ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2013, Vol. 49, No. 9, pp. 886–896. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © V.G. Bondur, V.E. Vorobjev, Yu.V. Grebenjuk, K.D. Sabinin, A.N. Serebryany, 2012, published in Issledovanie Zemli iz Kosmosa, 2012, No. 4, pp. 3–11.

Study of Fields of Currents and Pollution of the Coastal Waters on the Gelendzhik Shelf of the Black Sea with Space Data

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Received February 2, 2012

Abstracts—This paper presents the results of hydrophysical measurements and processing of space imagery of the fields of currents and pollution of the coastal waters on the Gelendzhik shelf of the Black Sea. The results of measurements with a towed acoustic Doppler profiler reveal the strong spatial and temporal variability of the fields of near-surface currents and impact of the deep discharge on the dynamics of coastal waters. The characteristics of the near-surface seawater pollution are studied under the influence of the submerged outfall. The analysis of space imagery of high spatial resolution reveal small-scale optical seawater heterogeneities caused by intense anthropogenic impact directly on the Gelendzhik Bay, the surface influence of the submerged outfall on the coastal waters, and the pollution jet area.

Keywords: aerospace monitoring, fields of currents, vortices, near-bottom convection, sound-backskattering layers, acoustic current Doppler profiler, submerged outfall, water pollution, Black Sea

DOI: 10.1134/S000143381309003X

The peculiarities of the water circulation in the Black Sea are well studied on the basis of hydrological research (*Kompleksnye...*, 2002; Titov, 2002) and space monitoring (Bondur, 2004; Lavrova et al., 2011). A combination of the bottom topography and circulation of seawaters and air flows on the northeastern coast of the Black Sea govern the highly intense dynamic processes in the sea and atmosphere typical of this region. The strongly hydrodynamically unstable Major Black Sea current (MBSC) causes the main peculiarities of the water circulation in the Black Sea (Titov, 2002). The MBSC instability forms the vortex structures of various scales on the Black Sea shelf (*Kompleksnye...*, 2002; Titov, 2002), the most interesting of which are insufficiently studied small-scale vortexes, which play an important role in the spread of coastal pollution (Bondur et al., 2009, 2011a, 2011b).

The intense exploration of the Black Sea shelf and fast growth of seaside towns; resorts; and, especially, mass coastal cottage reclamation result in the significant reinforcement of anthropogenic impact on the coastal ecosystem of this region. The major pollution sources of the Black Sea shelf are small rivers; downpour and wastewater discharges via submerged reservoirs near the towns and settlements; and anchorage places where technological waters, oil, and its products are disposed into the sea (*Tekhnogennoe...*, 1996; Bondur and Grebenjuk, 2001; Bondur, 2004; Lavrova et al., 2011). A series of industrial enterprises located on the coast dispose the polluted waters directly to the sea, and some pollution sources (e.g., downpour discharges) in the town of Gelendzhik are uncontrolled (*Tekhnogennoe...*, 1996). All of this strongly worsens the quality of seawater near the Black Sea coast and decreases the value of this important Russian recreation zone.

Thus, a study of the fields of currents and analysis of spreading anthropogenic pollution in this water area with subsatellite and space data are topical and important for revealing and elimination of the water pollution sources.

Modern aerospace methods and tools, including the satellite measurement of water color, which are effective for estimating the anthropogenic impact on the coastal waters, play an important role in solving these tasks (Bondur, 2004, 2011). Multispectral data from the aerospace monitoring of high spatial resolution in the visible and nearest infrared (IR) spectrum range give the most reliable information on the local pollution of the coastal waters caused by the outfall of individual enterprises, sewage treatment plants, and small rivers (Bondur, 2004, 2011; Bondur and Zubkov, 2005).

