Methods of Estimation of Influence of Man-Caused Chemical Contamination of the Atmosphere on Forest-Swamp Complexes in Oil-Producing Regions of West Siberia

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Abstract

Methodical problems and results of analysis of influence of atmosphere pollution on forest-swamp complexes of the taiga zone of West Siberia are considered on the example of emissions of ecologically harmful chemical compounds released during combustion of casing head gas in torches installed in the territory of petroleum-gas deposits. The analysis was carried out using a comprehensive approach based on combination of the sanitary-hygienic and landscape-geochemical methods. A quantitative estimate of the dimensions of the area of landscape units contaminated with discharges of soot and nitrogen dioxide into the atmosphere, depending on the burning gas volume and on the threshold level of atmosphere pollution, is given. The studies were carried out using the data on air contamination obtained on the basis of ecological certificates of petroleum deposits in the oil production territory.

INTRODUCTION

Solution of the problems of estimation of man-caused influences on the natural environment is nowadays hindered not only by the practical absence of ecological monitoring systems as sources of operative and reliable information about the current state of the environment, but also due to insufficient development of methodology of estimating the influence of chemical atmosphere pollution on the natural environment [1, 2]. The most difficult is taking into account the influence of aerosol atmosphere pollution because of its complex and multi-component nature.

The purpose of the present study is to develop methodology of ecological estimation of man-caused influences on the example of influence of the oil-producing industry on the natural environment.

ANALYSIS OF THE STATE OF ENVIRONMENT IN OIL-PRODUCING REGIONS

An analysis of the state of environment in the territories of activities of oil-and-gas complex shows [3, 4] that the factors influencing the natural environment may be subdivided into three main groups. The first group includes mechanical influences which violate the surface and change the hydrological regime. In application to the conditions of activities of the oil-and-gas complex of Siberia, the change of hydrological regime as a result of construction of roads and pipelines should be regarded as one of manifestations of mechanical influences. Being objects of geological environment, causeways exert their influence during a long time. As a result, replacement of some ecosystems by different ones can take place, *e.g.* due to rise of ground waters or drying [5]. The second group includes geodynamic influences [6] arising due to changes of reservoir pressure as a result of extraction of large volumes of petroleum and gas, which lead to geomorphological changes. An example of such geomorphological changes may be the catastrophic collapse of Earth surface that occurred due to a long-term exploitation of the large Wilmington deposit (California, the USA) which caused destruction of buildings and transport roads [7].

The third group is formed by factors of chemical contamination of air, soils, water bodies and soil-ground waters [3]. From the viewpoint of soil and water contamination two factors are of great importance: influences of spill oil and salt contamination linked with overflows of reservoir waters which mineralization degree may exceed by hundreds of times the background value, and chemical pollution of subterranean waters as a result of the ubiquitously increasing use of chemical additions for heightening recoverable oil. The influence of spill oil has been studied most of all [8, 9] and it is usually limited in time and space. So, *e. g.*, in swamp ecosystems with a high sorption activity the effect of petroleum products is limited to tens of meters from the boundaries of the oil patch. More mobile and aggressive are salt contamination caused by overflows of reservoir waters with mineralization of as much as 40 g/l, which exceeds by 400 times the background level [10]. Therein, the very dangerous chloride-sodium salinization is most often, and there are already data on the change of swamp water composition at considerable distances from oil-and-gas field. Salt contaminations of high concentration (over 100 mg/l) lead to impoverishment of species composition and simplification of structure of forest ecosystems [5].

Very aggressive and dangerous agents of chemical contamination are the products of combustion of casing-head gas in flare installations scattered all over the territory of the West Siberian petroleum-gas deposit province. Their hazard is linked with the cumulativeness of effect and "remoteness" of biological consequences, including those expressed in drying of forests which can become manifest only in several years when the concentration of soot and other toxic compounds reaches dangerous values (which seems to take place in spruce forests of the Agan ridges in the vicinities of the Samotlor deposit).

A comparative analysis of the above described factors of negative influence of oil production on the forest-swamp complexes of West Siberia has demonstrated [11] that the most important of them has to be considered the pollution of the atmosphere resulting from combustion of casing-head gas in flares around which extended tails of aerosol contamination are formed, which effect is manifested at long distances from the sources of discharge of contaminants. This negative effect is increased by fine dispersion products of incomplete combustion that have strong toxic properties. When gas is burnt in torches, large volumes of carbon oxide (II), soot, nitrogen dioxide and hydrocarbons are released into the atmosphere [10, 12].

