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Original article

Colored Dissolved Organic Matter and Total Suspended Matter as the Indicators of Water Pollution in the Kerch Strait

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Abstract
Purpose. Based on the data collected from expeditions conducted in 2001–2014, this study aims to identify patterns in the structure of concentration fields of colored dissolved organic matter and total suspended matter of anthropogenic origin in the Kerch Strait, to reveal polluted areas in the region under study, to identify the associated sources, and to assess the linear scale of their impact on the aquatic environment. Additionally, the study compares these findings with the existing data on water pollution in the strait, derived from the contact hydrochemical and satellite measurements.
Methods and Results. Polluted areas within the studied water region were identified by locating local maxima in the concentrations of colored dissolved organic matter and total suspended matter. These anthropogenic substances are shown to be localized in the form of individual lenses with elevated concentrations relative to background levels. The concentration profiles of these lenses exhibit a characteristic intrusive shape, with similar empirical concentration distributions for both substances. Thirteen lenses, with horizontal scales of 1–6 miles, were identified. Each lens is associated with a specific anthropogenic source, primarily shipping routes and canals, dredging and dumping of excavated soil, ports, offshore transshipment points, cargo terminals, and landfills. The Tuzla Ravine is examined separately as a source of anthropogenic suspended matter. Data indicate that, even 5–10 years after its formation, the ravine remains a major contributor, increasing suspended matter concentrations in the central strait by an order of magnitude compared to the surrounding background.
Conclusions. The structure regularities of concentration fields of colored dissolved organic matter and total suspended matter of anthropogenic origin in the Kerch Strait have been identified. The polluted areas within the water region, along with their associated sources, have been delineated, and the linear scale of their impact on the aquatic environment has been assessed. Comparison of these findings with existing studies of water pollution in the region demonstrates strong agreement.

Keywords: colored dissolved organic matter, total suspended matter, water structure, pollution, Kerch Strait

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Introduction

The Kerch region has experienced significant industrial growth since the 1960s. Shipping activity in the Kerch Strait has intensified, accompanied by the development of infrastructure to support vessels of various sizes and purposes. This has led to substantial anthropogenic pressure on the region's aquatic environment, which leading research institutions have been studying systematically since the 1970s using various methods.

These studies include traditional hydrochemical methods: monitoring of water pollution in the Kerch Strait by the State Hydrometeorological Service of Ukraine from 1979 to 2009 [1]; monitoring of water and sediment pollution in the strait and adjacent areas by the Southern Scientific Research Institute of Marine Fisheries and Oceanography (YugNIRO) from 1990 to 2015 [2]; studies of heavy metal pollution in the bottom sediments of the Kerch Strait by Marine Hydrophysical Institute (MHI) based on expeditionary data from 2005 to 2008 [3]; research on water, suspended matter, and sediment pollution by the Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO RAS) from 2019 to 2022 [4]. Currently, IO RAS researchers are monitoring technogenic pollution in the region using optical and radar remote sensing methods [5].

From 2001 to 2015, expeditionary data collected by leading domestic research institutions were used to study water pollution in the Kerch Strait caused by colored dissolved organic matter (CDOM) and total suspended matter (TSM) of anthropogenic origin. These studies employed an oceanographic method of analyzing the structure of concentration fields of these substances. CDOM and TSM are notably considered effective indicators of pollution in the coastal waters of oceans and seas [6–8].

The purpose of this study is to identify patterns in the structure of the CDOM and TSM concentration fields of anthropogenic origin, analyze the statistical characteristics of their variability, determine the polluted areas of the Kerch Strait and their associated pollution sources, assess the linear scale of the identified sources' impact on the aquatic environment, and compare the results with existing water pollution data in the strait obtained through contact hydrochemical and satellite methods.

Initial data and research methods

The analysis is based on data collected from a series of expeditions to the Kerch Strait conducted between 2001 and 2014 by Marine Hydrophysical Institute (MHI), as well as joint expeditions involving MHI, the Southern Institute of Fisheries and Oceanography (YugNIRO), the Institute of Biology of the Southern Seas (IBSS), the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO), the State Oceanographic Institute (GOIN), and the Southern Scientific Center (SSC) of the Russian Academy of Sciences.

The expeditions included comprehensive surveys of the entire Kerch Strait and targeted areas, specifically the northern and central parts of the strait and Kerch Bay, comprising 1,443 soundings conducted primarily from small vessels at drift stations. Additionally, a series of micro-surveys, including 83 stations, were performed in polluted areas of the studied water body. A detailed description of the dataset is available in [2]. Each sounding provides data on the vertical distribution of temperature, salinity, and concentrations of CDOM and TSM. These parameters were measured synchronously *in situ* with a depth resolution of 0.1 m.

In both international and domestic experimental research, CDOM concentrations are commonly measured in two units: optical (QSU) and weight (mg/L) (see the work [1] and [9–11]). These publications provide linear conversion formulas for these units across various regions, including the World Ocean, the Mediterranean Sea, and freshwater bodies, with high correlation coefficients ranging from 0.92 to 0.97. In this study, CDOM concentrations is expressed in QSU, with measurements taken across a depth range of 0.5–50 m. For analysis, 702 soundings from areas of the studied water body with depths greater than 2 m were selected.

All observations were conducted using the autonomous hydrobiophysical multiparameter optical sensing complex "Kondor" [2].

In this study, the term "pollution" encompasses two types of environmental contamination: *contamination* and *pollution*. C*ontamination* is defined as the presence of a substance in an environment where it is not naturally expected or where its concentration exceeds background levels. *Pollution* refers to contamination that causes or may cause adverse biological effects on local ecosystems.

