The use of remote sensing data for estimation of the anthropogenic load on the coastal areas of the Crimea in 2017–2019

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***Abstract*—The paper discusses spatial distribution of suspended matter in the southwestern Crimean coast of the Black Sea according to high-resolution satellite data from *Sentinel-2 MSI* scanner and medium-resolution satellite data from *MODIS Aqua* and *Terra* in 2017–2019. Spatial and temporal evolution and wind transport of suspended matter are studied along with their contribution to the anthropogenic load of the coastal areas. Satellite observation data are compared with long-term annual mean data on the concentration of suspended matter from 1998 to 2018. The analysis of remote sensing data helped identify the areas with the highest values of bio-optical indices, which are consistent with the location of the river mouths and municipal sewage pipes.**

***Keywords*—Crimea, coast, satellite data, water pollution, bio-optical index, suspended matter**

I. Introduction

The Black Sea is an internal basin largely dependent on its catchment area of 2 million km^2 including the territories of 20 states of Europe and Asia Minor. The effect of the continental waters is the most noticeable in the northwestern shelf of the Black Sea, where the Danube, Dniester, Dnieper and Southern Bug flow into the sea with a total catchment area of 1.46 million km^2 [1]. The cities and industrial centers located along the shores put high anthropogenic pressure on the coastal waters due to the pollutants entering the sea with liquid effluents, solid waste, and precipitation. Estimates of the level of anthropogenic load on the Black Sea coast as a result of the economic development were proposed in [2, 3]. The current environmental state of the groundwater intakes of the Crimea, local rivers, and adjacent sea areas was considered in [4]. This paper investigates the spatial and temporal evolution of water areas with high suspended matter content based on the analysis of remote sensing data.

II. Data and Methods

Study Area

The study area is at the northwestern shelf of the Black Sea and includes the southwestern part of the Crimean coast adjacent to Sevastopol – constituent territory of the Russian Federation. This area follows the coastline along the west, southwest, and south of the Crimea, including successively Kalamitskiy Bay, the northern side of Sevastopol, the Heracleian Peninsula, and the Southern coast of the Crimea up to Foros (Fig. 1). To the north of the Heracleian Peninsula, the Kacha, Belbek, Alma, and Chernaya rivers flow into the Black Sea bringing in the pollutants. In addition, along the entire coast, there are pipes of centralized municipal waste water discharge. The coastal area under study also gets the anthropogenic pressure from numerous unauthorized waste water discharges of illegal tourist sites. The recreational importance of the region emphasizes the relevance of the choice of the study area.

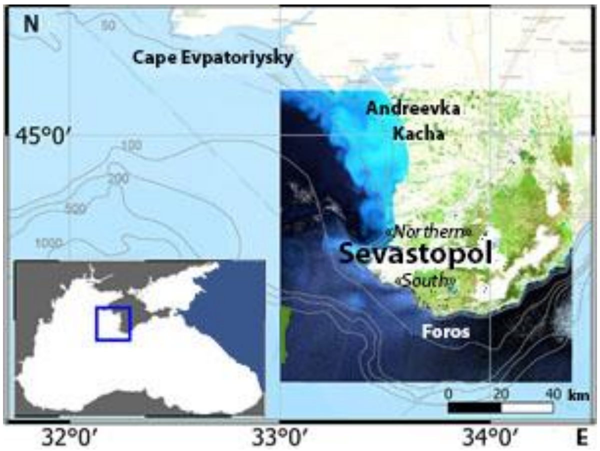

Fig. 1. Bathymetry scheme of the study area: 33.1º–34.0ºE; 44.2º–45.1ºN combined with the sea surface image from Sentinel-2 (27 April 2017). Blue rectangle in the tab on the left – the position of the study area in the Black Sea. Light gray contours – isobaths from 20 to 1000 m.

In Situ Data for 1998–2018

In order to obtain representative data on the level of anthropogenic pressure, the summary data of the General Directorate of Natural Resources and Ecology of Sevastopol were used. The averaged statistics on the concentration of suspended matter in 1998–2018 were taken as the basis. The selection of parametrically related indicators, such as the annual mean runoff, the volume and concentration of pollutants in the discharged waters, other available data on sewage, made it possible to analyze quantitative characteristics of the spatial distribution of suspended substances in the study area (Fig. 2).

