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INVESTIGATION OF THE PROCESSES OF ECOLOGICAL AND ECOSYSTEM CHANGES IN WATER BODIES USING UAV DATA

ҰҰА МӘЛІМЕТТЕРІН ПАЙДАЛАНУМЕН СУ НЫСАНДАРЫНЫҢ ЭКОЛОГИЯЛЫҚ ЖӘНЕ ЭКОЖҮЙЕЛІК ӨЗГЕРІС ПРОЦЕСТЕРІН ЗЕРТТЕУ

ИССЛЕДОВАНИЕ ПРОЦЕССОВ ЭКОЛОГИЧЕСКИХ И ЭКОСИСТЕМНЫХ ИЗМЕНЕНИЙ ВОДНЫХ ОБЪЕКТОВ С ИСПОЛЬЗОВАНИЕМ ДАННЫХ БПЛА

Abstract. *In recent years, the water landscapes of inland rivers have been subjected to significant anthropogenic impacts exceeding the limits of their self-healing ability. Traditional methods of monitoring geoecological parameters - sampling of water in the field with subsequent laboratory analysis - require significant financial and time costs. Traditional methods allow assessing the ecological state of the entire watercourse not spatially, but pointwise. In this research, sensors on board the UAV measured solar radiation reflected from the surface of the water and used image data from different camera ranges. The combination of images used was based on a common methodology for identifying key features, and a geographic information system (GIS) modelling approach was used for spatially analyze the distribution and interaction of environmental features. In addition, research the ecological condition of the Yertis River and the quality of water discharged after the municipal wastewater treatment facilities of Ust-Kamenogorsk city into the Yertis River, the data from the DJI Phantom 4 RTK/multispectral drone was processed and the normalized vegetation index NDVI, normalised water level difference index NDWI, water chromaticness index CI, turbidity index NDTI and chlorophyll concentration index "a" were calculated. The results obtained can serve as a basis for scientific analysis of the environmental conditions of the researching area, including for learning the processes of eutrophication and other changes in the environment.*

Keywords: *eutrophication, unmanned aerial vehicle, remote sensing of the Earth, water indices, chlorophyll concentration index "a", water blurring, GIS.*

Аңдатпа. *Соңғы жылдарда, ішкі су ағындарының аквalанг кешендері өзін-өзі қалпына келтіру қабілетінің шегінен асатын үлкен антропогендік әсерге ие. Дәстүрлі бақылау әдістерін қолдана отырып, геожүйелердің параметрлерін бақылау, яғни зертханалық талдаудан кейін жергілікті жерде су сынамаларын алу – оларды жүргізу үшін айтарлықтай қаржылық және уақыт ресурстарды қажет етеді. Дәстүрлі әдістер жалпы ағынды су экологиялық жағдайының кеңістіктік көрінісін емес, нүктелік бағалауды береді. Жұмыста ҰҰА орналасқан сенсорлар көмегімен су бетінен шағылысқан күн радиациясын өлшеу арқылы алынған әртүрлі диапазондағы камералардан түсірілген кескіндердің деректері пайдаланылды. Қолданылатын сурет комбинациясы негізгі сипаттамаларды анықтаудың жалпы қабылданған әдістемесіне, сондай-ақ* *қоршаған орта қасиеттерінің таралуы мен өзара әрекеттесуін кеңістіктік талдау үшін геоақпараттық жүйелерде (ГАЖ) модельдеу әдісін қолдануға негізделген. Сонымен қатар, мақалада DJI Phantom 4 RTK/Multispectral ҰҰА мәліметтерін өңдеумен, Ертіс өзенінің экологиялық жағдайы және Өскемен қаласының тазалау ғимаратынан кейін Ертіс өзеніне төгілетін судың сапасын зерттеу үшін NDVI нормаланған вегетациялық индексі, NDWI нормаланған су айырмашылығының индексі, CI су түсі индексі және NDTI бұлыңғырлық индексі, хлорофилл «а» концентрациясының индексі анықталды. Алынған нәтижелер зерттелетін аймақтың экологиялық жағдайларын ғылыми талдауға, соның ішінде эвтрофикация процестерін және қоршаған ортадағы басқа өзгерістерді зерттеуге негіз бола алады.*