A widely used method in global practice for identifying polluted areas in coastal waters of oceans, seas, and freshwater bodies relies on detecting local maxima (non-natural formations) in the concentration fields of studied substances [12]. In this study, CDOM and TSM of anthropogenic origin were identified in the horizontal distribution fields of their concentrations based on local maxima. The degree of anthropogenic impact on specific areas of the studied water body was assessed by calculating the ratio of maximum concentration to background concentration.

The analysis of the concentration fields of CDOM and TSM in polluted areas followed a systematic sequence. For each survey, areas with local maxima in surface layer concentrations of the studied substances were identified, and their vertical profiles, CDOM(z) and TSM(z), were selected and analyzed. Clusters of these profiles were then compiled across the entire dataset, and histograms of the frequency of CDOM and TSM concentrations in the surface layer were calculated. Subsequently, the most significant local maxima of CDOM and TSM concentrations were mapped, and their locations were correlated with the positions of industrial and economic facilities in the region to identify specific pollution sources for each area. The polluted areas and their associated sources were then

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[2] Ecodevice. *Ecodevice Catalogue. KONDOR "Multi*ZOND" Complex*. 2024. [online] Available at: http://ecodevice.com.ru/ecodevice-catalogue/multiturbidimeter-kondor [Accessed: 23 November 2024].

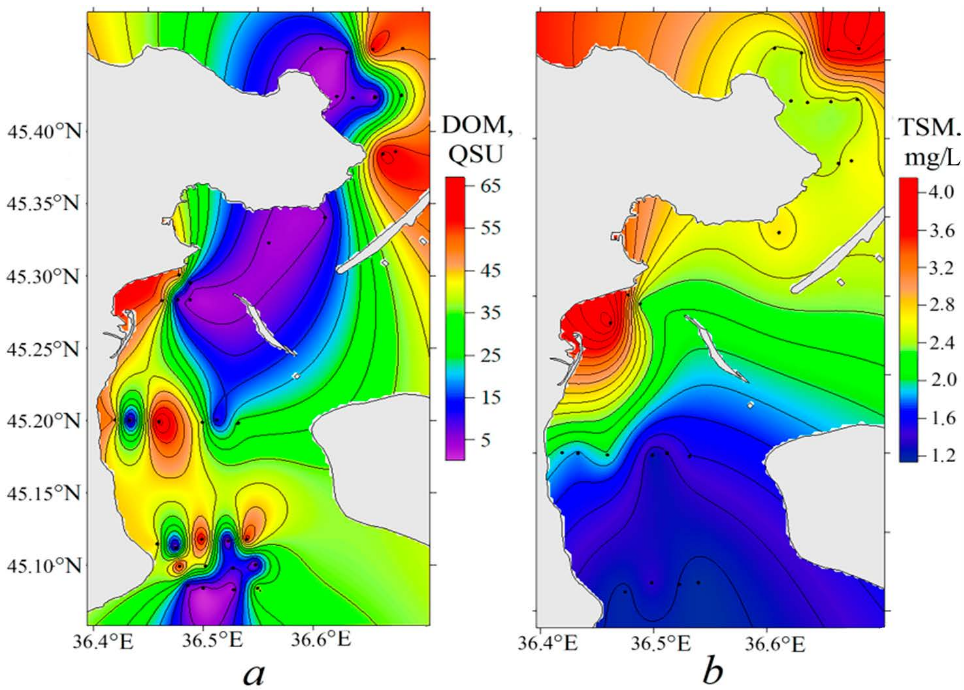
compared with findings from previous studies on pollution sources in the Kerch Strait, as reported in [1–5].

To evaluate the impact of shipping on anthropogenic suspended matter pollution in the strait, systematic monitoring of vessel wake trails along the main shipping channel was conducted. The expedition vessel was moored to a buoy marking the channel boundary, allowing water samples to be collected from the wake trail for TSM content analysis and visual assessment of trail composition and propagation velocity.

TSM concentrations during dredging operations at the Kerch Sea Trade Port were analyzed based on a micro-survey conducted by YugNIRO in the summer of 2000.

Discussion of results

Analysis of the structure of CDOM and TSM concentration fields for each survey revealed distinct characteristics in the Kerch Strait. Unlike the open waters of the Sea of Azov, the Black Sea, or unpolluted coastal areas, these fields are distorted by inhomogeneities – lenses of water with varying scales and volumes containing anthropogenic CDOM and TSM. These frequently observed formations appear as local maxima against the relatively homogeneous natural concentration fields of these substances (Fig. 1), which, according to [12], are not expected in natural settings.

