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Environmental Monitoring of Ecosystems under the Impact of Gold and Tin Mining Wastes in the Far Eastern Federal District

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Abstract—The necessity of local environmental monitoring of ecosystems polluted by wastes from gold placer and tin ore deposits has been substantiated by considering former Sofiiskii gold placer mine and Solnechnyi ore-dressing and processing enterprise (Far Eastern Federal District). The results of studying their negative effect on the biosphere have been discussed. Principles of local environmental monitoring have been developed with account taken of specificity of anthropogenic flows generated during gold and tin extraction processes.

Keywords: local monitoring, anthropogenic pollution, ecosystem, ecosphere, wastes

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INTRODUCTION

Vigorous growth of the consumption of mineral resources is observed in Russia and worldwide since the second half of the XXth century. Age-old development of mining industry in the Far Eastern Federal District (FEFD) has led to accumulation of a huge amount (billions of tons) of mining wastes, so-called tailings which may be regarded as **anthropogenic deposits** with considerable concentration of a number of elements, including toxic ones (Sn, Cu, Pb, Zn, Cd, etc.). Hypergene processes (oxidation, dissolution, hydrolysis, etc.) transform the whole spectrum of chemical elements occurring as sulfides, tellurides, selenides, silicates, sulfosalts of various metals, etc., into other mineral forms and aqueous solutions which spontaneously migrate to the atom-sphere, lithosphere, biosphere, and hydrosphere, thus favoring heavy pollution of the environment. This is especially important for the Russian Far East where a large number of gold and tin extraction plants that are most hazardous for the environment have not overcome economic difficulties during the transition period, were declared bankrupts, and no longer operated. Specific features of tin and gold mining and processing include treatment of a large amount of rocks with the use of metallic mercury (e.g., in the gold extraction, from the prerevolutionary period till 1990s). However, only a small part of mined rocks was processed, whereas waste rocks accumulated as anthropogenic wastes polluted with mercury in placer gold-concentrating sites in the mining village area. Termination of operation of gold and tin extraction plants has aroused a great environmental problem, heavy anthropogenic pollution of the ecosphere and contiguous landscapes with wastes dumped virtually in the residential community. Therefore, not only treatment of anthropogenic deposits but also estimation of their effect on the ecosystem constitutes most urgent problem in the FEFD in the nearest future. Its importance is also determined by the fact that many chemical elements in wastes are characterized by different toxicities with respect to vegetation and living organisms, including humans. Once entering animal or human organism with food, water, and air, such elements induce many diseases, functional disorders, and even death. Statistical data indicate impairment of the gene pool and increase of the number of children with some physiological and psychological pathology. Adverse effect of the past activity of mining industry in the FEFD on the environment is represented by numerous abandoned open pits, ditches, clearings, galleries, waste rock and offgrade ore piles, and mine waste (tailings) stacked in tailing dumps. These lumps make up anthropogenic systems where primary minerals are transformed and toxic elements and their compounds are released into the environment as a result of hypergene processes. These processes are most vigorous in open-pit mining which produces huge amounts of unpayable ore and mineral overburdens piled on the earth surface, thus creating a potent source of pollution for tens and hundreds of years. In this respect, the problem of estimating the effect of mineral raw materials unused in gold and tin extraction on the environment and human health is quite important since anthropogenic deposits may be considered to be natural geochemical anomalies and potential and real sources of toxic elements. However, some aspects of the evaluation and prediction of environmental hazards created by anthropogenic systems and organization of environmental monitoring in the FEFD remain poorly explored. Development of mining industry in that region favored considerable variation of ecosystems, and the necessity of studying the degree of their pollution has arisen. Here, not only environmental assessment of biosphere components but also development of a monitoring system for the effect of mining industry on the ecosphere with the use of modern geo information systems (GIS technologies) is important. Solution of this problem has become possible due largely to up-to-date computational tools and technologies. Therefore, the goal of the present work was to perform environmental assessment and develop principles of an efficient system for local environmental monitoring of ecosystems under the impact of bankrupted gold and tin mining enterprises on the basis of the information approach. In terms of that goal, the following tasks have been formulated:

(1) Analysis and generalization of the existing methods for environmental assessment of areas affected by gold placer mining;

(2) Assessment of wastes of gold placer and tin-ore mining as a source of pollution and their effect on the environment on the basis of the information approach;

(3) Development of principles of the first step of local environmental monitoring of ecosystems affected by gold placer and tin-ore mining wastes.

