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Ensuring of Environmental Safety in the Reclamation of Anthropogenic Placer Gold Deposits in the North of Khabarovsk Krai

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Abstract—The results of studying mercury pollution of ecosystem in the zone affected by anthropogenic placer gold deposits are given. A major hazard to the environment and human health results from minerals processing wastes polluted with mercury and dumped in the placer gold-concentrating sites (PGCS) near mining villages, which have transformed into unequipped authorized landfills. The recent tendency to their reclamation should favor extensive mercury pollution. Actions have been proposed to ensure environmental safety of mineral processing wastes and reclamation of anthropogenic placer gold deposits.

Keywords: mercury pollution, placer gold-concentrating plant, minerals processing wastes, anthropogenic deposits

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INTRODUCTION

It has now become evident that former landmarks in the development of mining industry in Khabarovsk Krai have no prospects. Long-term exploitation of placer gold deposits in Khabarovsk Krai favored rapid degradation of ecosystems. For example, placer gold mining involves anthropogenic pollution, degradation and disappearance of biosphere components, and sharp impairment of the environment. Furthermore, economic reorganization led to bankruptcy of many mining enterprises, which raised the risk of undesirable change of the environment. Anthropogenic pollution of natural systems with mercury is the most hazardous. The situation is aggravated by the fact that depletion of natural gold placers in the South of the Russian Far East, particularly in Khabarovsk Krai, has aroused the necessity of extensive reprocessing of large volumes of anthropogenic deposits polluted with mercury and development of environmentally safe technologies for their exploitation. However, as yet, there is no scientifically substantiated system for assessment of mercury pollution, which would ensure both economic and environmental safety. Therefore, the importance of studies in this field is beyond doubt. Thus, the goal of this work was to estimate environmental consequences of anthropogenic mercury pollution and develop actions directed toward its elimination (placer gold-concentrating sites and dredge piles of gold mining enterprises) to ensure environmental safety in the exploitation of anthropogenic mineral raw materials. This goal implies the following tasks:

(1) Analysis, generalization, and systematization of published data on anthropogenic mercury pollution of the environment;

(2) Assessment of wastes from placer gold concentration and dredge piles as sources of environmental pollution;

(3) Development of actions to eliminate mercury pollution in the placer gold-concentrating sites and ensure environmental safety in the reclamation of anthropogenic placer gold deposits.

EXPERIMENTAL

The studies were carried out in 2001–2013 in the North of Khabarovsk Krai. The subjects were wastes from placer gold-concentrating plants (PGCP) in Sofiiskii, Kherpuchinskii, and Kerbinskii placer gold mines and related anthropogenic soils, plants, and sediments.

The climate in the region under study is monsoon–continental. The mean annual air temperature is –1.5 to –1.8°C, the maximum air temperature (July) is +23 to + 26°C, and the minimum air temperature (January) is –29 to –31°C. The total annual precipitation in 2004–2012 ranged from 660 to 780 mm. North, north–west, and west winds at a flow rate of 0 to 3 m/s dominate over a year. The annual number of calms is 38 to 40%. The frost-free period lasts on the average for 102 to 115 days. Persistent snow cover is formed in November and disappears in April.

The territory under study belongs to the Far East taiga forest region, including the following zones: near-Pacific tundra forest, mid- and south-taiga, and Amur–Sakhalin. The major landscapes are strongly dissected mountains with vigorous water circulation, dissected high plains with medium water circulation, and weakly dissected lowland plains with slow water circulation.

The North of Khabarovsk Krai features a wide diversity of soils: brown taiga, illuvial humic podzols, marsh humic peat gleyic, bog cryogenic soils, peat gleyic podzols, mountain podburs, and mountain brown taiga.

Brown forest soil was accepted as the zonal soil in the area under study. It is typical of coniferous/broad-leaved and broad-leaved forests. Soils of taiga forests in the Far East are called brown taiga and are characterized by a high humus concentration in the upper horizon (23–24%), high concentration of bases in the humus horizon, and acid reaction. However, podzolization is usually weak or absent at all.

