

Original article

Oil Pier at Cape Manganari (Sevastopol) as a Source of Anthropogenic Suspension and Dissolved Oil Products Based on Numerical Modeling and Expedition Data

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Abstract

Purpose. The purpose of the study is to identify the patterns of propagation of anthropogenic suspended matter and dissolved oil products conditioned by operation of the oil pier located at Cape Manganari in the Sevastopol region, to assess the linear scale of its impact on the surrounding water environment, as well as to determine the parts of water area which are subjected to maximum anthropogenic load.

Methods and Results. Application of the numerical modeling methods, namely the Felzenbaum three-dimensional barotropic linear model generalized for the case of Rayleigh friction, made it possible to reveal the patterns of anthropogenic suspended matter distribution by wind currents from the area where the oil pier was located. It is established that depending on the wind direction, the suspended matter flow spreads from the head of oil pier to the open sea and penetrates into the neighboring bays. The data obtained during the expeditions in the adjacent Kazachya, Kamyshovaya and Abramov bays permitted to examine the structure of the concentration fields of suspended matter and dissolved oil products as an indirect indicator of distribution of these substances. The most polluted areas of the region under study were revealed. The radius of the oil pier impact upon the surrounding water area is assessed.

Conclusions. The modeling results are confirmed by the expedition research data. According to the performed model calculations and the analysis of observational data, the radius of pier impact upon the surrounding water environment is estimated to be 0.5–1.0 miles, and the maximum anthropogenic load falls on the northern halves of the Kazachya and Kamyshovaya bays. At the north-eastern and northern winds, the anthropogenic suspended matter and oil products are accumulated in the northern part of Kazachya Bay, at the western and north-western winds, these pollutants penetrate into Kamyshovaya Bay, and when the wind is southwestern – into Abramov Bay.

Keywords: modeling, wind, total suspended matter, oil pier, Sevastopol bays, Black Sea

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Introduction

The history of active comprehensive studies of pollution in the waters of Sevastopol bays and open coastal areas spans more than three decades. These studies have been and are being conducted at both empirical (contact and satellite) and modeling levels [1–5].



At present, an understanding has been formed of the main sources and chemical composition of pollutants; of the propagation, accumulation, and dispersion of contaminants; and of the degree of pollution of individual parts of the studied water area.

The results of long-term research on pollution sources in the Sevastopol region, obtained mainly by hydrochemical methods, are summarized and presented in [5]. According to the authors, not all existing sources polluting the water area off the Sevastopol coast have been identified.

During expeditions carried out in 2004–2019 with the participation of the authors of this work, in the area to the northwest of the Heracles Peninsula, seaward of Cape Manganari, and in the water areas of adjacent bays (Kazachya, Kamyshovaya, Abramov), local maxima of anthropogenic origin were constantly recorded in the total suspended matter (TSM) field. Dissolved oil products (DO) were also found there [6–8]. The presence of pollutants in this water area is likely related to the oil pier located at Cape Manganari, which separates Kazachya and Kamyshovaya bays (Fig. 1).

