

Original article

## Simulation of a Fuel Oil Spill Using the Oil-Spill Model *SPILLMOD*

V. V. Solbakov<sup>1, ✉</sup>, S. N. Zatsepa<sup>2</sup>, N. A. Diansky<sup>2, 3, 4</sup>,  
A. A. Ivchenko<sup>2</sup>, E. A. Korshenko<sup>2</sup>, I. I. Panasenkova<sup>2, 5</sup>,  
V. V. Fomin<sup>2, 4, 5</sup>

<sup>1</sup> Federal Research Center “Computer Science and Control”, Russian Academy of Sciences,  
Moscow, Russian Federation

<sup>2</sup> N. N. Zubov’s State Oceanographic Institute, Roshydromet, Moscow, Russian Federation

<sup>3</sup> M. V. Lomonosov Moscow State University, Moscow, Russian Federation

<sup>4</sup> Marchuk Institute of Numerical Mathematics, Russian Academy of Sciences, Moscow, Russian  
Federation

<sup>5</sup> Hydrometeorological Center of Russia, Moscow, Russian Federation

✉ vsolbakov@frccsc.ru

### Abstract

**Purpose.** The aim of the work is to comprehensively analyze the key factors distinguishing the accident involving the *Volgoneft-212* and *Volgoneft-239* tankers in the Kerch Strait on December 15, 2024 from many other spills, namely the fuel oil characteristics, the pollution source features, and the hydrometeorological conditions significant for mathematical modeling.

**Methods and Results.** The oil spill transport was simulated using a set of the *SPILLMOD* mathematical models. An integrated system for operational forecasting of hydrometeorological characteristics (Marine Hindcast and Forecast System, MHFS) including the regional atmospheric model WRF and the Russian marine circulation model INMOM was applied for hydrometeorological forecasts. The conducted assessments have shown that the specific features of the accident and the properties of transported fuel oil resulted in the prolonged fuel oil release from the source. However, 95 % of the tank contents was released within the first few days. During this period the source power decreases by at least two orders of magnitude.

**Conclusions.** The results of simulation performed in the first days after the accident are confirmed by coastal monitoring data. Application of the *SPILLMOD* model made it possible to determine the time and locations of the release of fuel oil pollution into the coastal zone. Subsequent assessments of the intensity of fuel oil spill revealed the fact that the bulk of the fuel oil that entered the sea was brought to the coast and shallow waters in the area from Veselovka settlement to Anapa resort city. The information on time, locations and volumes of fuel oil collected in this area are consistent with the proposed hypothesis on a rapid decrease with time of the intensity of fuel oil release to marine environment, and also indicate the adequate choice and successful application of the selected models, forecasts of hydrometeorological characteristics and calculation systems. The similarity between the density of fuel oil and that of water, its high viscosity and the hydrological characteristics of the Kerch Strait, the Sea of Azov and the Black Sea may result in both positive and negative buoyancy, as well as formation of seabed oil-mineral aggregates when fuel oil is combined with suspended matter and sand. Adequate forecast of the distribution of heavy oil types requires the improved models describing the transformation processes which include sedimentation of the dispersed and floating oil.

**Keywords:** fuel oil spill, Kerch Strait, mathematical modeling, numerical modeling, forecast of hydrometeorological characteristics, hydrometeorological characteristics, marine oil spills, INMOM, *SPILLMOD*, Black Sea

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## Introduction

Emergencies associated with large-scale spills of oil and petroleum products at sea, despite their rarity, pose a serious challenge both to society as a whole and to the agencies responsible for response and remediation due to their severe negative consequences. Such events provide invaluable lessons.

During the storm of December 15, 2024, at the Black Sea entrance to the Kerch Strait, two tankers of the same series, the *Volgoneft-212* (VN212) and *Volgoneft-239* (VN239), were wrecked. Both vessels suffered the same type of structural failure: they broke in two along their frames into separate parts. As a result, at least two tanks on each vessel were breached on one side, and the fuel oil came into direct contact with the marine environment. Three fragments of the vessels subsequently sank and still lie on the seabed; the fourth, after drifting freely, ran aground off the coast of Taman<sup>1, 2</sup>. For brevity, this incident is hereinafter referred to as the “2024 Kerch Strait Fuel Oil Spill” (KSFOS-2024).

More than six months after the accident, several circumstances can be identified. Taking these into account in the future would help reduce the damage caused by similar events. The storm conditions, which were the main cause of the disaster, prevented immediate containment of the spill and recovery of fuel oil from the sea surface [1, 2]. The storm also made reliable detection of the fuel oil slick on the sea surface using satellite remote sensing impossible. The first confirmation of pollution came from the processing of satellite images obtained only on December 18, 2024 [3–5].

During the first few days after the accident, the main beaching events of fuel oil occurred predominantly on the coast of the Taman Peninsula, from Volna settlement to the resort city of Anapa. Later, on the seabed of the coastal zone near Anapa, significant accumulations of fuel oil mixed with sand were discovered, forming so-called oil mats, in some places buried beneath a layer of sand – a phenomenon typical of heavy fuel spills [6, 7]. Fuel oil was also observed off the Crimean Peninsula, in the Sea of Azov, and on the shores of the Kerch Strait, but there were no reports of large-scale beaching. There is also no information indicating that fuel oil was observed in significant quantities along the Black Sea coast over the entire stretch from Anapa to Sochi.

The most extensive beaching of fuel oil occurred on December 17, when the sea surface along the coast was covered by a continuous layer of fuel oil for a considerable distance and the shore was heavily contaminated. Subsequently, although fuel oil strandings were still recorded, they were on a much smaller scale: only individual lumps of fuel oil were observed, possibly lifted from the seabed by wave action. The stern section of the VN239, which had run aground off the Taman coast, was for some time not regarded as a source of pollution;

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<sup>1</sup> Rostransnadzor, 2025. [Review of Accidents Involving Ships at Sea and on Inland Waterways of the Russian Federation for 2024]. Moscow: Federal Service for Supervision of Transport, 22 p. [online] Available at: <https://rostransnadzor.gov.ru/storage/Госморречнадзор/Анализ%20состояния%20аварийности/Обзор%202024.pdf> [Accessed: 15 August 2025] (in Russian).

<sup>2</sup> Rostransnadzor, 2025. [Collection of Typical Accidents Involving Ships at Sea and Transport Incidents on Inland Waterways of the Russian Federation that Occurred in 2024]. Moscow: Federal Service for Supervision of Transport, 90 p. [online] Available at: <https://rostransnadzor.gov.ru/storage/Госморречнадзор/Анализ%20состояния%20аварийности/2024.pdf> [Accessed: 15.08.2025] (in Russian).

however, after January 10, substantial fuel oil leakage from this part of the vessel was detected.

Prediction of the spread of oil pollution at sea based on mathematical (numerical) modeling serves as an important source of information for management decisions during oil spill response and is also an integral part of the monitoring system for the accident area. The diversity of physicochemical properties of oils and petroleum products, their weathering processes, and range of possible hydrometeorological conditions make every spill unique.

At present, there is a limited number of publications devoted to the fuel oil spill under consideration [3–5, 8–11]. Studies [3–5, 8, 9] devote considerable attention to the analysis of satellite information; study [10] analyzes the physicochemical transformation of fuel oil based on the results of field surveys; and study [11] presents the findings of field investigations of the coastline. Only references [9, 12] provide the results of modeling of fuel oil spread.

