Hydrodynamic model of an oil spill on the Earth's surface and the use of expert technologies in its implementation to assess pollution methods

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Abstract. A volumetric model of accidental oil spills on the land surface was developed, based on numerical methods for solving hydrodynamic equations, and taking into account the processes of oil spreading over the surface, its filtration into the soil and evaporation into the atmosphere. Based on the results of calculations using the hydrodynamic model for the most probable scenarios of oil spills, it is possible to obtain an estimate of the spatial-temporal scale of the spill, which, together with data on the terrain and the presence of water bodies, is the input data for the expert model. Based on the joint use of the hydrodynamic model of the oil spill and expert technologies, the territory of the Nenets Autonomous Okrug and the South Khylchuyu-Varandey oil pipeline were zoned in more detail. It makes it possible to predict the scale and areas most susceptible to negative impact in the event of an accidental oil spill, and to make the necessary decisions for the location of the spill response facilities, as well as the facilities themselves, already at the stage of selection and design of the pipeline route.

1. Introduction

Despite notable progress in ensuring the safety of production and transportation of oil and oil products, as practice shows, completely trouble-free operation of oil transport infrastructure facilities, and especially oil pipelines and oil product pipelines, is impossible. Thus, according to the Ministry of Energy of Russia, 10 544 cases of breakthroughs occurred in 2015 on the oil pipelines of the Russian Federation, in 2016 - 9599, in 2017 - 9472, in 2018 - 8126. The shortage of oil for this reason amounted to 68; 125.4; 58; 54.9 thousand tons, respectively. Thus, for the period 2015-2018, the average volume of oil spilled per spill was 8.1 tons. The main cause of accidents in 90-92% of cases is corrosion of oil pipelines. According to the Ministry of Natural Resources, in 2016, 6 emergencies occurred at the enterprises of the fuel and energy complex, in 2017 - 1, in 2018 - 8 [1, 2].

In the works of M. Fingas, the following statistics are presented [3, 4]. On land pipelines, the amount of oil spilled has been steadily decreasing, for example, in the United States for the period from 1998 to 2007. by 35% in comparison with 1988-1997, and by 75% in comparison with 1968-1977, nevertheless, about two hundred accidents are recorded annually. At the same time, an average of 11,000 tons of oil per year enter the environment, i.e. about 55 tons per bottling. These are significant enough values to cause significant damage to the environment, albeit at the local levels, especially for the polar tundra region considered in the work, which is characterized by high vulnerability.

An oil spill on a land surface is a complex phenomenon in which many physical and chemical processes can be observed. The most important, from the point of view of assessing the potential damage to the environment, are: spreading over the surface, filtration into the ground and evaporation from the
surface of the oil film [5]. The spreading process is determined, first of all, by the surface topography, as well as by the physical properties of the spilled oil. For the filtration process, the most important are soil properties, such as oil capacity and percolation rate, characterized by the filtration coefficient. Some types of soils can absorb up to half of their own volume of oil, depending on their properties. When calculating the amount of oil film evaporated from the surface, it is necessary to take into account the characteristics of the environment, such as the temperature of the underlying surface and air, wind speed, as well as the properties of the fluid - temperature, viscosity.

Despite the available work devoted to various models of oil spills on land, there are no complex, ready-to-use models based on hydrodynamic equations. Regulatory documents in this case give a rough estimate, not taking into account many factors. In turn, the issue of modeling oil spills on the water surface of the Arctic shelf has been worked out quite well [6-10, etc.). The physical and chemical processes occurring during spills on land and on the water surface differ significantly from each other, so the use of these developments is impossible.

The aim of the study is to develop a hydrodynamic model of oil spills on the land surface, based on finite difference method for solving hydrodynamic equations, taking into account the processes of oil spreading over the surface, its filtration into the ground and evaporation into the atmosphere. The task of taking into account such important parameters as the slope of the surface and the presence of reservoirs near the source of pollution was solved using expert assessments (technologies). As an approbation of the developed model of oil spreading, the territory of the Nenets Autonomous Okrug (NAO) was zoned and, in more detailed resolution, the Yuzhnoye Khylchuyu - Varandey oil pipeline was carried out in terms of the scale and degree of negative impact on the natural environment caused by possible emergency oil spills in the polar tundra.