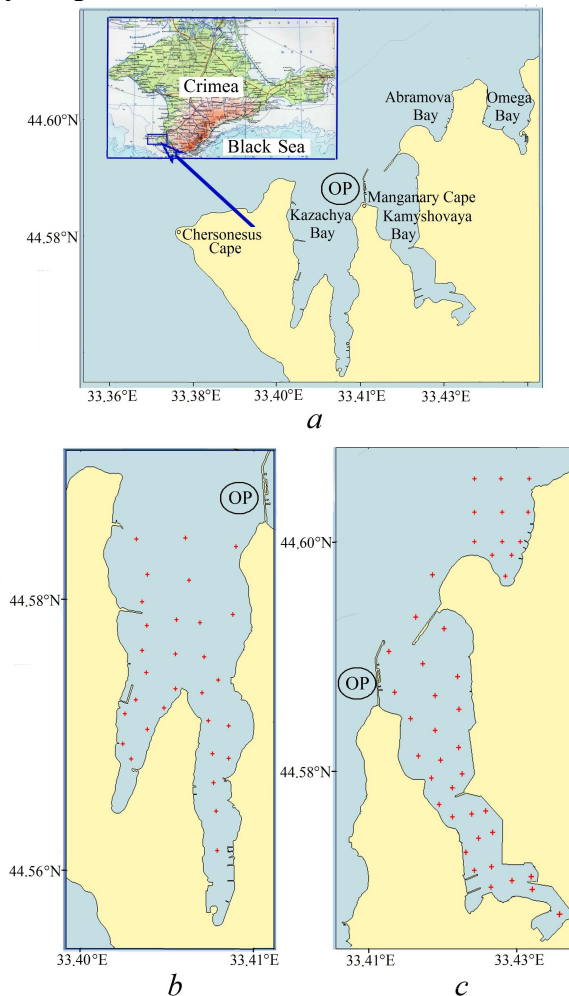


Fig. 1. Studied area (a) and schemes of the oceanographic survey stations in Kazachya (b), Kamyshovaya and Abramov bays (c). OP – oil pier
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In [5], this object was neither studied nor indicated as a source polluting the waters of the Sevastopol region. However, it is known [9–11] that significant sources of coastal water pollution are associated with factors related to fleet operations, port operations, and onshore loading and unloading complexes.

The purpose of this work is, based on numerical model experiments, to examine the propagation patterns of anthropogenic suspended matter by wind currents from the area adjacent to the oil pier into the open coastal waters and adjacent bays; to estimate the linear scale of the pier's impact on the surrounding water environment; to compare the modeling results with expedition data; and to identify the parts of the water area that experience the maximum anthropogenic load.

Note that TSM is considered one of the most effective indicators of pollution in coastal areas of oceans, seas, and freshwater bodies [12].

Initial data and research methods

The pier under consideration is a meridionally oriented solid concrete wharf ~ 450 m long, built at Cape Manganari. In essence, it is an artificially created headland, and like any headland, this object concentrates wave energy [13], forming a local source of intense stirring of the water column in the coastal zone (Fig. 1).

Anthropogenic suspended matter and other pollutants also enter the water during fleet operations – due to vessel movement, mooring, and loading and unloading operations – and with storm runoff. To identify the features of anthropogenic suspended matter propagation from this source, numerical modeling methods were used.

Due to the shallowness of the area under study and the homogeneity of the water column, currents are mainly determined by bottom topography as well as wind direction and speed. We assume that the advection of a pollutant is carried out by steady currents, since three hours are sufficient for the establishment of a drift current, and the development time of a gradient current for shallow waters does not exceed 10–12 hours. To calculate currents, we use the Felzenbaum three-dimensional barotropic linear model, generalized to account for Rayleigh friction [14].

At the sea surface, which is a stream surface, the tangential wind stress is balanced by turbulent friction in the water. At the bottom, a no-slip condition is applied. At solid lateral boundaries of the basin, a soft impermeability condition (zero normal component of the total flow) is imposed. At open boundaries, a free-flow condition is imposed. Details of the algorithm are given in [14].

The barotropic model satisfactorily describes water dynamics not only in winter but also in spring, when vertical gradients are still small, and in autumn, when the pycnocline drops below the mean depth of the area. Baroclinic effects are significant only in summer.

The process of suspended matter propagation due to currents and turbulent diffusion is described by the equation in divergent form [15]:

$$C_t + (uC - \mu C_x)_x + (vC - \mu C_y)_y + ((w + w_c)C - \kappa C_z)_z = 0,$$

where C is suspended matter concentration; μ is horizontal, κ is vertical turbulent diffusion coefficients; w_c is the settling velocity of suspended matter; u , v , and w

are current velocity components along the coordinate axes. The pollutant release occurs at a given point $x_1, y_1; z = 0, C = C_0$. At lateral boundaries and at the bottom, zero-flux conditions are imposed. At the initial time, the suspended matter concentration is zero.

The suspended matter source is located at the northern tip of the pier. The suspended matter concentration at the source was taken as 100 arbitrary units. We are interested not in absolute values but in the dynamics of distribution patterns.

Wind stress is assumed to be uniform, since the characteristic scale of wind variation is much larger than the scale of the study area. Numerical experiments were performed for winds from the 8 main directions. We assume $\tau = 1$ dyne/cm² (corresponding to a wind speed of $\sim 6\text{--}9$ m/s). The calculations were performed for a two-day period.

Note that similar models, both domestic and foreign [4, 16–18], have been widely used in studies of water and suspended matter dynamics in coastal regions of oceans and seas.