Aerosol pollution, as a rule, spreads over tens of kilometers from the emission source. In [13], results of long-term airborne studies of atmospheric aerosol are presented on the basis of wich a map (Fig. 1) of spatial distribution of countable concentration of aerosol contamination of the atmosphere in the territory of West Siberia has been drawn up.

As one can see in Fig. 1, the spatial nonuniformity of distribution of aerosol concentration is characterized by two zones of abnormal pollution in the territory of West Siberia.

Formation of the southern zone situated in the Novosibirsk Region may be linked with the activity of the industrial centers of the south of West Siberia. As the analysis of the chemical composition of aerosols has shown [13], this zone, just like the anomalies in the region of Ekatherinburg, is characterized by connection with emissions of enterprises of metal working, electrotechnical and metallurgic industry. According to [13], hydrocarbons are prevalent in the composition of aerosol of the anomaly formed in the vicinities of Nizhnevartovsk, which permits to link the origin of this anomaly with the activity of oil production enterprises. Really, in the region of Nizhnevartovsk – Strezhevoy, as one can see in Fig. 1, *a* large number of petroleum deposits is concentrated, including the larg-

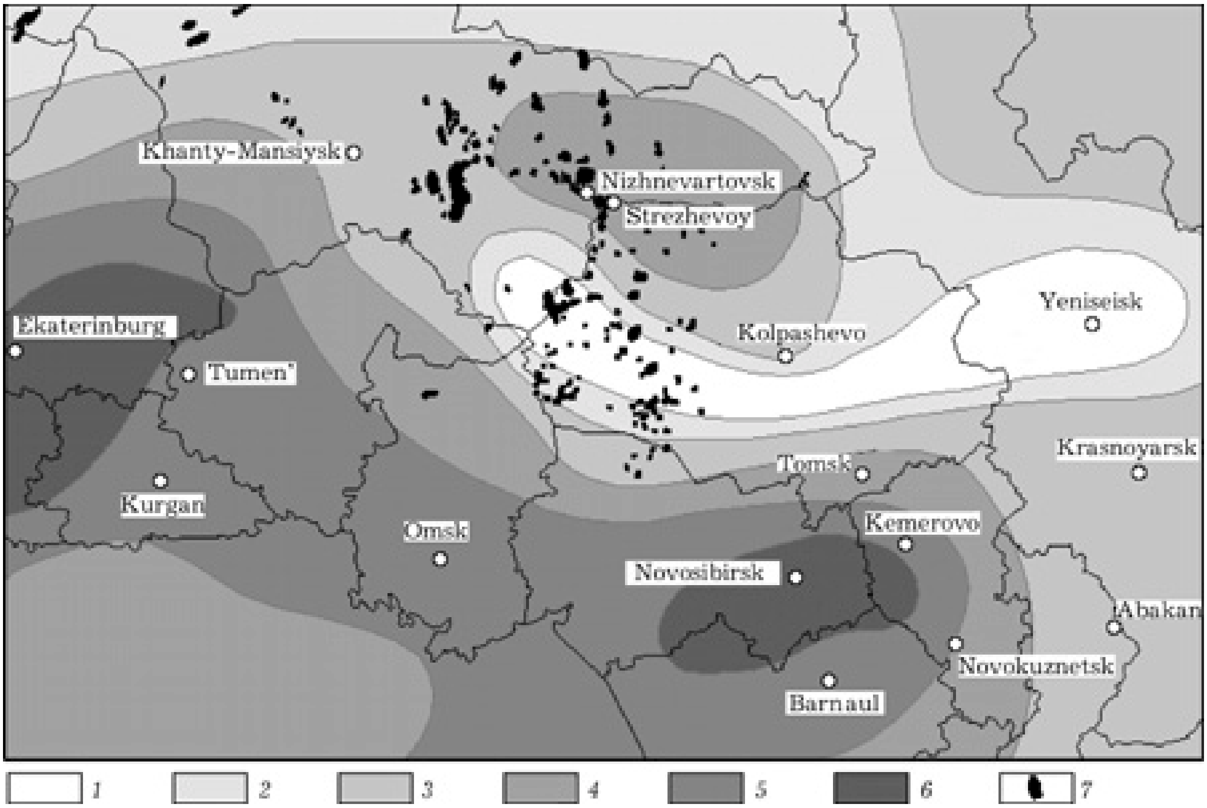

Fig. 1. Distribution of countable concentration of aerosol in West Siberia: 0–5 (*1*), 5–10 (*2*), 10–20 (*3*), 20–30 (*4*), 30–40 (*5*), > 40 cm^{-3} (*6*); 7 – deposits.

est of them – the Samotlor deposit in which in 1980, according to [14], as much as 150 million tons of petroleum per year was extracted.

