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Using digital maps to identify areas of mass development of phytoplankton in small freshwater reservoirs

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Based on the results of field observations and interpretation of space images, the authors of the article have analyzed the spatial distribution and temporal dynamics of phytoplankton development in four reservoirs of the Kirov region (Russia) from 2015 to 2021. Characteristic features of reservoirs are high color and turbidity of water, high content of organic substances in water. To identify areas of mass development of phytoplankton, the authors calculated four spectral vegetation indices. These are the normalized difference algoindex (NDAI), the normalized difference vegetation index (NDVI), the chlorophyll *a* concentration index (TBDO) and the normalized difference turbidity index (NDTI). The initial data for the calculation were satellite images from the Sentinel-2 satellite, posted on the resource EarthExplorer (U.S. Geological Survey). Based on the results of the calculation of spectral indices in the QGIS software product, the authors built digital maps of the studied reservoirs. They noted that phytoplankton developed mainly in coastal shallow areas of reservoirs. The mass development of algae and cyanobacteria was most often observed in July and August. This is typical for reservoirs of temperate zone. The most intense "blooming" of water was in July and August 2016, 2018, 2020 and 2021. At the same time, the following species dominated in phytoplankton samples: *Anabaena lemmermannii* P.G. Richter, *A. spiroides* Klebahn, *A. planctonica* Brunnthaler, *Aphanizomenon flos-aquae* Ralfs ex Bornet & Flahault.

Keywords: reservoir, eutrophication, phytoplankton, cyanobacteria, remote sensing of the Earth, spectral indices.

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Использование цифровых карт для выявления участков массового развития фитопланктона на акватории малых пресноводных водоёмов

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По результатам полевых наблюдений и дешифрирования космических снимков проанализировано пространственное распределение и временная динамика развития фитопланктона в четырёх водохранилищах Кировской области (Россия) за период с 2015 по 2021 гг. Характерными особенностями водохранилищ являются высокая цветность и мутность вод, высокое содержание в воде органических веществ. Для выявления участков массового развития фитопланктона был проведён расчёт четырёх спектральных вегетационных индексов. Это нормализованный разностный альгоиндекс (NDAI), нормализованный разностный вегетационный индекс (NDVI), индекс концентрации хлорофилла *a* (TBDO) и нормализованный разностный индекс мутности воды (NDTI). По результатам расчёта спектральных индексов в программном продукте QGIS построены цифровые карты изучаемых водохранилищ. Отмечено, что фитопланктон развивался преимущественно на прибрежных мелководных участках водохранилищ.

Массовое развитие водорослей и цианобактерий чаще всего наблюдали в июле и августе. Это является типичным для водохранилищ умеренной зоны. Наиболее интенсивное «цветение» воды отмечали в июле и августе 2016, 2018, 2020 и 2021 гг. При этом в пробах фитопланктона преобладали следующие виды: *Anabaena lemmermannii* P.G. Richter, *A. spiroides* Klebahn, *A. planctonica* Brunnthaler, *Aphanizomenon flos-aquae* Ralfs ex Bornet & Flahault.

Ключевые слова: водоём, эвтрофирование, фитопланктон, цианобактерии, дистанционное зондирование Земли, спектральные индексы.

