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ASSESSMENT OF THE INFLUENCE OF TECHNOGENICALLY TRIGGERED HYDRODYNAMIC PROCESSES ON GROUNDWATER CONTAMINATION IN THE AREA OF KALUSH MINING INDUSTRY BY APPLYING GEOPHYSICAL METHODS

The aim of the research is to substantiate the scientific foundations of an integrated approach to solving environmental and geological problems related to groundwater salinization in the Kalush mining region; quantitative evaluation of the dynamics of such salinization and its relationship with the river system based on geochemical and geophysical observations. The relevance of the research is determined by the need to solve the following tasks: 1) identification of the sources of the groundwater contamination; 2) determination of saline areas, including settlements within which drinking water horizons become unsuitable for the direct use; 3) characteristics of the dynamics, that is, the degree of salinity and the rate of its changes in space and time; 4) determination of the danger to the operation of water intake facilities; 5) determination of the risk of contamination of the river basin. The methodology consists in establishing the correlation between hydrogeochemical and electrometric observations, as well as determining the transition patterns from measurements of electrical resistance to the groundwater salinity. It also includes creating spatio-temporal models of groundwater salinity dynamics and assessing the risks of surface watercourses contamination taking into account its main sources and providing initial data for making management decisions. With the help of the hydrogeochemical observations (the groundwater mineralization) and electrical exploration (measurement of electrical resistance), correlations were established between the geophysical characteristics inherent in the aquifer and the groundwater mineralization. As a result, this made it possible to concretize the sources and determine the area and degree of salinization according to the planar geophysical surveys. Regime observations allowed us to establish the movement direction and speed of the salinity front. The obtained quantitative characteristics of the salinization dynamics of the aquifer allowed calculating the contamination risks of the Limnytsia and Dnister Rivers. The scientific novelty consists in the further development of the methods for assessing underground mineralization based on the results of geophysical research, including the method of electrical exploration. For the first time, spatio-temporal models of the groundwater mineralization dynamics in the territory of the Kalush mining region (KMR) were created. In addition, the assessment of the risks of the surface watercourse contamination (the Limnytsia and Dnister Rivers) was given, taking into account the main sources of contamination within the KMR. The application of the obtained results makes it possible to quickly research the areas associated with probable contamination of the territory, to provide initial data for further planning and management actions. A reliable forecast allows envisaging the measures for reducing the environmental load on the aquifer, which is the only drinking horizon for the town of Kalush.

Key words: salinity; electrical resistance; aquifer; mineralization; observation wells; pollution sources; water intake system.

Introduction

The problem of groundwater and surface water contamination almost always arises in the territories of existing or exhausted mineral deposits. To a large extent, this applies to salt deposits, where the contamination of the underground aquifers, as well as surface landscape objects and morphological forms, is intensified due to the dissolution of rock or potassium salt. The brine of underground workings and quarries, salt dumps, tailing ponds, accumulating tanks, etc. can be considered as pollutants. A trivial method for assessing groundwater contamination is the selection and protection of the borehole, water, and watercourses with the further laboratory determination of general mineralization and element-by-element analysis. Regime observations of the groundwater levels allow establishing the paths and speed of migration of pollutants.

Recently, geophysical research has been actively used as a method for determining groundwater salinity. Thanks to the latter, an operational expert assessment of the salinization degree was conducted with its detailed differentiation. It was possible due to using a dense network of geophysical observations in the presence of individual parametric wells.

The purpose of this article is to substantiate the scientific basis of an integrated approach to solving the problem of determining areas of groundwater salinity at a particular site; quantify the dynamics of such salinity and its relationship with the annual system based on the analysis and synthesis of research data and the findings of the authors' observations. At the same time, the expediency of involvement in complex geophysical research is emphasized. From a practical point of view, the relevance of the work is determined by the need to solve the following tasks: 1) identification of groundwater contamination sources; 2) definition of the salinization areas, including settlements, within which drinking water horizons have become unsuitable for direct use; 3) characteristics of the dynamics, that is, the degree of salinity and the rate of its changes in space and time; 4) determination of the danger to the performance of water intake facilities; 5) assessment of the risk of contamination of the river basin.

Review of literature sources in the field of research (state of the problem)

Considering ecological and geological issues of the exploitation of salt deposits in the world is mainly associated with the peculiarities of development and activation of karst processes in mining areas. In total, more than 80 cases of accidental damage to mines have been recorded in world practice for the entire period of underground salt mining [Pavliuk, 2011; Haidin and Rudko, 2016]. Examples are large-scale accidents in Congo (1977), Russia [Sol-Iletsk, 1983, 2010; Solikamsk, 1995; Berezniaky, 2007], Germany (Ronenberg, 1976), and Ukraine [Stebnyk, 2017, Solotvyno, 2008, 2012] and other countries of the world. Karst phenomena are always associated with the activity of groundwater, which is the subject of this study. Because salinization is studied in a much broader field than in the development of salt deposits, we will turn to a corresponding range of scientific works. First of all, we will appeal to the publications that cover geophysical methods of karst research and groundwater contamination due to the development of natural and man-made karst. According to the review of literature data, one of the first scientists who substantiated and practically proved the possibility of studying karst phenomena and, in particular, the assessment of groundwater mineralization according to geophysics (electrical exploration) was a Russian scientist O. O. Ogilvi. He described this in the famous monograph “Karst Geophysics”, 1956. Further, his findings were developed in the works of other Soviet researchers and described in the fundamental monographs [Kobranova, 1962; Melkanovitskyi et al., 1982; Methods ..., 1985; Lyakhovitskyi et al., 1989]. Powerful research in this direction was carried out by Polish geophysicists. In particular, in the work [Bialostocki et al., 2007], in the section “Application of the electric pore method in geology and environmental protection”, a classification table is provided, in which, among all the tasks, the determination of the degree of the groundwater mineralization is formulated. In [Bialostocki et al., 2008], this task is developed to “identify contamination zones based on direct measurements in the case of an anomalous decrease in electrical resistivity, possibly based on cyclic measurements in a monitoring system”. The research papers [Bialostocki et al., 2006, Pacanowski et al. 2014, Sappa, 2012, Oyedele, 2009, Jansen, 2011, Hamdan et all, 2010, Paine et al., 2012] discuss the issues and provide the examples of effective mapping of salinity by applying geophysical methods, namely, the method of resistivity and electromagnetic induction in coastal zones in the territory of California (USA), Nigeria, Egypt, Italy. There, a good correlation between measurements of total mineralization and resistivity is established as well as the effectiveness of the integration of the resistivity method in the modification of vertical electrical soundings, seismometry and electrical tomography for visualization of salinity zones in karst formations.

There are a lot of similar sources in world literature, and it is impossible to list them all. In the future, we will dwell in more detail on the analysis of monographs, which quantitatively demonstrate the possibility of obtaining characteristics of water properties of a wide range of rocks during united hydrogeological works on the one hand and electrometric ones on the other.

Meanwhile, we will focus on the relationship between the mineralization of groundwater and the electrical resistivity of rocks saturated with aqueous solutions. To illustrate this connection, let us consider the model and practical dependencies of the distribution of specific resistivity ρ on water salinity M : $\rho = f(M)$.

The monograph [Kobranova, 1962] presents a family of dependencies for aqueous solutions. From their consideration, an important conclusion is made about the difference in dependencies $\rho = f(M)$ for various compositions of solutions and, accordingly, for different lithological varieties of rocks, which to a certain extent are characterized by the groundwater of one composition or another.

That is, according to the above graphs, it is possible to determine the concentration of salt by electrical resistivity under one condition that the chemical composition of groundwater is known in advance. In real research conditions, such a requirement is not feasible.

In the research work [Methods..., 1985], graphs are provided for assessing the dependence of mineralization on electrical resistivity in conditions of pebble and sandy-clay sections.

Analyzing the graphs, it is clear that only with little mineralization $(M < 10\text{g/l})$ does lithology affect the electrical resistivity of rocks. At higher values M , it is the mineralization that has the main effect on their resistivity, regardless of lithology. These graphs were obtained in the laboratory conditions, and the measurements were made in simulated wells with the ideal sorting of rocks, which does not happen in nature. Real correlation dependencies $\rho = f(M)$ for different regions of the former Soviet Union and different lithological components obtained from geophysical measurements in the field are illustrated in the monograph [Melkanovytskyi et al., 1982]. They are quite similar and on a bilogarithmic scale can be represented in the first approximation by a family of straight lines intersecting at an angle of about 45 to the coordinate axes, namely $\lg M = \lg A - \lg \rho$, where $\lg A$ is a constant value determined by the lithological composition of rocks.

Based on the visual analysis of these dependencies, the following conclusions can be drawn: 1) for each territory and each lithological complex of rocks, we should look for correlations present in this territory between the electrical resistivity of aquifers and the groundwater salinity; 2) since the combination of the ionic composition of groundwater and lithology is unpredictable, we should not expect the same dependencies for rocks of the same lithology; 3) the criterion for the reliability of correlation graphs is their belonging to a family of subparallel lines with an angle of inclination close to 45 while digitizing coordinate axes on a logarithmic scale. In conclusion in the literature review, we can note that in Ukraine, where the authors of the article work, the use of geophysical methods for mapping aquifers by mineralization is limited. In recent years, we have observed only a few scientific works, such as those [Onyschuk, 2005, Demkiv et al., 2014, Shurovskyi et al., 2012, Bagriy et al., 2013, Onyschuk, 2006, 2010].

