Geoecological situation in the region of the Erdenet mining and processing facility (Mongolia)

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Abstract. The Erdenet mining and processing facility (Mongolia) develops a large copper-molybdenum deposit. The volume of waste in the tailings dump of the enterprise reaches 600 m. m^3 and its area is more than 1300 hectares. Quarries and tailings pits release significant amounts of persistent pollutants into the environment. They penetrate groundwater and surface water and also spread as dust. The results of comprehensive geochemical and geoecological studies indicate the irreversible anthropogenic transformation of the area. In 25 years, the operation of the Erdenet deposit will be terminated. Mongolian government decided to develop a "Concept of the program for closure of the enterprise, and further development of the area". Based on the results of this research, it is proposed to identify several areas and develop special renovation projects for each of them. An enterprise for the production of construction materials can be created on the tailing's dumpsite. Companies extracting residual amounts of valuable elements from waste can be profitable. The network of transport communications of the deposit can ensure the operation of facilities in areas of mining landscapes and technogenic geochemical anomalies. After planning the terrain and covering the surface with insulating materials on these sites, a technology park can be organized. Implementing these projects as part of a single program will provide jobs for the Erdenet residents, and the budget revenues generated by their operation will allow for the renovation of the urban area.

1 Introduction

The most ecologically dangerous consequences of the operation of mining enterprises, which carry out the extraction of ore and its primary processing (enrichment), are the rise to the surface of the Earth of significant amounts of heavy metals and several other elements, their uncontrolled migration and accumulation in biological objects [1-5]. These technogenic elements are persistent, non-degradable and, as a rule, toxic pollutants that cause degradation of ecosystems and pose a threat to public health [6-13]. Their impact is manifested not only during the period of exploitation of mineral deposits, but also after its termination [14-20].

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The wastes generated during mining and concentration of nonferrous metal ores are accumulated in the tailing [21-22]. Usually these are terrain areas filled with wastes in the form of a slurry, that is to say a mixture of mineral particles and water used for their transportation. The spread of these streams is limited by dams, and the water accumulating within their boundaries, is reused. In this way, circulating systems of technical water supply are created.

Spreading of pollutants (of which heavy metals are the most important) in the regions of mining and processing plants occurs in two main ways. Firstly, it is filtration of water from the tailing ponds through the enclosing dams and underlying rock massifs. Secondly, it is the transport of dust particles containing technogenic elements from the pits and other areas of the production area. As a result of migration and subsequent accumulation of heavy metals in the areas of mining enterprises technogenic geochemical anomalies are gradually formed.

In addition to environmental pollution, the development of mineral deposits in most cases causes changes in the soil and vegetation cover, relief and hydrographic network in large areas, which leads to the formation of the so-called mining landscapes. There is a significant change in the population of the region and its composition, the development of infrastructure. Part of the territory is urbanized. Thus, fundamentally different geo-ecological conditions are formed.

When the ore reserves are exhausted, the work of mining enterprises stops, and the population deprived of work finds itself in an environment of irreversible geochemical and geoecological transformation. A return to the traditional forms of economic activity that existed in the previous period is no longer possible. The situation is often aggravated by the fact that control over tailings ponds and other sources of pollution is significantly weakened after the termination of mining operations. As a result, environmental and social conditions often deteriorate in such regions [23]. It is possible to avoid a negative scenario of development of the situation by timely development of programs of multifaceted renovation of the region, allowing after the closure of mining enterprises in the shortest possible time to implement a set of measures that can ensure the preservation of a favorable environmental situation and prevent a sharp decline in the living standards of the population [24]. According to forecasts, the depletion of the reserves of the deposit and the closure of the Erdenet mine will occur in approximately 25 years [25]. For this reason, in 2013. The Mongolian government decided to develop a "Concept for the Mine Closure Program, the Enterprise, and Further Development of the Territory. The purpose of this study was to obtain materials that can be used to form a scientific basis for the implementation of this government decision

2 Characteristics of the research object, materials and working methods

The Erdenet mine is located in the central part of Mongolia on a flat, hilly plain covered with alternating steppe and forest areas. Its creation in the form of joint venture with the USSR to develop the reserves of copper-molybdenum deposit by open method was started in 1973 [26]. The mine was put into operation in 1978. The third most populous city in the country was built to provide the enterprise with manpower. Over the decades of operation of the mine a huge amount of waste was formed, which accumulates in the tailings dump in the dammed section of the valley of the river Zuni. The area of the tailings dump is more than 1,300 hectares, and the volume of waste accumulated in it is 600 million m^3.