At present, the most important factor in the negative impact of human activity on the productivity and ecological state of water bodies is anthropogenic eutrophication. The unfavorable consequences of eutrophication are the "blooming" of water, the massive development of higher aquatic plants, and the violation of the oxygen regime of water bodies. This leads to a decrease in fish productivity and the recreational potential of water bodies, has a negative impact on water purification systems for drinking water supply from water bodies, and causes allergic reactions in humans and animals. The problem of intensive "blooming" of water, or the mass development of algae and cyanobacteria, is very relevant for freshwater bodies of various countries [1, 2]. To develop measures to preserve the quality of water bodies, it is necessary to use environmental monitoring data. Environmental monitoring is an information system for observing, assessing and forecasting changes in the state of the environment, created to highlight the anthropogenic component of these changes against the background of natural processes. Solving the problems of environmental monitoring requires the use of analytical tools that provide the presentation of actually obtained data in a spatially distributed form, which simplifies the assessment of their current state and visualization of future changes. One of such means is ecological maps [3]. To study the state of water bodies, digital maps are widely used, built according to the data of remote sensing of the Earth and, in particular, according to the calculation of spectral vegetation indices. For example, a map of the distribution of chlorophyll *a* concentrations over the water area was constructed for Lake Beysehir, the largest freshwater lake and source of drinking water in Turkey, based on *in situ* observations and the results of interpretation of Terra ASTER satellite data [4]. Chlorophyll *a* is the main pigment of phytoplankton. Its concentration in water can be used to assess the trophic state of the reservoir and the quality of the water in it. A series of maps built according to the NDVI calculation data for a long-term period was used to monitor the dynamics of the vegetation cover of estuaries in the Sea of Azov region [5]. Maps built on the basis of the calculation of the NDVI and NDWI indices were used to assess and predict the ecological state of Lake Manzherok (Altai, Russia) after dredging [6]. The maps constructed according to the NDVI and MNDWI calculation data were used to estimate the area of the water area and the dynamics of macrophyte overgrowth of the Krasnodar Reservoir [7] and subaquatic landscapes of the Zeya Reservoir (Russia) [8]. The spatial and temporal distribution of chlorophyll *a* in the water area of the Krasnodar reservoir was studied using maps constructed according to the NDCI calculation data [9]. To assess the spatial distribution of chlorophyll *a* and suspended solids in the lakes of the Czech Republic, NDVI, NDTI, SR, SRWC, and various modifications of the NDWI, MNDWI, WRI, and AWEI indices were calculated [10]. As can be noted, the tasks solved using digital maps built from the values of spectral indices are very diverse. The choice of specific spectral indices for research depends on the physical and geographical features of the studied water bodies and on the nature of their use.

The purpose of this research is to evaluate the possibility of using digital maps built according to the calculation data of NDAI, NDVI, TBDO and NDTI to identify areas of mass phytoplankton development in the water area of small freshwater reservoirs of the Kirov region.

Objects and research methods

The Kirov region is located in the northeast of the Russian Plain in the central-eastern part of European Russia. The largest reservoirs are in the northeastern part of the region, in the Vyatka-Kama physical and geographical district. These are the Belokholunitskoye, Omutninskoye, Bolshoye Kirsinskoye and Chernokholunitskoye reservoirs. These are channel lowland reservoirs created in the period from 1729 to 1810. The surface area of water bodies is 3.0 to 17.4 km^2, length – 4.5 to 11.6 km, width – 0.7 to 3.0 km. The reservoirs were formed under similar geographical conditions. Reservoirs have long been used to supply water to metallurgical enterprises. All reservoirs belong to the category of reservoirs of cultural and household water use.

On the banks of the reservoirs there are settlements, industrial enterprises, health-improving and recreational facilities, and horticultural societies. The reservoirs of the Kirov region are subject to the development of eutrophication processes [11]. Characteristic features of reservoirs are high values of color (from 42 to 398 degrees of color on the chromium-cobalt scale) and water turbidity (above 2 units of turbidity according to formazin), high content of organic substances in water. These features of reservoirs are associated with both the natural conditions of the territory and the anthropogenic impact on water bodies. In order to assess the degree of eutrophication of reservoirs and offer recommendations for improving their ecological state, researchers of the Biomonitoring Research Laboratory of Vyatka State University have been conducting regular monitoring studies in the water area of reservoirs since 2011. Monitoring studies include a route inspection of the water area of reservoirs and coastal areas, identification of thickets of higher aquatic and coastal aquatic plants, areas of mass development of phytoplankton, water sampling, algological and hydrochemical analyzes, water biotesting. A detailed survey of the entire water area of reservoirs requires serious labor, time and financial costs. As a rule, during the growing season it turns out to make only 5–6 trips to the objects of study. In order to reduce the cost of fieldwork on reservoirs and to quickly obtain data throughout the entire growing season for the entire study area, we began to use satellite Sentinel-2 imagery in our work since 2019 in order to study the ecological state of the reservoirs of the Kirov region.

