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IMPROVING THE ASSESSMENT OF THE ECOLOGICAL STATE OF SURFACE WATERS BY SATELLITE DATA

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Abstract. *The article presents the results of research into the ecological state of surface waters using newly developed scientific approaches based on the use of high spatial resolution satellite data. The systematization of all available indicators and the development of new methodological approaches significantly improves the existing methodology for determining the ecological state of water bodies, which is the goal of research. In the studies of water bodies within the city of Kyiv, Obolon Bay and Lake Verbne, the optimal set of such indicators as spectral indices was determined, which made it possible to comprehensively assess the state of water bodies: NDWI – for distinguishing vegetation and water bodies, GCI – to assess the extent of blue-green algae, NDTI – to determine turbidity, IO – to determine the presence of soluble iron in water, NDSI – to assess the extent of flooding. According to the NDSI, NDWI indices and a combination of the red and infrared channels of the Sentinel-2 L2A satellite, the flooding of the floodplain of the Irpin River was traced, caused by the destruction of a hydraulic structure near the village of Kozarovichi. Wave abrasion of the shores was studied on the example of the Kremenchuk Reservoir near the villages of Pronozivka and Mozoliivka using Landsat4 (1984) and Landsat8 (2016) satellite images. The study of the reshaping of the coastline near the village of Tsybli in the Kyiv region used the method of determining spatio-temporal changes of the coastline as a result of its erosion. The assessment of spatio-temporal changes of the coastline should be carried out taking into account the water levels on the dates of the measurements. The conducted studies established that all the identified evaluation indicators can be grouped as biological, hydro morphological, and physicochemical, and it can be concluded that methodical approaches to assessing the ecological state of surface waters using satellite data are based on established cause-and-effect relationships of processes affecting water objects.*

Key words: *surface water, ecological condition, satellite data, spectral indicators, databases, spatiotemporal changes*

Relevance of research. The problem of deterioration of the ecological condition of water bodies due to significant anthropogenic load and changes in climatic conditions is acute enough for all river basins of Ukraine. Therefore, in 2020, the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine developed methodological recommendations for assessing the ecological state of water bodies and reclaimed land based on spatially distributed satellite data [1], which was proposed to assess the state of surface waters according to individual indicators determined based on multispectral satellite images. Over time, new developed indicators for assessing the ecological state of surface waters were added, and the methodology needed improvement, especially regarding the systematization of the indicators themselves. The basis of the improved methodology was the existing methodology, which is based on the use of ground information and was approved by the Order of the Ministry of Environmental Protection and Natural Resources of Ukraine dated January 14, 2019 No. 5 “On approval of the Methodology for classifying a body of surface water, as well as a significantly changed body of surface water to one of the classes of ecological potential of an artificially or significantly changed body of surface water” [2]. In the algorithm for determining the state of the surface water body, the ecologically-chemical state is considered. Ecological state indicators are: biological, hydromorphological, chemical,

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and physicochemical. However, in satellite data use, chemical analysis of water is not considered separately, but only physicochemical with selection for laboratory chemical analysis of water samples to confirm its spectral characteristics. Therefore, suggested to use the algorithm of the approved methodology as a basic one, and to attract and increase the number of indicators that can be determined by satellite data. This article is dedicated to solving this problem.

Analysis of recent research and publications. The domestic and international community pays considerable attention to the problems of creating an effective surface water monitoring system using satellite data. Among the domestic scientific developments of recent years, the work of V.I. Zatserkovny (2018) [3] stands out, in which the development of separate technologies in the form of a surface water quality monitoring database, which is intended for data storage, description of the parameters of the investigated substances, their maximum permissible limits, is considered concentrations that meet the requirements of the EU Directive 2000/60 (paragraphs 39, 40), description of observation posts, passport data of water bodies, data analysis and forecasting of the further impact of pollutants on the environment, detection of extreme situations on a water body after technogenic disasters. It is worth noting the published scientific work of R. Keklyu, A. Alkish (2021) [4] on the creation of a new trophic level index using water quality parameters. The use of water indices for the identification of water bodies in the Kyiv region is described in detail in the work of V. Belenko (2023) [5] and O. Apostolov (2020) [6] for determining the sufficiency or lack of moisture in the territory according to the ERS (Earth Remote Sensing) data.