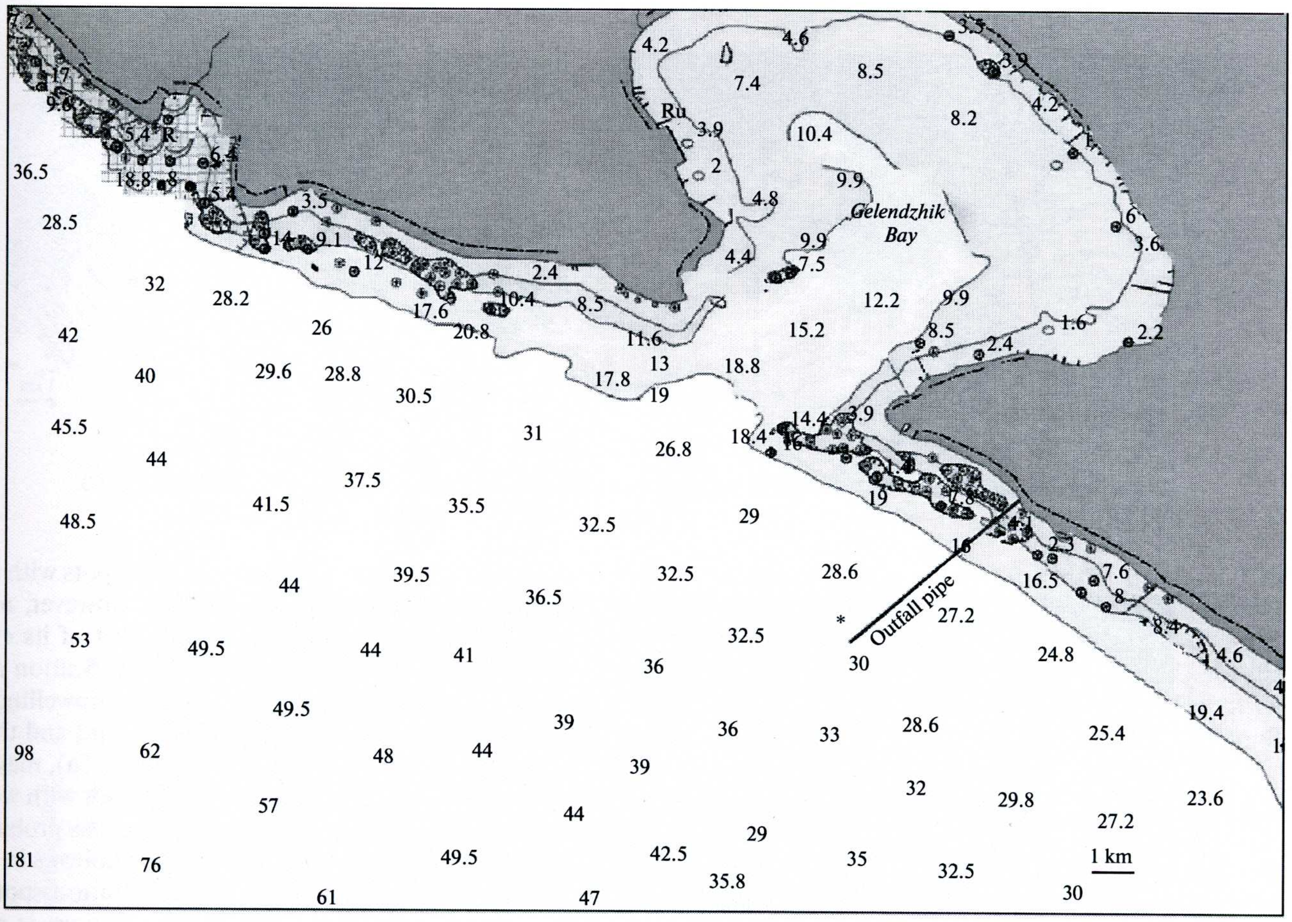

Fig. 1. Map and space image of the region of hydrophysical measurements in the Black Sea water area near Gelendzhik (the outfall pipe of polluted waters is shown).

The given paper presents the results of an analysis of experimental data on the characteristics of the fields of currents and spreading of the pollutants under the discharge of polluted waters from the submerged reservoir to the Black Sea coastal water near the town of Gelendzhik. The experiments were conducted using a submersible Conductivity, Temperature, and Depth (CTD) sounder; acoustic current Doppler profilers; and temperature sensors. In addition, the survey from the IKONOS satellite was carried out and multispectral images of high spatial resolution were processed.

CHARACTERISTIC OF THE COASTAL CURRENTS AND SEAWATER POLLUTION INDICES ON THE BASIS OF ACOUSTIC CURRENT DOPPLER PROFILER MEASUREMENTS

In 2008–2011, the fields of currents and seawater parameters were studied in the outfall pipe area on the Black Sea shelf near the town of Gelendzhik (Fig. 1) with a complex of hydrophysical equipment, including a CTD-sounder, anchored termistor string, a distributed temperature senor (Konyaev and Sabinin, 1973), and towed and bottom acoustic Doppler current profilers (ADCPs). Using this equipment, the temporal and spatial variability of the fields of currents, temperature, density, and salinity of seawater were studied and the degree of pollution of the coastal waters was estimated in different areas of this area. The characteristics of small-scale variability of the fields of currents were determined and the impact of the deep discharge near the town of Gelendzhik on the dynamic processes related to the pollution of the coastal waters was estimated. The domestic and technical waters near the town of Gelendzhik are released via submerged pipe ~2 km long, the output of which is located at a depth of ~30 m. Divers have observed serious damage to this pipe, which is confirmed by environmental services.

Three constituents of vector of the fields of currents and intensity of the sound backskattering (SBS) were measured by ADCPs towed by a motor yacht. The data were registered at different horizons in a depth range

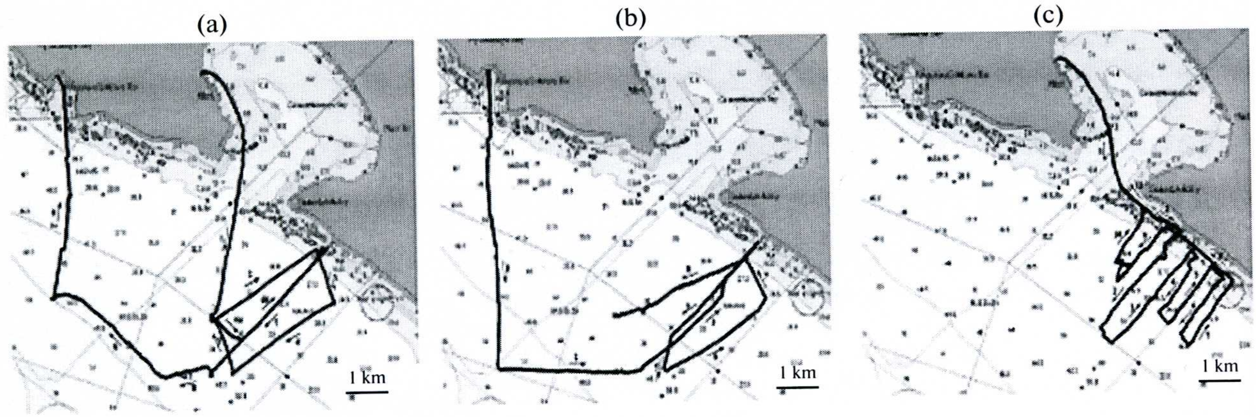

Fig. 2. Schemes of traverses on the Gelendzhik shelf with a towed ADCP: October 1 (a), 4 (b), and 10 (c), 2009.

of 0.8–64 m with a 0.5-m step after each 0.8 s on October 1, 4, and 10, 2009, on the traverses shown on Figs. 2a–2c. The characteristics of currents and intensity of the dispersed acoustic signal were measured with the bottom profiler placed near the pipe end from September 29 until October 11, 2011.

To decrease the level of the noise splashes in the input ADCP data, ten neighbor counts were averaged and data with temporal discreteness of 8 s were further processed, which corresponds to a spatial resolution of 16 m at the yacht velocity of 2 m/s. Using the Surfer program, the vector maps of the fields of currents were constructed in the longitude–latitude coordinates to study the peculiarities of the current rates in various shelf areas and to estimate the impact of the submerged outfall on the pollution of the coastal waters.