Aim

The aim of the research is to substantiate the scientific foundations of an integrated approach to solving environmental and geological problems related to groundwater salinization in the Kalush mining region; quantitative evaluation of the dynamics of such salinization and its relationship with the river system based on geochemical and geophysical observations.

The aim of the further research provided in the article is the following. Firstly, the task is to check the efficiency of the above method for determining groundwater salinity by the distribution of electrical parameters under the specific conditions of salt deposits. Secondly, we should determine the empirical dependencies. Thirdly, the study will define how these dependencies can be used for practical purposes.

By the above-mentioned statements, further studies are presented in the following sequence: characteristics of the research subject, ecological and geological problems, geological and hydrogeological characteristics of the territory, characteristics of water intake systems, geomorphology, groundwater levels and directions, aquifer salinity estimates, correlations between salinization and geophysical parameters, informativeness of salinity maps compiled according to the VES (vertical electro sounding) method, analysis of the dynamics of groundwater salinity according to regime observations, the threat of contamination of the Dnister river basin.

Characteristics of the subject of research

The subject of research is the processes of groundwater and surface water contamination in the Kalush mining region (KMR), which is located within the mining branches of the largest reserves of raw materials in the Carpathian region of Ukraine - Kalush-Golynskyi potassium salt deposit (Fig. 1). The research area belongs to the Pre-Carpathian lowland, the surface of which is a flat plain. The main part of the described territory is located within the Kalush basin with accumulative-plain relief. It covers the valley of the river Limnytsia with its tributaries which belong to the basin of the Dnister river.

On the territory of KMR, the following main industrial complexes are singled out:

Dombrovskyi quarry. The period of operation was 1967–2003. During this time, 35.4 million m^3 of overburden rocks and 14.7 million m^3 of potash ores were extracted from the quarry; a total of 50.1 million m^3 of the rock mass. The quarry is self-flooding at an average rate of approximately 2.5 million m^3 per year. Currently, about 32 million m^3 of brine is concentrated in the quarry. The absolute mark of the quarry coast is about 300 meters, and the maximum depth from the earth's surface is 92 m. The absolute mark of the brine surface as of 2021 is 284.5 m. The mineralization of brines ranges from 10-20 g/dm^3 in the subsurface part to 400-430 g/dm^3 in the bottom part.

Mine "Kalush". The operation period was 1967-1978. It is divided into four minefields: Northern Sylvinite, Northern Cainite, Central Cainite, and Khotyn Sylvinite. The depth of development of minefields, respectively, is 160–440 m, 100-260 m, 60–250 m, 140–270 m. The total size of the cavities of the mine “Kalush” is 7.4 million m^3. The cavities were filled with solid material (92.5 % of the total size) in three minefields and remained dry in the Khotyn minefield (7.5 % of the total size).

Mine “Novo-Golyn”. The period of operation was 1966–1995. It is divided into two minefields: “Eastern Golyn” and “Sivka-Kaluska”.

The depth of development is 66–270 m. The total size of cavities is 12.6 million m^3. Most of the mine cavities (96 %) are filled with undersaturated brine (approximately 250 g/l).

Mine “Golyn”. The period of operation was 1930–1972. The depth of development is 70–250 m. The total size of cavities is 1.7 million m^3. The mine is preserved in a dry state.

Thus, in just three mines there are 21.7 million m^3 of voids – flooded, filled with solid material, or dry. During the operation of the quarry and mines, salt dumps, tailing ponds and accumulating tanks were formed as auxiliary production facilities.

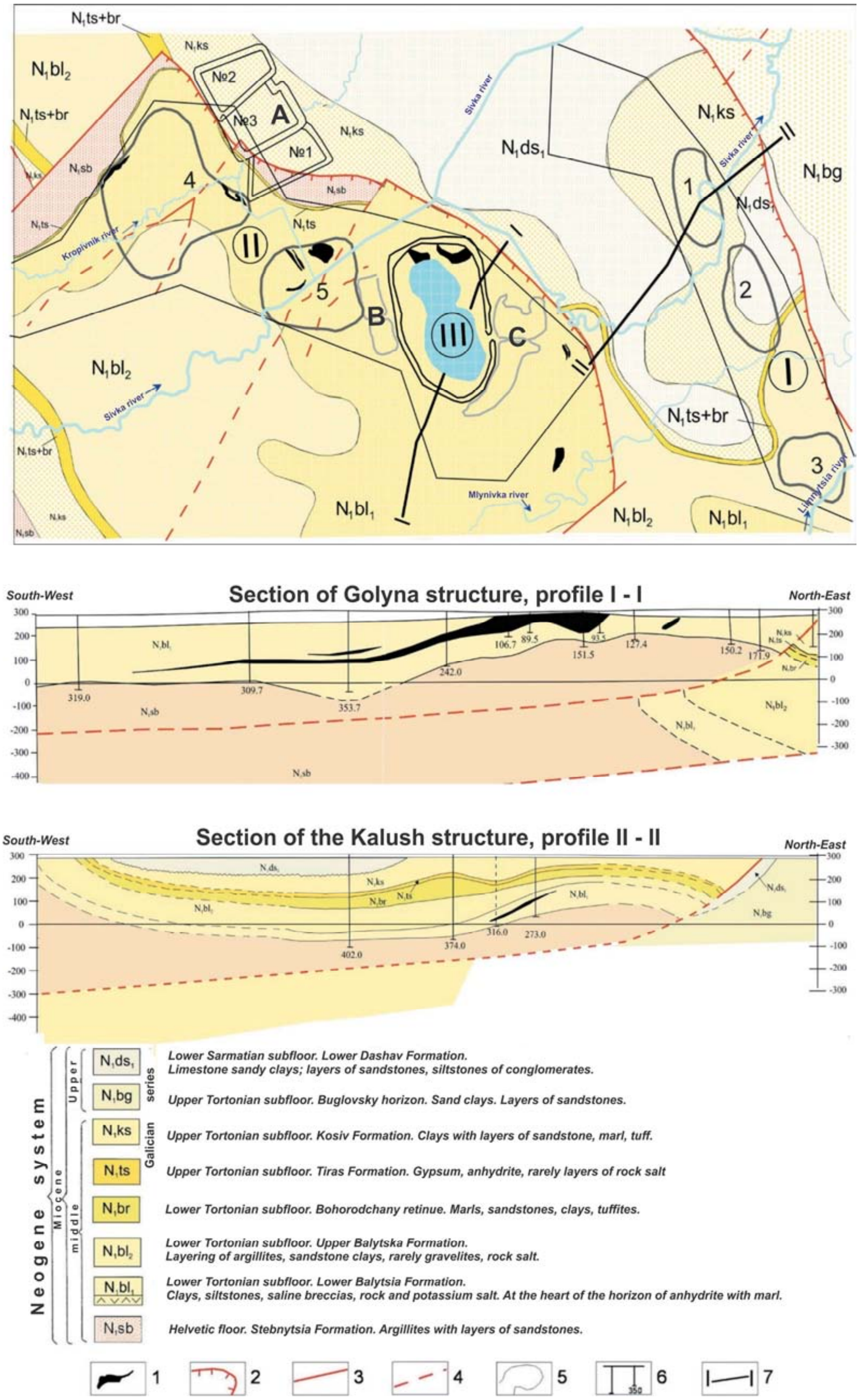


Fig. 1. Location and geological structure of the Kalush-Golynskyi deposit of potassium salt.

1 – deposits of potassium salts; 2 – thrust lines; lines of tectonic transverse faults; 3 – established; 4 – expected; 5 – boundaries of stratigraphic units; 6 – drill wells by sections; 7 – lines of geological sections; A – tailing ponds No. 1, 2, 3; B – accumulating tanks; C – salt dumps No. 1, 4; mining branches of mines on the geological scheme: I – mine "Kalush", 1 – northern kainite minefield, 2 – central kainite minefield, 3 - Khotyn mining field; II – mine "Nova Golyn", 4 – minefield "Eastern Golyn"; 5 – minefield "Sivka Kaluska"; III – Dombrovskyi quarry.

Salt dumps, tailing ponds and accumulating tanks. Two salt dumps contain mainly overburdened rocks of the quarry. They consist of sandy-clay rocks with a significant content (up to 30 %) of sodium chloride. The salt dump No. 1, with an area of 0.48 km^2, contains 11.3 million m^3 of rocks.

The height of the dump is 55 m. 0.035 km^2 has been restored. The salt dump No. 4, with an area of 0.39 km^2, contains 7.4 million m^3 of rocks. The height of the dump is 30 m. 0.341 km^2 has been restored.

Tailing ponds are artificially constructed tanks for the accumulation of the so-called "tails" of unused highly mineralized waters. The tailing pond No. 1, which covers an area of 0.54 km^2, contains halite waste with a volume of 12–14 million m^3. The tailing pond has been partially restored by covering the surface with a layer of loam and gypsum clay rock 1.5 m thick. The tailing pond No. 2 with an area of 0.48 km^2 is filled as follows: a solid phase – 9 million m^3, a liquid one – 1.7 million m^3.