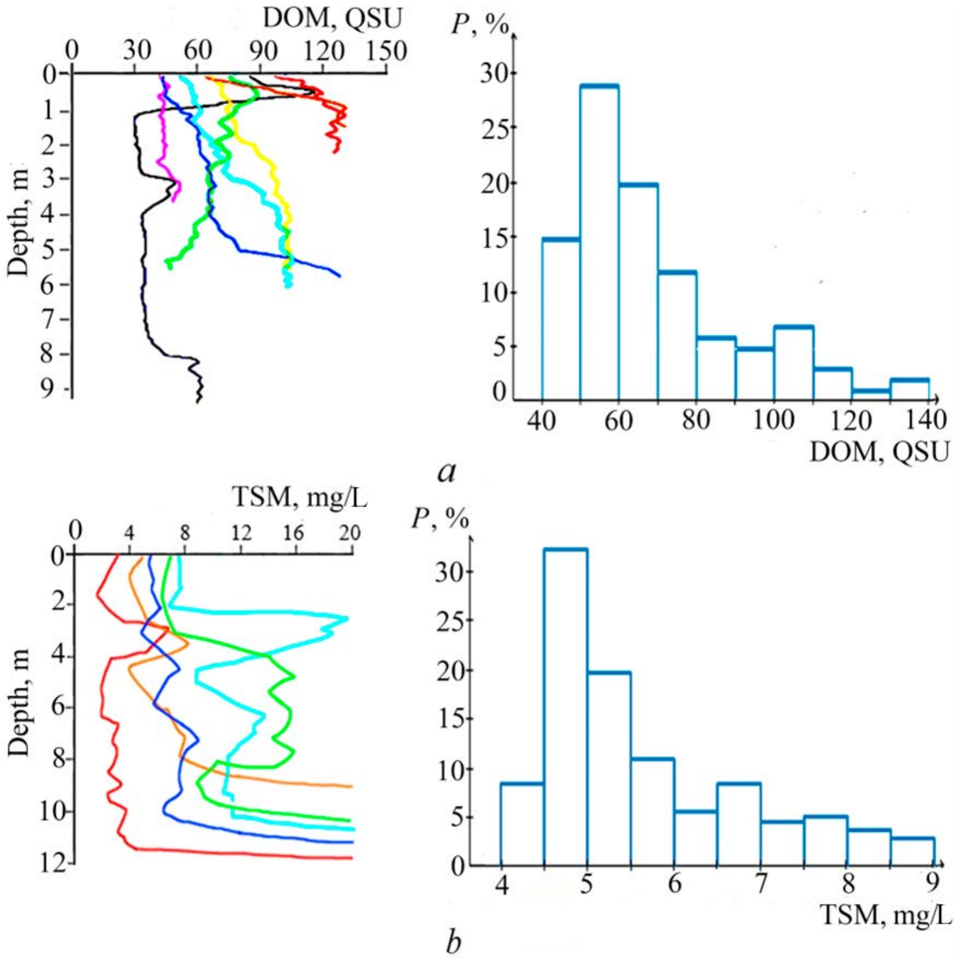


F i g. 1. Distribution of CDOM (*a*) and TSM (*b*) concentrations in the surface water layer, April 2008

Analysis of the vertical profiles, concentration distribution diagrams, and locations of the main local maxima in the Kerch Strait revealed the following. Both substances share similar vertical stratification characteristics. The CDOM(z) and TSM(z) profiles, are non-monotonic function of depth, displaying a characteristic jagged shape that contrasts with the "smooth" profiles observed in unpolluted surrounding waters, indicating intrusions with elevated concentrations of these substances.

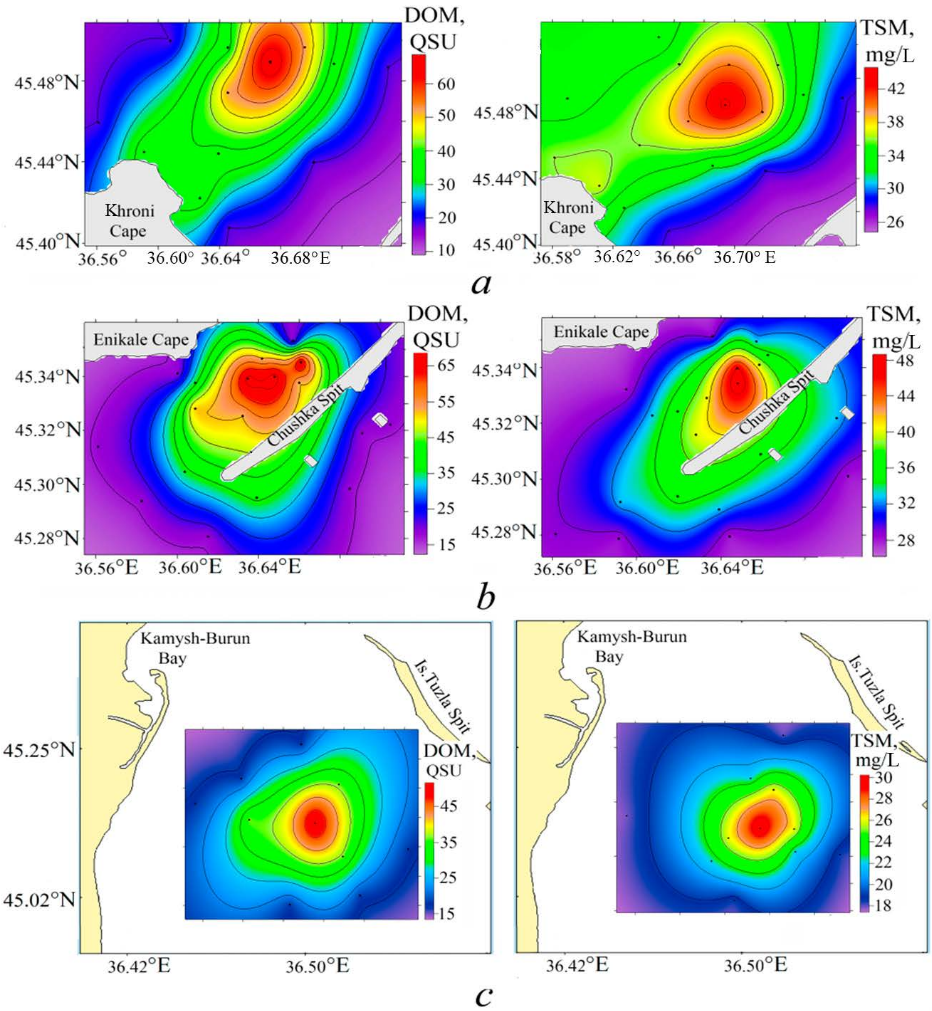
In the water column of polluted areas, distinct layers and interlayers with significantly elevated concentrations of CDOM and TSM are observed. These structural features, manifesting as local concentration maxima, indicate the presence of anthropogenic dissolved and suspended substances polluting the Kerch strait waters (Fig. 2).