The original space images are freely available on https://earthexplorer.usgs.gov/. For our research we chose low-cloud images taken from May to September (2015–2021). We processed satellite images, calculated spectral indices, and built digital maps using the QGIS software version 3.20. NDAI was calculated according to [12], NDVI – according to [13], TBDO – according to [14], and NDTI – according to [15]. When constructing digital maps for each of the calculated indices, we empirically selected our own scale of values. The data obtained in the calculation of spectral indices were compared with the results of field studies.

Results and Discussion

According to the results, the NDAI values in the water area of the studied reservoirs during the growing season varied widely: from 0.3 to 1.0. On most digital maps, the value of the algoindex increased in the direction from the central deep-water areas to the coastal shallow areas of the reservoirs, while the range of NDAI values for the central and coastal areas reached 0.15–0.20. When visually inspecting the water area of the reservoirs and comparing the results of algological analysis of samples from different parts of the water area, we also noted that the biomass of phytoplankton in coastal shallow areas was higher than in deep water areas. The optical density of water taken at a depth of 0.3 m in the Omutninskoye reservoir in areas of mass development of phytoplankton, measured at a wavelength of 615 nm in a cuvette with an optical path length of 10 mm, was 0.150–0.220. In the central deep-water areas of the water area of the Omutninskoye reservoir, where phytoplankton accumulations were not visually detected, the optical density of water at the same depth was 0.011–0.056. A similar distribution of NDAI values over the water area and an increase in phytoplankton biomass in shallow coastal areas compared to the central part of the reservoir were noted for Lake Lukomskoe in Belarus [16]. A higher level of phytoplankton development (by 2–3 times) in shallow waters compared to the channel in summer is also characteristic of the Volga reservoirs (Russia) [17]. This is due to a number of factors: more intense heating of the aquatic environment and an increased content of biogenic elements in coastal areas. Probably, the same factors influenced the development of phytoplankton in the shallow waters of the reservoirs of the Kirov region.

The minimum NDAI values (0.32–0.38) were noted in May, early June 2017 and 2020, the maximum (0.75–0.84) – in July and August 2016, 2019 and 2020. The visually observed “blooming” of the water corresponded to NDAI values above 0.55. The water area of the Matyr reservoir (Russia), which is comparable to the reservoirs of the Kirov region in terms of morphometric parameters and hydrochemical characteristics, during the observation period from May to September 1984–2014, had NDAI values averaged from 0.26 to 0.44 [18], the water area of Lake Lukomskoe (Belarus) on May 18, 2015 – from 0.42 to 1.16 [16], and in the water area of the Kakhovka reservoir (Ukraine) in August 2010 – from 0.12 to 1.01 [19].

If we trace the time dynamics of changes in NDAI values, we can note that from May to July, the average value of NDAI for all water areas increased, and then, from July to September, it decreased (Fig. 1).

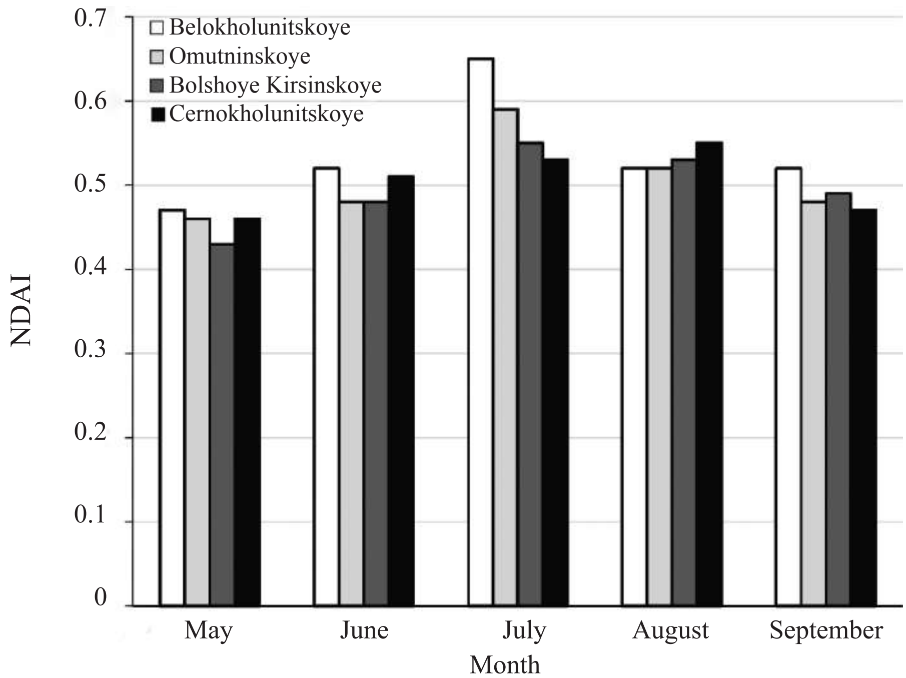

Fig. 1. NDAI values for the largest reservoirs in the Kirov region, calculated from satellite Sentinel-2 imagery for 2015–2021