Түйін сөздер: *эвтрофиялау, ұшқышсыз ұшу аппараты, Жерді қашықтықтан зондтау, су индекстері, хлорофилл «а» концентрациясының индексі, судың бұлыңғырлығы, ГАЖ.*

Аннотация. *В последние годы водные ландшафты внутренних рек подвергаются значительному антропогенному воздействию, превышающему пределы их способности к самовосстановлению. Традиционные методы мониторинга геоэкологических параметров – отбор проб воды в полевых условиях с последующим лабораторным анализом – требуют значительных финансовых и временных затрат. Традиционные методы позволяют оценить экологическое состояние всего водотока не пространственно, а точечно. В данном исследовании датчики на борту БПЛА измеряли солнечную радиацию, отраженную от поверхности воды, и использовали данные изображений с разных диапазонов камер. Комбинация используемых изображений основывалась на общей методике выявления ключевых характеристик, а для пространственного анализа распределения и взаимодействия экологических характеристик применялся подход, основанный на моделировании с помощью географической информационной системы (ГИС). Кроме того, для исследования экологического состояния р. Ертис и качества воды, сбрасываемой после городских очистных сооружений г. Усть-Каменогорска в р. Ертис, была проведена обработка данных с дрона DJI Phantom 4 RTK/multispectral и рассчитаны нормализованный индекс растительности NDVI, нормализованный индекс разности уровней воды NDWI, индекс цветности воды CI, индекс мутности NDTI и индекс концентрации хлорофилла «а». Полученные результаты служат основой для научного анализа экологической ситуации в районе исследования, в том числе для изучения процессов эвтрофикации и других изменений окружающей среды.*

Ключевые слова: *эвтрофирование, беспилотный летательный аппарат, дистанционное зондирование Земли, индексы воды, индекс концентрации хлорофилла «а», мутность воды, ГИС.*

Introduction. One of the main causes of today's environmental problems is the increasing pollution of the natural environment. Pollution of the natural environment should be understood as 'changes in the properties of the environment (chemical, mechanical, physical, biological and related information) as a result of natural or anthropogenic processes associated with any biological or technological object, leading to a deterioration of environmental functioning' [1]. Humans change the quality of the environment by using various elements in their activities. Such changes often take the form of unwanted pollution. Water resources [2], with their dynamic diffusion and dispersion characteristics, are carriers of pollutants and further increase the pollution level of water bodies. Pollution sources are considered to be the spillage and ingress of toxic substances into waterways that degrade the quality of surface water in a water body and limit its use, as well as negatively affect the condition of rivers and coastal waters [3].

One source of pollution of water bodies is domestic and industrial wastewater that flows into reservoirs and has a significant impact on the reservoir ecosystem. Even small wastewater inflows into reservoirs can cause negative impacts leading to significant environmental changes [4]. The physical properties and chemical composition of water bodies and the organisms living in them are changing. The influx of organic and biogenic substances gradually changes the chemical composition of water, the species composition of aquatic organisms and restructures the structure and functioning of the entire ecosystem. In the initial stages of pollution, ecosystem changes are small and can be gradually restored. However, after prolonged exposure, the ecosystem is degraded and completely destroyed [5].

The purpose of this work is to determine the qualitative indicators and the level of pollution of water bodies, conduct an analysis of environmental novelty, and monitor by selecting information spectral indices from UAV survey data.