It is known [19] that the dissolved fraction of oil products is sorbed onto suspended matter and is transported together with this suspended matter in the water column. This property allowed us to trace the pathways of DO product propagation based on the results of modeling the suspended matter distribution.

The processes of propagation and accumulation of pollutants in the studied water area were also examined by analyzing the actual concentration fields of TSM and DO products based on data from three expeditions. Two of them were conducted by Marine Hydrophysical Institute and Institute of Biology of the Southern Seas in Kazachya Bay in August 2004 and September 2018; the third expedition was carried out by Marine Hydrophysical Institute jointly with the Institute of Natural-Technical Systems in the water areas of Abramov and Kamyshovaya bays in November 2019 (Fig. 1).

During the expeditions, *in situ* TSM measurements were carried out using the “Kondor” optical probing system (<http://ecodevice.com.ru/ecodevice-catalogue/multiturbidimeter-kondor>). The sampling resolution in depth was 0.1 m, and the accuracy of TSM concentration measurements was ± 0.2 mg/L.

There is a simple method for identifying polluted areas in coastal waters of oceans and seas, as well as in freshwater bodies, which is widely used in international practice. In the concentration field of the studied substances, such areas are identified as local maxima of non-natural origin [20]. The authors of that work use the term “pollution” to refer to two forms of aquatic contamination – *contamination* and *pollution*.

In using the term “pollution”, we adhere to the definition of *contamination* – the presence of a substance where it should occur: either it is not naturally present, or its concentration is above the background level. *Pollution* is also contamination that leads or may lead to adverse biological consequences for local communities.

In the analyzed situations, anthropogenic TSM was distinguished in the horizontal distribution fields of this quantity by local maxima. The degree of anthropogenic impact on a particular part of the studied water area was estimated by the ratio of the maximum concentration to the TSM concentration with the minimum anthropogenic component, which we conditionally call

the natural background. The natural background TSM concentration in the coastal waters of the Sevastopol region is 0.8 mg/L [21].

The concentration of DO products was determined in water samples taken from the sea surface under laboratory conditions using the traditional UV-fluorescence method [22]. This value is expressed in relative units (rel. units) and indicates how many times the measured content of DO products exceeds their concentration in the open waters of the central Black Sea, which is taken as unity. The accuracy of DO product concentration measurements is ± 0.005 rel. units.

All expeditions were conducted from small vessels. The studied depth range was 1–27 m.

Discussion of results

The results of numerical modeling are considered – each case for the 8 principal wind directions, shown in Fig. 2 for meridional winds and in Fig. 3 for zonal winds. Here, the suspended matter distribution is indicated by concentration isolines at intervals of 1% of the maximum value at the source. This method allows the distribution range of anthropogenic suspended matter to be shown regardless of the source strength (a quantity that can only be assumed).

It can be assumed that, over time, suspended matter will most likely accumulate in the places of maximum concentration identified in the numerical experiments. Of particular interest are the situations in which the simulated flows reach the shore or penetrate into bays, where accumulation of anthropogenic suspended matter is also most likely.

The following general feature of the simulated flows should be noted. Regardless of wind direction, the suspended matter flow is directed downwind with a slight deviation to the right, and the bulk of the suspended matter (~ 60–70% of the source concentration) spreads over an area with a radius of about 300–400 m from the pier head. Flows oriented into open waters reach a distance of about one mile from the source (Figs. 2, 3).

Winds from the northern quadrant, which have the longest fetch, generate intense suspended matter flows that spread from the pier area into the water areas of Kazachya and Kamyshovaya bays. With a north-westerly wind, the suspended matter flow penetrates into Kamyshovaya Bay, reaching its eastern shore (Fig. 2, *a*). With a northerly wind, the suspended matter flow is directed into Kazachya Bay and flows around the shore of its eastern arm, where the beach area is located (Fig. 2, *b*). The north-easterly wind contributes to the formation of a well-developed suspended matter flow in a south-westerly direction, which penetrates into the northern part of Kazachya Bay as far as the shore of its western arm (Fig. 2, *c*).

With winds from the southern quadrant, suspended matter from the studied source area does not penetrate into Kazachya and Kamyshovaya bays (Fig. 2). The south-westerly wind causes an east-northeastward alongshore flow of suspended matter that passes along the coastline between Abramov and Kamyshovaya bays and spreads throughout the water area of Abramov Bay, where the city beach “Admiralskaya Laguna” is located (Fig. 2, *d*).

