Changes in hydrogeological conditions at the territories adjacent to tailings storage facilities in Kryvyi Rih iron ore basin

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Abstract. Tailings of mining and processing plants of Kryvbas are new areas of groundwater supply which have led to significant changes in the hydrodynamic and hydrogeochemical regimes of aquifers. The purpose of the research was to assess the degree of damage to the areas adjacent to the tailings of mining enterprises by dangerous hydrogeological processes, flooding and inundation. The quantitative regime of groundwater is in a stable state and corresponds to the modern conditions of operation of industrial facilities. During the research, chemical pollution in groundwater of all aquifers was recorded. At the time of research, there was an increased content of such microcomponents as: carcinogenic cadmium and nickel (up to 1.9-34 MPC; and 2.6-8.4 MPC, respectively); non-carcinogenic lead (up to 1.7-7 MPC); manganese (up to 2-320 MPC); bromine (up to 14-94 MPC) in the groundwater of all aquifers in the north. In the center, there was the accumulation of abnormally high concentrations of elements such as iron, manganese (up to 36-1420 MPC rate of 0.3 mg / dm³ and 1.3-66 MPC rate of 0.1 mg / dm³, respectively, and a significant increase in the value of dry residue and the content of major macrocomponents in all aquifers. In the south for the modern period there is pollution of groundwater of the Quaternary and Neogene systems with such elements as total iron (15-2800 MPC), manganese (1.9-132 MPC), sometimes vanadium, cadmium. The geochemical essence of the formation of the chemical composition of polluted waters lies in the intensity of changes in the hydrogeochemical system and in the change in the migratory properties of chemical elements. The newest techniques and scientific developments on localization and the prevention of migration of heavy metals with the subsequent pollution of waters are required.

1. Introduction

The Kryvbas iron ore deposits have been developed for more than 140 years. Over the years of operation, tens of billions of tons of overburden and concentration tailings have been accumulated. Tailings storage facilities are an integral part of the ore treatment process.

At present, six tailings storage facilities belonging to Mining and Beneficiation Works are operated within the area of Kryvyi Rih.

Tailings storage facilities are sets of structures required for impounding and storage of tailings, including a tailings pond, a tailings dam(s), a settling pond, pipelines, etc. The Kryvbas tailings storage facilities were made in natural gullies more than 60 years ago and did not have any anti-leakage pad liners. All of them use a washed-in way of filling, 5,700 hectares of fertile land...
were alienated for them. The embankments of the tailings impoundments have been raised to the absolute elevations from 120 m to 170 m. Tailings storage facilities are subject to potential environmental risk [1, 2]. In accordance with existing regulations, the companies conduct a system of monitoring the conditions of dams, groundwater, surface water, and soil in order to prevent emergencies.

The tailings storage facilities of the Kryvbas Mining and Beneficiation Works are new sources of groundwater supply, they were formed after the 1960s and have led to significant changes in the hydrodynamic and hydrogeochemical regimes of aquifers. The main aquifers in the areas adjacent to these hydraulic structures are confined to the Quaternary and Neogene sediments. Water-bearing rocks include loams starting from light loess soil to medium silt loams, sands and limestones of the Neogene age.

Prior to the creation of tailings storage facilities, aquifers of the Cenozoic sediments were widely exploited by wells, single holes, used for economic purposes by the local population, and represented the only source of water supply.

According to existing data Natarov, D.V. for the period from 1950 to 1955 groundwater in almost all research areas was of satisfactory quality. No flooding was observed; the depth of groundwater levels was 5-10 m [3].

Subsequently, the hydrotechnical and hydrochemical regimes of these aquifers have undergone significant changes. For the period from 1963 to 1974, the increase in levels reached 10-15 m and 18-30 m respectively in some areas. The intensive rise of groundwater levels occurred in the period from 1970 to 1980, when water levels in tailings storage facilities reached +84.7 - +98.0 m. During a year the rate of level rise reached 0.6-1.2 m for the first aquifers from the surface and 0, 62 -2.52 m for the Neogene sediments horizon.

