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Erosion Processes in Anthropogenic Systems in the South of the Russian Far East

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Abstract—The results of studying erosion processes in anthropogenic systems in the South of the Russian Far East are given. The surface of tailings dumps has been shown to be subjected to not only air and wind but also chemical erosion, which creates a great hazard to the environment and human health. A direct relation has been found between the anthropogenic material discharge and precipitation amount. Its maximal value during intense erosion processes has been estimated. A set of measures has been proposed to reduce the impact of erosion processes in mining anthropogenic systems.

Keywords: Erosion, anthropogenic materials, carryover, tailings dump, recultivation.

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INTRODUCTION

Soil cover is a specific shield of deeper lithosphere layers and the main factor ensuring persistent Earth surface topography; it performs diverse ecological functions, including anti-erosion protection. Undoubtedly, the problem of protection of soils from erosion is very urgent for the Far East. This is related not only to important role of soils in the biosphere but also to the acknowledgement that the state of soil cover in this region can now be characterized as critical. It was convincingly demonstrated that soil is the most important component of terrestrial biogeocenoses, controller of the composition of atmosphere and hydrosphere, powerful energy accumulator on the Earth, and reliable barrier to pollutant transport. However, this important component of the Far East biosphere is subject to considerable degradation. The most threatening is erosion of soils by the action of anthropogenic, atmospheric, hydrological, and hydrochemical factors. Thus, exploitation of solid mineral deposits in the South of the Russian Far East is accompanied by inevitable deterioration of the Earth surface due to appearance of heaps, waste banks, tailings dumps, and other anthropogenic matter, which act as environmental pollution sources. Despite distribution of anthropogenic objects throughout the Far East region, this problem has not yet been studied. Moreover, these objects have never been included into the area of control over harmful natural or anthropogenic phenomena, primarily over erosion processes. No special studies have been performed to assess the risk of erosion in mining areas and its impact on the environment. In view of the aforesaid, the goal of the present study was to elucidate the mechanism and assess the risk and magnitude of erosion in anthropogenic landscapes to ensure their environmental safety. In keeping with that goal, the following problems were defined: (1) analysis of published data; (2) assessment of the risk and magnitude of development of erosion processes on the surface of anthropogenic formations; (3) analysis of the set of already occurring and possible geomorphodynamic processes that affect restoration of woodland; (4) development of actions directed toward reduction of erosion impact on the environment.

SUBJECTS AND METHODS

The subjects for the study were mining systems of the Russian Far East. The methodology of the study was based on the Vernadskii theory of biosphere and noosphere, as well as on the basic principles stated in the Program and Procedure for Studying Anthropogenic Biogeocenoses and other publications [1, 2]. A set of methods and methodical tricks, including scientific prediction, systematization, modeling, and classification, was applied. In addition, both modern instrumental and traditional physicochemical, chemical, and statistical data processing methods were used. Field researches in the mining-affected areas were carried out over a period of 2001 to 2012 according to a unified procedure at the following mining plants formerly known as Solnechnyi ore-dressing plant (Komsomolsk tin-ore complex, Solnechnyi region, Khabarovsk Krai, river Silinka basin and Amur–Gorin interfluve), Khinganskii ore-dressing plant (*Khinganolovo* tin-ore works joint stock company; Obluchensk region, Jewish Autonomous Oblast, river Khingan basin), and Khrustal'nenskii ore-dressing plant (Primorsky Krai).

The amount of the removed finely dispersed anthropogenic material was calculated according to Sobolev [3]. For this purpose, the length of gullies and their average width and depth were measured. Samples of mining waste materials, snow cover, soils, vegetation, toxic dust, and runoff water were withdrawn, uniformly prepared to analysis, and analyzed for heavy metals (HMs) at the Khabarovsk Innovative Analytical Center (Institute of Tectonics and Geophysics, Far Eastern Branch, Russian Academy of Sciences) using an ISP instrument. Biological methods described in [4] and others were used.

While solving problems with a view to elucidate how exploitation of the Earth interior affects the soil cover and vegetation, soil evolution and natural overgrowth processes in anthropogenic landscapes were studied by conventional methods (see, e.g., [2].