INFLUENCE ON VEGETATION

One of the main consequences of the influence of atmosphere pollution on the natural environment are acid rains arising as a result of human economic activities accompanied by emission into the atmosphere of large volumes of sulphur, nitrogen and carbon oxides which bring about acidification of surface and ground waters and soils. At the same time, acidification of soils by nitrogen acid rains stimulates development of forest pests.

Soil acidification has some negative consequences, such as liquidation of nitrogen-fixing bacteria, poisoning of earthworms, desorption of nutritious substances, damage to mycelium and roots of plants. All this results in disturbance of supply mechanisms and deficit of nutritious compounds, which, apart from the direct injury, leads to decrease in plant viability. The negative effect of acidification is enhanced by supply of heavy metals from the air, because in acid media the ions of heavy metals that have got into the soil from the air conserve their mobility and can be assimilated by plant roots [15].

Soil acidification is considered as one of the main causes of shrinkage of forests of the moderate zone of the northern hemisphere, and this can manifest itself in many years, even after the cessation of harmful acid emissions into the atmosphere. In the territory of West Siberia spruce-fir forests suffer most of all. The direct influence of acid deposition leads to disturbances in evaporation processes from the surface of leaves and in photosynthesis due to destruction of chlorophyll. Visually, the results of this influence can be detected by browning of leaves and coniferous needles and formation of necroses.

Indirect influence is manifold: contamination play the role of triggering mechanisms of biological and biochemical processes weakening the plant, inhibiting its growth, increasing its susceptibility to climatic changes. In particular, the plant becomes less resistant to frosts and pests – fungi, bacteria, beetles *etc.* [16, 17].

Let us give a brief characteristic of harmful effects of certain chemical compounds of the atmosphere on plants.

Nitrogen dioxide is very dangerous. It is known that when it gets into higher layers of the atmosphere, it participates in destruction of the ozone layer of the Earth, in the presence of steam it forms nitric and nitrous acids, which leads to formation of acid deposition. As it is noted in [18], photochemical transformations of nitrogen dioxide are accompanied by formation of free oxygen radicals which react with hydrocarbons with formation of peroxides having toxic properties, and ozone. The latter retards photosynthesis in plants and weakens them, which results in a decrease in plant biomass. Interaction of nitrogen dioxide with hydrocarbons results in formation of photochemical smog.

It is known that pollution of the air environment by soot leads to disturbances in respiratory systems of plants. Coniferous forests suffer most of all, because the soot clogs the respiratory stomata of needles, which results in shrinkage of forests.

The interaction of carbon monoxide with plants is not quite clear. A certain part of CO is assimilated by means of the assimilation apparatus of plants. No negative influence of this compound on plants has been found. However, there have been observations that in the presence of carbon monoxide, negative effect of other pollutants, *e. g.* sulphur anhydride, is intensified. The major part of CO seems to be transformed into carbon dioxide or fixed by soil bacteria [19].

According to [20], groups of plants may be arranged, according to the degree of sensitivity to phytotoxic gases, as follows:

1) mosses, lichens and fungi;

2) coniferous forest species (dark conifers are the most sensitive);

3) deciduous forest species;

4) grassy plants.

Estimation of the influence of pollution on woody species is of the greatest interest for us. The majority of coniferous species are more sensitive than deciduous ones to the influence of harmful gases, because gases act longer on multi-annual coniferous needles than on leaves which fall off every year. Among conifers, the less susceptible ones are the larch that changes its needles every year, and other light coniferous species in which the needle change cycle under usual conditions is 3–4 years. Dark conifers change their needles at a period of 5–7 years.

