Prospects for the Assessment of Phytoplankton Biomass in the Black Sea (on the Example of the Karkinitsky Bay) using Earth Remote Sensing

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Abstract. The aim of the study is to assess the dynamics of phytoplankton biomass in the Karkinitsky Bay of the Black Sea, as well as the annual trend of its abundance based on satellite information. The article briefly describes the methodological steps for study the dynamics of phytoplankton biomass from satellite images, indicates the possible reasons for the formation of the eutrophication process in the Karkinitsky Bay, identifies and describes the optical categories of phytoplankton depending on its concentration, the reasons for the seasonal shift in the biomass of phytoplankton in comparison with other parts of the Black Sea by period from 19.02.2019 to 11.04.2020. The study allows to assess the possibilities of using the NDCI index for assessing the biomass of phytoplankton and make the conclusions on the process of eutrophication using the example of the Karkinitsky Bay. The scientific novelty of the work is the use of the NDCI index to study the dynamics of phytoplankton biomass in the Black Sea. As a result, several maxima and minima of phytoplankton biomass accumulation during the year (from 2019 to 2020) were identified and possible reasons for the observed results were described, the main of which can be considered a high anthropogenic load on the studied part of the Black Sea.

1. Introduction

The problem of surface water pollution has become especially relevant in the XX century. This is mainly due to the speedy growth of cities, industry and agriculture, which has resulted in the problem of excessive water pollution with organic and biogenic components in the reservoirs, leading to the degradation of separate ecosystem elements, as well as entire groups of water bodies [1-3]. An excess of nutrients leads to a sharp increase in the phytoplankton biomass [4] (some is considered to be very toxic) [5]. Since the middle of the 20th century, due to the growth of anthropogenic pollution, there has been a rapid increase in the number of water basins with a process of eutrophication [6-10].

Waste waters of settlements, agricultural lands, industrial enterprises can be a source of anthropogenic input of nutrients into water bodies [11]. The nutrients accompanying the eutrophication process in the bulk flow reach the sea via rivers [12].

Nowadays, the active development of information and space technologies makes it possible to use Earth remote sensing systems to monitor various objects and resources on our planet.

Any changes in aquatic ecosystems are reflected primarily in the communities of autotrophic organisms - the primary producers of organic matter. The first link in the trophic chain and the main producer of organic matter in water bodies is phytoplankton, which includes unicellular algae (diatoms,
dinoflagellates, coccolithophorids, etc.), as well as cyanobacteria [13]. Therefore, the generally accepted method for assessing the biomass and development of phytoplankton, as well as the productivity of water bodies, is to determine the concentration of chlorophyll "a" - the main pigment of phytoplankton, which allows to track the dynamics of the total bioproductivity of a water body depending on season or selected time intervals [14, 15].

The selected object can be explored with the help of various satellite systems, for example, Landsat-8, SeaStar, MODIS-Terra, MODIS-Aqua, MERIS, SeaWiFs, MERIS, AVHRR, Sentinel-2, etc.

The goal of study was to assess the dynamics of the growth of phytoplankton biomass in the Karkinitsky Bay of the Black Sea, as well as the annual trend of its abundance based on satellite information.

2. Methodology

Some images of Sentinel 2 are used in the research. The main selection criterion is the spatial resolution (one pixel = 10 m for the blue and green spectral channels) [16], which makes it possible to increase the accuracy of its dynamics graphs in comparison with the spatial resolution of 30 meters per pixel (spatial resolution satellite system Landsat 8), because there will be no merging of several pixels into one, and the boundaries of the water mass and phytoplankton will be more clearly defined.

The study is based on the Karkinitsky Bay satellite images from February 2019 to April 2020. The investigated part of the Karkinitsky Bay belongs to the territory of the Russian Federation.

![Figure 1](image)

Figure 1. Karkinitsky Bay (the boundaries of the Karkinitsky Bay are marked in red, the area of the Karkinitsky Bay is selected for research in green).

The Karkinitsky Bay was selected for the study due to:

1) The high anthropogenic load on this area [17], which is expressed in the large amount inflow of polluted industrial and municipal wastewater into the bay through the Dnieper River and the extraction
of sand in the area of the Bakalskaya spit. The selected area is also used as a recreational area, which increases the anthropogenic impact.

2) Availability of satellite images of the selected area according to the necessary parameters (temporal - the availability of images for the required period, high-quality - low cloudiness).