Materials and methods of research. An important consequence of domestic pollution is that, in addition to large amounts of organic matter, urban wastewater contains many biogenic elements. This leads to anthropogenic eutrophication of reservoirs and waterways [6]. Many authors distinguish between eutrophication (the natural aging process of aquatic ecosystems) and anthropogenic or experimental eutrophication. Nitrogen and phosphorus compounds, the main causes of eutrophication, are mainly present in the form of nitrate and phosphate. In the process of eutrophication, aquatic ecosystems go through several stages [7]. First, nitrogen and phosphorus mineral salts accumulate in water. This period is usually short, the added limiting elements are immediately incorporated into the circulation and intense algal blooms begin in surface waters. Phytoplankton biomass, water turbidity and oxygen levels in the upper layers increase. The algae then die and aerobic decomposition of detritus and the formation of chemoclines begins. Chemoclines are characterized by the formation of hydrogen sulfide, organosulfur compounds and ammonia. The organic cycle is closely linked to the cycles of various biogenic elements, especially carbon and nitrogen and sulfur, iron, phosphorus and manganese, and consists of two processes: synthesis or production and mineralization or decomposition of this material and the conversion of simple mineral compounds into biogenic elements. Bacteria are actively involved in these processes. Decomposing organic matter passes through the reservoir and falls to the bottom, where it is significantly mineralized and formed throughout the reservoir [8].

Although various anthropogenic substances have a significant impact on the complex ecology of water composition, each reservoir is an ecosystem that tries to clean itself under natural conditions. Reservoir self-cleaning is a set of interrelated hydrodynamic, physico-chemical, microbiological and aquatic biological processes leading to the restoration of the initial state of the reservoir [5].

Small water bodies in urbanized areas are particularly vulnerable to the impacts and accumulation of pollutants. Water bodies located in or passing through urban areas require special attention. This is because water bodies have a significant impact on environmental quality and can be both recreational areas and ecological disaster zones [9]. Under these conditions, it is not possible to accurately assess changes in aquatic ecosystems, accurately determine the extent of destruction, identify the mechanisms of destruction and predict further changes. Currently, environmental monitoring systems for surface water quality in the US and EU countries are undergoing a major shift from chemical methods to biological indicators to manage the status of water bodies, biological methods based on bioassays and biomonitoring, and predictive methods using satellite imagery to assess the water quality of mass runoff [10]. The use of satellite imagery and UAV data for these surveys has not only enabled rapid and accurate data acquisition with less effort, but also the use of chemical and biological indicators of pollution symptoms to identify the causes of water quality degradation in aquatic environments [11].

In Kazakhstan, many rivers and lakes, with the rapid development of the economy and the intensification of human activity in the country, are becoming the main problem in industrial cities for water pollution and quality [12, 13], therefore, conducting research on pollution of water bodies to preserve clean water necessary for normal production and daily life of people, and planning activities In order for the results of the study to provide accurate data, it becomes necessary to use high-tech research tools.

Modern satellite images and the use of aerial photography of UAVs allow remote monitoring of water bodies at a high-quality and high level of reliability, complementing and partially replacing direct field remote sensing studies [14]. The use of remote sensing data allows real and operational monitoring of the condition of large reservoirs and the spread of phytoplankton throughout the reservoir [15]. Since the late 1990s, work on the "algae" of water and the use of remote sensing data for topographic and morphometric assessment of water bodies has been applied abroad. Most often, studies are conducted for marine areas and large bodies of water [14-16]. During these works, it was necessary to confirm the correctness of the interpretation of remote sensing data, the results of ground-based observations and studies (hydrochemical, algological, etc.).

Traditional monitoring of water quality in rivers and lakes consists mainly of field sampling and laboratory analysis. This method has been used for many years, with observations at specific sampling points followed by laboratory analysis. Although it has a certain degree of accuracy, it cannot reflect the overall spatial and temporal status of water quality, it requires too much time and the observation coverage is localized. It also requires too much time and the observation coverage is localized, so it cannot meet the requirements of operational and large-scale monitoring and real-time assessment [17].

Modern technologies, including those based on the use of unmanned aerial vehicles (UAVs), make it possible to expand the prospects for their use [18].

Drones equipped with spectrometers can now be used to manage indicators that allow reference analysis of suspended sediment concentration, turbidity, transparency, total phosphorus concentration, total nitrogen concentration, water depth, chemical oxygen demand and known ecological water conditions in rivers and lakes [19]. Shooting images are created on public platforms by various software packages [20].

The site of the field test flights is the watershed on which the municipal sewage treatment filter of the Yertis river tributary from Ust-Kamenogorsk is located. The geographical location of the research area on the Google Hybrid map is shown in figure 1.