The development of methods and methodology for predicting the spread of oil and petroleum products in the marine environment during accidental spills has a long history. The main methodological approaches of Russian practice are set out in the handbook [13]. International experience and progress in this area are described in [14], which was funded under the Gulf of Mexico Research Initiative (GoMRI) following the Deepwater Horizon (DwH) accident. In [15], “oil” models from the perspective of describing oil transport and weathering are analyzed. In [16], an attempt to compare oil spill forecast systems (the authors call them models) is made. Considerable attention is given in [16] to the datasets used for marine oil spill forecasts by the hydrometeorological services of different countries. However, these reviews [14–16] cannot be considered exhaustive without mentioning the Russian experience and the models presented, for example, in [9, 17–21].

A number of oil spill models developed by Russian scientific groups are presented in two papers published almost simultaneously [22, 23]. In the first paper [22], numerical modeling in the Sea of Azov and the Black Sea is analyzed, and the results of modeling real-life incidents at sea are presented for two Russian models. The second paper [23] briefly describes two models developed in Russia, but in the context of studying pollution of the Black Sea by various substances, not limited to petroleum hydrocarbons.

The problem of predicting the spread of oil and petroleum product spills in the marine environment remains far from fully solved. As noted in [13, p. 47], forecasting requires a system approach, and “in the absence or inadequate functioning of one of the components, the forecast will be impossible or of limited effectiveness.”

The aim of this work is to comprehensively analyze the key factors that distinguish this accident from many other spills: the physicochemical characteristics of the fuel oil, the features of the pollution source, and the hydrometeorological conditions relevant to mathematical modeling.

### **Models, methods, and input data**

A comprehensive technology is required to address the tasks of analyzing and forecasting the spread of oil pollution. This technology includes mathematical support (programs implementing process models); information support

(cartography, data on the accident source, forecasts of hydrometeorological characteristics, and results of aerospace monitoring); and organizational support, which includes a situation center and a duty team, as well as the transfer of input and forecast data between the system components [13]. The procedures, formats, and specifications must be agreed upon during the stages of system development, testing, and commissioning.

#### *Hydrometeorological forecast data*

During the incident under consideration, operational analyses and forecasts of hydrometeorological fields were computed using the Marine Hindcast and Forecast System (MHFS) implemented for the Sea of Azov, and the Kerch Strait, and the adjacent Black Sea area [24]. In most cases, surface meteorological fields were calculated using the regional nonhydrostatic atmospheric model WRF (Weather Research and Forecasting Model)<sup>3</sup> with a spatial resolution of 10 km. However, during the first weeks after the accident, meteorological fields based on COSMO-Ru meteorological forecasts with a spatial resolution of 6.6 km, provided daily by the Hydrometeorological Center of Russia with a lead time of 5 days, were used.

The meteorological fields calculated by these atmospheric models were employed in the MHFS to compute hydrological fields using the Russian marine circulation model INMOM (Institute of Numerical Mathematics Ocean Model) [25–27]. For this incident, the MHFS was implemented for the Kerch Strait area and the adjacent waters of the Sea of Azov and the Black Sea with variable spatial resolution: 120–200 m in the Kerch Strait, increasing to several kilometers with distance from the strait, while the resolution remained sufficiently high in the area of fuel oil spread (not coarser than 1 km). The details of MHFS operation are described in [24].

The development and operational implementation of marine state forecasts are being pursued in Russia by several scientific teams. These activities are both theoretical [28–30] and practical in nature [31, 32]. In addition, software tools for accessing forecast data arrays are being developed [33]. The choice of the MHFS for forecasts of fuel oil spread during KSFOS-2024 was motivated by the absence of technical, organizational, and administrative difficulties in arranging data access, as well as by successful experience in modeling the spread of oil and petroleum products in other seas of the Russian Federation and in areas of the Black Sea [34, 35].

In most cases, search and rescue operations and response to oil and petroleum product spills are completed within a few days after the emergency. Accordingly, forecasting the spread of oil pollution assumes the availability of hydrometeorological information over a domain covering the area of pollution spread during the first few days. Such a compromise with respect to domain size is adopted because of the increase in disk storage capacity required for the data as the domain is enlarged, as well as the increased time for data transmission and processing.

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<sup>3</sup> Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Liu, Z., Berner, J., Wang, W., Powers, J.G., Duda, M.G. [et al.], 2019. *A Description of the Advanced Research WRF Model Version 4*. Boulder, Colorado, USA: National Center for Atmospheric Research, 162 p. (NCAR Technical Note; NCAR/TN-556+STR). <https://doi.org/10.5065/1dfh-6p97>

In the case of KSFOS-2024, the storm conditions prevented operations at sea during the first days after the accident, and the area of fuel oil spread – and consequently the domain for which the hydrometeorological forecasts were prepared – had to be expanded several times. While the first calculations were performed on a grid of  $321 \times 201$  nodes with a grid spacing of  $\sim 500$  m, a month later, computations had to be carried out on a grid of  $1421 \times 730$  nodes with the same spacing. The final computational domain encompassed the entire Sea of Azov and the adjacent Black Sea area, including the coastal waters of Crimea and the North Caucasus as far as Tuapse.

#### *SPILLMOD software suite for oil spill transport forecasting*

The SPILLMOD software suite is designed to calculate and forecast the evolution of an oil spill on the sea surface, including the oil slick thickness field, the amount of oil on the surface, the amounts of oil evaporated and dispersed into the water column, as well as to assess the probability of impact on specially protected natural areas (SPNA).

SPILLMOD implements a numerical solution of a mathematical model of oil spill spread and transformation on the sea surface based on two-dimensional equations of oil slick motion in a domain with free and moving contact boundaries [20, 21]. The numerical method is a development of the particle-in-cell method [36], employing adaptive Eulerian and Lagrangian grids [37]. Algorithms for the application of countermeasures, including deployment of booms, oil recovery by skimming vessels, and dispersant application<sup>4</sup>, are also implemented. The user interface is integrated with a geographic information system used for visualization of the calculation results. A detailed description of the functional capabilities, structure, and main functions of the SPILLMOD suite is given in [13].

#### *Incident information*

On December 15, 2024, at 08:57 LT (UTC + 3) in the Black Sea part of the Kerch Strait, at coordinates  $\varphi = 45^{\circ}03'03''\text{N}$ ,  $\lambda = 36^{\circ}32'06''\text{E}$ , during a storm, a hull fracture occurred in the area of tanks Nos. 3 and 4 of the tanker *Volgoneft-212* (shipowner LLC “KamaTransOil”, port of registry Saint Petersburg). An SOS signal was transmitted by the master via VHF. The crew of 13 persons gathered in the aft part of the vessel. The vessel was carrying a cargo of heavy-grade petroleum products (fuel oil) in bulk, amounting to 4,251.781 t, and 10.0 t of bunker fuel. Fuel oil leaked into the sea. At 12:58, the stern section of the *Volgoneft-212* sank. Twelve crew members were rescued, and one died<sup>1, 2</sup>.

On December 15, 2024, at 10:20 LT (UTC + 3) in the Black Sea part of the Kerch Strait, at coordinates  $\varphi = 45^{\circ}04'03''\text{N}$ ,  $\lambda = 36^{\circ}31'09''\text{E}$ , during a storm, a hull fracture occurred on the tanker *Volgoneft-239* (shipowner CJSC “Volgatransneft”,

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<sup>4</sup> Ivchenko, A.A., Zatsupa, S.N., Solbakov, V.V. and Zuravel, V.I., 2019. Certificate of State Registration of a Computer Program No. 2019613316, Russian Federation. SPILLMOD-RF Modeling Suite for Calculating the Characteristics of an Oil Spill at Sea, Taking into Account the Use of Response Measures: No. 2019610949: filed 02/04/2019: published 03/13/2019. Applicant: Federal State Budgetary Institution “N. N. Zubov State Oceanographic Institute” (in Russian).

port of registry Astrakhan) <sup>1, 2</sup>. The crew consisted of 14 members. The vessel was carrying a cargo of fuel oil amounting to 4,300.938 t and 15.0 t of bunker fuel. The bow section of the vessel was at anchor; the stern section with the crew drifted toward the Taman Peninsula, toward Cape Panagia. At 13:10, the stern section of the *Volgoneft-239* was driven aground near Cape Panagia, 82 m from the shoreline. No crew members were injured. The weather conditions at the vessel's location were as follows: wind speed 20 m/s, wave height up to 3.0 m, air temperature +3 °C.