Satellite images that were used during the study had to meet the following criteria: low cloudiness, full coverage of the study area, the absence of various software or spatial errors, a time parameter (disproportionate temporal frequency).

The disproportionate temporal frequency in the images used caused due to several factors: 1) the lack of images at a certain time; 2) the presence of images, but with various distortions, for example, clouds in the surveyed area, the presence of anomalous zones (which arise directly when trying to display data).

There are various types of indexes that can be used in multispectral satellite imagery processing for phytoplankton and eutrophication analysis. Each of the indexes assumes a different combination of spectral channels and offers different outputs. When interpreting the maps and results, the same gradient values were used with linear interpolation and the number of color classes defining the categories of the output data (high green concentration - pronounced eutrophication, high blue concentration - water mass devoid of pronounced chlorophyll).

The NDVI index was chosen to analyze the dynamics of phytoplankton biomass and assess the eutrophication of the area indirectly [20]. This index can help to detect water and phytoplankton biomass. Also, when compared with other indexes on the phytoplankton biomass growth detection, NDVI has the most reliable images of the sea:
- with a high concentration of phytoplankton (eutrophication),
- with areas difficult to identify for the satellite,
- with water mass.

For Sentinel-2, the formula for this index is as follows:

\[
NDVI = \frac{\text{GREEN} - \text{BLUE}}{\text{GREEN} + \text{BLUE}} \quad [18]
\]

To calculate NDVI, tools of the QGIS program version 3.12 were used. The choice of QGIS is determined by the following parameters: an extensive set of tools, a large number of methodological materials and scientific sophistication of using the program for various studies, a well-developed software interface, stability and a small number of software errors.

An arbitrary polygon tool was used to create the study area; to calculate the index - raster calculator; to build dynamics - creation and analysis of an attribute table created on the raster layer basis for the study area.

The process of eutrophication was estimated indirectly, focusing on the average distribution of phytoplankton biomass in the Karkinitsky Bay. To estimate the phytoplankton biomass in the studied objects, a table of the NDVI index [19] and maps of the average distribution of phytoplankton biomass in Karkinitsky Bay were created [20].

| NDVI  | Chl-a range (mg/m³) | Phytoplankton categories (optically inferred) |
|-------|---------------------|--------------------------------------------|
| <−0.141 | <7.5               | z.n.                                        |
| −0.141 to −0.118 | 7.5–16            | s.s.                                        |
| −0.118 to −0.096 | 16–25             | z.v.                                        |
| −0.096 to −0.074 | 25–33             | b.p                                         |
| −0.074 to −0.052 | 33–50             | p.s.                                        |
| −0.052 to −0.011 (0.076) | >50              | p.w.                                        |
The optically inferred categories of phytoplankton are indicated:
- z.n. - phytoplankton under the water surface with low concentration;
- s.s. - phytoplankton under the water surface of medium concentration;
- z.v. - phytoplankton under the water surface with high concentration;
- b.p. - phytoplankton on the water surface with low concentration;
- p.s. - phytoplankton on the water surface of medium concentration;
- p.w. - phytoplankton on the water surface with high concentration.

It is also possible to single out a category that is difficult for optical perception, which is located between z.n. and a water mass, which can be called z.o.v.n. - phytoplankton under the water surface, difficult in optical perception with a low concentration.

The submerged phytoplankton layer listed in the optically suspected category can be classified as plant-type benthos (phytobenthos), i.e. it is a set of plant organisms growing in the ground or on the ground of a water body (in this case, the sea) [21]. Of the plant organisms, the main mass of benthos in the seas is diatoms, green, brown and red algae. Some flowering plants are also common near the coasts: zostera, phyllospadix, ruppia, etc. The richest and most diverse phytobenthos is on rocky and stony bottom areas, which serve as a strong substrate for algae attachment [22].

The investigated area of the Karkinitsky Bay is represented by both an ordinary bottom and stony (rocky) bottom areas, which can be seen from various photographs of the studied bay, which can explain the presence of a green line, which can be optically classified as phytobenthos (it is visible almost always and is located next to coastline).

At the same time, the category of optically suspected surface phytoplankton is presented by pelagic organisms that inhabit the water column or on its surface. Pelagic organisms include phytoplankton, which consists mainly of diatoms, peridinium and coccolithophorids.