Among the foreign works, it is worth noting the work of Polish scientists K. Dyba, S. Ermid and others. (2022) on the development of a method for remote monitoring of water temperature in lakes in a spatio-temporal context based on Landsat8 images [7]. A combination of the time series analysis method and a simplified algorithm based on the Planck equation was proposed by Italian scientists to determine and analyze the surface temperature in the lakes of Central Italy (De Santis D., 2022) [8]. The work of scientists from many countries around the world is devoted to surface water pollution, in particular, M. Golizade (2016) [9]; H. Adzhov Ebenezer (2023) [10], etc.

Special attention is paid to the examination of the Copernicus program of the European Union created in 2011, which is the best example of international observation and decision-making systems using remote sensing of the Earth for all components of the environment. Information services are provided free of charge and open access to authorized users of the Copernicus Program. Specialists of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences actively use Copernicus as part of Google Earth Pro when downloading high spatial resolution images and using archives of Landsat and Sentinel images, as well as Land Viewer and Crop Monitoring. An example of this is the research on the effect of the explosion of the protective dam of the Kyiv Reservoir on the Irpin River basin using remote sensing of the Earth.

Analytical studies have determined that with the development of technologies for processing and presenting the results of satellite information analysis, methodological approaches to assessing the ecological state of surface waters based on satellite data have also changed. The literature review shows that research is mainly conducted to identify the deterioration of ecological situations and for this purpose, certain informative parameters are considered, such as water temperature, the presence of surface formations (specular reflection), concentrations of various substances dissolved and suspended in water (diffuse reflection): transparency, turbidity, color, soluble iron. The use of various indicators requires systematization, which, in general, corresponds to the problem we have established, and a conclusion was drawn about the need to improve the existing methodology for assessing the ecological state of water bodies based on satellite data.

The purpose of the research is to improve the assessment of the ecological state of surface waters based on satellite data.

Research methods and materials. In the analysis of satellite data, the energy and polarization characteristics of the own and reflected radiation of water and vegetation surfaces and the atmosphere are determined in various ranges of the electromagnetic radiation spectrum. In conducting research with satellite data, the passive method of remote sensing of the Earth, analytical analysis of scientific works, spectral and geospatial analysis, and system analysis were used, and soil surveys and experimental studies were carried out using generally accepted and certified methods.

The research methodology included the following components:

- searching for publicly available satellite information and analyzing the possibility of its application to the task;

• analytical analysis of scientific works on the established problem;

• calculations of spectral water and vegetation indices, comparison of channel combinations;

• carrying out field observations, taking water samples, and measuring transparency, turbidity (the content of suspended substances), color, and temperature of water;

• analysis of the results obtained and determination of changes occurring in water bodies.

During the monitoring, biological and hydromorphological indicators were determined using satellite data and field surveys, and conclusions were drawn about the ecological state of surface waters.

Research results and discussion. The main attention was paid to identifying possible and systematizing tested indicators characterizing the ecological state of surface waters according to satellite data using the example of water bodies with different hydromorphological characteristics. At the beginning of the research, there was a search for satellite images of high spatial resolution in the Google Earth Pro and Land Viewer software products open to users. These typically include archival Landsat and Sentinel imagery, for which spectral empirical metrics can be obtained through indices or channel combinations, as well as high-resolution Aerbus and Maxar imagery. The studies used indicators such as the NDTI (Normalized Difference Turbidity Index) [11], which assessed the development and scale of distribution of blue-green algae ("blooming" of water), its turbidity; NDWI (Normalized Difference Water Index) [12–14], which at small values showed the absence of vegetation, and at large values (greater than zero) – the presence of water; GCI (Green Chlorophyll Index), which showed the content of green chlorophyll in areas of "blooming" of blue-green algae and the overgrowing of the reservoir with taller aquatic and surface vegetation; IO (Index of iron oxide content), according to which the presence of soluble iron in water was determined; NDSI (Normalized Difference Snow Index) [15], which made it possible to record the scale of floods when snow melts.