Bog cryogenic soils widely occur in grass, larch–melilot, and sphagnous “seas” in lowlands. Large areas are occupied by peat-bog soils (upland bogs). Floodplains are characterized by meadow alluvial soils with sedge–grass and willow cover. With respect to thermal conditions, these soils belong to the cold long-term frozen soil facies.

Implementation of actions for protection of these soils is related to their natural specific features and socioeconomic conditions.

It is known that the degree of development and extent of soil degradation and contamination processes depend on the magnitude and character of anthropogenic activities and on the resistance of soils to those activities. The resistance of soils is determined by their properties (mechanical composition, structure, sorption capacity, biogenicity, etc.) and ecological and geographic conditions of their occurrence (relief, climate, vegetation, ground waters, distance from contamination sources, and mode of their contact with the latter).

In keeping with the geobotanic zoning of the Russian Far East, the region under study belongs to the Eurasian coniferous forest area and Southern Okhotsk Subarea of dark coniferous forests of the Amur–Okhotsk province [1]. Three zones are distinguished with respect to the occurrence and species composition of plants: high-mountain vegetation zone, forest zone, and swampy meadow vegetation zone. The high-mountain zone including mountain tops and steep slopes is the poorest in plant species. Forests occupy about 80% of the surface area. Swampy meadow vegetation occurs in the Nimelen-Chukchagir lowland and Amgun’ flood plain (with tributaries).

A combination of the climate pattern and ridge-and-valley topography favors considerable pollution of atmospheric air, as well as secondary pollution of hydrographic network, soil, and vegetation as a result of washing out of pollutants. Undoubtedly, harsh climate and soil degradation over a large area of the region owing to exploitation of mineral raw materials should affect formation of specific anthropogenic areas and natural reforestation processes.

Methods of study. Vernadskii’s theory of biosphere and noosphere [2] was the methodological basis of the study. The following methods were employed.

(1) Analysis and generalization of relevant theoretical and experimental data;

(2) Scientific prediction;

(3) Statistical data processing.

A systematic integral approach was the principal and determining method.

Wastes and anthropogenic soils were sampled in the areas of interest, geobotanic description of vegetation was performed, a herbarium was collected, vegetation diversity was studied, and dominant plant species were sampled to determine the concentration of toxic metals therein (according to GOST 27262-87). Biological methods were used. Soils samples were withdrawn in the center of the PGCP and at distances of 100 and 300 m to the north, east, west, and south. Soil, vegetation, and sediment samples were analyzed with the aid of

Table 1. Anthropogenic mercury pollution sites (waste dumps of placer gold deposits in Khabarovsk Krai)

no.	River basin, settlement	Placer	*S*, km²	Mined gold, kg	Mercury loss, kg	Specific amount of mercury, kg/km²
1	Yasnyi	Yasnenskii	1500	7350	1840	5.0
2	Oktyabr'skii	Oktyabr'skii	1150	49724	12430	10.8
3	Sofiisk	Sofiiskii	1250	75900	18975	15.2
4	Briakan	Kerbinskii	1850	50100	12525	7.1
5	Kherpuchi	Kherpuchinskii	1460	26710	6680	4.6
6	Tumnin	Tumninskii	1130	8500	2125	1.9
7	Maiskii	Maisko-Glubokinskii	1690	2650	660	
8	River Ul, Bekchi		2050	4530	1130	0.7
9	Lower Amur	Takhtinskii	500	N/s	N/s	
10	Agnie-Afanas’evsk	Pil’da-Limuriiskii	2150	18160	4540	2.1

modern instrumental and traditional physicochemical methods. The data were statistically processed using MS Excel and Geostatic.

RESULTS AND DISCUSSION

Analysis, generalization, and systematization of published data and patent search results indicated insufficient information on chemical elements, including mercury, as environmental pollutants and the lack of reliable environment protection methods in mining areas. Almost no studies on the localization of anthropogenic mercury pollution of soils in the vicinity of mining enterprises have been performed in Khabarovsk Krai. Unfortunately, no actions aimed at decontaminating mercury-polluted mining areas and ensuring environmental safety in the reclamation of anthropogenic placer gold deposits have been developed so far [3–10].

