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Assessment of environmental hazard of accumulated mineral processing waste of closed mining enterprises in the Amur river region and Primorye

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Abstract: The subject of research was technogenic waste systems formed in the last century due to the activities of presently closed mining enterprises in the Amur River Region and Primorye of the Far Eastern Federal District of the Russian Federation. Experimental studies allowed to establish that toxic sulphidized mineral processing waste accumulated for the 20th century in tailings storage facilities (TSF) in large quantities produce negative impact on the environment. It was revealed that their conservation and reclamation were not carried out. However, they pose huge threat not only to the environment, but also to public health. In this regard, the research goal was to assess environmental hazard of the accumulated toxic waste and substantiate the possibility of mitigating their negative impact on biosphere components and human health. Based on the research goal, the following tasks were set: 1) analysis and generalization of the existing experience of studying the problem in Russia and abroad; 2) identification of the main sources of crisis situations at closed mining enterprises, indicators and criteria for assessing the environmental hazard of the accumulated mineral processing waste; 3) assessment of the environmental hazard of the accumulated mineral processing waste; 4) development of principles and measures aimed at ensuring environmental safety of TSF comprising toxic waste. The following methods were used: physical-chemical, biological, as well as mathematical modeling, GIS technologies, etc.Based on the study of the TSF current state, assessment of the level of technogenic environment pollution, and patent search, the authors substantiate the need for effective solution to this problem. It was found that the waste belongs to the second hazard class (highly hazardous). The excess of 4 to 46 times above the regional background indicators (metal concentrations), and more than 200 times above MPC was revealed. It has been proven that the TSF surface does not naturally run wild for 30 years. Patent search and our own experimental research allowed developing measures to ensure environmental safety of sulfidized tin ore processing waste, novelty of which was confirmed by patents of the Russian Federation.

Keywords: toxic sulphidized waste of tin ore processing, tailings storage facilities, potential of biological systems, closed mining enterprises, reclamation, crisis situations

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Оценка экологической опасности накопленных отходов переработки минерального сырья закрытых горных предприятий в Приамурье и Приморье

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Аннотация: Объектом исследования явились сформированные в прошлом веке деятельностью ныне закрытых горных предприятий природно-горнопромышленные техногенные системы в Приамурье и Приморье Дальневосточного федерального округа Российской Федерации. Экспериментальные исследования позволили установить, что складированные в хвостохранилища сульфидизированные токсичные отходы переработки минерального сырья, накопленные в прошлом веке в большом количестве, негативно влияют на окружающую среду. Выявлено, что их консервация и рекультивация не были проведены. Однако они представляют огромную угрозу не только для окружающей среды, но и для здоровья населения. В связи с этим цель исследования состояла в оценке экологической опасности накопленных токсичных отходов и обосновании возможности снижения их отрицательного влияния на компоненты биосферы и здоровье человека. Исходя из цели исследования, определены следующие задачи: 1) анализ и обобщение существующего опыта изучения проблемы в России и за рубежом; 2) выявление основных источников создания кризисных ситуаций на закрытых горных предприятиях, показатели и критерии оценки экологической опасности накопленных отходов переработки минерального сырья; 3) оценка экологической опасности накопленных отходов переработки минерального сырья; 4) разработка принципов и мероприятий, направленных на обеспечение экологической безопасности хвостохранилищ с токсичными отходами. Использованы следующие методы: физико-химические, биологические, а также математического моделирования, ГИС-технологий и др. В статье на основе изучения современного состояния хвостохранилищ, оценки уровня техногенного загрязнения объектов окружающей среды и патентного поиска обоснована необходимость эффективного решения названной проблемы. Установлено, что отходы относятся ко второму классу (высокоопасные). Выявлено превышение регионально фоновых показателей от 4 до 46 раз, а ПДК – более чем 200 раз. Доказано, что поверхность хвостохранилищ естественным путем не зарастает в течение 30 лет. Патентный поиск и собственные экспериментальные исследования позволили разработать мероприятия по обеспечению экологической безопасности сульфидизированных отходов переработки оловорудного сырья, новизна которых подтверждена патентами РФ.

