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Monitoring of the development of blue-green algae in the Kuibyshev reservoir using remote sensing indices

Danil N. Sherstobitov ✉, **Vasiliy V. Ermakov**,
Vitaliy N. Pystin, **Olga V. Tupitsyna**

Samara State Technical University, Samara, Russian Federation
✉sherstobitovdn@gmail.com

Abstract. The research presents the results of remote monitoring of blue-green algae of the Kuibyshev reservoir, leading to eutrophication of the reservoir. Multispectral images were taken by the European Space Agency's Sentinel-2 remote sensing satellite and were processed by using QGIS software. Satellite images were processed using spectral indices. After using several spectral indices, the three most informative ones were selected: NDVI, NDWI and SIPI. The usage of processed images made it possible to define the boundaries of the distribution of blue-green algae more clearly, as well as the zones of the most intensive development of biomass. The use of several spectral indices made it possible to determine the most suitable data for the usage under adverse meteorological conditions. The analysis of the processed satellite images makes it possible to assess the intensity of the development of blue-green algae. This is the basis for the development of a forecast model of biomass changes in the reservoirs of the middle zone of the Russian Federation.

Keywords: blue-green algae, remote sensing, reservoir, environmental monitoring

Мониторинг развития сине-зеленых водорослей в Куйбышевском водохранилище при помощи индексов дистанционного зондирования Земли

Д.Н. Шерстобитов[ID]✉, **В.В. Ермаков**[ID],
В.Н. Пыстин[ID], **О.В. Тупицына**[ID]

*Самарский государственный технический университет (СамГТУ),
Самара, Российская Федерация*
✉sherstobitovdn@gmail.com

Аннотация. Представлены результаты дистанционного мониторинга сине-зеленых водорослей Куйбышевского водохранилища, приводящих к эвтрофикации водоема. Мультиспектральные снимки, выполненные спутником дистанционного зондирования Земли Европейского космического агентства Sentinel-2, были обработаны при помощи программного обеспечения QGIS. Обработка спутниковых снимков производилась при помощи спектральных индексов. После применения нескольких спектральных индексов были выбраны три наиболее информативных: NDVI, NDWI и SIPI. Использование обработанных снимков позволило более четко определить границы распространения сине-зеленых водорослей, а также зоны наиболее интенсивного развития биомассы. Применение нескольких спектральных индексов позволило определить наиболее подходящие для использования данных при неблагоприятных метеорологических условиях. Анализ обработанных спутниковых снимков дает возможность оценивать интенсивность развития сине-зеленых водорослей. Это является основой для разработки прогнозной модели изменения биомассы в водоемах средней полосы Российской Федерации.

Ключевые слова: сине-зеленые водоросли, дистанционное зондирование Земли, водохранилище, мониторинг

Introduction

The intensive development of blue-green algae has become a relevant problem for rivers and freshwater bodies of the middle zone due to climate change,

in particular, an increase in temperature on the surface of the earth, and active anthropogenic impact.

In recent years, this issue has also become characteristic of the Kuibyshev reservoir of the Volga River. The Kuibyshev reservoir is the largest reservoir on the Volga River, formed by the dam of the Zhigulevskaya hydroelectric power station. The construction of a cascade of reservoirs changed the flow and hydrological regime of the Volga River. Low flow rates, rising temperatures [1], and nutrient-rich effluents lead to thriving blue-green algae. Blue-green algae, under favorable conditions for them, intensively multiply in the surface layer and limit the saturation of the reservoir with oxygen. It is worth noting that upon death blue-green algae settle to the bottom and are a source of food for bacteria. Biomass decomposition leads to a further reduction in dissolved oxygen throughout the water column.

The main threat, in addition to reduction in the amount of oxygen in water bodies, is also the ability of blue-green algae to produce toxic metabolites (cyanotoxins) [2], posing a threat to human life and health [3]. Intensive reproduction of blue-green algae leads to eutrophication of water bodies [4] considered by the UN as one of the important problems of the modern world [5].

To solve the problem of increasing the number of blue-green algae, a lot of different methods have been developed to collect them using mobile devices [6–8]. In order to promptly adjust their position and select areas for the most effective collection of algae, first of all, it is necessary to monitor the state of water bodies. At the same time, monitoring should cover not only the current state of the reservoir, but also the rate of distribution of blue-green algae, the stages of their life cycle, and also be the basis for designing a predictive model for the development of algae. The relevant way of monitoring is the analysis of aerial photography data, meanwhile, to determine the various characteristics of blue-green algae, using visible spectrum images is not sufficient enough.