Satellite Data

To implement the approach based on the analysis of satellite images, we used the data of *Sentinel*-2 *MSI* optical scanner from the open archives of the European Space Agency available on the Copernicus Open Access Hub portal (*https://scihub.copernicus.eu/dhus/#/home*). These data include visible channels (490–665 nm) with a 10-meter spatial resolution and near infrared channels (705 nm) with a 20-meter resolution. First, among the images for 2017–2019, those with no or minimal cloud cover above the coastal zone were selected, then the data were decrypted using *SNAP Desktop* software. In the selected satellite archives, the suspended matter was detected by a combination of channels: B02 (Blue) – 490 nm, B03 (Green) – 560 nm and B05 (Vegetation red edge) – 705 nm. Then, the values of remote sensing reflectance ($Rrs(\lambda)$ at a wavelength λ) were extracted for each pixel and transferred to a model grid using the *Panoply* application.

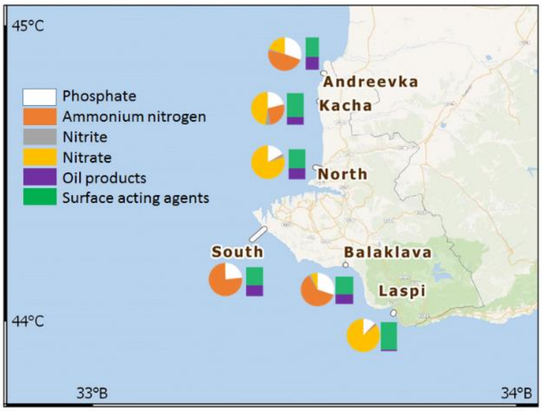

Fig. 2. The proportion of nutrients and other pollutants in wastewater discharges along the coast of Sevastopol according to the long-term average data for 1998–2018.

Primary hydrooptical characteristics obtained from NASA Ocean Color (*http://oceancolor.gsfc.nasa.gov*) were also used for analysis. These data are standard *MODIS L*2 products with a spatial resolution of kilometer. Part of them were previously rejected according to the criteria listed in [5]. In case of partial or complete absence of images, the *MODIS-Aqua* datasets were supplemented by *MODIS-Terra*.

Atmospheric Reanalysis Data

Local wind situation plays an important role in the transport of anthropogenic pollution. In the framework of this study, statistical analysis of the time series of wind speed and direction for the period 2017–2019 was carried out, based on the data from the *SKIRON* regional atmospheric reanalysis (*http://forecast.uoa.gr*). The version of the atmospheric model used is a 72-hour forecast of meteorological parameters for the Azov-Black Sea and Mediterranean basins with a time step of 2 hours and a horizontal resolution of 0.1°, which was created at the University of Athens based on the assimilation of meteorological observations [6].

The prevailing wind directions in the study area were determined as well as the frequency of their wind speed in different years and seasons during the study period. For the entire region under study and separate points corresponding to river mouths and municipal effluents, mean wind speed and direction were determined. Vectors in Fig. 3–5 show the results of the wind speed averaging over the two days before the date of the shot. These values were also averaged over space in three latitudinal ranges: (1) 44°–4.5°N; (2) 44.5°–45°N; (3) 45°–45.7°N, – and summarize the data on wind direction and speed for the sections of the coast near major cities: Saki, Sevastopol and Yalta.

Approach to determining the bio-optical features of the Black Sea in the study area

Satellite observation data were converted into spatial distribution maps of the bio-optical indices *index* and b_{bp} on a model grid with a resolution of ~ 300 m at the shelf of the southwestern part of the Crimean coast (*http://www.gebco.net*). The dimensionless *index* characterizes total concentration of the living and nonliving components of organic matter in sea water [7] and represents the ratio of the remote sensing reflectance of the sea. According to the optical data of *Sentinel*-2 *MSI*, $index23 = [R_{rs}(560)\cdot F_o(560)]/[R_{rs}(490)\cdot F_o(490)]$ was calculated, and according to *MODIS* data, $index34 = [R_{rs}(531)\cdot F_o(531)]/[R_{rs}(488)\cdot F_o(488)]$, where $F_o(\lambda)$ is the solar constant for a wavelength λ [2]. Index b_{bp} (m^{-1}) is the index of backscattering by particles of suspension; it was also calculated at different wavelengths according to high resolution data. Index b_{bp} was calculated at a wavelength of 560 nm for the *MSI Sentinel-2* data, and at a wavelength of 555 nm for *MODIS* data based on the formula $b_{bp}(\lambda) = \{6{,}76\cdot L_{WN}(\lambda) + 0{,}03\cdot [L_{WN}(M)]^3 + 3{,}4\cdot L_{WN}(\lambda)\cdot [I]^{3{,}8} – 0{,}84\}\cdot 10^{-3}$, here $L_{WN}(\lambda) = R_{rs}(\lambda)\cdot F_o(\lambda)$ ($mW\cdot sm^{-2}\ nm^{-1}\cdot sr^{-1}$) and $I = L_{WN}(\lambda)/L_{WN}(\lambda)$ [5].