The tailing pond № 3 remains under construction and contains 0.25 million m^3 of brine. The sides of all tailing ponds rise above the ground. The average mineralization of brine is 40 g/l.

Accumulating tanks No. 1 and No. 2 are analogous to small-sized tailing ponds with a total brine content of 0.4 million m^3.

Ecological and geological problems of Kalush mining district

The area adjacent to the Dombrovskyi quarry. The problem with the Dombrovskyi quarry is that it is continuously being filled with brine. With an average annual rainfall of 700 mm and an evaporation rate of 40 %, the water level in the quarry should rise by 450 mm annually. In addition, aqueous solutions enter the quarry due to the filtration of subsurface groundwater. Therefore, for example, over the past five years, the level of brines in the quarry has risen by 8 meters. The absolute marks of the base of the Quaternary alluvial horizon along the perimeter of the quarry range from 278.6 m to 282.1 m. Therefore, at the level of brines at the beginning of 2021 – 284.5 m. An insignificant part of the brine volume of the quarry is filtered through its side into the aquifer alluvial horizon, causing its pollution. Every year the size of the filtration flow from the quarry will increase. The process will continue until the total balance of the volumes of water entering and leaving the quarry. According to preliminary estimates, this balance will be established for the level of brines in the quarry at about +295 m, that is, in about 15–20 years. At that time, the aqueous solution in the subsurface layers will be significantly desalinated. But for some time, the quarry will serve as a source of groundwater contamination. Filtration from the quarry will primarily occur in the eastern, southeastern and southern directions, followed by the water movement in the direction of the drain, that is, in the direction of the Limnytsia river.

The area around salt dumps, tailing ponds and accumulating tanks. The salt dumps are not sufficiently protected from natural precipitation which dissolves halite and subsequently infiltrates into the aquifer. According to the reports, salt dumps during their erosion form more than 345 thousand m^3 of brine annually. The sides of the tailing ponds and accumulating tanks filter the brine accumulated in them and it also goes to the aquifer. With a stable level of brine in tailing ponds, according to our estimates and taking into account precipitation and natural evaporation, tailing ponds annually lose about 0.6 million m^3 of brine. For tailing pond No. 2, there is a danger of a dam burst and a sudden discharge of 1.7 million m^3 of brine into the river basin, which would be a disaster. Thus, the ecological danger of this territory lies in the salinization of the adjacent groundwater horizon, the further movement of these waters in the natural southeastern direction and the pollution of the river system of the Dnister basin. In addition, pollution of the aquifer threatens the functioning of water intake facilities that supply drinking water to the town of Kalush (70 thousand people).

Geological and hydrogeological characteristics of the territory

The territory under consideration is located in the Sambir subzone of the Precarpathian downfold. The formation of the Miocene section of the Neogene is a part of the formation of this large structural unit. Meanwhile, potassium salts belong to the Lower Tortonian. The basis is made up with the platform Jurassic, occasionally the Cretaceous deposits. The main feature of tectonics is the presence of long linear structures which are superimposed over each other and extend mainly in the Carpathian direction (in Ukraine) – from the northwest to the southeast. Numerous transverse faults dissecting the subzone arose as a result of horizontal and vertical displacements during the formation of thrusts. Mixed sulfate-chloride salts occur in the form of separate layers and folds at considerable depths in saline deposits, mostly breccias. All of the above-mentioned bedrocks do not contain sustained aquifers suitable for water supply.

The Quaternary aquifers are of practical importance for water supply. These deposits are suitable for drinking and in the area of water intake systems on the banks of the Limnytsia River and adjacent areas are represented by diluvial and alluvial formations.

Alluvial deposits from the ancient terraces of the Limnytsia River. Rocks of modern and floodplain terraces are widespread within the study area. According to lithology, these are pebbles, sands, sandstones, and loams with a predominance of pebble material in younger deposits. Horizon thickness from 3–5 to 12–18 m, depth of occurrence – 3–7 m, filtration coefficient – up to 10 m/day [Haidin and Rudko, 2016].

The characteristics of the water intake structures. The issue of the water intake facilities is considered in connection with the hypothetical risk of contamination of groundwater which is used for water supply. The main water supply for the town of Kalush is Dobrivlia water intake (Fig. 2). It comprises 64 wells and is located a few kilometres southwest of Kalush on the left bank of the river Limnytsia. The aquifer is exploited within the floodplain, which stretches from west to east in the form of a strip 0.3 to 0.8 km wide along the Limnytsia river. The length of a row of water intake wells is 3840 m. Relative to the established level of groundwater, depths of 1.0–2.4 m predominate. The thickness of the aquifer is 5.4 m.

The aquifer has a direct hydraulic connection with the river and the Quaternary aquifer. The boundary conditions of the water intake section are illustrated as a semi-boundary layer with a constant pressure contour – a river located at a distance of 2–3 to 300 m from several wells. The water intake system operates under the conditions of an established mode of filtration with reductions of level less than admissible. There are no observation wells to track the depression funnel and, accordingly, the radius of the impact of the water intake operation. Regular monitoring of levels in production wells is not carried out. The distance from the water intake well to the nearest boreholes of the regional regime observation network within the mining area reaches about 200 m.

The peculiarity of the construction of the water intake structure is the implementation of a feeding trench 3.4 km long, 2.5–3 m wide and 1.5–2 m deep. The method of self-infiltration is used in the feeding trenches.

The water supply balance for the water intake system is as follows:

10–15 % – natural resources of the aquifer;

30–35 % – involved waters of the river Limnytsia;

50–55 % – artificially created water reserves infiltrated from the feeding trench.

Four kilometres downstream of the river Limnytsia, on the left bank, there is the Khotyn water intake, which has been in operation since 1927 and currently occupies a small area of 500×200 meters. The water intake is currently considered as a reserve for supplying technical water.

Geomorphology, levels and direction of groundwater movement. The research area belongs to the Limnytsia river basin, which is the main waterway here. The territory of the basin is composed of Neogene sediments, which are overlain by Quaternary formations. The aquifer is fed by the infiltration of surface water (precipitation), as well as by the transit of groundwater from the hills, which are located northeast of the territory. The direction of groundwater movement to the main drain – the Limnytsia River – is controlled by the directions of lowering the relief. Figure 3 shows a map of levels built according to measurements in observation wells for the time of the summer boundary of 2014 (July–August), that is, after the flood caused by summer rains. Currently (December 2019) all these wells have been destroyed.

The difficulty of analyzing the map lies in the fact that the landscape of the territory is distorted due to artificial objects, that is, quarries, salt dumps, tailing ponds and accumulating tanks. It is clear that these structures significantly change the configuration of the piezoisogypsum. However, there are no necessary additional measurements and, accordingly, there is no reproduction of the detailed real map. Therefore, when analyzing and providing objective conclusions, it should be taken into account that the piezoisogypsum which are drawn through the sections of these structures are approximate and, to a certain extent, virtual. Taking into account this factor, the arrows of the direction of relief inclination and movement of the groundwater are shown on the map of groundwater levels (Fig. 3). The arrows are directed as sub perpendicular to the isolines of absolute relief marks and isolines of groundwater levels. The map was compiled for the summer-autumn low-water period.

Let us take into account that the water collecting trench runs along the western, southern and eastern sides of the quarry. This trench bisects the aquifer and, during the operation of the quarry, it performed the task of collecting transit groundwater heading to the Dombrovskyi quarry.

At present, the drain is actually a quarry from its northern side, where the water collecting trench is destroyed. Karst processes and landslides are actively developing here, and numerous sources in the quarry are visually recorded. The regional flow of groundwater in the aquifer is directed from the northwest to the southeast.

In general, the relief of the earth's surface corresponds to the map of hydroisogypsum in terms of the shape and direction of the isolines. The exception is the southern part of the plateau where the Limnytsia river does not drain the left-bank aquifer. This is explained due to the increased marks of water from the feeding trench, which is discharged both towards the Limnytsia and in the north-eastern direction into the aquifer, that is, the feeding trench is a barrier to the regional south-eastern flow of groundwater. In Fig. 3, the direction of the trench discharge is indicated by the north-easterly arrows (see the southern edge of the plateau).

As a result, the regional south-eastern groundwater flow also bypasses the water intake and, outside it, on the east, is likely to be drained by the Limnytsia River.

Preliminary assessment of the salinity of the aquifer. Salinization of the aquifer was observed in the previous years in some wells, as well as in drinking water wells in the households of residents of surrounding villages.