The concentration distribution diagrams for CDOM and TSM in the surface water layer exhibit similar characteristics, displaying unimodal and right-skewed distribution. The most frequently occurring concentration for both substances is below the mean value, with modal concentration values having a similar frequency of approximately 30% (Fig. 2).



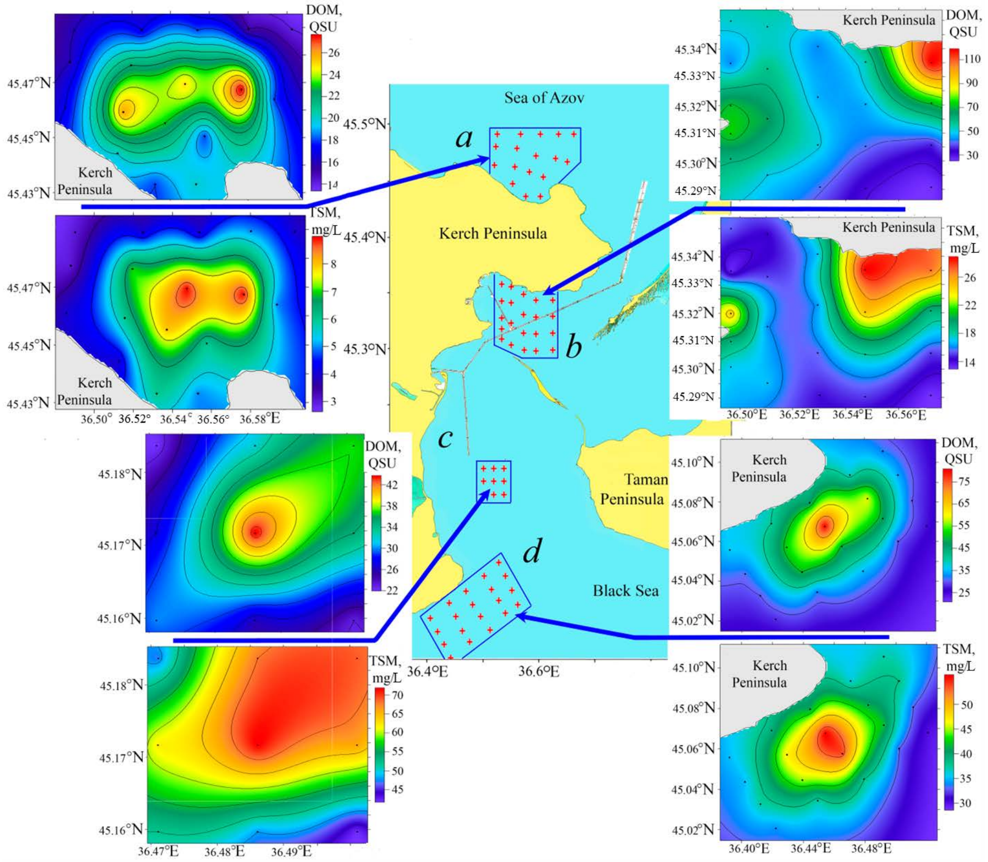
F i g. 2. Typical CDOM(*z*) profiles for the waters containing anthropogenic component (*left*), and histogram of CDOM concentration frequency in the sea surface layer (*right*) (*a*); the same characteristics for TSM (*b*)

Local maxima in the concentration fields of CDOM and TSM were observed in nearly all polluted areas of the Kerch Strait. This pattern is illustrated for three closed landfills of sediment from dredging operations (Fig. 3) and four polluted areas located near the wastewater treatment facilities of Kerch, in Kerch Bay, near the offshore transshipment site, and at the active sediment landfill near Cape Takil (Fig. 4). In the concentration fields of both substances, well-defined local maxima are evident, with their location closely aligned. The configuration and extent of these pollution patches vary.



F i g. 3. CDOM (*left*) and TSM (*right*) concentrations in the bottom layer of dumping zones: *a* – landfill near Khroni Cape, May 2012; *b* – landfill near Chushka Spit, October 2013; *c* – landfill south of Tuzla Island, May 2005

The similarity in vertical structure, empirical concentration distribution characteristics (Fig. 2), and spatial alignment of local maxima (Figs. 3, 4) suggest that these “unnatural” structures in the Kerch Strait are formed under the influence of similar anthropogenic factors and sources polluting the aquatic environment.



