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Ecological Risks of Oil Contamination in the Arctic Zone

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Abstract

In solving the ecological problems caused by the contamination of the Arctic shelf with oil products, the application of satellite images is relevant. These images allow monitoring observations of the state of oil-producing territories and timely revelation and evaluation of the risks of oil pollution in hard-to-reach and fragile tundra and marine ecosystems. On the basis of remote and land-based imaging data, the zones under the risk of oil pollution were mapped over the territory of the Kolguyev island. The ecological state of soils and coastal waters of the island are considered. A technology for the purification of oil-polluted regions with the application of aboriginal psychrophilic microflora stimulated by nutritive mineral substrates is proposed.

Keywords: satellite images, the Arctic zone, the Barents Sea, subsea and terrestrial oil pipelines, oil spills, oil pollution, hydrocarbons, microflora, tundra soils.

INTRODUCTION

In connection with increased demand for hydrocarbon raw materials and the worked-out state of the continental deposits, special attention is paid to new efficient methods of exploration and development of the mineral raw material basis of the oil and gas complex in the Russian shelf of the Arctic region [1]. At present, oil and gas producing complexes are built and brought into operation in the regions with a high concentration of commercial hydrocarbon resources [1, 2]. For example, the oil and gas producing complex of the Pechoromorskiy and Yuzhno-Barentsevskiy regions include oil pools of the Prirazlomnoe, Severo-Medynskoe, Severo-Gulyaevskoe, Varandey-More, Pomorskoe, Dolginskoe and Peschanoozerskoe deposits with hydrocarbon resources estimated as 600–700 mln t [3, 4].

Continental Arctic deposits are characterized by severely depreciated field equipment, corrosion and technological defects of pipelines, which causes ecological risks at the territories of oil production. In the regions of stationary offshore platforms, the sea and coastal regions are subject to oil pollution during tank ship loading and unloading and in the cases of accidents at subsea pipelines [5].

The application of satellite images (SI) in solving ecological problems is relevant because they allow monitoring observations of the state of oil-producing territories of the Arctic. Mapping of the areas of vegetation distribution, its classification, evaluation of the disturbed land areas, deciphering oil spillage over land and sea, and identification of the operating flare installations are performed with the help of SI [6, 7]. Under modern conditions, the methods of the detection of oil pollution over sea surface were improved with the help of radar and satellite images MODIS, Landsat 8, Sentinel within different wavelength ranges [8, 9]. Ecological risks are evaluated, and simulation models are built up to calculate the volumes and areas of water pollution with oil [10, 11].

The northern deposits Peschanoozerskoe and Tarkskoe are situated at the island of Kolguyev in the Barents Sea at 70° northern latitude [12, 13]. The island, with its overall territory of