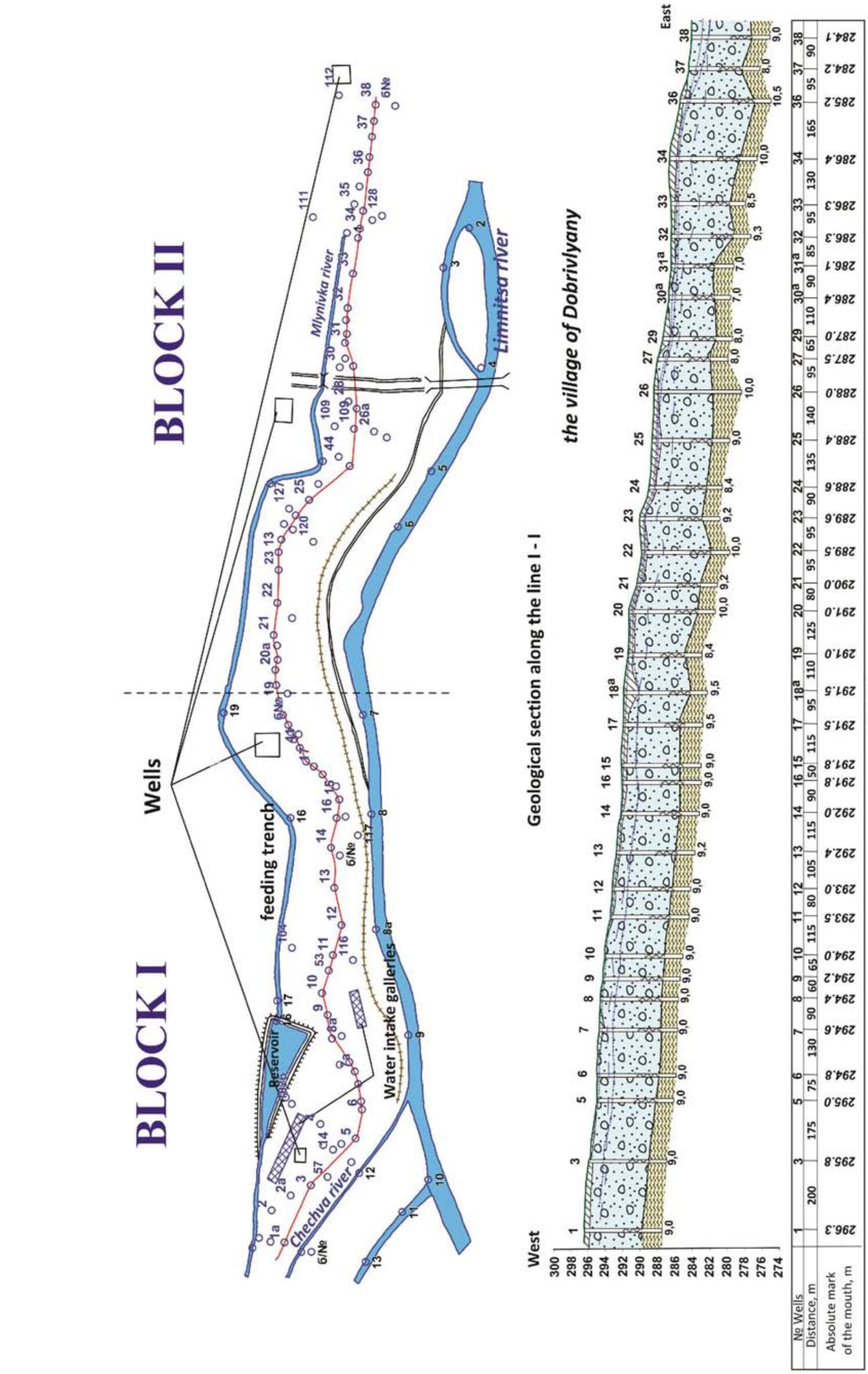


Fig. 2. Situational plan of Dobrivlya water intake and hydrogeological section along the well line.

According to the results of laboratory tests of water samples taken from all the preserved wells (2012), the value of total mineralization ranged from 0.160 to 104.37 g/dm^3, that is, from fresh to brine. The main elements or compounds due to which salinization takes place are Cl, Na, K, SO4, and Mg.

The outline of groundwater salinization is shown in Fig. 3. According to the diagram, salinity is irregular. As it is known, brine from the quarry, tailing ponds, and accumulating tanks are potential sources for the salt dumps. However, the availability of tests on a limited number of hydrogeological observation wells (only 15) in an area of about 15 km^2 is obviously not enough to build a reliable large-scale map and reproduce a reliable detailed planar model of salinity and connect it with the real sources. Currently (2021), the network of observed hydrogeological wells has been destroyed. In 2019, 20 new wells were constructed; 16 of them have survived for the time being.

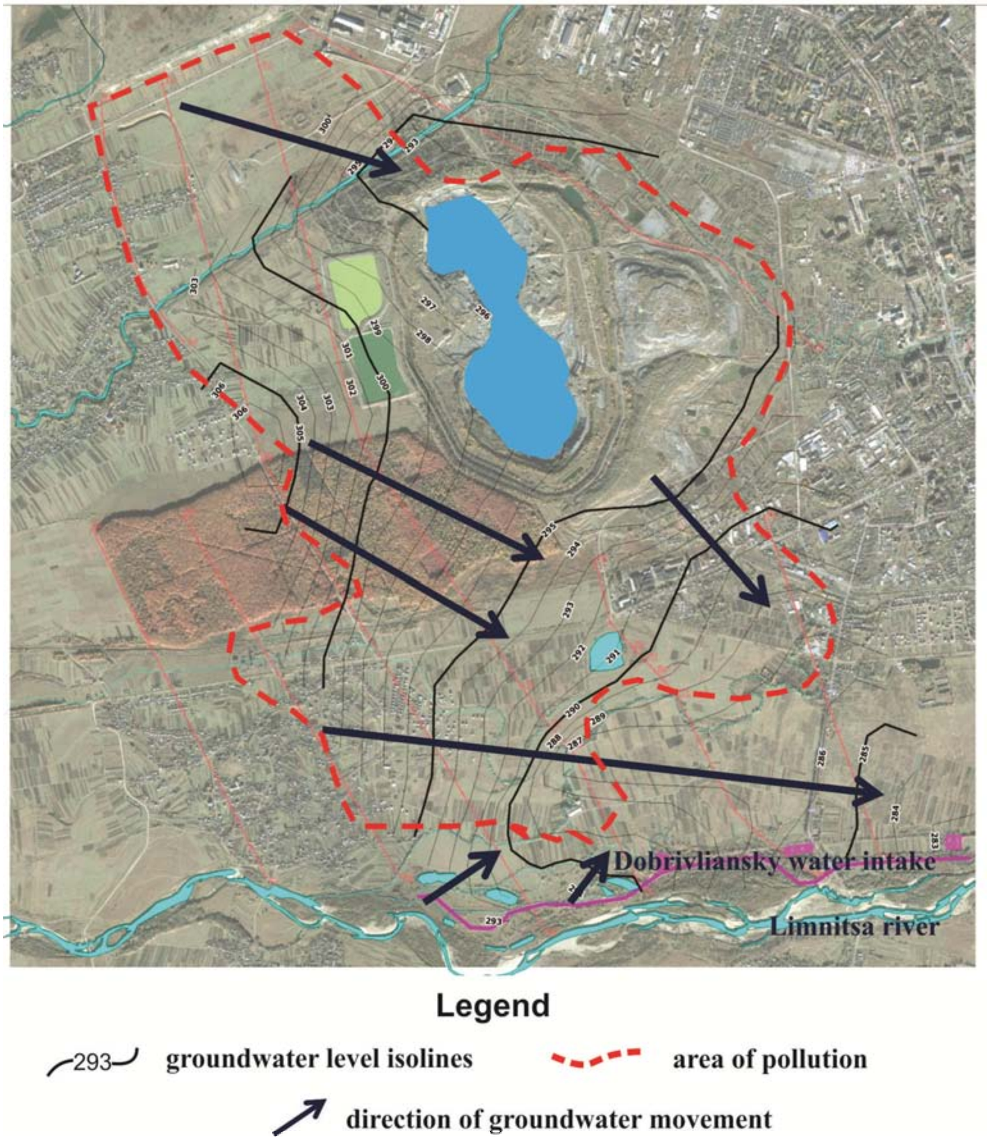


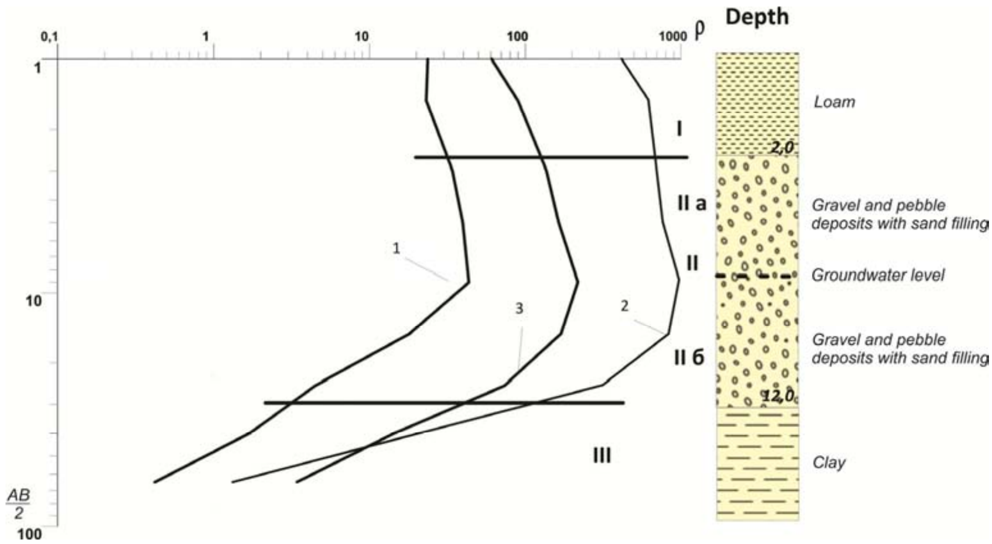
Fig. 3. Map of levels and diagram of the direction of groundwater movement

