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ASSESSMENT OF THE AQUATIC ENVIRONMENT QUALITY OF THE URBAN WATER BODIES BY METHODS OF SYSTEM ANALYSIS BASED ON INTEGRATING REMOTE SENSING DATA

The work presents the comprehensive methodology for assessment of the state of the urban aquatic environment such as Lakes Opechen, Verbne, and Redkyne in Kyiv using the methods of system analysis. The methodology includes structural-textural analysis of the satellite images and the method based on statistical criteria. The spectral-texture analysis of the satellite images was used to get input information for remote assessment of reservoirs as index images: Normalized Difference Pond Index (NDPI), Normalized Difference Turbidity Index (NDTI), and Normalized Difference Algae Index (NDAI) computed from the Sentinel-2. The surface temperature distribution was estimated from the Landsat 8. The method based on statistical criteria is used for a detailed assessment of the aquatic environment using the obtained indexed images and the corresponding cartographic representation of the water quality. The probabilistic and statistical approaches were used to present the statistical criterion for recognizing classes of objects based on the results of measuring their informative features. These approaches are used to solve optimization problems in statistical theories of identification and recognition. This method allowed the cartographic representing of the change in the water quality and aquatic ecosystem in accordance with the reference areas of the state of the reservoir in 2017.

Keywords**:** *water quality, aquatic environment, methods of system analysis, remote sensing, spectral indices, NDTI, NDAI, NDPI, temperature map.*

INTRODUCTION

Knowledge of the functioning mechanisms of aquatic ecosystems is a basis for solving many practical problems related to improving the productivity of water bodies, water quality, and the implementation of water protection measures in fishing areas. The shortage of water resources leads to the fact that the ability of reservoirs to restore is approaching a critical level and, at the same time, reduces the biological diversity of the aquatic environment. Today, most aquatic ecosystems are exposed to anthropogenic impacts. Frequently this impact is complex, multifactorial,

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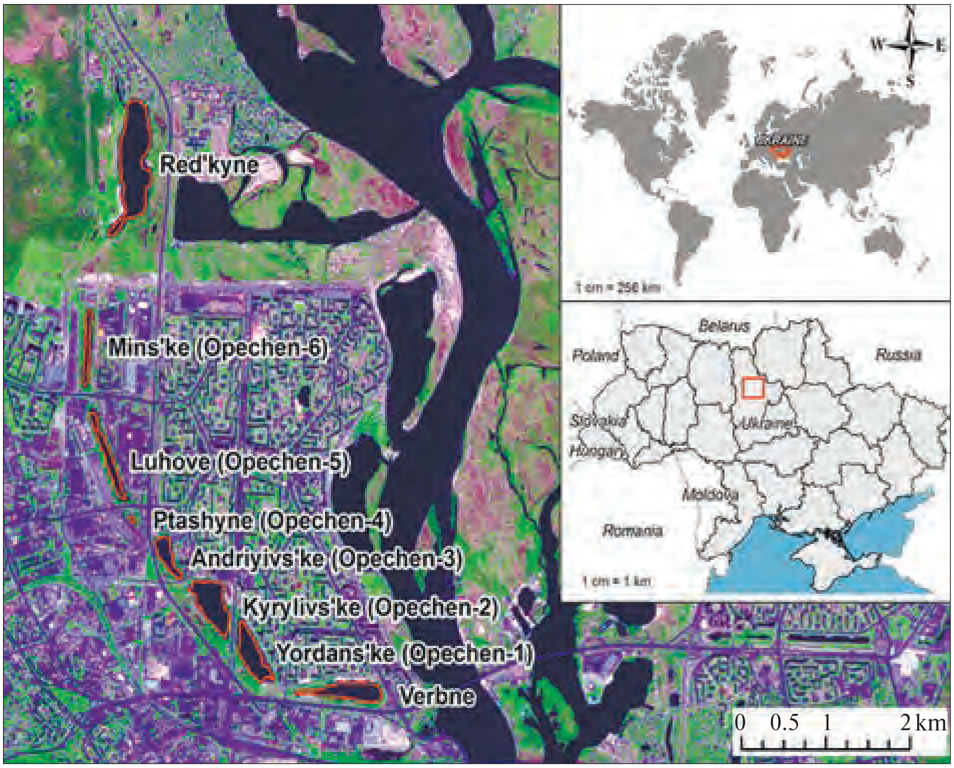