*Characteristics of the petroleum product*

According to the product quality certificates (Quality Certificate No. 4744 for M100 fuel oil, dated November 8, 2024, loaded on board VN212, and Quality Certificate No. 4467 for M100 fuel oil, dated October 22, 2024, loaded on board VN239), the density of the fuel oil at 15 °C is 976 kg/m<sup>3</sup> (VN212) and 980 kg/m<sup>3</sup> (VN239), respectively. Thus, as the fuel oil leaks from the tanks in the sunken vessel fragments, it is expected to rise to the sea surface.

According to the appendices to the aforementioned quality certificates, the transported cargo contained approximately 2% of fractions boiling up to 250 °C and 25% of fractions boiling up to 350 °C. These data suggest that over time, due to evaporation from the sea surface and dissolution in seawater, the density of the fuel oil may increase. It is known that petroleum residues from oil refining, with various compositions, form the basis of fuel oil. To achieve standard viscosity and pour point values, diesel fractions are added to the base blends.

According to the quality certificates, the density of VN212 fuel oil at 20 °C is 972.6 kg/m<sup>3</sup>, and that of VN239 fuel oil is 977.1 kg/m<sup>3</sup> (Table 1). The information provided, together with data indicating seawater temperatures of 8–11 °C during the first few days after the accident, suggests that the fuel oil spilled as a result of the accident floated on the sea surface.

Table 1

**Assessment of the temperature dependence of density (kg/m<sup>3</sup>) of seawater with different salinity and of fuel oil in the initial state (I), after removal of fractions boiling up to 250 °C (II) and up to 350 °C (III)**

t, °C	Sea water at salinity, PSU			Fuel oil					
				VN212			VN239		
	18	12	5	I	II	III	I	II	III
0	1014.4	1008.8	1003.9	986.0	988.5	1018.3	990.4	993.0	1024.2
5	1014.4	1008.8	1004.0	982.7	985.2	1014.8	987.1	989.7	1020.7
10	1014.4	1008.8	1004.0	979.3	981.8	1011.3	983.7	986.3	1017.2
15	1014.3	1008.8	1004.0	976.0	978.5	1007.9	980.4	983.0	1013.8
20	1014.3	1008.7	1004.0	972.6	975.2	1004.5	977.1	979.7	1010.4
25	1014.2	1008.7	1003.9	969.4	971.9	1001.1	973.8	976.4	1007.0
30	1014.2	1008.6	1003.9	966.2	968.6	997.8	970.6	973.1	1003.6

The pour point, according to the quality certificate, for this grade of petroleum product is 9 °C. This means that at temperatures below 9 °C, the viscosity increases sharply and the spreading rate decreases significantly. Under such conditions, the fuel oil predominantly spreads in the form of lumps or pancakes several centimeters thick, with horizontal dimensions ranging from tens of centimeters to meters. During transportation, the fuel oil temperature was maintained in the range of 45–50 °C; therefore, at the moment of the accident, the tank contents were capable of spreading.

Another important point should be noted. As reported by eyewitnesses and confirmed by the analysis of fuel oil samples taken from Anapa beach, mineral suspended matter, in particular sand, mechanically binds to this petroleum product. When the content of suspended matter in the oil-mineral conglomerate exceeds 4% by volume, its density clearly exceeds the density of seawater, and such formations tend to sink to the bottom.

#### *Characteristics of the fuel oil discharge sources and outflow regime*

The first information about the accident was received by the Main Maritime Rescue Coordination Center (MMRCC) at 10:50 msk on December 15, 2024, from the Maritime Rescue Subcenter (MRSC) of Kerch. According to the Marine Rescue Service, the bow section of VN239 sank at 45°05'14"N, 36°32'02"E at 10:50 msk, and at 12:58, the bow and stern sections of VN212 sank – the bow at 45°03'60"N, 36°32'20"E, and the stern at 45°08'08"N, 36°32'03"E. The preliminary assessment of the damage gave grounds for estimating the amount of fuel oil that had entered the sea at ~ 3500 t. Later, on January 2, this estimate was reduced to 2500 t in a press release issued by the Ministry of Transport, which is approximately twice the volume of the fuel oil spill from the *Volgoneft-139* tanker accident that occurred in 2007 [38, 39].

It is important to note that the fracture locations do not coincide with the vessels' positions on the seabed, which were determined later from satellite remote sensing data [5]. On SAR images, three sources of fuel oil release, identifiable by slicks, were recorded.

At the same time, as is often the case with accidents in the open sea, there is no reliable information on the rate and duration of the fuel oil outflow. In some cases, the problem of estimating the volume of spilled oil becomes a challenging research task<sup>5</sup>. Initially, as a conservative scenario, continuous leakage from the accident site was assumed. Such a scenario is the most challenging for response at sea and for shoreline protection.

In general, various oil or petroleum product discharge scenarios are considered in the event of a vessel accident. The most common one is an instantaneous or nearly instantaneous discharge, when the entire transported cargo reaches the sea surface within a short time, which corresponds to the complete or substantial destruction of a tank containing a low-viscosity, low-density substance. In another scenario, when the vessel's tanks are relatively slightly damaged, the outflow is considered to be prolonged, with a slowly changing discharge rate. In the case under consideration, the fracture of the tanker along a frame and the opening of one wall

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<sup>5</sup> Lehr, B., Bristol, S. and Possolo, A., 2010. Oil Budget Calculator–Deepwater Horizon: Technical Documentation: A Report to the National Incident Command. The Coastal Response Research Center [S. l.], 217 p.

of both tanks to the marine environment appear to represent a new outflow regime. At the moment of the accident, the heated fuel oil (during transport, its temperature is normally maintained close to the discharge temperature, i.e., far above the pour point) was highly viscous but still fluid, and a significant amount was presumably released (a large fraction of the total tank volume).

We estimate the outflow regime using the Poiseuille flow model. The tank is represented as a rectangular prism of length  $L$ , width  $B$ , and height  $H_0$ , with a volume of  $V_0 = L \cdot B \cdot H_0$ . The volumetric flow rate of a viscous fluid in a pipe, according to Poiseuille's law, is  $Q = \pi R^4 \Delta P / (8\eta L)$ , where  $R$  is the pipe radius;  $\Delta P$  is the pressure drop over a pipe section of length  $L$ ; and  $\eta$  is the dynamic viscosity of the fluid. The excess pressure caused by buoyancy forces in the tank is  $\Delta P = \Delta \rho g H$ , where  $\Delta \rho = \rho_w - \rho_m$ ;  $\rho_w, \rho_m$  are the densities of water and fuel oil; and  $H$  is the depth of the fuel oil layer in the tank. Substituting the expression for excess pressure into the flow rate equation, and taking into account that  $H = V/(BL)$ , we obtain a differential equation with respect to volume, the solution of which gives the following exponential time dependence:

$$V(t) = V_0 \exp(-\alpha t), \quad \alpha = 3.85 (R^4 \Delta \rho) / (\eta L^2 B). \quad (1)$$