Materials were collected in 2019-2021 (fig. 1-3). Sampling of soil, surface water and groundwater was carried out in accordance with the requirements of international standards ISO 18400-104:2018, ISO 5667-1:2020. When planning the research, the area was divided into four zones:

1. Production zone – areas directly adjacent to mine workings and facilities of the mine.

2. Tailings Management Facility zone, including areas near its boundaries.
3. Residential area – the territory of Erdenet town.
4. The zone of natural landscapes located within a radius of 10 km around the mine, at a distance of not less than 1 km from the industrial zone, the tailings dump and urban development.

Soil and soil samples were taken from the surface layer (0-20 cm). The mass of each sample was at least 100 g. Their preparation for analysis was carried out in accordance with the requirements of international standards ISO 18400-104:2018 Soil quality. Sampling. Part 104: Strategies. After drying at a temperature of 30-40°C, the soil (soil) sample was crushed in special mills and sifted through a sieve with a hole diameter of 2 mm. The material for analysis was taken from the mass of the sample by the method of double quartering.

Sampling of surface water and groundwater from wells was carried out in accordance with the requirements of the international standard ISO 5667-1:2020. They were stored in sealed plastic containers. The sample volume was 100 ml. Nitric acid was used as a preservative. The storage time did not exceed 10 days.