Fig. 1. The study area in the Sentinel-2 space image

and includes both local pollution and global climate change. All of this leads to a deterioration of the aquatic environment quality and worsens the conditions for the development of flora and fauna. There are many approaches to assess the ecological condition of water bodies and the quality of the aquatic environment. The essence of these approaches is either to establish environmental standards of water quality or to establish the level of negative impact on water bodies by certain pollutants.

The use of methods for Earth Observation (EO) has been proved to give far better coverage both in spatial and temporal scale for evaluation of in-water constituents in the water bodies. Since urban lakes are shallow, information about the surface layer, as achieved with EO methods, reflects the entire water column, whereas, in the case of deeper lakes, the surface layer is not representative for the deeper layers [7]. The purpose of the work was to present the methodology of integrated assessment of urban water bodies using the methods of systems analysis [5]. Approbation of the proposed methodology is presented at actual sites in Kyiv (Ukraine). For research, we have chosen reservoirs that are typical representatives of urban reservoirs, where recreational areas are equipped, there are spontaneous unorganized beaches, there is fairly intensive amateur fishing; most of the lakesides are residential. All of them are subject to anthropogenic impact, which determines the structural features of hydroecosystems and water quality in them. The study of surface water quality by remote sensing methods will cover the system of lakes Opechen and reservoirs of Lake Verbne, Redkyne in Kyiv, which are different not only in hydromorphological, hydrological parameters but also water quality, primarily for contaminated water from the surface.

The lakes Redkyne, lakes of the Opechen system, and lake Verbne arose on the site of the former right-bank branch of the Dnieper river — Pochayna river. These water bodies were used as sand quarries in 1970—1973 and deepened to 15 m. Most of them are connected by pipelines and formed the Opechen lakes system (Fig. 1).

This system of lakes accumulates rain, melt, and groundwater runoff from the north-western part of the city and lowers the groundwater level in the surrounding area [2].

MATERIALS

To assess the spatial structure of the biotic and abiotic components of Kyiv Lakes, we used data from remote sensing of the Earth from the Sentinel-2 satellite for the following dates in 2017 (as close as possible to the dates of ground observations): 03.04, 03.05, 05.06, 20.07, 11.08, and 18.10. We used the Landsat 8 satellite for the calculation of water surface temperature maps for the following dates 02.04, 04.05, 05.06, 23.07, 17.08, and 25.09.

METHODS

1. ***Methods of remote sensing data processing.*** The main indicators of remote sensing of the lakes are the integral values of the following index images: *NDPI* (Normalized Difference Pond Index), *NDTI* (Normalized Difference Turbidity Index), and *NDAI* (Normalized Difference Algae Index). These indicators were obtained based on decoding and analysis of space images from the Sentinel-2 satellite and surface temperature distribution data from the Landsat 8 satellite for different months of 2017.

Normalized Difference Pond Index (*NDPI*) identifies stagnant water when vegetation is present, which can more accurately account for shallow water bodies difficult to see in other water indexes that focus on clear water or turbid water with little vegetation that may dominate deeper flooded areas [4].

$$NDPI = \frac{I_{SWIR} - I_G}{I_{SWIR} + I_G},$$

where I_G and I_{SWIR} stand for the spectral reflectance measurements acquired in the green (visible) and short wave infrared regions, respectively.