Zoning is an important method of zoning territories on specific grounds. Its application in the problem of assessing the degree of negative impact on the natural environment from oil spills makes it possible to present a large array of calculation results in a form that is convenient for perception and analysis. Assessments of the scale and degree of negative impact on the natural environment from possible oil spills are necessary, first of all, for planning actions to eliminate the consequences, namely, for the selection of locations for the location of means for their elimination. On the other hand, these estimates can be used in the design of oil industry facilities to select the most favorable conditions in terms of minimizing potential damage to the environment.

2. Materials and methods

The oil infrastructure of the Nenets Autonomous Okrug is located in its eastern part, in Fig. 1 shows a diagram of its main objects. The largest is the Varandey Coastal Reservoir Park, located near the coastline of the southeastern part of the Barents Sea. The total length of the oil pipelines shown in the diagram is 1265 km, this calculation does not take into account the presence of several branches on one oil pipeline, as well as some small, under construction and projected oil pipelines.

Based on the types of vegetation growing in the polar tundra, it can be argued that, an oil spill on land will cause significant damage, destroying most of it at the spill site. It is also exacerbated by long-term natural regeneration of fragile tundra ecosystems. It should be noted that the lichen of reindeer moss growing on this territory forms the basis of the forage base for reindeer husbandry. This lichen is vulnerable to anthropogenic impact, as it grows at a very slow pace, increasing in height by several millimeters per year, so an accidental oil spill can cause significant damage to the local agricultural industry, which is based on reindeer husbandry.
Based on the analysis of soil maps, it was concluded that the most common types of soils here are peatlands with different layer thickness and degree of decomposition. A characteristic feature of this territory is the presence of local unevenness of the relief with a width and length from several tens of centimeters to several tens of meters (hummocky and hilly tundra, polygonal swamps). In peat soils in summer, the depth of seasonal thawing is about 1 m. In this region, permafrost can serve as a barrier to oil penetration into the soil. Thus, the harsh climate, high water cut and other features of natural conditions, as well as the fragility of the ecosystems of the polar tundra are complicating the initial conditions of the modeling process.

From a mathematical point of view, for the problem of modeling liquid spreading over the surface, there are solutions with varying degrees of simplification, which is achieved mainly by reducing the dimension of the space under consideration. The three-dimensional formulation of this problem is practically not used due to its high computational complexity. Proceeding from this, as well as from the high complexity of the described physical and chemical processes (multicomponent composition of oil, heterogeneous soil structure), it can be concluded that to assess the spatial and temporal scales of oil pollution on the land surface, a model based on hydrodynamic equations is needed, with the possibility of using empirical dependence evaporation rate. Another conclusion that follows from this is that one cannot focus only on analytical solutions of equations, since this requires significant assumptions to the original equations. Despite the available works devoted to various models of oil spills on land, there are no complex, ready-to-use models based on hydrodynamic equations.

For the development of a hydrodynamic model of oil spills on the earth's surface, the main processes occurring during spills are considered: spreading and evaporation of oil, filtration of oil into the ground. The main equation of the model has the following form (a one-dimensional version of the equation was first proposed by L. S. Kuchment [11]):

$$\frac{\partial h}{\partial t} = \text{div}(D \text{ grad } h) + Q,$$

(1)

where \( t \) is time, \( x, y \) are spatial coordinates, \( h = h(t, x, y) \) is the thickness of the oil film, \( D = D(h) \) is the function that determines the velocity of fluid propagation, \( Q \) is the function of the source and sinks, which has the following form:

$$Q(t, x, y) = Q_1 - Q_2 - Q_3,$$

(2)
where Q1 is a point source that determines the oil flow rate from the pipeline; Q2, Q3 are runoffs representing oil losses from filtration into the ground and evaporation, respectively.