Figures 3, 5, and 6 show vector maps of the depth-averaged (barotropic) currents and maps of the backskattering of the acoustic signal based on measurements on October 10, 2009, which strongly reflect variable fields of currents and concentrations of the pollutants in the studied region. It should be noted that SBS intensity characterizes the degree of water pollution well. Let us analyze these maps in detail. According to measurements on October 1, 2009 (Figs. 3a, 3b), mostly eastward currents with rates of up to 10–15 cm/s were observed in the western and southeastern parts of the region. At the same time, N- and NW-trending currents were dominant to the north and northwest from the outfall pipe. In the central part of the region, northwest from the pipe, we observed the area of weakened and chaotic currents with clear flow divergence, where one may find a small vortex about 4 km across, probably related to the upwelling of fresh polluted waters, which are released to the sea via submerged pipe. The increased pollution content of this region, which is manifested on the map of the level of the reverse sound-dispersing signal (Fig. 3b), is in accordance with such a suggestion. The spots with the highest pollutant content are located, however, near the middle part of the pipe, 1.6 km west of its end. Some gap between the intense SBS spot location and situation, which should be formed at the upwelling of the released fresh waters from the pipe end and their transportation by barotropic currents (Fig. 3a), may be explained as follows. The most intense spot with weak currents near the middle part of the pipe was probably related to the water that vented from the hollows in the corroded pipe. The location of the pollution spot to the west from the pipe end, in our opinion, is also related to the released waters. It should be accounted that emerging waters are characterized by some impulse directed to the southwest, as well as the pipe. This causes a spot shift in the indicated direction that is supported by SBS observation in the sections over the pipe (Fig. 4 in color insets).

It should be noted that maps of barotropic currents not always allow us to estimate the transfer of the released waters very well, because the real currents change with the depth and the period of upwelling of these waters to the sea surface is not short enough to ignore the temporal variability of the currents. For example, at a typical rate of upwelling of fresh water of 1 cm/s, water from a depth of 30 m arises for 50 min. The tongue of increased intensity arising from the pipe end at a depth of 30 m toward the open sea is very visible on the echolocation contrast (SBS intensity) pattern based on a measurement from October 1, 2009, over the pipe (Fig. 3b). Such a pattern corresponds to the upwelling of the stream that emerges from the pipe with a significant velocity. The vertical jets of increased SBS intensity arising from the bottom at shallower depths indicate the seepage of the released waters through the pipe hollows (Fig. 4).

An analysis of the vector map of the field of currents based on measurements on October 4, 2009

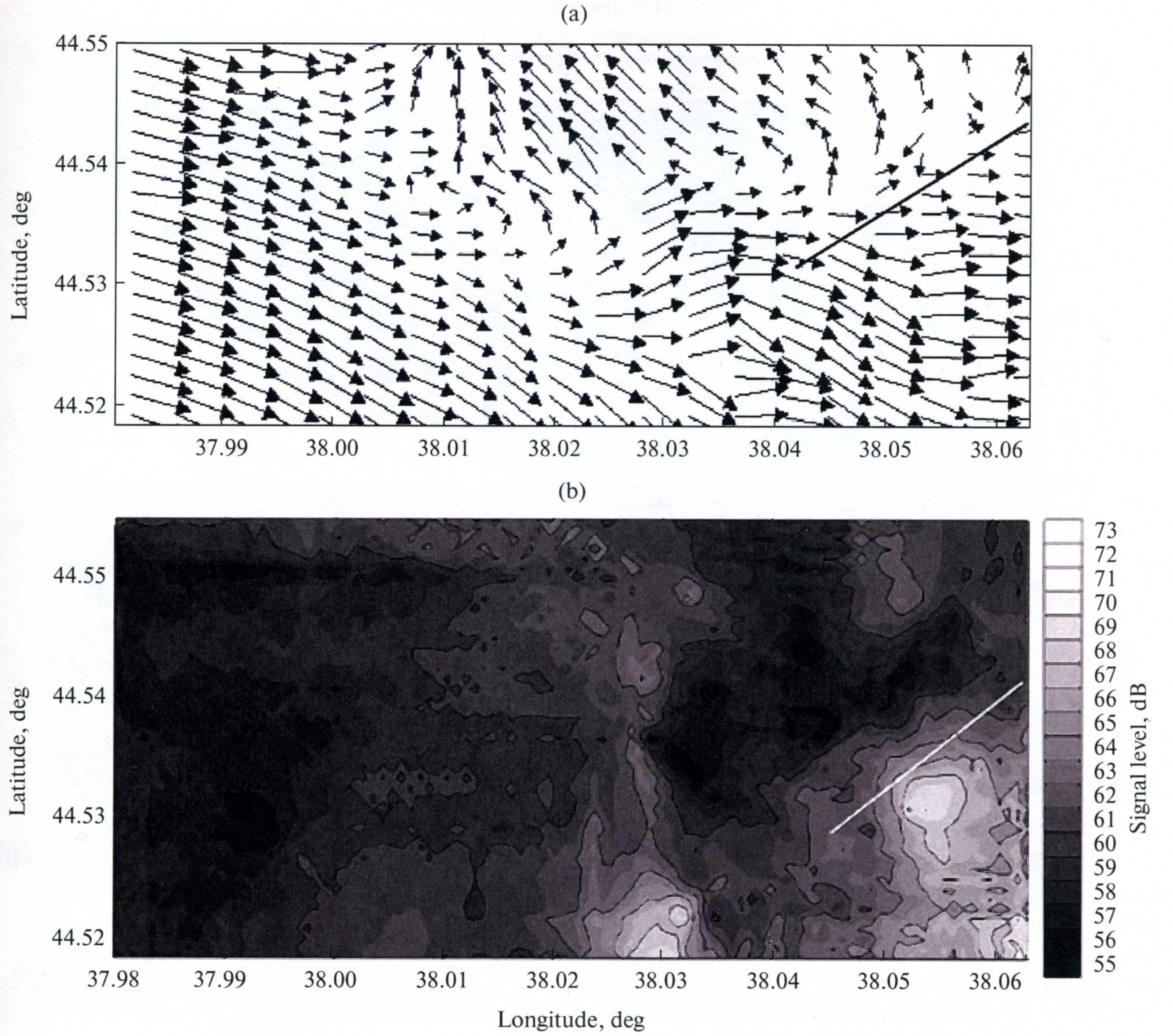

Fig. 3. Vector maps of barotropic currents based on measurements on October 1, 2009 (a) and the level of backskattering of the acoustic signal in dB (b). Gradation of the acoustic signal in dB is shown from the right. The outfall pipe is shown by a white line.

(Fig. 5a), indicates the cardinal change in circulation of the coastal waters under the influence of the large-scale anticyclone vortex in this region. The strong homogeneous current is arranged near the outfall pipe and only in the northeastern angle of the pattern do we observe weakened currents and flow rotation to the south, which is probably related to the impact of released waters, which emerges from the pipe hollows. The increased SBS intensity in this place (Fig. 5b) confirms such a supposition. The spots of slightly weaker but significant SBS intensification (~70 dB) may be noticeable near the middle and end of the pipe and 1.7 km southwest from it (Fig. 5b). Let us note that SBS concentration in the well distinguished spots was less on October 1, 2009 (Fig. 3b).