Normalized Difference Turbidity Index (*NDTI*) is determined by the relationship between suspended sediments and negative radiation [4])

$$NDTI = \frac{I_R - I_G}{I_R + I_G},$$

where I_R and I_G stand for the spectral reflectance measurements acquired in the red (visible) and green regions, respectively.

Normalized Difference Algae Index (*NDAI*) detects the presence of the process of algae overgrowing of the reservoir and its stage of development [4]

$$NDAI = \frac{I_G + 2I_{NIR} - I_B - I_R}{I_G + 2I_{NIR} + I_B + I_R} + 0.5,$$

where I_B, I_G, I_R, I_{NIR} stand for the spectral reflectance measurements acquired in the blue, green, red (visible), and near-infrared regions.

Temperature maps of the reservoir's surfaces. The study of the surface temperature of the water mirror for the identification of patterns of changes in the state of the reservoir depending on the temperature change.

Determination of the Earth's surface emissivity distribution using remote sensing data is performed by processing images of the visible and near-infrared range, in particular, by establishing the relationship between emissivity and the *NDVI* index distribution [6].

Thus, the spectrum of radiation of the body and its radiant capacity can determine its temperature. Determining the temperature of the surface is the main task of remote sensing data processing in the long-wavelength region of the infrared spectrum. For this, the inverse Planck's law for the "gray body" through the expression for the spectral density of the radiation flux is used (Tang and Li, 2014):

$$T = \frac{c_2}{\lambda \ln\left(\frac{\varepsilon(\lambda) c_1}{\lambda^5 L_s} + 1\right)},$$

where L_s — spectral radiance from the Earth's surface, estimated from calibrated and atmospherically corrected satellite longwave infrared data; $\varepsilon(\lambda)$ — spectral emissivity; $c_1 = 2hc^2 = 1.191 \cdot 10^{-16}$ W·m^2 and $c_2 = hc/k = 1.439 \cdot 10^{-2}$ m·K — first and second Planck's constant; λ — radiation wavelength. For large homogenous areas, like water surfaces, the common table-value can be used (water emissivity is ≈0.985).

2. ***Methods of system analysis.*** To assess the condition of water bodies within urban areas, the methodology is built on a method based on statistical analysis [3]. This method comes down to the fact that it is possible to quantify the state taking into account various criteria and to model their impact, and the

