ISSN 0001-4370, Oceanology, 2014, Vol. 54, No. 3, pp. 265–280. © Pleiades Publishing, Inc., 2014.
Original Russian Text © P.O. Zavialov, P.N. Makkaveev, B.V. Konovalov, A.A. Osadchiev, P.V. Khlebopashev, V.V. Pelevin, A.B. Grabovskiy, A.S. Izhitskiy, I.V. Goncharenko, D.M. Soloviev, A.A. Polukhin, 2014, published in Okeanologiya, 2014, Vol. 54, No. 3, pp. 293–308.

MARINE PHYSICS

2 Hydrophysical and Hydrochemical Characteristics of the Sea Areas Adjacent to the Estuaries of Small Rivers of the Russian Coast of the Black Sea

P. O. Zavialov[a], P. N. Makkaveev[a], B. V. Konovalov[a], A. A. Osadchiev[a], P. V. Khlebopashev[a], V. V. Pelevin[a] A. B. Grabovskiy[a], A. S. Izhitskiy[a], I. V. Goncharenko[a], D. M. Soloviev[b], and A. A. Polukhin[a]

[a] *P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia*
e-mail: peter@ocean.ru
2 [b] *Marine Hydrophysical Institute, National Academy of Sciences of Ukraine, Sevastopol, Ukraine*

Received June 27, 2013; in final form, January 18, 2014

Abstract—This paper presents the results of long-term in situ and satellite measurements at shelf areas adjacent to the estuaries of the small rivers of the Russian coast of the Black Sea (Mezyb, Pshada, Vulan, Tuapse,
2 Bitkha, Sochi, Cudepsta, Mzymta). The quantitative characteristics of the response of the hydrophysical and hydrochemical fields at the sea shelf on the influence of the continental river discharge are presented for each of these areas. A number of indicators of the water quality (the concentrations of the nitrate and nitrite forms of nitrogen, the phosphorus, the silica, the dissolved oxygen, the value of the total alkalinity and pH, the mineral and organic suspended matter, and the chlorophyll a) are considered in the context of the anthropogenic and terrigenous influence. In this paper, the emphasis was placed on the Mzymta River plume at the shelf area adjacent to the city of Sochi, where the measurements were repeatedly performed during the spring flooding conditions in the period from 2007 until 2012. The interannual variability of the water quality indicators and the seasonal and short-term variability of the area and the configuration of the plume, which transports suspended matter and anthropogenic pollution, were considered.

DOI: 10.1134/S0001437014030151

1. INTRODUCTION

Considerable fluxes of fresh water, buoyancy, heat, and momentum into the ocean are related to the continental river discharge. The total average annual river discharge into the World Ocean makes up 39000 km^3/yr [12], which equals roughly 12 Sv and makes up a quarter of the incoming part of the water balance of the ocean (the atmospheric precipitation on its surface supplies the remaining three quarters). However, the relative contribution of the continental discharge on individual regions of the oceanic shelf or in inner and marginal seas may be an order of magnitude higher than in the whole ocean. For example, the annual river discharge entering the Black Sea (338 km^3/yr) exceeds the atmospheric precipitation (238 km^3/yr), while being close to the evaporation losses (396 km^3/yr). In many cases, the desalinated waters of continental origination determine the stratification of the surface layer over vast water areas.

The continental discharge is also a major source of terrigenous suspended and dissolved substances, nutrients, and products of anthropogenic pollution incoming to the sea. Thus, according to official data [7], the seas of Russia are annually enriched with riverine ammonium nitrogen (200000 tons) phosphorus (60000 tons), metals (Fe, Zn, and Cu; 50000 tons), oil products (30000 tons), and phenols (1000 tons).

Leaving a river and entering the sea, the inland waters form there mesoscale structures, which are adjacent to the mouth and distinguished by their low salinity and temperature differing from that of the surrounding waters and, as a rule, by stronger turbidity and a higher content of suspended particles and dissolved organic matter. Such structures are called plumes in the current literature. The spatial extent of the plumes can reach tens (or, for the largest rivers, hundreds) of kilometers, but, at the same time, they retain sharply defined boundaries only few meters (or even centimeters) wide, which separate a plume from the surrounding seawater. River plumes are almost always confined to the surface due to the reduced density of their water, but they may vertically occupy a more or less significant layer depending on the power of the discharge flow and the mixing intensity. Considerable diversity of the morphological shapes and types of dynamic behavior is characteristic of river plumes, which is known from observations, including satellite ones. They feature their own inertial motions; interact with the bottom topography and vortex formations on the shelf; are driven by the wind and background coastal circulation; and, as a result, they eventually mix with the surrounding water and supply the sea with terrigenous substances signaling the anthropogenic impact. Thus, in the dynamics of the plume lies the key to understanding the mechanisms of the propagation of the continental discharge into the ocean and its interaction with the sea waters. At the same time, the patterns of the behavior of the plumes of large and small rivers under different conditions are poorly understood (for a detailed review on this topic see [15]).

Being an inner almost closed marine area, the Black Sea is strongly subjected to the impact of the fresh-water continental discharge. The total number of large and small rivers entering this sea is close 1000, but only ten of them are classed as large ones (i.e., possessing a catchment area exceeding 10000 km^2). According to the majority of authors, the long-term average annual discharge into the Black Sea makes up about 350 km^3, of which 80% is supplied by the ten largest rivers, first of all the Danube (200 km^3), Dnepr (44 km^3), Rioni (13 km^3), and Dnestr (9 km^3) rivers [4]. A lot of studies are dedicated to these rivers, particularly to the Danube. However, there are no regular observations of the water flow discharge of multiple small and medium Black Sea rivers, whose total contribution to the water balance of the sea is quite considerable. Within the Russian sector, more than 20 small rivers enter the sea, as well as several rivers of medium size: the Pshada, Vulan, Tuapse, Psezuapse, and Sochi rivers. An average annual discharge of about 10–15 m^3/s and an annual discharge of 0.3–5 km^3 is typical of each of theses rivers. Larger rivers such as the Shakhe (37 m^3/s, 1.2 km^3) and Mzymta (49 m^3/s, 1.6 km^3) entering the sea stand out in the east on the Russian coast. The total long-term annual discharge into the Black Sea from the Russian territory is about 7 km^3 per year [8]. This is only 2% of the total freshwater discharge to the Black Sea. Perhaps, for this reason, the effect of the discharge of small and medium-sized rivers in the Russian Black Sea has been paid relatively little attention in the literature, although some publications on this topic, of course, exist (for instance, monograph [11], paper [1], and others). However, in spite of the relative insignificance of this discharge as a component of the total water balance of the basin as a whole, it, nevertheless, markedly influences the land–sea system at regional scales, the bioproductivity of the Russian Black Sea shelf, the water quality, and the level of terrigenous and anthropogenic pollution in this area.

The pollution of the coastal waters due to the continental discharge from the Russian sector of the Black Sea takes place particularly in water areas of such large cities as Anapa, Novorossiysk, Gelendzhik, Tuapse, and Sochi [11]. First of all, this is true concerning the largest seaside resort of Russia and the capital of the 2014 winter Olympics. It is known [3] that this region suffers from significant pollution. About 90 million tons of wastewater are annually dumped into the water basins of the region, including the sea itself. Only 15% of this waste can be regarded as clear or nominally clear. More than 20 industrial enterprises lengthwise the rivers Mzymta and Sochi represent one of the sources of pollution. As a result, the waters of the Sochi River involve concentrations of oil products and heavy metals (Cu, Fe, Zn, and others), which exceed the respective MPCs by 16 and 3–5 times [3]. The water in the city of Sochi is classed as polluted (class V of pollution). In addition, sewage wastewater was partially discharged directly into the sea here at a depth of less than 10 m and a distance of about 1 km from the shore abeam of Khosta Township. In recent years, an additional source of pollution was the construction works intensively conducted on some of the coastline due to the upcoming Olympics. Such works were particularly intensive at the site of new port facilities in Mzymta estuary, where gravel and soil was directly excavated from the riverbed, as well as in the area of the central sea terminal near the mouth of the Sochi River.

All of the above circumstances determine the urgency of the exploration of the processes of the river discharge propagation over the Russian Black Sea shelf. Of interest are quantitative evaluations of the scope of the influence of the river discharge upon the hydrochemical and hydrophysical indicators of the 2
water quality in the coastal zone, the features of the variability of this influence at different time scales, as well as the patterns of the river plume dynamics at different atmospheric forcings.

The program Minor Rivers of the Black Sea was initiated in 2006 with the goal to examine these problems in the framework of annual complex field missions run by the Shirshov Institute of Oceanology of the Russian Academy of Sciences (SIO RAS) in the Black Sea.

2. MATERIALS AND METHODS

We used materials of the following expeditions:

(1) Measurements aboard the motorboat *Ashamba* (BRP-74) conducted at three testing sites in the estuary regions of the rivers Pshada (settlement of Krinitsa), Vulan (settlement of Arkhipo–Osipovka), and Mezyb (settlement of Divnomorskoe) on June 1–9 of 2006.