The NW-trending intense shore current was revealed on October 10, 2009, in the coastal zone (northeastern part, Fig. 6a). A similar intense SE-directed current with a cyclonic vortex near the central part of the pipe was registered in the deeper southwestern part of the studied water area (Fig. 6a). An analysis of the pollution map of the surface waters (Fig. 6b) reveals that the spot of maximum SBS intensity is observed slightly northward from the pipe center; it is probably related, along with the vortex, to the stream of the released waters that seep from the hollows in the corroded pipe and is transited by current to the north-

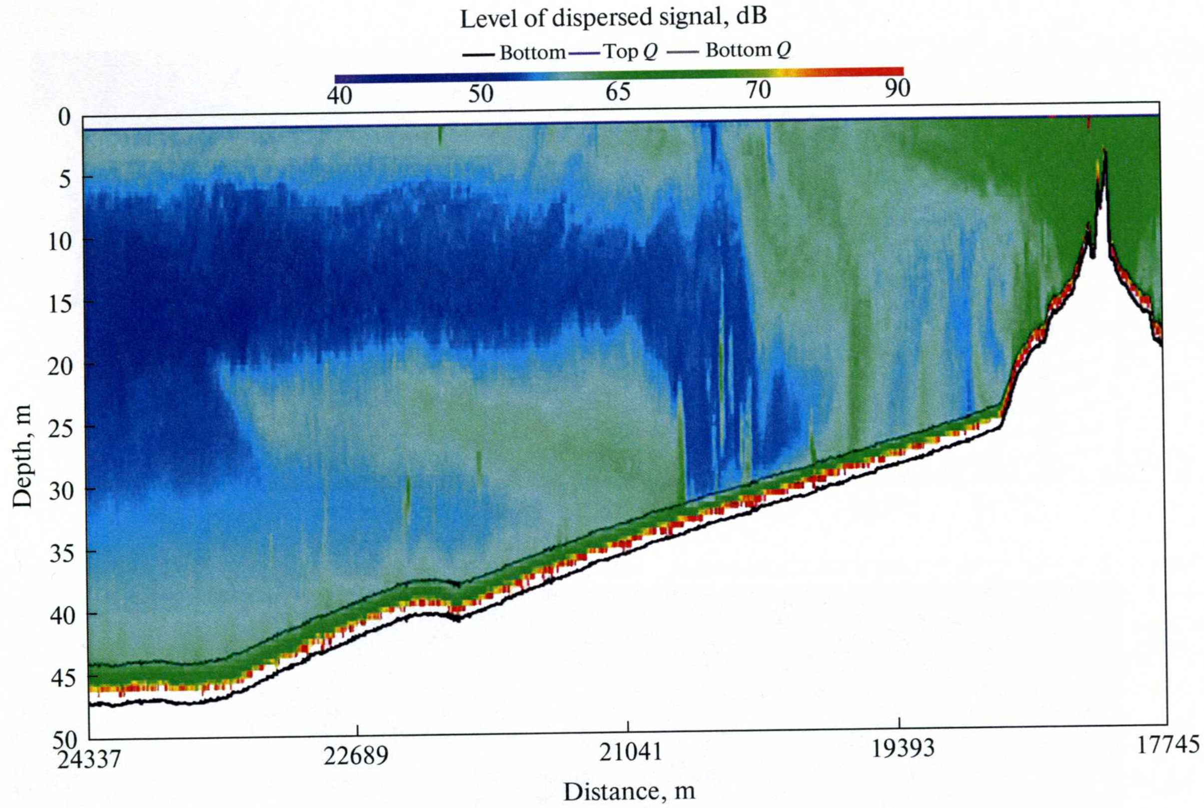

Fig. 4. Intensities of a dispersed acoustic signal based on measurements on October 1, 2009, near the outfall pipe: color scale of intensity of the dispersed signal in dB (top) and reflections from the seafloor (bottom).

west. Southeastward from the pipe center, there is one more area of increased SBS intensity, probably related to the seepage of the released waters from another hollow in the impact zone of the transverse southeastern flow. No other manifestations of the main stream of the released waters, which emerge from the pipe end, are found in Fig. 6b. These waters probably reach the surface beyond the examined polygon.

The analysis of data reveals a certain relation between heterogeneities in the field of subsurface SBS and currents in respect to both the location of spots of increased SBS intensity transported by the current from the pipe hollows and local heterogeneities of the fields of currents, which are produced by the upwelling plumes of the released polluted waters. The narrow waterspout-like vortexes in such plumes (vortex columns) were previously found at a detailed study of small-scale currents near the reservoirs of the deep outfall on the Honolulu (Bondur et al., 2009) and Gelendzhik (Bondur et al., 2011a, 2011b) shelves. In the present paper, we see larger vortices also related to deep discharges. Thus, the released waters and background currents, which horizontally transfer them being distorted under the impact of upwelling waters, are dynamically interacted. All of this leads to a rather complicate pattern of pollution spread related to the outfalls to the sea.

POLLUTION MANIFESTATIONS CAUSED BY DEEP DISCHARGE ON AEROSPACE IMAGES

The negative impact of the deep discharges on the ecology of the coastal waters is confirmed by aerospace surveys of the Gelendzhik shelf. Slicks related to the released waters on the surface are typically observed on the sea surface in the outfall pipe area. Such slicks are well manifested on satellite radar images of the sea surface (Bondur, 2004; 2011; Bondur and Grebenjuk, 2001). The pollution of the water area is well displayed on the aerospace images and in the visible range (Bondur, 2004, 2011; Bondur and Zubkov, 2005). The arch-shaped tale of dirty waters which emerge from the pipe hollow at a distance of 168 m (!) from the coast (Fig. 7 in color inset) is easily seen on the helicopter image of the coastal shelf (Lavrova et al., 2011). Smaller scale heterogeneities similar to the vortices found by ADCP measurement may be recognized in the tail (Bondur et al., 2011a, 2011b).