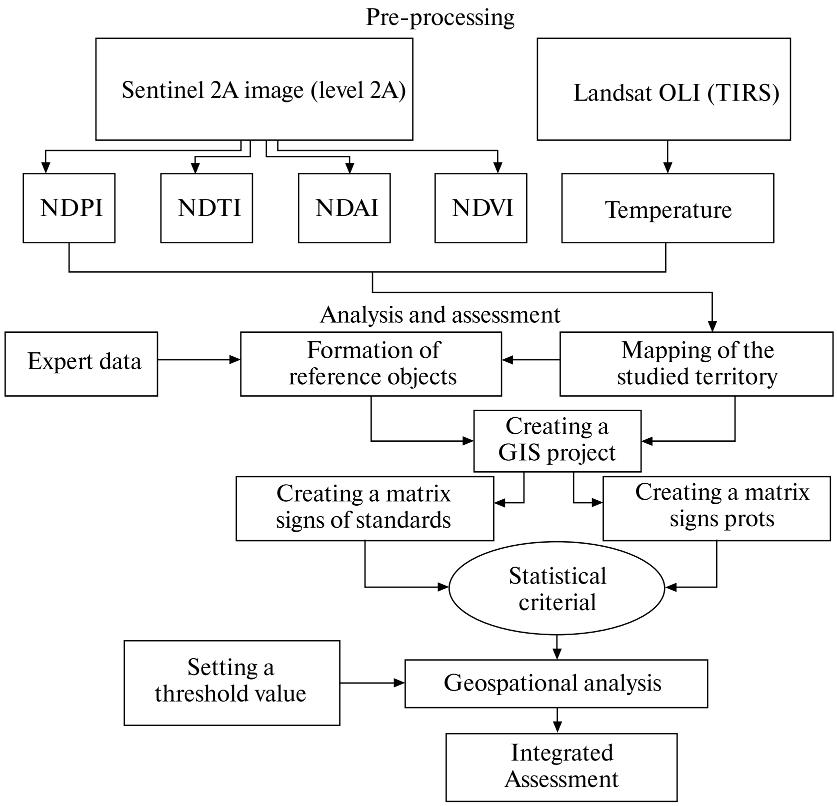


Fig. 2. Flowchart of pre-processing and combined processing of methods based on statistical criteria.

results are obtained in the form of a map in relative units or brightness gradations. Figure 2 shows the stages of pre-processing procedures, which include the proposed methodology.

Probabilistic and statistical methods used to solve optimization problems, statistical theories of identification, recognition, and number theory are applied in [1] for the representation of the heuristic criterion of object classes' determination by the results of measuring their informational features. The calculation of the heuristic criterion (1) involves previously entered informative features of each standard class and automatic calculation of the probability ratio of the belonging of the studied object to the standard classes:

$$T = \frac{c_2}{\lambda \ln\left(\frac{\varepsilon(\lambda) c_1}{\lambda^5 L_s} + 1\right)}, \qquad (1)$$

where

$$p_q(\overline{X}) = \left(\frac{1}{2\pi}\right)^{K/2} \prod_{k=1}^{K} \exp\left[-\frac{(L_k - L_{q,k})^2}{2\sigma_{q,k}}\right] \cdot \frac{1}{\sigma_{q,k}}$$

— multidimensional distribution density;

$$L_{q,k} = \frac{1}{N_q} \sum_{n=1}^{N_q} L_{q,k,n}$$

— average value of spectral brightness;

$$\sigma_{q,k} = \pm\sqrt{\frac{1}{N_q - 1} \sum_{n=1}^{N_q} (\xi_{q,k,n} - D_{q,k,n})^2}$$

— average dispersion value; Q — the number of classes of objects to be identified, q — the current number (index) of a particular class of objects, K — number of informative features used, k — the current number of a specific informative feature, L — the result of a particular measurement of an informative feature (vector of dimension K with coordinates $L_1, ..., L_k$), N_q — the sample size for the random variable $L_{q,k}$, n — current value.

RESULTS AND DISCUSSION

We visually compared the distribution of index images for 8 research objects for the same period — August 2017 — to rank their condition in the subsequent position of assessing the quality of the aquatic environment. *NDPI* indexed images have been found to help detect low water flow, which creates the conditions for the development of higher aquatic vegetation in shallow water. In the considered lakes, the highest index *NDPI* in August 2017 was typical for the lakes: Minske, Luhove, Yordanske, and Verbne. This is due to the high proportion of shallow water by dint of the morphometric features of reservoirs. The average values of *NDPI* indicators for each reservoir were able to reflect the seasonal course of changes in the overgrowth of higher aquatic vegetation and the probability of low water flow in the studied reservoirs.

According to *NDTI* on the presence of suspended solids in the lakes considered, the least turbid in 2017 is Lake Redkyne. It is explained by several factors: geographically, the lake is located first in the cascade of lakes studied, so it does not accumulate those substances that are in other lakes. The lake is surrounded by a green zone, which is a kind of barrier to the entry of pollutants into the water body. Based on average value of *NDTI* for each water body, it shows seasonal course of turbidity change in the studied reservoirs and, in the spring and early summer, several peaks in the turbidity of lakes. It is attributed to spring floods, i.e., the growth of sediment and runoff due to melting snow cover and the wear of various chemical compounds in the reservoirs. In the late spring-early summer season, it is usually the extinction of some groups of algae (diatoms), more intense destruction processes, and more intense development of other groups of phytoplankton, which, apparently, causes an increase in turbidity. In summer, due to evaporation, the concentration of suspended solids in the water increases slightly, and their number increases due to rainfall, which causes an increment of turbidity due to suspended solids from groundwater.