Ключевые слова: токсичные сульфидизированные отходы переработки оловорудного сырья, хвостохранилища, потенциал биологических систем, закрытые горные предприятия, рекультивация, кризисные ситуации

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Introduction

The events that took place in tin mining industry in the last century, as well as socio-economic processes in Russia [1], could not but affect environmental safety of mining industry in the Far Eastern Federal District (FEFD). In this sphere, certain negative trends have developed and are steadily manifesting themselves [2]. The accumulated damage in the form of tailings storage facilities containing large amount of toxic pollutants (historically generated by presently closed tin ore enterprises) requires urgent organization of work on assessing and stage-by-stage elimination of its environmental consequences [3]. This task is one of the conditions for achieving the goal of the Concept of long-term socio-economic development of the Russian Federation until 2020 for improving the environment quality and ecological conditions of human life [4].

Analysis and generalization of domestic and foreign experience in solving these problems indicates that the problem of eliminating the consequences of the accumulated (in the last century) damage remains on the agenda for more than twenty years. This is due to active and often uncontrolled closure of mining enterprises and other hazardous facilities both here in Russia and abroad. For example, the paper of K. A. Gegiev et al. [5] considers the current state of the Tyrnyauz TSF of the closed Tyrnyauz Tungsten-Molybdenum Combine (TTMC, Kabardino-Balkaria), which currently causes great concern. Active development of erosion-landslide processes with the formation of mudflows along the Gizhgit Rive takes place now at the TSF.

Ivanova O. A. et al. [6] analyzed the state of the most unfavorable part of the Baikal Natural Territory, namely Zakamensk district of the Republic of Buryatia, where tungsten ores were mined and large volumes of waste from their processing were accumulated in the last century.

Ecological situation there is heavy and even critical. All natural environment components have been polluted. Oxidation of sulfide minerals of the ore field with the formation of sulfuric acid and the removal of environmentally hazardous chemical elements from the dumps by mine, open-pit and infiltration waters led to the pollution of a number of watercourses in the Dzhida River basin, which are the most polluted in the Baikal Lake basin. The authors believe that a significant gap is the lack of such legislation in the Russian Federation that would strictly prescribe responsibility for historical environmental damage.

In the paper of Pashkevich M.A. et al. [7], the results of the study and assessment of the landscape-geochemical situation in the area of the apatite-nepheline processing plant TSF (ANOF-2, Apatity) are presented. Violations were revealed within the area affected by the studied production facility. It is concluded that at heavy environmental situation in the territory under consideration and urgent necessity to reduce the anthropogenic load, the issue of developing a balanced strategy for managing environmental safety of the functioning ANOF-2 TSF becomes especially urgent.

Gurbanov A. G. et al. [8, 9] performed a set of geochemical studies in the territory of the Tyrnyauz Tungsten-Molybdenum Combine (TTMC, Kabardino-Balkaria) and the Sadon Lead-Zinc Combine (North Osetia - Alania), including comprehensive analysis of various surface waters by modern analytical and instrumental methods, soils of farmland and natural pastures, buried industrial waste of TTMC, open pit dumps. As a result of generalization of the data obtained, taking into account the geological-geochemical and physical-geographical features of this region, the main sources of environmental pollution were established, represented by two groups: technogenic and natural. The researchers have proven that for reducing the risk of human losses, mitigating possible material damage from natural and man-made disasters, and minimizing negative environmental impact in the region and on the protecting human health, it is necessary to fully utilize the industrial waste accumulated in the TTMC TSFs, with mandatory preliminary extraction of economically valuable metals and toxic elements from them. As priority measures to reduce negative environmental impact in the area of TTMC operation and adjacent territories, it is proposed to create an integrated technique for processing of the technogenic waste with their gradual disposal, as well as to construct water intakes for streams, primarily those draining the

Mukulansky open pit, with a series of purification filters in the form of ion-exchange columns of various types.

According to A. G. Gurbanov et al. [9], the primary task for the Sadon Lead-Zinc Combine (SLZC) is temporary isolation of polluted waters, first of all, those discharged through a pipe from the TSF into the Ardon River and Archondon River, which are the main suppliers of toxic elements into the Ardon River (with extraction, from the waters, of a set of elements with concentrations above the MPC for drinking water). Such a measure will significantly reduce pollution of the Ardon River with these elements and improve environmental situation in the area of the SLZC operation and adjacent territories. In addition, in the process of extracting the set of elements, it is quite possible to simultaneously obtain pure oxides of a number of valuable metals (Pb, Zn, Cd, Sb, Bi, etc.), that will significantly increase economic attractiveness of this measure.

Chigoeva D.N. et. al. [10] studied the state of the Ardon River downstream of the discharge from the TSF of the Sadon Lead-Zinc Combine. It was revealed that long-term exploitation of the lead-zinc deposits in the Sadon mining region has led to formation of extensive aureoles of chemical pollution of surface watercourses, which corresponds to the category of "ecological disaster". The necessity of organizing their monitoring within the TSF-affected area has been substantiated.