At the beginning of the 1990s, the total area of flooding around tailings storage facilities ranged from 30 km$^2$ to 500 km$^2$. Since 1976, there has been flooding of some settlements, especially within the area of influence of the southern group tailings impoundments.

At present, in general, all Mining and Beneficiation Works have efficient drainage facilities, which mainly intercept filtration seepage and provide safe groundwater depth. Some local flooding areas are concentrated on the industrial sites of GOKs, in surface depressions areas of natural and man-made origin. To date, the problem of chemical pollution of groundwater aquifers has come out on top.

Today, almost all water sources in the world are polluted. [4, 5] Water contains more than 13,000 toxic elements. Depending on the “technophilicity” of each element there is a change in the composition of water with the accumulation of the most popular ones. For the first time, professor - hydrochemist M. Hlazovska drew attention to this fact, she noticed that increase in iron content is typical for cultural landscapes [6]. Her research was based on her own studies conducted in Russia and Kazakhstan, and the generalization of data of scientists from almost all countries.

The studies have confirmed the increased level of iron content in the urban area and have expanded the list of pollutants.

2. Aim and methodology
The aim of the research was to assess the degree of damage to the territories adjacent to the tailings storage facilities of mining enterprises by dangerous hydrogeological processes, flooding and inundation with further development of measures to localize the environmental consequences of mining and reduction of impact on the ecosystem.

To solve the tasks
- analysis, systematization, generalization, comparative analysis of the results of monitoring observations of groundwater condition over a long period of time, both at the facility and regional levels;
3. Results

Groundwater monitoring in Ukraine is carried out in accordance with the Water Code of Ukraine, the Regulation № 391 “On the State Environmental Monitoring System”, approved by the Cabinet of Ministers of March 30, 1998 and with “Procedure for State Water Monitoring” №815, approved by the Cabinet of Ministers of July 30, 1996.

The obligation to conduct on-site monitoring by enterprises, institutions and organizations whose activities affect adversely the state of groundwater, especially those that operate industrial wastewater or waste storage, is defined by Article 105 of the Water Code of Ukraine.

Organizing and arranging a special network of observation wells for systematic monitoring industrial sites of enterprises, areas adjacent to the tailings storage facilities, dumps began in 1977 and were followed by its subsequent expansion over the entire area of the potential impact of enterprises facilities on groundwater and surface water.

During the construction of tailings storage facilities, natural outcrops of rocks in the bottoms of the gullies were not isolated. When filling the tailings storage facilities to the mark of the earth’s surface and above (1970-1980), filtration seepage resulted in the process of groundwater backing-up, and in the formation of new man-made horizons in previously arid areas.

Dozens of research and production organizations, institutes of various profiles and areas of activity (VIOGEM, VSETINGEO, VODGEO, “Ukrvodokanalproekt” and others) have been involved in solving the problems of groundwater formation, quantitative assessment of groundwater balance components, forecasting changes in the hydrological and engineering-geological situation for many years. According to the researchers, the areas where large structures are located (tailings storage facilities, gathering pond for mine waters, etc.) are areas of high risk of emergencies. The reason is that these technical facilities are located in natural gullies, which in themselves are the products of certain tectonic disturbances, associated primarily with cracks in the earth’s crust.

When creating large mass technical facilities in the gullies, areas of increased water permeability may occur due to additional excessive load on the blocks and fracture zones, which can significantly disrupt the natural hydrogeological regime of the whole region, and reduce seismic resistance.

During 2019-2021, the work was performed at the request of the Kryvbas Mining and Beneficiation Works to assess the effectiveness of the existing network of observation wells; control testing of wells, reconnaissance survey of drainage structures, territories, detection of flooding and other hazardous geological processes, studies of archival materials and those of the enterprises concerning hydrogeochemical and quantitative regime of groundwater have been conducted (“The development of design solutions to protect against flooding, directing them to prevent the development of unsafe geological processes, or reduce to an acceptable level of negative influx of the territory and objects of PRJSC “InGZK” (PRJSC “PIVNGZK”, PJSC “CGZK”). Carrying out field hydrogeological studies, laboratory and cameral work.”). The works were performed on the basis of the City Program for Solving Environmental Problems of the Kryvbas and Improving the State of the Environment for the years 2016-2025.