It is known that seasonal changes in the content of chlorophyll *a*, by which the phytoplankton biomass is estimated, can be explained by the dynamics of weather and hydrological conditions [17]. Increase in NDAI values from May to July in 2015–2021 is consistent with the increase in air temperature in the same observation period. The average air temperature in May reached 15 °C, in June and September – 17 °C, in July – 22 °C, in August – 20 °C.

Outbreaks of intensive development of phytoplankton visually and on digital maps were recorded in all the studied reservoirs in August 2016 (images from 25.08.2016, NDAI 0.58 to 0.80), July 2020 (08.07.2020, NDAI 0.60 to 0.84) and August 2021 (08.07.2021, NDAI 0.61 to 0.84). Also, the massive development of phytoplankton was noted in the Bolshoye Kirsinskoye and Omutninskoye reservoirs in 2018 (images from 26.07.2018, NDAI 0.62 to 0.80), in the Bolshoye Kirsinskoye, Omutninskoye and Chernokholunitskoye reservoirs – in 2021 (images from 01.09.2021, NDAI 0.57 to 0.92). The highest NDAI values on digital maps were noted in shallow waters along the shores of reservoirs and in bays. The depths in these areas are shallow (up to 3 m), water exchange is slow, and the water warms up well. Weather conditions were also favorable for the development of phytoplankton: in August 2016, July 2018 and 2020 the days were mostly clear, calm, and the average monthly air temperature was quite high (20–22 °C), which also contributed to the "blooming" of the water.

With the help of NDAI index images, one can quite clearly trace the dynamics of phytoplankton development. Figures 2 and 3 (see color insert I, II) shows images taken before and during the intense "blooming" of water in the Omutninskoye reservoir.

It can be noted that in the image taken on July 5, 2021 (Fig. 2, see color insert I), the maximum NDAI values are observed mainly along the banks of the reservoir. In the image taken on July 13, 2021 (Fig. 3, see color insert II), the areas characterized by intense "blooming" of water increased significantly in the central section of the reservoir and in the bay. Phytoplankton samples taken at these areas were dominated by *Anabaena lemmermannii* P.G. Richter, *A. spiroides* Klebahn, *A. planctonica* Brunnthaler, *Aphanizomenon flos-aquae* Ralfs ex Bornet & Flahault.

In addition to calculating NDAI, we also calculated other spectral indices used to study water bodies. According to the results of NDVI calculation, the value of this index in the water areas of the studied reservoirs varied from -0.5 to 0.4. According to [20], the NDVI value for the surface of water bodies is usually less than zero. Positive values of the index, as a rule, indicate the

