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Monitoring studies of the ecological and hydrogeochemical situation in the zone of influence of technogenic objects of the mining and industrial complex of the Kalush-Holyn Potash Deposit

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Abstract. The assessment of groundwater and surface water conditions in areas of depleted salt deposits is a crucial component of monitoring studies due to the significant anthropogenic impact of objects such as tailings ponds, sludge accumulators, and the Dombrovskyi Quarry. The aim of the study was to establish, based on real experimental data from hydrogeochemical analyses of long-term groundwater monitoring via a network of hydrogeological observation wells, the areas of groundwater salinisation in the Kalush mining and industrial region, to assess the dynamics of chemical and physico-chemical indicators, and to identify threats to the region's ecological situation. The research stages included the systematisation of monitoring data for 2021-2023, the creation of digital cartographic layers and attribute databases with quantitative data on groundwater chemical composition, geoinformation modelling, and the development of salinisation maps of the Kalush mining and industrial region and the dynamics of the aquifer salinisation. In 2023, hydrogeochemical studies were conducted in the Kalush mining and industrial region with the collection of 25 samples from observation wells, the Dombrovskyi Quarry, sludge accumulators, and the Limnytsia River. Water mineralisation and chemical composition were analysed. The study results showed the highest levels of mineralisation in the waters of sludge accumulator No. 3 and tailings pond No. 2, where mineralisation levels exceeded maximum allowable concentrations by

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140 and 110 times, respectively. Chloride and sulphate contents in these objects also significantly exceeded permissible standards. A comparison of data for 2022 and 2023 revealed a significant increase in pollutant concentrations in several wells, confirming the continued negative impact of anthropogenic objects. Meanwhile, water quality in the Limnytsia River remained stable. The value of the study lies in evaluating the environmental condition of groundwater in the Kalush mining and industrial region based on the systematisation of hydrogeochemical monitoring data through observation wells using geoinformation modelling approaches

Keywords: depleted salt deposits; observation wells; groundwater; geoinformation system; modelling

Introduction

Depleted potash and rock salt deposits frequently create a complex environmental situation with a range of ecological challenges. In Ukraine, notable examples include the Stebnyk, Kalush-Holyn, and Solotvyno salt deposits. Key environmental issues arising from these sites include soil and water contamination, surface subsidence, collapses above mines, disruption of the groundwater and surface hydrosphere regimes, the generation of mining waste in the form of tailings ponds and sludge storage facilities, erosion and land degradation, as well as biodiversity loss. These environmental problems resulting from salt deposit exploitation have been extensively documented in scientific research.

Y. Khomyn *et al.* (2019) identified the environmental risks associated with highly mineralised saline brines and proposed their disposal using depleted hydrocarbon extraction wells. Additionally, researchers V. Dyakiv (2022) and I.Ya. Sapuzhak (2023) examined the issue of activated subsidence and collapse phenomena in depleted salt deposits. These phenomena arise from the voids formed after raw material extraction via underground mining methods. Abandoned mines can collapse, causing ground surface subsidence and posing significant risks to infrastructure and human safety.

The hydrogeological situation plays a crucial role in the environmental challenges associated with depleted salt deposits, often exacerbated by the intrusion of groundwater into mining workings. E.D. Kuzmenko *et al.* (2018; 2020) explored the application of geodetic and geophysical monitoring over abandoned underground workings to forecast surface subsidence dynamics. They proposed a comprehensive research framework enabling the prediction of deformation processes. Similarly, A. Zhang *et al.* (2018) and M. Pakshyn *et al.* (2020) examined deformation processes above depleted mine workings using remote sensing data, particularly radar interferometry. P. Zhyrnov *et al.* (2021) classified zones prone to hazardous natural and anthropogenic processes within the influence areas of mining infrastructure in the Kalush-Holyn Potash Deposit.

Groundwater regime disturbances, including the inflow of freshwater and intensified water exchange, can activate hazardous exogenous geological processes, notably karst phenomena. Monitoring and modelling the progression of these processes are vital for predicting their activation. Furthermore, L. Davybida *et al.* (2020) and A. Stroj *et al.* (2020) emphasised the significant influence of groundwater regime dynamics on the development of hazardous geological processes. Mining waste, containing residual salts and other chemicals, poses additional environmental risks. Improper storage and exposure to atmospheric factors can lead to environmental contamination. C. Li *et al.* (2020) and A. Zaryab *et al.* (2021) highlighted the increased salt concentrations in surface and groundwater as a major threat. This escalation significantly deteriorates water quality, potentially causing water supply issues for local communities and adversely affecting aquatic ecosystems.

Most large potash salt deposits face similar environmental challenges, including water and soil contamination, land erosion, the formation of underground cavities, and biodiversity loss. Assessing the condition of groundwater and surface water in areas associated with both active and depleted mineral deposits is a critical component of comprehensive monitoring studies. Such evaluations enable the tracking of mining activities' impacts on the hydrological situation, ensuring the timely detection of changes in water composition and potential environmental threats. Given that mining operations or the closure of deposits can significantly influence the surrounding environment, monitoring provides essential data for the development of conservation measures aimed at minimising risks to water quality, public health, and the overall ecological stability of the region. This research focused on assessing the dynamics of chemical and physicochemical indicators and the potential threats to the environmental situation in the area. The primary objective was to identify zones of groundwater salinisation in the Kalush mining and industrial district, based on real experimental data obtained from long-term hydrogeochemical monitoring conducted through a network of hydrogeological observation wells.