Materials and methods

Multispectral images of the Kuibyshev reservoir made by the Earth remote sensing satellites of Sentinel-2 series of the European Space Agency with a spatial resolution of 10, 20 and 60 meters were used as a source of initial data.

Of the 13 spectral channels of the Sentinel-2 satellite, 4 were involved in the processing of satellite images (Band No. 2, 3, 4, 8). The characteristics of the channels are presented in Table 1.

As a result of the analysis of spectral indices applicable to solving the problem of assessing and predicting the state of water bodies, the 3 most relevant ones were selected: NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index) and SIPI (Structure Intensive Pigment Index). The use of NDVI is due to the detection of the reflection of chlorophyll, which is contained in blue-green algae [9]. This index does not provide more information than visual

observation of images in the visible region of the spectrum. NDWI is traditionally used to highlight the boundaries of water bodies against the background of soil and vegetation. The authors of this work used this index to specify the boundaries of algae distribution and to estimate the amount of biomass in more detail. SIPI is mainly used to determine how efficiently plants use incoming light for photosynthesis and to help evaluate their condition. SIPI is considered as an index to monitor the developmental cycles of blue-green algae, including: early development, full activity, developmental decline and death.

Sentinel-2 Bands

Sentinel-2 bands	Sentinel-2A		Sentinel-2B		Spatial resolution, m
	Central wavelength, nm	Bandwidth, nm	Central wavelength, nm	Bandwidth, nm	
Band 1 – Ultra blue	442.7	21	442.2	21	60
Band 2 – Blue	492.4	66	492.1	66	10
Band 3 – Green	559.8	36	559.0	36	10
Band 4 – Red	664.6	31	664.9	31	10
Band 5 – Visible and Near Infrared	704.1	15	703.8	16	20
Band 6 – Visible and Near Infrared	740.5	15	739.1	15	20
Band 7 – Visible and Near Infrared	782.8	20	779.7	20	20
Band 8 – Visible and Near Infrared	832.8	106	832.9	106	10
Band 8A – Visible and Near Infrared	864.7	21	864.0	22	20
Band 9 – Short Wave Infrared	945.1	20	943.2	21	60
Band 10 – Short Wave Infrared	1373.5	31	1376.9	30	60
Band 11 – Short Wave Infrared	1613.7	91	1610.4	94	20
Band 12 – Short Wave Infrared	2202.4	175	2185.7	185	20

Source: MultiSpectral Instrument (MSI) Overview. Sentinel Online. European Space Agency. Available from: https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi/msi-instrument (accessed: 03.03.2022).

It is known that indices developed directly for algae, such as Floating Algae Index (FAI) [10], Seaweed Enhancing Index (SEI) [11] are used. When calculating these indices, specific spectral channels of limited use are used, which are not available for most territories of Russia. The formulas for calculating the indices proposed for consideration (NDVI, NDWI and SIPI), which are publicly available and presented for the entire territory of the Earth, are given below

$$NDVI = \frac{NIR - red}{NIR + red},$$

where red is the red region of the spectrum (Band 4); NIR is the near infrared region of the spectrum (Band 8).

$$NDWI = \frac{green - NIR}{green + NIR},$$

where green is the green region of the spectrum (Band 3), NIR is the near infrared region of the spectrum (Band 8).

$$SIPI = \frac{NIR - blue}{NIR - red},$$

where red is the red region of the spectrum (Band 4), blue is the blue region of the spectrum (Band 2), NIR is the near infrared region of the spectrum (Band 8).

Analysis of the data obtained using various remote sensing indices allows a more comprehensive approach to reservoir monitoring. Observing the growth of cyanobacteria during the summer season can help to find the main sources of nutrient (wastewater) discharges into the surface water.

Results and discussion

Approbation of the proposed method of monitoring was carried out in summer – the season of the most intensive development of blue-green algae. The following dates were selected as tracking periods:

06/20/2021 – the beginning of the flowering of blue-green algae;

07/18/2021 – the biomass gain stage;

08/14/2021 – the maximum amount of algae;

08/19/2021 – the period of reduction in the number of blue-green algae.