EXPERIMENTAL

From the viewpoint of methodology, the present study was based on the Vernadskii ideas [1], as well as on the basic concepts set forth in the Program and Procedure for Studying Anthropogenic Biogeocenoses and other publications [2]. The subjects for the study were anthropogenic systems.

To assess the real environmental state of gold and tin extraction wastes piled in sites and tailings and their effect on the biosphere, field, analytical, and laboratory studies were performed since 1998 to 2013 (from June to October). This paper deals with the results obtained in the zone affected by placer gold-concentrating wastes of the former Sofiiskii gold placer (Verkhnebureinskii Region, Khabarovsk Krai, lake Olga basin) and by the tailings dump of the former Solnechnyi ore-dressing and processing enterprise (Solnechnyi Region, Khabarovsk Krai, rivers Silinka and Kholdomi basin).

Samples of wastes, snow cover (SC), soils, vegetation, and toxic dust were withdrawn. The snow cover was analyzed according to Vasilenko [3]. The concentrations of heavy metals and of dispersed substances in atmospheric air were determined according to RD 52.04.186-89 and GOST 17.2.4.02-81 “Environment Protection. Atmosphere. General Requirements to Methods for Determination of Pollutants.”

Mixed anthropogenic soils for chemical analysis were sampled by the envelope technique from layers at depths of 0–10 and 10–20 cm, as well as across the depth from 0 to 30 cm (0–1, 2–8, 9–25, and 25–30 cm), with account taken of the wind rose (GOST 17.4.3.01-83; GOST 17.4.4.02-84). All samples were prepared according to a common procedure, subjected to microwave-assisted acid decomposition, and analyzed by ICP-MS (inductively coupled plasma mass spectrometry) using a Perkin Elmer ELACH DRC II instrument. Mobile Zn, Pb, Cu, and Mn were determined by atomic absorption spectroscopy using an AAS-30 instrument.

The concentration of humus in anthropogenic soils was determined according to Tyurin (GOST 26213–91), organic matter was quantitated according to GOST 26213-91, and pH was determined according to GOST 26483-85.

Geobotanic description was made, herbarium was collected, vegetation species diversity was studied, and dominant plant species were collected for analysis for toxic elements according to GOST 27262-87. Vegetation samples were withdrawn in the same areas as soil samples. Top grass cover was cut off using scissors to avoid contamination with soil, and samples were packed into fabric bags and labeled. Leaves were collected around the crown at a height of about 1.5 m to obtain an overall sample of a given species. Leaf samples were air-dried at room temperature (+25°C) in the dark under good aeration, ground with a laboratory electric mill to a particle size of less than 1 mm, and subjected to extraction and determination of heavy metals. Vegetation samples were mineralized by dry combustion.

The following basic methods and methodical tricks were applied: scientific prediction, modeling, systematization, and scientific classification. Modern instrumental and traditional physicochemical, chemical, and biological methods and statistical data processing methods were used.

The state of the environment was evaluated by calculating concentration coefficients (Kc) and overall pollution index (Zc) [5]. The risk of soil pollution with toxic elements was assessed by the PI value according to the scale proposed in [5] on the basis of studying health of population residing in areas with different soil pollution levels.

The article was typed in using MS Word. All results were processed using MS Excel. Images were prepared using Adobe Photoshop, MS Office Picture Manager, Paint, and MS Visio. Illustrative materials were prepared using MS Power Point.

RESULTS AND DISCUSSION

Analysis and generalization of published data [6–11] and patent search materials indicate especial urgency of the problem of estimation of the risk of anthropogenic environmental pollution as a result of gold and tin mining. However, available quantitative data on the accumulation and transport of toxic chemical elements in anthropogenic systems in the FEFD are few in number [6, 8–11]. The problems related to assessment of environmental pollution due to placer gold and tin-ore mining, protection methods, and environmental monitoring both in the FEFD and in Russia as a whole turned out to be poorly studied [6–8]. It is necessary to apply novel, more perfect approaches based on prediction of probable variations of all biosphere components during the gold mining process. The best tool for the prediction of possible versions with account taken of the effects of all factors (both positive and negative) on living organisms is computer modeling based on GIS technologies [12].