Materials and Methods

Annual environmental monitoring is conducted in the Kalush mining and industrial district to assess the salinity levels of surface and groundwater, as well as the subsidence zones above the former Kalush, Holyn, and Novo-Holyn mines. Particular attention is given to Quaternary aquifers, which serve as sources of drinking water for the local population. Quaternary deposits in the area include deluvial sediments, Lower Quaternary alluvial deposits, Middle Quaternary alluvial deposits, Upper Quaternary alluvial deposits, and modern alluvial deposits. The study involved hydrogeochemical investigations through a network of observation wells, geodetic monitoring of land subsidence, and geophysical surveys to identify potential zones of subsidence and surface collapse. In the QGIS environment, the inverse distance weighting (IDW) interpolation method was used to analyse data and create cartograms. Using QGIS and GRASS GIS modelling modules, maps were generated to visualise changes in salinity and concentrations of specific substances in the observation wells across the Kalush mining and industrial district.

To monitor salinisation zones and determine the degree of groundwater salinity, wells equipped with Ukrainian-made filters capable of sampling from the first aquifer were utilised. This aquifer comprises gravel deposits, lies at depths ranging from 0.5 to 13 m, and has a thickness of several to 12 m. Groundwater sampling for hydrogeochemical monitoring was performed through a network of observation wells. Most of these wells – 20 in total – were installed in 2019 by Noosphere LLC, although some of them are no longer operational. Additional samples were collected from wells established during the operational period of the Kalush Potash Plant.

The water sampling methodology from observation hydrogeological wells followed standard procedures to obtain representative and accurate data on groundwater composition. The primary steps of the sampling process included the preliminary cleaning of the well by pumping out three volumes of water. This ensures the collection of fresh, non-stagnant water, which better reflects the current state of the groundwater aquifer. A valve-type sampler was used for the collection of samples. In 2023, samples were taken from 19 observation wells in the monitoring hydrogeological network of the Kalush mining and industrial district, as well as from hazardous technogenic objects, including the salinisation zones of the groundwater aquifer – such as the Dombrovskyi Quarry, tailings pond, tailings dam No. 2, drainage trench, and the Limnytsia River. A total of 25 samples were collected. The locations of the objects from which the samples were taken are shown in Figure 1.

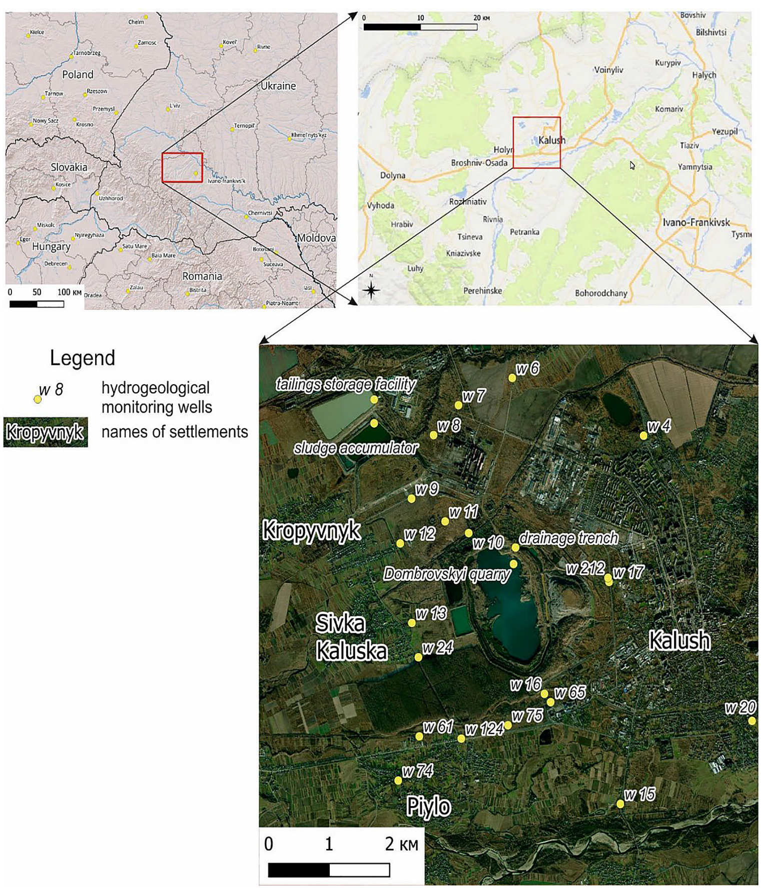

Figure 1. Cartogram of the study area and the network of observation wells

Source: developed by the authors based on ArcGIS (n.d.), Bing Maps (n.d.), Google Maps (n.d.)

Chemical and physicochemical indicators, including the content of salts and chlorides, were determined in the samples. These indicators are crucial for assessing the condition of the water, as highly mineralised waters and runoff may penetrate groundwater aquifers and the Limnytsia River, which serves as a source of drinking water for the city of Kalush and flows into the Dniester River, a transboundary waterway. The analysis of the test results was carried out in accordance with the hygienic standards approved by Order of the Ministry of Health of Ukraine No. 721 (2022). The determination of chemical and physicochemical parameters was performed at the water monitoring laboratory of the Western Region of the Dniester River Basin Water Resources Authority using the following instruments: Ulab 102 HD spectrophotometer (China), Horiba Ltd Lagua-pH meter PC 1100 (Japan), and Horiba Ltd Lagua-conductometer PC 1100 (Japan).

Results and Discussion

The results of the study confirmed a high salt content in the sludge reservoir, tailings pond, and Dombrovskyi Quarry. With the maximum allowable concentration (MAC) of salts in water set at 1,000 mg/dm³, the mineralisation levels of the water in tailings pond No. 3 were found to be 140 times higher than the norm, reaching 140,800 mg/dm³; in tailings pond No. 2, it was nearly 110 times the norm at 110,840 mg/dm³; and in the Dombrovskyi Quarry, it was almost 20 times the norm at 19,600 mg/dm³. The qualitative composition of the water is characterised by the presence of chloride and sulfate salts. With standard values of chlorides at 350 mg/dm³ and sulfates at 500 mg/dm³, the samples taken from tailings pond No. 2, the sludge reservoir, and the Dombrovskyi Quarry showed exceedances of the established MAC. Chloride concentrations exceeded the MAC by 110.4, 147.3, and 25.6 times, respectively, and sulfate concentrations by 26.2, 42.4, and 3.9 times. These indicators were also high in the drainage trench, where mineralisation exceeded the MAC by 3.8 times, chloride content by 3.7 times, and sulfate content by 1.3 times. The ionic composition of the water clearly shows higher than the standard values of calcium and magnesium salts.