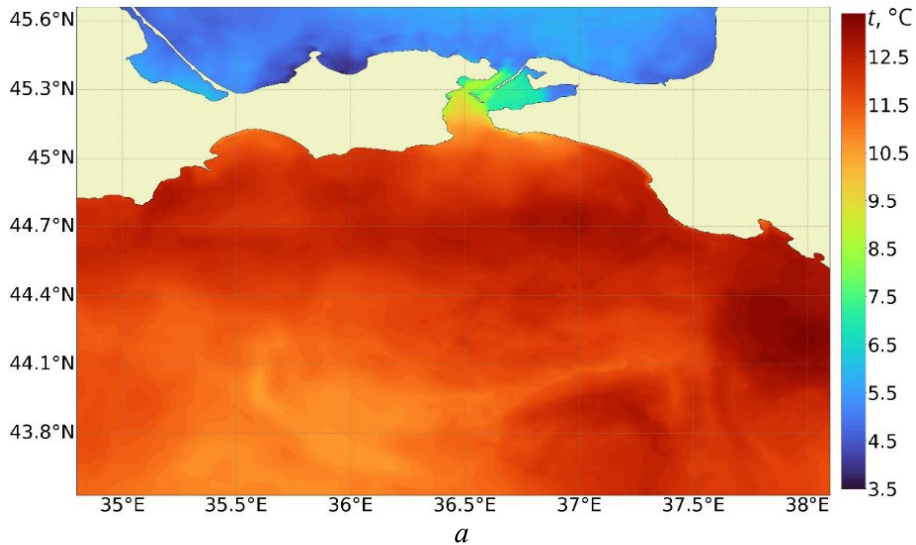
Denoting the fraction remaining in the tank as  $\lambda = V(t)/V_0$ , the time required to empty the tank to a specified level is  $t = -\ln(\lambda)/\alpha$ .

In the modeling, the discharge of fuel oil from the damaged tanks of the vessels was considered the most significant source of oil and petroleum product pollution. In addition to fuel oil, each vessel at the time of the accident had on board 10–15 t of bunker fuel and 0.5–1 t of engine oil in its engines<sup>6</sup>. However, the possible locations and outflow regimes of these types of petroleum products have been studied even less than those of the fuel oil. It should be noted that in [9], an exponential decrease in the rate of fuel oil release into the marine environment from the tanker fragments is assumed, however, without specifying the parameters.

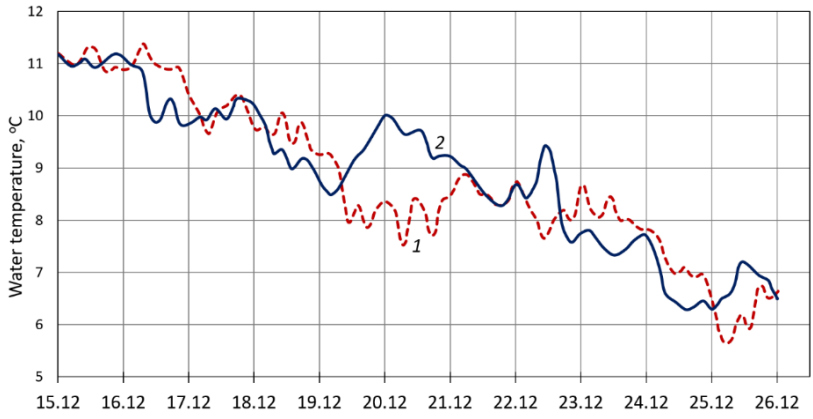
### Calculation results and discussion

Information on the thermohaline fields of the Kerch Strait and adjacent waters is of key importance for this spill. This is due to the fact that the density of the spilled petroleum product was found to be close to that of seawater and varies depending on temperature. Fig. 1, *a* shows the temperature distribution in the surface water layer in the Kerch Strait and adjacent waters of the Black Sea and the Sea of Azov on the day of the accident. The temperature change in the near-surface and bottom layers in the area of the sunken vessel fragments during the first weeks after the accident is shown in Fig. 1, *b*. Fig. 1, *c* shows a diagram of changes in wind speed over 5 days, including the day of the accident. A comparison of the data from Table 1 and Fig. 1 allows us to conclude that if fuel oil is transported to the Sea of Azov, the density of the weathered petroleum product will exceed that of seawater (see columns “5” and “III” in Table 1), and it will sink; however, fuel oil that has not undergone weathering will remain on the sea surface over the entire range of seawater temperatures in the area of the sunken vessel fragments.

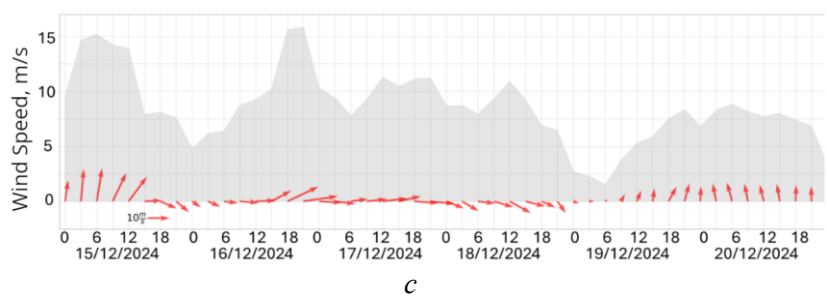
<sup>6</sup> Giprorybflot, 1965. Operation and Repair of NVD-48, NVD-36, and NVD-24 Engines: A Manual. Moscow: Food Industry, 368 p. (in Russian).



*a*



*b*



*c*

**Fig. 1.** Water temperature (°C) in the Kerch Strait and adjacent water areas (*a*), as well as in the region of sunken ship fragments (*b*) at the near-surface (*1*) and bottom (*2*) horizons; wind speed in the accident region (*c*)

Table 2 presents estimates of the fuel oil outflow parameters from the tank. The selected parameter values reflect the uncertainty in the fuel oil characteristics. Several fuel oil temperature values were selected. The most likely temperature of the cargo in the tanks exceeded 20 °C; however, it is known from accident reports

that on one of the tankers, the cargo heating equipment failed a few days before the accident and the fuel oil temperature decreased. Dynamic viscosity values can be estimated using the model proposed in study<sup>7</sup>, based on data on the petroleum product viscosity at different temperatures. However, near the fuel oil pour point, this model may be inaccurate. Therefore, based on the results of the analysis of fuel oil samples from Anapa beaches<sup>8</sup>, it was decided to estimate the outflow rate in the viscosity range from 2 to 150 Pa·s. Table 2 provides estimates for five viscosity values within this range: I – 2 Pa·s, II – 10 Pa·s, III – 50 Pa·s, IV – 100 Pa·s, and V – 150 Pa·s. The following parameter values were used in the estimates: tank volume – 566 m<sup>3</sup>, tank width – 5.7 m, tank length – 20 m, tank height – 5 m, water density – 1014 kg/m<sup>3</sup>, fuel oil density – 983 kg/m<sup>3</sup>, density difference between water and fuel oil – 31.4 kg/m<sup>3</sup>, and the fuel oil remaining fraction in the tank was set to 0.05.