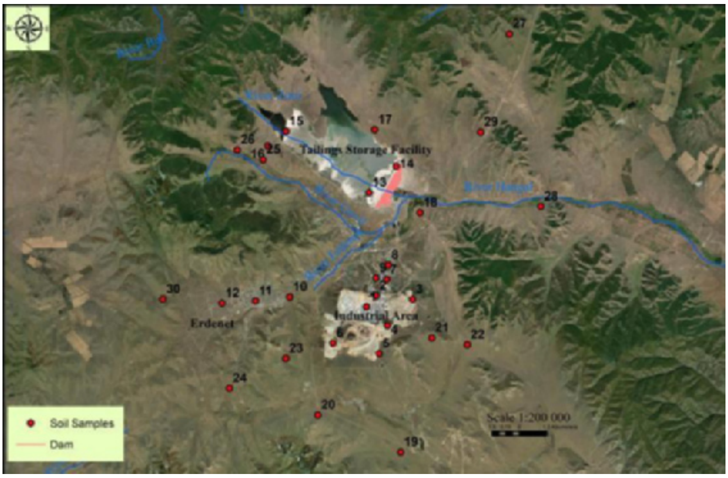

Fig. 1. Soil sampling points of Erdenet mine area

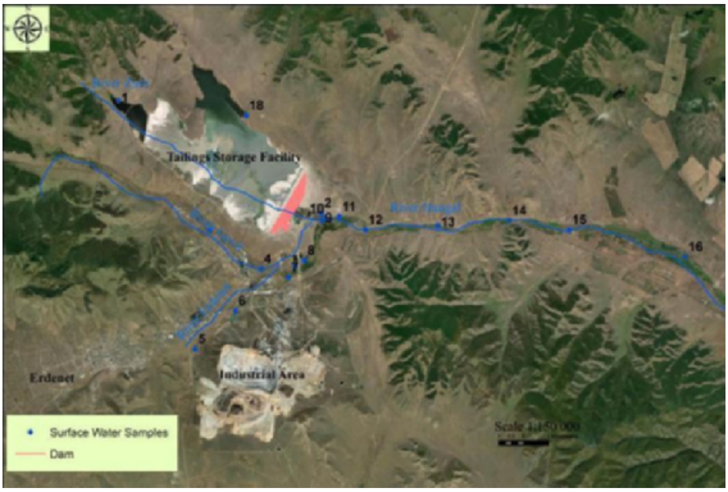

Fig.2. Surface water sampling points of Erdenet mine area

Fig. 3 Groundwater sampling points of Erdenet mine area

The content of heavy metals and other elements in soil, surface and groundwater samples was determined by inductively coupled plasma mass spectrometry (ICP-MS) [27-28]. During the research, the ICP40B device was used. This technique requires the transfer of the elements to be determined into the dissolved state. The purpose of the analysis was to determine the content in the samples of only technogenic elements capable of migration. For this reason, samples were prepared for analysis by their extraction method. The complete dissolution of soil samples could give a distorted idea of the level of their technogenic pollution due to the transition of elements that make up mineral particles of natural origin into the solution. For the extraction of technogenic elements, a sample of dry soil weighing 500 mg was heated to 50°C in hermetically sealed vessels with 20 ml of 5% nitric acid. Then, for 10 minutes, the contents of the vessel were intensively mixed on a vibrator and filtered through a glass filter No. 4.

For the analysis of surface and underground waters, 20 ml of a sample was placed in sealed vessels and nitric acid was added. Its concentration was brought up to 5%. Natural waters usually contain a certain amount of suspended particles that are capable of absorbing technogenic elements. To transfer them into solution, water samples were also heated to 50°C, mixed for 10 minutes and filtered through a glass filter No. 4.

The content of dissolved substances in all analyzed samples did not exceed 2 g/l. At least 3 aliquots were taken from each sample. The acceptable level of convergence of the results was 90%.

The results were evaluated based on Mongolian state standards:

– MNS 5850: 2019 Normative values of contaminating elements in soil.
– MNS 4586:1998 Qualitative indicators of the aquatic environment. Basic requirements for surface waters.
– MNS 6148:2010 Water quality. Normative values for the content of contaminants in groundwater.

A feature of Mongolia's environmental standards is the assessment of the degree of pollution of the environment is carried out by three levels of substance content in the environment: the maximum allowable concentration (MAC); toxic concentration (TC); hazardous concentration (HC).

3 Results

During all surveys, the highest level of contamination of surface soils with technogenic elements was observed in the industrial zone, where sampling sites are located in close proximity to the main source of pollution – mine workings. Thus, according to studies conducted in 2021, the range of test results on copper (***Cu***) content in the soil of this area was very significant – from 50.0 to 4410.0 mg/kg (Table 1). The average value was 1257.5 mg/kg, which exceeds the hazardous concentration level set by MNS 5850:2019. Similar data was obtained for molybdenum (***Mo***). The range of fluctuations in the content of this element was also very large, and the average value was more than twice the level of its dangerous concentration. The content of arsenic (***As***) in a number of samples from the production area was higher than the hazardous concentration, and the average value exceeded the MAC. The zinc (***Zn***) content in some samples was above the MAC, but the average value of this indicator was below this level. The content of lead (***Pb***) was above the MAC in only one sample. A similar result was obtained for vanadium (***V***). Strontium (***Sr***) was not exceeded MAC in any sample.

Table 1. Heavy metal content in soils of the Erdenet mine area (June 2021)