Southerly and south-easterly winds favor the removal of suspended matter away from the coastline and its export into open waters to a distance of up to one mile (Fig. 2, *e, f*).

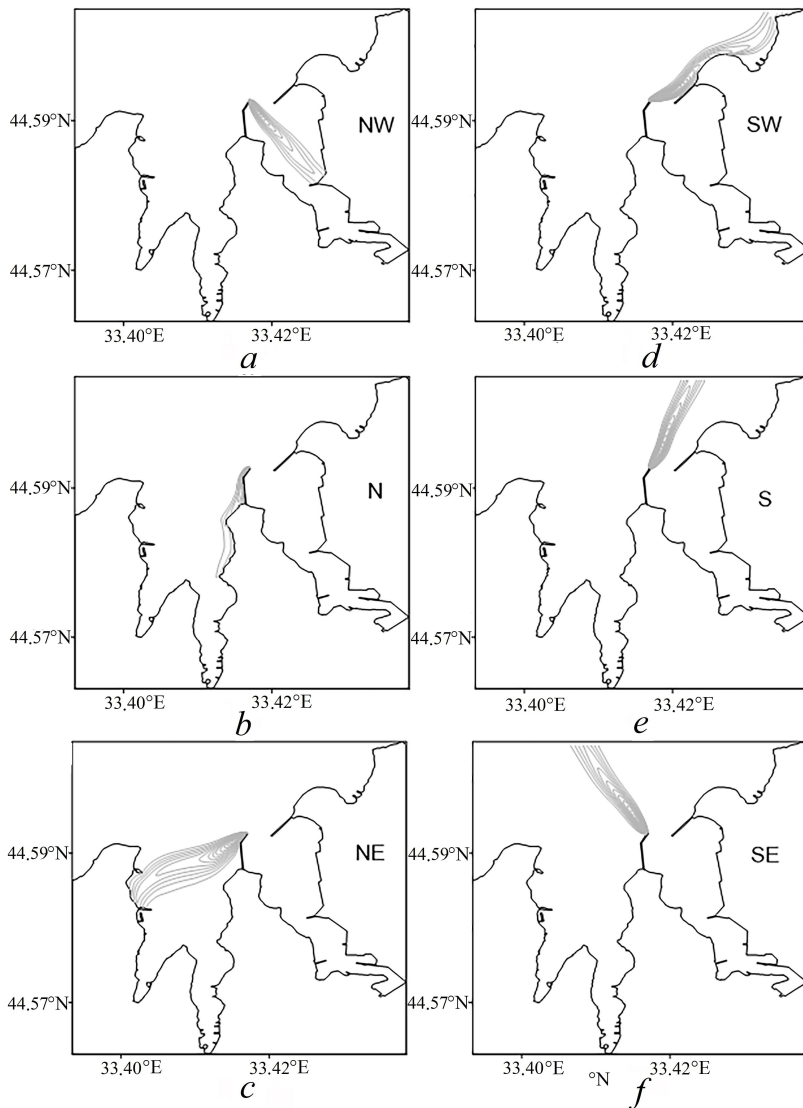


Fig. 2. Suspended matter distribution in the water surface layer under the impact of meridional winds of the northern (NW, N, NE) (*a, b, c*) and southern (SW, S, SE) (*d, e, f*) quarters

Westerly and easterly winds cause zonal transport of suspended matter (Fig. 3). With a westerly wind, the main suspended matter flow is directed east-southeastward. It penetrates into the northern part of Kamyshovaya Bay and reaches its eastern shore (Fig. 3, *a*). An easterly wind generates a suspended matter flow from the pier area directed west-northwestward into the open waters to a distance of about one mile (Fig. 3, *b*).