The information approach implying new information technologies (geoinformation and expert systems) makes it possible to not only quantitatively describe processes occurring in complex eco- and geosystems but also simulate mechanisms of these processes and give scientific credence to methods for assessment of the state of the environment. It was found that the most urgent problem in the estimation of the environmental effect of, e.g., tailings dump should be development of a new software tool and/or adjustment of the one tailored for other fields of knowledge [13, 14]. Its application should ensure express analysis of environmental situation, plotting of various ecological maps, modeling of probable scenarios for the development of environmental situation in mining areas, and implementation of local environmental monitoring in the areas affected by hydrotechnical plants producing toxic wastes. This problem remains almost unexplored in the South of the Russian Far East.

While estimating wastes from placer gold and tin ore processing (including those from the placer gold concentrating plant and tailings dump) [6, 11] as a source of environmental pollution, it should be kept in mind that these wastes have long been accumulated as piles within the mining village area; for instance, the placer gold concentrating wastes have been stored for more than a century. The major part of the heavy fraction therein is represented by magnetite, hematite, sulfides (pyrite, cinnabar, in some cases, halenite). Limonite widely occurs in pyrite. Furthermore, ilmenite, zircon, chromite, grossular, and anatase can be found. Obviously, once appearing on the earth surface, wastes undergo vigorous oxidation, dissolution, and transformation into other mineral species

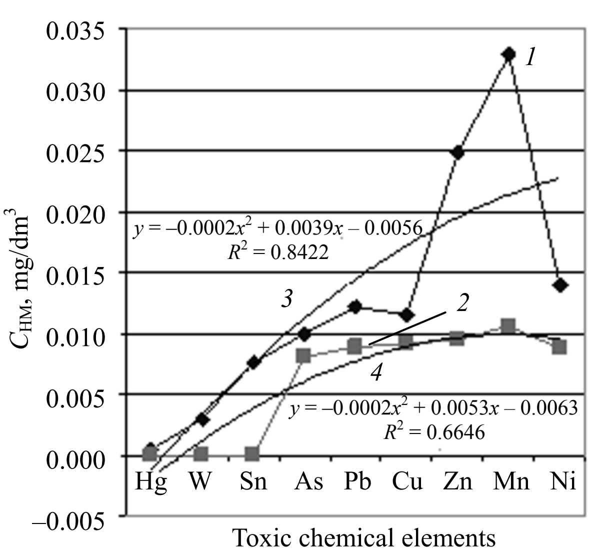

Fig. 1. Heave metal content of snow water and background concentrations in the area affected by the former Sofiiskii gold placer: (*1*) snow water, (*2*) background, (*3*) polynomial (snow water), (*4*) polynomial (background).

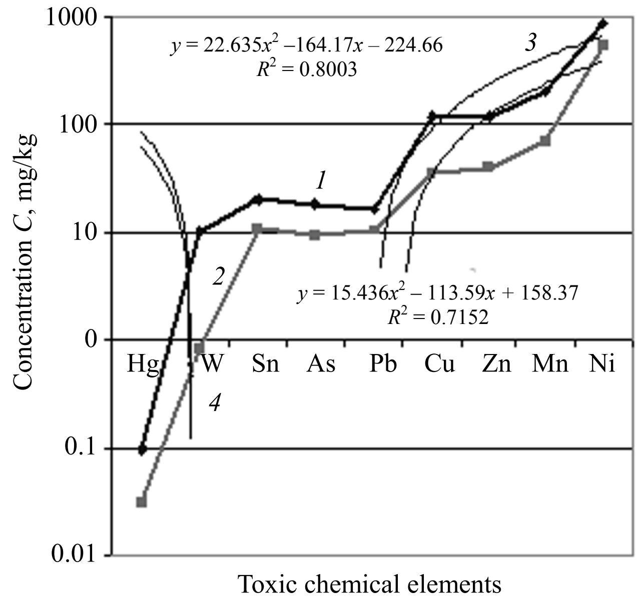

Fig. 2. Heave metal content of snow (solid) and background concentrations in the area affected by the former Sofiiskii gold placer: (*1*) snow water, (*2*) background, (*3*) polynomial (snow water), (*4*) polynomial (background).