The filtration of oil into the ground is described using Darcy’s law, which, when applied to this problem, is as follows:

$$v = k \left( 1 + \frac{ρgh}{p_0} \right),$$  \hspace{1cm} (3)

where $v$ is the speed of oil penetration into the ground, m/s; $k$ - filtration coefficient, m/s; $h$ is the thickness of the oil film on the soil surface, m; $p_0$ - atmospheric pressure, Pa; $g$ - acceleration of gravity, m/s$^2$; $ρ$ - oil density, kg/m$^3$.

The filtration process is limited by the ability of the soil to absorb oil - oil capacity, which in turn depends on its moisture content and porosity. The filtration coefficient for various types of soils was determined in accordance with the data [12, 13]:

In addition, a laboratory experiment was carried out to determine the intensity of oil evaporation, according to the results of which for oil with a viscosity of 3.545 cSt and a density of 813.9 kg/m$^3$, empirical dependences of evaporation and viscosity on time were obtained [14]:

$$E = 2.28 + 0.91 \cdot \ln(t + 0.008),$$ \hspace{1cm} (4)

$$\mu(t) = \mu_0 + 3.559\sqrt{t}$$ \hspace{1cm} (5)

where $E$ - volatility, %; $t$ - time, day; $\mu$ - oil viscosity, cSt; $\mu_0$ - oil viscosity at the initial moment of time, cSt.

The process of oil evaporation is described using an empirical dependence for each specific oil composition, since it is a multicomponent liquid and its evaporation rate depends on the unique fractional composition.

The main equation of model (1) is approximated by a finite difference scheme, as a result of which a system of linear algebraic equations is solved at each iteration of the algorithm by splitting it into a block matrix. Deliberately unattainable wall boundary condition for horizontal area were used for solving equation (1). Which calculated from contamination source parameters before it. Oil losses from filtration and evaporation are calculated as effluents. The script calculation algorithm is implemented as a console application in the C / C++ programming language.

It should be noted that the developed computational algorithm is applicable only in the case of a horizontal surface, at the same time, the model equations can be used for an arbitrary surface. When assessing the potential hazard of an oil spill, it is important to consider such important factors as the slope of the surface and the presence of water bodies near the potential source of the spill. Their inclusion in the hydrodynamic model presents significant difficulties associated with the solution of the system of differential equations. Therefore, in this study, this problem was solved with the help of expert assessments (technologies), consisting in determining the influencing factors, assigning weight coefficients to them, and then calculating the integral indicator of the environmental hazard of potential pollution [15].

The territory of the NAD was divided into squares with a side of 30 km, each of them corresponded to the values of the predicted area of pollution, the average slope of the surface, the prevalence of rivers and lakes. The weighting factors for these indicators, and the total indicator of the degree of negative impact of oil spills on the environment itself, is calculated using the following formulas:

$$a_j = \sum_{i=1}^{n} k_i p_{ij}; \quad k_i = \frac{n_i}{\sum_{i=1}^{n} n_i},$$  \hspace{1cm} (6)
where \( a_j \) - total hazard indicator in the square with number \( j \), points; \( k_i \) is the weighting factor of the \( i \)-the factor; \( p_j^n \) - normalized value of the indicator of the factor with the number \( i \) in the square with the number \( j \), points; \( i = 1 \ldots n \) is the number of factors; \( j = 1 \ldots m \) is the number of grid squares; \( n_i \) - sequence number of the factor, starting from the end (\( n_4 = 1, n_1 = 4 \)). The values of the weight coefficients obtained by this formula are equal to: 0.4; 0.3; 0.2; 0.1 for the predicted area of pollution, the average slope of the surface, the prevalence of rivers and lakes, respectively.

The indicator of the predicted contamination area is calculated using the developed hydrodynamic model; for its calculations, it is necessary to assign values of such properties to each type of soil as: permeability, maximum oil penetration depth, maximum and minimum oil capacity. These properties mainly depend on the type of soil. From the point of view of assessing damage from oil spills, only the upper soil layer up to 30-50 sm thick is important. In many tundra soil types, this layer is represented by peat of varying degrees of decomposition and a gley horizon. Since the latter has low permeability, it serves as a barrier to oil penetration into the depths. Based on this, the various soil types were grouped into 8 groups. In each square of the grid, taking into account [16], from one to three prevailing soil types belonging to one of the eight formed groups were determined. Each of them was assigned a significance factor (1/3, 1/2, 2/3, 1) based on the occupied area share within the square, which is necessary for further calculation of the weighted average indicator of the predicted oil spill area in each square.