Kachor O.L. et al. [11] on the basis of geoecological and geochemical monitoring revealed the extent of pollution of three mining zones, located in the Irkutsk Region and the Trans-Baikal Territory. The expediency of using the ash of slime-lignine (waste of the Baikal PPM) for neutralizing toxic soil mixtures is shown. The possibility of sorption of residual (after treatment with the reagent) mobile forms of arsenic using modified carbon sorbents for the most complete extraction of the hazardous toxicant to achieve its MPC values has been revealed. The results obtained are of great practical importance for implementation of the method for chemical immobilization of As mobile ionic forms in the technogenesis zone. The same conclusions were obtained by foreign scientists [12–14].

The paper of A. Romero et al. [15] is devoted to assessment of the risk of scattering toxic microelements from the waste dumps of the Rio Tinto mine (in the south-west of Spain). In this study, a model was developed to delineate risk zones, which are affected by atmospheric scattering of fine particles from the mine waste dumps, assess their impact on the soil and population in accordance with the concentration of compounds of toxic chemical elements in them [16].

Zhigang H. et al. [17] studied the distribution of heavy metal compounds and estimated soil pollution within the area affected by a lead-zinc mine located in Inner Mongolia (China). For this purpose, the Nemerov index and the index of potential environmental risk were used, which allowed to identify high level of technogenic pollution.

The studies of Sung-Min Kim et al. [18] have shown that closed mines in Korea are the most hazardous. The studies of Rosario García-Giménez et al. [19] and Gbadebo A.M. et. al. [20] indicate that mine tailings intensively pollute soils within the territory of the abandoned Monica mine (Bustarviejo) in the Autonomous Region of Madrid (Central Spain), as well as in southwestern Nigeria.

The studies of Mayra Peña-Ortega et al. [21] are of great interest. They are devoted to environmental assessment and calculation of soil erosion at abandoned mine tailings storage facilities in the semi-arid zone of northwestern Mexico. The research was carried out using unmanned aerial vehicles (UAVs) in combination with geochemical data to assess the erosion processes and taking into account the indicators of pollution and hazard from the TSFs containing compounds of toxic heavy metals and arsenic.

Research objectives and tasks

The research objective was to assess environmental hazard of the accumulated toxic waste and substantiate the possibility of mitigating their negative impact on biosphere components and human health. Based on the research goal, the following tasks were set: 1) analysis and generalization of the existing experience of studying the problem in Russia and abroad; 2) identification of the main sources of crisis situations at closed mining enterprises, indicators and criteria for assessing the environmental hazard of the accumulated mineral processing waste; 3) assessment of the environmental hazard of the accumulated mineral processing waste; 4) development of principles and measures aimed at ensuring environmental safety of TSF comprising toxic waste.

Research area and methods

Field studies within the area affected by the waste of the closed mining enterprise were carried out during 2010–2018. The subject of research was presented by technogenic waste systems formed in the last century due to the activities of presently closed mining enterprises in the Far Eastern Federal District (located in the basin of Amur River of biospheric significance (Solnechny GOK (Khabarovsk Territory), Khingansky GOK (Jewish Autonomous Region), Khrustalnensky GOK (Primorsky Territory)). Its constituent parts include atmospheric air, water, soil, plant and animal organisms, microorganisms and humans, as well as mining waste, equipment and technology.

In the course of the research, generally accepted physicochemical, chemical, biological, and mathematical-statistical methods were used.

The assessment of the potential risks of soil pollution by heavy metal compounds from a TSF dump using the one-factor pollution index (*PI*) and pollution load index (*HLI*) was carried out using equations (1) and (2) (according to the methods described in the paper of Mari Luz García-Lorenzo et al. [22]):

$$PI = \frac{C_{soil}}{C_{background}}; \quad (1)$$

$$PLI = \left(PI_{\mathrm{Co}} + PI_{\mathrm{Cu}} + PI_{\mathrm{Zn}} + PI_{\mathrm{As}} + PI_{\mathrm{Mo}} + PI_{\mathrm{Sn}} + PI_{\mathrm{Hg}} + PI_{\mathrm{Pb}}\right)^{1/n}, \quad (2)$$

where *PI* is a single factor, namely, pollution index of each metal: $PI < 1$ – not polluted; $1 \le PI < 2$ – slightly polluted; $2 \le PI < 3$ – moderately polluted; $PI \ge 3$ heavily polluted; C_{soil} and $C_{background}$ are metal concentrations in the soil sample and corresponding background values, respectively (mg/kg); *PLI* is pollution load index, and n is the number of assessed pollutants (eight in our study: $PLI < 2$ – moderately polluted to unpolluted; $2 \le PLI < 4$ – moderately polluted; $4 \le PLI < 6$ – heavily polluted; $PLI > 6$ – very heavily polluted; *PI* is a single pollution factor for each metal.