(2) Measurements during cruise 119 of the R/V *Akvanavt* at six testing sites in estuary regions of the rivers Mzymta (city of Sochi), Sochi (city of Sochi), Mezyb (settlement of Divnomorskoe), Tuapse (township of Tuapse), Vulan (settlement of Arkhipo–Osipovka), and Pshada (settlement of Krinitsa) on May 2–5, 2007.

(3) Measurements aboard the motorboat *Ashamba* (BRP-74) at Vulan bay (settlement of Arkhipo–Osipovka) near the mouth of the River Vulan on November 7–13, 2008.

(4) Measurements aboard the motorboat *Ashamba* (BRP-74) at the coastal zone testing site between the mouths of the rivers Cudepsta and Mzymta (city of Sochi) on May 20–27, 2009.

(5) Measurements aboard the motorboat *Granit-1* at the coastal zone testing site between the mouths of the rivers Cudepsta and Mzymta (city of Sochi) on May 25–30, 2010.

(6) Measurements aboard the motorboat *Ashamba* (BRP-74) at the coastal zone testing site between the mouths of the rivers Cudepsta and Mzymta (city of Sochi) on May 25–31, 2011.

(7) Measurements aboard the motorboat *Ashamba* (BRP-74) in the near-mouth regions of the rivers Mzymta, Cudepsta, Sochi, and Bitkha (city of Sochi) on May 15–19 of 2012.

(8) Measurements in the region of the settlements of Sochi, Adler, and Arkhipo–Osipovka on November 28 to December 6 of 2012.

As can be seen from this list, all the expeditions, excluding in the autumn of 2008 in Vulan Bay and the works in late 2012, were carried out in one and the same season (May or early June), which usually corresponds to the flood period of the local rivers.

The location of the sites of the measurements is shown in Fig. 1.

Single-fold measurements were carried out the testing sites Tuapse (May 4, 2007) and Bitkha (May 19, 2012). Two-fold measurements were fulfilled at the testing sites Mezyb (June 4, 2006 and May 4, 2007), Pshadà (June 2, 2006 and June 3, 2007), and Sochi (May 3, 2007 and May 17, 2012). At the sites Vulan (2008) and Mzymta–Cudepsta (2009–2012), the surveys were repeated daily or even twice a day, which resulted in nine surveys at the Vulan site and 17 surveys at the Mzymta–Cudepsta testing area.

In every area, the measurements were arranged in 3–5 lateral transects 1.5–4 km long each (depending on the dimensions of the river plume), which extended from the 5 m depth contour to the 30, 40, or 50 m isobath and were spaced 1–3 km apart. Three or two stations were occupied during every transect for vertical profiling and water sampling. Continuous measurements of the surface layer properties were carried out when sailing in transects or passing from one to another.

The following instrumentation was operated aboard and ashore:

(1) A flow-through sounding system that involves a centrifugal pump of about 1 L/s capacity and a CTD probe of type SBE911 or SBE19 plus stowed in a special on-deck container 30 L in volume. The measurement data were averaged over 10 s time intervals. The same system supplied the hydrochemical sensors (see below).

(2) Underway, the water was also pumped into a flow-through cell with sensors of the oxygen and temperature along with an electrode for the pH measurements. The measured parameters and the boat's coordinates were recorded every 10–30 s (more frequently in the onshore and rarer in the offshore parts of the testing area). The underway recording of the hydrochemical parameters was performed with the help of a 4-channel ionometer (Econika Expert 001) and an amperometric dissolved oxygen sensor (DKTP-02.4) manufactured by a research and development production facility (Econika Expert) in Russia.

(3) The UV fluorescence detector (lidar UFL-8 or UFL-9) mounted on the foredeck of a boat or ship provided rapid underway determination of the content of chlorophyll, suspended particles, and dissolved organic matter at a rate of 4 Hz, which secures spatial resolution better than 1 m at a 5 knot sailing speed. The specifications of the lidar and the procedures for the retrieval of the concentrations from the electric signal are described in [1].

(4) In addition, another CTD probe of type SBE19 plus or Idronaut was used to obtain vertical profiles of the temperature, salinity, and density at the stations.

(5) Water samples for the consequent analysis of the hydrochemical parameters and filtering for the chlorophyll and suspended particles were collected with 5 L Niskin bottles according to [5] from the surface of the sea, in the near-bottom layer, and at the lower boundary of the upper mixed layer. Just after collecting, the water was poured into containers for storage of the samples [6]. The determination procedures corresponded to the standard techniques accepted by institutions of the Academy of Sciences [14] and the fishery industry [13]. The determinations were performed at a temporary on-land laboratory not later than 12 hours from the time of the collection. In addition, we prepared samples for the later assessment of the content of dissolved and suspended metals and organic matter at the laboratories of the SIO RAS.

(6) To determine the components of the seston, the water was filtered with glass fiber filters (Whatman GF/F) 47 mm in diameter (pore size 0.7 μm). The fil-

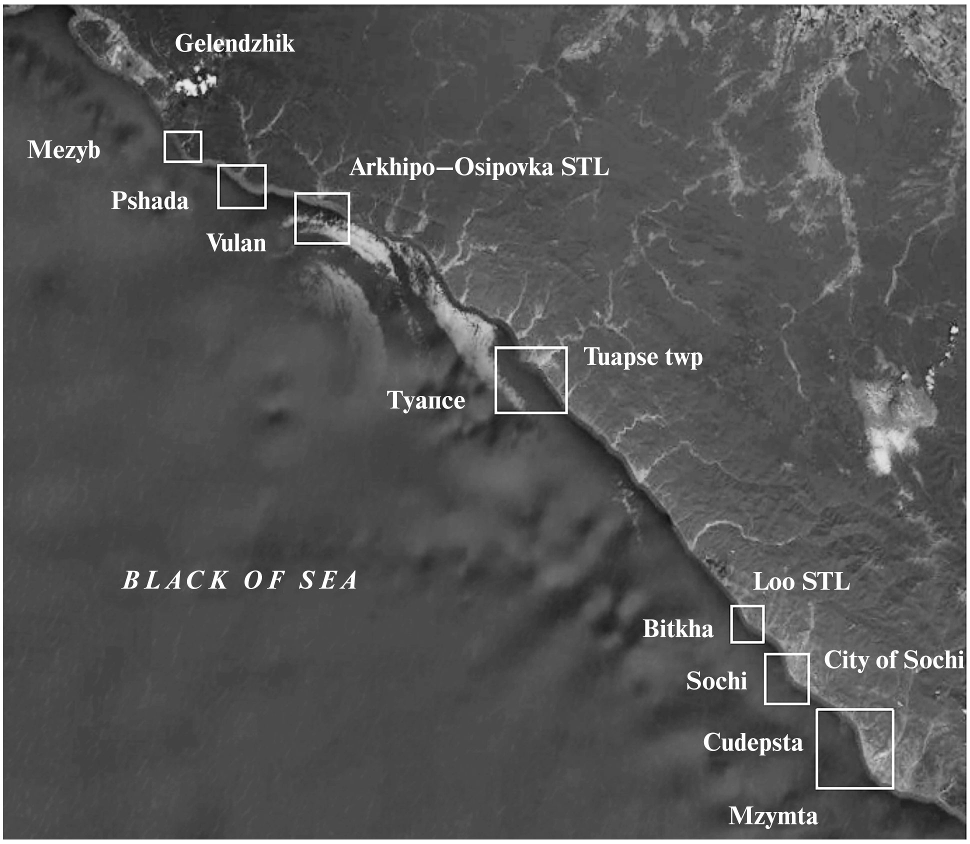

Fig. 1. Location of testing sites in the water areas adjacent to river mouths in the Russian sector of the Black Sea.

ter with the sediment was used to determine the concentration of chlorophyll and the color of the seston, i.e., the absorption spectrum in the visible region, which allowed us to calculate the partial absorption coefficients of its components. The standard spectrophotometric technique involving a water solution of acetone for extracting the chlorophyll was used to determine the latter. The contents of phytoplankton, detritus, and mineral particles were determined with the help of a spectrophotometer (SF-14) with an integrating sphere and expressed in optical terms. The latter were recalculated into units of weight using a formula in [9].

(7) Anchored stations were deployed at the Mzymta–Cudepsta testing sites during the observations (Fig. 2). Every station involved a near-bottom current meter (SeaHorse) [16], and an acoustic current meter (Aquadropp) was additionally deployed at the 3 m depth at the station nearest to the river mouth. The speed and direction of the currents were recorded with averaging over 10 min time gaps. The results of the treatment of the current velocity data in the estuary regions are described in [10].

(8) Current meters (Aquadopp or SeaHorse) were deployed at a depth of 1.5–2.5 m in the beds of the rivers Mzymta and Vulan at a distance of 50–100 m from their mouths. The meters recorded the 10-minute averaged water velocity in the rivers in order to assess the variations of the river discharge.

(9) Portable weather stations (Heavy Weather) were deployed ashore at the testing sites Mzymta–Cudepsta and Vulan. The stations were placed at a height of 8–10 m above the water level near the river mouths at places more or less free of relief elevations, high trees, or buildings. The ten-minute averaged wind speed and direction, along with the main weather parameters, were recorder for the whole period of the observations.

As an example, Fig. 2 demonstrates the design of the measurements at the testing site Mzymta–Cudepsta on May 21–27, 2009. Our measurements were arranged in the same way during the remaining expeditions.