and aqueous solution, which essentially impairs environmental situation in areas neighboring to the mining site. According to the semiquantitative spectral analysis data (T.S. Banshchikova), some schlich fractions contained 0.2–0.3% of Pb, 0.02% of Cd, 0.03–0.06% of Zn, 0.02% of Sb, 0.1% of As, and 0.03% of Sn. The concentrations of toxic chemical elements therein were as high as follows, g/ton: Zn, 3536; Pb, 2891; Cu, 2122; As, 1234.

From the environmental–geochemical viewpoint, snow cover is a deposit environment which stores information on the character and level of air pollution. Snow possesses a high sorption capacity, and it traps and deposits onto the earth surface a considerable part of gaseous and finely dispersed anthropogenic products that are conserved while snow cover persists. Naturally, snow cover accumulates dust particles of various origins. Its chemical composition reflects anomalous accumulation of anthropogenic products on the earth surface and their origin. Thus, snow cover may act as a substrate for accumulation of substances and as a factor determining environmental situation. The concentration of heavy metals in molten snow was found to considerably exceed the maximum allowable concentration in snow cover for fishery purposes (4 times for Zn, 2–31 times for Cu, 3 times for Mn, and 5 times for Hg). Increased background heavy metal content of snow cover (both solid and liquid) was detected (Figs. 1, 2). Mercury contributes most to snow cover pollution (64.58%).

Comparison of the overall pollution indices shows (Zc) that the snow cover is polluted by Hg, Sn, W, and As to the East, by Hg, Sn, Zr, Cu, W, and As to the South, by Hg and Zr to the North, and by Hg, Zr, and As to the West. The contributions of heavy metals to snow cover pollution decrease in the series Hg > As > Pb > Zn > Cu > Ni.

Soil cover as deposit environment fixes persistent perennial pollution. Figures 3 and 4 illustrate migrations of some toxic elements. For example, the highest concentration of Pb was found in the 0–10 cm horizon and was 5 to 58 mg/kg for mobile Pb and 14 to 64 mg/kg for total Pb. High Pb pollution was observed 100 m north of the mid placer gold-concentrating plant.

Copper accumulates in soils at a depth of 0 to 10 cm, and its concentration varies from 2 to 32 (mobile Cu) and from 8 to 35 mg/kg (total Cu). Copper migrates northward. Increased concentration of mercury in anthropogenic soils was found at a depth of 0 to 10 cm (0.1 to 1.6 mg/kg, total Hg). Mercury migrates southward and eastward (Fig. 5). The maximum concentrations of heavy metals (Zn, Cu, Pb,