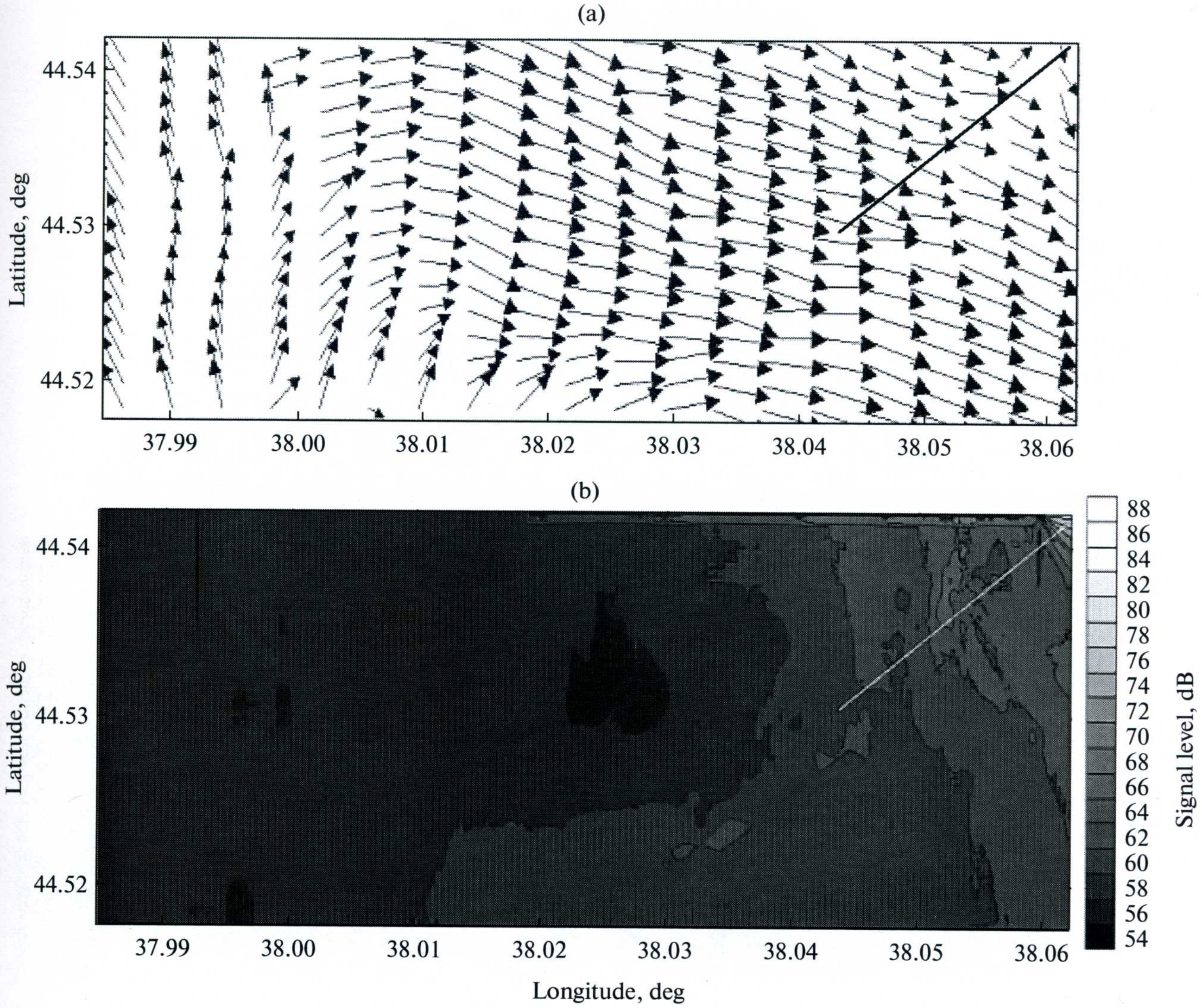

Fig. 5. Vector maps of barotropic currents based on measurements on October 4, 2009 (a), and the level of the backskattering of acoustic signal in dB (b). Gradation of the acoustic signal in dB is shown from the right. The deep outfall pipe is shown by a white line.

The satellite-registered pollution from the released waters near Gelendzhik is also manifested as small-scale optical water heterogeneities (Bondur, 2004, 2011). Similar heterogeneities were revealed after the processing of multispectral images of high spatial resolution from the IKONOS satellite based on characteristics of the relative variability of the backskattering signals in different areas of the spectrum of electromagnet waves (Bondur, 2004, 2011; Bondur and Zubkov, 2005). Such an approach is unrelated to the measurement of absolute values of seawater parameters, but it is mostly oriented to identifying various dynamic oceanic processes.

A color index may characterize the relative variability of the backskattering signals (Erlov, 1980; Bondur, 2004; Bondur and Zubkov, 2005)

$$I_C = B(450)/B(520), \quad (1)$$

where $B(450)$ and $B(520)$ are the luminance of the radiation that arises from the water column at wave lengths of 450 and 520 nm in nadir.

The color index is gaining acceptance as an individual characteristic which is used for the presentation of results of oceanic studies and their qualitative interpretation (*Optika...*, 1983; Bondur and Zubkov, 2005). This index is sensitive to multiple factors which govern the condition of the water column. For example, the luminance in the short-wave (blue) spectrum area of the visible radiation depends on the chlorophyll content and composition and concentration of dissolved organic substances, whereas the luminance in the green spectrum area is mostly caused by the composition, concentration, and size distribution of the emulsion particles (Bondur, 2004; Bondur and Zubkov, 2005).