The indicators were obtained in 2023 during the study of the ecological state of the waters of Lake Verbne (Fig. 1) and Obolon Bay (Fig. 2) within the city of Kyiv using Landsat8 and Sentinel2 satellites.

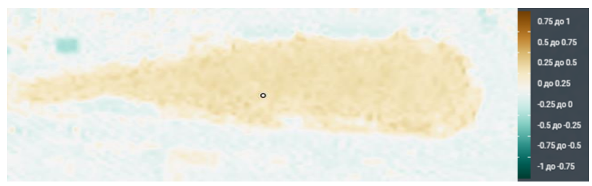
The obtained results were verified by ground surveys (Fig. 3), during which the following were measured: water temperature with a standard water thermometer, which is used on the network of the hydrometeorological service; transparency using a Secchi disk, as well as color, suspended solids concentration (turbidity) and soluble iron, which were evaluated from water samples collected in laboratory studies.

The results of surveys based on satellite data according to the colors of the legend of their values show that the average values of the indices within the area of the water surface of a water body are:

• in Obolon Bay NDTI 0–0,25; GCI 0,25–0,5; NDWI 0,1–0,2; IO -0,75;

• in Lake Verbne NDTI 0,25–0,5; GCI 0,5–0,75; NDWI 0,3–0,6; IO-0,5.

a



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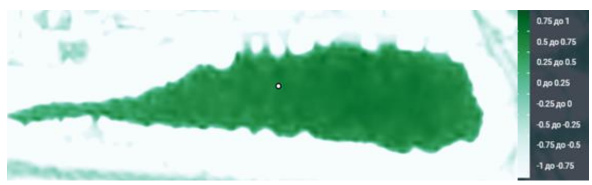

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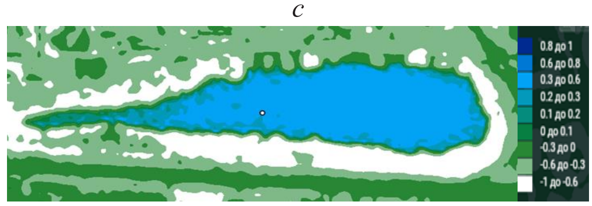
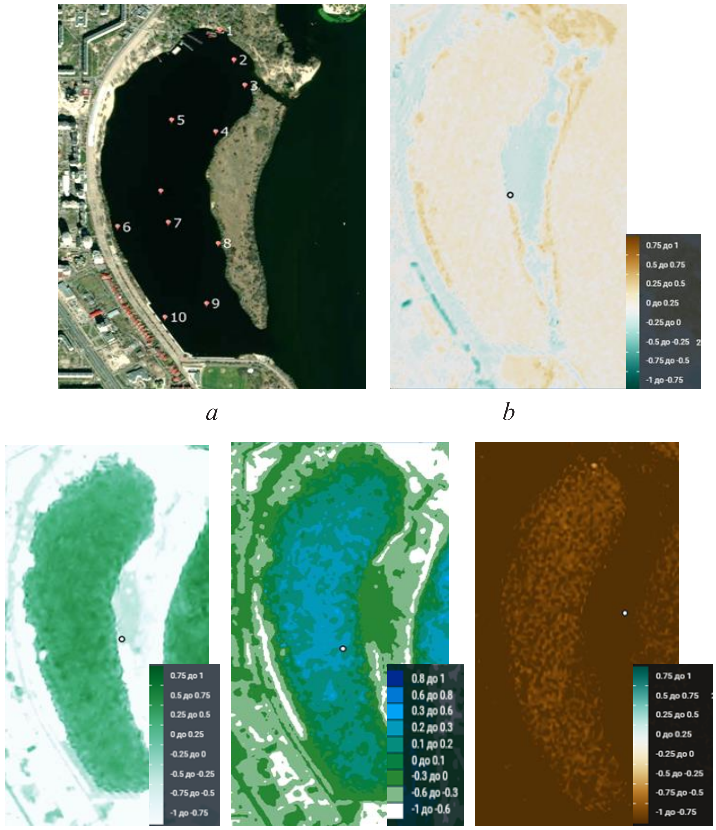


d

f

Fig. 1. Satellite image 07/04/2023 Sentinel-2 L2A of Lake Verbne with plotted ground observation points (*a*) and thematic maps of spectral indices:

b – NDTI, *c* – GCI, *d* – NDWI, *f* – IO



a *b*

c *d* *f*

Fig. 2. Satellite image 07/04/2023 Sentinel-2 L2A of the Obolon Bay with plotted ground observation points (*a*) and thematic maps of spectral indices:
b – NDTI, *c* – GCI, *d* – NDWI, f – IO