In addition, *PI* and *PLI* were also calculated to assess the mobilization of potentially toxic elements (PTE) in water. The natural mobility of PTE was studied by the method of water extraction, representing the soluble fraction. Natural mobility indices for compounds of chromium ($NMIn_{\mathrm{Cr}}$), nickel ($NMIn_{\mathrm{Ni}}$), copper ($NMIn_{\mathrm{Cu}}$), zinc ($NMIn_{\mathrm{Zn}}$), strontium ($NMIn_{\mathrm{Sr}}$), tin ($NMIn_{\mathrm{Sn}}$), mercury ($NMIn_{\mathrm{Hg}}$), and lead ($NMIn_{\mathrm{Pb}}$) were calculated as the ratio of a PTE concentration and its background value:

$$NMIn_n = \frac{C_{sample\ after\ water\ extraction}}{C_{background\ after\ water\ extraction}}. \quad (3)$$

Natural Mobility Index (*NMI*) is defined as the *n*th root of the product of *n* indicators of natural mobility. In our case,

$$NMI = \left(NMI_{\mathrm{Cr}} \cdot NMI_{\mathrm{Ni}} \cdot NMI_{\mathrm{Cu}} \cdot MI_{\mathrm{Zn}} \cdot NMI_{\mathrm{Sr}} \cdot NMI_{\mathrm{Sn}} \cdot MI_{\mathrm{Hg}} \cdot MI_{\mathrm{Pb}}\right)^{1/8} \quad (4)$$

The research results are presented in the Table, where the indicator values below 2 points mean low mobility; the values from 2 to 4 present moderate mobility; from 4 to 6, significant mobility; those above 6 indicate very high mobility.

The index of geoaccumulation in soils, proposed by Mueller [24], was calculated (according to the paper of Jiang F. et al. [23]) using the formula

$$I_{geo} = \log_2 \frac{C_n}{1{,}5 \cdot BE_n}, \qquad (5)$$

where C_n is the measured concentration of heavy metal compounds in the sample; BE_n is average geochemical background value for the measured elements.

The results of the calculation of the geoaccumulation index (I_{geo}) will be shown in the Table with highlighting levels: from less than 0 to more than 5, indicating the degree of pollution: from practically unpolluted to highly polluted materials.

The research results were processed in MS Excel, the drawings, using Photoshop, MS Office Picture Manager, Paint, MS Visio.

The findings discussion

Risk analysis in the study area is important as a process of identifying individual sources of hazard and predicting their possible negative impact on the ecosphere to provide sustainable development of the Far Eastern Federal District.

The research results allowed to identify the following main factors causing crisis phenomena leading to environmental risks of storing accumulated mineral processing waste of the closed mining enterprises: Solnechny GOK and Khrustalnensky GOK: 1) the presence of toxic waste as sources of intense negative impact on the ecosphere; 2) ecological constraints of the territory and the peculiarities of the orographic and bioclimatic conditions, as well as the ecological capacity; 3) the degree of the territory development; 4) the population living within the territory affected by the TSFs; 5) imperfection of environmental legislation and the absence of mining-and-environmental monitoring of changes in environment components within the toxic waste-affected territory.

The study of the factors allowed to propose the following classification of environmental crisis situations: 1) technogenic-and-ecological, connected with accumulation of environmental damage; 2) technogenic impact, contributing to intensive pollution of the ecosphere; 3) socio-ecological, connected with the population living in a technologically polluted area.

The impact of the above negative factors may lead in the near future to further aggravation of the ecological situation in the investigated Solnechny (Khabarovsk Territory) and Kavalerovsky (Primorsky Territory) tin ore districts in the Far Eastern Federal District, if urgent and effective measures are not taken to solve the problems in the coming years. Any of these risks can entail the following environmental and economic problems of primary importance:

1) deterioration of the human and biota habitat;

2) the lack of responsibility:

- for the quality of the environment;

- for health protection of the population living in the miner's village;

- for compliance with safety measures (for example, compensation claims);

3) costs for elimination of technogenic pollution and its consequences;

4) inconsistency of technological solutions used in the last century with current environmental standards;

5) incorrect solution of environmental problems and public discontent;

6) noncompliance with international standards.