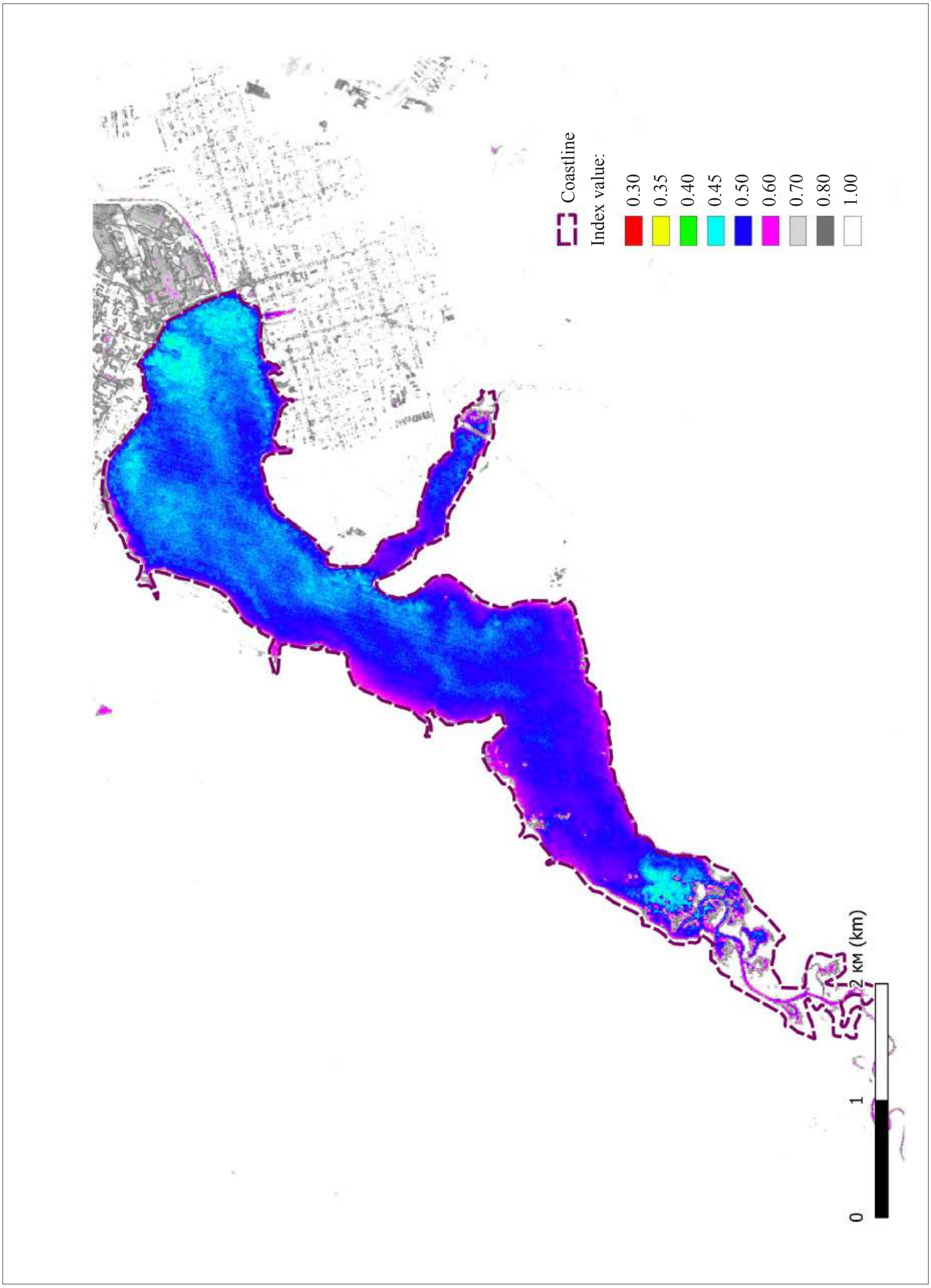

Fig. 2. Map of the Omutninskoye Reservoir based on the results of the NDAI calculation on 05.07.2021