Obolon Bay is located east of the Obolon residential area. This bay is connected to the Dnieper by a wide strait in its southern part, as well as a small strait in the northeastern part. The presence of two canals determines sufficient water exchange with the Dnieper. The length of the bay is 1,5 km, the maximum width is 430 m, and the depth is up to 17–19 m, because at one time sand was taken from it to wash the territory of the Obolon residential area. The area of the bay is 57,1 hectares. The shores of the bay are moderately gentle and sandy. It is used for recreational purposes (Fig. 3, a).

Lake Verbne (Fig. 3b) is located on the southern edge of the Obolon residential area. Non-flowing The length is 1070 m, the maximum width is 240-250 m. It is partly of artificial origin – it was a source of sand for washing the Obolon residential area. The area of the water mirror is 16.4 hectares. It is quite deep – up to 15 m. In 1994, by the Decision of the Kyiv City Council No. 14 dated February 17, 1994, Lake Verbne was declared an ichthyological and botanical reserve. In the lake there is a floating Salvinia fern – a species listed in the Red Book of Ukraine. There are also more than 20 species of lake-river complex fish here.

Since there are no standard indicators for comparison of spectral indices, during ground surveys the obtained indicators were compared with surveys of previous years. The results of ground-based surveys showed that in the studied water bodies over the summer period, the color of the water changed significantly and increased. Thus, compared to 07/08/2014, when the chroma in Obolon Bay was 33°, and in Verbne Lake – 13°, on 07/04/2023, the chroma in Obolon Bay was 132°, and in Verbne Lake – 89°. The main reason is the different types of algae, due to which the water acquires different colors, the presence of humic substances, compounds of ferric iron, as well as the influence of anthropogenic factors that can cause intensive coloring of the water. However, the transparency of the water has increased significantly. Thus, compared to July 8, 2014, when the transparency in the Obolon Bay was 14,5 cm, and in Lake Verbne – 9,2 cm, on July 4, 2023, the transparency in the Obolon Bay was 80 cm, and in Lake Verbne – 85 cm.

a *b*

Fig. 3. Photographs of places where ground-based surveys of water bodies were conducted: *a* – Obolon Bay, *b* – Lake Verbnoye

Based on the data of the calculated index and field surveys of Obolon Bay and Lake Verbne, graphs of the dependence of laboratory values of iron oxide and the IO index were constructed (Fig. 4). The coefficient of determination R2 for Verbnoy Lake is 0,898, and for Obolon Bay – 0,876.

The concentration of iron oxide should decrease as the volume of the water body increases, which is a natural phenomenon. But in Obolon Bay, the concentration is higher, which indicates an excess of iron coming from the upper reaches, that is, from the Kyiv Reservoir. Lake Verbne is non-flowing and has less soluble iron. It was established that the indicators of the ecological condition in Obolon Bay are worse compared to the indicators of Lake Verbne:

• the average temperature is lower by 1 °C;

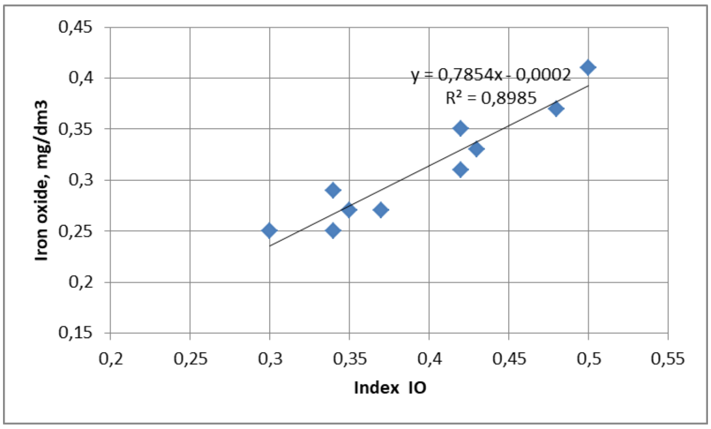
• chroma is higher on average – 147,06°/94,12°;

• turbidity is lower – 5,51/6,38 mg/dm^3, soluble iron is higher – 0,93/0,41 mg/dm^3.