To assess the degree of damage to the research area by flooding, groundwater pollution, archival materials of geological organizations, research institutes, materials on existing hydraulic and drainage structures provided by enterprises, the results of monitoring investigations of groundwater conditions, field hydrogeological surveys of drainage structures and adjacent areas have been studied in the process of research work. The available materials on changes in the quality of groundwater composition in the areas of Kryvbas tailings storage facilities have been
analyzed, a comparative analysis of current data with retro data from previous studies of the facilities and regional levels have been fulfilled. These kinds of works have been carried out for the facilities of PJSC “Northern GOK”, PJSC “Central GOK” and PJSC “Ingulets GOK”.

The geological structure, namely the bottoms of the gullies, are composed mainly of sand, loam, limestone, or a layer of weathered crystalline rocks, water-resistant deposits are thin, in some areas they are missing. In the northern and central parts of Kryvbas, in the tailings facilities locations, sands lie directly on the weathering crust of granites and migmatites, which creates conditions for the hydraulic interconnection of aquifers. In the south, the Neogene limestones of various cavernosity, fissility and water-filtration properties are widespread in the bottom of the gullies. They represent an individual sustained aquifer.

Geophysical studies have confirmed that all gullies are “alive” and their tectonic activity affects the state of the rock massif of the territory as a whole. They serve as “conductors” for contaminated water to the aquifers and further to the rivers due to the high natural fissility of rocks.

The qualitative composition of groundwater in the entire study area is undergoing significant changes moving towards increasing contamination by chemical elements.

Today there is a threat of spreading of heavy metals inherent in ore treatment processes throughout the area and to the depth. The presence of man-made zones of high water permeability of rocks, man-made fissility in the sedimentary cover, the absence of water-resistant rocks in some areas facilitates their penetration into aquifers.

Generalization and systematization of the available factual material concerning changes in the hydrogeological, hydrogeochemical, geological and ecological situation in the study area, allow us to draw the following conclusions.

All drainage structures in the tailings storage facilities and adjacent areas were designed and built in the days of the Soviet Union, mainly before 1990, taking into account the hydrogeological and hydrodynamic conditions at that time.

The purpose of creating a system of protective measures was to intercept filtration losses, to reduce groundwater levels and maintain them at safe depths. According to previous studies, the intensive rise of groundwater levels, the formation of man-made aquifers in previously anhydrous strata occurred in 1970-1980. The set of special engineering measures allowed to minimize the impact of tailings impoundments filtration losses on the environment. In recent years, significant fluctuations in groundwater levels have not been observed. The hydrodynamic regime of groundwater within the study areas is in a very stable state and meets modern operating conditions for tailings storage facilities and drainage systems. At their change, or in emergency situations deterioration of a quantitative condition of underground waters massif is possible.

There occur such processes as flooding, contamination of groundwaters and surface waters on the research territory.

Today, the hydrodynamic situation in the area of the potential impact of the enterprise’s facilities is stably tense, but there is a deterioration in the quality of groundwater composition of all aquifers.

Characteristics of changes in groundwaters and surface waters chemical composition of the study areas are given below from north to south.

In the northern part of the Kryvbas, today the most difficult in hydrogeological terms is the situation between the tailings storage facilities and the Saksagan floodplain, taking into account geochemical processes and phenomena occurring within the influence of production activities of PJSC “Northern GOK”. The floodplain and the Saksagan River itself serve as a reservoir for both filtration water and surface runoff. Groundwater pollution of the Neogene-Paleogene aquifer and fractured crystalline rocks below the drainage depths is occurring (before 60 m).

Existing drainage structures today have largely minimized the impact of filtration losses from the tailings storage facilities on the environment. In recent years, significant fluctuations
in groundwater levels have not been observed.

Ground geophysical surveys were conducted to identify the impact of filtration waters from the tailings on the aquifers of the Saksagan floodplain. Zones of the stress of moistened rocks, with a high degree of their man-made fissility, have been found along the southern boundary of the tailings dam. Geophysical studies have confirmed modern neotectonic disturbances at the bottom of the Petrikov gully and the upper reach of the Bezimenna gully. The gullies themselves are alive and, due to the high natural fissility of rocks, serve as “conductors” of contaminated water to aquifers and further to the Saksagan River.