The study of the samples taken from the wells in the Kalush district revealed that the highest concentrations of salts were found in well No. 9: the mineralisation level was 59,900 mg/dm³, sulfates were 14,900 mg/dm³, chlorides were 21,766 mg/dm³, calcium was 1,804 mg/dm³, and magnesium was 1,798 mg/dm³. Additionally, in five samples, the sulfate content ranged from 1,351 mg/dm³ in well No. 8 to 6,419 mg/dm³ in well No. 13, exceeding the MAC by 2.7 to 12.8 times, respectively. Chloride levels exceeding the MAC were recorded in five samples, with the highest concentration found in well No. 65 at 13,542 mg/dm³, which is 38.7 times the norm. The lowest chloride concentration was found in well No. 6 at 16 mg/dm³. In 13 samples (No. 4, 6, 7, 10, 12, 15, 17, 20, 24, 61, 74, 75, and 212), the salt, sulfate, and chloride levels were within the MAC limits. In four samples, the calcium and magnesium content exceed the standard values of 200 mg/dm³ and 50 mg/dm³, respectively. In sample No. 8, the calcium content is 523 mg/dm³, which is 2.6 times the MAC. In sample No. 11, the calcium content is 1,209 mg/dm³, which exceeds the MAC by 6 times, and magnesium is 1,067 mg/dm³, exceeding the MAC by 21.3 times. In sample No. 13, calcium is 303 mg/dm³, which is 1.5 times the MAC. In sample No. 65, calcium is 1,230 mg/dm³, which exceeds the MAC by 6.2 times, and magnesium is 533 mg/dm³, exceeding the MAC by 10.7 times.

Biogenic elements – ammonium ions, nitrites, nitrates, and orthophosphates – were also analysed. The results confirmed contamination with biogenic elements in the tailings pond No. 2 and the sludge reservoir, where ammonium ion concentrations exceeded the MAC by 3.7 and 2.1 times, respectively, and nitrate ions in the sludge reservoir exceeded the MAC by 1.3 times. Among the wells, ammonium ion concentrations exceeded the MAC in three samples: No. 9, 11, and 13. Ammonium ion concentrations ranged from 0.52 mg/dm³ in sample No. 124 to 29 mg/dm³ in sample No. 13, which is 11.3 times the MAC, 22 mg/dm³ in sample No. 11 (8.6 times the MAC), and 9.3 mg/dm³ in sample No. 9 (3.6 times the MAC). No exceedance of the MAC for nitrite ions was found in any sample, and only one sample, No. 9, showed an exceedance for nitrate ions (1.5 times the MAC).

Toxicological indicators, including manganese, iron, chromium, and copper, were measured. In tailings pond No. 2 and sludge reservoir No. 3, manganese concentrations exceeded the MAC by 3.3 and 80 times, respectively. Iron concentrations in tailings pond No. 2 were 21 times the MAC and in sludge reservoir No. 3, 2 times the MAC. In well samples, manganese concentrations exceeded the MAC in 10 samples. In 4 of these, the exceedance was slight, with manganese levels ranging from 0.13 mg/dm³ (1.3 times the MAC) in sample No. 75 to 20 mg/dm³ in sample No. 65, which is 200 times the MAC. The highest manganese content was observed in sample No. 13, at 5.7 mg/dm³, which exceeds the MAC by 57 times. The iron content is high in 13 samples – No. 4, 6, 7, 9, 10, 11, 13, 16, 17, 61, 65, 124, and 212 – ranging from 0.36 mg/dm³ in wells No. 17 and 212 (1.2 times the MAC) to 65 mg/dm³ in well No. 65 (217 times the MAC). The iron content in sample No. 61 is high at 18 mg/dm³, exceeding the MAC by 60 times. No exceedance of the MAC for chromium and copper was detected in well samples.

Testing of a sample from the Limnytsia River for mineralisation, according to V. Khilchevskyi's classification, confirms that the water is moderately fresh and soft, with a chemical composition of bicarbonate-sulfate. The salinity indicators are low and have remained almost unchanged over an extended observation period. The concentrations of biogenic and toxicological elements are within normal ranges. In 2023, laboratory chemical analyses were conducted on samples taken from the monitoring well network, with the same structure as in 2022, except for the determination of metals using spectrometric methods. To evaluate the dynamics of substance concentrations in the water, it is necessary to systematise and compare the obtained results from 2022 and 2023. The values of mineralisation and salt composition for 2022 and 2023, along with their differences (as a measure of dynamics), are presented in Table 1.

Table 1. Mineralisation of water samples

No.	Indicator	Mineralisation, mg/dm³			
	Sampling location	Test results			
		2021	2022	2023	Δ
1	Tailings Pond No. 2	83,916		110,840	
2	Sludge Accumulation Pond	80,356		140,800	
3	Drainage Trench		2,604	3,780	1,176
4	River Limnytsia		189	199	10
5	Dombrovskyi Quarry	20,320	24,829	19,600	–5,229
6	No. 3	783	747		
7	No. 4	335	497	662	165
8	No. 5	1,347	1,072		
9	No. 6	1,197	504	232	–272
10	No. 7	422	345	220	–125
11	No. 8	3,810	4,421	2,890	–1,531
12	No. 9	23,746	18,164	59,900	41,736
13	No. 10	1,227	3,764	692	–3,072
14	No. 11	1,680	8,474	26,400	17,926
15	No. 12	630	649	359	–290
16	No. 13	2,908	5,199	16,023	10,824
17	No. 15	292	264	297	33
18	No. 16	3,859	8,465	1,740	–6,725
19	No. 17	998	886	676	–210
20	No. 19	2,626	4,183		
21	No. 20	443		330	
22	No. 24		495	381	–114
23	No. 61			852	
24	No. 65			29,211	
25	No. 74			343	
26	No. 75			780	
27	No. 124		4,344	5,836	1,492
28	No. 212		707	874	167