NDAI maps help to identify the presence of algae in the water, similar to *NDPI*. But in contrast to *NDPI, NDAI* is more sensitive to microscopic aquatic vegetation. It was found that from the considered lakes, the least eutrophicated in 2017 were Yordanske and Verbne because these lakes are located lowest in the cascade, and therefore, the concentration of nutrients in the water was highest due to runoff (Fig. 3).

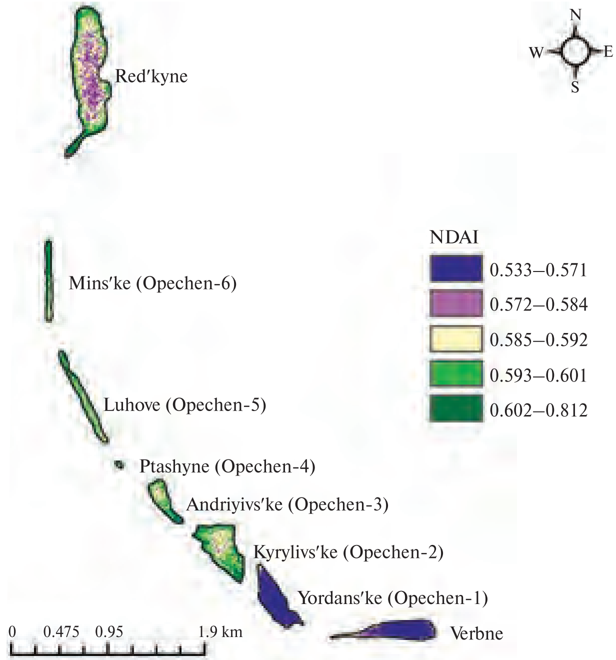


Fig. 3. Distribution of *NDAI* values in the lakes of Kyiv as of August 11, 2017.

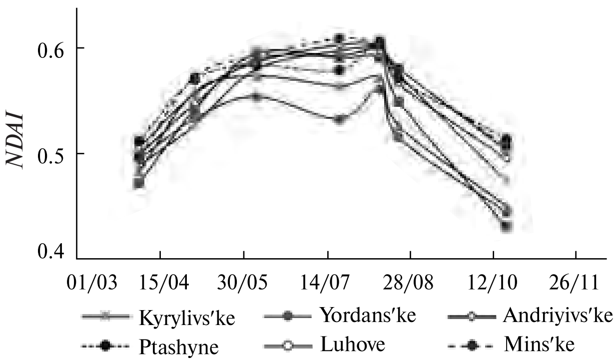
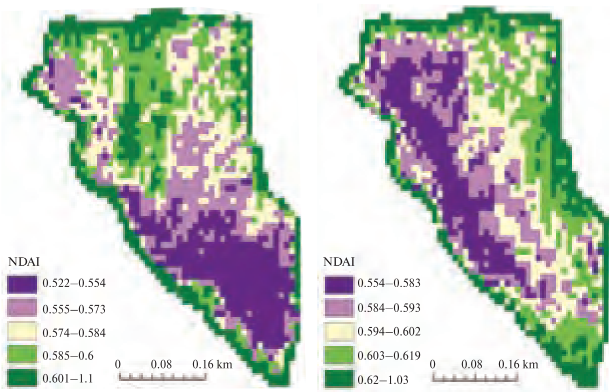