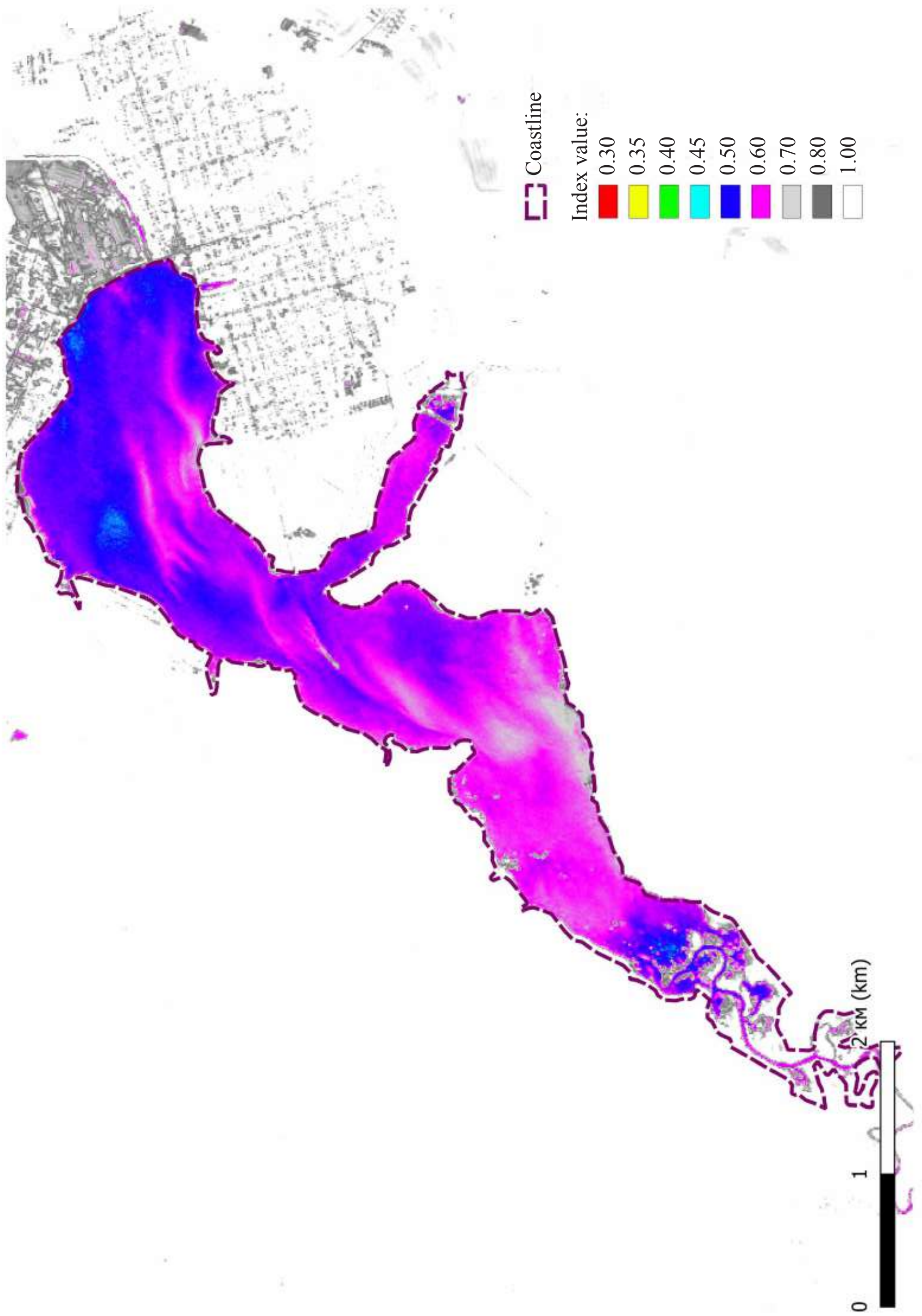

Fig. 3. Map of the Omutninskoye Reservoir based on the results of the NDAI calculation on 13.07.2021

presence of vegetation cover in the territory. In this study, positive NDVI values were recorded in areas covered with thickets of higher aquatic plants with leaves floating on the water surface, and in areas of mass development of phytoplankton. The largest range of NDVI values we observed in the Belokholunitskoye and Omutninskoye reservoirs in August and September, in the Bolshoye Kirsinskoye reservoir in July and August, and in the Chernokholunitskoye reservoir from June to August. The average value of NDVI in all water areas increased from May to July, and then decreased again. It indicates a more intensive development of phytoplankton in July compared to other months. A similar seasonal dynamics of phytoplankton development is also observed in other water bodies with increased anthropogenic load [21]. When comparing the results of calculating NDAI and NDVI, both indices are suitable for identifying areas of mass development of phytoplankton, but the normalized difference algoindex allows to get more detailed information, since it takes into account the brightness of the radiation of objects in four wavelength ranges, and the normalized difference vegetation index only in two. When comparing the calculations of two spectral indices with the data of field observations and the results of algological analysis, NDAI makes it possible to more accurately assess the degree of phytoplankton development under the dominance of CB in comparison with NDVI. However, if green algae dominate in phytoplankton, both indices are equally informative.

