Ecological and Hydrogeological Problems of the Old Industrial Regions of the Middle Urals (Russia)

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Abstract. Mining of mineral deposits leads to the formation of mining landscapes, within which specific hydrogeochemical systems arise. Following the dewatering to the depths of tens and hundreds of meters, processes of technogenic hyper-genesis and mineral formation are developing, especially in areas where the continuity of rocks is disturbed. Here, the sulfuric acid weathering crust is formed, which contains secondary minerals, including readily soluble crystalline hydrates of sulfates. The article presents the results of the analysis of the hydrochemical situation within the abandoned Levikha mine (Middle Urals). It is shown that the reason for the formation of unloading of acid mine waters on the surface during postmining is the change in the hydrodynamic conditions (cessation of the drainage and the filling of the depression cone), the dissolution of secondary minerals in the technogenic zone of hypergenesis (in the zones of collapse and displacement). The mass consumption of components at the post-operational stage is comparable to the rate of oxidative weathering of sulfides during the operation of the dewatering. The half-life of the components is about 5 years, and the formation of contaminated mine waters will last at least 50 years. These results are the basis for determining the strategy and tactics of planning work to eliminate the accumulated damage to the environment of the mining landscapes of the Middle Urals at the post-mining stage.

1. Introduction

The completion of a large number of mines in recent years (both in the world and in Russia) has led to the need to manage mining landscapes - areas disturbed by long-term mining operations, as well as environmental hazards in the areas of old abandoned mines at the post-mining stage [1, 2, 3]. After the production is stopped and the mining plant is closed, the negative impact on the surrounding area may continue for a long time. The activities of the mining industry are one of the main causes of environmental pollution [4, 5, 6]. This is particularly true of the environmental damage resulting from past mining activities. The need to eliminate past (accumulated) environmental damage has now been reflected at the legislative level. According to the Federal law № 7-FZ, accumulated damage to the environment is the damage to the environment resulting from past economic and other activities, the duties to eliminate which have not been fulfilled or have not been fully fulfilled. In 2016 the Federal service for supervision of natural resources of the Russian Federation together with the regional authorities engaged in the registration of companies and the assignment of categories of environmental risk. Based on these data, a list of 300 pilot enterprises will be formed [7]. The liquidation of such facilities will be carried out within the framework of the «Clean country» project. According to the
preliminary assessment of the Ministry of natural resources of the Russian Federation, the most problematic subjects of the Russian Federation in the direction of "Environmental rehabilitation of territories exposed to the negative impact of objects of accumulated environmental damage as a result of past economic activities of mining and processing industry" are the Transbaikal region territory, Kemerov region, the Republic of Sakha (Yakutia), and Sverdlovsk region. Among the priority measures proposed are elimination of pollution by mine waters of water bodies used for water intake (Sverdlovsk region), including stopped copper mines - Levikha and Degtyarsk.

The aim of the work is to identify ecological and hydrogeological problems of the old industrial regions, connected with the redistribution of chemical elements within the mining landscapes of the Middle Urals in the mining process and after its completion on the example of the Levikha mine.

2. Case study and research methods

Features of the mining landscape, hydrochemical and geoecological situation in the area of the Levikha mine currently are formed by several objects, most of which are located within the former mine allotment. These are flooded pits (depth up to 70 m); mine shafts (depth up to 618 m); dumps (volume 3.5 million m$^3$); zones of collapse and displacement (size 0.5*3.3 km); zone of concentrated discharge of mine waters (technogenic reservoir in the failure with depth of about 30 m, volume of about 50 thousand m$^3$).

The work of the Levikha mine was completed in 2003 after 80 years of operation. A group of Levikha copper-pyrite deposits is located 120 km to the north of the city of Yekaterinburg in the valley of the river. Tagil. Geochemical type of deposits - copper-zinc; mineralogical composition of ores: pyrite, chalcopyrite, sphalerite, bornite, faded ores, pyrrhotite, magnetite, galena, chalcocite, covellite, native gold. A feature of the Levikha deposit is a large number of ore bodies (about 800, of which about 100 worked), an abundance of disseminated ores that surround the bodies of massive pyrite.