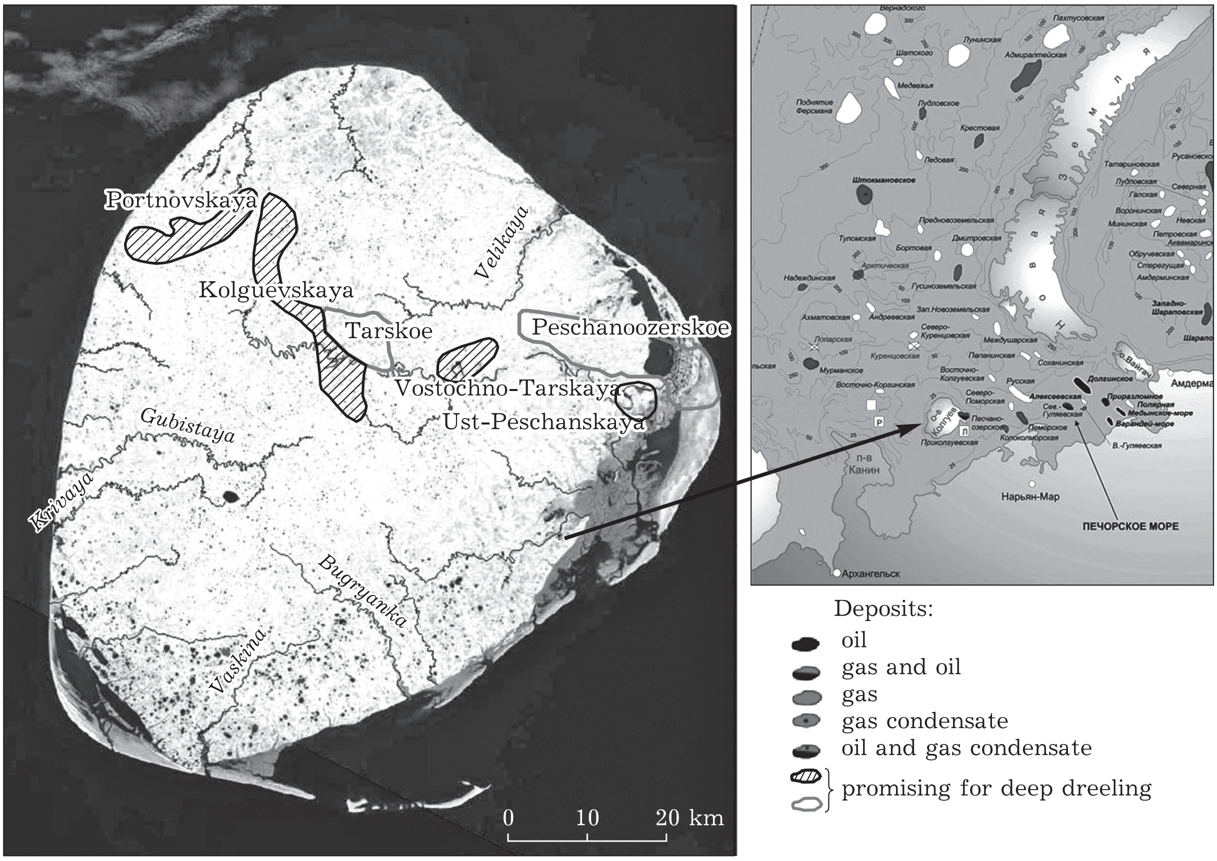

Fig. 1. Shelf deposits of the Barents Sea [14] with the Landsat 8 satellite image of the territory of the island of Kolguyev.

5121.6 km^2, with unique nature, tundra landscapes and offshore strips, is situated in the south-eastern region of the Barents sea (Fig. 1). According to landscape classification, the island of Kolguyev is a lacustrine alluvial valley with outwash and biogenic lake and boggy deposits. Loamy soil, peat and sandy soil are prevailing. The island is amenable to pollution with oil and oil products during the loading and unloading of oil tankers, as a result of accidents at subsea and land oil pipelines and at the field oil-producing equipment [15].

The goal of the present work was to reveal the zones of ecological risk of the contamination of the island of Kolguyev with oil on the basis of remote and land-based data; to develop an ecologically safe method of recovering oil-polluted regions with the help of aboriginal microflora.

EXPERIMENTAL

The Peschanoozerskoe oil and gas condensate deposit belongs to the Timan-Pechora oil and gas-bearing province [12]. Oil production by Arktikneft company was 31 thousand tonnes according to the data for 2014 [13]. The physicochemical composition of oil samples is presented in Table 1. Oil is light, with low content of sulphur, resins and asphaltenes.

Application of satellite images

In the work, we used the images accessible on the Internet: SI Landsat 8 taken on 11.07.2017 and MCD43A4 product of 22.09.2013. The following zones at risk of water and land area pollution with oil and oil products at the island of Kolguyev were revealed with the help of GIS technologies using SI and the data of land-based survey:

1. Polluted zone around Bugrino settlement with the adjacent shallow water region.

2. The zone of oil pollution in the sanitary protective belts of industrial objects.

3. The zone of the pollution of near-shore water area by oil products in the Barents sea.

Laboratory studies

In 2014, the samples of oil-polluted soil were collected in the field survey over the coast line

TABLE 1

Properties of oil samples from the Peschanoozerskoe deposit

Density, g/cm^3	Viscosity at 20 °C, mPa · s	Content, mass %				Coking capacity, mass %
		Paraffin	Resin	Asphaltenes	Sulphur	
0.7684	5.03	–	1.25	–	–	–
0.7713	–	–	1.28	–	–	–
0.7951	–	–	0.90	–	–	–
0.8366	–	9.00	3.61	0.67	–	–
0.7758	2.07	3.02	1.23	–	0.04	0.14
0.7760	2.17	4.60	0.53	–	0.10	–
0.7872	–	–	–	–	0.13	–
0.8260	–	2.35	4.03	–	0.35	–
0.8080	5.27	3.50	2.83	0.72	0.13	–
0.7684	–	–	1.25	–	–	–

Note. Dash means the absence of data.

near the settlement of Bugrino. Physicochemical and microbiological analyses of these samples were carried out.