Below we consider the environmental risks at the closed mining enterprises of the Far Eastern Federal District.

1. Technogenic and environmental risks associated with accumulated environmental damage.

Among the environmental reasons, the following are highlighted: first, the location of facilities that are ecologically incompatible with the natural complex, and second, an erroneous assessment or underestimation of the environmental consequences of the natural landscapes transformation in the process of mining in the last century.

Intensive mining activity in the Far Eastern Federal District of Russia has led to the accumulation of large amount of toxic sulfidized waste of mineral processing, which produce very heavy impact on the environment and human health. In the last century, they were stored in tailing dumps, which are currently uncontrolled and are considered by us as manifestations of environmental damage. These include: Solnechny GOK (Solnechny district, Khabarovsk Territory), Khrustalnensky GOK (Kavalerovsky district, Primorsky Territory), Khingansky GOK (Obluchensky district, Jewish Autonomous Region), Karamken GOK (Khasynsky district, Magadan Region), etc.

Tin-sulfide deposits were developed here by open-cut and underground mining. The mining industry in Solnechny district functioned from 1957 to 2005. There were two processing plants and three tailings storage facilities in the district, covering an area of 80.8 hectares, with the amount of the processing waste of 41.5 million tons. Their material composition comprises (%): vein quartz – 37.5, hornfels-sedimentary rocks – 45, tourmaline – 12.1, and sulfides (galena and sphalerite, pyrite, pyrrhotite, arsenopyrite, chalcopyrite) – 3.8. They contain the following valuable components (g/t): Sn – 0.46, As – 0.629, Ag – 1.227, Pb – 0.123, Zn – 0.094, Bi – 0.03.

From 1941 to 2001, there were six mines and four processing plants in the Kavalerovsky district. There are five tailings storage facilities in the district of total area of 17.7 hectares, where 37.72 million tons of tailings have been accumulated. They contain pyrite, pyrrhotite, galena, sphalerite, arsenopyrite, chalcopyrite, quartz, fluorite, tourmaline, chlorite, and other minerals. Quantitative and semi-quantitative spectral analyzes of the tailings samples showed that the content of ore elements in them ranges as follows (%): Sn – 0.04–0.10; Cu – 0.0062–0.2600; Pb – 0.0039–0.0760; Zn – 0.08–1.00; As – 0.01–0.05; N – 0.0014–0.0033; Co – 0.0002–0.0009; V – 0.0043–0.0100; Ag – 0.0003–0.0030; Ga – 0.0011–0.0016; B – 0.01–0.05; Bi – 0.0001–0.0003; Sr – up to 0.01; Ca – up to 0.1 [25].

It was found that the studied TSFs were hazardous. Violations of the provisions of the federal laws "On Safety of Hydraulic Structures", "On Protection of Atmospheric Air", "On Production and Consumption Waste", "On Protection of Environment", as well as the requirements of the Safety Rules for hydraulic structures for accumulation of liquid and industrial waste, regulatory and instructive documents of Russian Gosgortechnadzor, Water and Land Codes of the Russian Federation were revealed. For instance, no measures have been developed to ensure industrial safety, protection of subsoil and the environment and safety of the hydraulic structures for the period of work suspension at hazardous production facilities. The closed mining enterprises did not comply with the directions of the supervisory authorities to eliminate violations of the industrial and environmental safety requirements. The TSF embankment (dams) was destroyed, and its repair is not performed. Pulp lines, recirculating water conduits, and equipment of the recirculating water station have been dismantled, spontaneous flow and washout of pollutants into the river network occur. There is no monitoring of the tailings storage facility safety in accordance with the regulatory requirements. Intensive dust pollution of the habitat occurs, because measures are not taken to reduce the TSF surface dusting and pollution of the atmospheric air by reclaiming the surface. Under specific local meteorological conditions, the TSF surface has undergone wind and water erosion over the past years and become intense sources of dust pollution of ecosystems, since they contain particles less than 2 mm with high content of toxic components. Here, for example, in the pond and intermediate zones of the closed mining enterprise Solnechny GOK, a dense network of erosion potholes and gullies over 1 m deep and 0.3 to 1.2 m wide, turning into ravines, was revealed. This is the result of the development of extreme natural processes in recent years, namely: intense abundant precipitation in the autumn of 2008 and during June – July 2009, due to the monsoon nature of the climate in the studied region. An equally important factor was the slope of the TSF surface of more than 3° from the beach zone to the pond zone. In addition, the dam slopes are also prone to erosion processes.