Meteorological data from the Khabarovsk Krai statistical compilations were analyzed.

Biological materials were taken from children up to 14 years old in the areas affected by tailings dumps. Samples were treated according to a unified procedure, which included microwave-assisted acid digestion, and were analyzed by inductively coupled plasma mass spectrometry using Perkin–Elmer ELAN DRC II IPC-MS instrument. The results were processed using Microsoft Excel.

The non-carcinogenic risk was assessed by calculating the hazard quotient (HQ) according to Kurolap et al. [5].

Mathematical processing of the obtained data was performed with aid of PC software packages based on conventional ANOVA methods.

RESULTS AND DISCUSSION

Analysis and systematization of published data related to erosion processes in anthropogenic landscapes showed [6–16, 20] that the most spacious landscape damages are caused by open-pit mining. In keeping with the soil classification and diagnostics given in [6, 7], overburdens and tailings dumps thus formed are anthropogenic surface formations (ASF). These are either deliberately built up soil-like bodies or residual stocks resulting from anthropogenic activities, which consist of natural or specific human-modified materials. All these surface formations affect the ecosystem but they cannot be regarded as soils in the Dokuchaev sense [6–8] since genetic horizons have not yet been generated therein. They are not covered by the unified system of natural (normally developed) soils. Anthropogenic surface formations lack a humus layer and consist of natural minerals [6–8]. Numerous studies have shown how soils and ASFs degrade under the action of anthropogenic factors [10, 15, 21], as well as due to mechanical washout or weathering of the surface material of heaps, waste banks, and tailings dumps and carryover of particles of various sizes with water flows to the adjoining areas and further to rivers, lakes, seas, and ocean.

In the past three years, a new line in regional soil science has emerged. It implies studies on the effect of