In view of the set of numerical values determined for each point of the survey area, conditional scales for numerical interpretation of the index values are presented under the images (Figure 1–3).
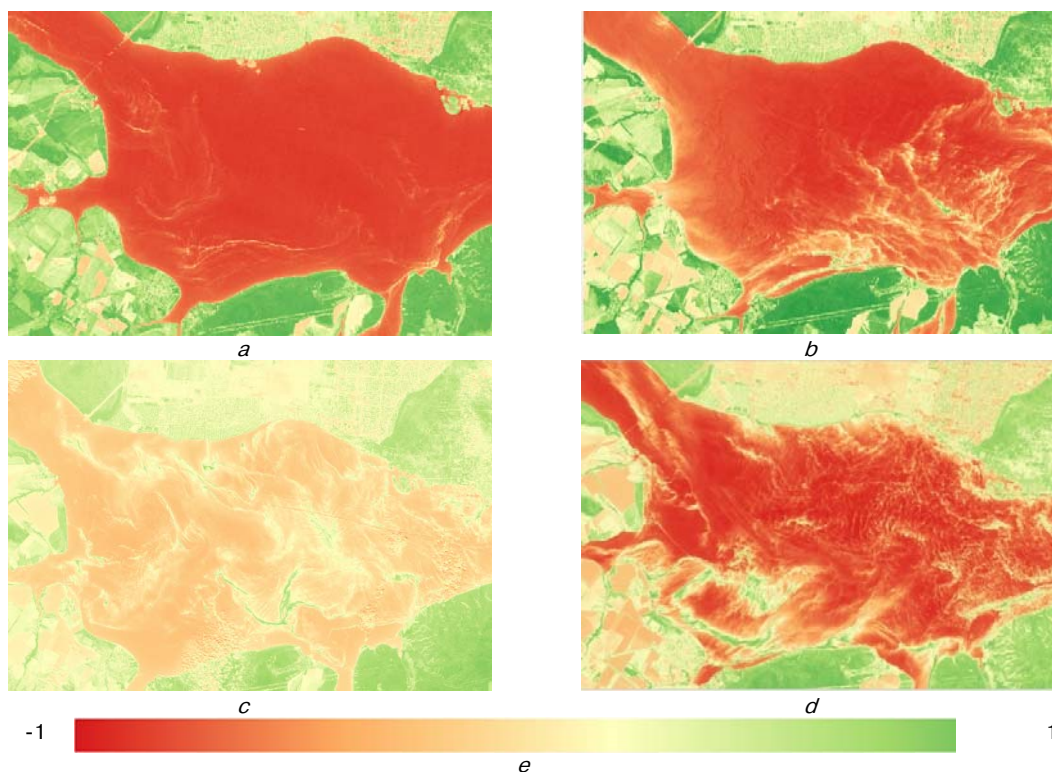

Figure 1. Satellite images processed with NDVI:
a – date of the image: 20.06.2021; *b* – date of the snapshot: 18.07.2021; *c* – date of the snapshot: 14.08.2021; *d* – date of the snapshot: 19.08.2021; e – NDVI value scale

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The presented images upon processing and calculation of the NDVI index illustrate the change in the activity of oxygen uptake during photosynthesis (see Figure 1). It is noted that there is practically no biomass in the image from June 20. The pictures taken later, starting on July 18, show significant massive accumulations. The most intensive formation of biomass occurs along the coastal strip. The increase in the number of blue-green algae in this area is due to higher temperatures, shallow depths and the presence of runoff entering the reservoir from nearby areas. The waters of small rivers flowing into the reservoir contain a large amount of fertilizers washed out from agricultural fields. Fertilizers are mainly represented by chemical compounds based on potassium, nitrogen and phosphorus. In addition to water coming from agricultural fields, untreated domestic wastewater with high concentrations of organic substances and inorganic salts is discharged into the reservoir. They are absorbed by the blue-green algae being their nutrient medium and stimulate growth.

