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The Influence of Karamkenskoe Deposit Tailing Dump on the Region Hydrosphere and the Dump Recultivation (Magadan Region)

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Abstract—The paper discusses the studies of anthropogenic pollution of Magadan region hydrosphere with the wastes of Karamkenskoe deposit after emergency destruction of the hydroengineering facilities of deposit tailing, dump having led to closure channel formation and volley of water and part of the tailings into the river Khasyn basin. Suggestions have been made on the neutralization of negative influence of Karamkenskoe deposit tailing dump and recultivation of its surface.

Keywords: Mineral raw materials, tailing dump, wastes, anthropogenic pollution, mud water.

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The Karamkenskoe ore field and the ore-dressing and processing enterprise are located in Khasynsky district of Magadan region, 3 km from Karamken township and 16–20 km from Palatka township, the latter is 80 km to the north from Magadan [1].

The Karamkenskoe ore field is characterized by increased concentrations of gold, silver, arsenic, potassium, and mercury. About 50 veins were located within the ore field. The field development took place in 1976–1993. Due to local conditions and the geological peculiarities, the mining was performed via adit method down to 545 m horizon, having allowed mining of about 80% of the Eastern and 50% of the Central areas.

The ore minerals of the deposit are noble silver ores (canfieldite, freibergite, naumannite, polybasite, etc), native gold (electrum) and silver as well as sulfides (pyrite, galenite, sphalerite, chalcopyrite, and markasite).

Gold of the deposit is mainly mined with ore minerals (65–70%), in the native form (20–35%), and associated with minerals of copper, antimony, arsenic, and with quartz (about 10%). The high-standard gold is located in the early quartz with pyrite and chalcopyrite, whereas the low-standard gold is found with sulfur-containing silver salts, galenite, and with grey copper ore. The gold from Karamkenskoe deposit contains admixtures of Bi, Cu, Sn, and other elements. The content of arsenic in the ores reaches 0.02%.

According to the applied technology, gold and silver were extracted with sodium cyanide, its yearly consumption being of 300 tons. The following chemicals (ton/year) were used to neutralize the wastes: polyacrylamide, 120; lead nitrate, 55; thiourea, 150; liquid chlorine, 1400; sulfuric acid, 450; sodium hydroxide, 630; calcium oxide, 2500; and ion-exchange resins, 30 [2].

Table 1. Mineral composition of the ore and the dump tailings of Karamkensky ore processing enterprise, % [3–5][a]

Mineral	Ore wastes		Tailings	
	range	average	range	average
Quartz	67–75	71	40–70	55
Feldspars	10.4–17	13	5–15	10
Calcite	2.9–7	4.7	–	–
Hydromica (sericite)	0.5–7.2	3.4	5–20	11.4
Caolinite	0.6–5	2.4	0–15	7.2
Pyrite and other sulfides	0.3–0.7	0.4	traces-0.35	0.15
Sulfates	–	–	7–20	10.3

[a] "–": mineral not found.

The wastes produced in the course of the ores concentration in 1977–1999 were stored at the tailing dump that was covered with water of the mud lake. The non-metallic minerals of the tailings were represented by quartz, feldspar, calcite, illites, and caolinite; the ore minerals are pyrite, chalcopyrite, galenite, arsenopyrite, stannite, and some silver minerals.

Initially, the content of pyrite in the tailings was of 0.7% and that of iron hydroxides was below 2%. Ten years after the enterprise had been stopped, the tailings surface layer was found to be significantly transformed. In particular, [3–5], due to geotechnogenesis, the carbonate decay occurred by sulfuric acid formed upon oxidation of sulfides. That led to increase of the content of clay minerals content (caolinite) and illites due to aluminosilicates argillization. The high content of calcium was due to the nature of the country rock of the veins (mainly calcite). Along with quartz and adularia, they compile about 95% of the rock. The unusual lithium concentration was found due to presence of mica. According to the analysis data, within ten years, quartz concentration in the ore mining wastes was decreased to 50–65%, the fraction of feldspar was decreased by more than 5%, and the amount of illites and caolinite was up to 15%, carbonates being absent (Table 1). The peculiarity of the tailings was the presence of newly formed sulfates (up to 20%) that were initially absent. Among the sulfates, the following minerals were found: halotrichite $FeAl_2[SO_4]_4 \cdot 22H_2O$ (up to 15%), jarosite $KFe_3[SO_4]_2(OH)_6$ (up to 5%); selected samples contained caolinite $KAl[SO_4]_2 \cdot 11H_2O$, gypsum $CaSO_4 \cdot 2H_2O$, and melanterite $FeSO_4 \cdot 7H_2O$ (up to 7% in total). Almost half of the samples contained traces of high-standard gold. The concentration of sulfide minerals was decreased, pyrite being predominant of them (below 0.35%) [5].