According to the available data, there is an increased content of such microcomponents as carcinogenic cadmium and nickel (up to 1.9-34 MAC and 2.6-8.4 MAC, respectively), non-carcinogenic lead (up to 1.7-7 MAC), manganese (up to 2-320 MAC), bromine (up to 14-94 MAC) and others in the groundwaters of all aquifers (figure 1).

![Figure 1](image.png)

**Figure 1.** Schematic map of groundwater contamination by heavy metals around the tailings storage facility of the Northern GOK for 2019 (iron, lead, cadmium, manganese, nickel, strontium, bromine). The values are shown in units of exceeding the maximum allowable concentrations (MAC) based on the isogypsum map of the aquifer of the Quaternary sediments as of October 2017 Northern GOK. SE “Ukrchermetgeologiia”.

Significant accumulation of iron total (up to 68-10576 MAC) was also found at the industrial site of the enterprise, near the dumps of overburden. As already noted, an abnormally high value of the content of heavy metals is observed at different depths and over the entire area of research at distances up to 5.0 km to the north, up to 2.7 km to the east, up to 7.5 km north-west, up to 3 km of the Saksagan floodplain.
In the waters of the tailings impoundment, return water supply pond an anomalous content of cadmium has also been recorded – it exceeds 22 and 12 MAC respectively, that of lead is 6.3 and 7 MAC, that of bromine is 122 and 127 MAC.

In addition, in some observation wells, there is a significant increase in the content of macrocomponents, and, accordingly, the growth of dry residue, total hardness, and others. The active reaction of water (pH) in the area varies from acidic (3.8-6.5) to alkaline (7.8-10.3) one.

The sands of the Neogene-Paleogene age, a planar weathering crust of crystalline rocks, the presence of neotectonic movement in both the sedimentary cover and the crystalline massif of rocks are probably the routes of pollutants migration.

For the central part of the Kryvbas, the analysis of observations of changes in groundwater chemical composition in the research area of PJSC “Central GOK”, their comparing with the regional background, indicates the unstable nature of its formation. During the year, there are sharp fluctuations of individual macrocomponents (sulfates, calcium, magnesium), ammonium, iron total, nitrates, total hardness, and others in some areas. There is a fluctuation of the active pH response from acidic (4.4-5.7) to alkaline (7.2-9.74) one. Changes in the quality of groundwaters can occur under the influence of both natural factors (precipitation, air temperature) and man-made (changes in the water level in the Ingulets River during dilution and washing of the riverbed with water from the Dnipro River, filtration losses from the tailings storage facilities, water-bearing communications of various purposes, use of mineral fertilizers on agricultural land, etc.).

The “tailings” strata are permeable. The penetration of polluted waters into aquifers is facilitated by geological and tectonic structure, geomorphological features.

The quality of groundwaters is subject to significant fluctuations, both in the direction of deteriorating quality and abrupt desalination of water, which differs from the natural state of groundwaters in areas remote from the facilities.

The tests of the groundwaters of all aquifers (10-70 m) have shown in some areas abnormally high iron content (up to 36-23660 MAC, at a norm of 0.3 mg / dm³), high manganese content (1.3-66 MAC at a norm of 0.1 mg / dm³), other elements (lead, cadmium, nickel) are not in evidence (figure 2). Changes in the quality of groundwaters are possible under the influence of both natural and man-made factors.

The direction of groundwater movement is to the west and southwest towards the river Ingulets. At the time of research, the direct impact of PJSC “CGOK” on the Inhulets River was not established, but, given the location of anomalies of various origins close to the river, there is a possibility of a further inflow of pollutants into river waters.