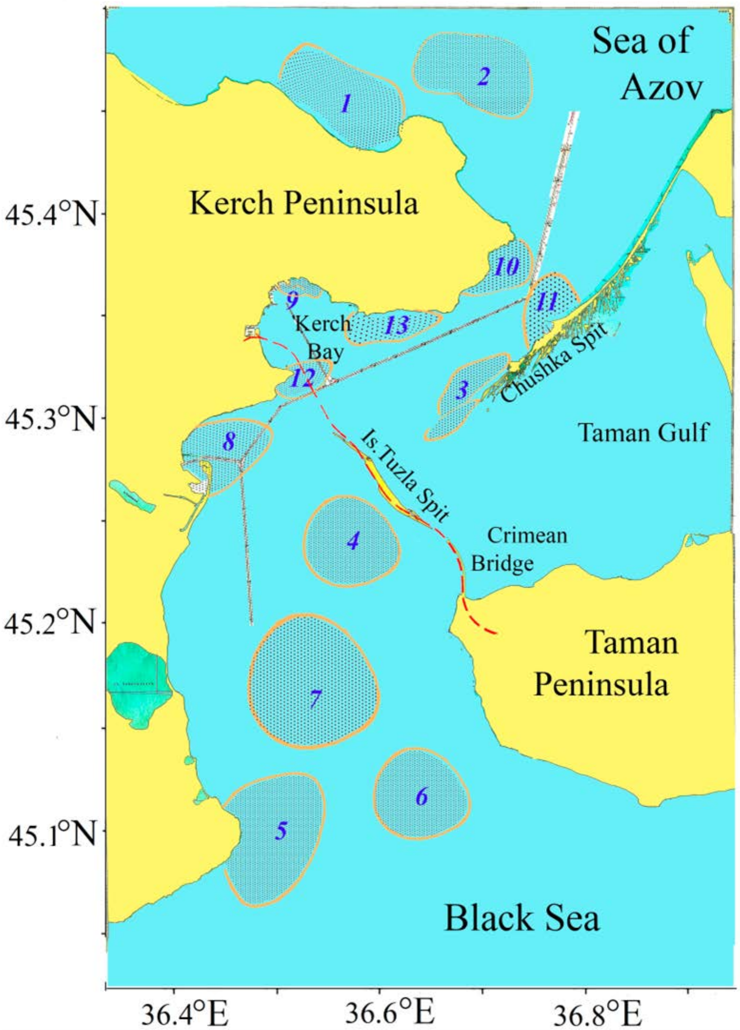
F i g. 4. CDOM and TSM concentrations in the polluted areas of the region under study: near treatment facilities, surface layer, May 2007 (*a*); Kerch Bay, the 3 m horizon, May 2005 (*b*); roadstead cargo handling site, bottom layer, September 2008 (*c*); operating landfill, bottom layer, June 2012 (*d*)

Water lenses containing anthropogenic CDOM and TSM were identified throughout the Kerch Strait and its adjacent areas. These lenses were mapped and presented as numbered patches in Fig. 5, while Fig. 6 illustrates the locations of the region's primary industrial and economic facilities, enabling the identification of pollution sources associated with each mapped area.

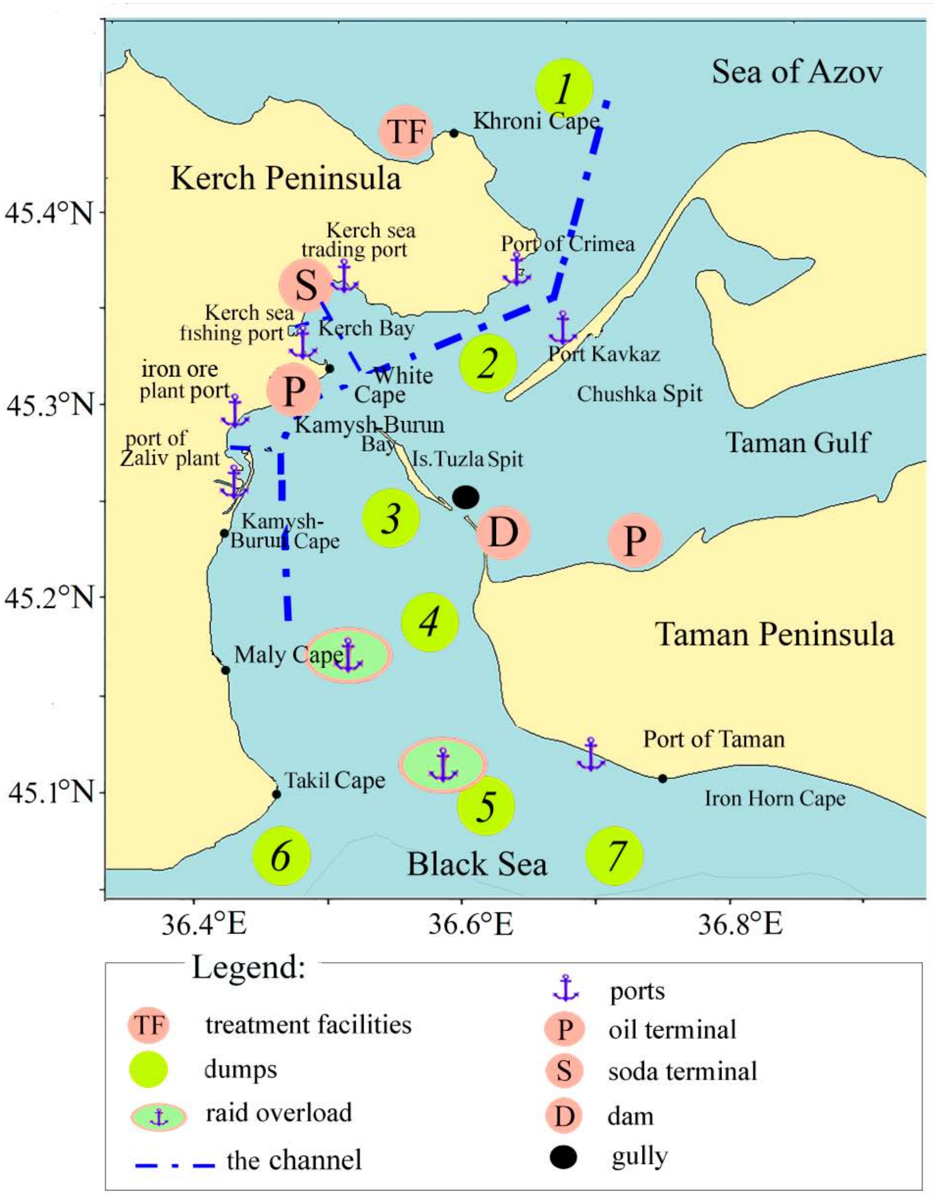
From all detected water lenses, 13 distinct large-scale lenses (horizontal extent of 1–6 nautical miles) contaminated with CDOM and TSM were identified and mapped (Fig. 5).