Elements	Value range, mg/kg	Mean value, mg/kg	Normalized levels by MNS 5850:2019, mg/kg		
			MAC	TC	HC
Industrial area					
Copper (Cu)	50.0 – 4410.0	1257.5	100	500	1000
Molybdenum (Mo)	0 – 182.0	42.1	5	20	50
Arsenic (As)	0 – 106.0	27.1	20	50	100
Zinc (Zn)	58.0 – 391.0	130.0	300	600	1000
Lead (Pb)	16.0 – 121.0	35.8	100	500	1200
Vanadium (V)	42.0 – 151.0	84.7	150	600	1000
Strontium (Sr)	72.7 – 640.0	348.0	800	3000	6000
Tailings impoundment area					
Copper (Cu)	31.8 – 1280.0	173.2	100	500	1000
Molybdenum (Mo)	0 – 34.0	6.5	5	20	50
Arsenic (As)	0 – 71. 0	13.8	20	50	100
Zinc (Zn)	64.0 – 193.0	90.2	300	600	1000
Lead (Pb)	10.0 – 43.0	17.8	100	500	1200
Vanadium (V)	76.0 – 138.0	89.8	150	600	1000
Strontium (Sr)	201.0 – 693.0	382.8	800	3000	6000
Selitic area					
Copper (Cu)	56.3 – 598.0	157.8	100	500	1000
Molybdenum (Mo)	0 – 18.0	4.4	5	20	50
Arsenic (As)	0 – 28.0	9.3	20	50	100
Zinc (Zn)	79.0 – 403.0	164.3	300	600	1000
Lead (Pb)	20.0 – 54.0	24.5	100	500	1200
Vanadium (V)	78.0 – 155.0	91.8	150	600	1000
Strontium (Sr)	455.0 – 1210.0	538.9	800	3000	6000
Natural Landscape area					
Copper (Cu)	54.9 – 190.0	120.0	100	500	1000
Molybdenum (Mo)	0 – 12.0	4.8	5	20	50
Arsenic (As)	0 – 15.0	5.7	20	50	100
Zinc (Zn)	69.0 – 330.0	167.8	300	600	1000
Lead (Pb)	20.0 – 50.0	28.6	100	500	1200
Vanadium (V)	75.0 – 112.0	91.9	150	600	1000
Strontium (Sr)	329.0 – 508.0	428.6	800	3000	6000

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High levels of ***Cu***, ***Mo*** were observed in most soil samples from the tailings area, but they were significantly lower than in the production area. The distribution of ***As*** was uneven. In samples taken directly in the tailings dump, its content was often much higher than MAC, but in many adjacent areas arsenic concentration decreased to analytical zero. This explains the low value of the average content of this element. The amount of ***Zn***, ***Pb***, ***V***, ***Sr*** did not exceed the permissible level in any of the samples taken in this area.

In the soil samples from the residential area, the average concentration of ***Cu*** exceeded MAC. Probably, it is connected with the Probably, it is connected with the transfer of aerosols from the industrial zone. The highest concentrations of ***Cu*** and ***Mo*** are noted in areas located near transport communications. This indicates a possible transfer of pollutants by motor transport as well. In the same samples, as a rule, higher content of ***As***, ***Zn***, ***V*** and ***Sr*** was also noted. At two sites the amount of ***Zn*** in the soil exceeded MAC. At one site, ***V*** and ***Sr*** exceeded MAC values.

In soils of natural landscapes, exceeding of MAC values for ***Cu***, ***Mo***, ***As***, and ***Zn*** was recorded in a number of points located within 5 km radius from the production zone and the tailing dump. Most of them were located in the path of prevailing wind directions. Consequently, the formation of these geochemical anomalies is due to air transport of contaminated aerosols.

Surface water samples were taken at 12 sections of the hydrographic network consisting of tributaries of the Hangal River - Erdenet, Govil, and Zuni rivers. Content of heavy metals in them varied greatly depending on hydrometeorological conditions at the time of sampling. Exceeding of acceptable concentrations of ***Cu*** was noted in a number of samples from the Zuni River, lower reach of the Erdenet River and the section of the Hangal River, below the confluence of these watercourses. The maximum value was 0.03 mg/l with MAC of 0.01 mg/l (MNS 4586:1998). Probably, the source of contamination was leachate effluents from the tailings dam and groundwater seepage in the area adjacent to the tailings.

Groundwater sampling was carried out from 14 wells and man-made springs located along the banks of the tailings dump, industrial and residential areas. High concentrations of ***Cu*** and ***Mo*** repeatedly exceeding MAC (respectively, 1.0 and 0.04 mg/l according to MNS 6148:2010) were constantly recorded in the wells in the areas surrounding the tailings dump and in the industrial zone. Many of them also had exceedances of MAC for ***Zn*** (5.0 mg/l according to MNS 6148:2010).

4 Discussion

The analysis of the obtained materials shows that in the region of the Erdenet Mine virtually irreversible changes in the environment have taken place. The main source of transformation of geochemical conditions are:

– migration of heavy metals from the tailings and production area into groundwater and surface watercourses;
– distribution of technogenic elements with dust generated during rock excavation, explosions, ore transportation, as well as deflation from the surface of mine workings and the tailings dump.