Use was also made of maps representing the distributions of suspended particles over the Mzymta–Cudepsta area. They were plotted from the data of an orbiting color scanner (MER1S-EnviSat) processed using the algorithm MERIS Case-2 Regional [17]. We selected 78 images of the region within a rectangle determined by 43°20′–43°40′ N and 39°30′–40°10′ E. The images correspond to different days from May 18,

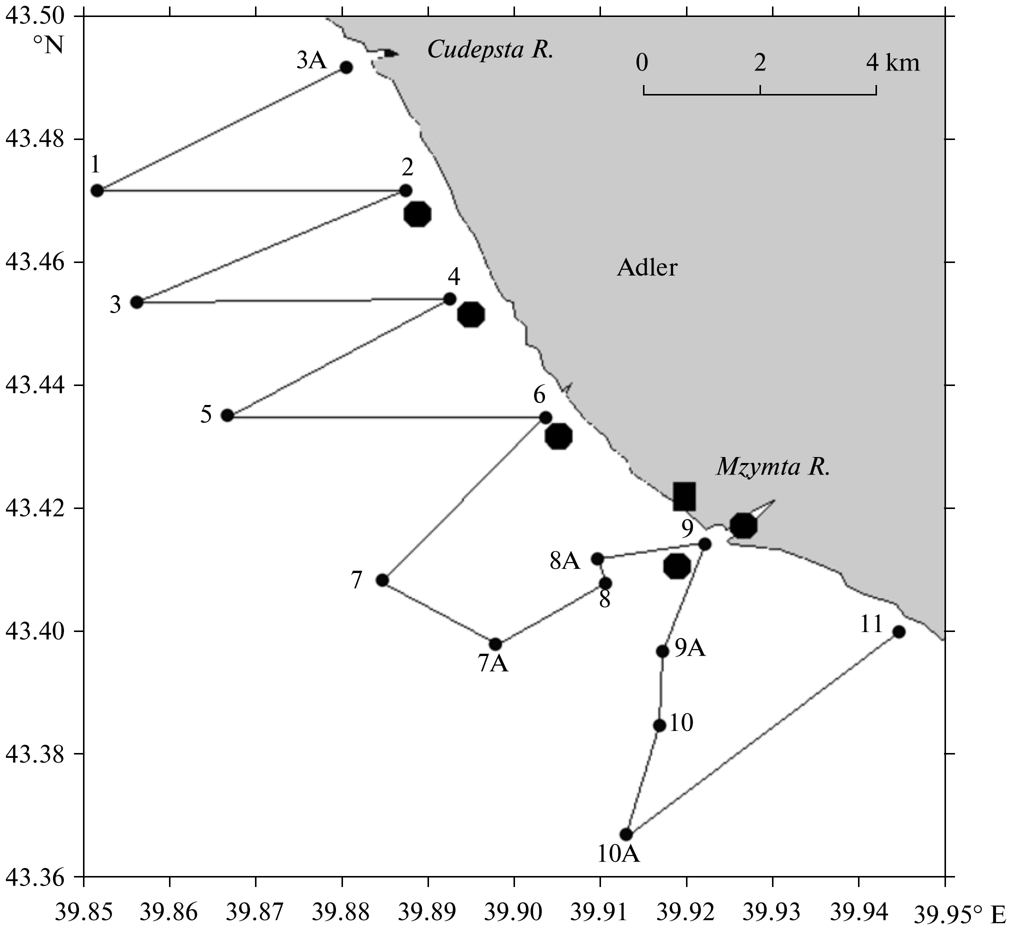

Fig. 2. Arrangement of measurements at the testing site Mzymta–Cudepsta on May 21–27, 2009. The solid line designates the track of the ship, the dots mark the hydrological stations, the large circles indicate anchored stations of the current meters, and the square stands for the portable weather station.

2010 to April 11, 2011 under fair weather with some clouds and provide a clear view of the plume of the river Mzymta distinguished by a high content of suspended particles in the surface layer (Fig. 3).

3. GENERAL CHARACTERISTICS OF THE IMPACT OF THE RIVER DISCHARGE

Clearly distinguishable mesoscale structures (or plumes) were observed during our expeditions in the surface layer from 1 to 4 m thick in the studied areas adjacent to the river mouths. As a rule, they featured a well-defined external boundary (especially on the windward side) and exhibited salinity and density reduced in reference to the background magnitudes in the surrounding waters. Higher contents of mineral and organic suspended particles, dissolved organic substances, and phytoplankton chlorophyll were inherent to the river plumes too. As for the hydrochemistry, there were relatively high pH and general alkalinity, as well as higher contents of silicon and other nutrients. The surface distributions of the salinity and the vertical profiles of the salinity, temperature, and density in the plume of the river Mzymta (May 29–30, 2011) are given in Fig. 4 and Fig. 5 as typical examples. Evidently, in this case, the desalination of the seawater in the plume at the depth of 1 m exceeded 5 PSU, while the desalinated layer was as thick as 3.8 m.

Figure 6 demonstrates a smoothed distribution of the content of mineral particles in the surface layer typical of the inner shelf between the mouths of the rivers Mzymta and Cudepsta. It is easy to see that the content of particles in the Mzymta plume was at least six times as high as their concentration in the background offshore waters, but the Cudepsta plume was only 2–3 times richer in suspended particles with reference to the same offshore waters.

The absolute values of the anomalies of the above parameters in the plumes of the small rivers of the Russian sector of the Black Sea, as well as the horizontal and vertical scales of the plumes, are widely variable

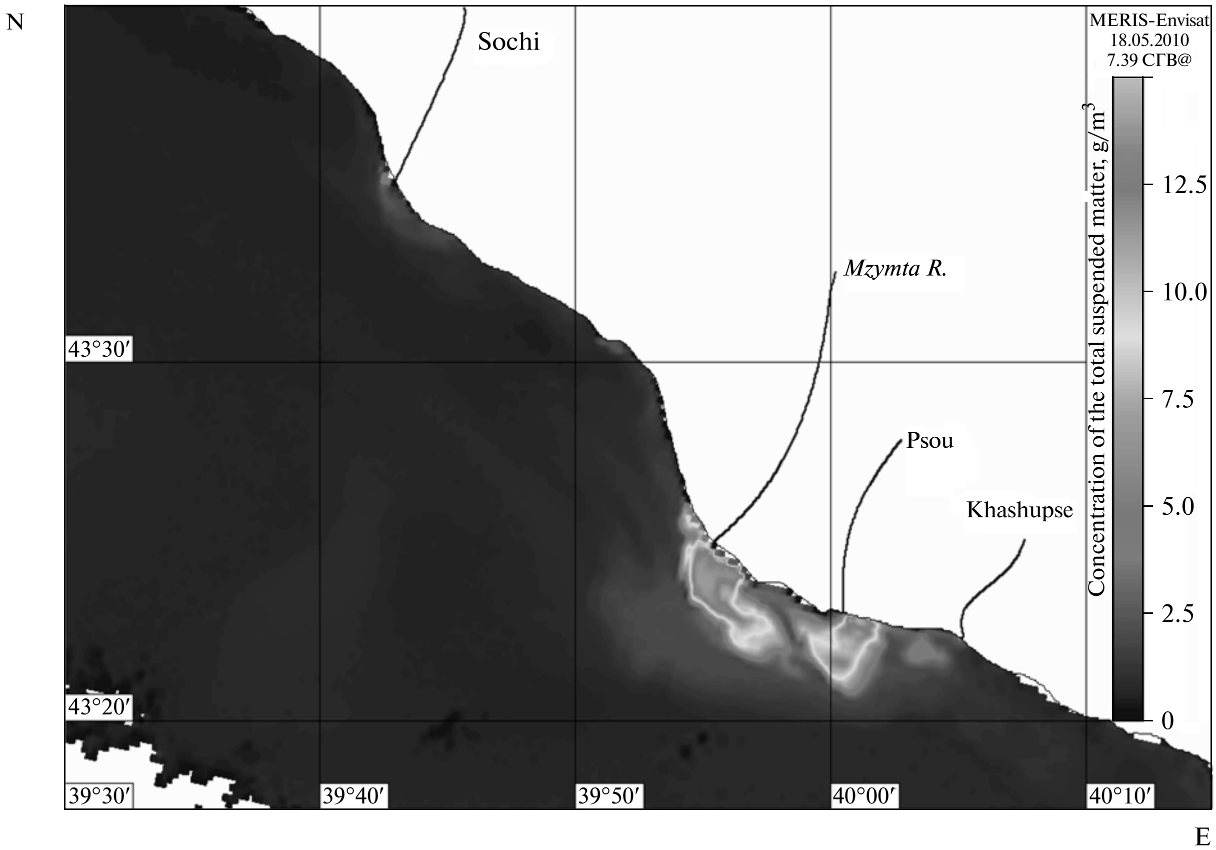

Fig. 3. Example of an image from the MERIS Envisat scanner for the suspended matter concentration in the surface layer (black-and-white reproduction of a color image). The plumes of the rivers Mzymta and Psou are easy to discriminate.

both when passing from one river to another and dealing with one and the same river depending on the discharge intensity and the weather conditions, specifically depending on the speed and direction of the wind. The analytical treatment of the mechanisms that define the characteristics of a plume under certain conditions is beyond the scope of our study (these problems were studied in detail by means of numerical simulation in [15]). Here, we try to present generalized statistics of these characteristics for the area of interest on the basis of field measurement data (in this section) and satellite observations (Section 5). Table. 1 shows the average values ??of the main characteristics of plumes of different Russian rivers entering the Black Sea, as well as relevant anomalies of the salinity, suspended matter concentration, and magnitudes of the hydrochemical parameters. The square root deviations are also given for the cases of more than one measurement. The boundary of every river plume involved was conditionally defined by the line coincident with the salinity contour of 16 PSU. The horizontal scale of a plume was found as the square root of the plume's area. The vertical scale of a plume was determined as the distance from the surface of the sea to the lower boundary of the plume (i.e., the isohaline surface of 16 PSU) at a reference point 200 m away from the mouth of the river. By an anomaly here and after is meant the difference between the respective values at the depth of 1 m at the reference point and the "background" point outside of the plume (as a rule, it was an offshore station of the near-mouth transect).