All the above-stated observations evidenced about the active hypergene process of sulfides oxidation occurred both in the ore veins and in the mining wastes. That led to crystallization of anthropogenic sulfates from the concentrated poral solutions. The anthropogenic mineral formation was noticed in all the mining regions where sulfides were present [6, 7]. The cryogenesis (hypergene process at negative temperature) at the Karamkenskoe deposit tailing dump was majorly due to pyrite oxidation and led to formation of typical sulfate oxidation products [3, 4]. During winter season as well as in the end of summer low water periods the pulp was covered with the white incrustation of sulfates, up to 1.5 cm thick, due to the described processes. Lead, antimony, arsenic, copper, and zinc were concentrated in the sulfates, their concentrations being tens and hundreds times higher than the maximum permissible concentration (MPC).

Since 1999, the tailing dump was not used and was transferred to the possession of Khasyn district administration. The capacity of tailing dump during the operation years reached 4.5 billion m^3, 3.85 billion of them being used for the tailings storage and 0.65 billion were used for water defecation and losses during ice formation. The land use for the tailings storage facilities was of 54 hectares and that of the liquid wastes storage was of 32.5 hectares. The length of tailing dump from the air face of the dam no. 2 to the drainage channel was of 1300 m, and its width was of 280 m at the average.

May 29, 2009, due to intensive rains (about 75 mm) during the previous two days, the water level in the

Fig. 1. General view of the storage before the accident (upstream Tumanny brook valley).

reservoir and in the Tumanny brook withdrawal channel was increased; in turn, that led to emergency destruction of the hydroengineering facilities along 20–30 m. The water got into the wastes storage reservoir of the tailing dump, and the closure channel about 50 m wide and 25 m deep was formed. The volley yield of water and part of the tailings occurred via the closure channel to the downstream of the dump, and impoundment of the river Khasyn flood-lands took place downstream from the Tumanny brook mouth, near Karamken. The one-time water evacuation in the course of the emergency was of 1 billion m^3 [8]. According to the geodetic surveys of the tailing dump surface (21.06.2010 and 26.09.2010), the total volume of the evacuated tailings was estimated to be of 9600 m^3. The general views of the storage before and after the emergency are shown in Figs. 1 and 2, respectively.

After the emergency, the water drain of Tumanny brook was almost completely run through the stored wastes surface; therefore, the tailings were eroded, and the erosion products were carried into the brook downstream and into Khasyn river. In order to decrease the pollution level, the ponds cascade was arranged in the downstream of Tumanny brook, so that its waters are mechanically cleaned of the suspended wastes. Currently, the tailing dump sections are not filled with water; however, minor rain and filtration drainage flows were detected [1].

The reported study aimed to estimate the influence of the eco-catastrophe of 2009 on the hydrosphere of the river Khasyn basin. In particular, we targeted to study the river waters composition in the emergency situation region, to estimate the effects caused, and to develop the suggestions of the tailing dump recultivation in order to compensate for the negative effects.

The water objects of the region are of primary importance for fishery. Therefore, the concentrations of various components in water were compared to the MPC values determined for the fishery industry (Table 2). According to the chemical composition, the