Other scenarios of the color index may be offered using other spectrum areas. It is evident that the sense

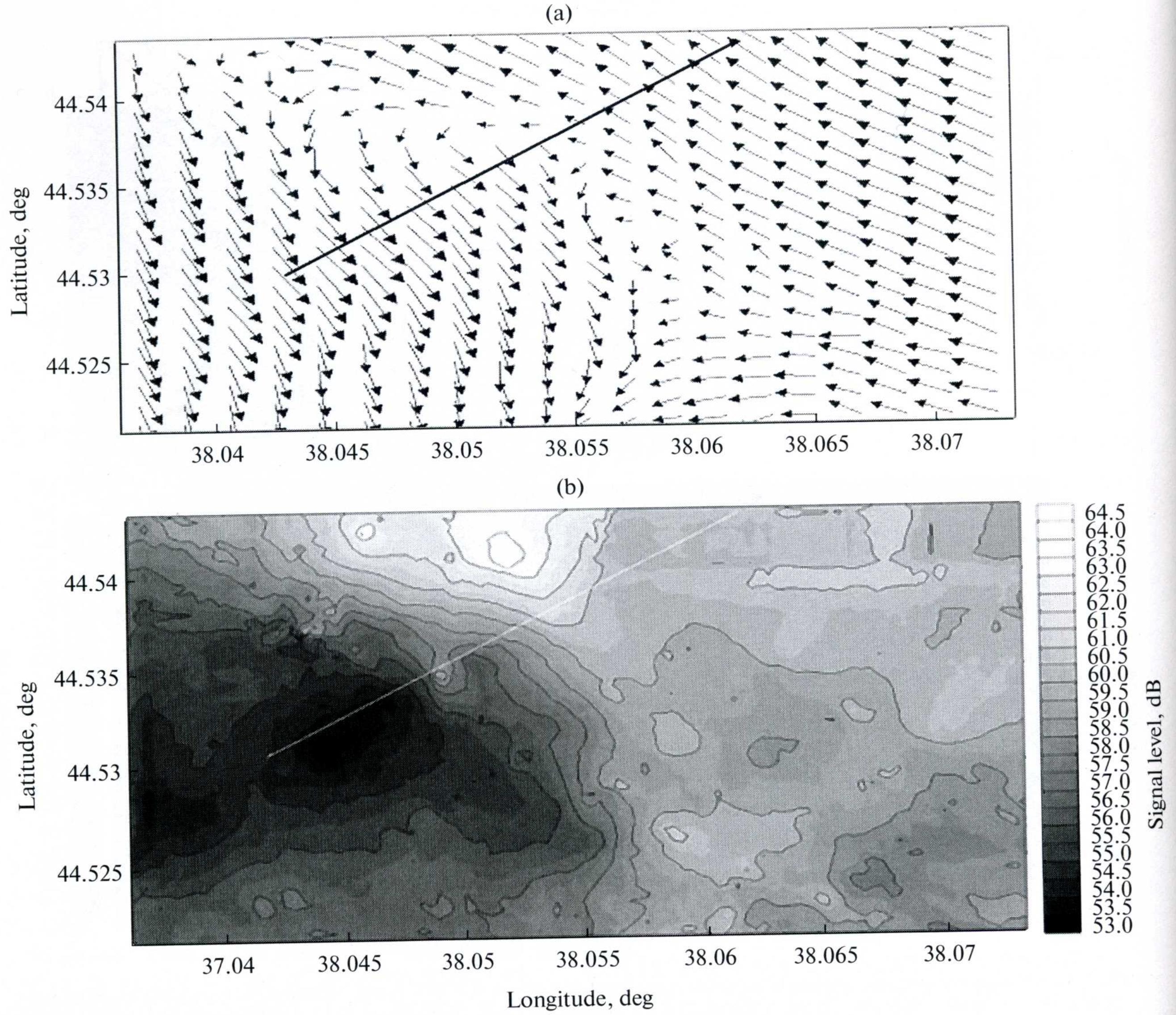

Fig. 6. Vector maps of barotropic currents based on measurements on October 10, 2009 (a), and the level of the backskattering of acoustic signal in dB (b). The deep outfall pipe is shown by a white line.

index load will depend on the combination of wave lengths in each specific case. For example, if we take

$$I'_C = B(520)/B(690), \quad (2)$$

then the luminance in the red spectrum area is mainly caused by the composition and concentration of emulsion in the fine subsurface layer of the water column (Bondur, 2004; Bondur and Zubkov, 2005). Under the processing and analysis of ocean surface images from the IKONOS satellite, the color indices may be presented as follows (Bondur, 2004; Bondur and Zubkov, 2005)

$$B(450\text{–}520)/G(520\text{–}600);$$
$$B(450\text{–}520)/R(600\text{–}690); \quad (3)$$
$$G(520\text{–}600)/R(600\text{–}690).$$

Two-dimensional distributions of values (in the ocean surface plane) were used to create the color-coded images and synthesized color imagery in the 3D space of the color indices. To reveal the optical anomalies of the water column by space multispectral data and fields of the color indices, it is appropriate to use the special processing of space images, for example, decorrelation expansion, transformation of color spaces, color coding, etc. (Gonzales and Woods, 2005).

Figure 8 (in the color inset) shows a fragment of an image from the IKONOS satellite made on October 8, 2008, for the studied region near Gelendzhik synthesized in natural colors (RGB color space) (Fig. 8a), a result of the decorrelation expansion of this fragment