In the course of the study, we calculated another spectral index. It assesses the concentration of chlorophyll *a*, designated in this work as TBDO. The advantage of this index is the ability to assess the development of phytoplankton in highly productive turbid waters, which include the studied reservoirs of the Kirov region. According to the calculations, the TBDO value in the studied water areas varied within a fairly wide range: from -0.15 to 3.89. The value of the index differs significantly in different water areas and in different periods of time. When comparing the prevailing TBDO values in different reservoirs in the period from May to September, the smallest range of values is typical for the Chernokholunitskoye reservoir, a little more – for the Bolshoye Kirsinskoye reservoir. For the Omutninskoye and Belokholunskoye reservoirs, where intense water “blooming” was visually recorded, the range of TBDO values was significantly larger. When comparing the results of TBDO calculation with visual observations on reservoirs and the results of algological analysis, this index is suitable for identifying phytoplankton accumulations in water areas, it allows comparing the degree of phytoplankton development in the four studied reservoirs.

The concentration of chlorophyll *a* in water is the most commonly used indicator for assessing the degree of development of phytoplankton in a water body. However, the degree of phytoplankton development can also be determined indirectly. For example, according to one of the main indicators of water quality – turbidity. It is known that during periods of intensive development of phytoplankton, as well as the formation of a large amount of detritus in the water of eutrophic reservoirs during the growing season of plants, the water turbidity increases [22]. In addition, the causes of increased turbidity of water may be the presence of clay, inorganic compounds (aluminum hydroxide, carbonates of various metals), colloids formed during the oxidation of iron and manganese compounds with atmospheric oxygen, organic impurities or living organisms, for example, bacterio-, phyto- or zooplankton [23]. Thus, the magnitude of turbidity can be used to judge both the quality of water in general and the degree of development of planktonic organisms in it. During the route inspection of reservoirs, we took water samples in different parts of the reservoirs for subsequent determination of turbidity in the laboratory using the turbidimetric method. Turbidity values ranged from 2 to 8 formazin turbidity units and more. In order to assess the turbidity of water in all water areas, the calculation of the NDTI was carried out according to satellite imagery. The values of the NDTI in the studied water areas varied from 0.16 to 0.52. The value of the NDTI at the beginning of the growing season (May–June) was quite high in all water areas. In July, we noted a slight decrease in the value of the NDTI in all the studied reservoirs. In August, an increase in the values of the NDTI was again noted in all water areas. It is known that water turbidity in the coastal areas of water bodies can increase during rains and floods [23]. Probably, these factors influenced the high values of turbidity in the water of the reservoirs in May and September. In the summer months, in addition to rains, the turbidity of the water could also be affected by the development of phytoplankton.

The spectral characteristics of water depend on many factors: the chemical composition of water, the nature of bottom sediments, the productivity of the reservoir, the presence of representatives of various divisions of algae in the water. In order to take into account all these factors, it is necessary to calculate several spectral indices. The calculation of NDAI, NDVI, TBDO and NDTI in this article made it possible to take into account, when assessing the degree of phytoplankton development, such features of the reservoirs of the Kirov region as high color and turbidity of water, high content of organic substances. This became possible due to the use of various combinations of channels of the Sentinel-2 satellite in the calculations. The most informative index turned out to be NDAI. Its values do not depend on atmospheric interference and the influence of the reflection spectrum of the water itself [12]. The TBDO index was also quite informative. This index is recommended for determining the concentration of chlorophyll *a* in turbid productive waters. Calculation of TBDO made it possible to distinguish areas of mass development of phytoplankton from areas of increased water turbidity, in areas associated with the development of phytoplankton.

Conclusion

In order to identify areas of mass development of phytoplankton, we calculated four spectral indices and built a series of digital maps for the four largest reservoirs in the Kirov region. Based on the results obtained in the course of field and office work, we estimated the spatial distribution and temporal dynamics of phytoplankton development. It was noted that phytoplankton developed mainly in coastal shallow areas of reservoirs. The mass development of algae and cyanobacteria was most often observed in July and August. Intensive “blooming” of water was recorded in 2016, 2018, 2020 and 2021. The use of a complex of spectral indices made it possible to refine and supplement the data obtained during route observations on water bodies. Thus, digital maps built according to the calculation data of NDAI, NDVI, TBDO and NDTI can be used to assess the ecological state of the reservoirs of the Kirov region.

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