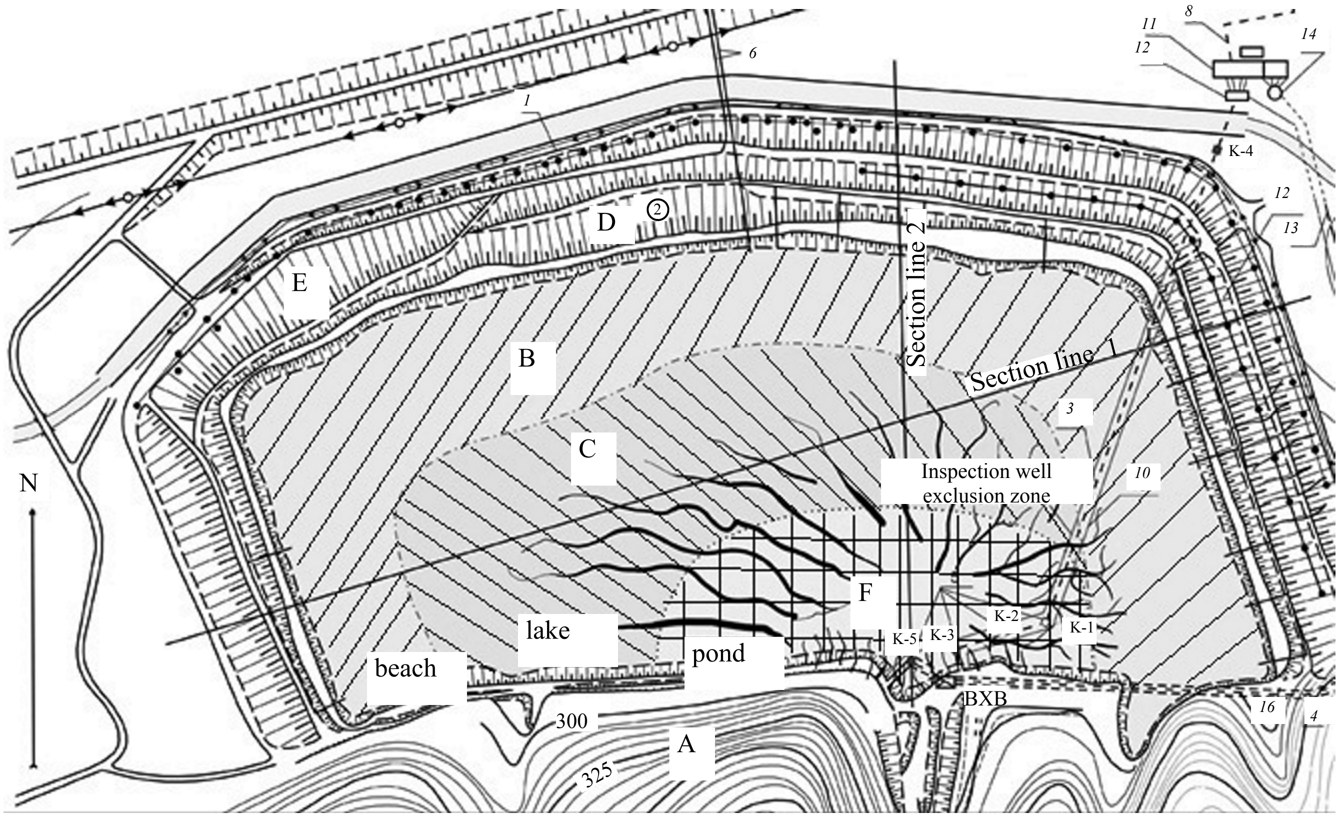

Fig. 1. Tailings dump of the Solnechnyi ore-dressing plant; sites affected by erosion processes (gullies) are shown.

physicomechanical properties of soils (in particular, of rheological properties) on the development of erosion processes [6, 9, 14, 16–17]. Shein et al. [16] made an attempt to extend the existing classification [17] via addition of such parameters as cohesive force of soil particles and normalized fatigue tensile strength. Furthermore, studies on erosion, deflation, and chemical erosion in such ASFs [11, 16–21] as tailings dumps, overburdens, mine waste piles, and ash dumps of thermal power plants have been initiated at the Soil Science Department of the Far Eastern Federal University jointly with the Pacific State University, Soil Science Department of the Institute of Biology and Soil (Far Eastern Branch, Russian Academy of Sciences) and Far Eastern Geological Institute (Far Eastern Branch, Russian Academy of Sciences).

Analysis of published data showed that major attention was given to the development of erosion processes in agricultural lands. We made an attempt to assess the risk of erosion in anthropogenic formations which, in our belief, are identical to farmland in consistence.

For instance, the present state of the tailings dump of the Central Dressing Factory of the Solnechnyi ore-dressing plant (which has been put to operation in 1969; it was built up 3 km south-west of the Solnechnyi settlement at the right slope of the river Kholdomi valley with no account taken of the wind rose) suggests that it is a source of anthropogenic pollution due to erosion. The long rear side of the tailings dump adjoins the right slope of the river Silinka valley, a large bedrock side with a slope of 0.34, which is split by four notches at the dam flank. The mouths of two more notches approach in length the edges of the dam beyond. The dam is 1760 m long at the ridge, and the tailings dump area is 640000 m^2 (Fig. 1).

Tin ore mining and dressing at the Solnechnyi plant included processing of rocks and extraction of only main useful copper- and tin-containing components, whereas the host rocks and residual sulfide components were stockpiled as industrial wastes called tailings which were buried disposed as a tailings dump. At present, the amount of tailings is estimated at 32 million MT. The tailings contain up to 48–52% of hornfelsed rocks and 35% of quartz and tourmaline. The major minerals are: cassiterite, arsenopyrite, galenite, pyrite, etc. Sulfides constitute an important part of tailings (about 5%), and they contain tin, copper, zinc, lead, arsenic, sulfur, iron, manganese, silver, cadmium, and other elements (Table 1). A characteristic geochemical feature of the waste material is a high content of toxic chemical elements, in particular 4461.8 g/t of copper, 2421 g/t of arsenic, and 1475.8 g/t of lead. Weathering and mechanical carryover of finely dispersed tailings material containing toxic elements favors pollution of the environment with heavy metals, arsenic, and other harmful elements.