Shortening of life span of coniferous needles under the conditions of pollution has been noted by many authors. The clearest and most widely described symptoms of pollution are necroses. In Siberian spruce they arise when the growth of needles is completed, in the form of yellow-brown spots, and sometimes they cover at once large areas of needles surface. In the zone of complete degradation of forest stands, the needles die off in 2–3 weeks after the appearance of necroses [21]. Pine conserves its damaged needles longer than spruce does and, despite the cessation of growth, is more viable even if only one-year needles have remained. Spruce loses the damaged needles more rapidly, which leads to dying off of the tree. Some researchers note that the degree of air pollution at which pine falls out of forest stands only initiates the dying-off of pine. Fir is still more sensitive to the effect of gases [22]. According to [23], the permissible average daily nitrogen dioxide concentration for coniferous plants is 0.03 mg/m^3, and for deciduous plants is 0.05 mg/m^3. In [24], the following permissible maximal concentrations for plants as a whole are given: nitrogen dioxide – 0.02 mg/m^3, carbon monoxide – 1.0 mg/m^3.

ESTIMATION OF INFLUENCES OF ATMOSPHERE POLLUTION ON THE NATURAL ENVIRONMENT

In modern practice, estimation of the influence of man-caused contamination of the atmosphere on the natural environment is based on the use of public health standards of MPC type. Thus, in expertise of building projects, 0.05 of maximum allowed concentration (MAC) [25]. However, such a formal approach to estimation of influence on the landscape sphere with its total biological diversity does not take into account the reaction of living organisms to air pollution and is therefore not substantiated.

In our opinion, a combination of public health and landscape-geochemical [26] approaches is promising to estimate the changes of the state of natural environment under the condition of man-caused influences. However, such a comprehensive approach requires the use of large volumes of cartographic and other quantitative information about the state of components of the natural milieu, which is practically impossible without the use of geoinformation systems (GIS) and GIS technologies [27, 28]. In this regard, the main purpose of the present work is to study the degree of pollution of various (forest, swamp) landscapes by discharges into the atmosphere in the oil production territories of West Siberia using the developed geoinformation approach [29] to ecological forecasts based on combination of public health and landscape-geochemical methods.

The essence of such a comprehensive approach to analysis of influence of oil production on the natural milieu consists in superposing on a landscape map the set of zones of environment pollution by emissions from various sources and estimating, using GIS, the size of landscape areas found under the influence of negative oil production factors, which makes it possible to detect the components of natural environment that are in critical condition. The use of GIS technologies which permit carrying out a combined spatial analysis of landscape structure of the territory and of results of the modeling of environment pollution using numerical maps simplifies the solution of problems of ecological forecast and permits solving complicated tasks of estimation of complex influences on the environment and operatively detecting the incipient abnormalities and taking measures for their elimination.

The questions of cartographic support of ecological forecast are of special importance for implementation of the mentioned comprehensive approach. Since the zone of activities of petroleum extracting enterprises in the taiga zone of West Siberia includes the lands belonging mainly to forest reserves, it is necessary, when drawing up a landscape map of the territory, to be based on forest management materials.

Another important aspect is the definition of are pollution zones and the forecast of the dynamics of their changes as the petroleum extraction will increase (or decrease). In our works [30, 31], computer means for definition of pollution zones based on the use of public health standards and on simulation of diffusion of contaminants in the atmosphere by the method OND-86 according to the nature protecting practice assumed in this country were described. These means permit also making forecasts of the dynamics of development of these zones based on taking into account the plans of economical development of industrial enterprises. As the experience of use of these means has shown [32, 33], they are convenient for computerized implementation with the help of GIS technologies, which makes it possible, by means of overlaying the outlines of pollution zone on the landscape map, to determine the relative area of landscape elements exposed to contamination.

For calculation of relative area of landscape units that get into the contamination zone, a special program in the language Avenue has been developed. It combines the set of standard GIS functions and is triggered by pressing a button added to the ArcView interface. The program calculates the area of the territory of each landscape unit found in the contamination zone, and then the relative area in terms of percentage of the complete area of the landscape unit or of the key site. The calculation results are displayed successively on the screen and then presented in a tabulated or graphic form.

CHARACTERISTIC OF THE KEY SITE

The destiny of the man-caused getting into the atmosphere and influencing the plants, soils and water bodies depends both on the nature of the very man-caused products and, in a considerable degree, on the landscape-geochemical situation. Under some conditions, the man-caused products are stored for a long time and a ccumulated in amounts exceeding the sustainability of the natural system, are actively included into the biological circulation and affect either negatively or positively the living organisms. Under other conditions, quantitatively and qualitatively the same man-caused products are easily processed by some natural objects, decomposed within certain time intervals, undergo chemical transformations, lose their toxicity, and are scattered over large space, which results in a decrease in their concentration to safe levels [34].