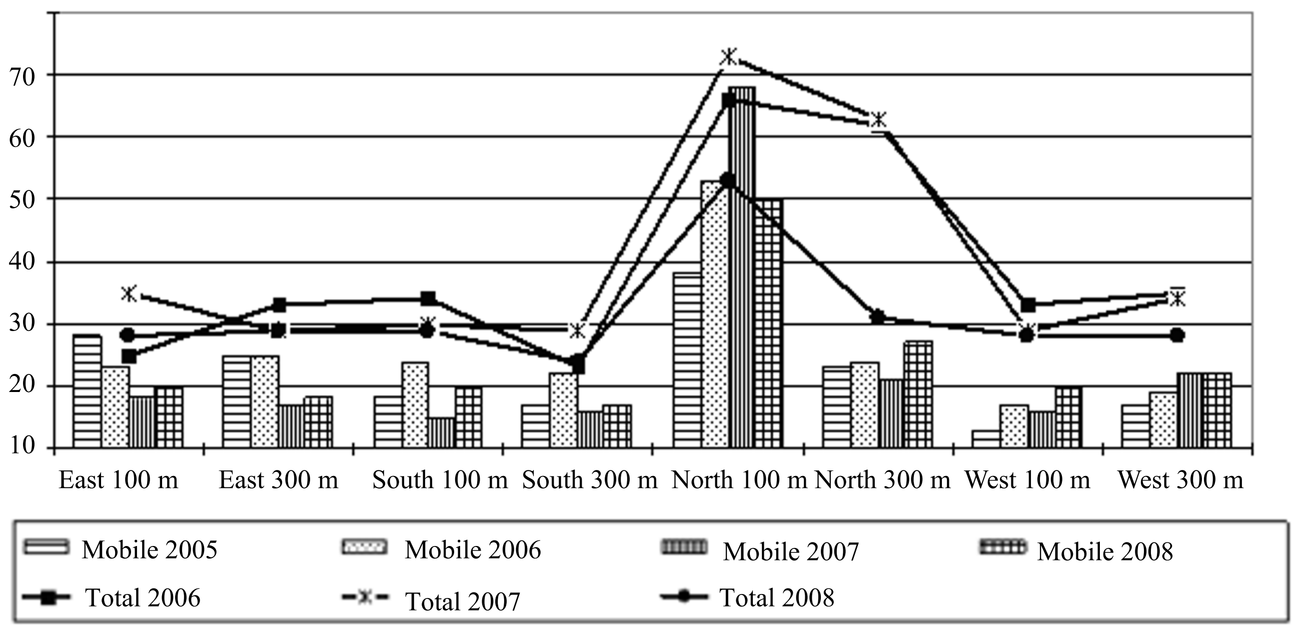

Fig. 3. Lead content of anthropogenic soils (0–10 cm) in the area affected by the former Sofiiskii gold placer, mg/kg.

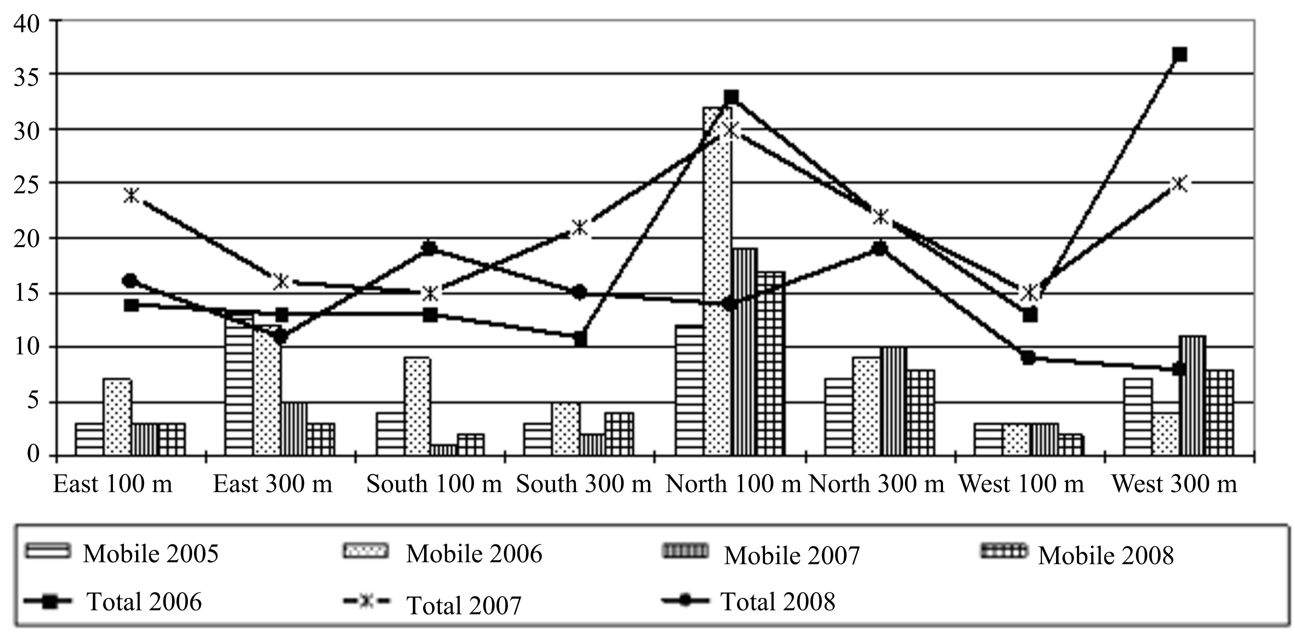

Fig. 4. Copper content of anthropogenic soils (0–10 cm) in the area affected by the former Sofiiskii gold placer, mg/kg.