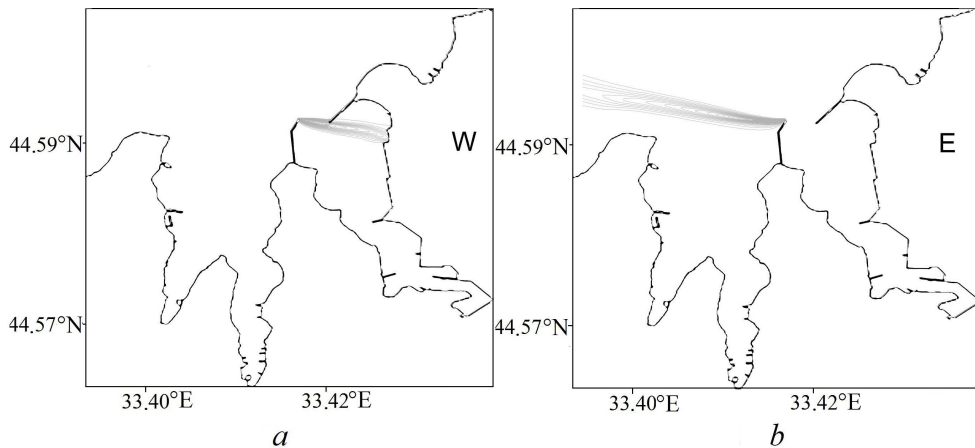


Fig. 3. Suspended matter distribution in the water surface layer under the impact of the zonal western (W) (a) and eastern (E) (b) winds

Based on data from all expeditions carried out in the study region, signs of anthropogenic impact of the oil pier on the water environment were identified in the structure of the fields of oceanographic variables. The most indicative in this respect were the TSM and DO product concentration fields.

We do not have observations of the concentrations of these substances directly at the pier walls, but in open waters and adjacent bays, at a distance of 0.1–1.2 miles from this facility, anthropogenic suspended matter and dissolved oil products, most likely originating from its operation, were found during the expeditions [6–8].

Based on data from two surveys carried out in Kazachya Bay, we found that the waters of the northern part of the bay contained anthropogenic suspended matter and dissolved oil products (Figs. 4, 5). The surveys were performed at the end of the warm season and were accompanied by moderate north-easterly winds.

During the survey in August 2004, observations were carried out only in the surface water layer. Analysis of the obtained data revealed two patches with TSM concentrations of 2.2–3.4 mg/L in the upper water layer of the northern part of Kazachya Bay, with values 3–4 times higher than the natural background. Their centers were located along the wind direction vector (Fig. 4, a). The patch of DO products was also elongated downwind from the north-east (where the pier is located) to the south-west (Fig. 4, b), which is consistent with the modeling results for a north-easterly wind (Fig. 2, c).

Analysis of the detailed survey data for Kazachya Bay, obtained in profiling mode in September 2018, allowed us to obtain a picture of the three-dimensional structure of anthropogenic heterogeneities in the TSM concentration field and to confirm their origin.

In particular, in the northern part of the bay, four lenses of water saturated with anthropogenic TSM, with concentrations of 2.2–4.1 mg/L, were found, which were 3–5 times higher than the natural background. These features were observed in the 0–10 m layer and were not associated with the bottom or the shores of the

bay (Fig. 5, *a*, *b*). They were transported by advective flows from the pier area in the wind-driven current system caused by the north-easterly wind.