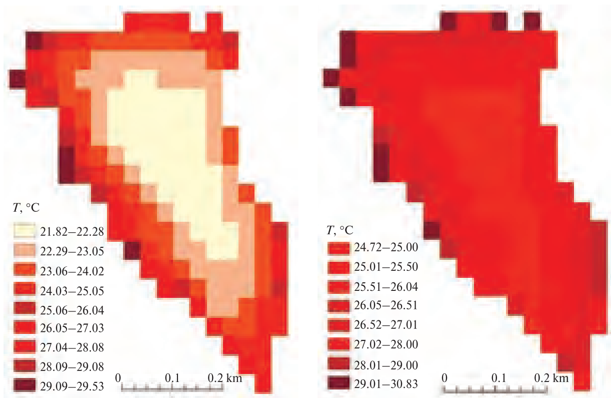
Fig. 4. Seasonal course of change of *NDAI* and presence of microscopic algae in lakes of Kyiv in 2017

Based on the *NDAI* value for each reservoir, the seasonal course of eutrophication is reflected in the studied reservoirs (Fig. 4), and in spring and autumn



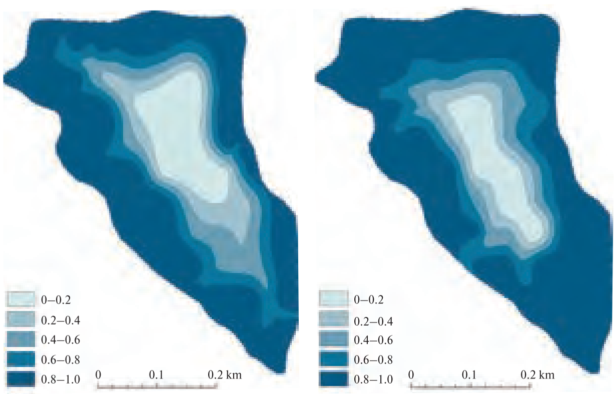
a *b*

Fig. 5. Distribution of values of the algae Index (*NDAI*) of Lake Kyrylivske: *a* — 05.06.2017, *b* — 20.07.2017



a *b*

Fig. 6. Distribution of values of the surface temperature of Lake Kyrylivske: *a* — 05.06.2017, *b* — 20.07.2017



a *b*

Fig. 7. Maps of the results of a detailed ecological assessment of the state of the aquatic environment of Lake Kyrylivske: *a* — 05.06.2017, *b* — 20.07.2017

the state of the lakes is characterized by the lowest values of the algae index. It increases with increasing temperature in the summer, hence, in the summer tendency of increasing the microscopic algae with the increase of temperature of air and, accordingly, water.

The developed method was implemented to assess the ecological status of one of the studied lakes in Kyiv, namely — Kyrylivske Lake. Located in the center of the cascade, it allows in some way to obtain averaged data for all lakes of the cascade. Table presents the average values of the lake in 2017 for all indices, as well as temperature indicators.

Figures 5 show how uneven the distribution of indexed images and water surface temperature can be on different dates, which is primarily due to different weather conditions. The distribution of water surface temperature values on the lakes of Kyiv in 2017 is given in Fig. 6.

The final stage of the comprehensive assessment was the application of the method based on statistical criteria. To obtain the values of all types of features at single points on the selected study area, we applied a grid with areas of 50×50 m, and each area was assigned the average values of pixel brightness in a separate channel and the values of the input data. For the correct operation of the program based on expert data and ground statistical information, areas-standards were allocated, 5 standards of each type of water quality.

Further, based on the obtained data, matrices of informative features for the studied plots and reference plots were created. This process involves the formation of feature values in the form of spreadsheets,

Average values of index indicators for Lake Kyrylivske in 2017

Data	*NDAI*	*NDPI*	*NDTI*	*t*, °C
03.04.2017	0.489	–0.586	–0.166	15.61
03.05.2017	0.527	–0.48	–0.203	21.38
05.06.2017	0.579	–0.427	–0.189	24.76
20.06.2017	0.597	–0.576	–0.209	27.24
11.08.2017	0.599	–0.543	–0.202	28.76
21.08.2017	0.574	–0.621	–0.214	18.35
18.10.2017	0.475	–0.724	–0.207	16.55

in each row of which there are the results of measurements of all types of remote information, and the columns provide feature values for each of the 80 sections. All data were translated into .txt format, and the probability values (1) of the ratio of the values of the informative features of each studied object to the values of the informative features of each reference object present in the space image were calculated.