Active strains of microorganisms tolerable to low temperatures were isolated from the soil samples. The taxonomic attribution of pure cultures was made on the basis of morphological signs by means of microscopy, saccharolytic properties were assessed according to the reference data. A medium with increased NaCl content (50 g/dm^3) was used to determine the halophilic properties of the strains under study.

Biodestruction processes were carried out for 60 days at a temperature of +10 °C by the isolated strains of microorganisms on the liquid Muntz medium and in oil-polluted soil with the natural microflora. To stimulate destruction processes, Destructive processes were stimulated with the nutrient substrate: 1 % solution of ammonium nitrate with the addition of 0.1 % $MgSO_4$ solution.

The concentration of initial and residual oil was determined using the gravimetric method. The extracted oil was analyzed by means of IR Fourier transform spectroscopy. Sample spectra were recorded within the range 400–4000 cm^{-1} in the thin layer using a Nikolet 5700 IR Fourier spectrophotometer with a Raman unit (Thermo Electron Corporation, USA).

Characteristic parameters for the comparison of oil biodegradation degrees are relative values – spectral coefficients calculated from the ratio of the optical densities (D) of absorption bands in a definite region of the IR spectrum. Biodestructive changes in spectral coefficients and the group composition of oil were calculated according to the data of IR spectroscopy. The results confirm the catalytic activity of microflora. Table 2 presents spectral coefficients: the degrees of aromaticity (C_1), aliphaticity (C_2), branching (C_b) and oxidation (C_o) of oil hydrocarbons. These coefficients depicting the enzymatic activity of bacteria were determined according to the procedure described in [16]. For example, the degree of aromaticity C_1 is calculated as a ratio of the optical absorption bands at 1600 and 723 cm^{-1} ($C_1 = D_{1600}/D_{723}$). The absorption band at 1600 cm^{-1}

TABLE 2

Spectral coefficients of oil samples under investigation

Oil samples under investigation	Spectral coefficients			
	C_1 (D_{1600}/D_{723})	C_2 ($D_{1465}+D_{1377}/D_{1600}$)	C_p (D_{1377}/D_{1465})	C_o (D_{1700}/D_{1465})
Reference (pure oil)	0.25	4.33	0.24	0.06
After destruction by bacterial association in soil	1.35	7.28	0.59	1.28
After destruction by the bacteria of *Pseudomonas* genus	0.96	5.27	0.51	0.85

corresponds to the stretching vibrations of C=C bonds in aromatic structures, while the band at 723 cm^{-1} characterizes the methylene group $(-CH_2-)_n$ in paraffin hydrocarbons containing methylene chains with $n > 4$.

Analysis of individual acyclic saturated hydrocarbons was carried out by means of chromatographic separation. Some biomarkers determining the degree of destructive changes in the composition of hydrocarbons were calculated.

RESULTS AND DISCUSSION

The indicated zones at the risk of oil pollution over the land and coastal territories of the island of Kolguyev were mapped schematically (Fig. 2). Oil and oil product spillage events occur periodically in the risk zone around Bugrino settlement with the adjacent shallow water territory of 2.5 km^2 during the transportation to the settlement from the Peschanoozerskoe deposit for communal needs (see Fig. 2, point *3*). For example, according to the data reported in [15] on 18.09.2004, a pontoon with 50 t of diesel fuel sank as a result of an accident in shallow water near the island of Kolguyev.

The concentration of pollutants in soil samples under investigation was determined to be within the range of 18–57 g/kg. Screening of collection cultures isolated from soil helped us to determine the strains of microorganisms, which were the representatives of *Acinetobacter*, *Pseudomonas*, *Bacillus* and *Rhodococcus* genera. *Bacillus* genus is distinguished by special diversity: it includes up to 6 species. Destruction in the liquid medium resulted in the most efficient oil utilization in the experiment with the association of microorganisms and strains of *Pseudomonas* and *Bacillus* cultures.