Mn, Ni) were detected at a distance of 100 m from the placer gold-concentrating plant (Sofiiskii placer mine) and tailings dump (Solnechnyi); they decreased as the distance increased.

The rate of heavy metal migration in soils near the Sofiiskii placer mine and Solnechnyi tailings dump depends on the concentration of humus and pH (Figs. 6, 7). As the humus content of soil increases, the mobility of Zn, Pb, and Cu decreases, and the total metal amount increases. Zinc, copper, and led readily migrate in acid soils (pH 4.5–5.9).

Vegetation samples collected in the affected zone were characterized by increased heavy metal content (Zn, Pb, Cu, As, W). Plants growing under the same

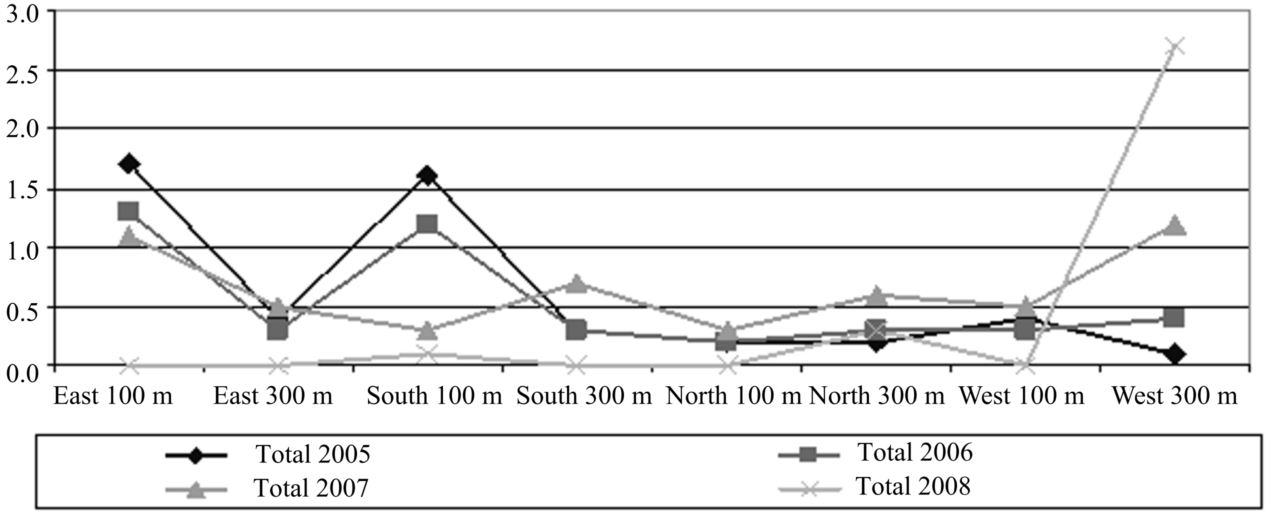

Fig. 5. Total mercury content of anthropogenic soils (0–10 cm) in the area affected by the placer gold-concentrating plant of the former Sofiiskii gold placer, mg/kg.

soil and geochemical conditions considerably differ in heavy metal uptake due to their biological specificities and physiological protective barriers which control intake of elements into plant organs. Therefore, different plant species exhibit different selectivities for heavy metals. For example, the maximum concentrations of heavy metals were found in *Rubus sachalinensis Levl.* (Cu, Zn, Pb; 119 mg/kg), *Polytrichum commune* (Cu, Zn, Mn, Ni, 52.3 mg/kg), and *Equisetum sylvaticum* (Zn, Mn, and others; 13.66 mg/kg). However, accumulation of tin was insignificant, 0.83 mg/kg in *Artemísia vulgaris* and 0.7 mg/kg in *Polytrichum commune*. *Equisetum sylvaticum*, *Betula platyphylla*, and *Ledum palustre* almost do not accumulate toxic elements.