This stage of work was automated in a software package, specially created based on the statistical criteria, which provides a priori input of informative features of all standards and automatic calculation of probability values of belonging of each studied object to all present objects-standards, which allows getting more efficiency and reliability in the recognition and classification of images of objects in space images. Next, the threshold value of the probability that the values of the informative features of each studied object belong to the values of the informative features of each reference object present in the satellite image is obtained. The final product of this process is to determine the class of studied objects by the maximum value of the probability of their relationship to a specific object-standard, the appropriate class, and create a map that characterizes the state of the lake for the study period (Fig. 7). In Fig. 7, we see that depending on the month of research and the increase in temperature of the reservoir, the ecological condition of the lake changes in direct proportion. That is, the warmer month, the lower the quality of the aquatic environment. Also, it is seen from the obtained results that the farther from the shoreline and with the increasing depth of the lake, the more the water quality improves. Therefore, from the obtained results, we can conclude that the proposed methodology works adequately and can be further used to assess the ecological status of the aquatic environment of other objects.

CONCLUSIONS

With the growing awareness of water pollution control and the desire to maintain lakes at high levels of quality, it is expected that the approach described in this work will be a useful tool in assessing water quality. The advantages of remote sensing to assess water quality in lakes are next: the ability to collect data from hard-to-reach areas; measurable indicators which help to obtain quantitative and qualitative data that complement expensive and slow data collection on the ground; the ability to obtain archived data for the period of operation of satellites. The application of the statistical criterion method allowed the cartographic representation of the change in the quality of the aquatic environment based on the union of indexed images of the *NDPI* lake index, *NDTI* turbidity index, *NDAI* algae index, temperature maps according to reference areas of the reservoir.

The algorithm of the methodology presented here will provide objective, reliable, and operative information to urban ecological services and decision-makers. In addition, it could be easily integrated into informational systems for smart city support as well. Further research will involve refinement of indices, integration of terrestrial and remote data, and detailed assessment of the impact of the surrounding areas on water bodies.

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ОЦІНКА ЯКОСТІ ВОДНОГО СЕРЕДОВИЩА МІСЬКИХ ВОДОЙМ З ВИКОРИСТАННЯМ МЕТОДІВ СИСТЕМНОГО АНАЛІЗУ НА ОСНОВІ КОМПЛЕКСУВАННЯ ДАНИХ ДЗЗ

Представлено методологію комплексної оцінки стану міського водного середовища на прикладі системи озер Опечень та водойм-кар'єрів озер Вербне і Редькіне у м. Києві з використанням методів системного аналізу. Методологія включає структурно-текстурний аналіз космічних знімків та наступну їхню інтерпретацію на основі методу статистичного критерію. Спектрально-текстурний аналіз космічних знімків застосовано для отримання вхідної інформації дистанційної оцінки водойм, такої як зображень індексу озерності, каламутності та альгоіндексу, отриманих з супутника «Сентінель-2», та даних розподілу температури поверхні з супутника «Ландсат-8». Для детальної оцінки якості водного середовища на основі отриманих індексованих зображень та відповідного картографічного представлення якості водного середовища застосовано метод на основі статистичного критерію. Для представлення статистичного критерію розпізнавання класів об'єктів за результатами вимірювання їхніх інформативних ознак застосовуються імовірнісні і статистичні підходи, які використовуються для розв'язування завдань оптимізації у статистичних теоріях ідентифікації і розпізнавання. Цей метод дозволив картографічно представити зміну якості водного середовища відповідно до еталонних ділянок стану водойми у 2017 р.

Ключові слова: якість води, оцінка якості водного середовища, методи системного аналізу, ДЗЗ, спектральні індекси, *NDTI*, *NDAI*, *NDPI*, температурна карта.