2. Risks of technogenic impact, contributing to intensive pollution of the ecosphere.

The prerequisite to arising environmental risk from technogenic pollution of, for example, atmospheric air, is the presence of the risk source, including one characterized by the concentration of a pollutant being harmful to the population and biota [26]. In addition, the hazard affected zone and the presence of pathways for the transmission of harmful effects from the source to the living beings are important. The key task is identification of priority objects, being the sources of risks capable to cause crisis situations with intensive technogenic pollution of the environment. On the basis of the collected information on the negative impact of the mineral processing waste stored in TSFs of closed mining enterprises Solnechny GOK and Khrustalnensky GOK on the ecosystems, it was concluded that the main sources of the environmental risks capable to cause crisis situations include:

1) tailings storage facilities, processing plants and sedimentation ponds left to their own devices as a result of bankruptcy of the mining enterprises;

2) physical deterioration and unreliability of the main process equipment and environmental facilities used in the last century, as well as drying plants and suction systems of processing plants, ventilation systems, and smelting shops;

3) low level of process environmentalization, for example, unregulated discharge of insufficiently treated wastewater (mine water, liquid waste, dump water) into natural water bodies;

4) the use of outdated processes;

5) on the part of heads and nature protection services of the mining enterprises operating in the last century, inattention to environmental protection, decreasing the volume and efficiency of environmental measures was revealed;

6) imperfection of the environmental legislation and the effective system of payments for environmental pollution;

7) a sore point is the lack of demand for existing scientific and technical environmental developments, the lack of incentives for their implementation in mining sector.

Thus, the above indicates that mining activities are potentially hazardous [27, 28], and there is always a potential of arising risks, including that of negative technogenic impact, leading to intensive pollution of the environment with waste tailings and increase in population morbidity.

For instance, finely dispersed toxic dust, rising from the TSF surface into the air, forms vortex flows, and then is precipitated on the soil. In addition, it was found that atmospheric precipitation, dissolving large amount of toxic substances, form technogenic flows [29, 30], being one more negative factor for the soil and vegetation cover.

The problem is complicated by the fact that as a result of increasing precipitation of solid waste on the soil, its properties and composition deteriorate at an ever faster pace. The results obtained indicate that the content of heavy metals in the studied soils and waters is tens of times higher than the background values and MPC. Technogenic soils located near the tailings storage facilities are characterized by extremely high concentrations of HM and As (from 31 to 300 mg/kg), exceeding, for example, the MPC by 1.5 to 15 and more times.

Higher vegetation affected by the studied tailings accumulates significant amounts of pollutants (Zn, Cu, Pb, etc.). Man-made pollution with heavy metal and arsenic compounds in soils and vegetation was revealed even at large distances from the TSFs, exceeding the regional background values by 2 to 6 times and more.

Tables 1 and 2 show the calculations of the soils pollution by heavy metal compounds based on the one-factor pollution index (*PI*) and the pollution load index (*PLI*), calculated by the method, described in [22], within the area affected by the waste (TSFs) of the closed Solnechny GOK and Khrustalnensky GOK.

The Müller geoaccumulation index [24] calculated for the soils is shown in Fig. 1. This indicator is rather high for such toxic components as arsenic, copper, antimony, and lead within the area affected by the waste (TSFs) of the closed Solnechny GOK and Khrustalnensky GOK.

Table 1

Calculations of the soils pollution based on the one-factor pollution index (*PI*) and the pollution load index (*PLI*) within the area affected by the waste (TSFs) of the closed Solnechny GOK

Facility Name	One-Factor Pollution Index (*PI*)								Pollution Load Index (*PLI*)
	Co	Cu	Zn	As	Mo	Sn	Hg	Pb	
Tailings Storage Facility of Solnechny GOK	13.5	187.1	16.2	59.0	11.8	12 631.9	343.9	330.1	119.2
1 km distant from the TSF	2.2	10.0	5.6	7.9	5.1	2008.9	231.4	45.8	22.6
2 km distant from the TSF	2.3	28.6	8.2	5.3	4.0	2135.0	116.8	43.9	21.8
3 km distant from the TSF	1.4	15.8	7.6	2.0	3.2	1216.3	30.9	74.3	14.8

Table 2

Calculations of the soils pollution based on the one-factor pollution index (PI) and the pollution load index (PLI) within the area affected by the waste (TSFs) of the closed Khrustalnensky GOK

