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Original article

Spread of Oil Pollution in the Black Sea after the Accidents at the "Volgoneft" Tankers in December 2024 Based on Numerical Simulations using the Model FOTS MHI, as well as Satellite and In-Situ Measurement Data

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Abstract
Purpose. This study investigates the chronology and spatial extent of fuel oil pollution resulting from the sinking of the tankers *Volgoneft-212* and *Volgoneft-239* in the Kerch Strait on 15 December 2024, assesses the associated environmental impacts and evaluates the performance of an operational oil spill transport forecasting system.
Methods and Results. Oil spill transport was modelled using Floating Object Tracking System (FOTS), a Lagrangian-based tool developed at Marine Hydrophysical Institute, RAS, and the data from the NEMO numerical model and the Global Forecast System (GFS) meteorological fields. The calculations were validated against Sentinel-1 and Landsat-8 satellite imagery as well as *in-situ* observations. The accident resulted in a spill of 2500–3000 tons of M-100 fuel oil, contaminating over 700 km of coastline from Yevpatoriya to Anapa. The active phase of pollution spreading lasted 25 days. Five types of coastal contamination were identified, including buried fuel oil layers (total mass is 25.3 tons) at depths of 12–35 cm. Subtidal accumulations of fuel oil in the Kerch Strait and near Anapa currently act as sources of secondary pollution.
Conclusions. The FOTS demonstrated good forecasting accuracy having promptly identified the areas of beach contaminations in Anapa, Kerch, Sevastopol and Yevpatoriya. Validation using satellite imagery and *in-situ* observations confirmed the model's quality and efficiency over timescales exceeding 25 days. The modeling results made it possible to construct a detailed spatial-temporal pattern of fuel oil distribution in the Black Sea. Most of the spilled oil was transported to the deep part of the Black Sea where depths exceeded 500 m. The specific features of M-100 fuel oil contributed to the exceptionally long period of active spreading phase and formation of secondary pollution sources, which require long-term ecosystem monitoring. The emergency response demonstrated the importance of applying FOTS to minimize environmental damage and underscored the need for developing similar regional forecasting systems for other regions of Russia.

Keywords: Volgoneft, oil pollution, fuel oil spill, satellite monitoring, trajectory modeling, propagation dynamics, Black Sea, Kerch Strait

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Introduction

On December 15, 2024, as a result of extreme weather conditions in the Kerch Strait, the largest accident involving oil tankers occurred in the Sea of Azov – Black Sea region. A southern storm with wind speeds exceeding 15 m/s and wave heights up to 3 m led to the destruction of two river-sea class tankers *Volgoneft-212* and *Volgoneft-239*. Each vessel was carrying more than 4300 t of M-100 fuel oil, leading to a large-scale environmental disaster in the Black Sea waters. Due to the action of storm waves, both vessels broke in half (Fig. 1, *a*), and about 2500–3000 t of fuel oil entered the sea [1, 2]. The sunken ship fragments became long-term sources of fuel oil pollution, creating conditions for the continuous release of oil products into the marine environment.

The specific properties of M-100 brand fuel oil determined the severe nature of the disaster. Fuel oil is relatively resistant to weathering processes (evaporation and dispersion), characterized by a high sulfur content of 0.5–3.5% and a density of 0.89–1 g/cm^3 at 20 °C, which is close to the seawater density. These properties determine the fuel oil behavior: it can remain in the marine environment for a long time without changing mass, partially sinking to the bottom when interacting with suspended matter, and partially remaining as suspension in the water column [3]. At low water temperatures in the winter season, fuel oil solidifies forming dense tar-like conglomerates that can persist in the marine environment for a long time [4].

A similar disaster occurred in this area on November 11, 2007. Then, as a result of the tanker *Volgoneft-139* sinking, between 1300 and 2000 t of fuel oil entered the waters. The primary consequences of the accident were most clearly manifested in the mass death of hydrobionts, especially seabirds [5]. Heavy fractions of fuel oil settled on the bottom, suppressing benthic communities. The long-term environmental consequences of the accident manifested over many years – fuel oil continued to release toxic substances, and studies showed the accumulation of petroleum hydrocarbons in the tissues of marine organisms [6–8].

However, unlike the 2007 disaster, when most of the oil products entered the limited waters of the Kerch Strait [7], the features of current variability in 2024 led to the fuel oil propagation over much more extensive coastal areas, which significantly complicated the liquidation of the accident consequences. After the disaster, fuel oil pollution was observed in various coastal areas from Yevpatoriya to Anapa, i.e., affecting more than 700 km of coastline. The unique ecosystem of the Anapskaya Peresyp Natural Park – the largest accumulative coastal landform along the Russian sector of the Black Sea coast of the Caucasus, extending from the Taman Peninsula to Cape Anapsky – was particularly severely affected [4, 9, 10]. Operational work for assessing the consequences of the disaster in this region in the first days after the accident was carried out by the Southern Research Centre of the Russian Academy of Sciences.

During the emergency response operations, specialists from the Ministry of Emergency Situations and the Marine Rescue Service relied heavily on operational forecasts of fuel oil transport trajectories. For this purpose, the Floating Object Tracking System (FOTS) for forecasting oil pollution transport, created at Marine Hydrophysical Institute (MHI) of RAS, and data from the monitoring system of the Azov–Black Sea region state, based on the operational sea dynamics models, were used. The forecast results demonstrated high quality of the calculations, confirmed by comparison with satellite images and data from in-situ observations on the state of beaches and the coastal zone, provided by the Ministry of Emergency Situations of Russia and the Marine Rescue Service.

The aim of this study is to reconstruct the chronology and spatial extent of fuel oil pollution resulting from the accident involving the Volgoneft vessels in the Kerch Strait on December 15, 2024, based on the use of FOTS for operational forecasting of oil spill transport, validation of the model predictions and assessment of the resulting environmental consequences.

The first part of this study describes the chronology of the fuel oil propagation after the accident on the Volgoneft vessels in December 2024 and presents the pollution areas of the Black Sea identified by modeling data and satellite measurements. The second part of the study presents a comprehensive assessment of the environmental consequences of the emergency fuel oil spill based on the results of field expeditionary research at the Anapskaya Peresyp, carried out by the Southern Research Centre (SRC) of the Russian Academy of Sciences, as well as the results of satellite observations of secondary pollution.