Consider the criterion for determining the boundary of the area using the satellite data. A total of 268 images were processed, of which the most regular data were from May to September (116 images). The boundary of the polluted area from the satellite data was determined by the minimum values of the color indices *index* and b_{bp}. The criterion for determining the boundary of the area includes several stages. At the first stage, spatial maps of color indices for the entire study period 2017–2019 were constructed on a model grid. At the second stage, the upper and lower boundaries of the color indices were determined, since the distribution of *index* and b_{bp} in each case lies in different ranges. When comparing with the satellite images which correspond to the cases of the most powerful sewage and river flows, the upper bounds for the indices were obtained: *index*23 = 2, *index*34 = 9, and $b_{bp}(560) = b_{bp}(555) = 1\ m^{-1}$. The upper boundaries correspond to the real maximum values from the ranges of the index variability and are driven by the need for correct data presentation on the maps. The lower boundaries are the same for all cases and are defined as 2.7% and 2.5% relative to the upper bounds of the bio-optical indices (*index*23 = 0.05; *index*34 = 0.25 and $b_{bp}(560) = b_{bp}(555) = 0.025\ m^{-1}$).

III. Results and Discussion

Maps of the bio-optical indices *index* and b_{bp} were constructed based on the satellite data sufficiently covering the water area under consideration. In order to study the cases of increased content of suspended matter at the sea surface, all satellite images for 2017–2019 from *Sentinel*-2 *MSI* and *MODIS Aqua/Terra* were analyzed. Due to the common problems of remote sensing (cloud cover), for each year, only three periods (1–3 days) were selected when the area adjacent to the southwestern part of the Crimean Black Sea coast was clearly visible in the optical images. Typical examples of these events demonstrating the spread of suspended matter in the study area in 2017–2019, are demonstrated in Fig. 3–5. They show the optical images obtained from *Sentinel*-2 for each date (Fig. 3–5, left panels) and the corresponding time samples of the *index* distributions from high and medium resolution satellite data (Fig. 3–5, central and right panels).

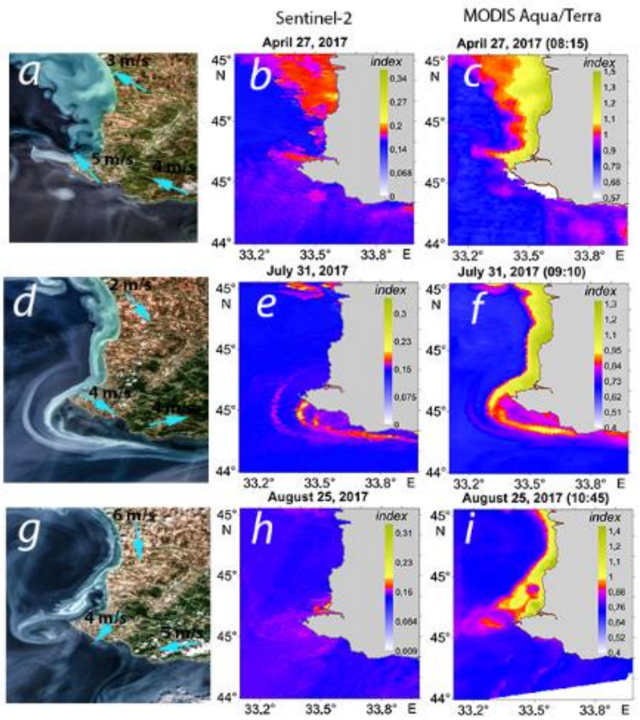

Fig. 3. Areas with high suspended matter content under wind action (arrows) in the optical images (left) and the maps of the bio-optical indices *index*23 (center) and *index*34 (right): 27 April 2017 (*a*, *b*, *c*), 31 July 2017 (*d*, *e*, *f*), 25 August 2017 (*g*, *h*, *i*).