Emissions of pollutants from stationary sources in Kazakhstan regions over the past few years by the level of pollution of the studied territory https://stat.gov.kz according to the data (table 1). As a result of the comparison, it was noted that emissions in the areas where the Yertis river flows are slightly higher and maintain a stable level of growth compared to other regional cities (fig. 2).

The results of the statistical comparison show that over the past three years, emissions of pollutants from stationary sources into the atmosphere have been consistently maintained at an average level in three regions crossing the Yertis river.

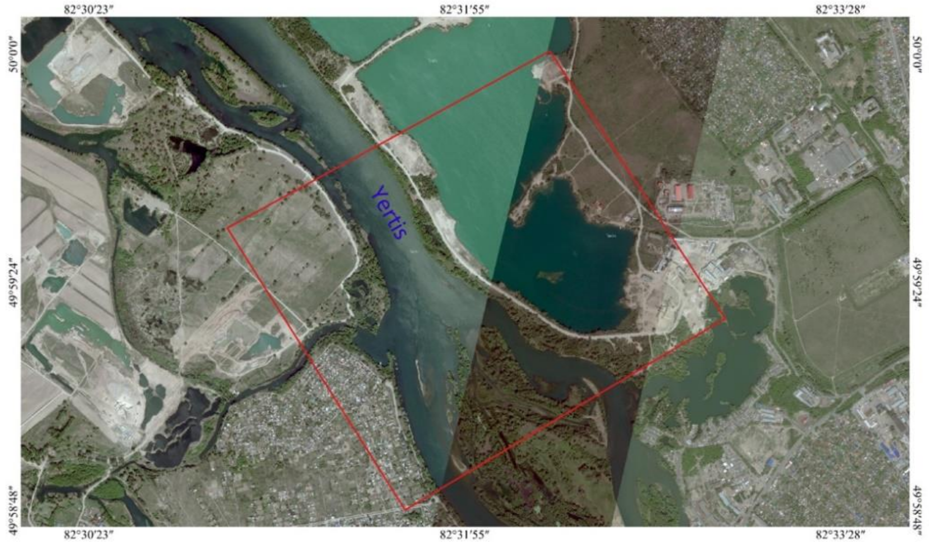


Figure 1. Geographical location of the research area on the Google Hybrid map

Table 1. Emissions of pollutants to the atmosphere from stationary sources

Name of the regions	Emissions of pollutants, thousand tons		
	2019	2020	2021
The Republic of Kazakhstan	2 483,1	2 441,0	2 407,5
Akmola region	76,7	77,2	77,3
Aktobe region	136,6	135,1	137,4
Almaty region	48,1	46,3	47,9
Atyrau region	164,5	153,9	160,3
West Kazakhstan region	41,2	30,8	26,0
Zhambyl region	55,8	55,0	55,8
Karaganda region	641,3	627,7	569,7
Kostanay region	130,5	123,4	137,9
Kyzylorda region	24,4	28,3	29,2
Mangystau region	64,5	72,5	75,2
South Kazakhstan region	-	-	-
Pavlodar region	721,5	723,0	736,1
North Kazakhstan region	74,7	76,0	61,2
Turkestan region	33,5	28,1	29,0
East Kazakhstan region	128,8	127,2	128,1
Astana city	65,1	62,4	62,2
Almaty city	46,1	44,5	40,8
Shymkent city	29,8	29,6	33,2

Figure 2. Indicator of 3-year statistics on the areas of emissions of pollutants into the atmosphere from stationary sources

The most common methods for assessing the ecosystem state of rivers include mainly predictive modelling methods and multidimensional assessment methods [20], multidimensional assessment methods [16], as well as assessment of the state of rivers, as a rule, as a basis for assessment by calculating indices, determining appropriate environmental parameters and biological indicators.