Data and methods

Expeditionary surveys conducted by the SRC RAS on January 22–24, 2025, were led by Academician G.G. Matishov. A coastal section exceeding 80 km in length, extending from Cape Panagia to the central beach of Anapa, was surveyed. Twenty-seven test pits were excavated, with documentation of sediment stratigraphy and identification of fuel oil layers. Quantitative accounting of fuel oil fragments sized 3–20 mm was carried out on control plots of 1 m². To assess air pollution by fuel oil vapors at a temperature of 10 °C, samples were collected through adsorbent tubes with subsequent analysis by gas pyrolytic chromatography (pyro-GC-MS) at 250 °C. Underwater research was carried out using the Chasing M2 remotely operated vehicle.

To simulate oil pollution transport, the specialized Floating Object Tracking System (FOTS), designed for forecasting the drift trajectories and transformation of oil products in the marine environment, was employed [11, 12]. The model is based on a Lagrangian approach to describing the movement of oil particles and includes a description of physical-chemical processes of oil product transformation, such as evaporation, oil film propagation and its emulsification.

The quality of oil pollution transport modeling critically depends on the accuracy of current field reconstruction and the incorporation of atmospheric forcing. Velocity fields were obtained from data produced by the Experimental Center for Marine Forecasts of the Azov–Black Sea Region at Marine Hydrophysical Institute of RAS [13]. These were supplemented by the data from the NEMO numerical model of the Azov–Black Sea basin, which assimilates satellite observations of sea level and sea surface temperature with a resolution of 5 km [14].

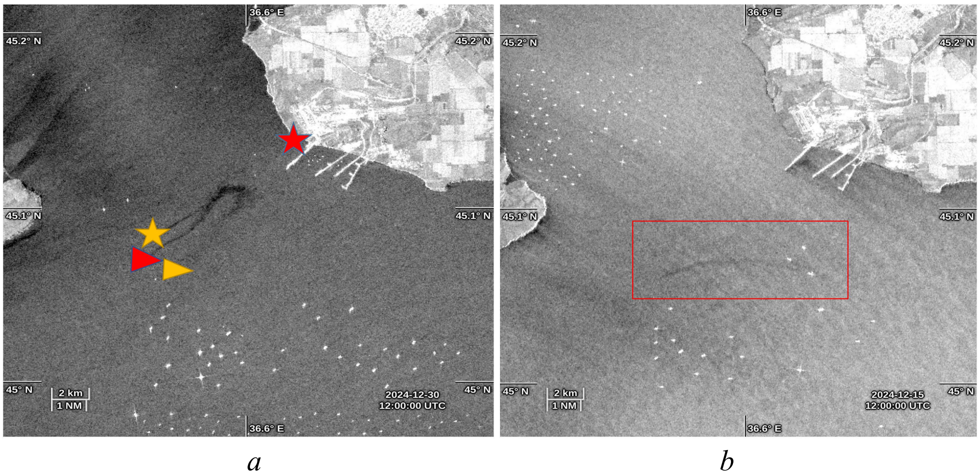
Wind speed and direction were obtained from the NCEP Global Forecast System (GFS) model, with a temporal resolution of 3 hours and a spatial resolution of 0.25°. The drift component of currents was determined based on the parameterization from [15], obtained from the analysis of a multi-year array of drifter observations. The FOTS assimilated data on the velocity of drift currents on the surface and modeling data on the upper horizon, the superposition of which determined the pollution transport in the upper layer.

For verification of the calculation results, satellite radar images from Sentinel-1, optical images from Landsat-8, coastal observation data, and reports from emergency rescue services were used. The observation data included results of visual inspection of shores and the sea surface, sampling of water and bottom sediments, as well as photo documentation of the state of beaches and the coastal zone, provided by the Ministry of Emergency Situations of Russia and the Marine Rescue Service and available in the public domain. Data from these services provided information on the actual impacts of pollution on coastal ecosystems and enabled estimation of pollutant arrival times at the shoreline.

Results and discussion

The cause of the accident (Fig. 1, *a*) was a southern storm with wind speeds exceeding 15 m/s and the waves it caused, with lengths over 20 m and heights up to 2.5–3.0 m, which exceeded the permissible values for river-sea class tankers (Fig. 2, *a*). As a result, the tanker *Volgoneft-212* broke in half between the 5th and 6th cargo tanks, after which both parts sank south of the Kerch Strait at 15–20 m depths. The vessel *Volgoneft-239* collapsed between the 3rd and 4th tanks, but the captain managed to steer the stern part to shallow waters in the area of the port of Taman, while the bow part with four tanks sank in the anchorage area (Fig. 1, *a*).

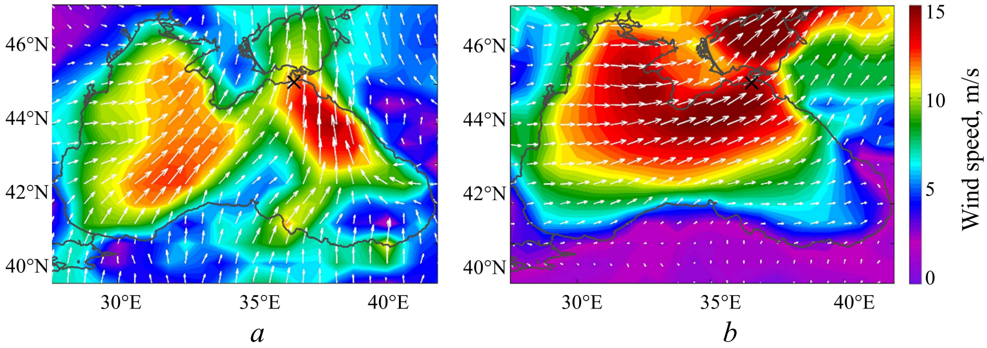
The sunken ship fragments became long-term sources of continuous release of oil products into the marine environment and the cause of fuel oil pollution. According to estimates by the Ministry of Transport of the Russian Federation, 2500–3000 t of fuel oil entered the sea [1].