To avoid the influence of the source characteristics on the impact on the environment, the simulation results were averaged over two oil spill scenarios, which differ in the size of the breakthrough in the oil pipeline - 1.4% and 100% of its cross-sectional area, and the expiration time - 12 hours and 10 minutes, respectively. Both of these scenarios correspond to a 130 m³ oil spill, which, taking into account the average oil density, corresponds to 108 tons. This volume is accepted as one of the most likely scenarios for oil spills in this region, taking into account the most common diameter of oil pipelines and average pumping rates through them. In addition, the calculation results for each group of soils were averaged according to two more scenarios - with the minimum and maximum oil capacity indicators, in order to avoid the influence of such a variable indicator as moisture. Based on this, as well as the characteristics of oils produced in this region, calculations were carried out on the developed hydrodynamic model according to 4 scenarios for each of the 8 soil types. Their characteristics used in the calculations and the averaged results obtained are shown in Table 1.

### Table 1. Characteristics of soil types and the results of model calculations for a 108 ton oil spill, averaged over 4 scenarios for each soil type.

| Cipher | Soil type                                      | \( k_0,D \) | \( h_{pr}, m \) | \( v_{min} \) | \( v_{max} \) | \( S, m^2 \) | \( V_f, \% \) | \( h, sm \) |
|--------|-----------------------------------------------|-------------|----------------|--------------|--------------|--------------|--------------|-------------|
| A      | Floodplain swampy and acidic                  | 1           | 0.05           | 0.05         | 0.15         | 2401         | 9.3          | 4.9         |
| GPR    | Arctic and stony polygons; mountainous primitive | 1           | 0.1            | 0.05         | 0.3          | 2337         | 31.0         | 3.8         |
| GTT    | Tundra gley peaty, peaty and peaty-humus; tundra surface-gley | 5           | 0.05           | 0.05         | 0.3          | 2393         | 16.2         | 4.5         |
| GTP    | Arctic tundra humus-gley, slightly gleyed and humus | 5           | 0.1            | 0.1          | 0.3          | 2328         | 35.6         | 3.5         |
| PBT    | Tundra podburs                                 | 5           | 0.2            | 0.1          | 0.4          | 1988         | 62.6         | 2.2         |
| PGT    | Peat and peat-podzol-gley; gley-podzolic; podzols gley peaty and peaty | 7.5         | 0.2            | 0.1          | 0.4          | 1942         | 61.8         | 2.3         |
| POMG   | Podzols                                       | 5           | 0.1            | 0.1          | 0.4          | 2255         | 42.2         | 3.2         |
| TP     | Peat boggly; peaty and peaty-gley boggly      | 10          | 0.3            | 0.1          | 0.3          | 1832         | 70.8         | 1.9         |
Note: $k_0$ - permeability; $h_{pr}$ - maximum depth of oil penetration into the ground, m; $V_{min}$, $V_{max}$ - minimum and maximum oil capacity of the soil; S is the maximum area of contamination in 24 hours, m$^2$; $V_f$ is the volume of oil absorbed into the soil in 24 hours,%; $h$ is the average thickness of the oil slick after 24 hours, cm).

The area of contamination, after 24 hours after the start of the spill, varied from 1800 to 2400 square meters, which corresponds to a circle with a diameter of 48 to 55 meters, respectively. The average thickness of the oil film is from 2 to 5 cm, which is consistent with the existing methods for calculating the area of pollution [17-18], where this indicator is used as the initial data for calculating.

The obtained values of the predicted area of pollution were assigned to each square, as a weighted average according to the proportion of the grid cell occupied by different soil types. On the basis of this, a diagram of the distribution of the predicted area of contamination during a spill of 108 tons of oil was obtained (Fig. 2).