The influence of the river discharge on the chemical composition of the water of the estuarine areas of the sea depends on the individual characteristics of the chemical composition of the discharge of the individual rivers. Table 2 shows the difference between the various hydrochemical indicators in the surface waters at stations near the mouth of the river and the "background" values at the seaward stations of the testing site. The contents of phosphate, silicon, and different forms of nitrogen is usually increased in estuarine waters. The level of the general alkalinity and the content of dissolved inorganic carbon may be both increased and decreased. Our studies show that the waters of the rivers Vulan, Teshebs, Pshada, and Mezyb are enriched in carbonate carbon against the seawater, and the influence of the river discharge is

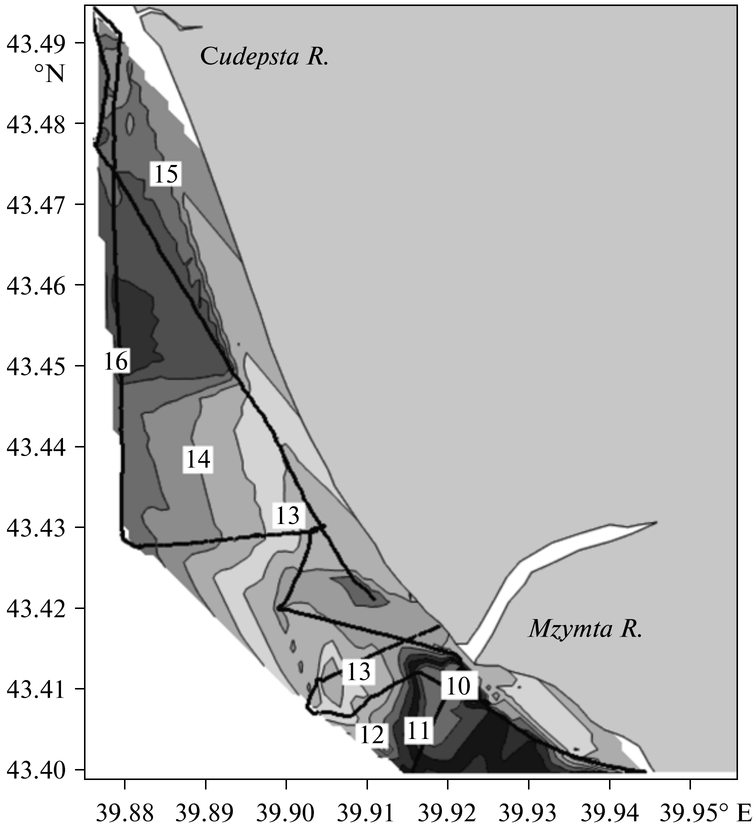

Fig. 4. Distribution of the salinity (PSU) at the 1 m depth at the testing site Mzymta–Cudepsta on May 30, 2011. The black line indicates the track of the ship at the site.

easy to trace by the level of the general alkalinity, while the rivers of the Tuapse–Sochi area are relatively poor in carbonate carbon (excluding the Cudepsta River). This is due to the specific features of the geology of the catchment area and due to the chemical composition of the underground discharge. Note that the chemical composition varies not only from river to river but also strongly depends on the weather conditions of the catchment area. As a rule, a rain flood usually increases the content of various forms of nitrogen and phosphate (likely due to flushing of fertilizers), while the content of silicon and carbonate carbon, on the contrary, decreases.

Direct recordings of the dissolved oxygen content show that the near-mouth zones of the rivers involved belong to the region of increased levels of pH and oxygen content. We can assume that, in the estuary section, there is an area where the biological activity is fueled by the incoming nutrients. However, such an area is able to disappear for a while due to the dynamical factor (for example, surge water). As a rule, this area is located at a distance of 1.5–2 km from the mouth of the river, and the width of this zone is a few tens of meters.

The horizontal scales of the investigated river plumes vary widely from values ??on the order of hundreds of meters to 3 km or more (more than 10 km in rare cases). At that, the plumes are locate in the upper layer, whose thickness varies from tens of centimeters to four and more meters. The maximal anomalies of the salinity in the plumes make up 5 PSU in reference to the surrounding surface waters.

Based on the data on plumes of various rivers in Table 1, it is possible to establish certain "average" statistical relations of the horizontal extent L_h of a plume to its vertical scale L_v and the level of the salinity anomaly in the plume ΔS. According to Fig. 7, these quantities exhibit fairly strong positive correlations. These are the respective linear regressions:

$$L_v \approx 0.86\, L_h,$$

$$\Delta S \approx -0.47 + 1.07\, L_h,$$

where L_h is in kilometers, L_v is in meters, and ΔS is in PSU. These ratios may be useful in practice for estimating L_h and ΔS in those particular cases when one knows only the area (for instance, from satellite data), i.e., the horizontal dimensions of a plume.

Figure 8 demonstrates the level of the total suspended matter concentration lengthwise the line par-

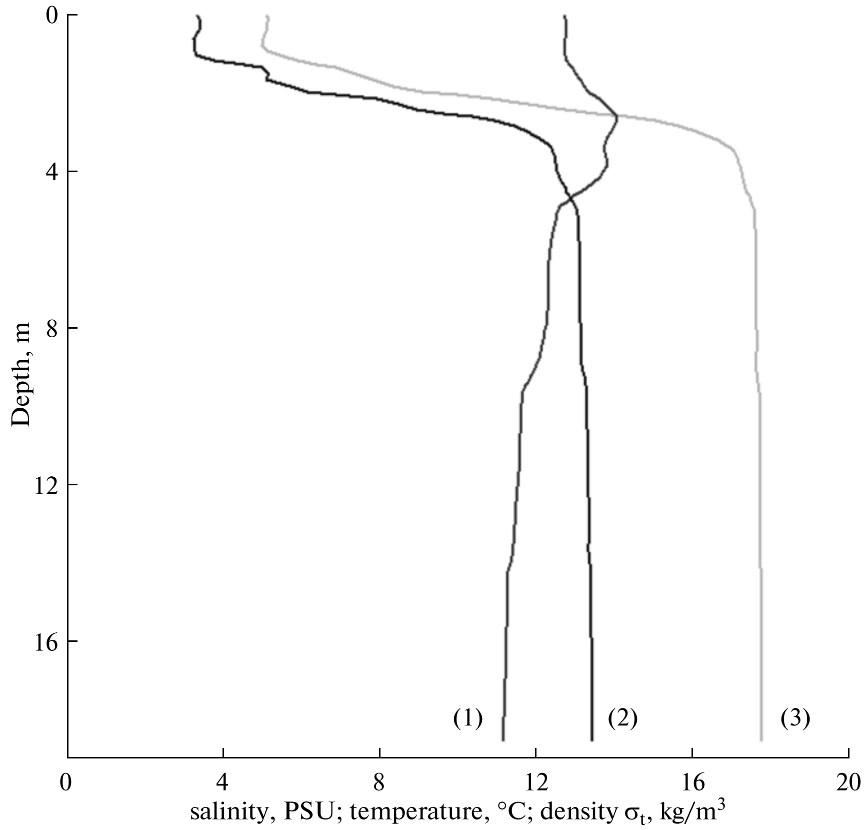

Fig. 5. Typical vertical profiles of the temperature (1), density (2), and salinity (3) in the Mzymta plume on May 29, 2011, at a distance of 220 m offshore the river mouth.

allel to the shore and extending from the mouth of the River Pshada to a site south of the mouth of the Mzymta River (R/V *Akvanavt*; cruise no. 119; May 2–5, 2007). As expected, extremely high values occurred at the stations most close to the river mouths. The highest content of suspended matter was found near the mouth of the Mzymta River; the second highest place was the Tuapse River. A quite significant particle concentration was discovered near the mouth of the relatively small Cudepsta River. At the same time, the

Table 1. Features of plumes of rivers in the Russian Sector of the Black Sea from data of field observation from 2006 to 2012