For the southern part of the Kryvbas, the generalized results of monitoring observations of PJSC “InGOK” for the period 2013-2020, their comparative analysis with hydrogeological studies of previous years 1950-1955, 2003-2008 indicate the stabilization of the groundwaters level in almost the entire study area. Existing drainage structures mainly intercept filtration seepage and provide a safe depth of groundwaters. Activation of flooding processes in previously identified local areas of flooding is not observed. Thus, the set of special engineering measures allowed to minimize the influence of filtration losses from the tailings storage facilities of PJSC “InGOK” on the environment. In recent years, significant fluctuations in groundwater levels have not been observed. But today, according to the results of long-term observations of groundwaters, there is another problem, which is the intensive change of the hydrogeochemical system.

According to monitoring observations, abnormally high content of elements such as iron total, manganese, sometimes cadmium and strontium has been found in the groundwater of Quaternary and Sarmatian deposits (10-90 m). Local water pollution is observed in alluvial sands near Andriivka, where the content of iron total is 832-1000 mg / dm³ at a maximum
Figure 2. Schematic map of accumulation of iron total and manganese (mg / dm$^3$) in groundwaters around the tailings storage facilities of the Central GOK for 2019-2020 based on the location of wells of the monitoring observation network of PJSC “CGOK”.

The chemical composition of groundwater of the Neogene sediments differs in anionic and cationic composition - mainly the mixed type prevails, which is three-component in terms of anions, their mineralization varies from 1.1 to 6.2 g / dm$^3$. The active reaction of water (pH) in the study area varies from acidic (3.2-5.86) to alkaline (7.9-9.79). The chemical elements might migrate through permeable loess loams strata, the horizon of karst limestones of the Sarmatian Regional Stage, the roof of which can be traced at depths of 5.7-18.0 m, and their outcrop can be observed in the Inhulets river valley.

The qualitative composition of groundwaters in the entire research area has undergone
Figure 3. Schematic map of the distribution of heavy metals (mg / dm$^3$) in groundwaters around the tailings storage facilities of Inhulets GOK based on the location of wells of the monitoring observation network of PJSC “InGOK”. Red marks show the content in 2018-2019, other colors in 2020.

significant changes and mainly in the direction of deterioration - contamination with chemical elements, the solid residue increase, hardness. Deterioration of the hydrogeochemical regime occurred in the aquifers of the Quaternary and Neogene systems.
According to laboratory studies, the groundwaters of the Quaternary sediments have, for the current period, abnormally high iron total content from 1.68 mg / dm$^3$ to 2530.46 mg / dm$^3$, which exceeds the maximum allowable concentrations by 5.9 and 8435 times. There is also an increased content of manganese, which is up to 267-1050 MAC.

The groundwaters of the first aquifer from the surface are characterized mainly by sodium chloride and sodium chloride-sulfate types, their mineralization varies widely from 3.3 to 6.07 g / dm$^3$ to 10.02-21.26 g / dm$^3$.

According to the given data for the current period, there exists contamination of underground waters of the Quaternary and Neogene systems with such elements as iron total, manganese, in some places it is with vanadium, cadmium. The highest content of iron total is observed in the west, south and southwest from the tailings storage facilities.

It is impossible to establish the sources of these microelements penetration in groundwaters, the factors influencing their content, changes over time, at this stage of research. The waters in tailings impoundments do not contain these elements.

The inflow of polluted waters into aquifers occurs through permeable loess loams, areas of carbonate rocks leaching, eroded limestones at the bottoms of gullies. As already noted, the research area is characterized by complex geological-tectonic and geomorphological conditions such as extensive development of gully network, the presence of karst limestones, which already had high porosity and cavernosity in natural conditions. The pond-accumulator of mine waters of Svistunov gully located above the facilities of PJSC “InGOK” also contributes to the pollution of groundwaters of the Neogene deposits and the Inhulets River.

Geological and ecological research in the period from 1997 to 2008 and special research works conducted in 2016 showed an abnormally high value of microcomponents such as iron (15-2800 MAC), manganese (1.9-132 MAC), strontium (1.2-4.79 MAC), lithium (1.2-6.3 MAC) in the groundwaters of the Neogene sediments located within the influence of the pond. During the hydrogeological survey of the territory of sheet L-36-IV (Kryvyi Rih) from the hydrogeological map of Ukraine in some exploration and production wells exploiting the groundwaters of the Sarmatian deposits within the Kherson region, increased iron content of up to 1.0-3.8 MAC has been found, other trace elements of II-IV class of danger have not been detected.