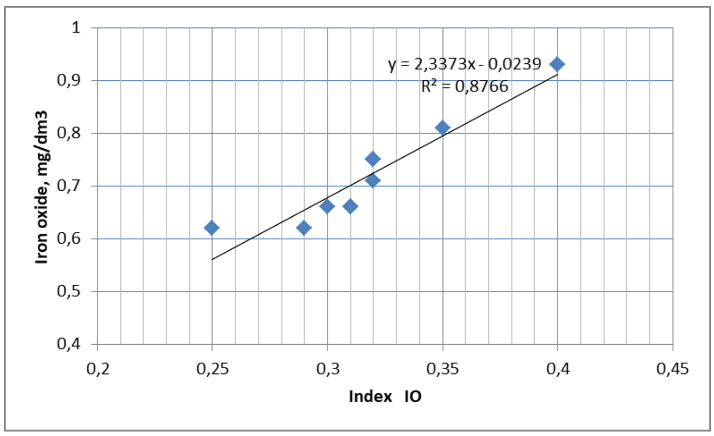
In addition to biological indicators, hydromorphological indicators were determined. Thus, according to the NDSI, NDWI indices and a combination of the red and infrared channels of the Sentinel-2 L2A satellite, the passage of the flooding of the floodplain of the Irpin River caused by the destruction of the hydro-technical structure in the village of Kozarovichi was traced [16]. The research also studied the spatiotemporal transformation of the coastline of the Kaniv and Kremenchuk reservoirs. The reshaping of the shore occurs under the influence of natural and anthropogenic factors, which is a completely natural process, but it leads to the loss of a certain part of the land and ecological changes. To establish, observe and evaluate the process of reshaping the coastline, the method of determining spatio-temporal changes of the coastline as a result of its erosion was used, based on a combination of time-varying space images and topographic maps (Fig. 5). The assessment of spatio-temporal changes of the coastline should be carried out taking into account the water levels on the dates of the measurements.

Bank erosion was studied in the example of the Kanivskyi (Tsybli village) and Kremenchugsky reservoirs (Pronozivka village) using Landsat4, 1984 and Landsat8, 2016 satellite images (Figs. 5 and 6).

Analysis of temporal topographic maps and space images of the left bank of the Kaniv Reservoir in the area of Pereyaslav – p. Tsybli showed that intensive erosion of the coastal zone is observed only on the part of the coast that is located frontally to the line of maximum acceleration of wind waves, that is, from the estuary near the village of Tsybli to the mouth of the Trubizh River. Fig. 5 shows the dynamics of changes in the bankline of the entire 6,7 km long erosion-dangerous section. The red line shows the location of the bank on a topographic map at



a



b

Fig. 4. Graphs of the dependence of the value of iron oxide and the IO index in 2023:
a – Lake Verbne, *b* – Obolon Bay

a

b

c

d

Fig. 5. Pictures:
a – basic CNES/Airbus near the village. Tsybli, 2014; *b* – the dynamics of the bankline of the Kaniv Reservoir in the section of the village. Tsybli – the mouth of the Trubizh River; *c* – Landsat 5, 1985; *d* – Landsat 5 and Maxar composite, 2008

a *b*

Fig. 6. Erosion of the left bank of the Kremenchuk Reservoir:
a – dynamics of the shoreline of the Kremenchuk Reservoir near the village of Pronozivka for the period 1985–2022 (below in enlarged view); *b* – part of the shore

a scale of 1:100,000 as of 1983, that is, almost 10 years after the construction of the reservoir, when the reformation of the bank had already partially passed the stage of abrasion leveling. The green line shows the coastline as of 2023. The total area of bank erosion in this area was 51 hectares. The average erosion area for every 100 linear meters of shore is 7,6 thousand m^2. Upstream, in the area of Pereyaslav and to the north, the bankline is relatively stable.