To analyze the features of groundwater formation in the area of the Levikhinsky mine, an array of monitoring data has been used for the period from the early 1950s to the present. Since the release of groundwater on the surface in April 2007, pH, Cu$^{2+}$, Zn$^{2+}$, Fe$_{tot}$, Mn$^{2+}$, As$^{3+}$, SO$_4^{2-}$, total mineralization, suspended solids are determined daily. Extended laboratory studies of macro- and microcomponent water samples are performed annually: the content of 70 components is determined using ICP-MS methods, the temperature, Eh, pH is determined in-situ.

Methods of statistical analysis and geochemical modeling using Visual MINTEQ ver code 3.0 / 3.1 were used to process the data. The code is based on MINTEQA2, which was developed by the US environmental protection Agency (US EPA) [8].

3. Research results

Within the mining landscapes of the abandoned Levikha mine, several types of groundwater are formed, which are confined to mine shafts, dumps, and collapse zones (figure 1). The maximum values of almost all indicators are typical for mine waters discharged into a technogenic reservoir (collapse zone). The contents of zinc, aluminum, iron, manganese, sulfur are three-four order of magnitude higher than Clark's concentrations, which accepted as average content in groundwater in the mixed-forest zone [9].
Figure 1. Geochemical spectrum of macro- and micro components in the water bodies of the Levikha mine (accordingly to Clark’s concentrations).

Table 1. Chemical composition of groundwater in the Leviha mine during the mining and post-mining period.

| Components | MAC° | Clarkc | Stage, object, date | miningd | post-mining | dump (21.07.2017) |
|------------|------|--------|---------------------|---------|-------------|-------------------|
|            |      |        | drainage            | reservoir (15.09.2014) | shaft (15.07.2013) |
| pH         | 6.0-9.0 | 6.88   | 2.35 (2.10-2.75)    | 3.18    | 3.90        | 2.48              |
| TDS        | 1    | 0.231  | 11.6 (7.1-24.8)     | 14.5    | 0.68        | 6.1               |
| SO₄²⁻      | 100  | 13.0   | 5 970 (816-13 785)  | 9 954   | 400         | 3 671             |
| Ca²⁺       | 180  | 26.7   | 260 (71-415)        | 423     | 71          | 55                |
| Mg²⁺       | 40   | 8.67   | 340 (35-856)        | 703     | 27          | 145               |
| Al³⁺       | 0.04 | 0.202  | 375 (20-806)        | 603     | 11          | 157               |
| Cu²⁺       | 0.001| 0.00429| 154 (109-453)       | 11      | 5           | 6                 |
| Zn²⁺       | 0.01 | 0.0364 | 317 (119-556)       | 323     | 17          | 4                 |
| Fe₅₆⁺      | 0.1  | 0.469  | 730 (210-3 242)     | 1 373   | 2           | 1 023             |
| Mn²⁺       | 0.01 | 0.0573 | 47 (31-110)         | 94      | 3           | 8                 |
| Ni²⁺       | 0.01 | 0.00411| 0.2 (0.13-0.29)     | 0.5     | 0.03        | 0.1               |
| Co²⁺       | 0.01 | 0.00037| 0.2 (0.01-0.3)      | 1.5     | 0.07        | 0.2               |
| Cd²⁺       | 0.005| 0.00015| 0.8 (0.7-1.0)       | 0.3     | 0.08        | 0.01              |
| As³⁺       | 0.05 | 0.00246| 0.1 (0.01-0.3)      | <er     | <er         | 0.44              |
| REE         | ni   | ni     | 6.1 (5.0-6.5)       | 8.9     | 0.28        | 0.51              |

a Dimensions: TDS - g/L, other components - mg/L, <er - less than the error of definition, ni - no information, TDS - total dissolved solids; REE - the sum of rare-earth elements.