More than 1.5 billion tons of mining wastes accumulated in Khabarovsk Krai, including those contaminated with mercury, constitute now a potential hazard to the environment and human health [7–10] (Table 1). The main sources of mercury in the region under study are the following [7–10, 12–15].

(1) Mechanical loss of metallic mercury and amalgam during the concentration process and technological loss intrinsic to amalgamation and amalgam annealing;

(2) Considerable amounts of mercury-containing wastes piled near mining villages (as overburdens and host rocks with increased mercury content dumped in dredge fields and cuts) give rise to continuous emission of mercury into atmosphere and surface and ground water streams with subsequent migration and accumulation in sediments and biota;

(3) Physicochemical, biochemical, and microbiological dissolution processes in sediment ponds and flooded water jet landfills under certain conditions may lead to distribution of mercury and formation of very toxic methyl derivatives which then accumulate along trophic chains in aqueous ecosystems and thus contaminate sediments in anthropogenic water basins;

(4) Reprocessing of anthropogenic placer gold deposits processed previously using gold amalgamation technique favors conversion of mercury into active state and increases its emission;

(5) Infringement of rules for disposal of mercury-contaminated wastes in PGCS.

A serious hazard arises from reclamation of anthropogenic placer gold deposits processed previously using dozer hydraulic and dredge techniques with sluice amalgamation, which is accompanied by activation of a large amount of mercury buried in anthropogenic cuts.

Lixiviation piles accumulated while exploiting placer gold deposits in the South of the Russian Far East amount to ~800 million cubic meters [11]. According to Koval’ [10], the amount of overburdens is 2–3 times larger. As shown by Mamaev et al. [11], waste dumps in placer deposits of Lower Priamurye contain 743.2 million m^3 of rocks. The rock volume in anthropogenic deposits of Upper Priamurye amounts to 1.13 billion m^3. A huge volume of mining wastes has been accumulated in Khabarovsk Krai in recent years. Their disposal requires large areas which are mainly productive lands withdrawn from forest resources. Until present, more than 750000 ha has been disturbed only in the South of the Russian Far East [12]. As a rule, natural landscapes in the waste disposal sites are

Table 2. Mercury concentration in wastewaters

no.	Sampling site	Description	Concentration of mercury, μg/L	
			soluble	dispersed
1		Control, settlement Kondon	1.37	1.00
2	P. 3a	Sedimentation pond, 44 m eastward from PGCP	1.59	2.51
3	P. 4	Sedimentation pond, 100 m eastward	3.39	1.80
4	P. 2a	Ditch, 100 m northward from PGCP	1.48	0.95
5	P. 7	Well, 100 m westward from PGCP	0.57	1.69
6	P. 5	Creek, 63 m southward from PGCP	0.40	0.92
7	P. 8	Creek, 26 m from old Staroe PGCP	0.43	0.64
8	P. 9	Creek, 60 m from the center of Staroe PGCP	0.79	0.59
9	P. 10	River Briakan	0.57	0.49
10	P.11	15-years old dumps, Creek, azimuth 110°	0.50	0.59
11	P. 12	15-years old dumps, sedimentation pond, azimuth 270°	1.28	0.48
12		Control. Amur oblast	0.69	0.78
13	P. 1	Prof. 1, Amur oblast. river Dzhalinda	0.35	0.58
14	P. 2	Prof. 1, river Dzhalinda, kl. Yankan, 110 m westward	0.54	0.69
15	P. 3	Prof. 1, river Dzhalinda, 1 km upstream kl.Yankan. West	0.49	0.68
16	P. 2	Prof. 2	0.99	1.19
17	P. 3	Prof. 2	0.48	0.98
18	P. 4	Prof. 2	1.17	0.69
19	P. 2	Prof. 3	0.99	0.58
20	P. 4	Prof. 3	0.69	0.98
21	P. 6	Prof. 3	0.88	1.17
22	P. 13	Prof. 3, river Dzhalinda, near camp	0.82	1.18
23	P. 14	100 m eastward from PGCP	1.49	0.68
24	P. 15	300 m eastward from PGCP, river Dzhalinda (turbid)	1.48	2.27
25	P. 16	PGCP, center	3.80	0.59
26	P. 17	300 m northward from PGCP	0.57	0.77

completely destroyed, and local natural mining systems appear therein.