Table 2

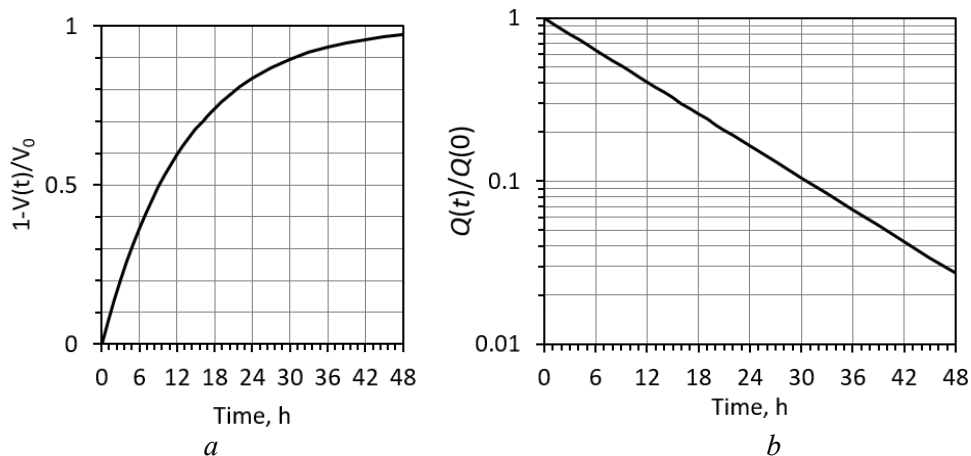
**Assessments of the parameters of fuel oil leakage for the scenarios with different dynamic viscosity**

Parameter	Leakage scenario				
	I	II	III	IV	V
Dynamic viscosity $\eta$ , Pa·s	2	10	50	100	150
Thickness of leakage layer $R$ , m	0.25	0.25	0.25	0.25	0.25
Parameter $\alpha$ , 1/s	1.0E-4	2.1E-5	4.2E-6	2.1E-6	1.4E-6
Emptying time $T(\lambda)$ , h	8	40	199	399	598
Emptying time $T(\lambda)$ , day	0.3	1.7	8.3	17	25
Remainder after 48 h $\lambda(48)$ , %	0	2.7	48.6	69.7	78.6

According to the data in Table 2, most of the fuel oil is released into the marine environment from the destroyed tanks in any of the scenarios within the first few days. One of the probable scenarios (II) suggests the outflow of about 95% of the fuel oil in slightly less than 2 days. For scenario II, Fig. 2 presents graphs of the normalized fuel oil volume in the tank and the normalized fuel oil flow rate as a function of time. It can be seen that the volumetric fuel oil flow rate into the marine environment decreases by two orders of magnitude during the first two days, and the volume in the tank at the end of the second day is about 3%. Thus, the scale of subsequent releases a few days after the accident should be substantially reduced. According to official information, the volume of spilled fuel oil ranges from 2500 to 3500 t. To obtain an estimate in tonnes for the scenario under consideration (II), the values shown in Fig. 2, *a* should be multiplied by the corresponding spill volume.

<sup>7</sup> Mackay, D., Buist, I., Mascarenhas, R. and Paterson, S., 1980. *Oil Spill Processes and Models*. Ottawa, Ontario: Environmental Protection Service, 91 p.

<sup>8</sup> ANKOOVO, 2025. *Report "As Part of the Initiative to Analyze Fuel Oil Samples Collected on the Coast of Anapa"*. Moscow: Center for Science and Technology of Hydrocarbon Production ANKOOVO "Skolkovo Institute of Science and Technology", 64 p. (in Russian).

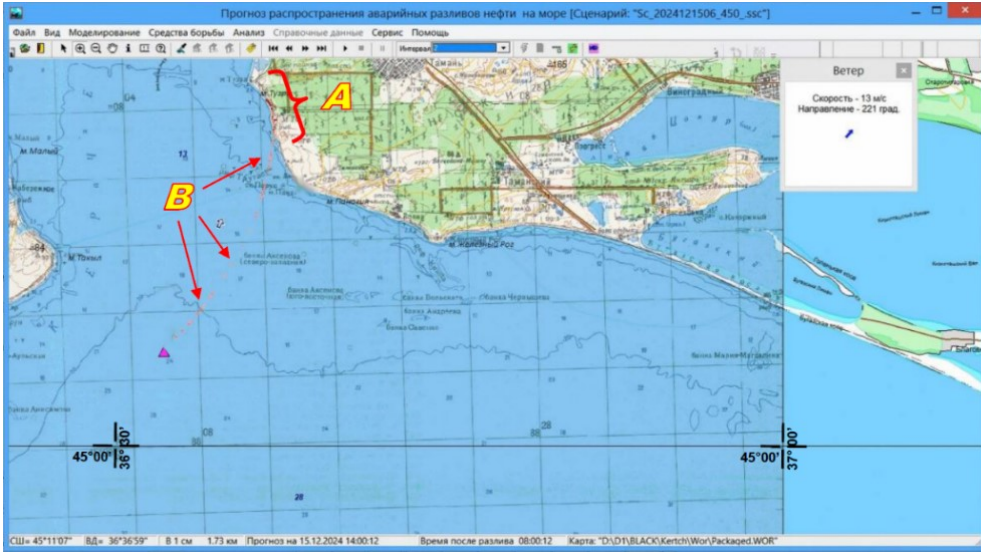


**Fig. 2.** Dependence of the amount of leaked fuel oil (*a*) and fuel oil flow rate (*b*) on time

Fig. 3 shows successive configurations of the fuel oil spill on the sea surface and indicates the locations of its beaching at 8, 24, 36, and 48 hours after the accident, obtained as a result of the simulation.

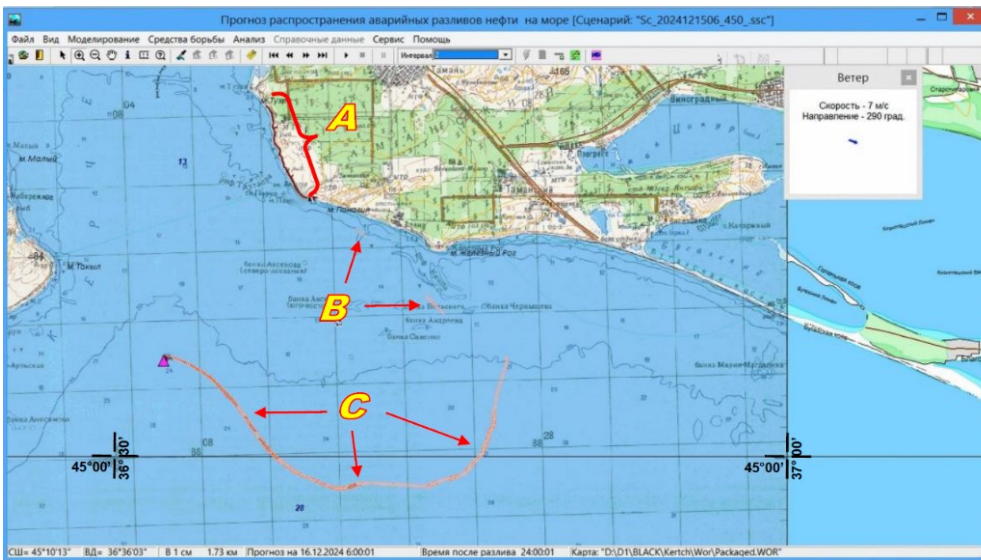
We consider the results of the forecast of fuel oil spill spread obtained during the first two days using the SPILLMOD software suite. KSFOS-2024 has a number of features. The high viscosity of fuel oil results in reduced evaporation. The SPILLMOD model [19, 20] uses a modern parameterization that accounts for this process [40]. The similarity of fuel oil density to that of seawater greatly hinders its spreading [20, 21], which leads to the formation of relatively narrow slicks on the sea surface. High values of density and viscosity characteristic of fuel oil also reduce natural dispersion. To describe this process in the SPILLMOD model, a modern dispersion model has been developed at the State Oceanographic Institute [41, 42].