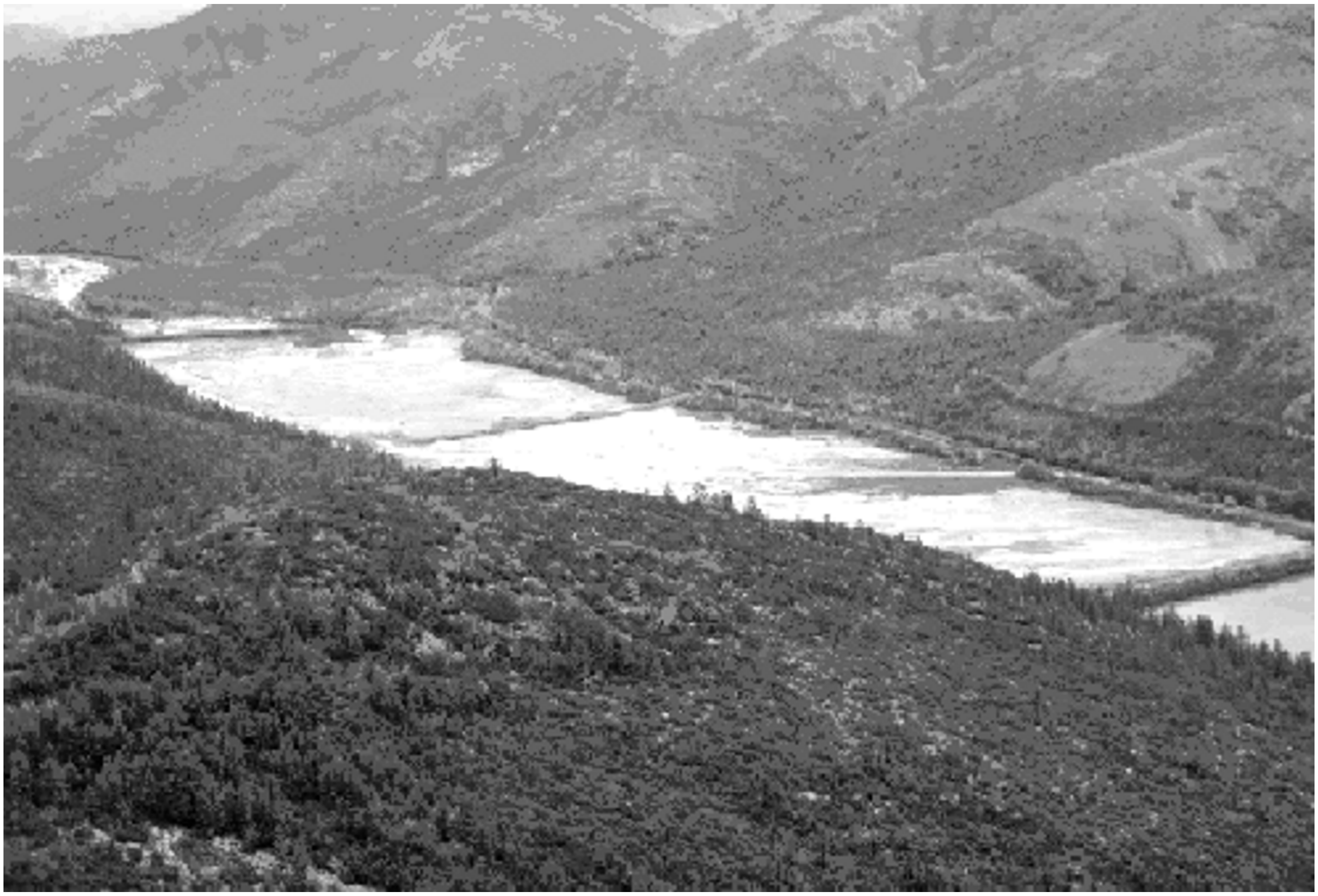

Fig. 2. General view of the storage after the accident (downstream Tumanny brook valley).

natural surface waters of the considered region were classified as of fresh chloride-sulfate-hydrocarbonate and magnesium-calcium-sodium types. The total solids content was of 40–60 mg/L, pH was close to neutral (6.8–7.2), the total hardness was of medium range (0.4–0.5 mg-eq), and the concentrations of most of the elements were low. The reference water specimens were classified as "clear" or "very clear". The parameters of reference water specimens were totally corresponding to the requirements put on fishery water objects. The same applied to the specimens of the considered region before the accident (2006).

In 2009, after the accident, waters of Tumanny brook and Khasyn river (downstream the accident) were highly polluted. In particular, the suspended solids content was 28400 (Tumanny) and 2120 (Khasyn) times MPC. The concentrations of ammonia (1.2 MPC) and of nitrites (1.5 MPC, Tumanny only) were also above the permitted values, the concentrations of other components being within the permitted range. The water quality was classified as "extremely polluted", mainly due to the suspended components.