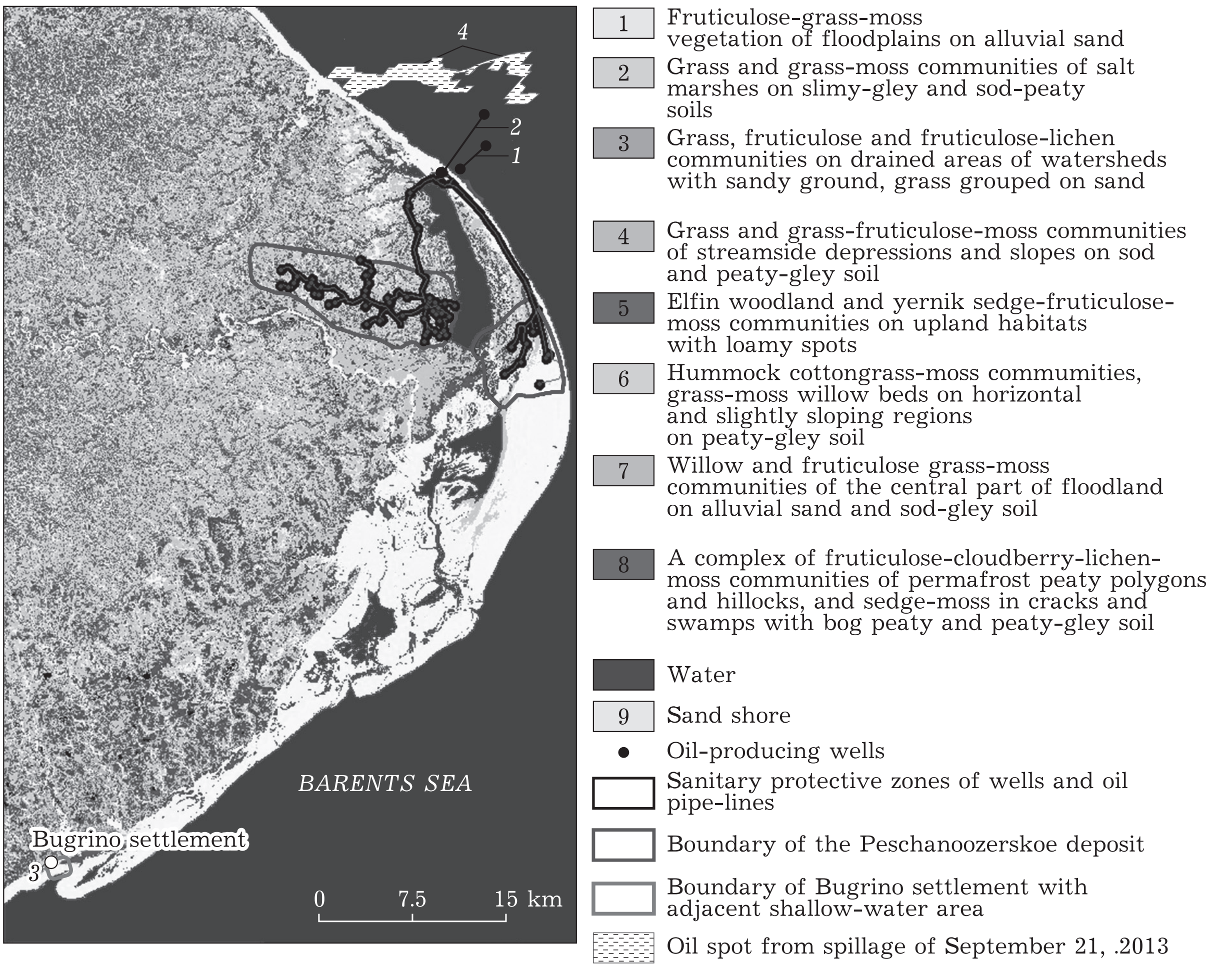

Fig. 2. Map of the vegetation cover of the island of Kolguev with the zones of ecological risk of the pollution with oil and oil products. Designations: *1* and *2* – underwater oil pipelines; *3* – site of land-based studies, soil sampling; *4* – oil spot resulting from spillage on the September, 21, 2013.