F i g. 1. Location of the fragments of *Volgoneft-212* (yellow) and *Volgoneft-239* (red) tankers in the Sentinel-1 radar image for December 30, 2024; asterisk indicates the positions of tanker stern, and triangle – its bow (*a*); oil slick (highlighted in red rectangle) in the accident area during the first days after it (December 18, 2024) (*b*)

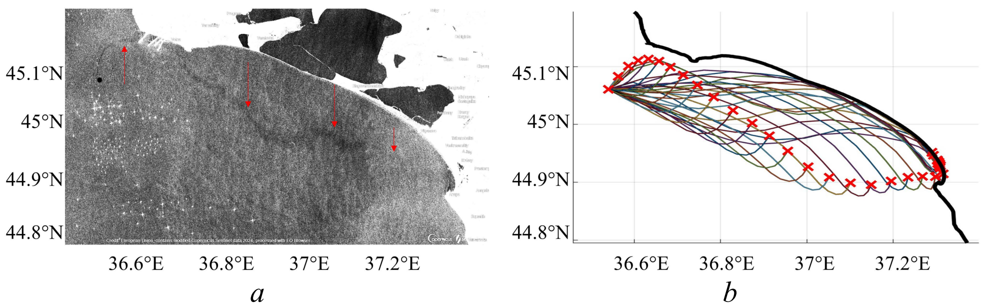
The Black Sea coast of Krasnodar Krai

After the tanker sinking on December 16–17, the wind changed direction to westerly (Fig. 2, *b*), and on December 18 to south-westerly. At the same time, wind speeds during the storm on December 16–17 exceeded 20 m/s. As a result, a region of intense westerly drift currents arose in the accident area, which transported fuel oil towards Krasnodar Krai.

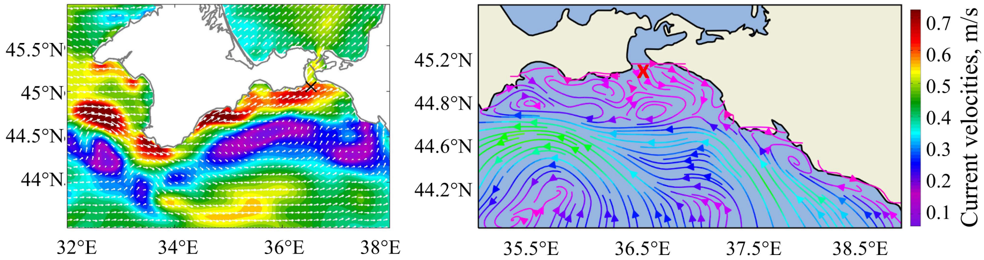


F i g. 2. Wind speed based on the GFS data for December 15, 2024, 06:00 UTC (*a*) and December 16, 2024, 18:00 UTC (*b*)

This transport was observed well in Sentinel-1 satellite images from December 18, 2024, in the form of an elongated slick propagating in an easterly direction from the stern of *Volgoneft-212* (see Fig. 1, *b*). The intensity of the radar signal in the slick area was significantly lower than in the surrounding waters. The slick is clearly visible despite the wind, indicating the presence of a dense oil film. By December 19, the length of the oil plume reached about 60 km (Fig. 3, *a*). The initially compact spill transformed into a long jet, which expanded as it moved away from the source under the mixing and spreading action and occupied an increasingly larger area. The image shows that the fuel oil slick initially moved towards the port of Taman but, according to rescue services, did not reach the coast and moved southeast towards Anapa.



F i g. 3. Spread of fuel oil towards Anapa after the accident in the Sentinel-1 image for December 19, 2024, arrows show the direction of jet displacement over time based on the model data (*a*); forecast calculation of fuel oil spread in December 15–19, 2024 based on the numerical modeling results and using the FOTS data, red crosses indicate the slick location based on modeling data at the time of satellite image, lines – the paths of fuel oil spread at the previous points in time (*b*)



a *b*

F i g. 4. Current velocities on the sea surface based on the FOTS calculations (*a*), and at the 10 m horizon based on the NEMO model data (the accident site is marked with a red cross) (*b*) on December 16, 2024

a *b* *c*

F i g. 5. Volunteers cleaning up fuel oil in Anapa [9, p. 48] *(a)*; fuel oil on the Kerch Peninsula coast [1] (*b*); Fiolent rocks in Sevastopol covered with fuel oil [2] (*c*)

[1] Crimea News Feed, 2024. [*Save Crimea. In the Leninsky District, Despite the Rain, People Are Cleaning Fuel Oil from the Beaches*]. [online] Available at: https://crimea-news.com/society/2024/12/22/1549629.html [Accessed: 07 November 2025] (in Russian).

[2] Spied on Kerch, 2025. *A Complaint about Fuel Oil Was Sent from Sevastopol*. [online] Available at: https://smartik.ru/kerch/post/225312996 [Accessed: 07 November 2025] (in Russian).

The results of numerical modeling of the fuel oil jet position on the date of the satellite image are represented in Fig. 3, *b*. The slick position, calculated from the modeling data, coincided well with the satellite data. The model results showed that in the first days after the accident, fuel oil spread from a continuous source located in the area of the *Volgoneft-212* stern. The oil jet position constantly displaced due to changes in prevailing winds. At times preceding the image, this jet was located somewhat further north, which led to the initial arrival of fuel oil on the coast in Blagoveshchenskoye, then in Vityazevo, and then directly in Anapa.

As mentioned above, the main cause for the observed fuel oil transport was the action of drift currents with a velocity of 0.5–0.6 m/s, caused by intense westerly winds (Fig. 4, *a*). Geostrophic currents at the time of the accident also contributed to the oil transport to the west. According to modeling data and satellite altimetry [9], in mid-December, the Kerch anticyclone was located southward of the strait in the Black Sea. This gyre transported pollution on its northern periphery at velocities of 0.1–0.15 m/s (Fig. 4, *b*). Note that such current velocities were observed almost throughout the water column to the bottom, so the predominant transport in the bottom water layers was also directed eastward.

Information about the easterly direction of the slick transport and the threat to the Krasnodar Krai, obtained from operational calculations by Marine Hydrophysical Institute of RAS on December 17, was forwarded to the relevant services. The forecast of model calculations about the spread of pollution on the coastal section from Vityazevo to Anapa was confirmed: on December 18–19, significant volumes of fuel oil began to arrive on the shore (Fig. 5), leading to large-scale pollution of the Anapskaya Peresyp coastline [9].