Geoelectric models of the study area

One of the methods for creating detailed mineralization maps is the use of geophysical methods performed on a detailed grid of observations. As a result, it is necessary to determine the electrical section, coordinate it with the litho-stratigraphic structure, identify the aquifer and establish a correlation between the electrical resistivity of this horizon and groundwater salinity. To solve these problems, the method of electrical exploration is used, namely vertical electrical sounding (VES) and time-domain electromagnetic method (TDEM). The VES method was performed and analyzed by the authors of the article, and the TDEM method was performed by the staff of the Carpathian Branch of Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine. The authors of the article used the results of the TDEM method, which are given in the publications [Romanyuk et al., 2008, Shurovsky et al., 2013] with relevant references to the authors. It should be noted that the geological and hydrogeological conditions in the places of VES and TDEM methods were identical.

The result of the VES method is a curve of the dependence of the change in apparent electrical resistivity on the length of the current line. The specified length of the current line AB is a geometric analogue of the depth of research according to the approximate dependence $H \approx \frac{1}{3} \div \frac{1}{10} \times AB$. Therefore, the VES curve reflects the change in electrical resistivity with depth. The values of electrical resistivity usually correspond to a certain lithological variety of rocks. Fig. 4 shows the comparison of the curves of soundings in areas with different degrees of salinity of groundwater. On the curves shown, the electrical resistivity generally decreases with depth, reaching its minimum values at the level of the aquifer, which in the figure corresponds to the lower-left branches of the curves. Sounding was performed near the wells from which water samples were taken and mineralization was determined.

Curve 1 in Fig. 4, at the minimum resistivity of the horizon saturated with brine, $\rho_{\min} = 0.12\ Om \cdot m$, corresponds to mineralization $M = 14.8$ g/dm^3; Curve 2 at $\rho_{\min} = 0.58\ Om \cdot m$ corresponds to mineralization $M = 3.2$ g/dm^3; curve 3 at $\rho_{\min} = 3.48\ Om \cdot m$ corresponds to mineralization $M = 0.6$ g/dm^3. Therefore, an increase in mineralization is consistent with a decrease in electrical resistivity. The figure also shows a detailed geological section of the near-surface part of the study area.



Curve 1 – $\rho_{\min} = 0.12\ Om \cdot m$, $M = 14.8$ g/dm^3; Curve 2 – $\rho_{\min} = 0.58\ Om \cdot m$, $M = 3{,}2$ g/dm^3;
Curve 3 – $\rho_{\min} = 3.48\ Om \cdot m$, $M = 0.6$ g/dm^3;

Fig. 4. Geoelectric models and VES curves with varying degrees of aquifer salinity.

Correlations between salinization and geophysical parameters. The correlation was determined independently by applying two methods – VES (vertical electrical sounding) and TDEM (time-domain electromagnetic method). The VES method was performed in 2012, and the TDEM – in 2010. The geophysical methods were performed in such a way that the points (centres) of soundings were located near the wellhead. The soundings were carried out for a short period (within several days). While VES or TDEM methods were performed, water samples were taken from wells; then element-by-element and general mineralization were detected.

The graphs of the correlation dependency are shown in Fig. 5. The equation established from the empirical data is in the variant of the linear scale of coordinates $M = a\rho^2 + b\rho + c$ (Fig. 5a); in the variant of the bi-logarithmic scale $\lg M = \lg \rho + f$ (Fig. 5b).

On the bilogarithmic scale, the dependence is linear and the relation is quite strong; the correlation coefficient is 0.87. Therefore, the dependency obtained can be used for drawing a map of groundwater mineralization by the electrical sounding data at a direct current. The question arises whether this graph is consistent with the graphs of the dependence of electrical resistivity on the groundwater salinity in other regions. Therefore, Fig. 6 shows a family of corresponding dependencies for different regions of the former Soviet Union (mentioned earlier in the analysis of the monograph [Melkanovytskyi et al., 1982]). The graph of Fig. 5b in bilogarithmic coordinates is presented in Fig. 6 under the number 15.

The parallelism of the obtained graph with the graphs of other geological regions indicates the reliability of the data obtained. It should be noted the fundamental possibility of using induction sounding methods to assess the mineralization of groundwater, in particular, transient electromagnetic sounding (TEM). To demonstrate the effectiveness of the use of induction soundings, let us use the work [Romanyuk et al., 2008, Shurovsky et al., 2013], which presents the correlation dependence between mineralization and the induction parameter. The length in time of the induction effect and, accordingly, its value depends on the electrical resistivity of rocks and is inversely proportional to it. The greater the mineralization of the groundwater, the lower the electrical resistivity and the greater the induction effect.

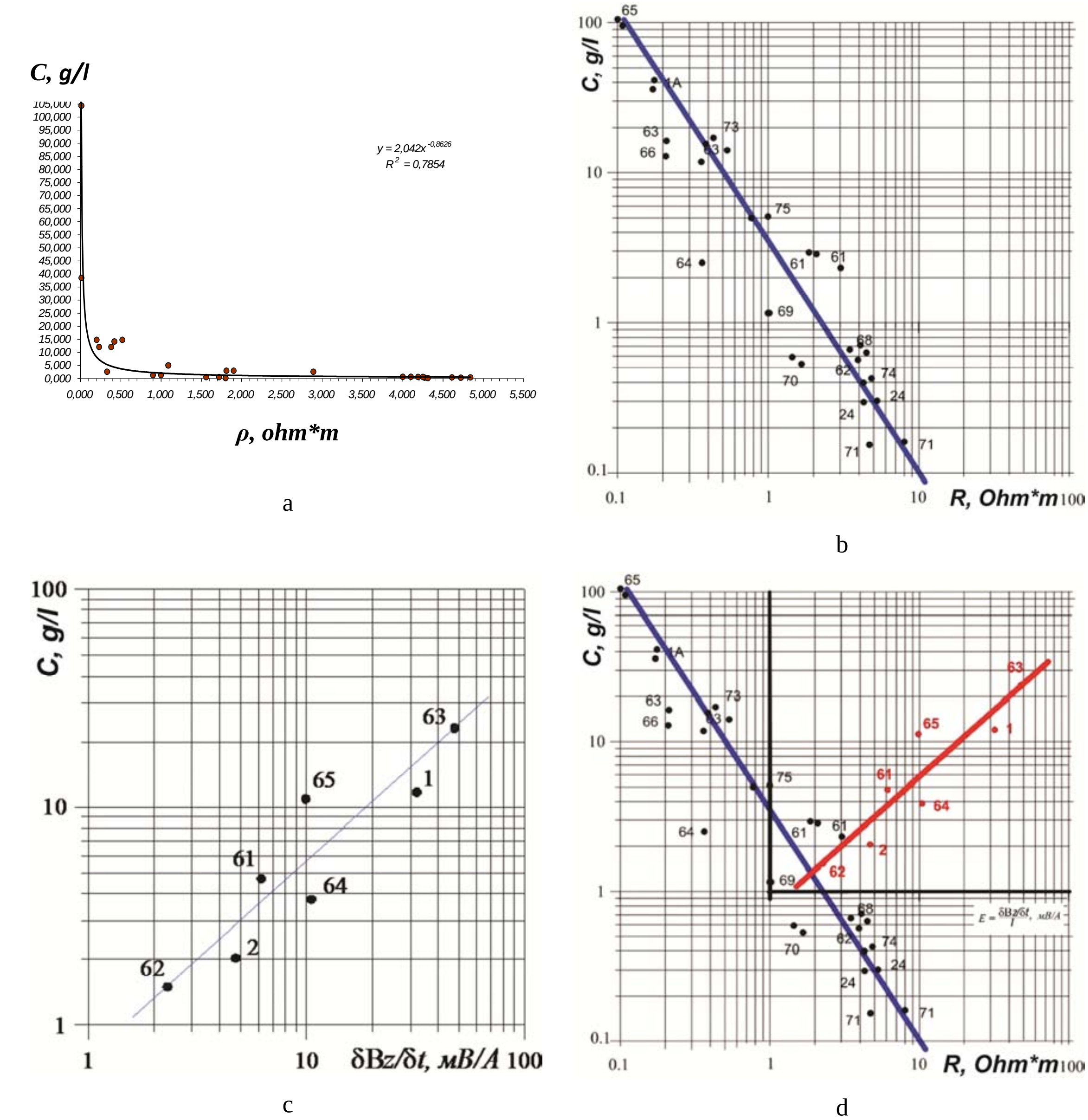


Fig. 5. Correlation dependencies by methods of electrical exploration:

a – graph of dependence of mineralization and electrical resistivity (VES method); b – correlation dependence of electrical resistivity and mineralization (VES method); c – correlation between induction parameter and mineralization (TDEM method according to the Carpathian Branch of Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine.); d – combined correlations according to VES and TDEM data.