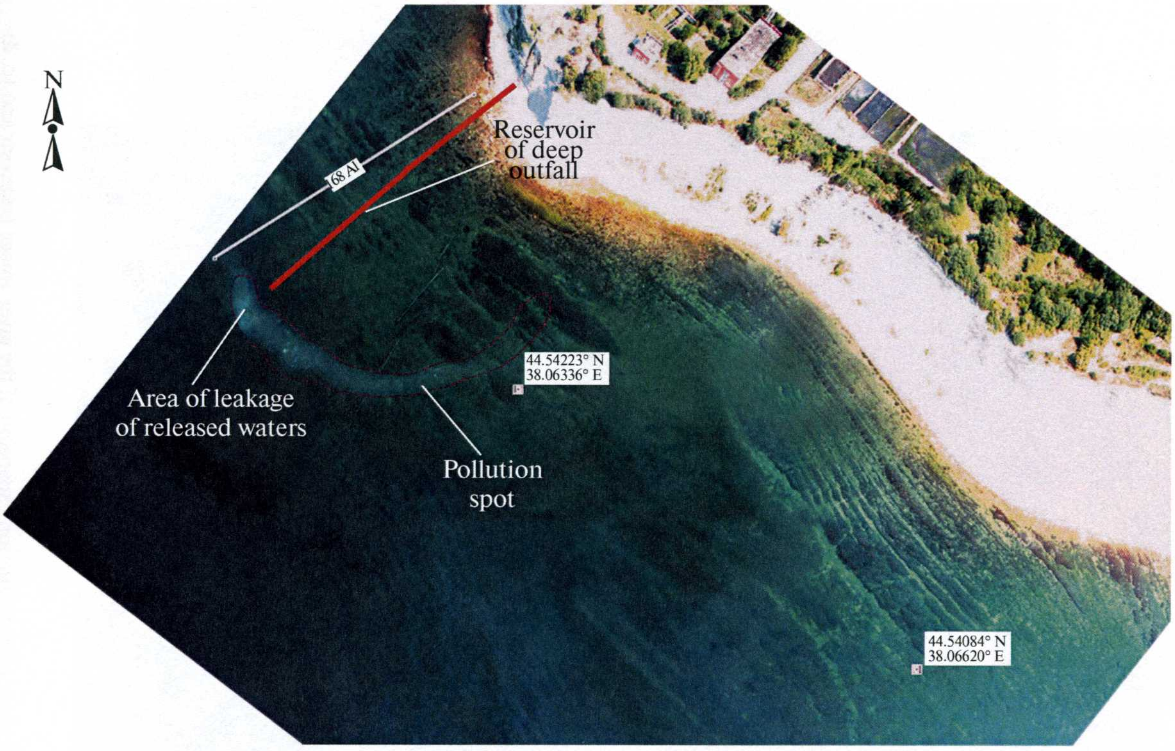

Fig. 7. Manifestation of deep outfall in the coastal waters near Gelendzhik on a helicopter image (Lavrova et al., 2011). Arrows indicate the reservoir of the deep outfall, the area of leakage of the released waters, and the pollution spot caused by these waters.

(Fig. 8b), and its enlarged areas (Figs. 8c, 8d). Two peculiarities may be distinguished on enlarged areas located in the lower part of the image.

Figure 8b demonstrates a green-yellow color anomaly on the yellow-red and blue-green background caused by the deep outfall of the polluted waters. The ~120-m wide and ~1400-m long latitudinal arch-shaped anomaly is related to the character of submarine currents in the Black Sea coastal zone, which were directed along the coast in the satellite survey day.

Figure 8d evidently shows the subsurface discharge that flowed into the coastal water area (marked by blue) southeastward from the outfall pipe. Spreading in the water column, a fresh stream, which is less dense relative to the surrounding salt waters, meanders with a spatial period of ~220 m and is clearly traced at a distance of 850 m from the coast.

Figure 9 (in the color inset) demonstrates the color-coded images of distributions of ratios of channel signals $\xi = B/G$ for the fragment of the initial image subjected to the decorrelation expansion.

As is shown in Fig. 9a, the studied water area contains zones of both extremely low (black and violet) and high (white and dark red) $\xi = B/G$ values. These zones are restricted to the shallow coastal areas (low $\xi = B/G$ values), where reflections from the seafloor and wind shades (high $\xi = B/G$ values) significantly contribute to the formation of the optical space images. The domains of the water area with natural drops of B/G values are colored in red, yellow, and green tones.

As can be seen from Fig. 9, the distribution of ratios of channel signals is heterogeneous. Zones of increased and decreased values are distributed by alternating spots along the entire image area. The areas of decreased $\xi = B/G$ values may be also related to the concentration of the dissolved organic substances, emulsion particles, land humuslike compounds, and changes in the water columns caused by these substances.

Figure 9a reveals three main pollution zones: (i) river runoff in the right lower angle, (ii) a vast anomaly caused by the impact of the deep outfall of the Gelendzhik municipal waters, and (iii) the outlet zone from the Gelendzhik Bay.

Because of the various anthropogenic and natural pollution sources on the Black Sea coast, the additional subsatellite measurements, mathematic modeling, and space data of high spectral resolution are required to reliably quantitatively estimate the impact area of the river and deep runoffs of the polluted waters. The general picture of the pollution of the coastal waters represents a superposition of fields of anthropogenic and natural impacts from a large amount of various sources.