For the studies, we chose a territory in the south-eastern part of the West Siberian oil-gas-bearing basin within the limits of the Vasyugan group (Pervomayskoye, Olenye, Lomovoye, West-Katylga, Katylga and Lontyn-Yakh) of oil fields of the Tomsk Region. This part of the territory referred to as the pilot territory (PT) herein below is characterized by a high hydromorphism, low bioclimatic potential values, a weak resistance of ecosystems to external influences and a poor capacity for recovery. The landscape structure of the PT territory has been formed by progressive swamping in the central part of the watershed plains and by the draining activity of not numerous rivers and brooks. In the territory of the PT with the area of 12.8 thousand km^2, three types of natural complexes are detached: swamps, swamped forests, and automorphic forests. A map of the landscape structure of the PT is shown in Fig. 2.

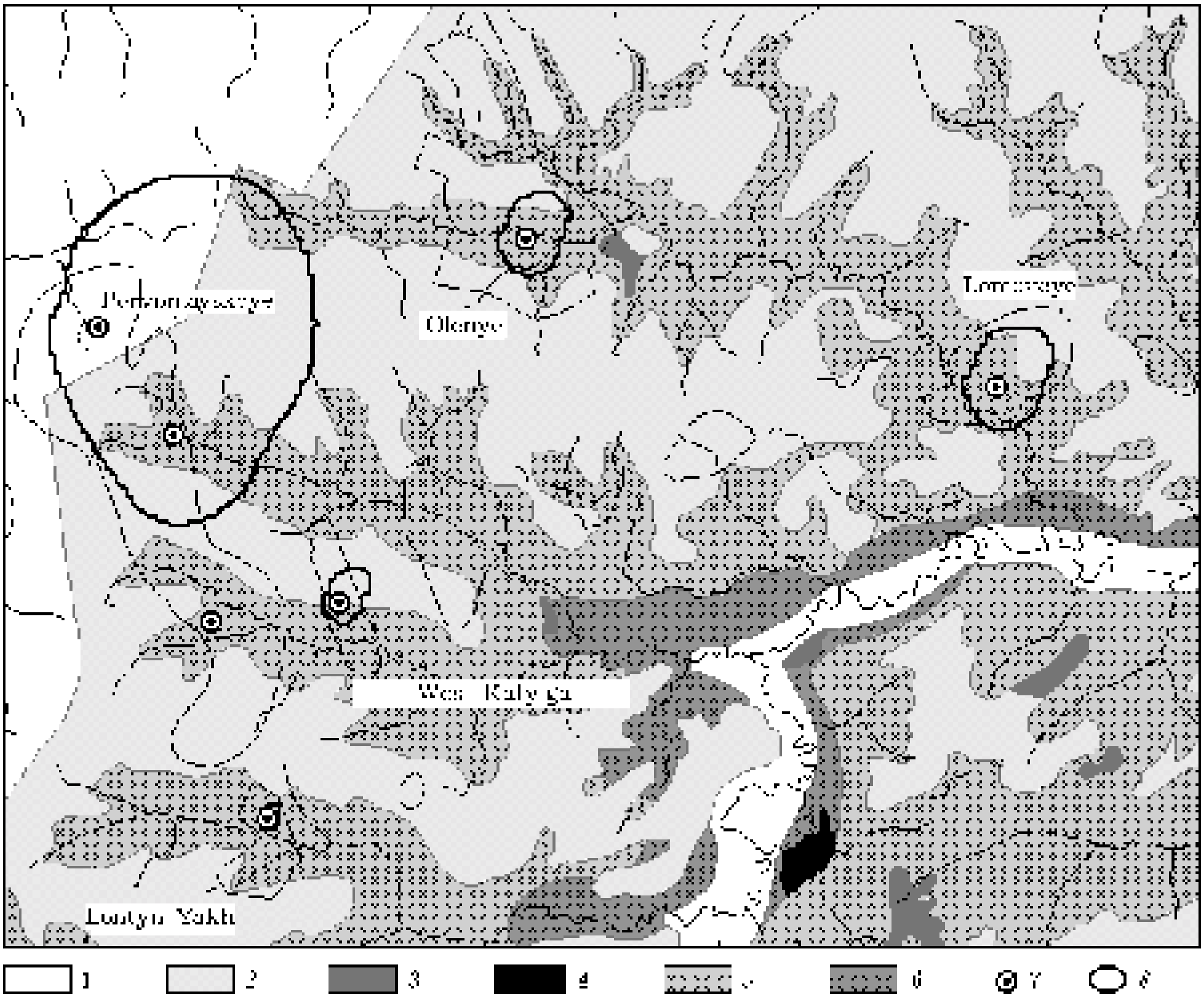

Fig. 2. Landscape map of the pilot territory with overlayed contamination zones: *1* − floodplain of the Vasyugan river; *2–4* − high bog (*2*), transitional bog (*3*), low bog (*4*); *5,6* − dark coniferous small-leaved forest (*5*), pine forest (*6*); *7* − flares; *8* − borders of contamination zones.

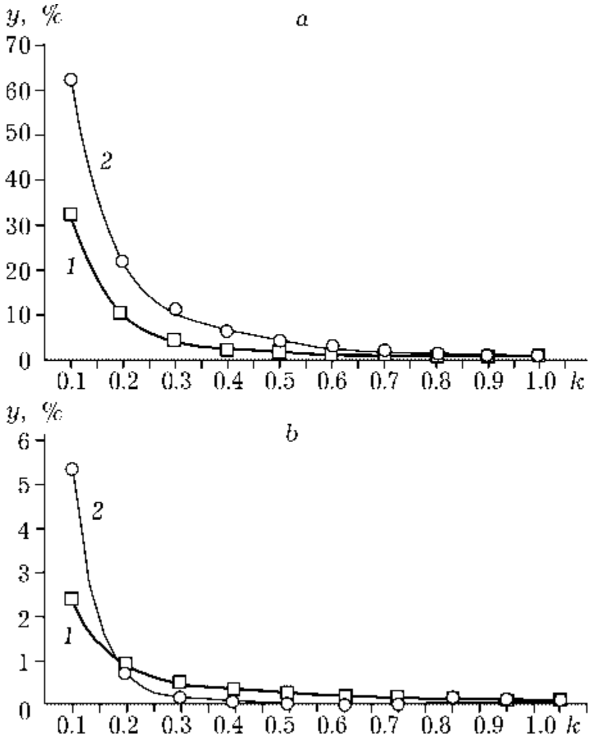

Fig. 3. Dependence of the relative area of contamination of landscape elements on the level of atmosphere pollution (in MPC fractions) by soot (*a*) and nitrogen dioxide (*b*): *1* – dark coniferous small-leaf forest, *2* – from high bog.