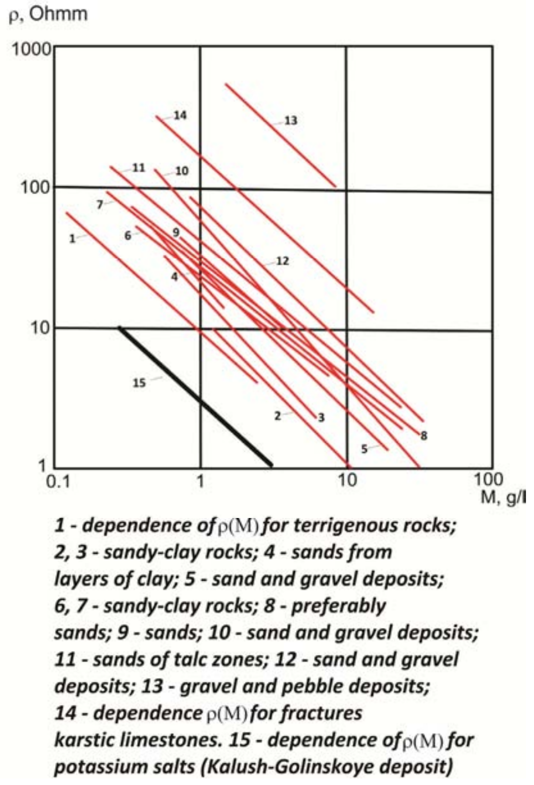


Fig. 6. Dependence of electrical resistivity on mineralization of aqueous solutions and groundwater for different geological areas.

Fig. 5c illustrates a graph featuring the correlation between the induction parameter and mineralization in six wells. The curve corresponds to the equation $\lg M = \lg B + f$, where is the induction parameter. The correlation coefficient is 0.92.

Let us compare the correlation graphs (Fig. 5b and 5c). If they are combined in the same form with bilogarithmic coordinates, then their mutual arrangement will be close to perpendicular (Fig. 5d).

So, firstly, such perpendicularity should be considered as a criterion for the reliability of parametric results; secondly, we can state that the methods are equally informative, especially since the values of the correlation coefficients are close to each other.

When deciding which method to use, the following should be taken into account. Differentiation of the section by electrical resistivity is best done using the VES method; however, the TDEM method is more effective when mapping low-resistivity formations, even of insignificant thickness. The depth of the VES is related to the linear spacing, and the TDEM is related to the size of the loop. In addition, there is a question of price, which is different for different conditions of implementation of methods. In our conditions, we prefer the VES method, which is quite informative and significantly cheaper. Informativeness of salinity maps constructed according to the VES method. The mineralization map was first compiled based on the results of geophysical surveys using the VES method in 2012 and then supplemented and recompiled in 2013 (Fig. 7).

Description of the salinity map of 2013 (Fig. 7). On this map, from north to south, there are three distinct anomalies. The northern anomaly No. 1 is located to the south of the tailing pond No. 1 and is consistent with the source. The level of mineralization varies between 5 and 25 g/l.

Anomaly № 2 to the south of the first one is located southwest of the accumulating tanks No. 1 and No. 2 and is probably related to them. The level of mineralization varies between 2.5–7 g/l.

Anomaly No. 3 is located to the south of the Dombrovskyi quarry and, most likely, is formed from several sources: the eastern part due to the salt dumps, the middle and western parts – to brine from the tailing ponds and accumulating tanks. It is not excluded that the brine from the southern part of the drainage trench will get in. Mineralization in this area ranges from 1 to 25 g/l.

In any case, these sources are hypothetical. However, first of all, we can state the fact of their existence; secondly, their presence is consistent with the mentioned possible sources and the fact of the regional southeast direction of the groundwater movement.

Description of the salinity map 2018 (Fig. 8). As noted, the study area is located between the Dombrovskyi quarry and the Limnytsia River, so compared to the description of the map of 2013, we do not have three anomalies, but only one – the southern anomaly. By contour and location, this anomaly repeats the anomaly No. 3, discovered in 2013. However, the level of mineralization has significantly decreased and amounts to (1–12 g/l). It should be noted that this anomaly tends to spread along the axis of the Dombrovskyi quarry and the Limnytsia River to the south. This “contour of distribution” is visible on both the 2018 map and the 2013 map. Mineralization is currently between 1 and 4 g/l. Pollution in 2013 and 2018 does not reach the water intake and most likely will never reach it since the water intake is artificially fed from the water supply system of the Chechva River.

Description of the map of salinity differences 2018–2013 (Fig. 9). This map is compiled by subtracting the mineralization data recorded in 2018 and 2013 at the points of geophysical observations. The map is presented in Fig. 9. The analysis of the map shows that the area of groundwater mineralization has increased during the year both to the south and east, that is, the contaminated area moves in these directions. It should be noted that the decrease in the value of the main anomaly in the west in the absence of connection with pollution sources and the increase in the east – in the direction of movement, indicates a tendency towards self-purification of the western part of the territory.

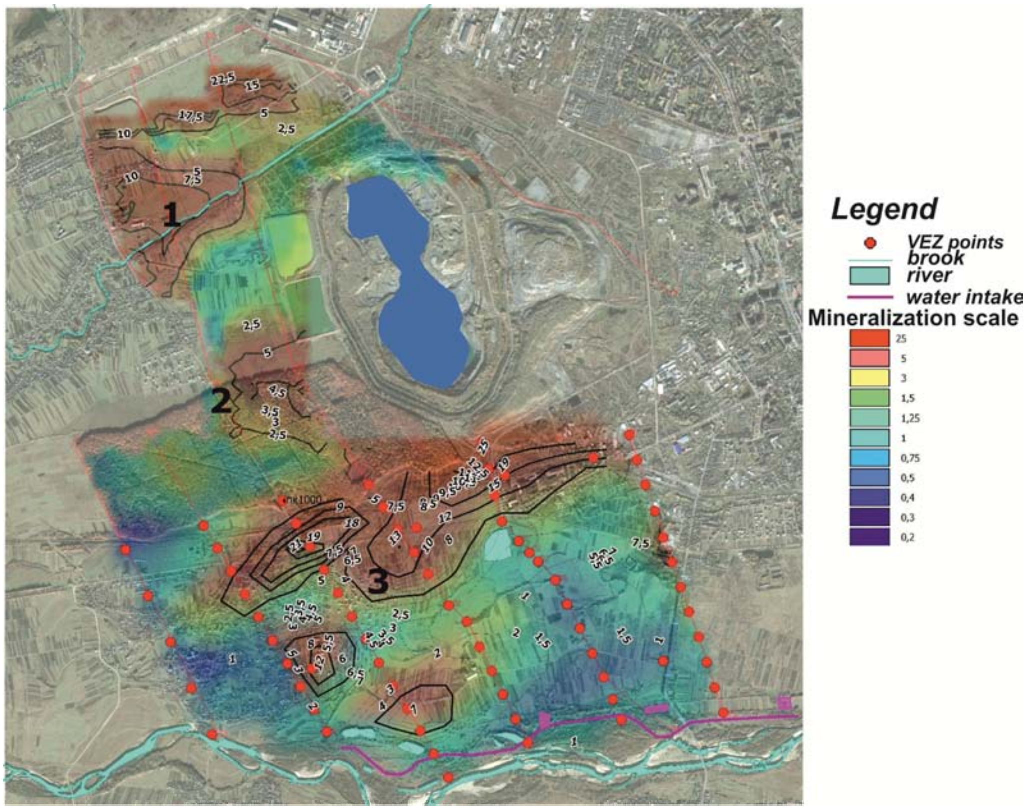


Fig. 7. Aquifer salinity maps with indicated anomalies (observation 2013).