An unmanned aerial vehicle (drone) was used in this study DJI Phantom 4 RTK/Multispectral [19]. The system is capable of storing aerial survey data for subsequent kinematics processing [20]. The device is able to carry out complex data collection and capture without additional parameters, being in the built-in image stabilization system. The capture camera consists of six 1/2. 9-inch CMOS matrices, including 1 RGB visible radiation matrix and 5 monochrome (blue, B) 450 nm ± 16 nm, (green, G) 560 nm ± 16 nm, (red, R) 650 nm ± 16 nm, (red edge, RE) 730 nm ± 16 nm, (near-infrared, NIR) 840 nm ± 26 nm. The number of effective pixels of each matrix is 2.08 million (the total number of pixels is 2.12 million). The reflection of the course of preparation of the unmanned aerial vehicle for operation is shown in figure 3. The flight altitude is 50 m. As a result of the shooting, 546 images were obtained with a resolution of 1600 x 1300 (4:3.25).

Figure 3. The working platform of the Phantom 4 RTK/Multispectral drone

With this approach, the calculation process and results are objective. The results of the assessment can directly reflect the ecological state of the river, and when evaluating one index, the calculation of many indices is taken into account in order to avoid bias [11].

The normalized water difference index (NDWI) and the color index were calculated, which are widely used in aerospace surveys using multispectral images to identify water bodies [14] and the indices of water turbidity and chlorophyll concentration "a" were determined, which are important for determining the degree of eutrophication of water bodies. NDVI was calculated using the following well-known formula:

$$NDVI=(NIR-Red)/(NIR+Red), \tag{1}$$

where NIR is a camera of the near-infrared reflection spectrum with a range of 840 nm ± 26 nm, in images obtained using the Phantom 4 RTK/Multispectral camera, this information, highlighting the shoreline of the reservoir and showing the level of development of plant biomass, a red camera with a range of visible reflection of solar radiation with a value of 650 nm ± 16 nm, shows the condition and quality of the plants, is used for evaluation.

The NDVI index is commonly used in agriculture to determine the condition of terrestrial plants. Usually, the water index for this index ranges from -1 to 0. However, the zero value of the index can only be accepted conditionally, because index values can be less than zero in wet areas. But the main disadvantage of this index is that the reflection coefficient of the red channel is too sensitive to atmospheric changes. To solve this problem, the NDWI (Normalized Difference Water Index) is used. It is calculated using a combination of NDWI (visible green and near-infrared green NIR), which allows detecting small changes in water in reservoirs [15]:

$$NDWI = (Green – NIR)/(Green + NIR), \tag{2}$$

where Green is a green camera of the visible radiation spectrum with a spectral range of 560 nm ± 16 nm, which makes it possible to identify plants. When analyzing the index, the presence of vegetation is significantly lower than the indicators of reservoirs (0.5 and higher), which makes it easy to distinguish plants from reservoirs. The values of construction objects can range from 0 to 0.2 [16].

The NDWI Index values correspond to the following ranges: 1) 0.2-1 - water surface; 2) 0.0-0.2 - flooding, humidity; 3) -0,3-0,0 - average drought, waterless surfaces; 4) -1 – (-0.3) - drought, waterless surfaces.

To obtain the most informative color for determining the shoreline of a reservoir and diagnosing the eutrophication process, the color index is determined by the following formula [11]:

$$CI = Green/Blue, \quad (3)$$

where Blue is the blue range of the visible electromagnetic radiation spectrum of 450 nm±16 nm. This is very important for studying the condition of reservoirs, especially such indicators as turbidity, concentration of chlorophyll "a" in water, density and spatial distribution of planktonic algae [16]. Turbidity of water is an indicator characterizing a decrease in water transparency due to the presence of inorganic and organic suspensions. The turbidity index was calculated using the following ratios [11]:

$$NDTI = Blue/(Blue+Green+Red). \quad (4)$$

The turbidity Index NDTI (The Normalized Difference Thermal Index) or the amount of suspension in water is modeled by studying reference samples on a spectrophotometer.