It should be noted that despite the fact that phytobenthos is attached to the bottom, it is impossible to separate it optically from phytoplankton, which can be located in the water column to a depth of 50-100 meters (on average, in the world. In case of the Karkinitsky Bay, this value is much lower, since the maximum depth of the bay is 36 meters) [23], which implies mixing of these two categories in this study, but their separation in the theoretical aspect, i.e. the optically assumed category of phytoplankton below the surface of the water is the totality of both phytobenthos and phytoplankton directly located in the water column itself (at some depth).

In turn, the optically assumed category of surface phytoplankton in this work is phytoplankton (and a very small part of phytobenthos), which is located directly on the surface of the Black Sea or at a very shallow depth. This ranking is due to the presence of a gradient of green and blue, where the greenest areas are classified as phytoplankton close to the surface and located at a shallow depth. This factor can relate both to phytobenthos and phytoplankton. It should also be understood that the presence of an almost constant already described line with high concentrations of the NDCI scale near the coastline is nothing more than the sum of phytofenthos and phytoplankton in general, since the depth of the Karkinitsky Bay near the coastline of the Crimean Peninsula is not excessively large (the greatest depth is equal to 36 meters [23]). This explains the presence of optically suspected surface phytoplankton in this zone.

At the same time, when moving away from the coastline, the sea depth increases. A pronounced phytobenthos located near the coastline cannot be optically classified, as well as its very existence in areas of the Karkinitsky Bay remote from the coast. This may be due to both the features of the Black Sea and the inability to see it with the help of remote sensing means. Therefore, it is assumed that only phytoplankton is involved in the study, which can be optically classified as a surface layer and a layer of phytoplankton under the water surface at the same time, since phytoplankton can be located in the water column to a depth of about 100 meters [24].

Thus, the classification was made using the already mentioned green-blue gradient: from bright green (high concentration of surface phytoplankton) to pale blue (optically assumed very low phytoplankton
concentration at depth), which is defined as optically difficult, because in this category, the transition from possible visible phytoplankton to visible water mass occurs.

The eutrophication process in Karnikitsky Bay is mainly indirectly estimated according to the amount of surface phytoplankton. The eutrophication process is typical for the Black Sea [17; 25-28].

3. Results

After calculating the NDCI index, images were created (Fig. 1), with the aim of further creating attribute tables for the graph of phytoplankton biomass plotting. The pixels in the resulting images were separated by a gradient from blue to green in fifteen color classes. The number of color classes was selected by methods for analyzing the resulting images from the point of view of optimal work both in technical terms (work of the QGIS program) and in research (reducing time costs). Fifteen color classes were categorized based on six optically inferred phytoplankton categories (Table 1).

Based on the data obtained, several maxima in the phytoplankton concentration were revealed in the winter period (January (12/06/2019); February (02/19/2019; 02/14/2020)) and autumn (September (09/02/2019)), as well as the spring period (March (12.03.2020)). The main minima in concentration are observed in the summer period (July (July 16, 2019); August (August 10, 2019)), which is related both to the sampling of images (due to the lack of the number of images, since the period of Sentinel-2 circulation is approximately 10-15 days), rapid withering away of phytoplankton, and factors related to the physical and geographical parameters of the Black Sea and the Karkinitsky Bay in particular.

![Image](image_url)

**Figure 2.** Changes in the dynamics of phytoplankton in the Karkinitsky Bay from 19.02.2019 to 11.04.2020.

Based on the images obtained (Fig. 2), the number of attributes (pixels) was calculated for the selected categories of phytoplankton (Table 1), which subsequently made it possible to calculate the overall dynamics of phytoplankton biomass from 02.19.2019 to 04.11.2020 in Karkinitsky Bay and build a graph of the biomass dynamics (Fig. 3), based on the sum of attributes (pixels) of all
phytoplankton categories. Based on the images (Fig. 1), the greatest manifestations of phytoplankton accumulations are observed in the area of the Bakalskaya Spit (clearly visible in February 2019, 2020). Coastal phytoplankton accumulations are typical for the winter-spring period (clearly visible in February 2019, 2020; March 2019; April 2019, 2020).

Figure 3. Dynamics of phytoplankton biomass in the Karkinitsky Bay.