Fig. 6 shows the erosion dynamics of the left bank of the Kremenchuk Reservoir south of the Sulsky Estuary, near the village of Diarrhea. The modern satellite image shows coastlines as of 1985 (red line) and 2009 (green line), which were determined from satellite images for the corresponding years. As the analysis of the data obtained shows, for the period 1985–2009, the maximum width of bank erosion in the area was 80 m, and over the next 13 years, it increased to 94 m.

Conclusions. Based on the results of our research, we found that it is advisable to improve the method of assessing the ecological state of surface waters based on satellite data by systematizing spectral indices, grouping them as biological (aquatic vegetation, cyanobacteria), hydromorphological (hydromorphological changes, processes of eutrophication, coastal erosion), physical chemical (concentration of various substances dissolved and suspended in water) and use them in an integrated manner.

In the studies of water bodies within the city of Kyiv, Obolon Bay and Lake Verbne, the optimal set of such indicators as spectral indices was determined, which made it possible to comprehensively assess the state of water bodies: NDWI – for distinguishing vegetation and water bodies, GCI – to assess the scale of blue-green algae distribution, NDTI – to determine turbidity, IO – to determine the presence of soluble iron in water.

It has been established that methodical approaches to the assessment of the state of surface waters with the use of data from ERS (Earth Remote Sensing) are based on the establishment of cause-and-effect relationships of processes affecting water bodies, the need to find evaluative informative parameters, and the development of methods for determining spatiotemporal changes that occur in within river basins.

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УДОСКОНАЛЕННЯ ОЦІНЮВАННЯ ЕКОЛОГІЧНОГО СТАНУ ПОВЕРХНЕВИХ ВОД ЗА СУПУТНИКОВИМИ ДАНИМИ

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Анотація. *У статті викладено результати досліджень екологічного стану поверхневих вод за новими розробленими науковими підходами, які ґрунтуються на використанні супутникових даних високого просторового розрізнення. Систематизація усіх наявних показників і розроблення нових методичних підходів істотно удосконалює існуючу методику визначення екологічного стану водних об'єктів, що є метою досліджень. У дослідженнях водних об'єктів у межах м. Києва затоки Оболонь і озера Вербне здійснено визначення оптимального набору таких показників, як спектральні індекси, які дали змогу комплексно оцінити стан водних об'єктів: NDWI – для розрізнення рослинності і водних об'єктів, GCI – для оцінювання масштабності поширення синьо-зелених водоростей, NDTI – для визначення каламутності, IO – для визначення наявності розчинного заліза у воді, NDSI – для оцінювання масштабу повені. За індексами NDSI, NDWI та комбінацією червоного і інфрачервоного каналів супутника Sentinel-2 L2A простежено проходження затоплення території заплави р. Ірпінь спричинено руйнацією гідротехнічної споруди біля с. Козаровичі. Хвильову абразію берегів досліджено на прикладі Кременчуцького водосховища біля сіл Пронозівка та Мозоліївка з використанням знімків супутника Landsat4 (1984 р.) та Landsat8 (2016 р.). Під час дослідження переформування берегової лінії біля с. Циблі у Київській області використано метод визначення просторово-часових змін берегової лінії в результаті її розмиву. Оцінювання просторово-часових змін берегової лінії повинно виконуватися з урахуванням рівнів води на дати виконання вимірювань. Проведеними дослідженнями встановлено, що всі визначені оцінювальні показники можна згрупувати як біологічні, гідроморфологічні та фізико-хімічні і зробити висновок, що методичні підходи до оцінювання екологічного стану поверхневих вод із застосуванням супутникових даних ґрунтуються на встановлені причинно-наслідкових зв'язків процесів, що впливають на водні об'єкти.*

Ключові слова: *поверхневі води, екологічний стан, супутникові дані, спектральні показники, бази даних, просторово-часові зміни*