River plume	Average discharge, m^3/s	Number of surveys	Horizontal scale, km	Vertical scale, m	Salinity anomaly, PSU	Anomaly in the suspended matter content, mg/L
Mzymta	49.5	17	3.0 ± 1.8	2.6 ± 1.2	3.1 ± 1.4	25.5 ± 17.3
Sochi	16.1	2	2.2 ± 1.2	1.9 ± 1.5	2.4 ± 1.0	3.0 ± 2.1
Tuapse	12.8	1	1.8	2.0	1.1	24.0
Pshada	9.8	2	1.3 ± 0.7	0.9 ± 0.7	0.2 ± 0.1	0.8 ± 0.3
Vulan	6.4	9	1.2 ± 0.6	0.6 ± 0.5	0.2 ± 0.1	0.9 ± 0.4
Mesyb	3.9	1	0.4	0.1	0.05	не обнаружена@
Cudepsta	3.4	10	0.9 ± 0.7	1.0 ± 0.8	1.1 ± 0.8	9.3 ± 8.3
Bitkha	0.3	1	0.08	0.4	0.1	не обнаружена@

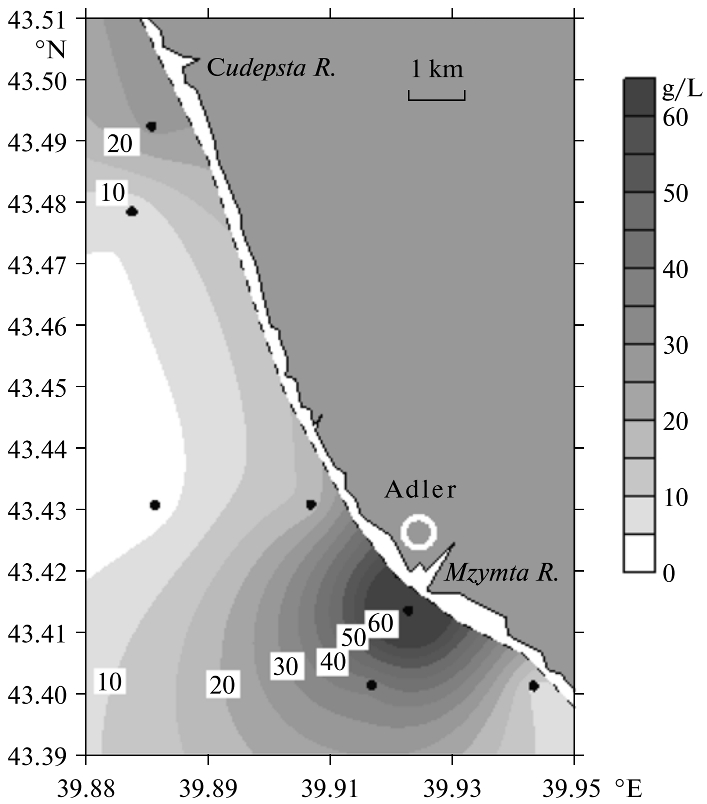

Fig. 6. Distribution of the mineral particle concentration averaged over the period of May 27–30, 2011. The black dots mark the sites of the water samples involved in the calculations.

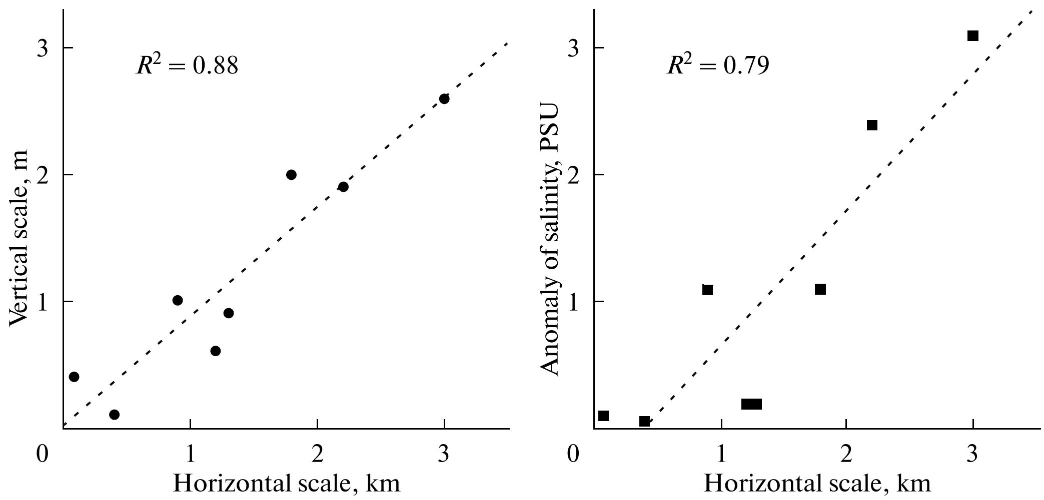

Fig. 7. Empirical dependences of the vertical scales of the plumes (at the left) and the salinity anomalies in the latter (at the right) upon the horizontal scale of a plume. The diagrams were plotted from the data on different plumes given in Table 1. *R* is the coefficient of correlation.

near-estuary zones of the rivers Sochi, Vulan, and Pshada exhibit relatively low contents of suspended matter despite the fairly large volume of the desalinated discharge of these rivers.

Figure 9 shows the changes in the ratio of the organic component of the suspended matter relative to the mineral one along the same transect. This ratio gradually reduces southwards. The rivers north of Tua-

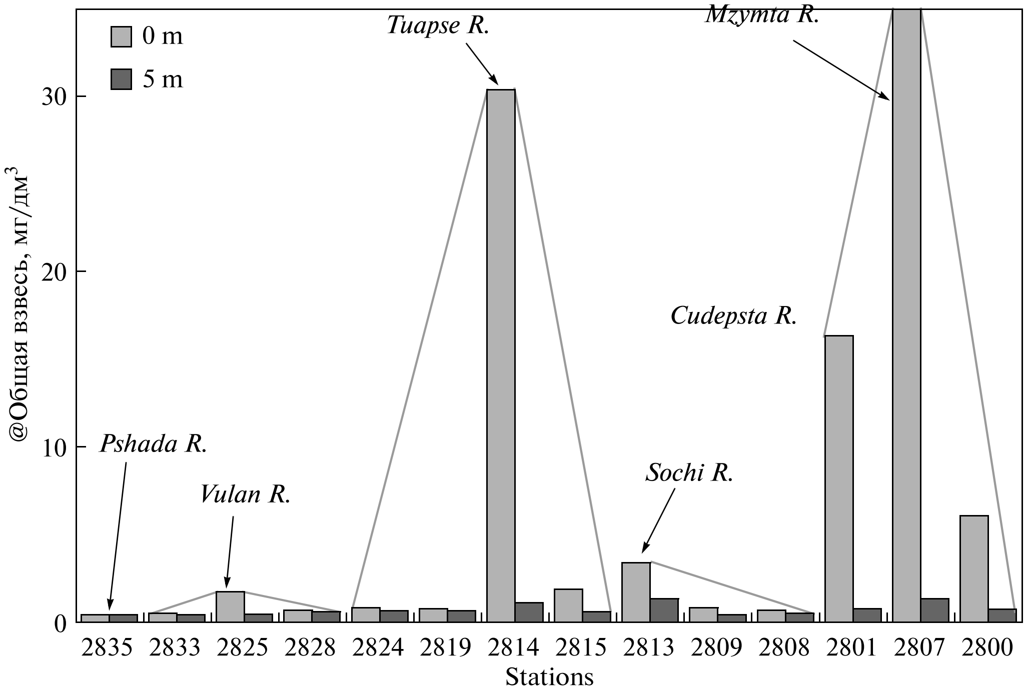

Fig. 8. Concentration of the total suspended matter at the depths of 0 m (light bars) and 5 m (dark bars) at the sites of the stations closest to the shore occupied during 14 transects of cruise no. 119 of the R/V *Akvanavt* (May 2–5, 2007). The station numbers are given on the x-axis and increase northwards. The sites of the coastal stations correspond roughly to the 7 m depth contour (200–500 m offshore). The arrows mark the stations occupied near the mouths of the rivers Pshada, Vulan, Tuapse, Sochi, and Mzymta.

pse transport larger amounts of organic suspended matter, while the Tuapse River itself and the rivers south of it bear mainly mineral particles. This effect seems to be caused by the change from the Mediterranean climatic zone (north of Tuapse) to the subtropical one (south of Tuapse), which is accompanied by a sharp increase in the annual precipitation. Another probable factor is related to the growth of the relief height of the catchment areas from the north to south and the changing of the lithological composition of their constituent rocks.