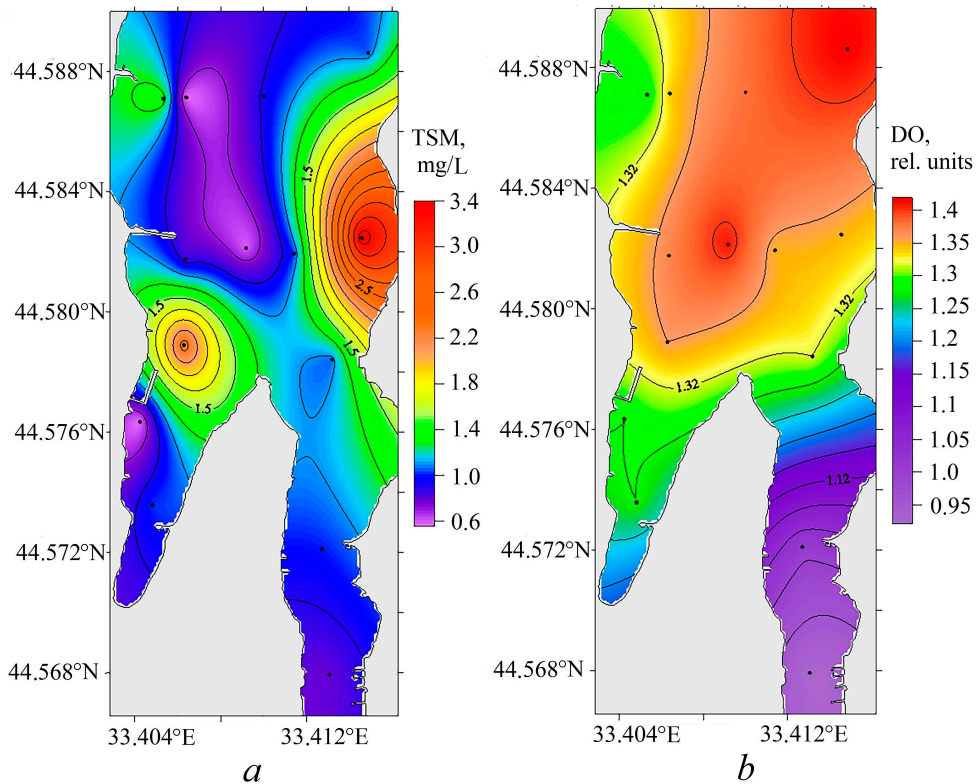


Fig. 4. TSM (*a*) and DO (*b*) concentrations in the water surface layer of Kazachya Bay, August 2004

The horizontal structure of the DO product concentration field in the surface layer of the northern part of Kazachya Bay proved to be similar to the structure of the TSM concentration field (Fig. 5, *b*, *c*). Thus, the fields of both variables were formed under the influence of similar factors, and the source of the analyzed pollutants was the oil pier at Cape Manganari.

Analysis of the observational data (Figs. 4, 5) confirms the results of the model experiment (Fig. 2, *c*) and allows us to state that, under north-easterly wind conditions, anthropogenic TSM and DO products from the oil pier area penetrate into Kazachya Bay to a distance of 0.5–0.8 miles, reaching its western shore, and spread in its open northern part. This part of Kazachya Bay, and especially the shallow areas near its western shore, appears to be a likely area for accumulation and deposition of anthropogenic suspended matter and other pollutants.

According to the results of the model experiment, anthropogenic suspended matter from the pier also penetrates into Kazachya Bay and spreads along its north-eastern shore under the influence of a northerly wind (Fig. 2, *b*).