Thus, the model under consideration performs adequately over a wide range of oil characteristics and hydrometeorological conditions. The southwest and south-southwest storm wind (see Fig. 1, *c*) led to the fuel oil spread toward the Taman Peninsula coast, as evidenced by the simulated spill configuration 8 hours after its start (see Fig. 3, *a*). In this figure, the symbol *A* marks the coastal zone affected by the spill, and the symbol *B* and arrows indicate the oil pollution on the sea surface, which is an elongated narrow slick consisting of fragments. Subsequently, the wind direction changed to westerly directions, and by the end of the first day after the accident, an elongated slick of complex configuration, 50–60 km long, had formed. During this time, according to estimates (see Table 2 and Fig. 2, *a*), a significant amount of fuel oil was released from the sunken fragments of the tankers. Part of the pollution initially located near the Taman Peninsula in the Cape Panagia area began to be transported along the coast toward Anapa, as evidenced by the slick configuration 24 hours after the start of the spill (see Fig. 3, *b*). In Fig. 3, *b*, the brown line and the symbol *A* indicate the coastal zone affected by the spill, the symbol *C* indicates an elongated slick connected at one end to the sunken fragment of the tanker, and the symbol *B* indicates a fragment of oil pollution on the sea surface that broke away from the main slick as a result of interaction with the shore.



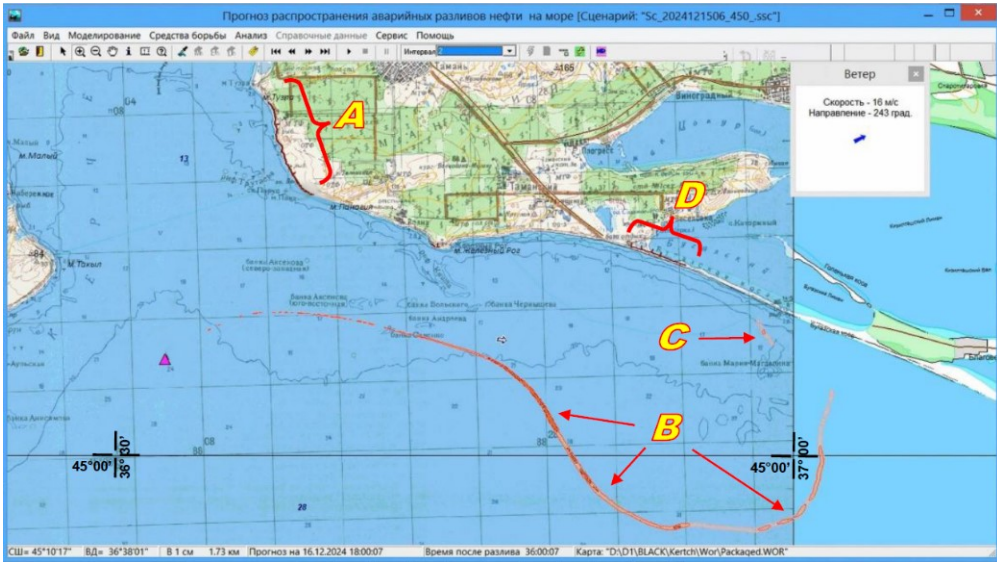
*a*

**Fig. 3.** Configuration of fuel oil pollution in the Black Sea and the Kerch Strait based on the results of simulation in 8 (*a*), 24 (*b*), 36 (*c*) and 48 (*d*) hours after the spill began. The calculated plume (*B*, *C*) is shown in red, the polluted coastal zone (*A*, *D*) – in brown, triangle indicates the position of the spill source used in the simulations



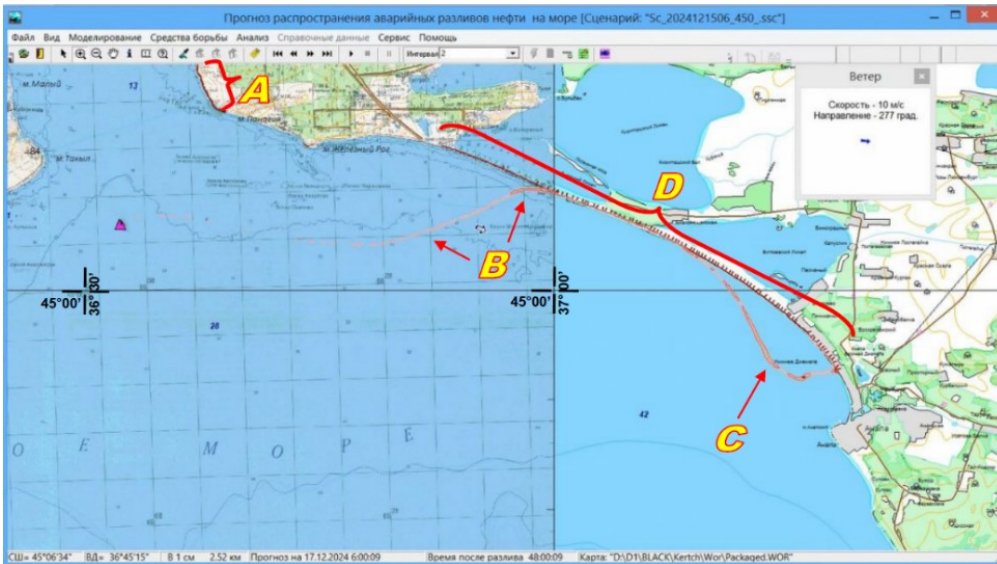
*b*

**Fig. 3.** Continuation



c

Fig. 3. Continuation

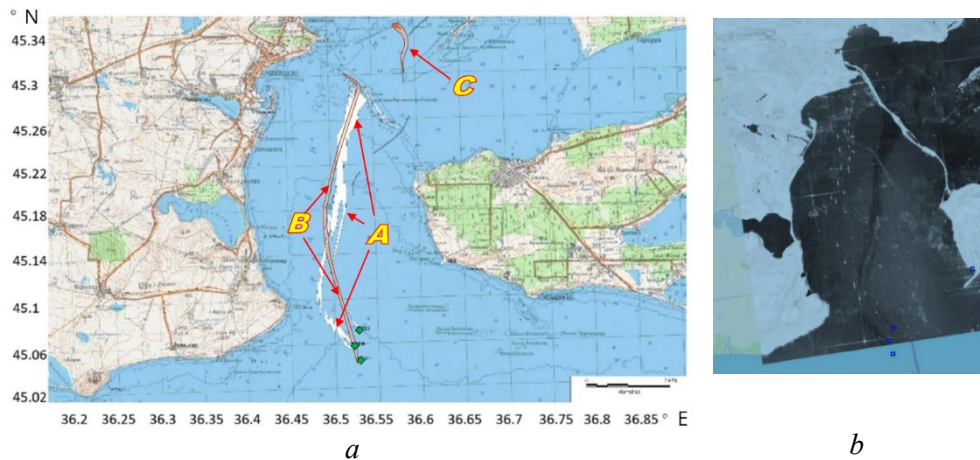


d

Fig. 3. End

During the second half of the second day after the accident, some fuel oil reached the shore in the area of the Bugaz Spit (the coastal zone area affected by the spill is indicated by the symbol *D* in Fig. 3, *c*) under conditions of strong wind with a southerly component (see Fig. 1, *c*). The pollution pattern 36 hours after the start of the spill is given in Fig. 3, *c*. Some fragments of the spill (symbol *C* in Fig. 3, *c*) continued moving toward the Anapa coast. The main area of sea-surface pollution is outlined in red and is indicated by arrows and the symbol *B*. The situation

with pollution of the coast and coastal waters at the end of the second day after the start of the spill is shown in Fig. 3, *d*. In the preceding period, a strong southwest wind prevailed, which caused the fuel oil pollution on the sea surface to reach the shore; waves brought fuel oil onto the shore, leading to intense interaction of fuel oil with coastal and beach sediment (sand) and partial burial of the oil in the beach sediment layer. At the same time, the fuel oil pollution on the sea surface continued moving toward the shore. Timing and locations of fuel oil beaching coincide with eyewitness and volunteer reports.