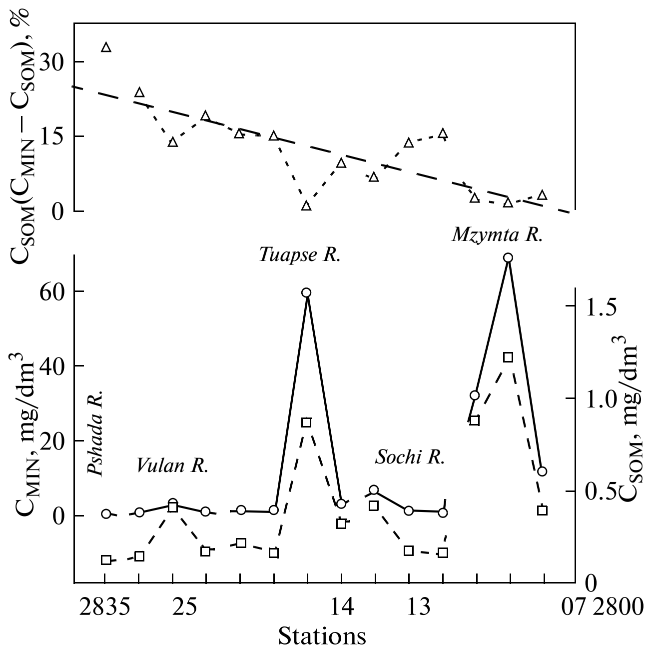

Fig. 9. Concentration of the organic (C_{SOM}, squares) and mineral (C_{MIN}) suspended particles (lower diagram) and the percentage of the organic suspension in the total amount of particles (upper diagram). The dashed lines represent linear regressions.

4. VARIABILITY OF THE PLUME OF THE MZYMTA RIVER

In this section, we analyze the variability of the estuarine environment using the example of the waters around the mouth of the Mzymta River as a region of multiple oceanological studies. We turn first to the interannual variability on the basis of the field data, and then we consider the seasonal and synoptic variability based on satellite information.

Interannual variability. Figure 10 shows the interannual variations in the concentration of the total suspended matter in the plume of the Mzymta River according to the surveys in May of 2007–2012 (with the exception of 2008 because of the lack of data). In all the cases, this data relates to a point 200 m offshore from the mouth. There should be noted the marked tendency for an increase in the content of the suspended matter, whose concentration increased by more than 2.5 times from 34 mg/L in 2007 to 89 mg/L

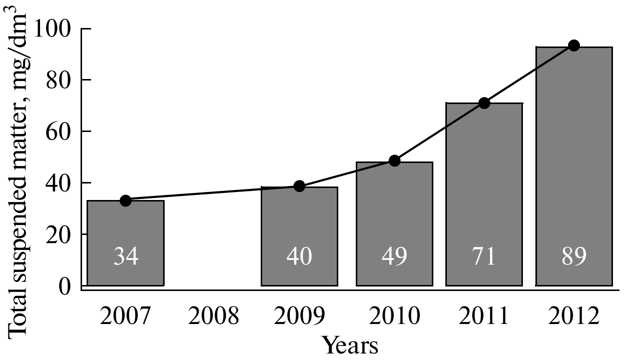

Fig. 10. The maximal concentrations of the total suspended matter in the region near the mouth of the Mzymta River according to the measurements during the expeditions of 2007 and 2009–2012.

in 2012. Of course, this does not allow us to state categorically that the content of the suspensions has been systematically increasing from year to year, because all the characteristics of the plumes exhibit strong short-period variability and because the data in Fig. 9 represent the results of single measurements. Nevertheless, the trend revealed merits attention the more so that it was found thanks to independent measurements and for another indicators (see below). The growth of the suspended matter content in the sea near the mouth of the Mzymta River from 2007 to 2012 may be due to the intensification of construction works in the area of a new port and in the river valley.

We worked in the Greater Sochi area every year around the same time (in the second third of May, when there remains a relatively high river discharge). The river water was repeatedly sampled during these works. The chemical composition of the water from 17 rivers and brooks has been analyzed since 2009. Continuous series of annual observations have been performed for the rivers Cudepsta and Mzymta. The analytical treatment of the data concerning these rivers shows that the maximum content of the dissolved forms of nitrogen, phosphorus, and silicon took place in 2010 (Fig. 11). We assume that this was due to the fact that work had already begun on the construction for the Sochi Olympics and that this year registered the highest volume of earthworks, due to which the rivers were supplied with higher amounts of these elements, silicon in particular.

As expected, the magnitudes of the relevant parameters in November–December of 2012 mostly exceeded those from the spring survey of the same year, but this is quite an ordinary seasonal variation of the chemical discharge.

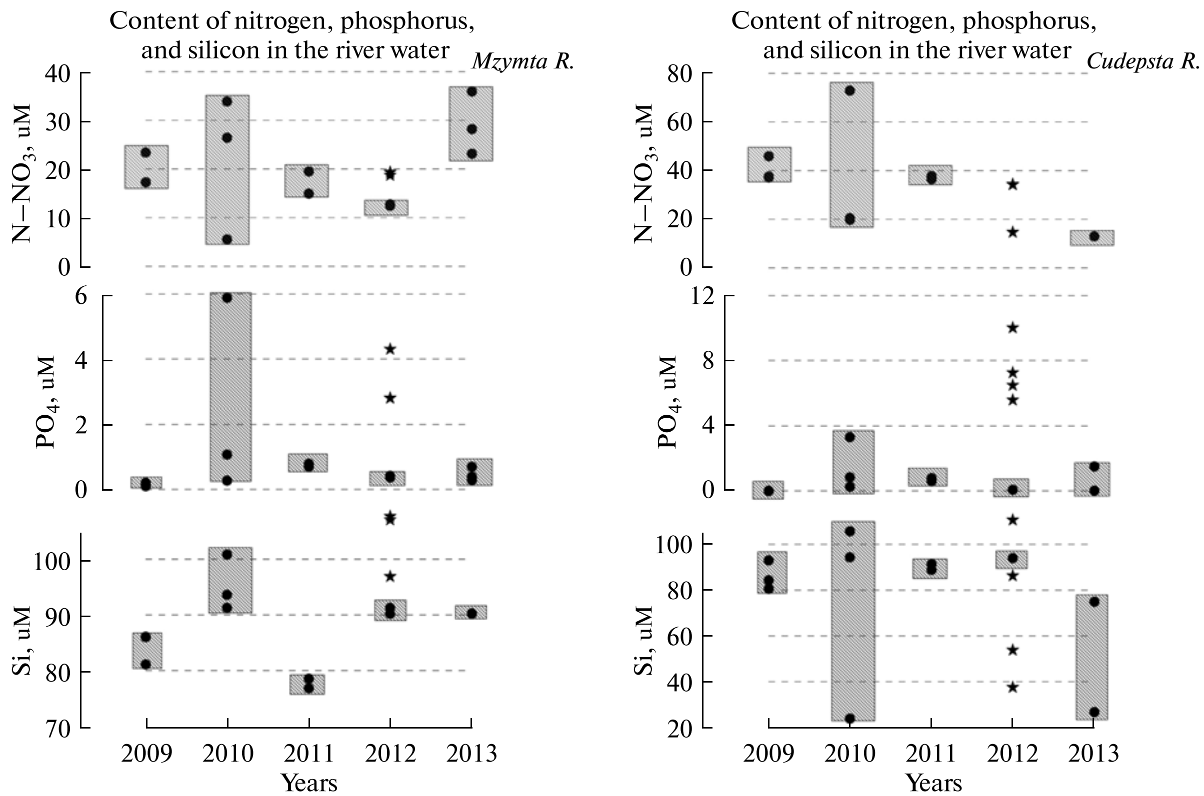

Fig. 11. Variability of the forms of nitrogen, phosphorus, and silicon in the waters of the rivers Mzymta (at the left) and Cudepsta (on the right). The asterisk marks the data from late November to early December of 2012.

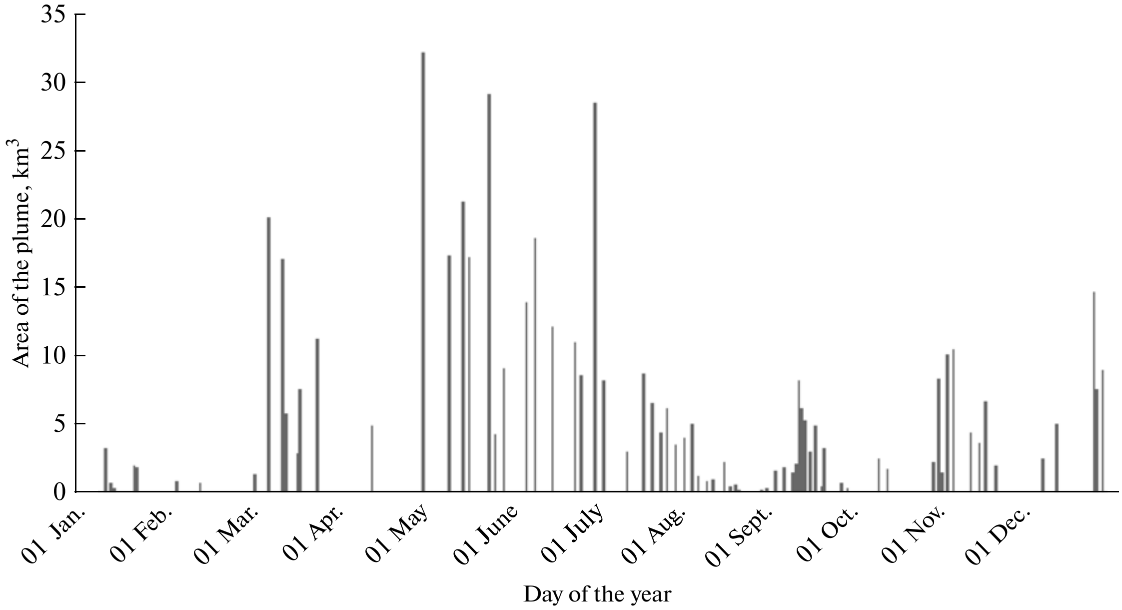

Fig. 12. Area of the Mzymta plume during the satellite observations of 2010–2011.