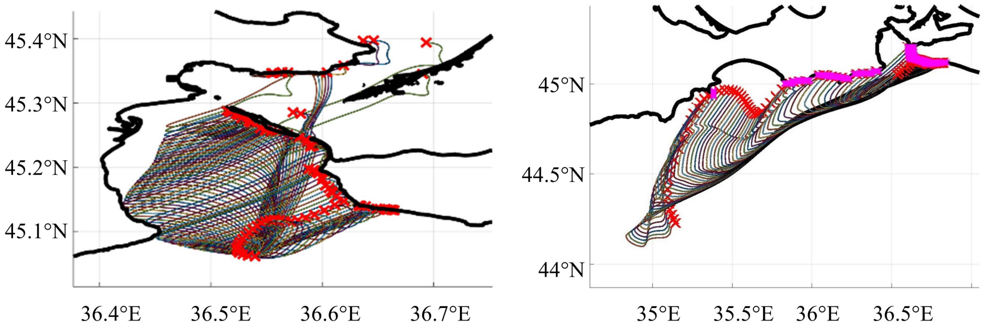
For cleaning the beaches in Anapa, according to official data, more than 170,000 t of fuel oil-sand mixture were removed; beach cleaning in Anapa continued until mid-2025. Some environmental consequences of this largest disaster for Anapa are described in detail in the monograph of the SRC RAS [9].

Kerch Peninsula

From December 19–21, the wind shifted to a southerly direction, causing the fuel oil to move northward (Fig. 6, *a*). The stern of the *Volgoneft-212* continued to be the main source of pollution. The modeling results predicted the penetration of fuel oil pollution into the Kerch Strait waters. According to the calculations, most of the fuel oil should have reached the coast of Tuzla and the port of Taman area. However, no information about pollution in these areas was received from open sources. Part of the fuel oil entered the Tuzla Spit channel to the right of Tuzla Island and moved through it to the northern part of the strait. Indeed, six days after the accident, on December 21, coastal observations confirmed fuel oil pollution in the area of Kerch (see Fig. 5, *b*).

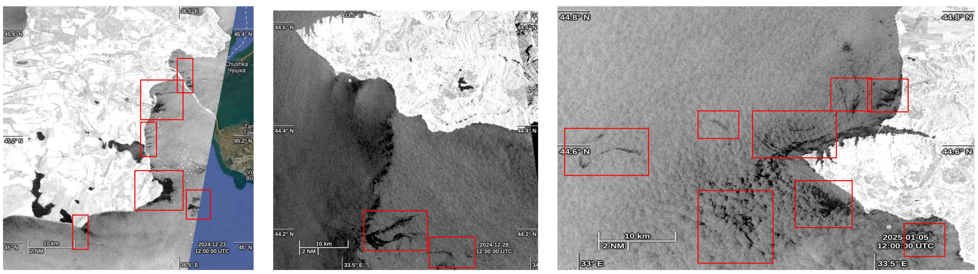
Fuel oil slicks were recorded in the water and on the shore in the area of the port of Krym and the fortress of Yeni-Kale. The operational forecast of the FOTS promptly predicted the oil arrival on the shore in the port of Krym area, which allowed the Ministry of Emergency Situations to concentrate the necessary grouping of forces to eliminate the consequences of coastal pollution.

A change in wind direction to easterly on December 23–25 led to the movement of pollution to the west. As a result, the fuel oil that was in the Kerch Strait was washed ashore on the western coast of the strait. Its slicks are clearly visible in the Sentinel-1 image for December 23 (Fig. 7, *a*). As can be seen, elongated zonally oriented slicks are observed along the entire western coast of Kerch. The largest area of oil slicks was in the area of Cape Takil, which was also confirmed by observations of the Marine Rescue Service. Partially, oil slicks also spread southwards of the Kerch Peninsula (see Fig. 6, *b*), resulting in the pollution affecting the coastal part of the reserve from Cape Opuk to Cape Takil and the coast of Feodosia, where focal releases of fuel oil were recorded.



a *b*

F i g. 6. Numerical modeling results for the sunken stern section of *Volgoneft-212* from December 19–24, 2024 (*a*) to December 26, 2024 – January 3, 2025. Purple crosses indicate the area of oil pollution along the coast, red dots – the final position of oil particles, and lines are their movement paths (*b*)



a *b* *c*

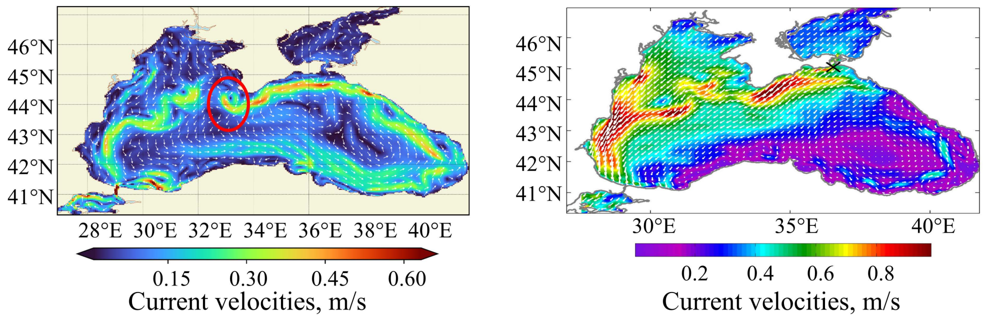
F i g. 7. Images of the Kerch Strait on December 23, 2024 (*a*), the areas south of Cape Sarych on December 29, 2024 (*b*), and near Sevastopol on January 5, 2025 (*c*) taken by the Sentinel-1 satellite. Red rectangles show the positions of oil slicks

City of Sevastopol

On December 25–26, intense north-easterly winds characteristic of this period, with up to 10–15 m/s speeds, arose over the Kerch Strait. Such wind direction contributed to the fuel oil transport from the shore to the open sea and was considered favorable, since it was assumed that in the deep part of the Black Sea basin, the fuel oil would sink into the deep hydrogen sulfide layer, where it would be processed by bacteria, and the coastal part would no longer be affected.

However, on January 4, 2025, reports about the presence of fuel oil pollution in the western part of the Black Sea on the coast in the area of Balaklava (Sevastopol) at a distance of more than 300 km from the source were received. Sentinel-1 image for December 29, 2024, made it possible to identify an area of fuel oil pollution southwards of Cape Sarych, which eventually reached the shore in the Western Crimea (Fig. 7, *b*). The fuel oil slick had a comma-like shape measuring 12 × 10 km. In the image, the slick was on the boundary of a wind front, so only the eastern part of the pollution that fell into the calm zone was visible. During the period from the beginning of the easterly winds (December 23) to the date of the image (December 29), this slick moved more than 280 km, i.e., the estimated velocity of its propagation exceeded 60 cm/s. The satellite image from Sentinel-1 for January 5, 2024, confirmed the presence of radar signatures characteristic of oil pollution southward of Cape Chersonesus, indicating mass pollution in this area (Fig 7, *c*).