Facility Name	One-factor pollution index (*PI*)								Pollution Load Index (*PLI*)
	Cr	Co	Ni	Cu	Zn	As	Sb	Pb	
Tailings Storage Facility of Khrustalnensky GOK	2.5	1.9	2.7	45.7	6.0	159	56.4	10.4	11.6
1 km distant from the TSF	2.0	1.9	2.4	44.5	5.3	133.8	42.8	10.0	10.3
2 km distant from the TSF	1.7	1.4	2.1	16.8	2.8	15.9	8.4	5.9	4..3
3 km distant from the TSF	1.2	0.6	1.7	5.9	1.2	5.0	3.3	2.8	2.1

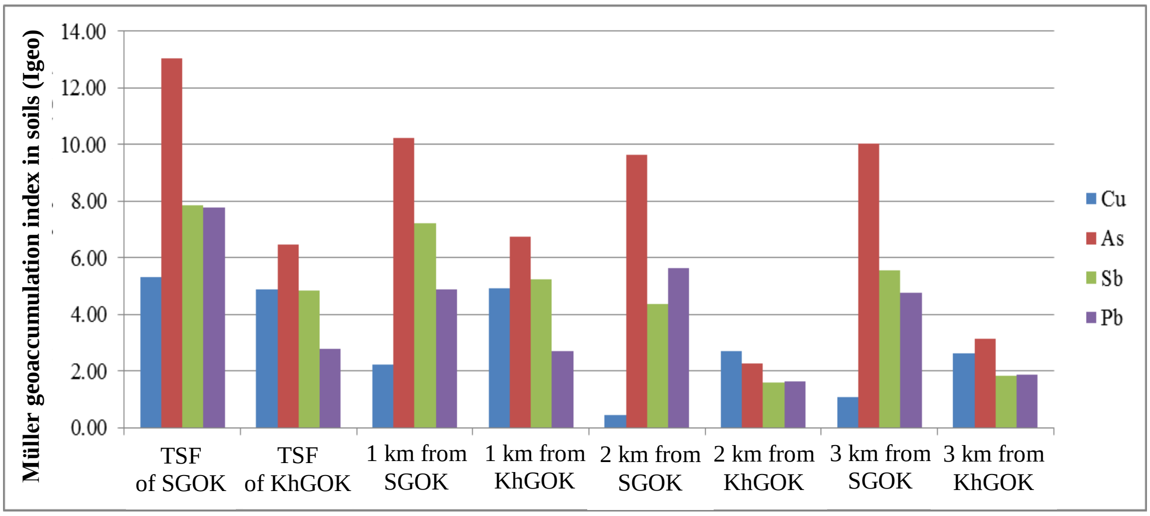

Fig. 1. Calculation of the Müller geoaccumulation index in soils (Y-axis) within the area affected by the waste (TSFs) of the closed Solnechny GOK (SGOK) and Khrustalnensky GOK (KhGOK)

Table 3

Calculation of Natural Mobility Index

Facility Name	Natural Mobility Index (*NMIn*)								Natural Mobility Index (*NMI*)
	Cr	Ni	Cu	Zn	Sr	Sn	Hg	Pb	
3rd Tailings Storage Facility of Khrustalnensky GOK	500.3	463.2	217.4	42.7	3.4	0.1	0.1	1.0	8.7
Tailings Storage Facility of Solnechny GOK	5.4	13.3	631.2	12.9	1.3	248.6	1.0	67 389.6	43.3
Gorny settlement, 3rd TSF, slurry water	2.5	7.8	488.3	8.1	1.0	1.0	1.0	53,657.5	16.0

According to the calculations (Table 3), the assessment of mobility of heavy metal compounds in watercourses near the TSFs is very high, especially near the TSF of Solnechny GOK, where Holdomi River flows, which runs into Silinka River, which then runs into Amur River of biospheric significance.

3. Socio-ecological risks connected with the population living in a technologically polluted area.

The 1997 Law of the Russian Federation "On Industrial Safety of Hazardous Production Facilities" [31] (as amended on 29.07.2018) provides for that an enterprise being a source of higher hazard is obliged to ensure measures to protect the population and the environment from hazardous effects. In this regard, there is a need for a assessment of social-and-environmental risks, implying not only their identification, prediction of adverse consequences, determination of harm to public health and environment components, but also elimination of the risks. In addition, it is also envisaged to obtain quantitative and qualitative indicators of crisis situations, as well as prevent accidents.