The composition of pollutant flows (Table 2) generated since mining has started may be assessed by the presence of satellite elements in ores and by the elemental composition of primary halos and enriched products.

Assessment of the effect of PGCP wastes on the biosphere components in several aspects (quantitative, i.e., wastes volume and area necessary for their disposal; qualitative, i.e., change of the quality of the environment; and spatial, i.e., indirect effect of mining wastes on the contiguous areas) revealed anomalously high amounts of toxic chemical elements (Hg, Pb, Zn, Cu, As, etc.) in mobile forms (Table 2). The rate of hypergene processes in wastes increases many times due to high permeability of anthropogenic materials and favorable conditions for removal of soluble substances, which enhances pollution of soils and biota. As might be expected, zones with different degrees of chemical contamination appear as a result of deposit exploitation; the area of these zones is always several times larger than that subject to mechanical disturbance. Insofar as waste dumps are almost not isolated from aqueous ecosystems, their effect on the latter is undoubtedly negative. Aggressive anthropogenic flows generated from wastes give rise to geochemical anomalies. It should be noted that shattered rocks in dumps possess a large surface area accessible to weathering agents and that weathering and leaching processes are very intense in the wet climate of the Russian Far East. Lithochemical pollution halos appear in the mining-affected zones, redeposited lithochemical anomalies are generated, and fine fractions are withdrawn and redeposited with temporary and perennial streams. Infiltration of precipitation and surface and ground waters through wastes gives rise to hydrochemical anomalies and pollutant flows. Wind and water erosion leads to removal of minerals from anthropogenic materials.

High environmental toxicity of placer gold wastes follows from their acidity (pH 4–5) which determines high mobility of heavy metals therein. Experimental studies in the PGCP-affected zone revealed deep involvement of toxic chemical elements, including mercury, in the geochemical cycle.

According to rough estimates, manufacture of one ton of gold is accompanied by release of more than 500 kg of mercury into the environment [10, 15]. It is known that 55% of this amount is transferred to atmosphere and then to soils, and 45%, into water basins and water streams. The major part of total waterborne mercury is represented by dispersed particles. As reported by Laperdina [13], Stepanov [14], and Sidorov et al. [15], anomalous mercury concentrations exceeding the maximum permissible concentration by a factor of 100 and more (up to 880 kg/m^3) were found in the surface layer of waste (tailings) stratum at the disposal sites, in soils, subsurface and atmospheric air, settling basins, and vegetation. Mercury concentration in waste rock piles may reach 0.6 to 2 mg/kg, indicating a very high contamination level. Analysis of our own data led us to conclude that PGCP wastes constitute the main source of environmental pollution in the mining areas of the South of the Russian Far East, particularly in Khabarovsk Krai. High mercury concentration was found in the middle of the PGCP in Kherpuchinskii placer (317.5 mg/kg). The highest mercury concentration was found in sediments of the water stream (1.38 mg/kg) draining dredge piles. Analogous mercury content was typical, e.g., of soils near PGCP waste disposal site in Zabaykalsky District. Our studies revealed long-range transport of anthropogenic mercury from the activation site. Radial sampling of soils around PGCPs in Sofiiskii, Kherpuchinskii, and Kerbinskii placers showed that mercury tends to migrate in the north-east direction, in keeping with the wind rose.

Table 2 contains mercury concentrations in wastewaters from placer gold mines. Ecological–geochemical characteristics of ecosystems of Khabarovsk Krai are given below.