Numerical modeling performed using NEMO model complex revealed physical mechanisms that provided such rapid transport of pollution over such a long distance. The intensification of north-easterly winds from December 23 to 25 played a key role. These winds cause a significant increase in Ekman pumping over the basin due to strong cyclonic shear on their southern periphery [16], which leads to an intensification of the large-scale cyclonic circulation of the basin. As a result, the Rim Current velocity in the area of the southern coast of Crimea increased from 0.2–0.3 m/s to 0.5–0.6 m/s (Fig. 8, *a*), which, in combination with the south-westerly wind drift, provided a total transport velocity of pollution equal to up to 0.7–0.9 m/s (Fig. 8, *b*).



a *b*

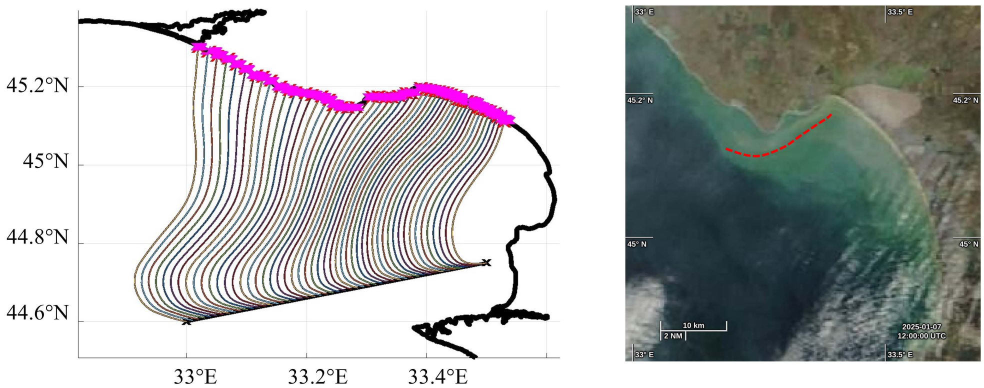
F i g. 8. Maps of surface currents without accounting for drift velocity of currents (*a*) (red oval indicates the Sevastopol anticyclone position) and with inclusion of drift velocity of currents (*b*) for January 4, 2025

Near the southwestern tip of Crimea, the fuel oil was drawn into the orbital motion of the Sevastopol anticyclone [17, 18], which contributed to the fuel oil transport towards Sevastopol on January 1–5 (Fig. 8, *a*). In addition, south-westerly winds on January 1–3 also caused the displacement of fuel oil pollution from the continental slope zone towards the shore.

This led to significant pollution of the coastal zone of Sevastopol with fuel oil, including the areas of Fiolent, Balaklava, Park Pobedy, which was particularly severe on the western shore near Kacha village, where several repeated releases of fuel oil were observed. The impact on the coastal zone of Fiolent was characterized by pollution of rocky sections of the coast (see Fig. 5, *c*), which differed significantly from the situation on the sandy beaches of Anapa. Fuel oil formed characteristic stripes and spots on the surface of rocks in the wave splash zone, creating specific problems for cleanup operations. The results of laboratory studies performed by Rospotrebnadzor confirmed the identity of the fuel oil composition with that transported on the *Volgoneft* tankers.

Western coast of Crimea

From January 6, 2025, southerly winds began to blow in the area of the western coast of Crimea. Forecast calculations predicted the fuel oil arrival in the area of Yevpatoriya, which was recorded by coastal services on January 9, 2025. However, most of the pollution reached the coast westwards of the city, which was associated with the emergence of a powerful alongshore jet 1–2 km wide southwards of Yevpatoriya. Such an alongshore current, often arising in this area under effect of south-westerly winds [19], acted as a frontal barrier, protecting the city (Fig. 9). As a result, most of the fuel oil reached the western part of the city's coast and the area of Okunevka, where mass pollution of the beach with fuel oil clots was recorded. The timely forecast data transfer from Marine Hydrophysical Institute of RAS to the Ministry of Emergency Situations 2–3 days in advance made it possible to prepare forces and means for pollution elimination.



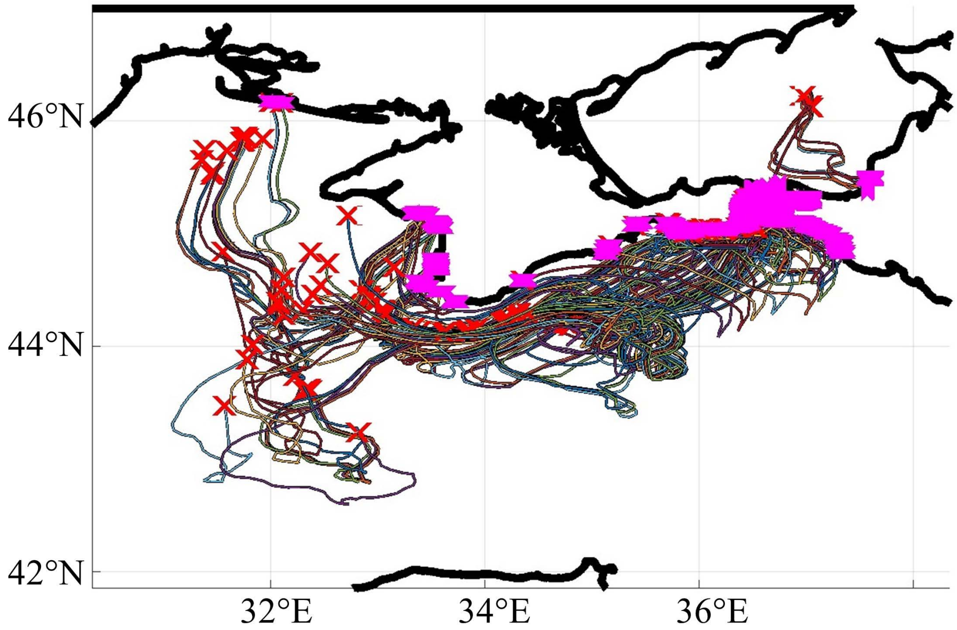
a *b*

F i g. 9. Numerical forecast of fuel oil slick drift originating from the contamination area detected in the Sentinel-1 image for January 5–9, 2025 (see Fig. 7, *c*), purple crosses show the fuel oil pollution zone along the coast; black strait line indicates the initial position of fuel oil pollution (*a*); the coastal stream off the Yevpatoriya coast which acted as a dynamic defense for the city western part in the MODIS image for January 7, 2025 (marked with a red dashed line) (*b*)

General characterization of pollution areas

The overall trajectory of pollution, simulated from the sunken stern section of *Volgoneft* between December 15, 2024 and January 29, 2025, is shown in Fig. 10. Notably, the primary transport pathway skirted Crimea, almost without affecting its resorts along the southern coast, which experienced the least impact under these circulation conditions.