Degradation of the host rocks (chlorites, tourmalines, carbonates, etc) due to mechanical and chemical weathering gives rise to carbon- and silicon-containing anions, etc. The presence of sulfide components in mine openings (trenches, strippings, open pits, galleries, as well as tailings dumps) favors their intense oxidation, hypergenesis and technogenesis, i.e., chemical erosion due to increase of contact area of sulfides with weathering agents (oxygen, carbon oxides, water, etc.) [11]. As a result, highly concentrated micropore solutions are formed, and they give rise to drainage and mine waters involved in modern anthropogenic formation of minerals both in mine openings and on the surface (Fig. 1), as well as in bulk tailings. The tailings material is transferred by wind to soils where sulfides are also oxidized, which favors soil contamination with formation of crusts and anthropogenic mineral films. Micropore solutions are then assimilated by wild-growing plants, fungi, animals, and birds.

Supergene and anthropogenic processes lead to crystallization from solutions of iron, copper, lead, zinc, aluminum, and other minerals as sulfates, carbonates, arsenates, silicates, etc. [11]. Highly concentrated drainage and mine waters containing a broad spectrum of cations and anions from sulfides and host rocks have been neither restrained nor treated over decades, and they amount to millions of cubic meters entering into ground and surface waters. Chemical erosion not only results in contamination of ground and surface waters but also impairs hydrochemical background. The concentrations of iron, copper, zinc, lead, and other elements in slime, drainage, mine, and even river water exceed background values by one to three orders of magnitude [11, 19].

Chemical erosion releases large amounts of various gases and heavy metals from anthropogenic materials, as follows from analyses of snow cover during the winter–spring period. The water-soluble fraction contained both carcinogenic (cadmium, nickel) and noncarcinogenic elements (copper, lead, cobalt, chromium, antimony, etc.). Polluted areas and pollutant flows are spread via natural migration mechanisms. The total pollutant content of snow cover in waste-affected areas may be used to assess their effect on the ecosystem and the risk to human health, related to atmospheric air pollution. Evaluation of the hazard quotients (HQ) showed the highest values for suspended particles (HQ = 47.3) and copper (HQ = 20.5) and somewhat lower values for manganese and sulfur dioxide (HQ = 3.9 and 1.3, respectively). A higher overall hazard index was found for a group of substances affecting the respiratory system (suspended particles, sulfur dioxide, copper, chromium; HI = 69.97), and next followed those affecting the nervous system (lead, manganese, and cobalt; HI = 4.62).

The major atmospheric pollutant is waste dust generated from tailings dumps subjected to wind erosion. The concentrations of toxic heavy metals therein exceed the maximum allowable concentrations by a factor of 5 to 45.

The chemical composition of old wastes (Table 1) indicates that they are highly hazardous to the environment; this id confirmed by the ecological state of air basin, anthropogenic soils, and vegetation in the affected area. We detected a large number of various gases and heavy metals which are released from the

Table 1. Average chemical composition of old tailings (%)

Component	Concentration	Component	Concentration
SiO_2	62.60	Sn	0.214
TiO_2	0.41	Cu	0.036
Na_2O	0.76	Zn	0.378
K_2O	1.75	Pb	0.110
CaO	0.354	Ag	0.691
MgO	0.65	S	1.936
Fe_2O_3 + FeO	15.90	Cd	0.034
$A1_2O_3$	10.20	Nb	0.024
MnO	0.13	Sc	0.001
P_2O_5	0.23	As	0.691

bulk tailings to the surface. According to the transverse gas survey data, the maximum concentration of sulfide sulfur amounts to 96 maximum allowable concentrations (MAC). Its average value across the tailings dump area exceeds the MAC value by a factor of 47. The concentration of hydrogen sulfide was estimated at 2 MACs, and the concentration of aerosols was higher than the background value by a factor of 80. These data indicate that the degree of pollution of the air basin by the tailings dump is extremely high.

Exceedence of maximum allowable concentrations of copper, zinc, lead, tin, and other elements in soils and vegetation was detected. The total pollution index in the affected area (up to 3–9 km) ranged from 140 to 12. The following relation was found: the higher the level of anthropogenic soil pollution, the higher the pollen sterility (up to 22%).