Judging by the concentration coefficients (Kc) and overall pollution indices (Zc) for total heavy metals, we can state that wastes from the placer gold-concentrating plant and tailings dump [6, 11] are the most hazardous for the environment. Anthropogenic soils at distances of 300 m to 3–4 km from the placer gold-concentrating plant and of up to 11–13 km from the tailings dump eastward, southward, and westward are characterized by considerable Zc values (Fig. 8). Here,

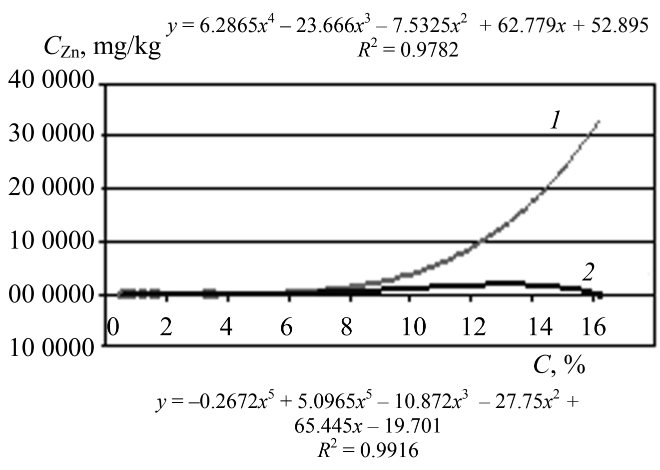

Fig. 6. Plots of (*1*) total and (*2*) mobile zinc concentrations in soils versus humus concentration.

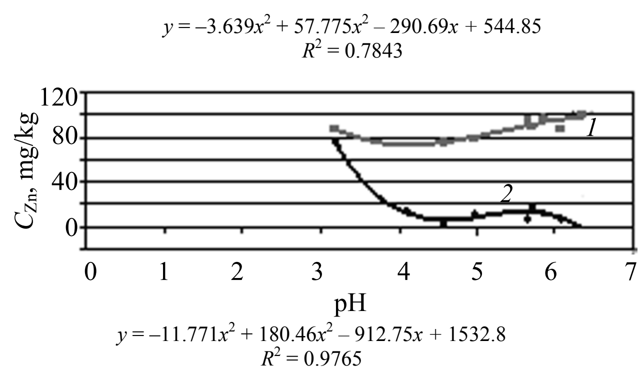

Fig. 7. Plots of (*1*) total and (*2*) mobile zinc concentrations in soils versus pH.