Despite the fact that the main part of the pollution moved southwards of the peninsula, in some of its areas, according to eyewitnesses, minor focal pollution was recorded (in the areas of Gaspra, Foros, Sudak), caused, according to modeling data, by the impact of southerly winds.



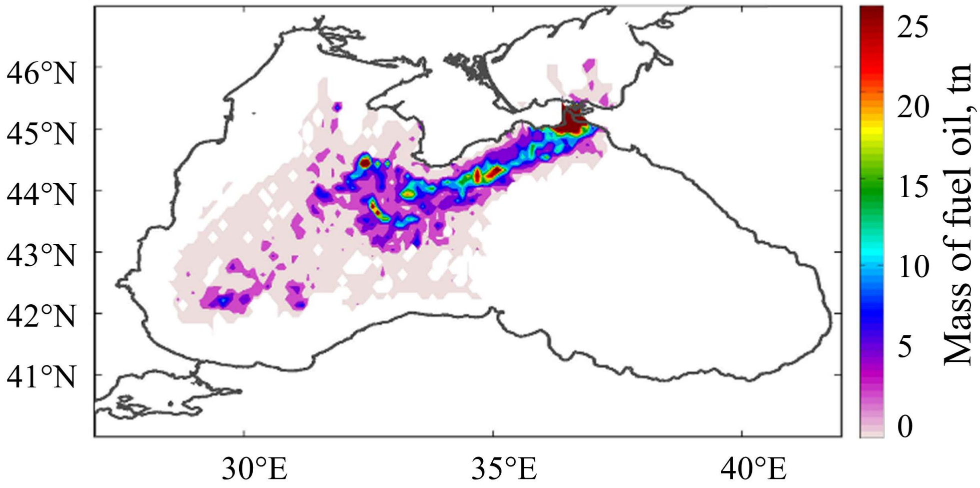
F i g. 10. Overall trajectory of fuel oil dispersion, as simulated from the sunken stern section of the *Volgoneft* tanker between December 15, 2024 and January 29, 2025. Purple crosses indicate the area of oil pollution along the coast, red dots – final position of oil particles, lines represent their movement paths

The total duration of pollution spread active phase was more than 25 days, which significantly exceeds the typical time scales for most cases of oil pollution. This fact reflects the specific properties of M-100 fuel oil, characterized by slowed weathering processes. As a result, the disaster on the *Volgoneft* tankers in December 2024 led to extensive coastline pollution stretching over 700 km.

The system we applied made it possible to promptly predict the pollution dispersion to the main resort areas (Anapa, Kerch, Sevastopol, Yevpatoriya) for a long period of more than 25 days, which speaks to the high quality of the models and modeling methods used. Throughout the month, the fuel oil did not undergo significant weathering and remained active, which caused its dispersion and pollution of beaches even at a distance of over 300 km from the source. After January 10, the modeling data indicate further pollution displacement to the southwest into the open sea under effect of prevailing north-easterly winds, which could lead to pollution spread to the southeastern or southern part of the sea by mid-February 2025.

In addition, according to the modeling results, fuel oil in the western part of the sea partially moved north and could reach the coast of the Kherson region in the area of Zhelezny Port on January 29–31. However, no signals of its spread to these coastal areas were received. Apparently, the main share of fuel oil had already weathered, reached the shore, or sank into the deep layers of the sea by this time.

The modeling results allowed to construct a detailed picture of the spatio-temporal distribution of fuel oil pollution in the waters of the Azov–Black Sea basin (Fig. 11).



F i g. 11. Simulation-derived total estimate of fuel oil mass that passed through each cell of a grid (5 × 5 km)

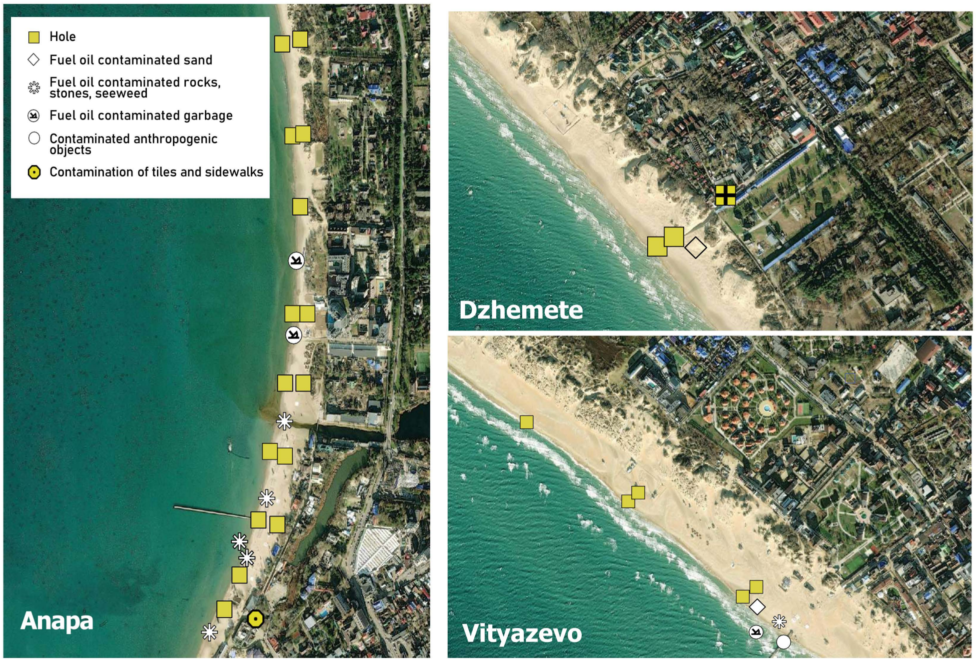
For a quantitative assessment of pollution distribution, the water area was divided into a regular grid of squares sized 5 × 5 km, in each of which the volume of oil that passed through this area during the entire modeling period was calculated. It was assumed that the total amount of spilled oil was approximately 3000 t. Due to the uncertainty in assessing the temporal dynamics of fuel oil release from the source, the calculation scenario assumed an exponential decay of the source intensity, reflecting the gradual depletion of fuel oil reserves in the damaged tanks and natural sealing of the damages.