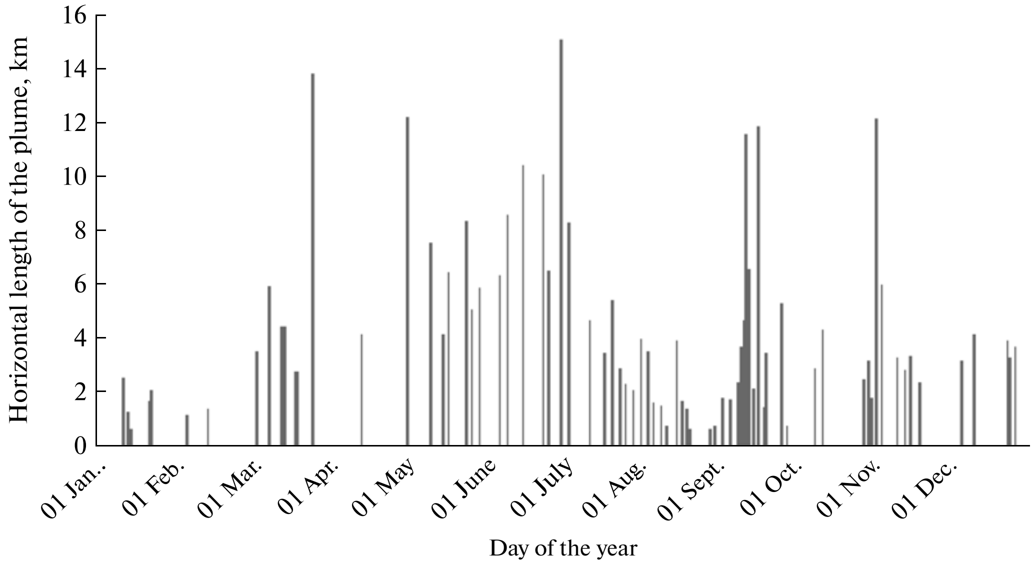

Fig. 13. Maximum horizontal extent of the Mzymta plume according to the satellite observations of 2010–2011.

Synoptic and seasonal variability. Here, we use the information on the characteristics of the Mzymta plume obtained from the data of the satellite ocean color scanner MERIS-EnviSat for the period of May 18, 2010 to April 5, 2011. We selected 78 satellite images of the surface concentration of the suspended matter, which is an appropriate marker of the desalinated waters near the mouth of the Mzymta River.

In order to determine the boundaries of the Mzymta plume from the satellite estimates of the surface concentration of the suspended matter, one has to relate them to the plume's boundaries found from field measurements of the surface salinity. For this purpose, we used three satellite images of May 27 and 30, 2010, and May 30, 2011, obtained concurrently with our observations. Numerical values for the boundaries of the salinity (16 PSU) and the "particle-bearing" (5 g/m^3) plumes were empirically determined. The best coincidence of these plumes is achievable at these values (see also [15]).

Thus, the isoline of the suspended matter concentration of 5 g/m^3 was used to determine the boundary

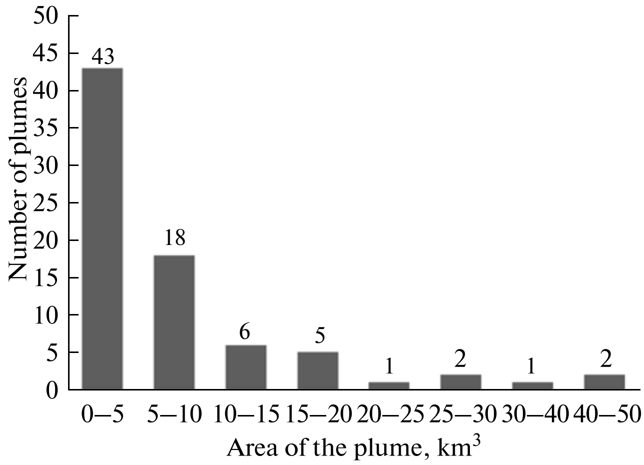

Fig. 14. Statistical distribution of the estimates of the plume area of the river Mzymta (% of occurrences).

of the spreading of the Mzymta plume and to estimate its area in each satellite image. The general statistics of the area of the Mzymta plume for the studied period demonstrate (Figs. 12–14) that it was relatively small in size throughout the year; it occupied less than 5 km^2 in almost half of all the cases, and it exceeded 10 km^2 in 20% of the cases. In a few images, the plume extended beyond the 30 km limit.

The seasonal distribution of the average area of the Mzymta plume is given in Fig. 15. As expected, it generally follows the seasonal variation of the river discharge: the largest size of the plume occurs in the spring (the maximum values take place April), and the smallest sizes correspond to the low-water period in August–September (especially in January–February). However, it is interesting to note that the intensity of the Mzymta discharge in April is three times as high as the February discharge, while the corresponding estimates of the average area of the plume differ by a factor of 30! This again suggests that the river discharge is not the only factor determining the area of the plume: it is reasonable to admit that the smallness of the winter plumes is due to their faster dissipation at the expense of the stronger wind mixing, on the one hand, and the lower water column stability, on the other hand.

Additionally, in every satellite image, we defined the "main axis of the plume's spreading," namely, a line from the mouth of the river to the most remote point of the lens of desalinated water. The length and direction of this line are two additional characteristics of a plume: the extension and the direction of its propagation. Figure 16 shows the average values of the extension of a plume as a function of the direction of its axis. It is evident that the plumes extended lengthwise the shore to the right of the mouth north-westwards or spreading offshore southwestwards reach the largest dimensions.

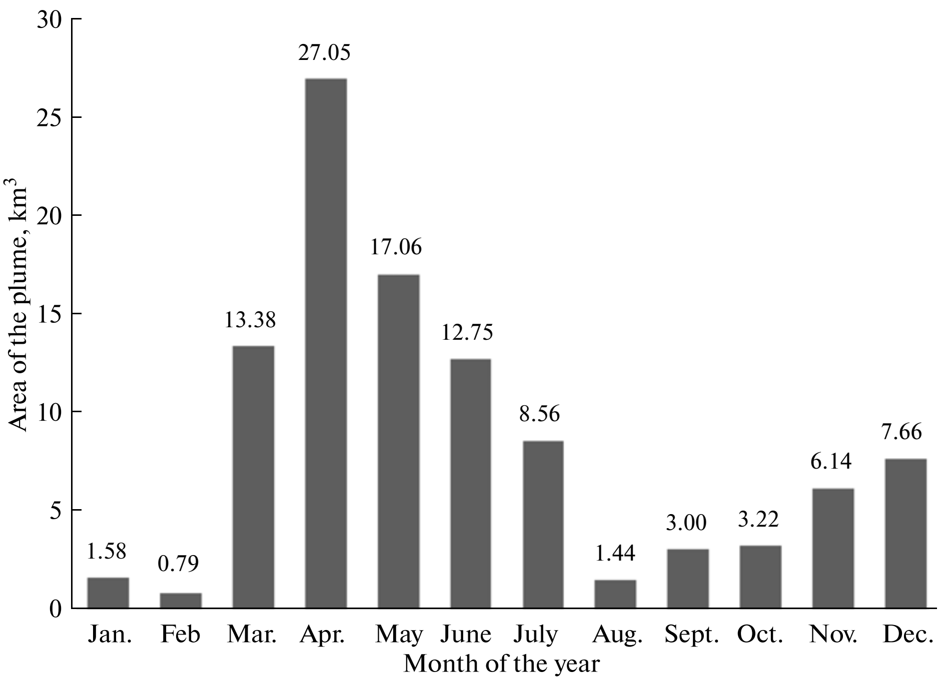

Fig. 15. Seasonal distribution of the estimates of the area of the Mzymta plume (km^2).