The largest amounts of carcinogenic chemical elements were found in dust. For instance, in 2008 the arsenic content of dust was 114 mg/kg, and the chromium content, more than 93 mg/kg. It is well known that increased pollution of air basin with suspended particles and other pollutants increases the incidence of such diseases as pharyngitis, conjuncttivitis, bronchitis, bronchial asthma, and respiratory function disorders among mining village people. Heavy metals (lead, copper, chromium, cobalt, nickel) present in dust favor dysfunctions of reproductive, nervous, cardiovascular, immune, and endocrine systems.

Undoubtedly, the tailings dump is the main source of pollution of ecosystems and habitats of living matter, and it aggravates erosion processes.

In keeping with morphodynamic characteristics, the tailings dump surface may be divided into several zones (Fig. 1). Zone A is a bedrock slope, many parts of which are free from vegetation. Detrital material from the bedrock (mainly slide rocks) falls onto a side cut, an artificial plateau along the foot of the slope, and partly into the tailings dump. Zones B and D constitute the area where tailings (tin-ore processing wastes) are dumped. Waste materials in zones B and C ("beach" and "intermediate") of the dry bottom surface inclined toward zone F (tailings storage pond) are subject to water and wind erosion leading to waste deposition in zone F via eolian and fluvial transport. Sandy clay material is flushed from zone D (internal slope of the embankment dam) and is spread by wind over the surface of the tailings dump and beyond it.

Water erosion is the most intense in the northeast part of the tailings dump (zone C) where gullies formed a dense network (Fig. 1, Table 2). Some gullies are more than 200 m long, 1.35 m deep, and (somewhere) 3 m wide. The volume of a part of gullies extending from northeast to southwest amounts to ~700 m^3. Their mouths are located in zone F, where the transferred waste material including various pollutants accumulates. The surface of the tailings storage pond is mostly covered by a multicolored crust formed by cemented deposits as a result of chemical erosion. A part of the polluted wastes transferred thereto falls into the drainage pit and goes beyond the tailings dump.

Zone E (outer bank of the dam) is also an area of fluvial and eolian transport of fine earth, which becomes much more intense under strong wind conditions with account taken of the lay of the river Silinka valley and covers a large distance beyond the tailings dump up to Solnechnyi urban settlement. Erosion products from zone E also enter the river Silinka catchment area. Zone E is subject to natural overgrowth, though very slow. Sparse undergrowth in the bottom part of the bank is represented by poplar, alder, and larch. In the northeast bottom part, one can see both pioneer vegetation (trees, bushes) and residual indigenous vegetation, which are covered by sand transferred from the tailings dump.

The bottom of the tailings dump is almost completely naked. Only in the western part where potentially rich rocks are piled, occasional poplar and alder specimens brought with the rocks are encountered. However, attempted re-cultivation of the tailings dump surface by sowing legume/grass mixtures in potentially rich rocks over an area of 0.25 ha was unsuccessful. The initial result was hopeful, but the sprouts were then buried under readily dispersible sand sediments due to their local character.

Examination of the present state of the tailings dump surface showed the necessity of changing the recultivation technology. It was concluded that the whole tailings dump area is subject to active geomorphogenesis and that it should be backfilled and graded. About 70% of gullies are located in the inter-mediate zone, and about 30%, in the tailings storage pond where the gullies end. Finely dispersed anthro-pogenic materials, including those resulting from erosion processes, also accumulate in zone F and partly leave the tailings dump through the drainage pit. Eolian and fluvial processes are periodic; they are enhanced

Table 2. Size and volume of gullies in the tailings dump of the Solnechnyi ore-dressing plant in 2009

Gully length, m	Gully width, m	Gully depth, m	Gully volume, m^3
Western sector			
104	0.43	0.56	136.9368
78	0.69	0.85	102.7026
62	0.83	0.94	81.6354
50	2.22	0.94	65.8350
53	1.71	1.32	69.7851
67	1.34	1.35	88.2189
42	1.90	1.03	55.3014
Σ = 456	Σ = 9.12	Σ = 6.99	Σ = 600.4152
L_{av} = 65.1428	V_{av} = 1.33	H_{av} = 0.99	V_{av} = 85.7736
Eastern sector			
2.15	1.05	0.25	304.5
1.50	1.35	0.53	212.4
1.30	0.5	0.67	184.0
	1.2	1.02	
	3.0	0.98	
Σ = 4.95	Σ = 10.62	Σ = 4.8	Σ = 7 00.9
L_{av} = 1.65	V_{av} = 1.77	H_{av} = 0[a]	V_{av} = 233.6337

[a] Average cross-sectional area of gullies $S = 1.4160$ m^2.

during strong winds (wind erosion) and downpours (water erosion), while chemical erosion is a continuous process. It was found that the erosion intensity and anthropogenic material discharge are related to the precipitation amount. The maximum discharge of finely dispersed anthropogenic material was observed in 2009 when the annual rainfall was the highest (Fig. 2).