Figure 2. Scheme of distribution of the average area of contamination during a spill of 108 tons of oil in the Nenets Autonomous Okrug.

The topography of the area during oil spills is important, as it characterizes the places where oil accumulates and can increase the area of potential contamination. In this article, the average slope of the surface, calculated on the basis of altitude data, is used as its indicator. In each square, diagonals were drawn, the heights of which were taken with a resolution of 500 m, after which the average slope of the surface was calculated based on 80-85 points with elevation data for each square. This indicator is derived from the terrain map and is necessary to adapt the data about it to the available computational grid.

The NAD is characterized by a developed hydrographic network, which contains a large number of rivers and lakes, the largest of which is the Pechora river and lake. In terms of potential damage to the natural environment, the presence of water bodies is an indicator of its increase. So, when oil enters the river, pollution can spread over a significantly greater distance, while its entering the lake also increases the damage to the environment, but to a lesser extent, due to less water consumption, or its complete absence. For this reason, rivers and lakes should be considered as two separate factors.
In this work, we calculated the prevalence rates of rivers and lakes, expressed in terms of the area of water bodies to the area of the territory on which they are located. For small rivers and streams, the area in each square was calculated based on their total length and average width. Since the width of small rivers varies in a significant range, for definiteness, this characteristic is taken equal to 10 m. For medium, large rivers, their areas were directly calculated. The calculations were performed using GIS technologies on a grid with a cell size of 30 by 30 km. For lakes, the density indicator was used - the ratio of their total area to the area of the grid cell, expressed as a percentage. Oil entering the lake will increase the damage to the natural environment. Despite the fact that the density of oil is less than the density of water, when its light fractions evaporate, it can precipitate. Anthropogenic pollutants, including oil, tend to accumulate in the bottom sediments of lakes [19], and in certain cases can serve as secondary sources of environmental pollution.

3. Results

Fig. 3 shows the results of the regionalization of the territory of the Nenets Autonomous Okrug according to the degree of impact of oil spills on the natural environment, in the form of a schematic map with oil pipelines and large objects of oil infrastructure marked on it. The score is expressed using a verbal five-point scale with exposure levels ranging from very low to very high.

![Figure 3. Zoning of the Nenets Autonomous Okrug territory in terms of the degree of negative impact of oil spills on the environment.](image)

Territories with the following combinations of factors correspond to a very low level of impact: a low predicted area of pollution, the absence of medium and large rivers, a small total area of lakes or their absence. Very high - the maximum predicted area of pollution, the presence of large rivers or a high total area of lakes. Territories with the same factors as of a very high level, but with lower indicators, or with absent medium and large water bodies, but with a high predicted area and slope of the surface have a high level of impact.

As can be seen from Fig. 3, the most affected fate occurs in the area near the Pechora River and some large lakes in the eastern part of the Nenets Autonomous Okrug, and the least in its southwestern part. While the bulk of the oil infrastructure is located east of the Pechora River and the regional capital,
Naryan-Mar, this zone contains both low and high impact areas. The largest oil transshipment point, Varandey Onshore Tank Farm, is located on the border of medium and high impact levels.

A feature of the developed hydrodynamic model for assessing the spatio-temporal scale of an oil spill on the land surface during the absence of snow cover is the simultaneous calculation of three main processes occurring during oil spills: oil spreading (diffusion equation); filtration into the ground (Darcy's law); evaporation into the atmosphere (empirical dependence obtained on the basis of the experiment). To assess the spatio-temporal scale of oil pollution on the land surface of the tundra, the parameters of the area and radius of pollution, and their dependence on time, are used.

The task of taking into account such important parameters as the slope of the surface and the presence of reservoirs near the source of pollution was solved using expert estimates (technologies), consisting in determining the influencing factors, assigning weight coefficients to them, and then calculating the integral indicator of the hazard of potential pollution. Based on these results, a conclusion can be drawn about the required location of the oil spill response facilities. So, in the area of the villages of Kharyaginsky and Ardalin, it is enough to locate them only on large objects, while along the Yuzhnoye Khylchuyu - Varandey oil pipeline it is necessary to place additional points.