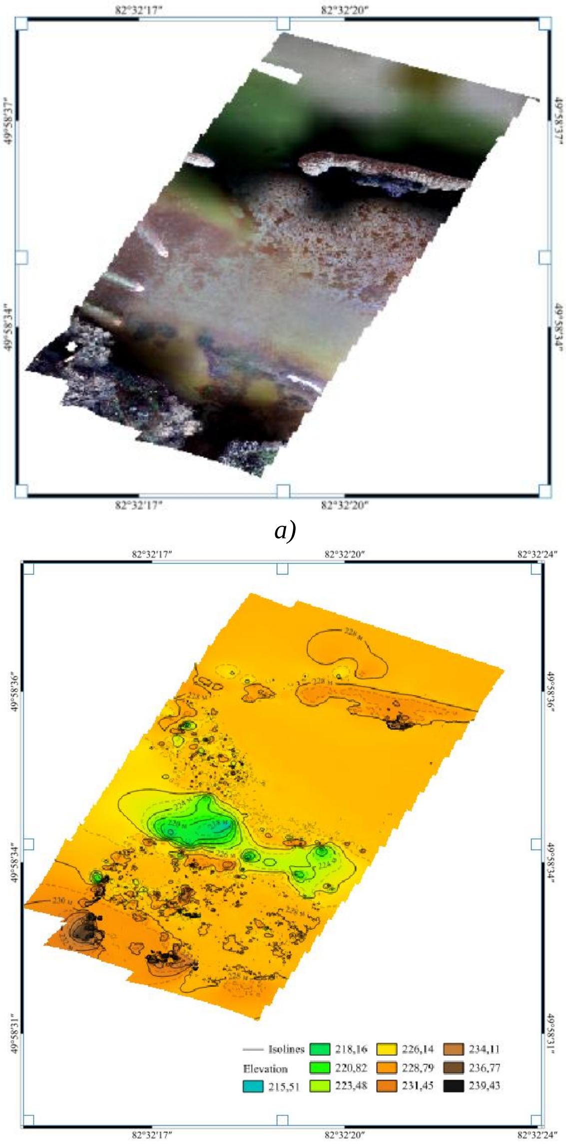
The next water quality indicator, chlorophyll "a", is the main pigment of green plants, including unicellular algae (phytoplankton). Information on the concentration of chlorophyll "a" in water and its variation in reservoirs serves as a benchmark for assessing phytoplankton biomass accumulation and products and as an indicator of water pollution [20]. The following channel combinations were used to calculate the chlorophyll concentration index "a" [16]:

$$Chl - a = (Blue-Red)/Green. \quad (5)$$

The range of the reflection spectrum of chlorophyll "a" is determined experimentally by examining water samples of algae on a spectrophotometer. Later, along with images of the Landsat and Sentinel satellites with a similar electromagnetic radiation spectrum, it is recommended to use hyperspectral, multispectral camera images of UAVs [19].

The minimum and maximum values of the index in water bodies are taken outside the scale. The Agisoft Metashape Professional program was used to create index maps [20].

Results and discussion. An orthophotoplane, a digital model of the Earth and a horizontal elevation map created using Agisoft Metashape Professional software [20] high-precision multispectral GNSS image using a DJI Phantom 4 multispectral drone with the D-RTK 2 mobile station of the Yertis river were obtained from the camera data for visual assessment (figure 4).



a)

b)