Notes: Δ – difference between 2023 and 2022
Source: compiled by the authors

The comparison of mineralisation and salt composition indicators between 2023 and 2022 shows significant fluctuations in concentrations for almost all indicators in well groups 9, 10, 11, 8 (tailings pond impact zone), 16, 19 (salt heap impact zone), and 13 (accumulating reservoir impact zone). In these cases, concentration changes of greater than or equal to 1 MAC fraction are observed. This phenomenon is logically explained by the proximity of the mentioned wells to the corresponding pollution sources of the aquifer. A significant reduction in overall mineralisation between 2022 and 2023 is observed in samples taken from the Dombrovskyi Quarry, wells 8, 10, and 16. A notable increase in overall mineralisation is observed primarily in well 9 (by 41.7 g/l), as well as in wells 11, 13, and 124. High mineralisation (over 29 g/l) was recorded in well 65, which was added to the monitoring network this year. This well is part of the monitoring network of the State Enterprise Potash Plant. For this well, MAC is also exceeded for all other components of the salt composition. The well requires special attention, as it is located to the south of the research area, between the Dombrovskyi Quarry and the Limnytsia River. Well No. 16, located 160 m north of No. 65, shows significantly lower mineralisation, about 1.7 g/l, and a negative concentration trend. This well is part of the new monitoring network installed by Noosphere. However, the samples taken from well 16 also exceed the MAC, though not by tens of times, as is the case for well No. 65.

The analysis of the dynamics of biogenic elements – ammonium ions, nitrites, nitrates, and orthophosphates – shows significant increases in concentrations, particularly in well No. 9, especially for ammonium and nitrate ions. An increase in ammonium ion concentration is also observed in well No. 13. Negative changes in concentrations between 2023 and 2022 are recorded in wells 10, 8 (tailings pond influence zone), 16 (salt heap influence zone), 124, as well as samples from the Dombrovskyi Quarry and drainage trench.

For toxicological indicators, a comparison of iron and manganese concentrations was made. In 2023, manganese concentrations exceeded the MAC in wells No. 11, 13, 15, 24, 61, 65 (significantly, by 200 times), 74, 75, 124, 212. However, in 2022, most wells showed a decrease in concentration, except for wells No. 13 and 15. The highest iron content in 2023 was observed in well No. 65, exceeding the standard by 216 times. High iron levels were also recorded in wells No. 11, 9, and 61. The year-on-year dynamics revealed a significant increase in iron content in samples from wells No. 11, 10, 4, and 16. Most of the samples taken showed iron concentrations exceeding the MAC, except for those from the Dombrovskyi Quarry, drainage trench, and well No. 15.

Assessing the condition of groundwater and surface water in the areas of active or depleted mineral deposits is a crucial component of monitoring research. Hydrogeochemical studies are especially important because dangerous anthropogenic objects in the Kalush mining-industrial region (tailings ponds, salt heaps, sludge collectors, Dombrovskyi Quarry) are sources of pollutants for the region's surface and groundwater. The use of GIS tools for modelling processes and assessing the geological environment provides undeniable advantages. In the work by L. Davybida & M. Tymkiv (2020), GIS were used to evaluate the state of the hydrogeological observation well network and to assess the optimal placement of monitoring wells. GIS cartography allows for the rapid generation of spatial distribution maps based on attribute tables. In this study, these maps represent the concentrations of pollutants obtained from the analysis of samples taken from observation wells. The presence of well coordinates allows for geocoding the tables with analysis results and generating the corresponding cartographic layer with attributes in a GIS environment.

O. Koshliakov *et al.* (2020) and O. Dyniak *et al.* (2023) confirmed that methods of hydrogeological and GIS modelling, based on monitoring hydrogeochemical studies, are essential as they help more accurately predict the dynamics of mineralisation and pollution, while considering all key influencing factors. They utilised spatial analysis and GIS modelling with the ArcMap toolkit, specifically the Darcy flow module, for modelling using the water balance method in the hydrogeological monitoring system for groundwater deposits. In particular, when interpolating data on the groundwater hydrostatic level in wells, the IDW method was used, which assumes that the influence of known data points decreases with increasing distance from the measurement location.

The researcher K.I. Sokolchuk (2022) also highlighed the suitability of using this method in interpolating hydrological data, comparing his results with those obtained using triangulation, spline interpolation, and Kriging. The IDW interpolation method was also applied in the current study to interpolate data from well analysis results and construct corresponding maps. As a result, maps were created that marked the research results from 2022 and 2023 (Fig. 2-4). A detailed analysis of specific indicators, based on their visual spatial distribution in the study area, can be made from the maps. All the maps share the common feature that the primary sources of increased pollutant values are tailings ponds, dumps of quarry No. 1 and No. 4, as well as areas of subsidence mounds.

Figure 2 presents the results of the analysis for total mineralisation (g/dm^3). As seen in the figure, elevated mineralisation (greater than 1 g/dm^3) is observed in the central and western parts of the study area in both 2022 and 2023. In 2022, the highest mineralisation values (over 18 g/dm^3) were observed in well No. 9, located southeast of the tailings pond. In 2023, the mineralisation significantly increased (by more than 3 times) to nearly 60 g/dm^3. A significant increase in mineralisation is also observed in wells No. 11, 13, and 124 (listed from north to south), which are located in the western part of the site. At the quarry, mineralisation decreased by 5.2 g/dm^3. For well No. 16, located south of the quarry, where an increase in mineralisation was observed in 2022 compared to 2021, a significant decrease of 6.7 g/dm^3 is now noted. The increase in mineralisation in wells No. 11, 13, and 124 should be associated with the influence of the tailings pond, resulting from the leaching of salts due to atmospheric precipitation. A large halo of salinisation located to the south of the quarry deserves special attention. It is associated with well No. 65, which belongs to the observation well network of the Potash Plant and from which samples were taken for the first time this year. No such high mineralisation values were recorded in nearby wells. Since a high mineralisation value is observed at point No. 65, the mineralisation isolines on the map are "artificially" interpolated, and consequently, the boundaries of the salinisation halo are not accurate. Repeated samples taken under monitoring conditions from well No. 65 and others added to the observation network this year will allow for more reliable conclusions regarding the mineralisation level of the aquifer.