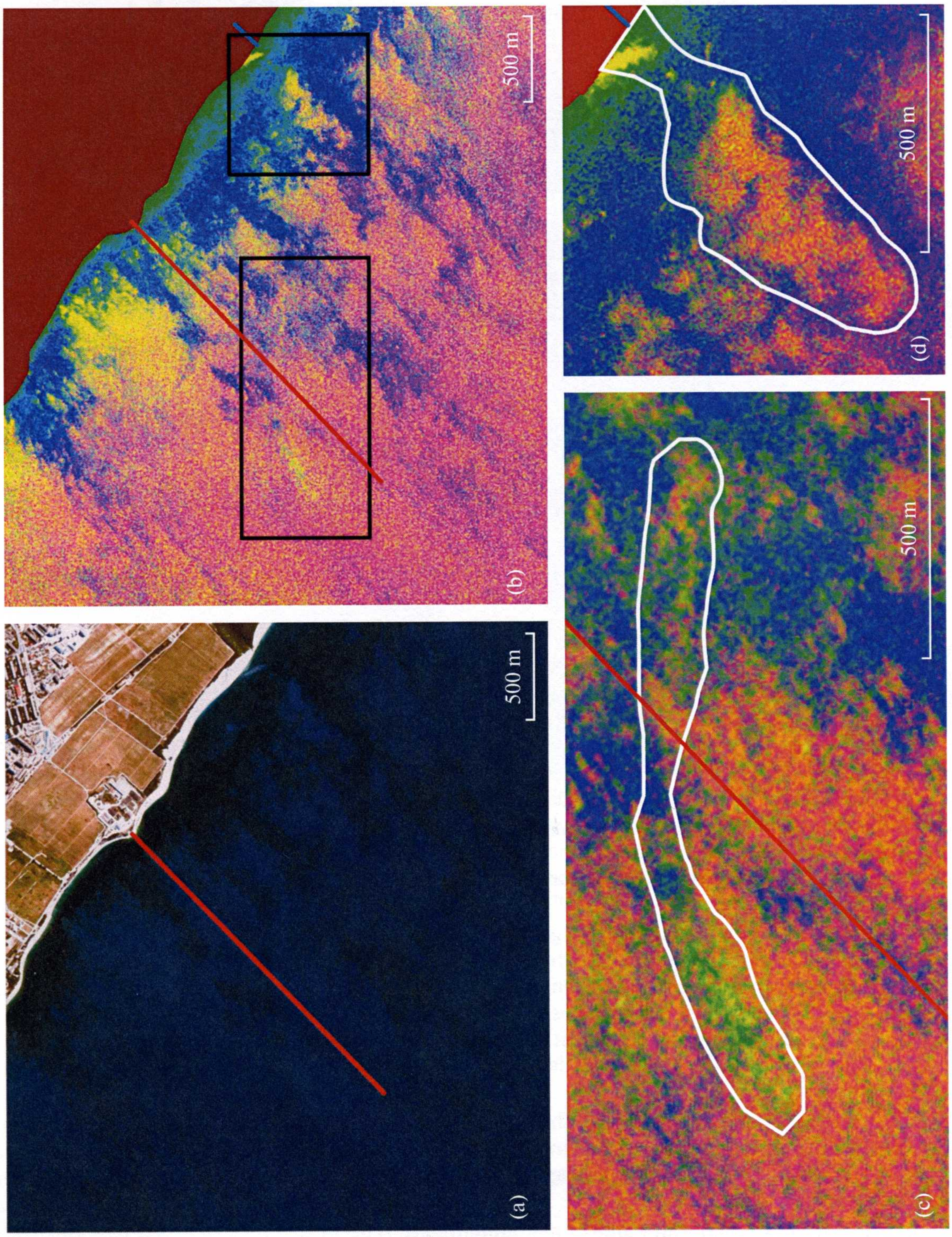

Fig. 8. Fragment of the initial space image from the IKONOS satellite for the outfall pipe area: (a, b) result of decorrelation expansion of the given image fragment and (c, d) enlarged fragments of (b).

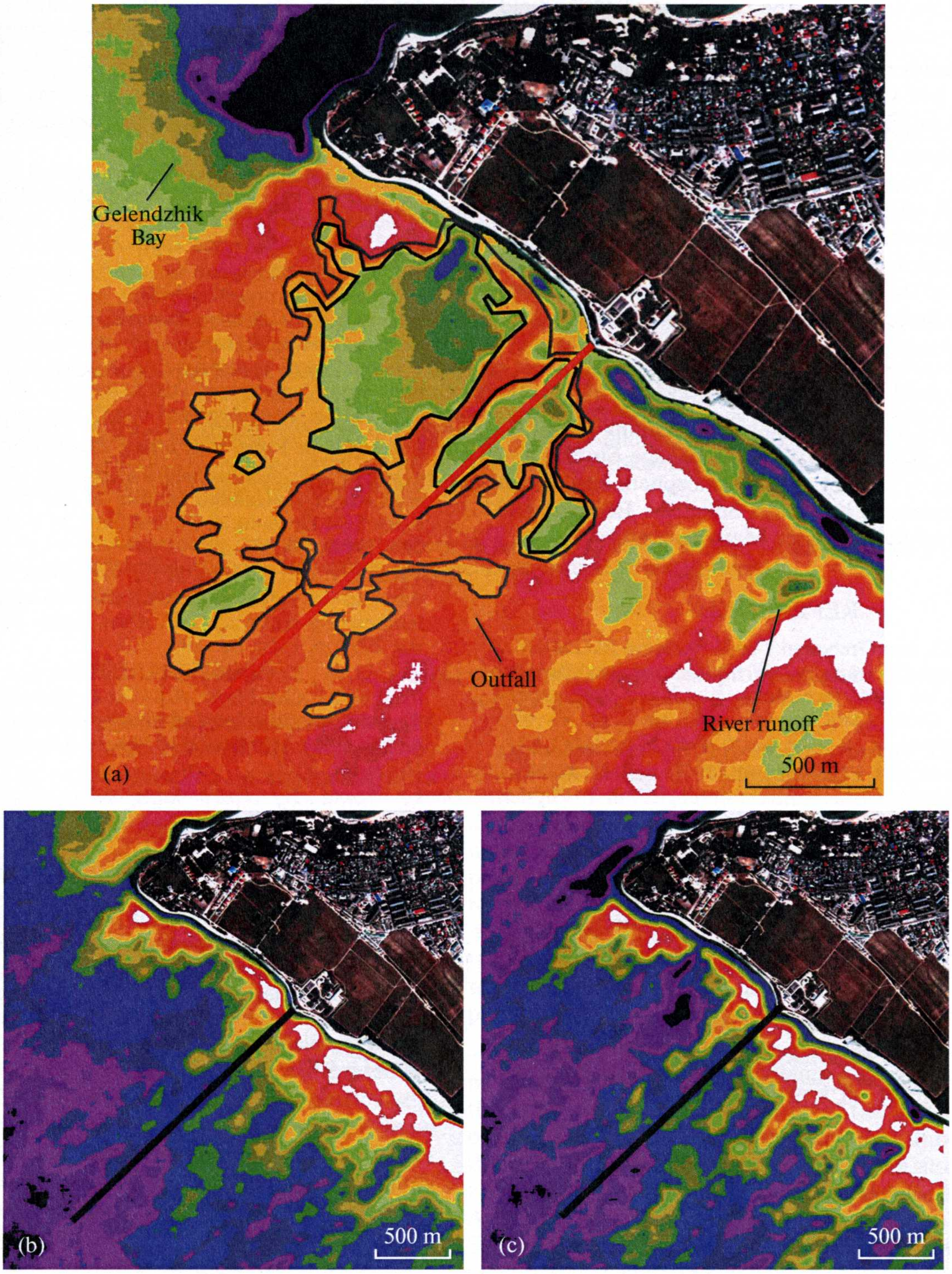

Fig. 9. Color-coded image of distribution of proportions of channel signals $\xi = B/G$ for the fragment of the initial image decorellation expansion.

CONCLUSIONS

The study of the Gelendzhik shelf of the Black Sea with a towed acoustic Doppler profiler revealed the strong spatial and temporal variability of subsurface currents in autumn. We established the impact of the deep outfall on the dynamics of the coastal waters, and characteristics of the surface seawater pollution are studied depending on the source of anthropogenic impacts. The heterogeneities in the field of subsurface pollutions are related to the peculiarities of the field currents.

The studies revealed strong water pollution in the Golubaya and Gelendzhik bays and universal pollution of the surface layer (0–10 m) on the shelf.

An analysis of multispectral space images of high resolution from the IKONOS satellite for the Gelendzhik water area has identified small-scale optical heterogeneities of the water column caused by natural and intense anthropogenic impacts. The surface influence of the submerged outfall on the water was found and the jet pollution area was determined.

ACKNOWLEDGMENTS

This work was supported by the Leading Scientific School no. NSh-374.2012.5 "Aerospace Studies and Monitoring of Impact of the Atmosphere and Ocean in the Interests of the Earth Sciences, Ecology, and Rational Natural Resource Management."

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Translated by I. Melekestseva