Changes in the geo-ecological situation are caused both by gradually increasing contamination of the soil cover and underground waters and by withdrawal of significant land plots for the mine facilities, open-pit mines, tailings dams, housing and infrastructure facilities.

When considering the possibilities of preventing the negative consequences of the mine operations, it is reasonable to divide the damage caused by it into current and accumulated damage. Current damage is the damage caused to the environment at a given stage of the enterprise's operation. In the case under consideration, the main measures for its minimization may be:

– improvement of the recycling system of the tailing pond water, as well as the drainage and water treatment systems at the mine facilities in order to reduce the migration of pollutants through ground and surface waters;
– dust suppression measures to prevent the spread of pollutants through the air.

The expected result of minimizing the current damage may be not a cardinal improvement of the environmental situation, but rather a reduction in the rate of its deterioration. The process of accumulation of heavy metals in environmental elements will continue, causing the formation of new technogenic anomalies and increasing the content of pollutants in already existing ones.

Thus, in any case, in the post-exploitation period, acute problems will inevitably arise in the region due to the accumulated environmental damage, that is to say deterioration of environmental quality, making it difficult to use the territory for other purposes and, as a consequence, causing a decline in the living standards of the population. As the experience gained during the closure of other mine sites shows, it is impossible to solve this problem by reclamation of disturbed areas [23]. It is necessary to develop a comprehensive renovation program that takes into account the specifics of the distribution of accumulated environmental harm in the area where the mine is located. For this purpose, this area should be zoned by identifying within it the areas whose technogenic transformation is fundamentally different in its nature and level. Thus, in the area of the Erdenet mine, the following types of landscapes are formed:

– mining landscapes (production area and tailings dump);
– technogenic geochemical anomalies - part of the natural landscape zone, which has preserved the natural relief and structure of the soil profile, but has accumulated a significant stock of persistent pollutants;
– areas not subjected to irreversible technogenic transformation (content of technogenic elements in their soils and groundwater does not exceed MACs);
– urbanized areas.

Earlier, on the example of the decommissioned Nalaikh mine, variants of renovation projects were proposed for each of the above types of sites [24]. Taking into account the local features, they can also be used in the region of the Erdenet Mine. For example, an enterprise for the production of construction materials, in which toxic elements are firmly bound and cannot have a harmful effect on humans and other biological objects, can be created from the accumulated waste at the tailings dump site. Modern technologies make it possible to use tailings dumps for cost-effective extraction of residual amounts of valuable elements contained in them [29-30]. The conditions of the production area, after planning the relief and creating isolating covers on it become suitable for organizing a technopark or a logistics center, which is facilitated by the network of transport communications created during the operation of the mine. The use of developed infrastructure creates conditions for the transformation of sites that have not undergone technogenic transformation into places of mass recreation and tourist facilities, that is to say into a system of organized resorts [31] (Suzdaleva and Beznosov 2012). The timely implementation of these projects will provide jobs for the residents of Erdenet, and from the budget revenues received from their operation, to carry out the renovation of the urban area.

5 Conclusion

A significant part of the territory surrounding the Erdenet mine has undergone an irreversible technogenic transformation. Over an area of more than 50 km^2, mining landscapes were formed. Their relief was formed in the process of mining and primary processing of minerals.

The natural ecosystems in these areas have been destroyed. The average content of technogenic elements in the surface layer of the soil is: ***Cu*** – 1257.5 mg/kg (more than 10 MAC), ***Mo*** – 42.1 mg/kg (more than 8 MAC). The industrial zone also has a high level of groundwater pollution. The concentration of technogenic elements in water samples from wells in this zone reached: ***Mo*** – 0.69 mg/l (more than 17 MAC), ***As*** – 0.20 mg/l (20 MAC). The maximum level of heavy metals in surface waters was noted in the places where effluents from the tailing dump enter the rivers. ***Cu*** concentration in this area reached 0.03 mg/l (3 MAC). As a result of air and water migration of persistent pollutants (***Cu***, ***Mo***, ***As***, ***Zn***), technogenic geochemical anomalies have formed in the preserved natural landscapes. The area of the territory within which areas of high content of these elements in the upper soil layer were found is more than 100 km^2.

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