Swamp landscapes occupy more than 45 % of the pilot territory. These are mainly large high bogs flowing together into one massif. The peripheries of the massifs are occupied by transitional bogs, and low bogs are attached by small outlines to river valleys. The power of the peat deposit is 8–9 m. A high water impounding, absence of a pronounced superficial run-off and a weak bearing capacity of the ground are characteristics of all swamp types.

Swamped forests are attached to wide outskirts of bog massifs, occupy up to 25 % of the area (by the pilot territory) and are represented mainly by pine, pine-cedar and cedar sphagnum forest types. These landscapes have a complicated, often mosaic, structure which is determined by mutual penetration of forest and swamp landscape elements. Due to frequent fires, as much as 60 % of area of indigenous hydromorphic forests is occupied by secondary small-leaf forests and young forest stands.

Automorphic indigenous small-leaf dark coniferous (most often birch and birch-cedar) forests are attached to the most drained surfaces – riverbanks and are also strongly altered by fires and human economical activities.

In the territory of PT, at present several deposits are functioning. During the time of exploitation of the largest of them – Pervomayskoye oil field, considerable changes in the landscape-geochemical situation have already taken place. Both in the waters and in the soils in the zone of influence of this deposit, the content of compounds dangerous to biota has increased. The soil content of heavy metals and petroleum products exceeds the background values.