Lens *1*, located near the coast of the Azov pre-strait area in the vicinity of the Bondarenkovo wastewater treatment facilities for municipal wastewater from Kerch, exhibited a maximum CDOM concentration of 26 QSU, approximately twice the background level of 14 QSU, and a maximum TSM concentration of 8.8 mg/L, about three times higher than the background level of 2.8 mg/L (Figs. 4, *a*; 5, 6).

Lenses *2–5* are located in areas associated with sediment landfills (Figs. 3; 4, *d*; 5, 6). Sediment landfills, or dumping zones for sediment extracted during dredging, are known to cause significant harm to both living and non-living components of marine ecosystems. The negative impacts of these landfills on marine ecology are actively studied globally. Contemporary literature addresses various aspects of this issue (e.g., [13–16]). Specifically, the impact of the active sediment landfill near Cape Takil as a source of pollution in the Kerch Strait and the adjacent Black Sea area has been investigated in [17].



F i g. 5. Water lenses containing CDOM and TSM of anthropogenic origin



F i g. 6. Main objects polluting aquatic environment of the region

Micro-surveys were conducted in four of the seven known sediment landfill areas in the region (Figs. 3; 4, *d*), including two of the “oldest” landfills, closed in the 1970s, located northeast of Cape Khroni and south of Tuzla Island. Despite decades since the last sediment dumping, these areas exhibit persistent local maxima in the concentrations of CDOM and TSM in the bottom layer.

At the landfill near Cape Khroni, a maximum CDOM concentration of 60 QSU was recorded against a background level of 10 QSU, alongside a maximum TSM concentration of 43 mg/L compared to a background of 25 mg/L (Fig. 3, *a*). Near the closed sediment landfill at the southern tip of the Chushka Spit, a local maximum CDOM concentration of 65 QSU was observed against a background of 15 QSU, with a maximum TSM concentration of 46 mg/L against a background of 28 mg/L (Fig. 3, *b*). Above the landfill south of Tuzla Island, corresponding concentrations were 50 and 15 QSU, 30 and 18 mg/L (Fig. 3, *c*).

The maximum CDOM concentrations in the studied closed landfills exceeded background levels by 3–6 times, while the ratio for TSM concentrations was significantly lower, approximately 2. This suggests that CDOM may be a more sensitive indicator of water pollution then TSM in these contexts.

According to [18], negative environmental consequences from dredging and dumping activities can persist long after operations cease, affecting both dredging sites and in dumping areas.

Lenses *6* and *7* were identified in areas corresponding to two offshore transshipment points (Figs. 4, *c*; 5, 6).

Micro-surveys conducted by YugNIRO and MHI at the western offshore transshipment point (site *451*) from 1997 to 2008 revealed the following. This site is a persistent source of anthropogenic suspended matter throughout the water column. In calm weather, the TSM concentration in this area was 1.5–3 times higher than the background level, with the polluted water lens estimated to have a horizontal extent of approximately 1 mile. Under strong southerly winds, the lens extended meridionally up to 6 miles, with TSM concentrations 5–6 times higher than the background level. Anthropogenic CDOM was also detected, with concentrations near the bottom reaching 45–52 QSU compared to a background level of 22 QSU (Fig. 4, *c*).

Lens *8* is located at the entrance to Kamysh-Burun Bay, corresponding to the polluted water area near the ports of the Zaliv plant and the iron ore plant. Anthropogenic CDOM and TSM were detected in this area during all large-scale surveys (Figs. 5, 6).

Lens *9* was identified in the western coastal part of Kerch Bay, associated with three adjacent facilities: the Kerch Sea Fishing Port, the soda terminal, and the Kerch Sea Trade Port (Figs. 5, 6).

Located between the trade and fishing ports of Kerch on the western shore of Kerch Bay, the soda terminal, commissioned in the late 20^{th} century, has not been previously studied as a source of water pollution. This facility was identified as a pollution source based on visual observations during surveys in Kerch Bay, where a matte spot was consistently observed on the sea surface near the terminal. Single soundings in this area detected local maxima in the surface-layer concentrations of CDOM and TSM, with vertical profiles exhibiting shapes characteristic of polluted areas.

The small rivers Melek-Chesme, Bulganak, and Dzhardzhava, which flow into the western part of Kerch Bay, are significant sources of anthropogenic impact on the aquatic environment. The influence on CDOM concentration fields is discussed in [2].