Changes in the concentration of salts were also studied. Figure 3 shows cartograms of chloride concentration changes across the area. The results are similar to those observed for total mineralisation. Significantly higher values are observed in wells No. 65, 9, 10, 11, 16, 13, and 124. In the eastern, southeast, and northeast parts of the study area, no elevated chloride concentrations were recorded – values were less than 350 mg/dm^3, except for well No. 5 in 2022, where elevated chloride levels can be attributed to the formation of a subsidence sinkhole.

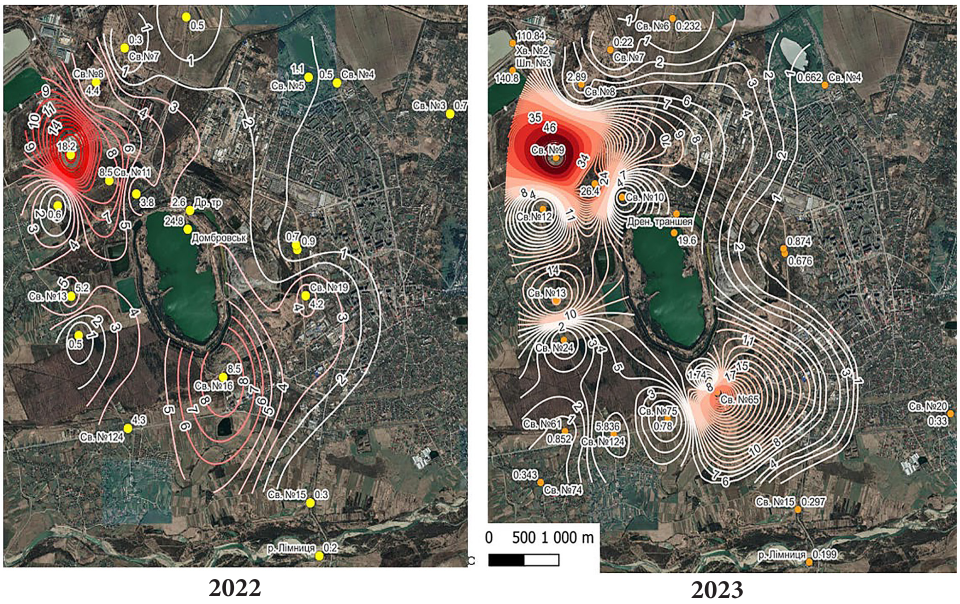

Figure 2. Cartograms of aquifer mineralisation, g/dm³, 2022-2023
Source: developed by the authors

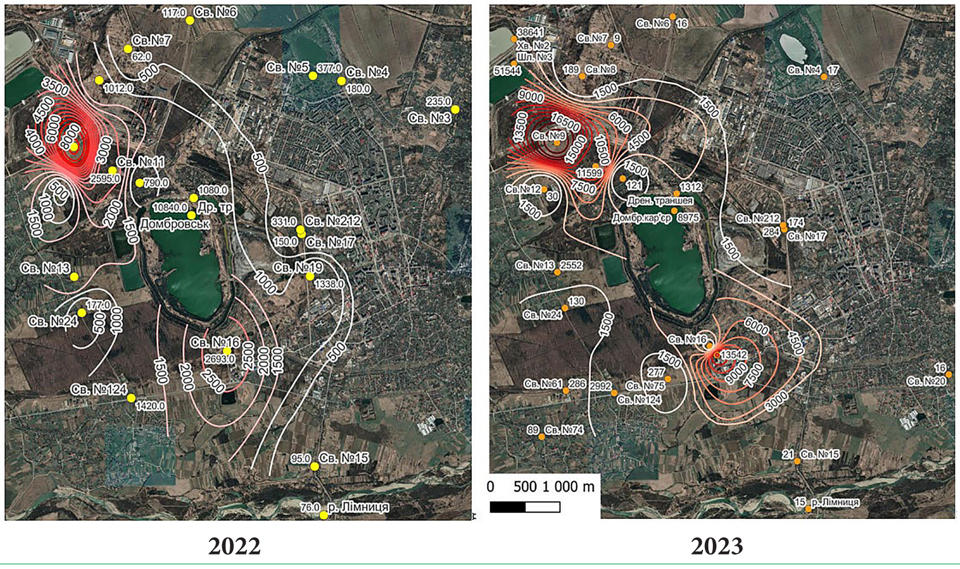

Figure 3. Cartograms of changes in chloride concentrations in the aquifer, mg/dm³, 2022-2023
Source: developed by the authors

The analysis of sulfate mass concentration changes shows that in 2022, the maximum permissible concentration (500 mg/dm³) was exceeded in wells located to the northwest of the Dombrovskyi Quarry (wells No. 8, 9, 10, 11 – tailings pond impact zone) and to the southwest (wells No. 16, 19 – salt dump impact zone). In 2023, sulfate concentrations in wells No. 8, 9, 10, 11 (tailings pond impact zone) and well No. 16 (salt dump impact zone) decreased. Notably, well No. 65 showed significantly high sulfate concentrations. The analysis of calcium concentration dynamics revealed two distinct anomalous zones of elevated calcium concentrations in the aquifer in 2022 and 2023: one to the northwest of the Dombrovskyi Quarry and another to the southeast. A decrease in calcium concentration by more than 1,200 mg/dm³ was observed in the sample from the Dombrovskyi Quarry.