Both in the main production facilities (drilling sites, pipelines, torches and furnaces) on all deposits, and under the conditions of auxiliary facilities (boiler houses, welding posts, repair shops and automobile stations), the lists

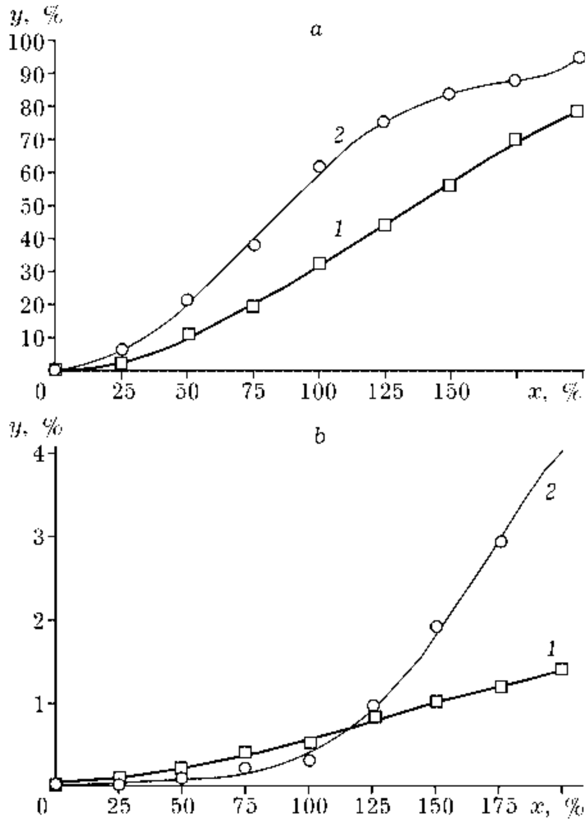

Fig. 4. Dependence of the relative area of soot-contaminated landscape elements on the volume of petroleum extraction at the contamination level of 0.1 (*a*) and 1 (*b*) MPC. *1* – dark coniferous small-leaf forest, *2* – high bog.

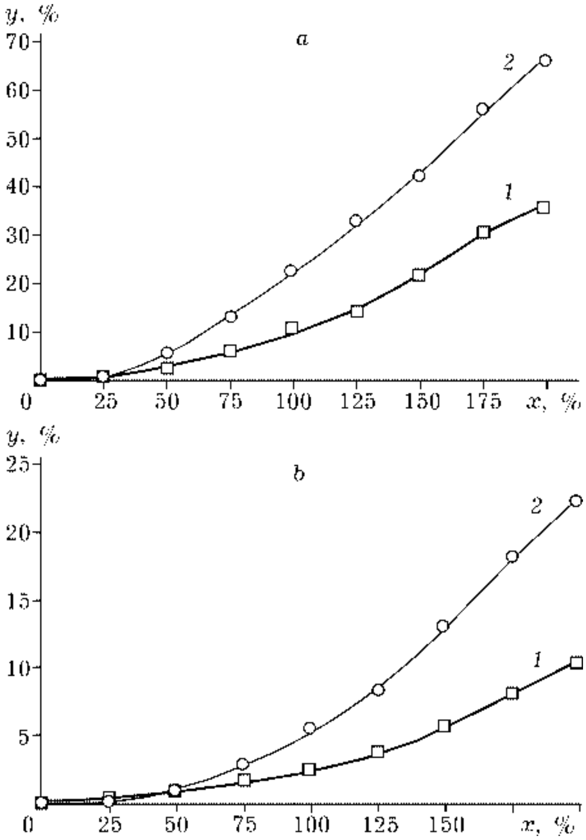

Fig. 5. Dependence of the relative area of landscape elements contaminated by nitrogen dioxide on the volume of produced oil at the level of 0.05 (*a*) and 0.1 (*b*) of MPC: *1* – dark coniferous small-leaf forest, *2* – high bog.

of chemical contaminants discharged into the atmosphere and water bodies and onto the landscapes are enormous. Thus, by the data of ecological certificates of deposits in the territory of PT, the following contaminants are emitted into the atmosphere: soot, hydrocarbons, nitrogen, carbon and sulphur oxides, manganese and its compounds, silicon compounds, fluorides *etc*.

RESULTS OF GEOINFORMATION ANALYSIS

On the basis of taking into account the volumes of emission from all the torches in the territory of PT, the area of nature elements found in the zones of atmosphere pollution was estimated. For contamination levels of 0.05, 0.1, 0.5 and 1 (of MAC) for various landscape types, the ratio of the area of pollution by soot or nitrogen dioxide emissions of a landscape element to its total area (y) and to PT area (z) depending on the atmosphere pollution level and on the volume of burnt gas was calculated.