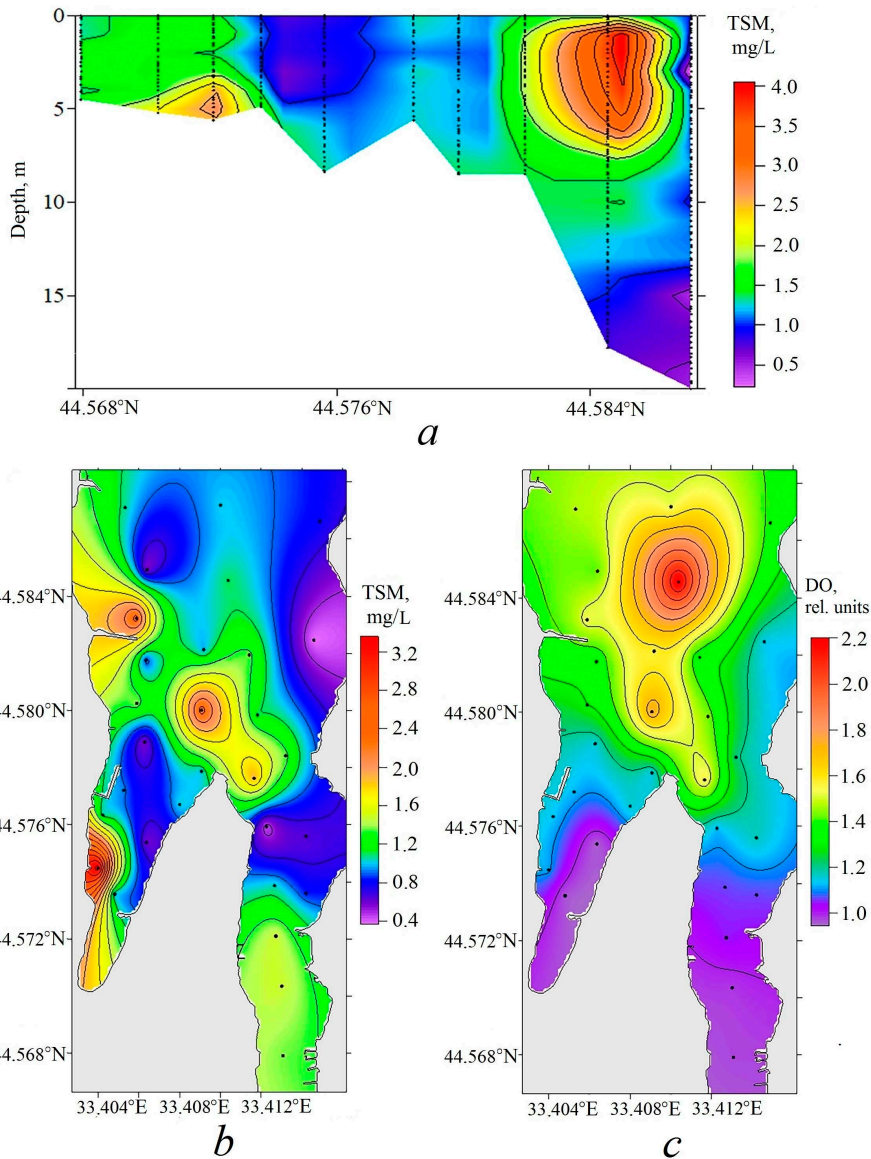


Fig. 5. Concentration of pollution sources in Kazachya Bay in September, 2018: total suspended matter – in the plane of axial section through the bay (*a*) and in the water surface layer (*b*); dissolved oil products (*c*)

The timing of the expedition to the area of Abramov and Kamyshovaya bays coincided with the beginning of the autumn-winter cooling of the sea surface and the development of convective mixing. During the first two ten-day periods of November 2019, the weather over the Black Sea was determined by the influence of the south-western periphery of the Siberian anticyclone. Calm and light-wind conditions prevailed in the Sevastopol region. Weak variable winds from the southern quadrant were observed. Against this background, a time interval (1–7 November) stood out when a steady south-westerly wind prevailed. The mean daily air temperature dropped from 13 to 3 °C.

In the open coastal waters and in the studied bays, under the influence of convective currents, the stratification of hydrophysical fields disappeared. As a result of active settling of suspended matter, water transparency increased noticeably.

The survey of Abramov and Kamyshovaya bays (Fig. 1) was carried out under calm weather conditions. Wave action was absent in both bays. Therefore, the data from this expedition allow us to assess the degree and spatial scale of the anthropogenic impact of the oil pier on the surrounding water environment under conditions of minimal dynamic activity.

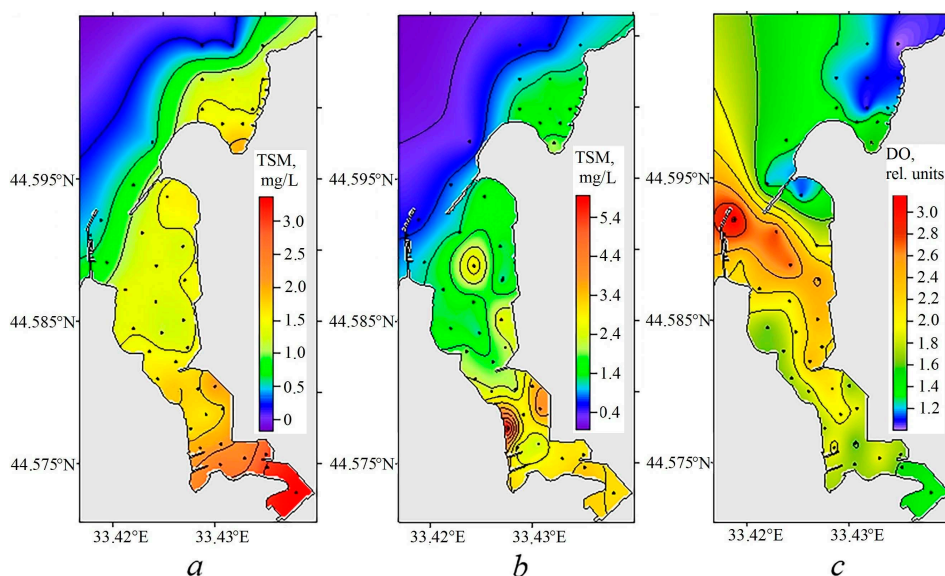


Fig. 6. Concentration of pollution sources in the region of Abramov and Kamyshovaya bays in November, 2019: TSM – in the surface layer (*a*) and by the bottom (*b*); DO – in the surface layer (*c*)

The structure of the TSM concentration field during the autumn-winter cooling period was characterized by relative homogeneity (Fig. 6, *a, b*). Clearly defined, separate lenses of water saturated with anthropogenic suspended matter, which were recorded in the warm season (Fig. 5, *a, b*), were not observed.