Relying on the use of aboriginal microflora, the authors developed the method for remediation and recovery of oil-polluted soil with the application of mineral stimulating substrates. The use of aboriginal oxidizing microflora allows us to conserve the natural soil biocenosis of northern latitudes [17]. The remediation of oil hydrocarbons accounted for 36–60 % at low temperature (+5 °C). An increase in the coefficients of aromaticity (C_1) and aliphaticity (C_2) after biodestruction in contact with the association and with the separate pure culture promotes the manifestation of psychrotolerant and halophilic properties, which points to the active biodestruction of alkanes and aromatic hydrocarbons (see Table 2). An increase in the branching coefficient (C_p, the ratio of methyl to methylene groups) is the evidence in favour of the destruction of hydrocarbons containing methylene groups. An increase in the oxidation coefficient (C_o) confirms the enzymatic activity of the isolated cultures in biodestruction processes under the conditions of low temperature and increased mineralization.

The quantitative analysis of the utilization of different hydrocarbon fractions at a low positive temperature showed that the most active decomposer is the association of bacteria, with which the oxidation coefficient C_o reaches 1.28. In the case when the pure culture of *Pseudomonas* genus is used, C_o is lower and equals 0.85 (see Table 2).

The area of the zone at risk of oil pollution over the sanitary protection belts of industrial objects related to the Peschanoozerskoe deposit was determined to be 31 km^2 (see Fig. 2). According to the regulations, the sanitary protection zone (SPZ) at both sides of an oil pipeline is 100 m, around oil-producing wells it is 300 m, and for reservoirs, it is 150 m [18, 19]. According to the data related to 2015, the number of wells drilled at the Peschanoozerskoe deposit is 64, among them there are 24 producing wells, 7 pumping wells, and other wells are either under conservation or abandoned. Within the boundaries of SPZ of the wells, the concentrations of oil products were found to be higher than the maximum permissible concentration at 5 sites (out of 24). A very high degree of pollution with oil products was detected in the ground of oil sumps and around the tanks at the sites of boreholes – the values exceeded 5000 mg/kg in seven cases (the MPC of oil and oil products in the soil is 1000 mg/kg). However, at the background regions of the island, the content of oil products is 7–230 mg/kg [20].

At the water area around the island, two underwater pipelines are situated at a depth of 14 and 18 m, which are used to charge tanks with the tonnage up to 30 000 t. This enhances the risk of seawater pollution (see Fig. 2, points *1* and *2*). With the help of remote data obtained with MCD43A4 (recorded on 22.09.2013), an oil spot was mapped to the north of the sea oil-loading terminal of the Kolguyev island (see Fig. 2), its area was about 20 km^2. Indeed, as reported in [21] on September 21, 2013, about 200 L of diesel fuel was spilt into the sea as a result of an accident. By September 26, 2013, the sea had cleaned itself in that spill site. The size of the oil spot and its self-dissolution are determined by mixing with the wind, insolation and air temperature. According to the data of the meteorological station at the island of Kolguyev, since September 21 to 26 the wind was mainly of the eastern direction, with the average velocity of 12 m/s, and the air temperature was 5 °C. The modulus of the average flow velocities in the Pechorskoe Sea was 2.6–4.8 cm/s to the north-east (30 to 70°) and characterized water carry-over in the direction of the Pomorskiy strait – Kara strait [22].

In general, without an accidental oil spill, the total content of oil products in the surface layer of water in the Pechorskoe sea is lower than the MPC (50 μg/L). These waters are characterized as the waters with weak pollution with oil products [23].

CONCLUSION

The zones of ecological risk of oil pollution over the territory of the island of Kolguyev and the water area around it were mapped on the basis of the remote and on-land data. The highest level of oil pollution relates directly to the territory of oil mining at the Peschanoozerkoe deposit. However, the coastal zone of the island is frequently contaminated as a result of accidents (for example, spillage during the transportation of diesel fuel in 2004 and 2013). As a result of the analyses of oil-polluted soil under the conditions of low temperature, the microflora possessing prychrotolerant and halophilic properties was isolated and used as the basis of the biopreparation for recultivation of oil-polluted soil under low-temperature conditions and increased mineralization. We recommend using ammonium nitrate-containing nitrous biogenic substrates to intensify oil degradation processes.

The proposed technique with the application of remote and land-based data allows us to reveal the zones at ecological risk of oil pollution over the Arctic territories and to build up the plans for prophylactic and recultivation measures.

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