The modeling results revealed that most of the pollution spread over the Black Sea deep part where depths exceed 500 m. This circumstance has important ecological significance, since the Black Sea deep part below 150–200 m is characterized by anaerobic conditions with high hydrogen sulfide content. Under such conditions, fuel oil that has settled to the bottom can undergo anaerobic biodegradation by specialized bacterial communities, which reduces the long-term environmental impact of the pollution.

The most critical situation was observed in shallow coastal zones where depths do not exceed 50–100 m. The interaction of suspended matter with fuel oil leads to an increase in its density and sinking to the bottom. Under such conditions, settled fuel oil can persist in bottom sediments for a long time, creating the potential for secondary pollution when hydrodynamic conditions or temperature regimes change. Particularly high concentrations of bottom pollution can be found in the areas of Anapa and the Kerch Strait, where the combination of shallow conditions and intense hydrodynamic impact contributes to the resuspension of bottom sediments.

Secondary pollution in the accident area

A major problem in liquidating the accident consequences is the fuel oil penetration into the soil and bottom sediments. One of the first works on assessing the pollution of the coastal zone of beaches and the seabed was the expeditionary work of SRC RAS under the leadership of Academician G.G. Matishov. From January 22 to 24, 2025, a comprehensive survey of fuel oil pollution consequences at the Anapskaya Peresyp coast was carried out. The research covered a section of more than 80 km long from Cape Panagia to the central beach of Anapa (Fig. 12).



F i g. 12. Expeditionary monitoring of the consequences of emergency oil spill (January 22–24, 2025) performed by SRC RAS at the central beach in Anapa and at the beaches in villages Dzhemete and Vityazevo [9, p. 36–37]

During the expedition, 27 test pits were excavated with documentation of sediment stratigraphy and fixation of fuel oil layers. It was found that fuel oil fragments are not only present on the beach surface but also occur in coastal deposits at 12–35 cm depth at a distance of up to 20 m from the water edge. The formation of buried fuel oil layers occurred at the stage of storm wave attenuation, when December storm waves 4–6 m high and the alongshore sediment flows induced by them buried the fuel oil under a layer of sand 15–50 cm thick.

Based on the survey results, five main types of fuel oil pollution of the coastal zone were identified:

1) buried pollution in the form of separate lenses and 1–2 cm thick fuel oil layers at depths of 12–35 cm, formed during its burial by storm waves under a layer of sandy sediments;

2) pollution in the form of fuel oil-sand aggregates sized from 3 to 20 mm, which moved under the action of hydrodynamic and aeolian factors and covered the surface of beaches, alongshore bars, and dunes. The of distribution area of such aggregates is 3–4% of the total surveyed territory;

3) pollution by oil products that have penetrated into groundwater, leading to the pollution transit into underlying horizons. This pollution is determined by a characteristic sharp smell even in the absence of visible traces of fuel oil on the ground surface;

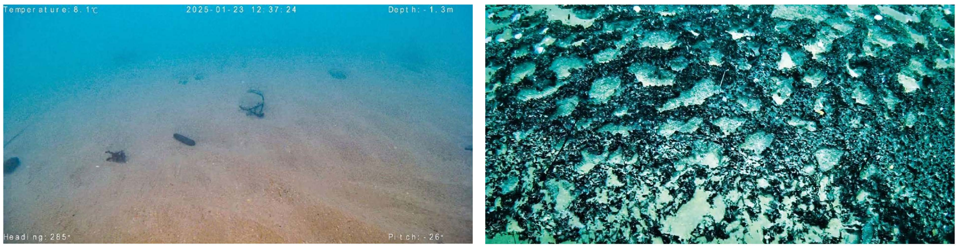
4) pollution of marine vegetation and anthropogenic objects: fuel oil was found on algae, mollusk shells, fragments of rigging, and various marine debris. The piers in the area of the city beach of Anapa and Vityazevo were completely covered with a thick layer of fuel oil;

5) fine-dispersed pollution, partially granulated to the size of sand fractions less than 3 mm, located in the thickness of beach deposits.

Quantitative pollution assessment was carried out on control plots of 1 m^2 by complete collection of fuel oil inclusions sized 3–20 mm. It was found that the content of fuel oil fragments on the surface varied from 15 to 50 g/m^2 depending on the plot location. The total mass of fine fuel oil scatter on the investigated coastal strip with an area of 2.1 km^2 was estimated at 83.1 t, including 57.8 t on the surface and 25.3 t in a buried state at a depth of 12–15 cm.

The pollution of the unique sand dunes of the Anapskaya Peresyp, which have the status of a specially protected natural area, is of particular concern. Scatters of fuel oil fragments sized 3–20 mm, accumulating mainly at the base of the dunes facing the sea, were found on the dunes. Under conditions of strong dry winds characteristic of this region in the warm season, these pollutions will move from the foot and windward slope upwards and further to the back side of the dunes, spreading pollution inland.

Underwater research of the coastal shelf, performed by the Chasing M2 remotely operated vehicle, revealed fuel oil pollution on the seabed (Fig. 13).



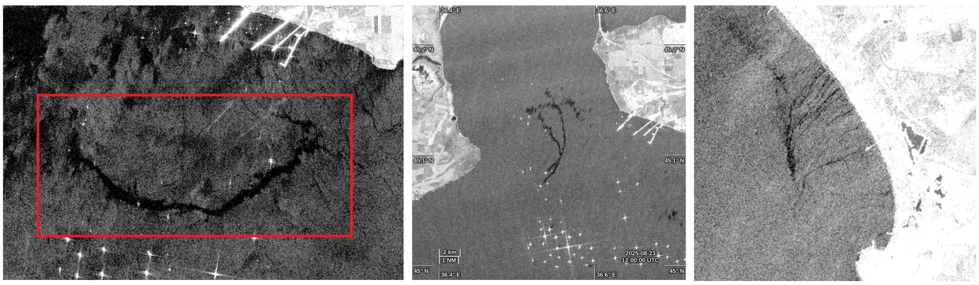
a *b*

F i g. 13. Fuel oil-sand fragments of 4–6 cm length recorded at the 5 m distance from the water line and at the 0.8 m depth by an underwater drone during the expedition of SRC RAS [9, p. 88] (*a*); fuel oil accumulations in the areas of village Verkhnee Dzhemete beaches [3] on February 3, 2025 (*b*)

[3] Telegram, 2025. *AnapaKite Team*. [online] Available at: https://t.me/anapakiteteam/1222 [Access: 07 November 2025] (in Russian).