Surface water streams play the crucial role in the formation of gullies. They perform the following

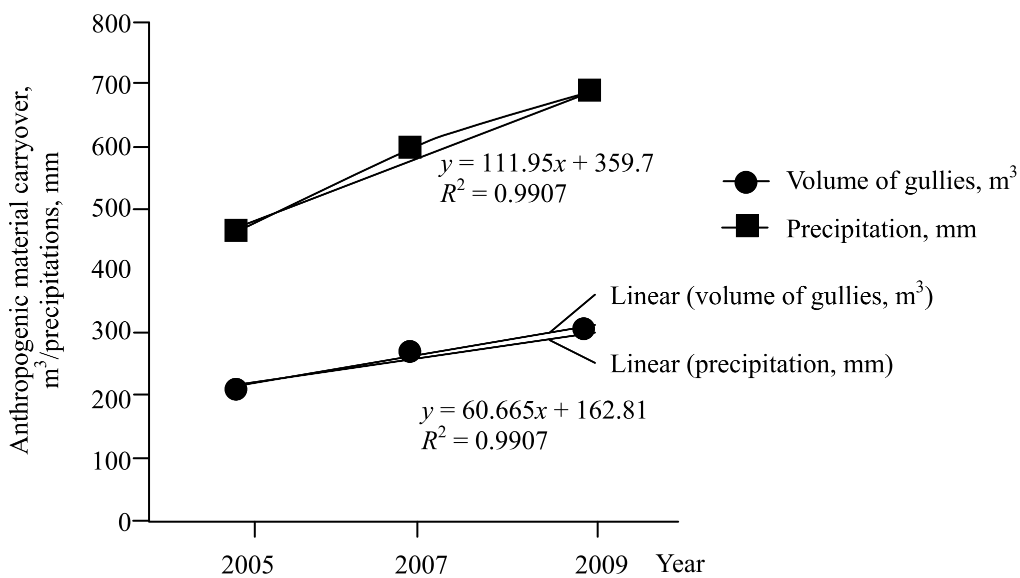

Fig. 2. Anthropogenic material carryover from the surface of the Solnechnyi tailings dump and precipitation amount in 2005–2009.

functions: favor washout of rocks in a bed, deepening of a gully, and extension of its bottom, stimulate gravity-induced processes on gully slopes and head via deep and side erosion, and remove erosion products from the gully [12, 21]. In addition, such processes as suffosion, hillslope erosion, and solifluction. Suffosion processes in some cases create primary depressions as washout routes, which favor formation of gullies, whereas hillslope erosion is responsible for extension of gullies in width and acceleration of their growth.

Thus, nowadays the tailings dump is at the active development stage; undoubtedly, it strongly affects the environment.

The results of our studies allowed us to propose the following actions directed toward reducing the environmental and social risks of pollution with toxic wastes from the tailings dump:

(1) Improvement of the technologies of ore mining and processing via more complete utilization of mineral ore materials;

(2) Recultivation of lands, including tailings dumps, deteriorated as a result of mining;

(3) Organization of mining and environmental monitoring;

(4) Improvement of the legislative and regulatory framework;

(5) Development of a program and strategy of environmental safety in mining areas with account taken of mining area zoning.

CONCLUSIONS

It may be concluded that weathering and chemical erosion of toxic wastes piled in tailings dumps create a high hazard to the environment and human health. A set of actions has been proposed to reduce the impact of erosion processes in anthropogenic mining systems, in particular recultivation of the tailings dump surface, implementation of environmental monitoring, improvement of the legislative framework via toughening of environmental requirements, and development of a program and strategy of ensuring environmental and social safety of toxic wastes.

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