Dependence on the pollution level

The results of calculation of the relative area of polluted landscape elements depending on the level of atmosphere pollution (in MPC fractions) are presented in Fig. 3 from which one can see that the dependence of the relative area (y) of polluted landscape on the contamination level (k) can be approximated rather well by a polynomial of 6th order which has the form of

$$y = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 \quad (1)$$

where $a_0, a_1, a_2, a_3, a_4, a_5, a_6$ are the coefficients of the polynomial.

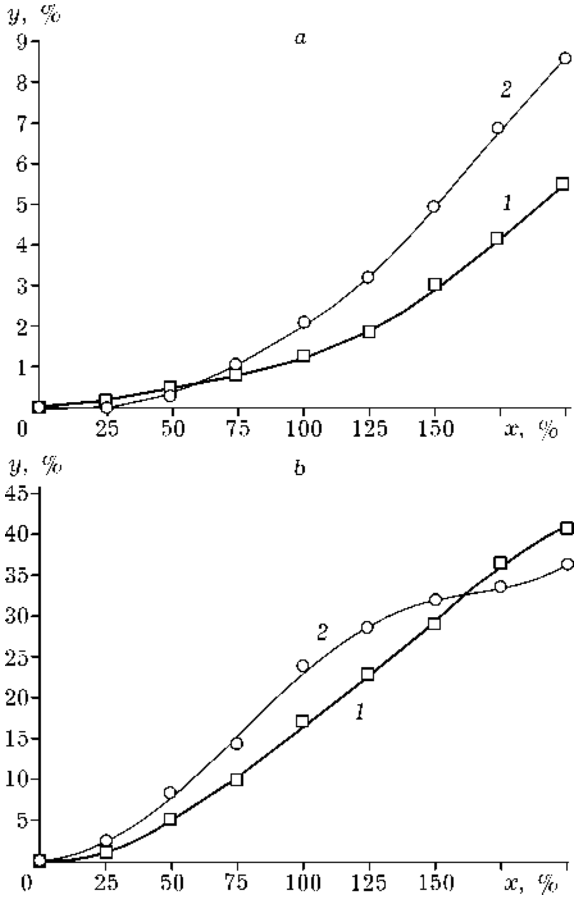

Fig. 6. Dependence of the relative area of landscape elements contaminated by nitrogen dioxide (*a*) and soot (*b*) on the volume of burned casing-head gas at the pollution level of 0.1 MPC: *1* – dark-coniferous small-leave forest, *2* – high bog.

Dependence on the volume of petroleum extraction

In Fig. 4, the dependence of the relative area (y) of landscape elements contaminated by soot on the volume of burned casing-head gas (x) is presented.

The dependence obtained is well approximated by a polynomial of 5th order:

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 \quad (2)$$

where a_0, a_1, a_2, a_3, a_4, a_5 are coefficients of the polynomial.

In Fig. 5, the results of calculation of the area of nitrogen dioxide-polluted landscape elements depending on the volume of burnt gas are shown.

The treatment of the results demonstrates that at a contamination level corresponding to MPC and at the current volumes of emissions the zones of nitrogen dioxide pollution are localized in the territory of oil field. As one can see in Fig. 5, the dependence of the relative area of contaminated landscape element on the level of burnt casing-head gas, like in the previous case, can be approximated by a polynomial of 5th order having the form of eq. (2).

In Fig. 6, the dependence of the relative area (z) on the volume of burnt gas at the pollution level of 0.1 of MPC is shown. Like in the previous case, such a dependence can be approximated by a polynomial of 5th order.

CONCLUSION

Atmosphere pollution due to emission of chemical compounds in burning casing-head gas on oil fields exerts a noticeable influence on the state of forest-swamp complexes in oil production regions of West Siberia. The effect of pollution on the functioning and viability of coniferous trees is more considerable than on those of deciduous species. Therein, dark coniferous forests, in particular spruce and pine, which occupy an important place in the species composition of forests of the taiga zone of West Siberia, are more vulnerable. As it has been noted in numerous studies of biologists, in atmosphere contamination zones the abundance of coniferous needles in the tree crown diminishes and their life span becomes shortened, dying-off of branches of different orders is accelerated and, as a result, the wood increment is decreased. For a quantitative evaluation of the area of air contamination zones, a geoinformation methodology of calculation of forest-swamp landscapes based on mathematical simulation of diffusion of contaminants in the atmosphere and on the use of landscape cartographic or air-space information has been developed. The developed methodology can be applied to solution of problems of optimal deployment of oil-producing enterprises and to estimation of permissible volume of burned casing-head gas or oil production.

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