Assessment of social-and-environmental risks includes the following stages:

1) identification of emergency situations connected with technogenic pollution of the environment, and determination of environmental damage to human health;

2) assessment of the cost of work on complete elimination of environmentally significant consequences caused by the crisis situation.

Our studies [32–34] indicate that the population of mining settlements lives in conditions of permanent exceeding the normative indicators for pollutants in the atmospheric air within the area affected by the TSFs. This results in a response in the form of physiological changes and environmental pollution-caused diseases. The child population requires special attention, since children are the most vulnerable and sensitive to the action of chemical agents [35].

The obtained data on the environment state based on the calculated hazard factors (*HQ*) and the hazard index (*HI*) for pollutants (sulfur dioxide and heavy metal compounds) show increasing incidence rate with increasing the level of the ecosphere technogenic pollution. A relationship has been identified between the level of environmental pollution by carcinogenic substances and initiation of malignant neoplasms (MO). Hazard coefficient (*HQ*) calculated by the formula [35] for groups of substances acting on the nervous system (Pb, Mn, and Co), is equal to 80.7; 3.6, and 3.9, respectively. This indicates high level of human environment pollution. Calculation of the hazard index (*HI*) for the substances negatively affecting respiratory system (suspended particles, sulfur dioxide, as well as copper and chromium compounds) shows high value of the index within the study area ($HI = 71.88$). Lead, manganese, and cobalt compounds rank second in terms of hazard of exposure, with the hazard index of 5.94. A close correlation has been established between the content of carcinogenic compounds, for example, Sb, and respiratory diseases, as well as the neoplasm initiation [32–34].

The existing situation at mined ore deposits in the Far Eastern Federal District requires developing principles of ensuring environmental safety of the tailings storage facilities containing toxic tin ore processing waste. The performed studies allowed proposing the following principles for normal functioning of technogenic objects within the area affected by the waste (TSFs) of the closed Solnechny GOK and Khrustalnensky GOK.

1. Rational safety as the need for the most economically justified decreasing the likelihood of environmental emergencies and mitigation of their consequences in conditions of closed mining enterprises.

2. Preservation of the most important component of life quality, favorable environment for biota and health of the population of the miner's village in the conditions of closed mining enterprises.

3. Taking into account various natural hazards and man-made impacts on the TSF ecosphere (balanced risk principle).

4. Analysis of the "cost – risk", "benefit – risk", "cost - benefit" ratios (the principle of acceptable risk). In international practice, this principle is known as the ALARA (As Low Reasonable Achievable) principle – i.e. as low as reasonably achievable.

On the basis of these principles, the following measures have been proposed to ensure environmental safety within the areas affected by the tailings storage facilities (of the closed Solnechny GOK and Khrustalnensky GOK) containing toxic tin ore processing waste.

1. Creation of a commercial mechanism for mitigating the risk of environmental damage from emergency situations.

2. Creation of a new technique for reclamation of the TSFS surface using an innovative approach (bioremediation), the novelty of which is confirmed by patents of the Russian Federation (2018, etc.) [36], and its implementation to reduce the negative impact on the environment.

3. Development of a system for mining-and-environmental monitoring of the state of environmental components within the area affected by the TSFs of the closed mining enterprises (Solnechny GOK and Khrustalnensky GOK).

4. Creation of a forest shelterbelt around the tailings storage facilities and maximum landscaping/vegetation of the territory of miner's settlements to prevent technogenic pollution of the ecosphere.

5. Conducting medical-and-ecological examination of the population for its recovery taking into account the environment pollution-caused diseases here.

Conclusion

1. High ecotoxicity of the waste of the closed mining enterprises (Solnechny GOK and Khrustalnensky GOK) has been identified, which undoubtedly contributes to intensive pollution of the environment components and increasing the incidence of diseases among the population of miner's villages in the Far Eastern Federal District.

2. Indicators and factors have been identified that have caused the crisis phenomena, leading to environmental risks of storing the accumulated mineral processing tailings of the closed mining enterprises.

3. An assessment of the level of soil pollution with heavy metal compounds is given based on the one-factor pollution index (*PI*) and the pollution load index (*PLI*), as well as using the indices of natural mobility and geoaccumulation.

4. The principles and measures have been developed to ensure environmental safety of the tailings storage facilities containing toxic tin ore processing waste. The new techniques have been created for reclamation of the surface of tailings storage facilities containing toxic mineral processing waste, novelty of which was confirmed by patents of the Russian Federation.

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