In the vicinity of the pier and in the open waters of the study area, the TSM concentration in the sea surface layer was minimal (0.3–0.8 mg/L) and corresponded to the natural background level. In the northern (closer to the pier) part of Kamyshovaya Bay, TSM concentrations of 1.2–1.5 mg/L in the surface layer and 1.5–2.5 mg/L near the bottom exceeded the natural background by a factor of 2–3 (Fig. 6, *a, b*).

The maximum concentration of DO products, 2.5–3.1 rel. units, was observed directly at the oil pier and in the northern part of Kamyshovaya Bay. Anthropogenic TSM and DO products penetrated into this part of Kamyshovaya Bay to a distance of 0.5–0.6 miles from the source (Fig. 6). Pollution of the southern part of this bay with anthropogenic TSM and DO products is associated with other sources and is discussed in detail in [7].

In the water area of Abramov Bay under calm weather conditions, anthropogenic TSM and DO products, with concentrations of ~1.5 mg/L and ~1.2 rel. units, respectively, were also recorded (Fig. 6). Most likely, these pollutants entered the bay

from the pier area in the wind-driven current system caused by the steady south-westerly wind in the first week of November. Under this wind, according to both observational data and the model experiment, the suspended matter flow from the source (pier) propagates to the north-east to a distance of about one mile, reaching the eastern shore of Abramov Bay. Thus, the modeling result for suspended matter propagation under a south-westerly wind (Fig. 2, *d*) are confirmed by expedition data (Fig. 6).

In [23], it was shown that the most significant sources of dissolved oil products in the Sevastopol region are located in Grafskaya, Kilen, Yuzhnaya, Korabelnaya, and Severnaya bays, where maximum concentrations of 2.5–4.2 rel. units were recorded.

Therefore, the pier at Cape Manganari, where the concentration of DO products reaches 2.5–3.1 rel. units, can be considered one of the main sources of oil product pollution in the coastal waters of Sevastopol.

Conclusion

Based on numerical modeling methods, the patterns of anthropogenic suspended matter propagation by wind currents from the area near Cape Manganari (where the oil pier is located) were identified. The results of numerical experiments were compared with expedition data. The impact radius of the pier on the surrounding water environment was assessed.

At the model level, it was demonstrated that, depending on the wind direction, the suspended matter flow from the head of the oil pier spreads into the open waters, penetrates into the adjacent bays (Kazachya, Kamyshovaya, Abramov), and passes along the coastline of open areas.

Southerly, south-easterly, and easterly winds favor the export of suspended matter into open waters. Northerly and north-easterly winds generate a suspended matter flow that penetrates into Kazachya Bay. Under westerly and north-westerly winds, suspended matter spreads into Kamyshovaya Bay. Under south-westerly wind conditions, the suspended matter flow passes along the eastern shore of the studied area and reaches the water area of Abramov Bay.

Based on expedition data, the features of the structure of TSM and DO product concentration fields under moderate north-easterly and weak south-westerly winds and in calm weather were examined. It was shown that, under the influence of a north-easterly wind, these pollutants penetrate from the oil pier area into the northern part of Kazachya Bay and accumulate near the shores. As a result of the influence of a south-westerly wind, TSM and DO products reach the water area of Abramov Bay. In calm weather, anthropogenic suspended matter and DO products of high concentrations were observed in the northern part of Kamyshovaya Bay.

For north-easterly and south-westerly winds, good agreement between the model experiment results and the analysis of observational data was noted.

According to the performed model calculations and analysis of observational data, the impact radius of the pier on the surrounding water environment (in the suspended matter concentration field) is estimated at 0.5–1.0 miles, and the maximum anthropogenic load falls on the northern parts of Kazachya and Kamyshovaya bays.

Due to the high concentration of DO products found during the expedition studies, the pier at Cape Manganari can be considered one of the main sources of oil product pollution in the coastal waters of Sevastopol.

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