(1) The maximum permissible concentration of mercury in soils is about 2.1 g/t;

(2) Background concentration of mercury in soils and sediments is 0.05 g/t (range 0.00001–0.0001%);

(3) Background concentration of mercury in surface water of Sikhote-Alin' geosynclinal fold system is 0.00099 mg/L, and in the volcanic belt, 0.00166 mg/L;

(4) Mercury concentration in deposit orefields is 0.0*n*%, in some cases, up to 0.*n*%;

(5) Dissolved mercury in natural water is in equilibrium with dispersed particles which contain approximately 160000 times more mercury than properly in solution.

The results of our studies indicate formation of lithochemical pollution halos in placer gold-concentrating sites and of redeposited lithochemical pollution halos in the affected zone, which leads to anthropogenic contamination of natural systems. As a result, land productivity and landscape value decrease, plant morbidity increases (teratological changes), species diversity impairs, and biota accumulates substances toxic for humans. The risk of environmental pollution in PGCP waste disposal areas is determined by the amount and properties of dumped wastes, rate of pollutant migration, and degree of natural and technical protection of the environment from the effect of anthropogenic areas.

Thus, mineral processing wastes favor formation of lithochemical pollution halos. Redeposited lithochemical halos disturb and contaminate soils, vegetation, and other biosphere components far beyond the waste disposal area. Lithochemical pollution flows are generated as a result of removal and redeposition of

Table 3. Characteristics of coniferous needles in the PGCP-affected zone

Length, mm	Width, mm	Lifetime, years	Number of needles per 10-cm shoot	Weight of 1000 needles, g	Necroses	
					%	description
18	2.0	3	180	15.0	89	Dots, mottles, spots
19	2.1	3	216	14.0	79	Mottles, spots
21	2.3	3	243	12.9	–	–

rocks from wastes with temporary and perennial flows. Infiltration of precipitations and surface and ground waters through waste materials gives rise to hydrogeochemical halos and pollution flows. Minerals are also extracted from wastes via water and wind erosion.

On the whole, mercury-contaminated wastes offer severe hazard to natural systems in the region under study.

Undoubtedly, extensive development of mineral resources sector induces disbalance of the substance circulation system in the biosphere. As the degree of lithosphere degradation increases, the biosphere is proportionally damaged, and its ability to assimilate wastes decreases. Therefore, a radical means of conserving natural biota on the Earth is reuse of mineral raw materials in closed cycles. However, the potential of this way is quite limited, although it may be important from the viewpoint of solution of environmental problems. In this connection, the following problems could inevitably arise. (1) In future, mineral resources will be depleted up to complete exhaustion; (2) Humans will inevitably become out of balance with the other biosphere components. Therefore, it is necessary to stabilize energy and raw material flows toward development of new technologies and utilization of all forms of solar energy and renewable resources. It is beyond doubt that mineral raw materials will be exploited in future, but this process should be organized in such a way that natural biota be conserved. Many ecologists believe [3–6] that the level of impact of mining industry on the biosphere should not exceed biologically justified thresholds of its stability. Therefore, successful development of mining industry is possible only on the basis of the sustainable development concept [3–6].

The hazard of PGCP wastes to living organisms is determined by the concentration of toxic elements in mobile soluble form. Soils, vegetation, sediments, and water in the PGCP-affected zone are enriched in toxic chemical elements (Tables 2, 3). Biogeochemical studies performed in the vicinity of PGCP showed deep involvement of heavy metals in the geochemical cycle. In particular, aluminum and iron are characterized by the maximum sorption capacity, next follow heavy metal group elements, whereas nutrients rank last in this series, i.e., their migration ability is strongly reduced despite relatively high concentration in soils. One reason is high acidity (pH 4–5) of soils in dumps, which is responsible for the high mobility of metals and their considerable accumulation in plants. The concentration coefficients of heavy metals are as follows: Pb, 2–9; Zn, 1.5–14; Cu, 7–29, Mo, 2–6. On the whole, the overall concentration coefficient of metals in, e.g., spruce needles expectedly decreases as the distance from the contamination source increases. In the vicinity of the latter, the level of anthropogenic pollution exceeds several times the natural geochemical anomaly level, especially in the Hg, Pb, Sn, As, and Ag contents of spruce needles and branches. The concentration of mercury in vegetation ranges from 0.20 to 0. 40 mg/kg.