Figure 4 shows the distribution of magnesium concentrations based on the analysis conducted in 2022 and 2023. In 2022, magnesium concentrations exceeded the MAC in wells No. 9, 10, 11 (tailings pond impact zone), well No. 13 (tailings pond and accumulation facilities impact zone), and wells No. 16, 19 (salt dump impact zone). In the quarry sample, magnesium concentration decreased from 1,477 to 379 mg/dm³ in 2022 compared to 2021, but in 2023, it increased to 679 mg/dm³ compared to 2022. In 2023, a clear expansion of the zone of elevated calcium concentrations was observed in the northeastern part of the area (near well No. 9), and likely an "artificial" extension of this zone to the south of the quarry due to well No. 65, where a single measurement in 2023 showed significantly elevated magnesium concentrations. In the planar representation of salinisation dynamics for the periods 2021-2022 and 2022-2023, the maps of mineralisation differences are presented (Fig. 5).

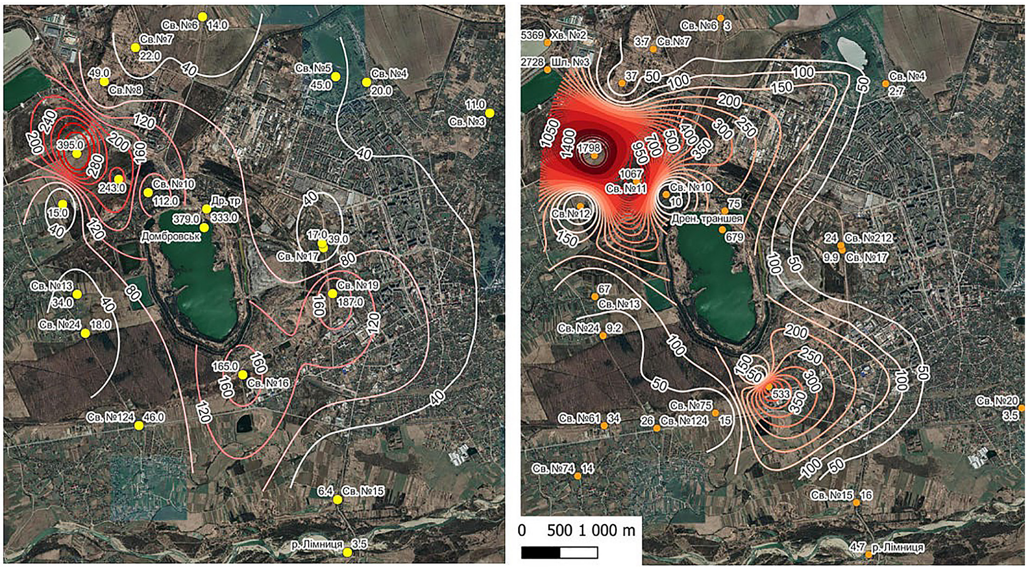

Figure 4. Cartograms of changes in magnesium concentrations in the aquifer, mg/dm³, 2022-2023
Source: developed by the authors

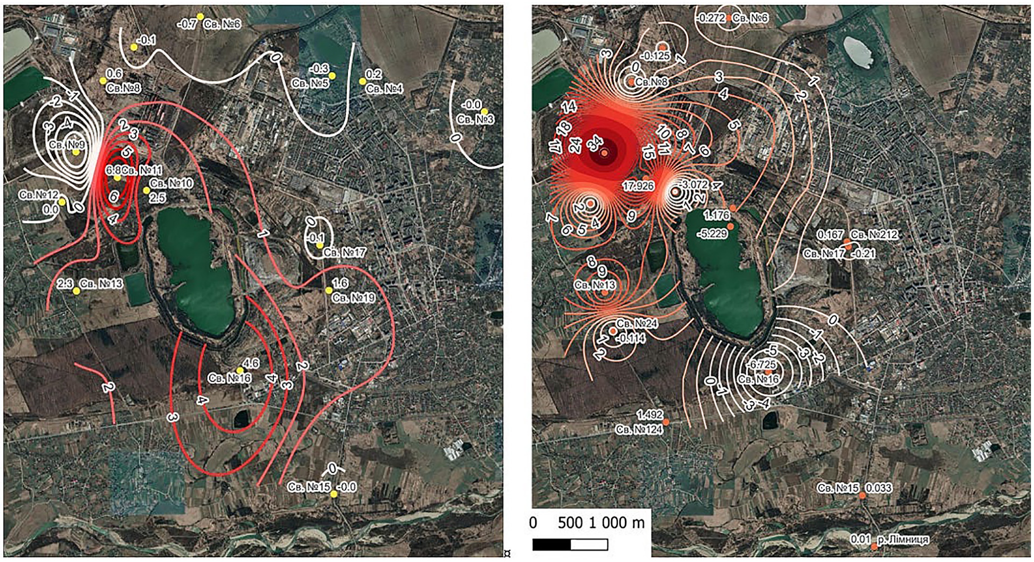

Figure 5. Cartograms with dynamics of groundwater salinisation
Source: developed by the authors

The dynamics of mineralisation for monitoring objects can also be traced through the graphs shown in Figure 6. In the figure, the vertical scale of concentrations is presented in a logarithmic form, as there is a significant gap between the minimum and maximum values of mineralisation.