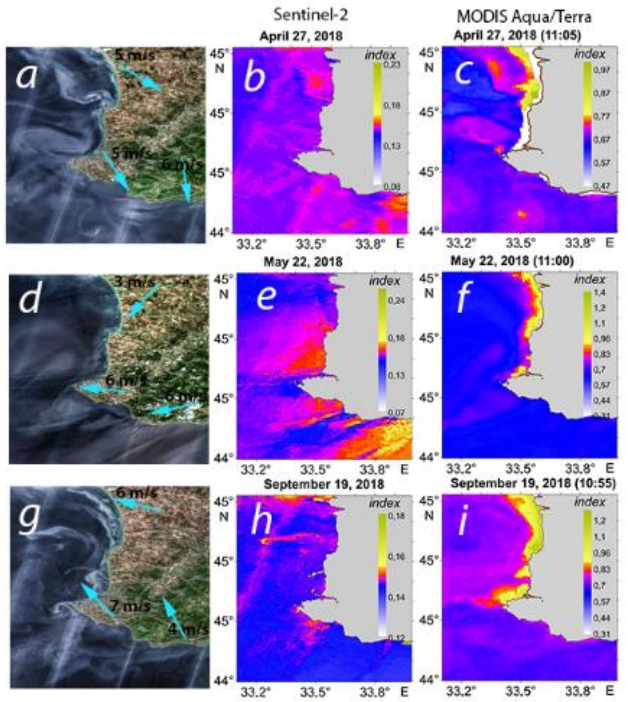

Fig. 4. Areas with high suspended matter content under wind action (arrows) in the optical images (left) and the maps of the bio-optical indices *index*23 (center) and *index*34 (right): 27 April 2018 (*a*, *b*, *c*), 22 May 2018 (*d*, *e*, f), 19 September 2018 (*g*, *h*, *i*).

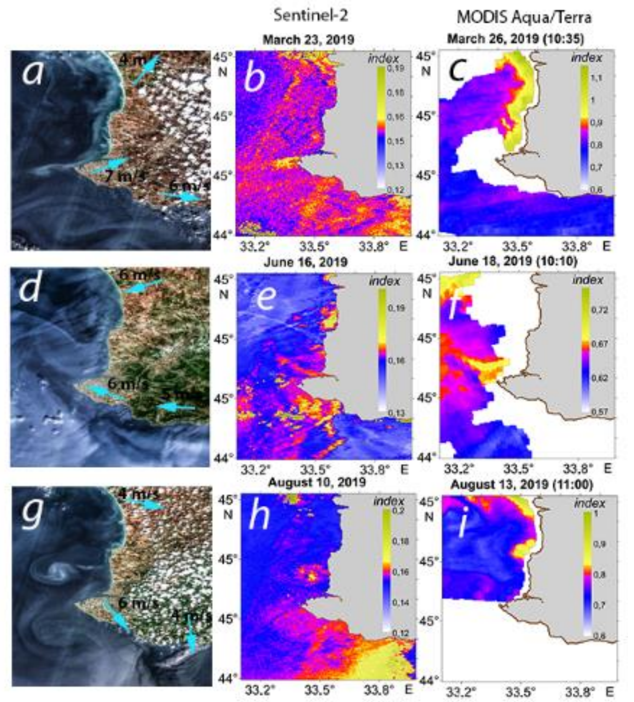

Fig. 5. Areas with high suspended matter content under wind action (arrows) in the optical images (left) and the maps of the bio-optical indices *index*23 (center) and *index*34 (right): 26 March 2019 (*a*, *b*, *c*), 18 June 2018 (*d*, *e*, *f*), 13 August 2018 (*g*, *h*, *i*).

Cases of the propagation of suspended matter are well recognized in both the constructed maps and in the corresponding satellite images (Fig. 3–5). In particular, there are cases with a relatively high content of suspended matter without sharp frontal changes off the western coast of the Crimea (the Kalamitskiy Bay and part of the area off the Heracleian Peninsula), and the cases where suspended matter transports along the southern coast of the Crimea are less common. As a rule, the narrow southern part of the area 5–20 m above the isobaths, stretches along the southern side of Sevastopol up to Foros. Note that within the shallow Kalamitskiy Bay, suspended matter can spread both along the coast and into the open sea. At the areas adjacent to the Heracleian Peninsula and the Southern coast of the Crimea, coastal transport (with clear boundaries) predominates, which is associated with the presence of temporary wind currents and the passage of sub-mesoscale eddies.

Comparing the wind fields obtained using *SKIRON* reanalysis data with the maps of bio-optical indices and satellite images confirms the influence of wind on the direction of suspended matter transport. Fig. 3–5 show the wind direction (clockwise from the north), which has the highest repeatability within the three subregions adjacent to major cities (Saki, Sevastopol and Yalta). They also show the average values of wind speed. All the observed suspended matter transfer cases along the southern coast found in the satellite imagery occurred either during strong southeast winds or shortly after them at an average wind speed of 7 m/s. The prevailing wind direction on the day of satellite sounding or on the previous day was between 120° and 170°.

At the same time, high amounts of suspended matter in the Kalamitskiy Bay were noted under weak wind with a predominant direction between 135° and 225°.