Table 2. Average values and ranges of anomalies of the hydrochemical characteristics

River plume	O_2, ml/L	pH, NBS	Alk, mEq/L	P–PO_4, uM	P_{tot}, uM	Si, uM	N–NO_2, uM	N–NO_3, uM	N–NH_4, uM	N_{tot}, uM	Number of surveys
Mzymta	0.00–1.37 0.52	0.01–0.99 0.23	0.02–2.73 1.12	0.02–3.54 1.25		0.15–88.5 40.7	0.01–2.26 0.58	0.00–22.9 9.05	0.36–2.10 1.23		15
Cudepsta	0.07–1.87 1.02	0.01–0.89 0.26	0.07–4.69 1.10	0.00–4.10 1.11		1.84–98.5 45.9	0.03–1.84 0.63	0.04–45.2 15.43			13
Bitkha	0.07–1.26 0.66	0.00–0.23 0.11	0.02–0.38 0.20	0.01–2.27 1.14		1.67–25.8 13.7	0.02–0.04 0.03	0.01–11.87 5.94	0.17–42.7 21.44		2
Sochi	0.05–0.92 0.42	0.01–0.20 0.06	0.01–1.22 0.48	0.00–1.69 0.47		1.60–36.7 20.6	0.13–0.33 0.23	2.94–16.92 9.93	0.04–7.16 2.40		3
R. Vulan	0.01–1.50 0.32	0.03–0.40 0.12	0.00–0.84 0.23	0.00–0.12 0.05	0.10–18.40 7.67	0.01–0.14 0.07	0.00–0.13 0.07	0.08–4.60 1.3	0.10–2.16 0.78	5.30–14.20 9.75	6
R. Teshebs		0.42–0.89 0.65	0.76–1.17 0.96	0.00–0.12 0.06		0.14–0.55 0.34	0.02–0.21 0.11		23.2–64.0 43.6		4
Tuapse	0.07	0.04	0.45	0.23		1.84			0.25		1
Pshada	0.48	0.36	0.05	0.02	0.04	7.45	0.19		0.12	5.95	1
Mesyb	0.50	0.52	0.26	0.04	0.07	21.40					1

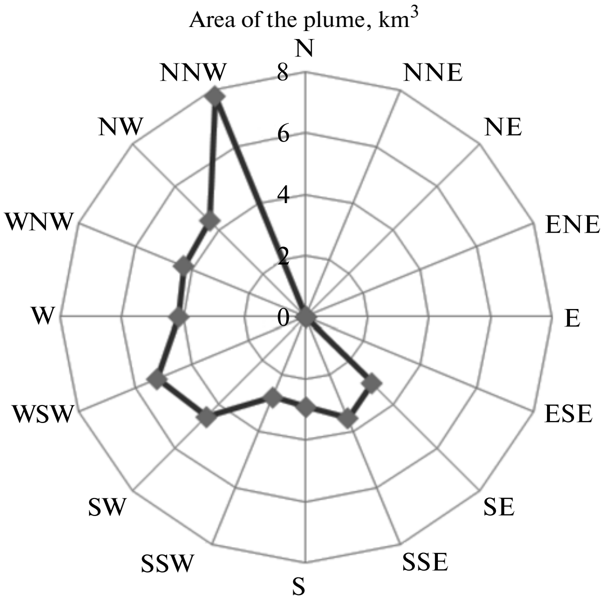

Fig. 16. Average estimates of the extension of the Mzymta plume (km) depending on the direction of the propagation of the plume (the orientation of the main axis).

5. CONCLUSIONS

We attempted to generalize the results of the long-term field and satellite observations in the areas of the Russian Black Sea shelf influenced by the runoff of small- and medium-size rivers (the Mezyb, Pshada, Vulan, Tuapse, Bitkha, Sochi, Cudepsta, and Mzymta rivers). For each of these areas, we give the quantitative
2 characteristics of the response of the hydrophysical and hydrochemical fields at the shelf to the forcing of the continental discharge. The horizontal scales of the plumes investigated widely vary from hundreds of meters to more than ten kilometers (the average value made up 3 km for the Mzymta River, the largest among the others). They locate in the upper layer, whose thickness ranges from tens of centimeters to more than four meters, while the maximal salinity anomalies relative to the surrounding waters reach 5 PSU. We proposed expressions describing the statistical interrelations of the extent of a river plume, its vertical scale, and the magnitude of the salinity anomaly.

The plumes in question featured a high content of suspended matter in the seawater. We established that the ratio of the organic and mineral components of the suspended matter gradually decreases southwards in the studied area: the rivers north of Tuapse transfer relatively larger amounts of organic particles, while the Tuapse river itself and the rivers south of the latter bear mainly mineral particles.

The interannual, seasonal, and synoptic variability of the characteristics of the influence of the river discharge have been studied using the example of the sea area near the mouth of the Mzymta River, for which the most abundant data has been collected. For this area, a tendency of the growth of the total suspended matter from 2007 to 2012 was found for this area, which supposedly is due to the anthropogenic impact. During the year, the largest dimensions of the plumes occurred during the flood in April, and the lowest ones took place in the low-water period in February. We have shown that the seasonal variation of the plumes is attributable both to the annual cycle of the river discharge and to the dynamical factors in the sea area. It was also found that the plumes extended along the coast to the right of the mouth (relative to an observer standing at the mouth of the river and facing the sea) reach the largest dimensions; on the average, the offshore extended plumes feature slightly smaller horizontal scales. The smallest spatial extent is typical of the plumes propagating to the left of a mouth. In this paper of descriptive nature, we do not consider the physical mechanisms underlying the above patterns. These mechanisms are partly considered in our earlier paper [15].

ACKNOWLEDGMENTS

This work was supported by the Presidium of the Russian Academy of Sciences in the framework of program no. 23 of the Ministry of Science and Education of the Russian Federation in the framework of a triple agreement (project nos. V.25.31.0028, GK 2042, and GK 8338), by the Russian Foundation for Basic Research (project nos. 07-05- 00240 à, 13-05-00626 à, and 13-05-96518 r_yug_a), and by the CLIMSEAS project in the framework of an international grant.

REFERENCES

1. N. A. Aibulatov, P. O. Zavialov, and V. V. Pelevin, 1
“Peculiarities of hydrophysical self-purification of Rus- 2
sian coasts of the Black Sea near river estuaries,” Geoekologiya, No. 4, 301–310 (2008).
2. E. M. Al’tman and N. I. Kumysh, “Long-term 3
intraspecific variability of the freshwater balance in the Black Sea,” Tr. Gos. Okeanogr. Inst., No. 176, 3–18 (1986).
3. M. M. Amirkhanov, N. S. Lukashina, and A. P. Trunev, *Natural Recreation Resources, Environmental Conditions, and Economic-Legal Status of the Coastal Resorts* (Ekonomika, Moscow, 1997) [in Russian].
4. *Hydrometeorology and Hydrochemistry of the USSR Seas,* Vol. 4: *The Black Sea*, No. 1: *Hydrometeorological Conditions* (Gidrometeoizdat, Leningrad, 1991) [in Russian].
5. *GOST* (State Standard) *17.1.5.05-85: Interstate Standard. Nature Protection. Hydrosphere. General Sampling Rules of Surface and Marine Waters, Ice, and Atmospheric Precipitation* (Izd. Standartov, Moscow, 2003) [in Russian].

6. *GOST* (State Standard) *17.1.5.04-81: Interstate Standard. Nature Protection. Hydrosphere. Devices and Tools for Sampling and Storage of Natural Water* (Izd. Standartov, Moscow, 2003) [in Russian].
7. *State Report "Environmental Conditions and Protection in Russian Federation in 2010* (Minist. Prirody RF, 2011). http://www.mnr.gov.ru/upload/iblock/da2/1fevr.rar
8. Sh. Dzhaoshvili, "Rivers of the Black Sea," in *Technical Report No. 71 of European Environmental Agency*, 2002. http://www.eea.europa.eu/ru/publications/technical_report_2002_71/at_download/file
9. B. V. Konovalov, M. D. Kravchishina, N. A. Belyaev, and A. N. Novigatskii, "Spectral analysis of marine suspension as an alternative method for its determination in environmental monitoring," in *Trans. XII Int. Conf. "Ecosystems, Organisms, and Innovations*, 2010, p. 35.
10. O. A. Korotkina, P. O. Zavialov, and A. A. Osadchiev, "Submesoscale variability of the current and wind fields in the coastal region of Sochi," Oceanology (Engl. Transl.) **51** (5), 745–754 (2011).
11. *Dynamic Processes of the Coastal Zone of the Sea*, Ed. by R. D. Kosyan, I. S. Podymov, and N. V. Pykhov (Nauchnyi Mir, Moscow, 2003) [in Russian].
12. M. I. L'vovich, *Water and Life: Water Resources, Their Transformation, and Protection* (Mysl', Moscow, 1986) [in Russian].
13. *Manual on Chemical Analysis of Marine and Fresh Waters in Environmental Monitoring of Fishery Reservoirs and the World Ocean Regions Prospective for Fishery,* Ed. by V. V. Sapozhnikov (VNIRO, Moscow, 2003) [in Russian].
14. *Modern Methods of Hydrochemical Studies of an Ocean*, Ed. by O. K. Bordovskii and V. N. Ivanenkov (Inst. Okeanol., Ross. Akad. Nauk, Moscow, 1992) [in Russian].
15. A. A. Osadchiev and P. O. Zavialov, "Lagrangian model of a surface-advected river plume," Cont. Shelf Res. **58**, 96–106 (2013).
16. V. A. Sheremet, "SeaHorse tilt current meter: inexpensive near-bottom current measurements based on drag principle with coastal applications," in *Trans. 15th Ocean Science Meeting, Abstract PO25C-13* (Am. Geophys. Union, Portland, Oregon, 2010), Vol. 91, No. 26.
17. A. Tanaka, M. Kashino, R. Doerffer, et al., "Development of a neural network algorithm for retrieving concentrations of chlorophyll, suspended matter and yellow substance from radiance data of the ocean color and temperature scanner," J. Oceanogr. **60**, 519–530 (2004).

Translated by G. Karabashev

SPELL: 1. Aibulatov, 2. hydrophysical, 3. Kumyshá 4, не обнаружена