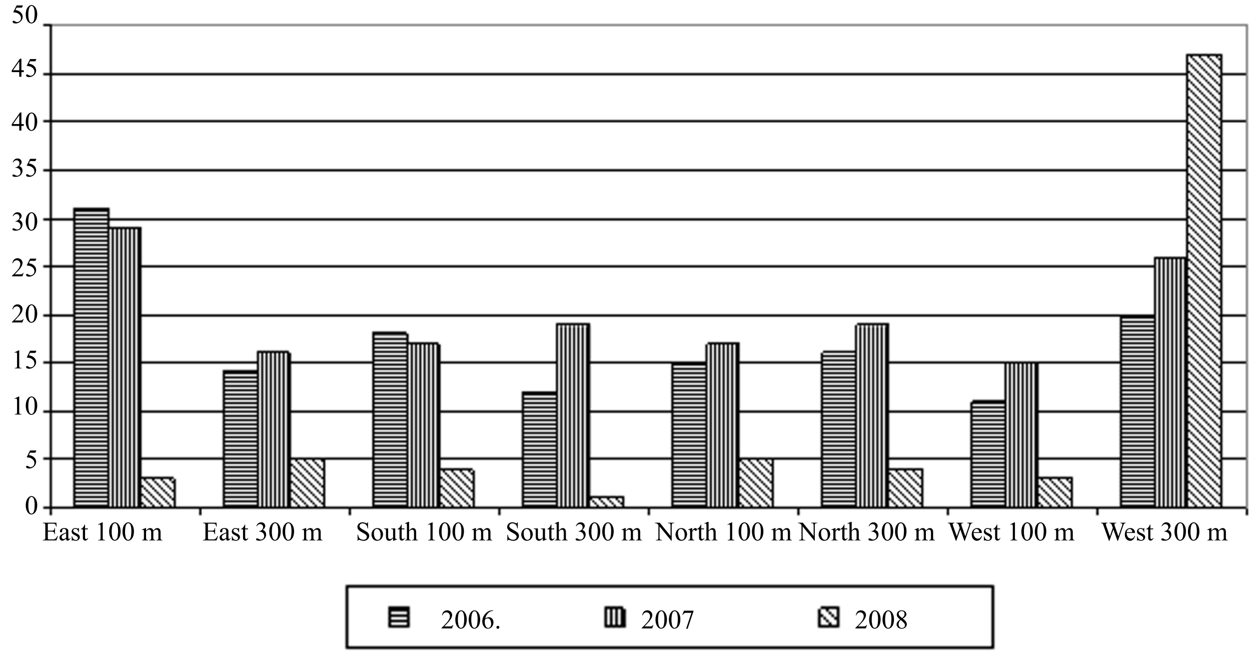

Fig. 8. Total pollution index of anthropogenic soils (0–10 cm) in the area affected by the placer gold-concentrating plant of the former Sofiiskii gold placer.

the environmental situation can be estimated as critical, which is confirmed by bioindication methods (pollen sterility and growth tests). A correlation was found between the anthropogenic soil pollution level (evaluated by mobile heavy metals) and cytogenetic changes of plant cells (bioindicators).

Heavy metals migrating from wastes to soils and vegetation favor pollution of residential soils, accumulate in agricultural products grown in the affected zone, and thus enter into human organism, which leads to environmental diseases, e.g., for the population of Sofiiskii gold placer mine, of respiratory organs (57%), locomotor apparatus (11%), and gastrointestinal system (12%).

The results of studies were used as a basis for the development of principles of environmental monitoring (EM) of the areas affected by mineral processing wastes, their disposal, placer gold-concentrating plants, and tailings dumps, as well as of recultivated and contiguous areas, and other actions related to topsoil disturbance. These principles are as follows: (1) degree of exploration of a given area; (2) minimization of the volume of work (selection of areas and placement of a minimum number of observation points therein) and aiming at a definite type of anthropogenic pollution; (3) substantiation of the observation scope and frequency and of the series of typomorphic chemical elements characterizing technogeochemical pollutant flows, their specificity, recommended test media, and methods of analytical studies; (4) consideration of the existing, probable, and future environmental problems arising from operation of mining enterprises and all environmental pollution sources; prediction of possible changes of the state of biosphere components on the basis of the revealed trends.

The procedure for organization of a local environmental monitoring system should include integral analysis of the effects of anthropogenic systems (including mineral processing wastes) and their ranking with respect to the degree of environmental hazard on the basis of environmental assessment of the employed technologies, results of mathematical modeling of pollutant dispersion, field studies of areas affected by mining enterprises, and data on analogous subjects. It should be implemented with the aid of modern geoinformation technologies and model complexes.

The newly created small-scale forecasting environmental map of natural mining systems in gold and tin mining areas and the positions of existing hydrometeorological stations were used as a basis for an including layout version for local environmental monitoring points, and operation technology therein was determined with account taken of anthropogenic geochemical flows generated from gold and tin mining wastes and local conditions [15]. The areas that are subject to environmental monitoring were bounded by the basin boundaries which can be unambiguously identified in topographic maps.

It was found that in the examined region water transfers 60 to 80% of toxic pollutants as dispersed rather than dissolved species. Therefore, to obtain more reliable estimates we propose to include determination of not only total soluble chemical elements but also their dispersed forms [15]. We believe that local environmental monitoring should necessarily include (1) analysis of the dry residue of water, (2) analysis of the dry residue of snow water, and (3) calculation of environmental indices of natural media (concentration coefficients, Kc, bioaccumulation factors, BCF, and total pollution indices, Zc).

CONCLUSIONS

As yet, there is no reliable estimate of the environmental effect of gold and tin mining wastes in the Far Eastern Federal District, and local environmental monitoring therein has not been developed to a sufficient extent. Local studies are isolated and are not aimed at creating a universal system adapted to specific local conditions. The level of anthropogenic load determined on the basis of estimation of the environmental effect of gold and tin mining wastes indicates that the environmental situation in the region under study may be regarded as critical.

It has been proposed to use small-scale forecasting environmental map of nonferrous and rare metal mining areas as a basis for local environmental monitoring of biosphere components. Principles of the first step of environmental monitoring have been developed with account taken of specificity of anthropogenic flows generated as a result of gold and tin mining.

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