Pollution in the Kerch Sea Trade Port and adjacent waters is associated with anthropogenic CDOM from the Bulganak River runoff, which flows through the industrial district of Kerch and enters the port's water area. Notably, in the port approach channel, the highest CDOM concentration in the study region was recorded, ranging from 210–250 QSU [19].

Lenses *10* and *11*, located in the ferry crossing area near the approaches to the ports of Crimea and Caucasus (Figs. 5, 6), were consistently observed in the concentration fields of both analyzed variables across all surveys of the northern narrows of the Kerch Strait. A significant increase in background TSM concentrations, reaching up to ~ 10 mg/L, was also noted in this area during periods of intensive Kerch ferry crossing operations.

Lens *12* was discovered near Cape Beliy in the southeastern part of Kerch Bay, within the oil terminal area (Figs. 4, *b*; 5, 6). This lens extended throughout the water column, with a horizontal extent of ~ 3–4 miles. At a depth of 3 m, maximum concentration of CDOM reached 70 QSU and TSM reached 23 mg/L, compared to background levels of 30 QSU and 13 mg/L, respectively.

Lens *13*, *the* most extensive polluted water lens, was recorded in the northern part of Kerch Bay, having been transported into the strait from the Sea of Azov. Its origin and the concentration fields of CDOM, TSM, and dissolved petroleum products are detailed in [20] (Fig. 4, *b*; 5, 6).

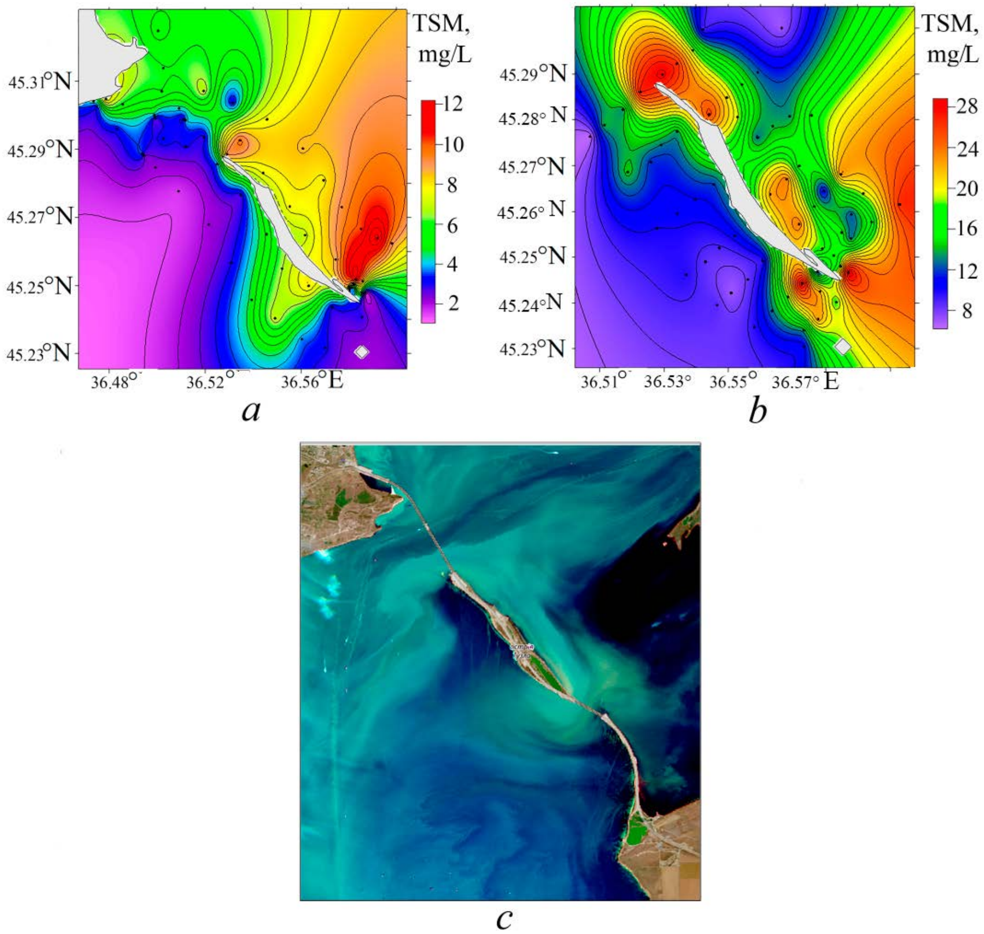
The total area of lenses containing anthropogenic CDOM and TSM accounted for ~ 10–15% of the strait's water surface area, indicating a significant anthropogenic impact on the region's aquatic environment.

The construction of the Tuzla Dam in autumn of 2003, followed by artificial deepening of the bottom in the resulting ravine, emerged as a major anthropogenic source of TSM in the Kerch Strait (Fig. 6). This activity caused the collapse of the eastern part of Tuzla Island [21], leading to significant release of suspended matter due to intense erosion of the shore and seabed. The influence of this source extended across a substantial portion of the strait's waters.

According to the data from YugNIRO and reports from the Hydrographic Service, the completion of the Tuzla Dam led to a significant intensification of current systems and suspended matter flows in the Kerch Strait, accompanied by increased sedimentation in bays, ports, port approaches, and shipping channels. Approximately 5–10 years after the construction, when the morphometric characteristics of Tuzla Island shore and seabed had largely stabilized, the Tuzla ravine remained a significant source of TSM. Even under light to moderate winds, TSM concentrations near the island were several times (or even an order of magnitude) higher than background levels (Fig. 7). Prior to the construction of the dam, the waters in this part of the strait were noted for their high transparency and, according to long-term hydrochemical studies [1], were the cleanest in the region, classified as Class II marine water quality.