Lichens of the *Cladonia*, *Usnea*, and other genera are very sensitive to anthropogenic mercury pollution (Table 3). These plants are food for animals. Analysis of the lichen flora revealed some general trends. The higher the anthropogenic pollution level, the lower the lichen species diversity and the smaller the lichen-covered area on tree trunks and other substrates. The number, occurrence, and diversity of lichen species in the test mining areas (PGCPs in Kerbinskii, Kherpuchinskii, and other placers) indicate degradation and in some cases disappearance of lichen cover as a result of vast pollution. This leads in turn to rupture of main trophic chains and reduction of deer livestock which provide food and clothes for northerners.

Analysis of anthropogenic soils in radial profiles and around Sofiiskii, Kerbinskii, and Kherpuchinskii PGCPs showed that mercury tends to migrate northeastward (according to the wind rose) and that the occurrence of lichens changes correspondingly. For example, reindeer moss grows only outside the mercury-polluted zone. The disappearance of pollution-sensitive lichen species formerly growing in a given area should be regarded as an alarm signal. Determination of the ash content of leaves, needles, barks, and buds of trees by the dry combustion technique indicated considerable accumulation of toxic heavy metals in these organs. The ash content of reference samples collected from unpolluted areas was 2.5 times lower. Especially high pollutant concentration was observed in winter, i.e., in the absence of liquid precipitation. Heavy metals accumulate in plants via binding to proteins, tanning agents, etc., to form less mobile complexes.

The level of anthropogenic pollution was assessed by analyzing needle-leaved plants as the most informative substrates (Table 3).

Experiments were performed to grow plants on soils collected at different distances from dumps, and wheat germs were watered with wastewater from the PGCP sedimentation pond. The germinative energy was 11% of control. The pollen sterility and growth tests indicated high level of anthropogenic pollution near the contamination source.

The risk of chemical and total anthropogenic pollution was predicted on the basis of Glazovskaya's classification of soils [16] with respect to their self-purification capacity, which makes it possible to relate probable rate of decomposition of organic and mineral anthropogenic products to genetic properties of soils. Actions have been proposed to protect anthropogenic soils and rationally exploit ecosystems. In the examined region the self-purification capacity of soils with respect to mineral substances is not high.

Thus, a set of characteristics, including biological ones, allows us to assert that the environmental situation in the PGCP-affected areas is quite complex, unsatisfactory, and even catastrophic. This is hazardous for not only biota but also humans. Actions have been developed to ensure environmental safety in the reclamation of anthropogenic placer gold deposits. These actions imply improvement of the regulatory legal base, organization of environmental monitoring, and recultivation on the basis of the innovation approach. Taking into account dramatic environmental situation related to mercury pollution of areas near placer gold mines, placer gold-concentrating plants, dredge pits, waste piles, and amalgamation tailings dumps, we believe it necessary to continue integral studies of distribution of mercury compounds and their release into the ecosphere. General trends revealed as a result of these studies should help us to reliably assess the consequences of mercury pollution whose extent has not been studied as yet. Former placer gold mining areas should become priority subjects for subsequent decontamination (demercuration according to the technology proposed by Pozdnyakov, Krupskaya, et al.). Only after decontamination it is necessary to set up reprocessing of wastes from PGCPs and dredge piles. Reprocessing of anthropogenic placers should favor extraction of additional minerals and underlie environmental enhancement and improvement of human health.

CONCLUSIONS

The results of studies related to assessment of mercury pollution and ensuring environmental safety in the reclamation of anthropogenic placer gold deposits have been presented. The region under study is characterized by quite complex catastrophic and unsatisfactory environmental situation. Minerals processing wastes stockpiled in placer gold-concentrating sites located near mining villages have been transformed into unequipped authorized landfills creating a serious hazard to biota. The recent tendency to reclamation of these wastes is expected to favor extensive mercury pollution of the ecosphere. Actions have been proposed to ensure environmental safety in the reclamation of anthropogenic deposits.

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