The occurrence of hydrogeochemical halos of pollution is facilitated by the infiltration of precipitation and surface runoff through overburden dumps, tailings dams composed of ferruginous quartzites and concentration wastes. Deterioration of the quality of groundwaters can also occur under the influence of agricultural production (mineral fertilizers), corrosion of metal casing in wells.

Due to the established fact of distribution of iron, manganese, other chemical elements and compounds in groundwaters along the area and to the depth, there is a possibility that they will be found in the Saksahan River, Inhulets River and Karachuny Reservoir. According to geological and ecological studies conducted in the periods from 1989 till 1997, from 2000 till 2012 abnormal concentrations of zinc, lead, phosphorus, manganese, cadmium, iron, etc. were found in the bottom sediments of the Inhulets River at the area of water discharge of the Karachuny Reservoir and further downstream.

It should be noted that in natural conditions, before the creation of the Mining and Beneficiation Works, a high content of heavy metals in groundwaters was not detected. At that time, almost on the entire territory of the Kryvyi Rih, there was an increased content of bromine and boron in groundwaters.

The movement of significant masses of rocks when extracting iron ore, the use of vibration and blasting technologies, the creation of dumps, hydraulic structures with their embankment dams, filtration seepage lead to the restoration of natural fissility, intensification of karst processes and, consequently, the emergence of man-made zones of high water permeability. All this contributes to filtration seepages into aquifers and their spread to the depth and throughout the area.
4. Conclusions
Tailings storage facilities are complex, potentially dangerous hydraulic structures that affect the hydrosphere of the location area. At present, quite effective drainage systems have been created that intercept filtration seepages and maintain the quantitative regime of groundwaters in a stable state.

Today there is a threat of spreading of heavy metals inherent in ore-treatment processes around the area and to the depth. The presence of man-made zones of high water permeability of rocks, man-made cracks in the sedimentary cover, the absence of water-resistant rocks in some areas facilitates their penetration into aquifers.

Accumulation of pollutants (mainly iron and manganese), growth of solid residue and main macrocomponents have been detected in all aquifers. At the same time, iron and manganese are not contained in tailings impoundment waters, and other indicators largely meet the requirements for technical water.

In general, contamination spreads over time and covers a large area around industrial facilities. Monitoring observations show the diversity of the chemical composition of polluted waters. It is clearly associated with the formation of redox (Eh) and the active response (pH) of aqueous media. Almost everywhere there is a significant temporal and spatial heterogeneity in the distribution of macro-components of the salt composition of water, which is due to the dynamics of man-made contaminated water and surface runoff.

The content of contaminating microcomponents increases over the years. Sharp fluctuations in the content of individual wells from abnormal to normal and vice versa during the year cannot be attributed to currently known factors. It is impossible to determine factors influencing their content, change over the course of time at this stage of the research.

Addressing the issue of accumulation and migration of pollutants requires special hydrogeochemical studies [7]. The geochemical essence of the formation of polluted waters chemical composition depends on the state and intensity of changes in the hydrogeochemical system and changes in the migratory properties of chemical elements. [8, 9] It is recommended to expand the observation network in the directions from outermost wells with signs of pollution, which are tested by enterprises, to a relatively clean area.

The involvement of heavy metals in the geochemical cycle can reduce the productivity of agricultural land, reduce the value of landscapes and species diversity of plants, may lead to diseases of domestic animals and humans, and to pollution of water bodies.

Man-made geochemical phenomena and processes that are being detected today are subject to a detailed comprehensive study. Today it is necessary to review the system of groundwaters protection from contamination taking into account the geochemical processes and phenomena that occur within the area of impact of enterprises production activities where research was conducted. According to world practice, the study of groundwater pollution processes, movement of heavy metals is a special field of research where computer modeling is extensively used. The latest methods and scientific developments are needed to localize and prevent the migration of heavy metals with subsequent pollution of groundwaters and surface waters.

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