood in 10 years, and in 15 years the water level in the quarry will reach a steady position, which is 3 times faster than when all mines cease to dewater.

Summing up the results obtained, it should be concluded that under the conditions of operating dewatering of adjacent open-pit and underground mining enterprises, the closed K. Liebknecht Quarry will remain unflooded. In the event of a complete cessation of water drainage from the adjacent mining enterprises, which is unlikely, the quarry will also remain unflooded for a rather long period of time, up to 50 years, due to the rock mass capacitive component renewal at this site, the restoration of the technogenically disturbed groundwater regime in all aquifers to their natural levels. As indicated in the survey data of previous years, the aquifers of the covering sedimentary deposits are currently drained and cannot serve as a source of water inrush to the quarry until they are restored. It should be added that the thickness of the Cenozoic sedimentary covering deposits at the site of the closed quarry is thin and is fed by infiltration of atmospheric precipitation. If to speak about the natural groundwater level, to which the quarry level will tend to be set in steady conditions after the complete regional depression restoration, it is conditioned, among other things, by local drainage basis at the research site. At this site, the drainage basis is represented by the water level in local watercourses – the Saksahan River is the nearest local watercourse (1 km) with an absolute water level mark of +43 m. This gives grounds to believe that in the absence of a complete dewatering for a sufficient period of time (decades) and when the groundwater regime reaches a natural steady state, the absolute groundwater level in the quarry will not differ significantly from the basis level.

Thus, when filling the mined-out quarry space with cemented paste backfill to restore the disturbed earth's surface and its further use for construction purposes, it has been proven that the quarry will be in dry conditions, water inrush from groundwater and water content of the backfill mass are not expected for more than 50 years from the moment of complete cessation of dewatering of the adjacent quarry and mines, as confirmed by the results of numerical modelling of geofiltration processes in conditions of complex technogenic impact. Over such a long period of time, the backfill mass will be fully hydrated, and its strength, elasticity modulus and water resistance will reach peak values. When backfilling the K. Liebknecht Quarry mined-out space, the monolithic backfill mass will not be prone to a decrease in physical-mechanical characteristics due to water exposure.

Predictive assessment of the probability and dynamics of water inrush to the backfill mass of the quarry cavity provides a lot of valuable information, namely, the need for additional sealing and isolation of the quarry cavity when forming the backfill mass and the need to add specific components to the backfill mixture composition that increase the backfill mass water resistance.

**Conclusions.** The use of numerical modelling of geofiltration processes when backfilling inactive quarry cavities allows for an effective predictive assessment of the probability of groundwater contact with the backfill mass and the negative impact on its physical-mechanical properties, which is important in achieving long-term geomechanical reliability of the restored earth's surface, especially during the construction of infrastructure facilities. In this research, the dynamics of changes in geofiltration processes under the significant technogenic influence of an active large quarry and a number of mines was studied on the example of one of the closed and unreclaimed quarries in the Kryvyi Rih region. It has been found that in the current situation of the hydrodynamic groundwater regime, the greatest impact is caused by drainage dewatering of mines, which has led to the formation of depression cones and groundwater discharge in a large Hleiuvatskyi Quarry and the closed K. Liebknecht Quarry planned for backfilling. It has been determined that if the drainage dewatering of all mining enterprises is completely stopped, which is unlikely, the groundwater level restoration in a closed quarry can occur no earlier than in 50 years, while the dependence is logarithmic. The greatest impact on the change in the groundwater level will be caused by the cessation of water drainage from the Kryvorizka Mine, which is located close to the closed quarry, but it still will not lead to a complete restoration of the natural groundwater level. It has been determined that in the absence of a complete dewatering for a sufficient period of time (decades) and when the groundwater regime reaches a natural steady state, the absolute groundwater level in the quarry will not differ significantly from the basis level. It has been proven that when backfilling the mined-out space of the closed K. Liebknecht Quarry, a monolithic backfill mass will not be prone to a decrease in physical-mechanical characteristics from the influence of aquifers, which will ensure its long-term geomechanical reliability.

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## Прогнозування геофільтраційних процесів у зоні закритого кар'єру у складних техногенно-порушених умовах

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**Мета.** Прогнозна оцінка обводненості відпрацьованої кар'єрної пустоти в умовах одночасного техногенного впливу діючих кар'єру та шахт на основі чисельного моделювання геофільтраційних процесів для встановлення ймовірності контакту й водонасичення сформованого закладного масиву протягом часу.

**Методика.** Для дослідження гідродинамічного режиму визначеної ділянки Криворізького регіону, на якій розташовано закритий кар'єр, що розглядається під закладання, використана реалізована у програмному комплексі MODFLOW чисельна модель геофільтрації. Застосоване вирішення обернених і прогнозних задач, у процесі яких була встановлена адекватність відображення в геофільтраційній моделі гідродинамічних умов досліджуваної території та отримані прогнозні швидкості й характер відновлення рівнів на ділянці ведення гірничих робіт.

**Результати.** Розроблена та апробована складна модель геофільтраційних процесів з урахуванням техногенного впливу діючих кар'єру та шахт, що дозволяє у динаміці оцінити характер відновлення рівня підземних вод. Встановлено, що у сформованій ситуації гідродинамічного режиму підземних вод ділянки найбільший вплив має дренажне водопониження шахт, яке призвело до утворення депресійних воронок і розвантаження підземних вод у крупному діючому кар'єрі та закритому кар'єрі, що розглядається під закладання. Встановлено, що за умов повного припинення дренажного водопониження всіх гірничих підприємств, що є малоймовірним, відновлення рівня підземних вод у закритому кар'єрі може відбутися не раніше, ніж через 50 років, при цьому залежність відновлення рівня із плином часу має логарифмічний характер.

**Наукова новизна.** На основі моделювання геофільтраційних процесів надана оцінка відновлення рівня підземних вод у закритому кар'єрі при розвитку різних сценаріїв припинення водопониження на гірничих підприємствах, що чинять значний техногенний вплив на гідродинамічний режим. Доведено, що при закладанні виробленого простору закритого кар'єру монолітний закладний масив не буде схильним до зниження фізико-механічних характеристик від впливу водоносних горизонтів, що забезпечить його довгострокову геомеханічну надійність.

**Практична значимість.** Розроблена методологія моделювання геофільтраційних процесів і відновлення рівня підземних вод закритого кар'єру з урахуванням складного комплексного техногенного впливу різних гірничих підприємств. Отримані результати є важливими для прогнозної оцінки ймовірності водонасичення закладного масиву в кар'єрній пустоті та проєктування інженерно-геологічних заходів з її ізоляції.

**Ключові слова:** *кар'єр, геофільтраційні процеси, підземні води, відновлення рівня, депресійна воронка, водопониження, закладний масив*

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