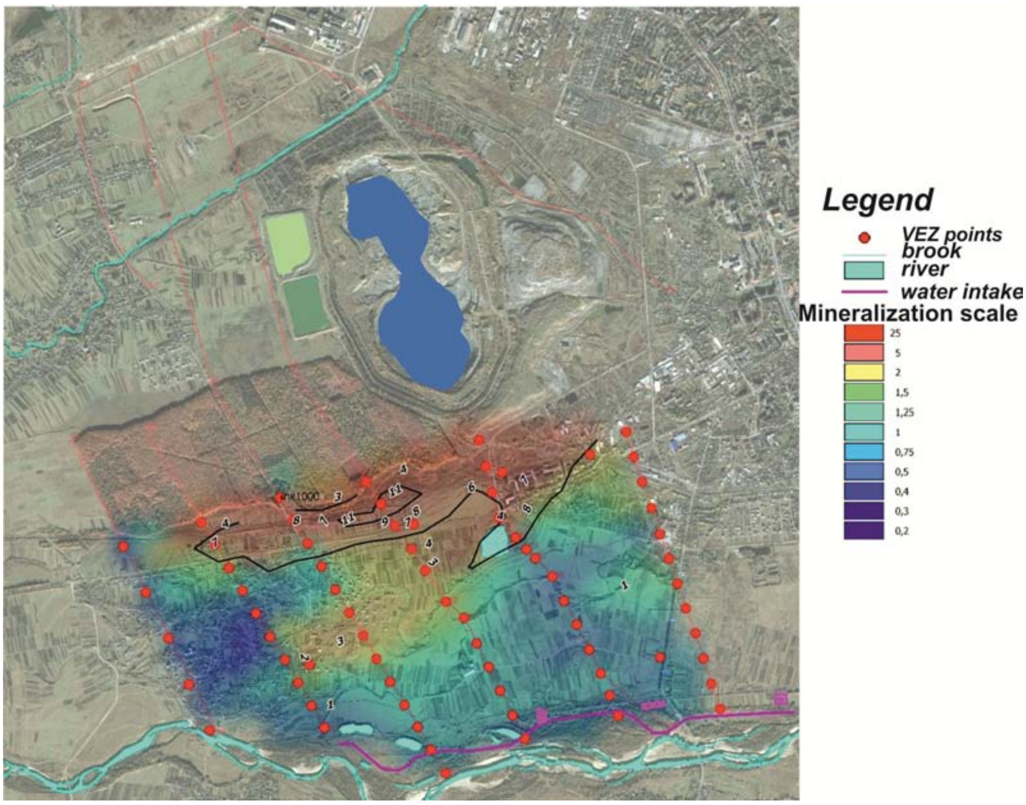


Fig. 8. Aquifer salinity maps (observation 2018).

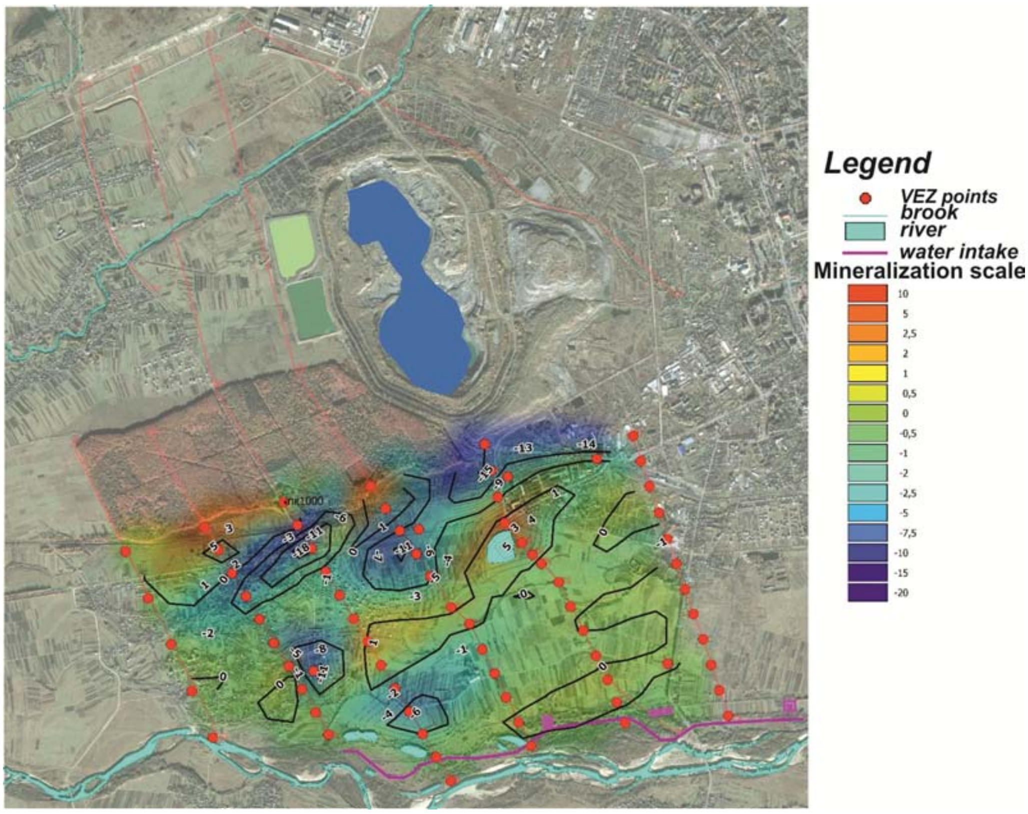


Fig. 9. Residual mineralization map.

At the same time, the ecological load in the east is decreasing due to the infiltration of precipitation and, accordingly, due to the decrease in mineralization in the direction of groundwater movement. Geophysical surveys also make it possible to determine the speed of groundwater. To do this, we need to compare the salinity maps based on the results of vertical electrical soundings in 2012 and 2013.

By measuring the distance between identical mineralization isolines shifted in an easterly direction during the year, we obtain 750 meters, that is, the speed of movement of contamination to the east is 750 meters per year.

Let us carry out an independent control of the assessment of the speed of movement of the contaminated waters in the east direction according to hydrogeological data. To do this, we will use a map of groundwater levels (Fig. 3).

According to this map, in the area under consideration (between the quarry and the Limnytsia River), the angle of the water surface in the aquifer is $I = 0.006$. The value of the filtration coefficient in accordance with the pumping data of 2013 is known to us – k = 30 meter/day on average.

The coefficient of water loss for a heterogeneous rock, represented by pebbles and sand of the rock of the corresponding alluvial terrace, according to the research data [Gaidin, Rudko, 2016], is estimated by the value $\eta = 0.1$.

Let us count: $L = \frac{k \cdot I}{\eta} \cdot 365 \approx 650\, meter\ /\ year$.

L – speed of movement of polluted waters per year.

Thus, the results of calculations by different methods are consistent (on average 750 meter/year – by geophysical data and 650 meter/year – by hydrogeological). For further research, we will consider this value – the speed of groundwater flow in the east direction – equal to 700 meter/year. Similarly, the speed of movement of the groundwater flow in the south direction has been calculated and equals 200 meter/year.

At such speed, the groundwater in the area of water intake structures must have been saline for a long time. However, according to regular analyzes of the sanitary-epidemiological service, drinking water from the water intake system meets standard requirements. What is the reason that it does not get contaminated? The fact is that for the efficient operation of the water intake system, a feeding trench was artificially created (Fig. 3) and it receives the water from the Chechva River; the water level in the feeding trench is higher than the level of the saline water coming from the north. Therefore, this trench is, firstly, a barrier to saline water, and secondly, its waters displace the brines of the aquifer, diluting them and directing them along the Limnytsia river to the east. This is illustrated on the map of the groundwater levels (see Fig. 3) by arrows in the direction of groundwater movement in the water intake area to the northeast.

Therefore, we can state that, in the current hydrogeological situation, the Dobrovlyanskyi water intake system in the town of Kalush is not threatened by contamination. However, when the situation changes (for example, the level of the contaminated groundwater rises under unfavourable natural or man-made conditions), the prospect of such contamination becomes real. Therefore, it is necessary to implement technical solutions for the reclamation of sources of pollution as well as eliminate the threat of rising brine levels in the Dombrovskyi quarry. In addition, regime observations of the groundwater levels in regime hydrogeological wells and synchronously in functioning wells of the water intake system must be continued.

The calculation of risks of contamination of the Limnytsia and Dnister rivers. Thanks to a set of the mentioned studies, the obtained materials are sufficient for preliminary approximate calculation of the increase in mineralization of waters of the Limnytsia river, and later – the Dnister river, due to drainage of the contaminated waters of the alluvial horizon on the territory of Kalush mining area.

To calculate the mineralization, it is necessary to know the area from which saline water will flow to Limnytsia each year, the capacity of the aquifer and its water yield. There is no threat of salinization of the Dobrovlyany water intake system under the current hydrogeological circumstances, as the groundwater transit takes place along the left bank of the river in the water intake area. The speed of movement of the groundwater is seven hundred meters per year in an easterly direction along the course of the Limnytsia river and two hundred meters per year in a southerly direction, that is, into the Limnytsia. Thus, the area will be used during the year to supply the Limnytsia River with contaminated water. The capacity of the aquifer will be taken with a margin slightly above average – 10 meters. Water yield – 0.1. Then, the amount of saline water, which will be directed toward the Limnytsia River during the year, will constitute $700 \times 200 \times 10 \times 0{,}1 = 0{,}14 million\, m^3$. We can assume from the data from the salinity maps of the shoreline that the average mineralization of the groundwater is 15 g/l. The average annual discharge of the Limnytsia in the area of water intake is known – 23.5 m^3/s, or 741.1 million m^3/ year. Mineralization of annual waters is estimated at 0.1–0.2 g/l – an average of 0.15 g/l. Mineralization of mixed water in the river under the influence of brine due to the auxiliary structures (tailing ponds, accumulating tanks, salt dumps) M_1 will be:

$$M_1 = \frac{V_n \cdot M_n + W \cdot M_p}{V_n + W}, \qquad (1)$$

where V_n – the annual volume of saline groundwater directed toward the Limnytsia River;

M_n – average mineralization of the groundwater;

W – the average annual flow of the river Limnytsia;

M_p – mineralization of river waters.