The considered method is applicable not only to large areal objects, but also to linear ones, such as oil pipelines and other transport routes. And also to local objects of oil infrastructure, such as fields, storage tanks, pumping stations and others. The detail of the applied method depends on the given computational grid. As an example, this method was applied to zoning the route of the South Khylchuyu - Varandey oil pipeline in the Nenets Autonomous Okrug. The total length of the pipeline under consideration is 153 km, it is laid through an area with five different types of soils found in the tundra.

For calculations, the pipeline is divided into 306 sections, each with a length of 500 m. The main differences of the method, in this case, is the calculation of indicators of factors, the average area is replaced by the average radius of the spill, the prevalence and density of water bodies - by their presence near 50 meters from the pipeline or its intersection. There are two categories of water bodies: lakes; rivers and streams. According to these criteria, 39 lakes, 20 crossings of streams and rivers were taken into account. The average slope of the surface is calculated along the line of the pipeline with a resolution of 500 m. For this pipeline, the maximum slope along the route was 6.2%, the average slope along the entire route was 1.0%. For 5 groups of soils, the minimum average radius at the spill of 108 tons found on the pipeline route was 23.9 m, the maximum - 26.8 m.

In fig. 4 shows the results of zoning - a diagram of the distribution of the values of the integral indicator along the route of the oil pipeline and their verbal interpretation. The maximum values of the hazard indicator correspond to the sections of the pipeline with the largest number of water bodies, which fits into the general picture of understanding the damage caused to the natural environment, since the scale of the accident when oil gets into them can significantly increase. The minimum values of the index correspond to areas where there are no water bodies, the minimum slope of the terrain and the smallest predicted area of pollution. On the pipeline under consideration, there are no sections with very low and very high total hazard scores. There are isolated areas with a high level of danger, and are mostly associated with the intersection of the pipeline route with water bodies. In the southwestern part of the pipeline, the average hazard level prevails. In the northeast, it is low, with the exception of the 20 km of oil pipeline closest to Varandey, where, due to the large number of lakes, small rivers and streams, the level rises to average.

Based on the results of applying the proposed method for the Yuzhnoye Khylchuyu - Varandey, located in the Nenets Autonomous Okrug, and taking into account the poorly developed transport infrastructure of the region, it can be concluded that it is necessary to place liquidation facilities not only at the final and starting point of the oil pipeline, but also at its most vulnerable part - the first 100 km from Yuzhnoye Khylchuyu.
4. Conclusion
To assess the spatio-temporal scale of the consequences of an oil spill on the surface of the polar tundra, a non-stationary hydrodynamic model has been developed, which makes it possible to perform a simultaneous calculation of oil spreading based on the hydrodynamic equation (diffusion equation), filtration (Darcy's equation) and evaporation (empirical dependence). The task of taking into account such important parameters as the slope of the surface and the presence of reservoirs near the source of pollution was solved with the help of expert assessments (technologies), which consists in determining the influencing factors, assigning weight coefficients to them, and then calculating the integral indicator of the hazard of potential pollution. To take into account the evaporation process, a laboratory experiment was carried out, according to the results of which an empirical dependence of the evaporation rate on time was obtained for a specific oil composition. The proposed model is based on hydrodynamic equations, has a modular structure and, due to this, has great potential for further addition and improvement. It makes it possible to predict the space-time scale of the consequences of accidental oil and oil product spills, to develop plans on the basis of these assessments for the prevention and elimination of emergency oil spills. The results of modeling and zoning of the territory can be used when choosing the optimal location in terms of minimizing the risk of potential pollution, the location of oil infrastructure facilities and when choosing the location of forces and means to eliminate emergency oil spills, as well as the facilities themselves already at the stage of selecting and designing the route of the oil pipeline. So, in the area of the villages of Kharyaginsky and Ardalin, it is enough to locate them only at large facilities, while along the South Khylchuyu-Varandey oil pipeline it is necessary to place liquidation means not only at the final and starting point of the oil pipeline, but also at its most vulnerable part - the first 100 km from Yuzhnoye Khylchuyu.
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