In July and September, 2010 the increased content of suspended solids was detected in the water specimens: up to 3100 MPC (Tumanny brook) and up to 533 MPC (Khasyn river); the contens of some other components was above the permitted level as well: Fe_{total} (27 MPC), Cu (4 MPC), Mn (12 MPC), and Zh (2 MPC) in Tumanny brook; Fe_{total} (12 MPC), Cu (2 MPC), Mn (7 MPC) in Khasyn river. Content of other components was within the permitted range. Waters were classified as "extremely polluted" (Tumanny brook) and "polluted" (Khasyn river) (Table 2).

In July-September, 2011, the following components concentration exceeded the MPC values: total suspended solids (1667 MPC), Mn (1.5 MPC), Fe_{total} (3 MPC), and Cu (up to 4 MPC) in Tumanny brook; total suspended solids (255 MPC), Zn (27 MPC), and Cu (up to 4 MPC) in Khasyn river. Waters were

Table 2. Composition of the surface water in the region before the accident (2006) and after the accident (2009–2011)[a,b]

Component	MPC (fishery)	Water object, specimens number, year, concentration (mg/L)															
		Tumanny brook								Khasyn river							
		T. 10 (reference)				T. 20 (downstream the dam)				T. 30 (reference)				T. 40 (downstream the Tumanny brook mouth)			
		2006	2009	2010	2011	2006	2009	2010	2011	2006	2009	2010	2011	2006		2010	2011
pH	**6.5–8.5**	6.73	6.82	6.91	6.74	6.64	7.8	7.65	7.80	7.16	6.9	7.15	7.65	7.2	7.96	7.23	7.4
Suspended components	**+0.25**	2	5	3.5	3.83	4	7100	775	416.78	2	3	6.25	4.17	4	530	133.25	63.78
Total solids	–	67	133	103.75	146.5	126	280	170	191.17	63	89	93.75	83.31	65	190	22.75	118.28
Cyanide	**0.05**	–	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Thiocyanate	**0.05**	–	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Sodium	**120**	4.7	3.76	3.22	–	10.3	6.82	3.22	–	5.22	2.67	2.39	–	5.6	2.87	1.95	–
Potassium	**50**	0.50	0.51	0.56	–	0.72	3.95	17.8	–	0.4	0.29	0.36	–	0.46	0.95	11.26	–
Calcium	**180**	10.79	23	19.32	–	20.75	41.9	17.62	–	11.55	16.90	17.03	–	11.79	32.2	11.45	–
Magnesium	**40**	1.55	2.3	1.45	–	5.21	2.8	1.44	–	1.53	1.5	1.27	–	1.98	6.7	1.75	–
Ammonium	**0.5**	<0.05	<0.05	0.16	0.42	<0.05	0.52	0.285	0.22	<0.05	0.05	0.21	0.30	<0.05	0.61	0.26	0.24
Total iron	**0.1**	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.27	0.035	<0.01	<0.01	<0.01	0.01	<0.01	0.01	0.12	0.03
Hydrocarbonate	–	18.0	19	12.25	–	27.0	62	11.08	–	35	21	15.5	–	35	40	10.38	–
Chloride	**300**	<1	<1	<1	2.1	8.59	2.3	2.63	2.55	<1	<1	<1	2.35	<1	<1	2.6	2.15
Sulfate	**100**	25.1	66.6	45.58	41.25	51.44	92.4	28.83	56.48	17.69	42	35.78	16.1	17.28	90.6	21.73	35.4
Nitrate	**40**	<0.1	1.6	1.7	–	1.07	1.3	1.58	–	<0.1	0.53	1.03	–	<0.1	0.96	1.38	–
Nitrite	**0.08**	<0.02	<0.02	<0.02	–	<0.02	0.12	<0.02	–	<0.02	<0.02	<0.02	–	<0.02	0.05	<0.02	–
Phosphate	**0.2**	<0.05	<0.05	–	–	<0.05	<0.05	–	–	<0.05	<0.05	–	–	<0.05	<0.05	–	–
Copper	**0.001**	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	0.004	0.004	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	0.002	0.004
Zinc	**0.01**	0.004	0.004	0.01	<0.004	<0.004	<0.004	0.02	0.006	<0.004	<0.004	0.008	0.017	<0.004	<0.004	0.02	0.023
Lead	**0.006**	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Manganese	**0.01**	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	0.12	0.015	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.07	0.01
Strontium	**0.4**	<0.05	0.07	0.07	–	<0.05	0.05	0.05	–	<0.05	0.05	0.07	–	<0.05	0.05	0.04	–
Nickel	**0.01**	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–
Cobalt	**0.01**	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–
Chromium	**0.07**	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–
Antimony	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–
Arsenic	**0.05**	<0.05	–	<0.05	–	<0.05	–	<0.05	–	<0.05	–	<0.05	–	<0.05	–	<0.05	–
Mercury, μg/L	**0.01**	<0.0015	–	<0.002	–	<0.0015	–	<0.002	–	<0.0015	–	<0.002	–	<0.0015	–	<0.002	–
Selenium	**0.002**	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–	<0.02	–
Cadmium	**0.005**	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–	<0.01	–