In the water area near Stanitsa Blagoveshchenskaya at a distance of 2.5–4 m from the water edge at up to 0.9 m depths, fuel oil-sand fragments (pellets) 4–6 cm long, moving along the bottom surface, as well as scraps of fine-mesh netting soaked in fuel oil and attached to the ground, were recorded. A group of divers led by Alexander Velichko [20] discovered near Verkhnee Dzhemete a fuel oil ridge 100–150 m long and 5–20 cm thick at distance of 300–350 m from the shore at 2.5 m depth, in places covered by sandy sediments. The results of chemical studies carried out by the group from the Institute of Oceanology of RAS on March 1–2, 2025 [4], also confirmed a high concentration of aliphatic hydrocarbons and polycyclic aromatic hydrocarbons in sediments and seawater near Anapa.

An important aspect of the disaster long-term impact is the ability of settled fuel oil to rise again when thermodynamic conditions change. As already noted, M-100 fuel oil is characterized by a pronounced temperature dependence of density; when heated, its density can decrease to values close to the sea water density, creating conditions for the bottom pollution floating-up.



a *b* *c*

F i g. 14. Sentinel-1 images showing the appearance of secondary pollution in the areas of Kerch Strait on April 24 (the slick location is highlighted with red rectangle) (*a*) and August 23, 2025(*b*), as well as the Anapa coast on April 14, 2025 (*c*)

Indeed, radar observation data starting from April 2025 record the appearance of signatures characteristic of fuel oil pollution in the Kerch Strait, in the area of the initial pollution source, and in the coastal zones of Anapa (Fig. 14).

In the zone where the stern of *Volgoneft-212* is located, such signatures are recorded almost every day in calm weather (Fig. 14, *a*, *b*), indicating the presence of a constant secondary source of pollution. Near Anapa, secondary pollution occurs episodically. In these cases, they are most often noted at the shelf edge, at a depth of 20–30 m (Fig. 14, *c*). The detection of fuel oil burial zones on the bottom is important, as these areas are a probable source of secondary pollution.

One of the important causes for the fuel oil deposition is its adsorption on suspended matter particles entering the water column due to the resuspension of bottom sediments. Resuspension is most effective in shallow areas, so the shelf boundary is a natural zone of in-situ between fuel oil and suspended matter. It is here, probably, that the main deposition of fuel oil occurred. During the period of its spread towards the Anapa coast, intense westerly and southerly winds were acting, contributing to shore erosion and resuspension of suspended matter. Fig. 15 presents an optical MODIS image for December 18, 2024, at the moment preceding the accident.

F i g. 15. Suspended matter in the MODIS optical image for December 18, 2024. Red line indicates the in-situ zone between the sea waters and those with high concentration of suspended matter near the coast

Near Anapa, significant concentrations of suspended matter were observed (red line), acting as a natural buffer that limited fuel oil penetration onto the shoreline and promoted its burial in bottom sediments. For waves with wavelengths of 20–30 m, a sharp increase in suspended matter concentration due to resuspension occurred along the 10–15 m isobaths, where the most rapid fuel oil deposition apparently took place. Currently, Marine Hydrophysical Institute of RAS is developing models to simulate the transport of fuel oil-contaminated bottom sediments in this area.

Conclusion

The scale of the consequences of the 2024 disaster exceeded the one of all previous cases of anthropogenic oil pollution in the Russian sector of the Black Sea. The accident led to the pollution of more than 700 km of coastline and the release of 2500–3000 t of M-100 fuel oil into the marine environment. For the first time in the conditions of the Azov–Black Sea basin, a case of long-distance transport of fuel oil over more than 300 km was documented. The revealed duration of the active phase of fuel oil pollution spread (more than 25 days) significantly exceeds the known time scales of similar incidents and is due to the slowed weathering processes of this fuel oil grade.

The numerical complex, including the dynamics model of the Azov–Black Sea basin of the Experimental Center for Marine Forecasts of Marine Hydrophysical Institute of RAS and FOTS for oil pollution transport, demonstrated high accuracy in forecasting the oil pollution spread. The time and place of fuel oil arrival on the coasts of Anapa, Kerch, Sevastopol and Yevpatoriya were successfully predicted. Verification of the results based on satellite data and in-situ observations confirmed the quality of the model on time scales exceeding 25 days, which made it possible to promptly warn emergency rescue services and concentrate forces in the predicted pollution areas, saving funds for the liquidation of the disaster consequences.

Five main types of fuel oil pollution of the coastal zone were identified, including buried pollution at depths of 12–35 cm, forming long-term sources of secondary pollution with a total mass of 25.3 t in the territory under study. Underwater fuel oil accumulations on the coastal shelf, creating constant sources of secondary pollution and posing a threat to benthic biocenoses, were discovered. The discovery of underwater fuel oil accumulations and the registration of secondary surface pollution in the spring-summer period of 2025 confirm the hypothesis of the formation of long-term pollution sources with a cyclical nature of impact on marine ecosystems. The temperature dependence of M-100 fuel oil density creates prerequisites for the seasonal reactivation of bottom pollution during summer heating of water masses, which is confirmed by satellite measurements.

The obtained results are of great importance for improving systems for monitoring and forecasting the oil pollution spread in the marine environment, as well as for developing more effective methods for liquidating the consequences of emergency spills of heavy oil products. The long-term nature of the identified secondary pollution sources requires organization of constant monitoring of the state of marine environment and coastal ecosystems in the disaster impact zone.

Declaration of AI use

To support the integrity of information presentation in the paper, the authors used LLM DeepSeek (version V3.2). The model was applied only for stylistic support of the manuscript text, not for generating data or their interpretation. The text edited using AI was critically analyzed, revised and verified by all authors.

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Sergey V. Stanichny – satellite imagery analysis and model validation

Anton L. Kholod – current field calculations

Aleksey V. Kleshchenkov – field research at the Anapskaya Peresyp

Valery V. Kulygin – field research at the Anapskaya Peresyp

Oksana S. Puzina – analysis of circulation fields in surface and deep layers

Artem I. Mizyuk – hydrodynamic model configuration

The authors have read and approved the final manuscript.
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