The image from August 14 illustrates the more intensive distribution of blue-green algae throughout the area of the Kuibyshev reservoir near the city of Tolyatti. The reduced clarity of the image processed using NDVI is the result of the detection of atmospheric aerosol and hinders the analysis of the obtained data.
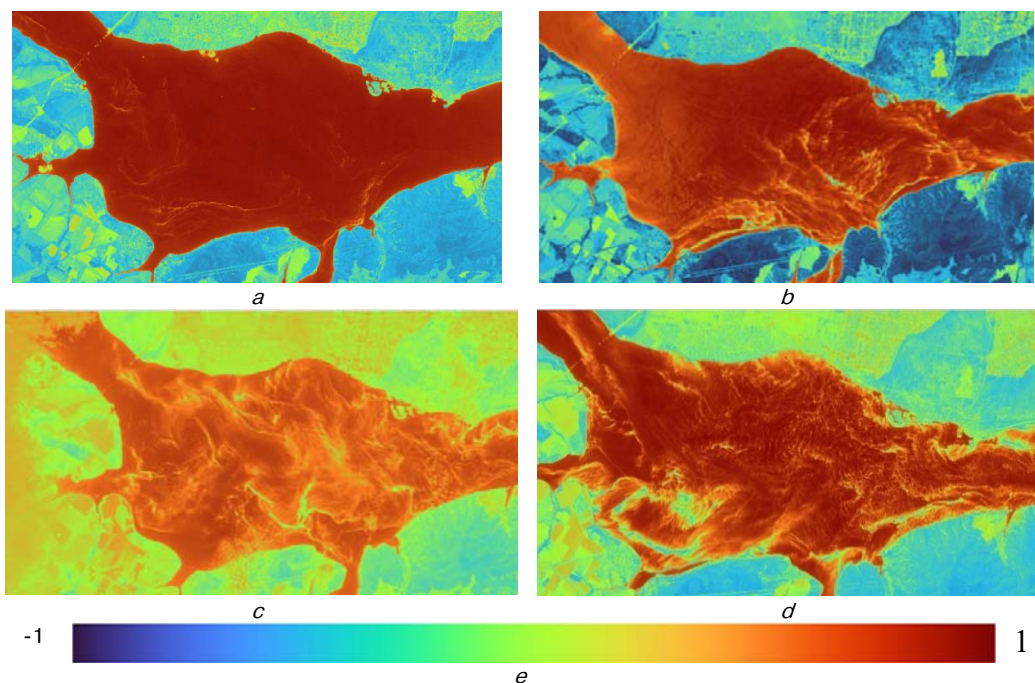
Figure 2. Satellite images processed with NDWI:
a – date of the image: 20.06.2021; *b* – date of the snapshot: 18.07.2021; *c* – date of the snapshot: 14.08.2021; *d* – date of the snapshot 19.08.2021; *e* – NDWI value scale

With the help of the image taken on August 19, 5 days after the previous one, it became possible to determine the change in the location of blue-green algae, which is caused primarily by the movement of water flows. It is on these dates that the peak of the intensity of biomass development falls. At the same time, there were no significant changes in the amount of biomass (no more than 3%) over the total area of the water surface, on which the presence of algae is detected.

Unlike NVDI, NDWI is mainly used to determine various characteristics of water bodies. The authors proposed the use of this index to more clearly define the boundaries of the distribution of blue-green algae (see Figure 2). In particular, it was noted that the images processed using NDWI, namely the image from August 14, are more informative due to the fact that they are less affected by atmospheric phenomena. It was determined that the decrease in the area of water surface coverage by algae, calculated using NDWI between August 14 and 19, was about 5%.