**Fig. 4.** Oil spill configuration on December 20, 2024: results of simulation and processing the *RADARSAT* satellite image (*a*) and the *GaoFen-3* radar image (*b*). The area of oil contamination resulted from interpreting satellite image is shown in white (*A*), and the estimated plume (*B*, *C*) is outlined in red

In the case of a continuous source with a constant discharge rate, the coastal zone of the Crimean Peninsula, including areas near Kerch, the shores of the Taman Peninsula in the Kerch Strait area, as well as some areas in the Sea of Azov, would have been significantly polluted. However, according to the Russian Emergencies Ministry<sup>9</sup>, “In Krasnodar Krai... <...> 629.14 km of coastline were cleaned (including repeatedly), more than 178.7 thousand tonnes of contaminated sand, soil, and pebbles were collected. In the Republic of Crimea... more than 259.5 km of coastline were cleaned (including repeatedly), about 908.4 tonnes of contaminated sand and soil were collected. In the city of Sevastopol... 850.17 tonnes of contaminated sand and soil were collected and taken to landfills for collection and disposal.” In addition, in the coastal zone of Anapa and Temryuk area, a joint diving team performed daily monitoring and recovery of fuel oil from the seabed. The significantly smaller extent of coastline pollution outside the Anapa–Temryuk area confirms the conclusions drawn about a significant decrease in the amount of fuel oil entering the marine environment over time (see Table 2 and Fig. 2).

Another confirmation of the hypothesis of a decrease in fuel oil release into the marine environment is provided by the simulation results presented in [9]. As

<sup>9</sup> Russian Ministry of Emergency Situations, 2025. [Work Continues to Clean up the Aftermath of the Oil Spill Caused by the Tanker Collision in the Kerch Strait]. [online] Available at: <https://mchs.gov.ru/deyatelnost/press-centr/novosti/5577800> [Accessed: 15 August 2025] (in Russian). PHYSICAL OCEANOGRAPHY VOL. 33 ISS. 3 (2026) 529

the authors of that study state, “On December 19–21, the wind changed its direction to southerly, as a result of which the fuel oil began to move northward... According to calculations, most of the fuel oil should have reached the coast of Tuzla and the Taman port area. However, no information on pollution in these areas was received from open sources” [9, p. 11]. The same source provides a photograph of the western coast of the Kerch Strait, where only isolated, relatively sparse fragments of fuel oil covering the splash zone are visible, which is markedly different from the pollution of the shores in the Anapa area (continuous coverage of considerable thickness). The seabed in the coastal zone near Anapa was also heavily contaminated by fuel oil, where divers later discovered oil-sand mats formed under wave action under conditions of high suspended matter concentration.

The amount of fuel oil carried to the coast of Anapa can be estimated rather roughly due to the uncertainty in the location of the tanker fragments on the seabed and the product viscosity, which depends on its properties and the ambient temperature. According to the simulation results, approximately half of the fuel oil slick that leaked from the tanker fragments during the first two days was carried into the coastal area from Cape Anapa to Blagoveshchenskaya settlement (see Fig. 3, *d*). Using equation (1) and estimates of the fuel oil outflow time constant (Table 2) for different viscosity values of the outflowing substance, it can be concluded that from 50 to 95 % of the tank contents could have been carried onto this section of the coast and settled in the form of oil-sand mats in the coastal zone. According to official information, the spill volume ranged from 2500 t to 3500 t; thus, the amount of fuel oil carried to the coast ranges from 1250 t to 3325 t.

We estimate the amount of fuel oil collected in the Anapa area. According to the Russian Emergencies Ministry<sup>9</sup>, 178.7 thousand tonnes of fuel oil-contaminated soil were taken to landfills. According to Sirius University<sup>10</sup>, the fuel oil content in the sand is 0.42%, which corresponds to ~ 700 t of petroleum hydrocarbons. Employees of the Russian Emergencies Ministry, the Kuban SPAS emergency rescue team, and the Marine Rescue Service collected 2000 t of oily waste in the coastal zone of the sea<sup>11</sup>. The fuel oil content in such waste is estimated at at least 15%. Thus, ~ 300 t of fuel oil was recovered from the seabed. In total, more than 1000 t of fuel oil were removed from the seabed and beaches in the Anapa area. Assuming that a certain amount of fuel oil is still in a dispersed state on beaches and the seabed, this estimate is in satisfactory agreement with the estimates given above.

We now turn to the analysis of the data presented in Fig. 4. The red outline of fuel oil pollution north of the Crimean Bridge (symbol *C* in Fig. 4, *a*) is noteworthy. In the model calculations, the “northern part” of the slick arises from the interaction of the fuel oil slick with the coast of the Taman Peninsula in the days preceding the satellite image. The slick shape obtained from interpretation of the satellite image (the white area in the figure, indicated by the symbol *C*) and its greater width compared to the simulation correspond

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<sup>10</sup> Nazarova, A., 2025. *Sirius Scientists: Sand Pollution from Anapa Exceeds the Norm by 14 Times*. [online] Available at: <https://kuban.rbc.ru/krasnodar/freenews/6793adfa9a7947c10ca57e17> [Accessed: 15 August 2025] (in Russian).

<sup>11</sup> Kuban, 2025. *Fuel Oil Has Been Completely Removed from the Seabed along the Coast of Anapa and the Temryuk District*. [online] Available at: <https://kuban24.tv/item/mazut-polnostyu-ubrali-so-dna-morya-na-poberezhe-anapy-i-temryujskogo-rajona> [Accessed: 20 September 2025].

to the evolution of the oil spill from three sources located at the sites of the sunken tanker fragments. The simulation assumed the action of a single source (oil pollution on the sea surface obtained from calculations is the area outlined in red, indicated by the symbols *B* and *C*). The modeled oil pollution slicks depend significantly on the specified discharge rate and duration. Considering the inevitable error in the hydrometeorological forecast, the comparison of model calculations with remote sensing data (Fig. 4, *a* and *b*) can be considered satisfactory.

The SPILLMOD software suite is designed to simulate the spread of oil and petroleum products on the sea surface based on a two-dimensional hydrodynamic model. The model parameterizes evaporation, dispersion, and interaction with the shore; however, the formation of oil mats is not modeled, as is the case in all other operational models whose descriptions are available to us [16]. Thus, a few days after the accident, when the fuel oil flow rate decreases significantly, the pollution consists of an area of scattered fragments or lumps of fuel oil. The evolution of the configuration of the polluted area is reproduced reasonably well by the simulation; however, the level of confidence in the estimated fuel oil content on the sea surface corresponds to the quality of the pollution source identification. In the performed estimates of fuel oil outflow, there remains uncertainty associated with the characteristics of the fuel oil (its exact temperature and viscosity after the accident are unknown), as well as with the spatial position of the tanker fragments on the seabed and the configuration of the fractures.

Since February 2025, Earth remote sensing (ERS) data have regularly recorded the appearance of presumed oil films on the sea surface in the area of the sunken tanker fragments; moreover, the positions of the sources of these films sometimes coincide with the coordinates of the wreckage on the seabed. However, according to ERS data, the zone of film distribution is limited to a radius of about 30 km around the sunken parts of the vessels, and the simultaneous absence of fuel oil beaching leads to the conclusion that these are thin films with a short lifetime on the surface [40, 43, 44]. It can be assumed that the oil films identified in satellite images may also be a manifestation of various sources of oil and petroleum products. Possible sources of the films include fuel oil seepage from tanks with the release of diesel fractions that form film pollution visible from space; fuel, engine oil, and technical fluids from the equipment, machines, and mechanisms of the tankers; and ship wakes and traces of lubricants generated during environmental safety activities in the area of the sunken tanker fragments.