According to the graph (Fig. 3), short-term bursts of phytoplankton concentration occur, but due to the lack of data on the Black Sea and the long return period of the Sentinel-2 satellite, it is impossible to trace more accurate phytoplankton population dynamics in order to make the graph smoother and more visual. Nevertheless, the data obtained characterize several problems identified during the study:

1) a rather high concentration of algae in the coastal zone of the Karkinitsky Bay, which can be characterized as a partial eutrophication of the study area;
2) a shift in cyclical bursts of phytoplankton concentration in Karkinitsky Bay (the maximum is observed in the autumn and winter periods, and the minimum values are observed in the summer and spring).

4. Discussion
The data obtained shows that the Karkinitsky Bay is characterized by a maximum biomass of phytoplankton in winter and autumn, which is not a typical result for most of the Black Sea. The findings can be largely related to the physical and geographical features of the Karkinitsky Bay and the high anthropogenic load. Similar results are found in other studies for other areas of the Black Sea [30], but most of the Black Sea is characterized by maxima of phytoplankton biomass for spring and summer. A similar result can be found in the northwestern part of the Black Sea, for example, off the coast of Romania, Moldavia at the end of the 20th and beginning of the 21st centuries, since active anthropogenic pollution with nutrients still existed due to runoff from agriculture and industry, and although in 1990-2000 the Black Sea had already begun to move into the post-eutrophication period, the problem with an excess of nutrients still existed, albeit much less than in 1960-1970s.

It is also worth noting that this area may be characterized by partial eutrophication of the coastal areas of the Karkinitsky Bay due to the constantly increasing pollution of the bay. Nevertheless, it is not possible to fully identify the factors that so strongly influenced the maxima and minima in the biomass dynamics in the Karkinitsky Bay. Presumably, this phenomenon can be influenced by anthropogenic
impact, as well as by the peculiarity of the Karkinitsky Bay in the form of its division into the eastern and western parts (the Bakalskaya spit can be considered the border of separation), in which the eastern part is shallower and more closed than the western part. The division also results in a different water exchange between the main part of the bay (western part) and the Black Sea (about two weeks in summer); between the eastern and western parts (water in the eastern part can remain without significant water exchange for up to two months); which, in turn, can contribute to the accumulation of pollutants and biogenic elements in the bay, which can contribute to the development of phytoplankton dynamics at the boundary between the eastern and western parts (this can be observed in most of the images in Fig. 2). Also, due to its relative proximity to the Dnieper, the Karkinitsky Bay is very slowly desalinated, which may also have implications for a decrease / increase in biomass.

The main limitations and obstacles for this study appeared at the program level, as well as with the lack of elaboration of some aspects that were associated with both the theoretical and practical part of the work. The theoretical part is mostly related to the small amount of data on the eutrophication process and the amount of phytoplankton in general, as well as the incorrectness of some data. Practical obstacles for the most part appeared in the process of creating a sample of satellite images for plotting biomass dynamics in the Karkinitsky Bay.

The future stage of this study will be to compare other areas of the Black Sea with the already available results, as well as to find and study the factors of influence on the biomass of phytoplankton in the Black Sea, in addition to physical and geographical features and high anthropogenic load. Also, it is necessary to study the influence of various degrees of anthropogenic load on the dynamics of changes in the amount of algae biomass in the marine environment.

5. Conclusions
1. It was found that the most optimal means for determining the phytoplankton concentration in the Karkinitsky Bay is the NDCI index, on the basis of which the annual dynamics of the phytoplankton concentration in the Karkinitsky Bay was compiled.
2. As a result of calculations of the amount of phytoplankton in Karkinitsky Bay, it was revealed that the process of eutrophication (the reason for the growth) is practically unchanged (static) in time, which is confirmed by the literature data that the Black Sea entered the post-eutrophication period (the concentration of phytoplankton in the Karkinitsky Bay in areas of accumulation of phytoplankton biomass can be from 16 to 50 mg / m³), in comparison with the end of the intense eutrophication period observed in the Black Sea in the 70-90s of the twentieth century.
3. The maxima and minima of algal concentrations in the dynamics of phytoplankton biomass (for the period from 19.02.2019 to 11.04.2020) were revealed, which are uncharacteristic for most of the Black Sea water area, but only for some of its areas [31], since mainly in the Black Sea, the maximums of the phytoplankton population are observed in the spring and summer, and the minimums in the winter and autumn. In the case of Karkinitsky Bay, various types of anthropogenic impact are a possible reason for the change in phytoplankton population cycles.

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