SIPI, in contrast to the vegetation and water index, is directly related to the assessment of the vital activity of phytoplankton. Unlike NDVI, it not only takes into account the presence of chlorophyll volume, but also affects metabolic processes that may indicate the stages of growth and development of blue-green algae (see Figure 3).
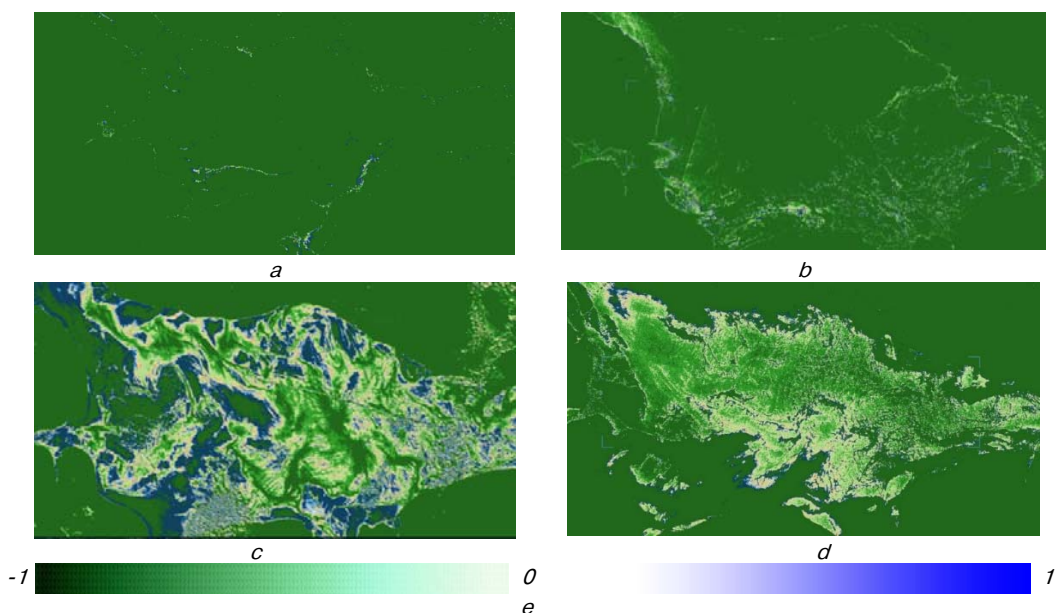

Figure 3. Satellite images processed with SIPI:
a – date of the image: 20.06.2021; *b* – date of the snapshot: 18.07.2021; *c* – date of the snapshot: 14.08.2021; *d* – date of the snapshot 19.08.2021; *e* – SIPI value scale

In the image from June 20, there is focal development of biomass. Further, with an increase in water temperature by July 18, there is more intensive reproduction of blue-green algae, while there are no areas with dying algae. In the

image from August 14, you can see areas of blue, which may be an accumulation of oppressed biomass with reduced metabolism. The image of August 18 no longer detects a significant part of the blue-green algae that are still highlighted in the images processed using vegetation indices. So, from August 14 to August 19, there was a significant change in biomass, from 47 to 38%.

Conclusion

Multiparametric analysis of the development of blue-green algae in the Kuibyshev reservoir using remote sensing indices can be used to make decisions on the timely protection of a reservoir. The most user-friendly NDVI shows the presence of biomass and its movement, and in general can be used to correct the positions of blue-green algae collection facilities. NDWI is more accurate than NDVI due to atmospheric correction.

High-resolution images processed in this way can be used to search for areas of unauthorized wastewater discharge by the presence of intensive algae growth.

SIPI makes it possible to evaluate the life cycle of algae and makes it possible to predict changes in the amount of biomass in the next few days.

In the future the joint analysis of data from remote sensing of the Earth and laboratory studies of the state of water and biomass is planned. Such studies will make it possible to reliably correlate the values of the indices with the state of objects, as well as to develop indices that are most suitable for the task being solved.

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Bio notes:

Danil N. Sherstobitov, Ph.D. student of the Department of Chemical Technology and Industrial Ecology, Samara State Technical University, 244 Molodogvardeyskaya St, Samara, 443100, Russian Federation. ORCID: 0000-0002-9160-5317, eLIBRARY SPIN-code: 6822-4868. E-mail: shersobitovdn@gmail.com

Vasiliy V. Ermakov, Cand. Sc. (Tech.), Associate Professor of the Department of Chemical Technology and Industrial Ecology, Samara State Technical University, 244 Molodogvardeyskaya St, Samara, 443100, Russian Federation. ORCID: 0000-0001-7720-2418, eLIBRARY SPIN-code: 5201-1408. E-mail: wassiliy@rambler.ru

Vitaliy V. Pystin, Cand. Sc. (Tech.), Associate Professor of the Department of Chemical Technology and Industrial Ecology, Samara State Technical University, 244 Molodogvardeyskaya St, Samara, 443100, Russian Federation. ORCID: 0000-0002-4027-1804, eLIBRARY SPIN-code: 8568-1200. E-mail: vitaliy.pystin@yandex.ru

Olga V. Tupitsyna, Dr. Sc. (Tech.), Professor of the Department of Chemical Technology and Industrial Ecology, Samara State Technical University, 244 Molodogvardeyskaya St, Samara, 443100, Russian Federation. ORCID: 0000-0003-0638-2700, eLIBRARY SPIN-code: 4203-9529. E-mail: olgatupicyna@yandex.ru