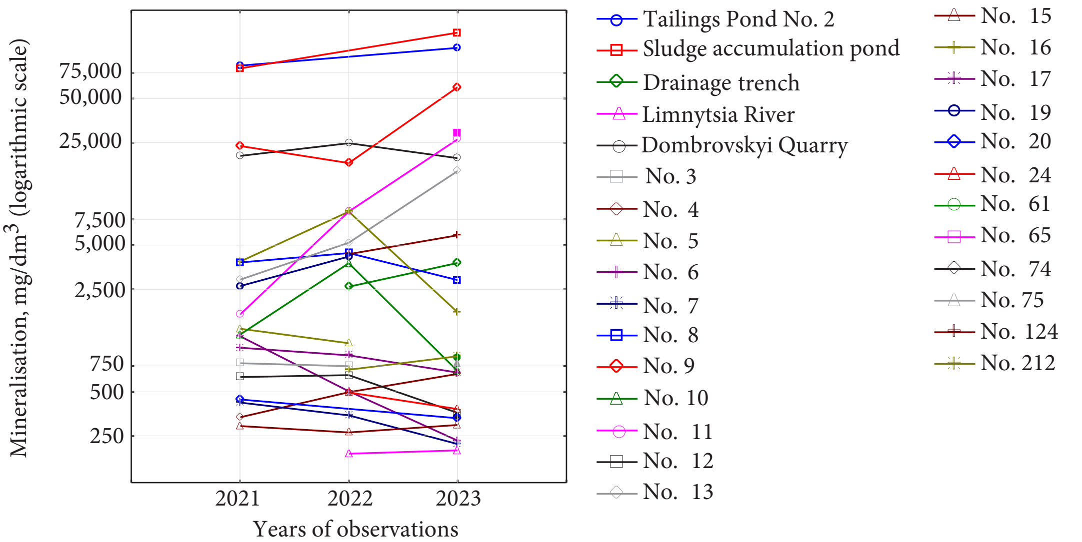

Figure 6. Graph of mineralisation dynamics for monitoring objects

Source: developed by the authors

In 2021-2022, the largest increases in mineralisation were observed in wells No. 11, 10 – the tailings pond zone, No. 13 – the tailings pond and accumulation facilities zone, No. 16, 19 – the salt dump zone. A significant decrease in mineralisation of more than 5 g/dm³ occurred in well No. 9. At the Dombrovskyi Quarry, during 2021-2022, an increase of 4.509 g/dm³ was observed, but in 2022-2023, a decrease of 5.229 g/dm³ was recorded. In 2022-2023, there was a significant increase in salinisation near well No. 9, with an increase of over 40 g/dm³, somewhat lower increases were observed in wells No. 13 and No. 124. A decrease in mineralisation was observed south of the quarry in well No. 16.

Analysis of Figures 5-6 suggests that, over the last year of observation, mineralisation has changed in a group of wells that are in the zone of direct influence of technogenic hazardous objects. The trend towards increased salinisation persists in wells No. 4, 9, 11, 13, 15, 124, 212, tailings pond No. 2, sludge collector No. 3, and drainage trench. The trend towards reduced salinisation is observed in wells No. 6, 7, 8, 12, 17, 20, and 24. Based on the analysis of the dynamics of mineralisation over the years, some trends can be traced (Fig. 2; Fig. 5-6). For example, a significant increase in mineralisation in 2023 compared to 2022 in the central and western parts of the study area, especially in well No. 9, where mineralisation increased by more than three times. In wells No. 13 and 124, located in the western part of the study area, an increase in mineralisation was also recorded, which is related to the influence of the tailings pond. The salinisation halo located south of the quarry was identified in well No. 65 (Fig. 2), where high levels of mineralisation were recorded. Chloride and sulfate levels vary across the study area and correlate with mineralisation, with increased levels noted in wells near tailings ponds and quarries. This analysis demonstrates that the main areas of technogenic influence remain the zones near tailings ponds and quarries, where pollutant accumulation occurs in groundwater.

Changes in mineralisation in wells depend on a number of key factors, among which the determining factor for the conditions of the Kalush-Holyn mining and industrial region during the post-mining period is technogenic impact – namely the presence of tailings ponds, salt dumps, and the Dombrovskyi Quarry, as well as subsidence sinks. Erosion and leaching of salts from salt dumps and tailings ponds under the influence of atmospheric water are some of the primary sources of salinisation in groundwater. Leaching of salts and other chemical elements due to precipitation leads to increased mineralisation in adjacent wells. The danger posed by tailings ponds to the geological environment of surrounding areas is highlighted by V. Snitynskyi *et al.* (2021) and Z. Hevpa *et al.* (2023), with particular emphasis on the stability of the embankments of tailings ponds and the importance of continuous monitoring of the pulp levels and composition. Precipitation accelerates the process of leaching salts from technogenic dumps and tailings ponds, contributing to groundwater pollution. The increase in mineralisation may be associated with intense precipitation that leads to the active leaching of salts into the aquifer. As a result, spatial dynamics of salinisation halos can be observed in the studied area. The climatic factor also plays a significant role in increasing the water level of the Dombrovskyi Quarry, which may eventually lead to the penetration of brines into the Quaternary aquifer.

In the study by N. Sosonna *et al.* (2023), the possibility of brine leakage from the Dombrovskyi Quarry into the gravel and pebble aquifer is noted. The results of modelling showed that, after 40 years, the area of salinisation in the aquifer under the influence of the Dombrovskyi Quarry will expand to 600 m. However, the leakage of brine from the Dombrovskyi Quarry is not expected to have a negative impact on the contamination of groundwater in the area of the Dobrovliany water intake, which is located to the south of the study area. Scenarios of flooding industrial salt extraction areas and their cross-border implications are presented in the work of S. Stadnichenko *et al.* (2023), where satellite imagery data were used to identify potential flooding zones during abnormal precipitation, and an assessment of water mineralisation in the flood risk areas was based on monitoring well data for the Quaternary aquifer. This highlights the need for constant hydrogeochemical monitoring of the observation well network. The necessity of organising comprehensive monitoring of the underground hydrosphere is also emphasised by B. Stetsenko *et al.* (2021), citing the example of the Solotvyn Salt Deposit.