In the numerical form, we obtain:

$$M_1 = \frac{0{,}14 \cdot 15 + 741{,}1 \cdot 0{,}15}{0{,}14 + 741{,}1} = 0{,}153 \quad g/dm^3 .$$

Let us make the conditions more severe. Supposing that a strip of saline groundwater 2000 m long and 200 m wide from the salt dumps with the same mineralization of 15 g/dm^3 is directed toward the Limnytsia without any changes. In this variant, the calculation is as follows:

$$M_1^{/} \approx 0.158\, g/dm^3 .$$

It is clear that in both the first and second variants, the Limnytsia River will not experience these changes in mineralization. Then, let us assume that the extraction of useful components from the brines of the Dombrovskyi quarry will not be carried out as expected, that is, the artificial reduction or stabilization of the level of brine in the quarry will not occur. In this case, when the level in the quarry rises so much that the brine is completely absorbed by the aquifer, the quarry will receive only precipitation in the amount of 760–768 mm/year. With the quarry area of 2 km^2, this is equivalent to 1.536 million m^3.

This will happen when the brine level in the quarry reaches an absolute mark of 295 m (with quarry board marks around 300 m). According to estimates given in [Dolin et al. 2010], the mineralization of brine in the subsurface part (at a depth of several meters) will be 60 g/dm^3, and according to the data [Pavliuk, 2011 Haidin and Rudko, 2016] – 10–15 g/dm^3. Consider the worst option – 60 g/dm^3. The evaporation rate for this brine concentration in the quarry is considered to be 0.4. Then, $2\, 1{,}536 \times 0{,}4 = 0{,}614 million\, m^3$ litres will evaporate. The remaining 0.922 million m^3 are brines that will be sent to the aquifer. Discharge, according to the groundwater level map, will take place to the east, south-east and south, that is, in the direction of the Limnytsia. As the dilution of brine from the other man-made objects (salt dumps, tailing ponds, accumulating tanks) has already taken place due to infiltration, the volume of 0.922 million m^3 and mineralization of 60 mg/dm^3 will be preserved upon reaching the Limnytsia River. Then, the mineralization of the mixed water in the Limnytsia River, taking into account the brine of the Dombrovskyi quarry and additional facilities, will be:

$$M_2 = \frac{V_k \cdot M_k + W \cdot M_p + V_n \cdot M_n}{V_k + W + V_n}, \qquad (2)$$

where: V_k – the volume of the brine of the quarry is directed toward the aquifer; M_k – mineralization of the quarry brine; V_n – the annual volume of saline groundwater directed toward the Limnytsia River; M_n – average mineralization of the groundwater; W – average annual discharge of the river Limnytsia; M_p – mineralization of the river water.

In the numerical form, we obtain:

$$M_2 = \frac{0.922 \times 60 + 741.1 \times 0.15 + 0.4 \times 0.15}{0.922 + 741.1 + 0,4} = 0.23 g/dm^3$$

This number is quite far from the allowable 1 g/dm^3, and it would seem that everything is fine, because the maximum allowable concentration is not reached. However, there are other requirements, namely, the content of individual elements. In particular, the potassium content of rivers should not exceed 3% of the sodium content. The latest analysis of the potassium content in the quarry brines showed that with a total brine mineralization of 287 g/dm^3, the Na content was 71.7 and the K content was 22.5 g/dm^3, so the potassium content is 31 % of the sodium content. With regard to heavy metals, the concentration of some of them in some samples was hundreds of times higher than the maximum allowable [Dolin et al., 2010]; in particular, for Pb – a concentration of 1.28 mg/dm^3 at a rate of 0.01 mg/dm^3. In subsurface samples, according to the analysis of 2018, there is an excess of bromides in all water samples by 254 times according to the standard values. Therefore, the issue of possible chemical contamination of the Limnytsia River, and later – the transboundary the Dnister, which is about 30 km away, with brine from polluting facilities of the Kalush mining area, – is currently open and requires further research in this area.

Scientific novelty

The scientific novelty lies in the further development of the method for assessing the mineralization of groundwater based on the results of geophysical studies, in particular, electrical exploration. For the first time, space-time models of dynamics of the groundwater mineralization on the territory of the Kalush mining region (KMR) have been created. In addition, an assessment of the risks of the surface watercourse contamination (the Limnytsia, the Dnister) has been provided, taking into account the main sources of contamination within the area of KMR.

Practical significance

Applying the obtained results can be an effective way to study the areas associated with possible contamination of the territories to provide immediate data for further planning and management of actions. A reliable forecast makes it possible to envisage the measures to reduce the environmental impact on the aquifer, which is the only drinking water supply for the town of Kalush.

Conclusions

The article deals with the hydrogeological aspects of the study of groundwater contamination (salinization) in the Kalush mining region, which is located in the Ukrainian Precarpathians, where for over a hundred years, potassium salt was extracted by open and underground methods.

For carrying out the research related to geological and hydrogeological studies of the territory, the observation hydrogeological wells were drilled with the lithological treatment of the section, measurement of changes in the groundwater levels, and clarification of hydrogeological characteristics and hydrogeochemical tests of brine.

A necessary component of monitoring the territory is geophysical research, the study of the distribution of electrical resistivity and electrical induction characteristics of rocks, This is followed by the determination of correlations between geophysical parameters and groundwater salinity, the construction of their main detailed planar maps of mineralization for different years of research.

An integrated approach to the analysis of the relief maps, the groundwater levels and mineralization allowed us to identify sources of salinity in the aquifer (tailing ponds, accumulating tanks, salt dumps) as well as to identify the area of salinity with differentiation in mineralization units. In addition, the components of the regional direction and speed of groundwater movement have been determined.

Based on the obtained quantitative characteristics of salinity dynamics, we conducted the corresponding calculations of the groundwater and river water balance. The results proved that with the current sources of contamination and the modern groundwater movement dynamics, there are no contamination threats for the main waterways, namely the Limnytsia and the Dnister Rivers, due to the increasing general mineralization. In addition, the elemental composition of contaminating waters has not been assessed. A detailed evaluation of this issue is the subject matter of subsequent research.

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ОЦІНКА ВПЛИВУ ТЕХНОГЕННО СПРОВОКОВАНИХ ГІДРОДИНАМІЧНИХ ПРОЦЕСІВ НА ЗАБРУДНЕННЯ ПІДЗЕМНИХ ВОД ТЕРИТОРІЇ КАЛУСЬКОГО ГІРНИЧОПРОМИСЛОВОГО РАЙОНУ ГЕОФІЗИЧНИМИ МЕТОДАМИ

Метою досліджень є обґрунтування наукових засад комплексного підходу до вирішення еколого-геологічних проблем, що пов`язані з процесами засолення підземних вод на території Калуського гірничопромислового регіону, кількісної оцінки динаміки такого засолення та його зв'язку з річковою системою на основі отриманих даних геохімічних та геофізичних спостережень. Актуальність робіт визначається необхідністю вирішення таких завдань: 1) виявлення джерел забруднення підземних вод; 2) означення територій засолення, зокрема населених пунктів, у межах яких горизонти питних вод стають непридатними для безпосереднього використання; 3) характеристика динаміки, тобто ступеня засолення та швидкості його змін у просторі й часі; 4) визначення небезпеки для працездатності водозабірних комплексів водопостачання; 5) визначення небезпеки забруднення річкового басейну. Методика полягає у встановленні кореляційного звязку між гідрогеохімічними та електрометричними спостереженнями та визначенні закономірності переходу від вимірювань електричного опору до мінералізації підземних вод, у створенні просторово-часових моделей динаміки мінералізації підземних вод та оцінці ризиків забруднення поверхневих водотоків з урахуванням основних джерел забруднення і в наданні вихідних даних для прийняття управлінських рішень. За допомогою гідрогеохімічних спостережень (мінералізація ґрунтових вод) та електророзвідувальних робіт (вимірювання електричного опору) встановлено кореляційні зв'язки між геофізичними характеристиками, притаманними водоносному горизонту, та мінералізацією ґрунтових вод, що в результаті дало змогу за даними площинних геофізичних досліджень конкретизувати джерела та окреслити площу та ступінь засолення. За режимними спостереженнями встановлено напрям руху фронту засолення та його швидкість. За отриманими кількісними характеристиками динаміки засолення водоносного горизонту наведено розрахунок ризиків забруднення річок Лімниця та Дністер. Наукова новизна полягає у подальшому розвитку способу оцінювання мінералізації підземних вод за результатами геофізичних досліджень, зокрема, методом електророзвідки. Вперше створено просторово-часові моделі динаміки мінералізації підземних вод на території Калуського гірничопромислового району (КГПР). Вперше наведено оцінку ризиків забруднення поверхневих водотоків (рр. Лімниця, Дністер) з урахуванням основних джерел забруднення в межах КГПР. Застосування одержаних результатів дає можливість у стислі терміни дослідити ділянки, що пов'язані з можливими забрудненнями території, надати вихідні дані для подальшого планування та прийняття управлінських дій. Надійний прогноз дає змогу передбачити заходи для зменшення екологічного навантаження на водоносний горизонт, що є єдиним питним горизонтом для м. Калуш.

Ключові слова: засолення; електричний опір; водоносний горизонт; мінералізація; спостережні свердловини; джерела забруднення; водозабір.

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