Despite significantly elevated TSM concentrations due to the influence of the Tuzla Dam, no anthropogenic CDOM was detected in the concentration field near Tuzla Island. Thus, unlike the other anthropogenic sources discussed, the Tuzla ravine did not contribute to anthropogenic CDOM pollution.

Globally, shipping and dredging, followed by the dumping of extracted sediment, are among the most significant sources (types of activity) of pollution in oceans, seas, and estuarine zones [22–25]. The evidence supporting this for the region under study is presented below.



F i g. 7. Distribution of TSM, concentration in the sea surface layer in the region of Tuzla Island under weak and moderate south wind in April 2008 (*a*), and in April 2009 (*b*); satellite image of the Tuzla Island area on October 05, 2020 (*Sentinel*-2 *L2A* (4, 3, 2)) (*c*)

Water samples collected from the wake trails of large-tonnage ocean vessels (30–40 thousand tons) navigating shipping channels contained TSM concentrations of up to 270–300 mg/L, two orders of magnitude higher than background levels and the highest recorded during all expeditionary research. Visual observations revealed clumps of sediment, fragments of fishing gear (including broken floats, ropes, net pieces, wood fragments and planks), uprooted grass, and various debris, including plastic, rising and sinking in the water.

The wake trails of large-tonnage vessels generate powerful turbulent flows that expand behind the moving vessel and rapidly propagate toward the shores of the Kerch Strait, disturbing a significant portion of its waters. Additionally, alongside large-tonnage vessels, numerous smaller vessels of various types and purposes constantly navigate the strait.

During dredging operations in the Kerch Sea Trade Port in summer 2000 [19], a significant increase in TSM concentrations (210–260 mg/L) was recorded in the port and adjacent waters, marking dredging as the second most significant pollution source after shipping.

Based on the characteristics of anthropogenic CDOM and TSM pollution sources in the Kerch Strait, combined with findings from prior studies [1–5], these sources can be ranked by significance as follows: fleet operations and supporting infrastructure, including shipping and shipping channels; dredging and dumping of extracted sediment; ports, offshore transshipment sites, cargo terminals, sediment landfills, polluted waters from the Sea of Azov, the Tuzla ravine, wastewater treatment facilities in Kerch, and polluted rivers flowing into the strait.

Comparison of our results with existing research on water pollution in the region demonstrates good agreement. Nearly all lenses containing anthropogenic CDOM and TSM correspond to polluted areas identified and studied in the long-term monitoring program by YugNIRO [2].

Exceptions include three previously unidentified areas, associated with the Tuzla Dam, the oil terminal, and the Port of Taman (Fig. 6). These facilities, as sources of water and sediment pollution in the strait, were investigated by YugNIRO [2], with the Port of Taman also studied by IO RAS [5]. In particular, the authors of [5] analyzed the propagation of suspended matter from dredging and dumping activities in the Port of Taman area, identifying these activities as the most significant source of anthropogenic suspended matter polluting in the southern Kerch Strait and the adjacent Black Sea pre-strait area.

Conclusion

Analysis of expedition data from 2001 to 2014 revealed the structure of concentration fields of anthropogenic CDOM and TSM in the Kerch Strait.

The analyzed substances are localized in distinct lenses with concentrations significantly exceeding background levels. The profiles of CDOM(z) and TSM(z) exhibit a characteristic intrusive shape, contrasting with the smooth profiles observed in unpolluted waters. Empirical distribution diagrams of CDOM and TSM concentrations in the upper water layer are similar, displaying unimodal, right-skewed distributions with comparable modal frequency.

The similarity in structural features of anthropogenic CDOM and TSM concentration fields, along with their empirical concentration distributions and spatial co-occurrence, indicates that these formations are driven by similar anthropogenic factors and pollution sources in the strait.

A total of 13 lenses, with horizontal extents of 1–6 miles, containing anthropogenic CDOM and TSM, were identified, covering 10–15% of the strait’s water area. The sources of these lenses, including specific facilities and types of industrial and economic activities, were also determined.

The Tuzla ravine, a newly identified source of anthropogenic suspended matter, was analyzed separately. Unlike other anthropogenic pollution sources in the Kerch Strait, the Tuzla ravine did not contribute to anthropogenic CDOM concentrations. In the initial years following the dam’s completion, anthropogenic suspended matter from the ravine dispersed across a substantial portion of the strait’s waters, intensifying sedimentation in bays, shipping channels, port approaches, and ports. Even 5–10 years after its formation, the ravine remained a significant source of anthropogenic suspended matter, maintaining TSM concentrations near Tuzla an order of magnitude higher than the surrounding background levels.

Analysis of the Kerch Strait revealed that the primary sources of pollution are associated with fleet operation and supporting infrastructure, including shipping and shipping channels, dredging and dumping of extracted sediment, ports, offshore transshipment sites, cargo terminals, and sediment landfills. Additional sources include polluted waters from the Sea of Azov, the Tuzla ravine, wastewater treatment facilities in Kerch, and runoff from polluted rivers flowing into Kerch Bay.

Comparison of these findings with existing studies on water pollution in the region shows strong agreement, with nearly all identified lenses containing anthropogenic CDOM and TSM corresponding to polluted areas previously documented and studied by YugNIRO through long-term hydrochemical monitoring programs.

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