### **Conclusion**

The modeling results correspond to media reports of observations of fuel oil slicks washing ashore and to ERS data. The modeling of the development of the emergency situation was carried out using the SPILLMOD software suite based on hydrometeorological parameters calculated by the MHFS for the Black Sea. The modeling makes it possible to estimate which marine areas were affected by oil pollution for subsequent field surveys.

According to our estimates, the specific features of the KSFOS-2024 accident and the properties of the transported fuel oil have led to the conclusion that the spill source operated for a long time; however, the outflow of up to 95% of the tank contents occurred within the first few days. The source strength, according

to the estimates made above, decreased by at least two orders of magnitude during this time. Preliminary estimates indicate that more than half of the fuel oil volume should have reached the surface within a few days after the vessel parts sank to the seabed. For this reason, the main impact occurred in the Anapa area, which is confirmed by actual data and modeling.

The recording of film pollution by ERS data in sequential images has shown that the identified pollution areas are never detected in subsequent images, which indicates that they are short-lived surface pollution due to the small film thickness.

The fuel oil spill that occurred in the Kerch Strait on December 15, 2024, on the one hand, caused enormous environmental damage, and on the other hand, is an event whose monitoring and analysis are extremely useful for the further development of the methodology for analyzing and forecasting oil spills. The following properties of fuel oil, which significantly determine its evolution in the marine environment, should be noted:

- fuel oil density is close to that of seawater; the thermal expansion coefficient of fuel oil and the ranges of variation in seawater temperature and salinity can cause fuel oil pollution fragments to migrate in the water column between the surface and the seabed due to changes in the density ratio between water and fuel oil;

- high viscosity of fuel oil results in limited spreading capacity on the sea surface and very limited dispersion into the water column, which leads to the presence of relatively large conglomerates in the sea under certain temperature conditions;

- high adhesion of fuel oil to suspended matter leads to the formation of submerged fuel oil mats in the coastal zone;

- the presence of diesel fractions added as process additives to improve the pumpability of fuel oil through pipelines leads to the release of these components to the sea surface, with the formation of thin films that can be detected using ERS methods.

In general, the experience gained as a result of this study confirms the validity of the chosen tools and methods. At the same time, it is evident that it is necessary to increase efforts, expand capabilities, and strengthen the resource base for conducting scientific, laboratory, and field studies of fuel oil spills. The need to increase the speed and quality of information exchange between organizations involved in responding to oil pollution spills at sea should be emphasized separately in order to ensure environmental safety. The authors of this paper hope that the results of the study will be used for future assessments of the possible consequences of heavy fuel spills in other marine areas of the Russian Federation.

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*About the authors:*

**Vyacheslav V. Solbakov**, Senior Researcher, Federal Research Center "Computer Science and Control", Russian Academy of Sciences, (44/2 Vavilova Str., Moscow, 119333, Russian Federation), CSc. (Phys.-Math.), **Scopus Author ID: 6506793953**, **ResearcherID: AAB-6735-2019**, **SPIN-code: 7656-6621**, [vsolbakov@frccsc.ru](mailto:vsolbakov@frccsc.ru)

**Sergei N. Zatssepa**, Head of the Laboratory for Modeling the State of the Marine Environment, N. N. Zubov's State Oceanographic Institute, Roshydromet (6 Kropotkinskiy Lane, Moscow, 119034, Russian Federation), DSc. (Phys.-Math.), **ORCID ID: 0000-0002-7072-3920**, **ResearcherID: T-1242-2018**, **Scopus Author ID: 55950369100**, **SPIN-code: 3922-3330**, [zatssepa@gmail.com](mailto:zatssepa@gmail.com)

**Nikolay A. Diansky**, Chief Researcher, M.V. Lomonosov Moscow State University (1 Leninskie Gory, Moscow, 119991, Russian Federation), DSc. (Phys.-Math.), Associate Professor, **ORCID ID: 0000-0002-6785-1956**, **ResearcherID: R-8307-2018**, **SPIN-code: 5450-6667**, [nikolay.diansky@gmail.com](mailto:nikolay.diansky@gmail.com)

**Aleksandr A. Ivchenko**, Senior Researcher, N.N. Zubov's State Oceanographic Institute, Roshydromet (6 Kropotkinskiy Lane, Moscow, 119034, Russian Federation), **ORCID ID: 0009-0003-3828-378X**, **Scopus Author ID: 55950528300**, **SPIN-code: 5443-1160**, [alivch654@gmail.com](mailto:alivch654@gmail.com)

**Evgeniya A. Korshenko**, Researcher, Department of Numerical Modeling of Hydrophysical Processes, Laboratory of Operational Modeling, N.N. Zubov's State Oceanographic Institute, Roshydromet (6 Kropotkinskiy Lane, Moscow, 119034, Russian Federation), **ORCID ID: 0000-0003-2310-9730**, **ResearcherID: AAE-3617-2019**, **Scopus Author ID: 57194570985**, **SPIN-code: 1754-4563**, [zhenyakorshenko@gmail.com](mailto:zhenyakorshenko@gmail.com)

**Irina I. Panasenkova**, Researcher, N.N. Zubov's State Oceanographic Institute, Roshydromet (6 Kropotkinskiy Lane, Moscow, 119034, Russian Federation), **ORCID ID: 0000-0002-8338-4825**, **ResearcherID: AAE-4131-2019**, **Scopus Author ID: 57202425753**, **SPIN-code: 1193-6046**, [ipanasenkova@mail.ru](mailto:ipanasenkova@mail.ru)

**Vladimir V. Fomin**, Head of Laboratory, Senior Researcher, N.N. Zubov's State Oceanographic Institute, Roshydromet (6 Kropotkinskiy Lane, Moscow, 119034, Russian Federation), **ORCID ID: 0000-0001-8857-1518**, **ResearcherID: C-2124-2017**, **Scopus Author ID: 57208310824**, **SPIN-code: 8803-9548**, [vladimirfomin@gmail.com](mailto:vladimirfomin@gmail.com)

*Contribution of the co-authors:*

**Vyacheslav V. Solbakov** – development of the article concept and structure; selection of illustrative materials; analysis and generalization of the results under consideration; critical analysis and revision of the text

**Sergei N. Zatsepa** – development and configuration of the SPILLMOD model; participation in the discussion of the article materials; participation in the analysis of the results; participation in the text editing

**Nikolay A. Diansky** – development and configuration of the INMOM model; participation in the discussion of the article materials; participation in the analysis of the results; preparation of the article text; text editing and refinement

**Aleksandr A. Ivchenko** – development and configuration of the SPILLMOD model; conducting numerical experiments; preparation of illustrative materials for the article; participation in the analysis of the results

**Evgeniya A. Korshenko** – preparation of atmospheric impact for the Marine Hindcast and Forecast System; conducting numerical experiments; preparation of illustrative materials for the article; participation in the analysis of the results

**Irina I. Panasenkova** – preparation of atmospheric impact for the Marine Hindcast and Forecast System; conducting numerical experiments; participation in the analysis of the results; preparation of illustrative materials for the article; participation in discussion of materials; participation in analysis of results; text editing and refinement

**Vladimir V. Fomin** – development and configuration of the Marine Hindcast and Forecast System; participation in discussion of materials; participation in analysis of results; text editing and refinement

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