"–": data not available. [b] Grey coloration indicates the values above MPC.

classified as “very polluted” (Tumanny brook) and “moderately polluted” (Khasyn river) (Table 2).

In 2009–2011, the yield of suspended solids was decreased by 17 times in Tumanny brook water and by 8 times in Khasyn river water. However, the concentrations of Fe_{total}, Cu, Mn, and Zn in Khasyn river were increased (both 2010 and 2011). As for Tumanny brook water, Fe_{total} and Zn concentrations were increased in 2010, whereas Cu and Mn concentrations were increased both in 2010 and 2011. Noteworthily, in 2011 the concentrations of Cu and Mn in Tumanny brook water were increased in the reference specimens as well.

Overall, in 2010 virtually all the studied parameters revealed sharp decrease of water quality both in Tumanny brook and in Khasyn river. In 2011, the suspended solids concentrations were somewhat decreased, as well as that of Fe_{total} and Mn; however, Cu and Zn concentrations were up. The described trends were due to the hypergene processes typical of the sulfide-containing suspended and bottom parts of the tailings. The increased concentrations of Cu and Zn will be likely detected in the waters for long in the future, as sulfides oxidation can take up to centuries (800 years in the case of pyrite [9]).

The chemical and mineral composition of the bottom deposits in the bed and flood-lands of Khasyn river in 2009–2011 was practically identical to that of the enrichment tailings stored in the Karamenskoe enterprise tailing dump.

In 2011, the ecological situation in the region turned better, however, the accident consequences are detected at the distance of up to 80 km. In particular, at Arman’ river mouth (Okhotskoe sea) the white deposits were observed at the rocks surface in 2011, being a sign of modern mineral formatin process due to high concentration of sulfides in water.

Therefore, recultivation of the territory is definitely needed in the Karamkensk district, otherwise, the accident can be easily repeated.

For example, in August 2010 similar accident took place in the Komsomolsky tin-ores region near Gorny (Khabarovsk region), when the tailings were washed into Silinka river from the tailing dump of Solnechnaya concentration factory [10]. Unfortunately, the recultivation measures are not generally taken at the tailings storage sites, even though this is required after the cancellation of the ore processing enterprise.

We propose the following two-stage recultivation of the tailing dump surface of Karamkenskoe enterprise [11, 12]. First stage (technical, or engineering) presumes the strengthening of the slope of the flow channel No. 2, at the site restored after the accident. Then, the standby channel at the tailing dump surface should be organized; filling of four-level filtration dam at the closure channel of the existing separating dam and arranging the spilling at the head dam should follow.

The second stage is a biological one. We suggest application of the bentonite-humate composition “Sever” with NPK and microbiological additives according to the technical specifications. Such compositions are used for recultivation of the anthropogenic sand substrates in the permafrost regions. “Sever” is non-toxic, fire- and explosion-safe; it does not form toxic of hazardous substances after applications. It is capable of binding, structuring, and conditioning of the sandy substrates, and therefore provides the plants nutrition leading finally to the strengthening of the ravines, open pits, and embankment slopes.

EXPERIMENTAL

The object of study was water at the Karamkenskoe tailing dump region before and after the 2009 accident. As judged from the chemical composition, the poral water of the tailings revealed the amounts of ammonia, sulfates, zinc, manganese, strontium, nickel, and cobalt significantly exceeding the corresponding MPC values. The subsurface water was classified as “very polluted,” except for well water at the separating dam, the latter being classified as “polluted.”

Metal cations concentration was determined by atom absorption method (THERMO JARRELL ASH); calcium and magnesium were determined by titration; aluminum, cyanides, and thiocyanates were determined by photometry (KFK-2). The anions were quantified by means of gravimetry, titration, and photometry (KFK-3).

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