Scientists S. Dovhyi *et al.* (2019), G.I. Rudko & E.O. Yakovlev (2020), and S.B. Shekhunova *et al.* (2021) highlighted that effective management of environmental problems at potash salt deposits requires investment in modern technologies, land reclamation, and continuous monitoring of the environment. This requires a scientific and production complex for post-mining activities based on scientific and technical measures aimed at preventing hazardous changes in the geological environment. A significant number of publications testify to the considerable negative impact of technogenic objects formed as a result of mining activities at potash salt deposits on the development of pollution and salinisation of groundwater. The study by Y.O. Malkova *et al.* (2023) also noted the impact of the Kalush-Holyn Potash Deposit‘s salt dumps on the chemical composition of groundwater. Through statistical processing of geochemical data, the levels of impact from potential sources of chemical contamination of groundwater (water from the Dombrovskyi Quarry, tailings ponds, sludge ponds, salt dumps, and saline soils) were analysed, as well as the correlation between heavy isotopes of hydrogen and oxygen and groundwater mineralisation.

The quantitative and qualitative values of the physicochemical and chemical indicators in the wells observed from 2021 to 2023 did not allow for a clear classification of wells by the probable technogenic source of contamination. On the maps, spatial dynamics of salinisation halos can be observed. Continuing monitoring observations will allow for the accumulation of time series data for each well, opening up the possibility of time series analysis. Modelling changes in mineralisation based on time series will help to identify long-term trends and predict future changes using regression analysis methods, autocorrelation models, or machine learning. It will also be possible to establish dependencies on meteorological and climatic factors, which directly influence the dynamics of chemical and physicochemical indicators in monitoring wells.

It is important to note that to obtain more reliable results for determining contamination zones in the aquifer based on various indicators, a denser network of observation wells and a uniform distribution across the area are required. It is also crucial to collect samples and conduct chemical analysis with less frequency, for example, quarterly, to obtain reliable data. For decision-making, an integrated management model for the Kalush-Holyn industrial area during the post-mining stage should be introduced. This model would include the management and search for optimal methods of monitoring studies and the development of a set of environmental protection measures to reduce the negative impact of technogenic factors.

Conclusions

Technogenic hazardous objects, created as a result of their operation, can be a source of significant water pollution. The Kalush mining and industrial district, with numerous objects such as the Dombrovskyi Quarry, sludge reservoirs, and tailings ponds, is one of the regions experiencing considerable technogenic pressure. Water samples have recorded exceedances of the MAC of chlorides and sulfates. In particular, at sludge reservoir No. 3, tailings pond No. 2, and the Dombrovskyi Quarry, the concentration of chlorides exceeds the norm by 25-147 times, and sulfates by 3-42 times. This indicates a critical level of salinity in the waters, which may negatively affect ecosystems and drinking water sources. Quaternary aquifers, which are used for public water supply, are experiencing significant technogenic impact. High mineralisation and exceedance of MAC for chlorides, sulfates, calcium, and magnesium in the wells suggest a gradual deterioration in the quality of groundwater in the area influenced by tailings ponds, sludge reservoirs, and the Dombrovskyi Quarry.

Comparison of data from 2022 and 2023 revealed significant fluctuations in pollutant concentrations in wells located in the zones of technogenic object influence. A considerable increase in concentrations was recorded in a number of wells, indicating the continued negative impact of technogenic sources on the aquifers. Despite the negative impact of technogenic objects on groundwater, the water quality of the Limnytsia River remains stable, with only minor deviations from regulatory values for mineralisation and chemical composition. It is necessary to strengthen monitoring and protection measures for the region's water resources. It is recommended to continue systematic sampling from wells, especially those located near sources of technogenic pollution. Regarding future research, measures for the reclamation of technogenic objects should be developed to reduce their impact on groundwater, along with additional studies to determine the possibilities for cleaning or minimising pollution in the water horizons.

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Conflict of Interest

None.

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Моніторингові дослідження еколого-гідрогеохімічної ситуації у зоні впливу техногенних об'єктів гірничопромислового комплексу Калуш-Голинського родовища калійної солі

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Анотація. Оцінка стану підземних і поверхневих вод на територіях відпрацьованих соляних родовищ корисних копалин є важливою складовою моніторингових досліджень через значний техногенний вплив таких об'єктів, як хвостосховища, шламонакопичувачі та Домбровський кар'єр. Метою дослідження було встановлення на основі реальних експериментальних даних гідрогеохімічних аналізів багаторічного моніторингу підземних вод за мережею спостережних гідрогеологічних моніторингових свердловин площ засолення підземних вод Калуського гірничопромислового району, оцінка динаміки хімічних та фізико-хімічні показників і загроз для екологічної ситуації району. Етапи досліджень передбачали систематизацію моніторингових даних за 2021-2023 роки, створення цифрових картографічних шарів та атрибутивних баз даних із даними щодо кількісних показників хімічного складу підземних вод, геоінформаційне моделювання та побудову карт засолення території Калуського гірничопромислового району та динаміки засолення водоносного горизонту. У 2023 році на території Калуського гірничо-промислового району було проведено гідрогеохімічні дослідження з відбором 25 проб зі спостережних свердловин, Домбровського кар'єру, шламонакопичувачів та річки Лімниця. Проаналізовано мінералізацію та хімічний склад води. Результати досліджень показали, що найбільший рівень мінералізації спостерігався у водах шламонакопичувача № 3 та хвостосховища № 2, де рівні мінералізації перевищували гранично допустимі концентрації в 140 та 110 разів відповідно. Вміст хлоридів і сульфатів у цих об'єктах також значно перевищував допустимі норми. Порівняння даних за 2022 та 2023 роки показало значне зростання концентрацій забруднюючих речовин у низці свердловин, що підтверджує продовження негативного впливу техногенних об'єктів. Водночас якість води в річці Лімниця залишилася стабільною. Цінність роботи полягає в оцінці екологічного стану підземних вод Калуського гірничо-промислового району на основі систематизації даних гідрогеохімічного моніторингу за мережею спостережних свердловин із використанням геоінформаційних підходів моделювання

Ключові слова: відпрацьовані соляні родовища; спостережні свердловини; підземні води; геоінформаційна система; моделювання