The values of bio-optical indices, which increase by the beginning of summer and remain within the limits of their upper bounds until the beginning of autumn, in many cases fit well into the existing ideas [8, 9]. In 2017 and 2019, suspended matter spread to the east, and in 2018 west. Note that during the season, the direction of propagation may change. Such situation was observed in 2017, when the eastern direction of suspended matter transport, which prevailed until mid-August, changed to the western direction by the end of September. In addition, a feature of 2017 was the stable position of the border of the area in the central part of the basin from late June to late July. For each cloudless satellite image (out of 116 analyzed images), the areas of regions bounded by the front line were calculated, which correspond to the 50% value of the upper boundary of the bio-optical *index*. Examples of the maps obtained for calculating the areas using *Surfer13* and *QGIS 3.4* with georeferencing as in [10] are shown in Fig. 6. Their analysis showed a high content of suspended matter west of the Heracleian Peninsula, where such areas covered from 34 and up 564 km^2, compared with their distribution along the Southern coast of the Crimea with 20 to 43 km^2.

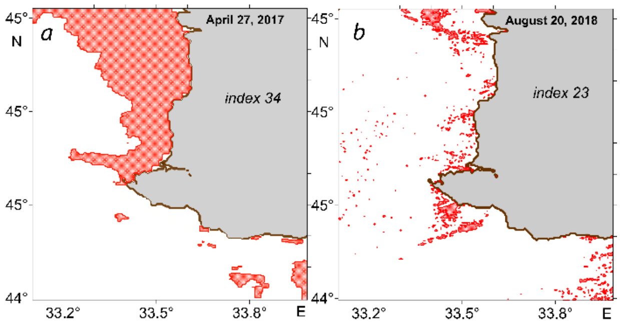

Fig. 6. Maps of the polluted areas limited by 50% of the upper limit of the bio-optical index: *a* – *index*34 (27.04.2017) and *b* – *index*23 (20.08.2018).

A joint analysis of the area with elevated amount of suspended matter from the satellite images and the corresponding *SKIRON* atmospheric reanalysis data (Fig. 3–5) demonstrates that the cases when the area is the largest detected on April 27, 2017 (708 km^2), September 19, 2018 (1144 km^2) and June 18, 2019 (1788 km^2), occur under the prevailing south and southeast winds at a speed of nearly 5 m/s. Satellite images obtained on April 27, 2017 correspond to the largest area with elevated values of suspended matter in response to a strong southeast wind (6–8 m/s), which dominated in the study area from April 22, 2017. Note that due to the shallow waters of Kalamitskiy Bay, suspended matter here is also connected with the presence of turbid seawater. Thus, with the prevailing southeast wind, the region with a high suspended matter content (1144 km^2) in the Kalamitskiy Bay occupies nearly twice its water area (504 km^2) limited by Cape Yevpatoriysky in the north and by Cape Lukull in the south.

IV. Conclusion

The paper shows the possibility of using satellite observations to detect the cases of suspended matter distribution in the sea that occur regularly in the coastal areas of the southwestern Coast of Crimea. Based on the meteorological and satellite data, the spatial characteristics of the areas with high suspended matter content in 2017–2019 were studied in relation to the wind action variability. The analysis of the area in the northwestern shelf of the Black Sea with high suspended matter content was carried out, the directions of suspended matter transport were established depending on the wind regime. Based on the comparison of atmospheric reanalysis and remote sensing data, it was revealed that the distribution of turbid waters is directed mainly along the coast and depends on the strength and direction of the acting wind. It was found that at the southwestern coast of the Crimea in 2017 and 2019, the predominant direction of the coastal suspended matter transport was east, and in 2018, north-west. To the east of the Heracleian Peninsula, coastal transport prevails, which is associated not only with the wind disturbances, but also with the passage of submesoscale eddies. As a result of the study, it was found that the greatest anthropogenic load in the summer of 2017–2019 affected the areas of the river Belbek mouth and the outfall of the waste water treatment facility "South" (Sevastopol). The southeast winds in the area of the Kalamitskiy Bay lead to an increase in the area with a high suspended matter content up to 1144 km^2.

A detailed study of the influence of wind effects on the structure and dynamics of pollution in the surface layers of the Black Sea coast of Crimea requires specific field measurements, as well as numerical modeling and is included in the scope of the future work. In further studies, it is supposed to estimate the magnitude of the displacement of the boundaries of the pollution and to use, along with satellite images, the results of three-dimensional hydrodynamic modeling and *in situ* measurements data.

Acknowledgment

This work was carried out as part of a state assignment №0827-2019-0004 (code “Coastal Studies”), and partially supported by RFBR grants № 17-05-00113 and No. 18-05-80025.

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