° maximum allowable concentrations for fishery water reservoirs.

c [9].

d Mean annual values and range of their changes (in parentheses), data from [10, 11, 12].
The composition of groundwaters differs also from the one that was formed during drainage dewatering at the mine (table 1). The content of most of the indicators of the chemical composition of mine waters unloading into the reservoir (discharge rate is half of the drainage during mining) is up to now higher than during mining. The composition of groundwater in the zone of discharge is sulfate, hydrocarbonate-ion is absent, chlorine is detected in an amount of 25-53 mg/L. The content of nitrogen compounds is insignificant: nitrate and nitrite ions are not more than 6 mg/L; ammonium ion from 2 to 24 mg/L. Water has become less acidic, pH varies from 3.1 to 4.1 units. Among the cations there are either aluminum, or magnesium, or iron in the first place. Groundwater temperature is 10°C, Eh = 266 mV, Fe^{2+} = 1209 mg/L, Fe^{3+} = 53 mg/L.

4. The discussion of the results
At the copper pyrite mines of the Middle Urals in underground mining, as a rule, technologies with the collapse of the roof of the worked out space are used. Sinkholes, caving and collapse zones are formed on the surface of the earth. Here, technogenic fracturing develops and as a result - the permeability and capacity of the rock increases, infiltration increases in several times [13]. These factors contribute to a more intensive penetration of infiltration water with oxygen into the disturbed zone and the formation of anthropogenic sulfuric acid weathering crust, the development of technogenic mineral formation processes.

After filling the depression cone, areas of concentrated discharge of groundwater on the surface are formed, which are timed to failures in the collapse zones. The quality of groundwater is characterized by a significantly unsteady hydrochemical regime: in the first years there is a sharp increase in the concentrations of most components, then a gradual decline in indicators begins, which can last for decades or more [14]. The change in the content of most components is well described by the exponential dependence (figure 2). The half-life (the time in which the concentration of the component is halved) is on average 5 years. For example, a decrease in zinc concentrations to values close to the maximum permissible will occur approximately 50 years after the flooding and the release of mine water to the surface.

![Figure 2](image_url)

**Figure 2.** A change in the content of zinc in mine water of the discharge zones: the actual content and prognosis. $R^2$ is a measure of the accuracy of the approximation.

The results of calculating the saturation of groundwater in the unloading zone show that they are: supersaturated with respect to hematite, magnetite, goethite, lepidocrocite, jarosite; are in equilibrium with gypsum, anhydrite, ferrrihydrite; are not saturated with respect to epsomite, chalcantite, melanerite, etc. High concentrations of sulfate sulfur determine the form of the migration of metals in the form of sulfate complexes: $\text{Al}^{3+}$ and $\text{Fe}^{3+}$ almost completely; the divalent cations ($\text{Ca}^{2+}$, $\text{Mg}^{2+}$, ...
Fe\(^{2+}\)) in an amount of about 50%; the monovalent cations is not more than 10% (the program code Visual MINTEQ ver 3.0 / 3.1 was used applied).

5. Conclusions
Hydrodynamic, and geochemical processes in mining industrial landscapes lead to the formation of a technogenic zone of hypergenesis, the composition of which depends on the processes of technogenic mineral formation in the zone disturbed by mining operations.

The formation of hydrogeochemical systems of mining industrial landscapes at the post-mining period is a consequence of the restructuring of the geofiltration structure of the flow, the hydrodynamic balance of the mining territory and the change in oxidation-reduction conditions.

The mass flow rate and rate of dissolution of secondary sulfates within the spent Levikha copper-pyrite deposit for 15 years after completion of its development are comparable with the rate of oxidative weathering of sulphides during the operation of the dewatering [15, 16]. The time for which the concentration of the component in the mine water discharge zone is halved (half-life) is about 1500 days. Formation of contaminated mine waters will last at least 50 years.

Rational nature management in the mining areas at the post-mining period is determined by the organization of measures to eliminate the accumulated harm to the environment, including the localization of the places of concentrated unloading of mine waters and their neutralization for dozens of years.

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