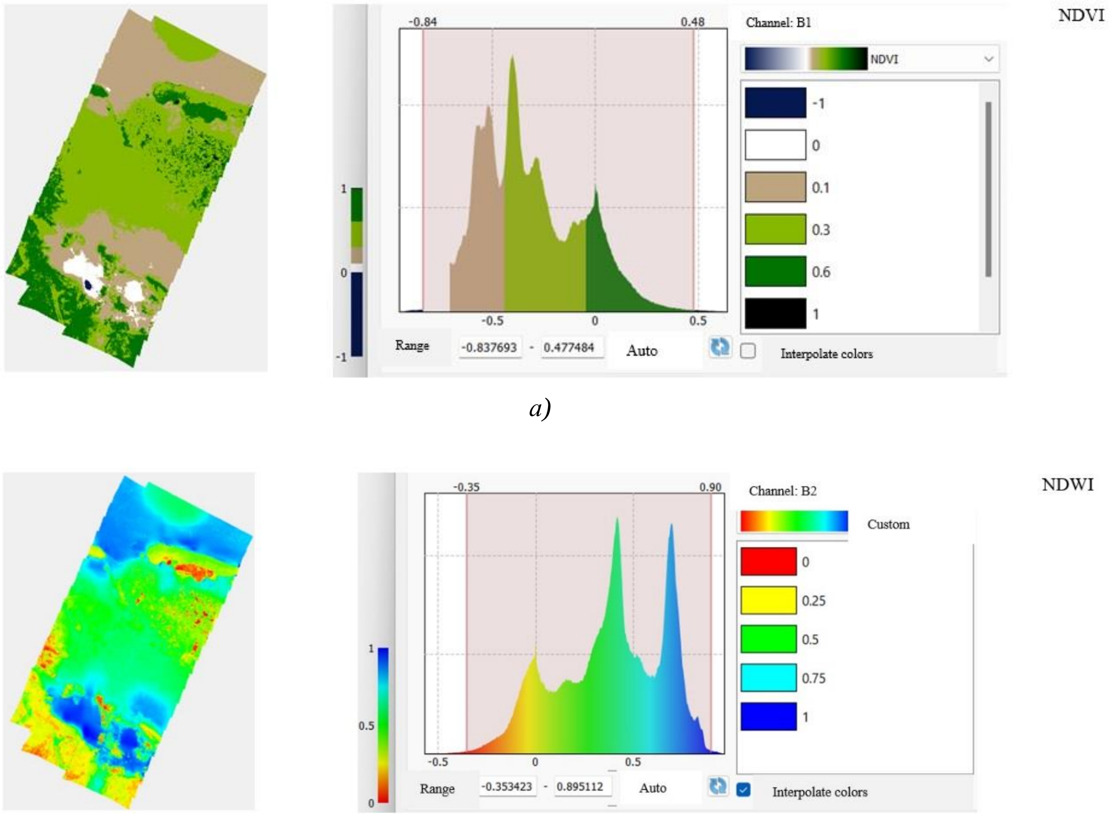
Figure 4. Visual assessment maps of the Yertis river from the UAV multispectral camera:
a) RGB orthophotoplane (Google Hybrid), b) elevation map

As a result of processing the aerial survey data, an assessment of ecosystems and water quality was carried out according to the values of the NDVI, NDWI, CI, NDTI and Chl – "a" indices in the Yertis river valley from Ust-Kamenogorsk, at the junction after the urban sewage filter. The NDVI index in the study area made it possible to determine the water boundary (fig. 5, a). Analysis of the constructed index maps showed that NDWI (fig. 5, b) in the study area allows you to most reliably determine the boundaries of the reservoir compared with the CI index (fig. 5, c) the color of the water. The CI values of the water color index showed the presence of eutrophication in the section of the captured river [11, 16].

To estimate the turbidity index from multispectral data using NDTI (fig. 5, d), color methods constructed with a combination of channels were used. There are examples of the use of combinations of different spectral regions in satellite and UAV imagery that show a high statistical correlation with water turbidity. Suspension promotes light scattering in water in all visible regions, but especially in the green and red regions. It is therefore recommended to use spectral modeling in these regions. The most consistent results are obtained when using models that combine several spectral regions. The choice of model and the intensity of the statistical relationship between UAV data and natural variations depends on the composition of impurities in the water.

In remote sensing of inland reservoirs, chlorophyll has a great influence on their spectral characteristics, and its spectral data are an important indicator showing the degree of eutrophication of reservoirs. As the concentration of chlorophyll "a" increases (fig. 5, e), the spectral reflectance of blue light decreases and that of red and green light increases, and when the concentration of chlorophyll "a" reaches a certain value, the sensitivity band of chlorophyll "a" moves in the long-wave direction. Therefore, remote sensing of chlorophyll "a" usually involves empirical and semi-empirical models of the optimum bandwidth and the establishment of different channel combinations according to the sensitivity band of chlorophyll "a" [16].

In the studied part of the Yertis river, as shown in figure 5 Chl-"a", multispectral images obtained from UAVs were used to invert the distribution of chlorophyll "a" concentration in river water.



Channel: B1

Range -0.837693 - 0.477484

☐ Interpolate colors

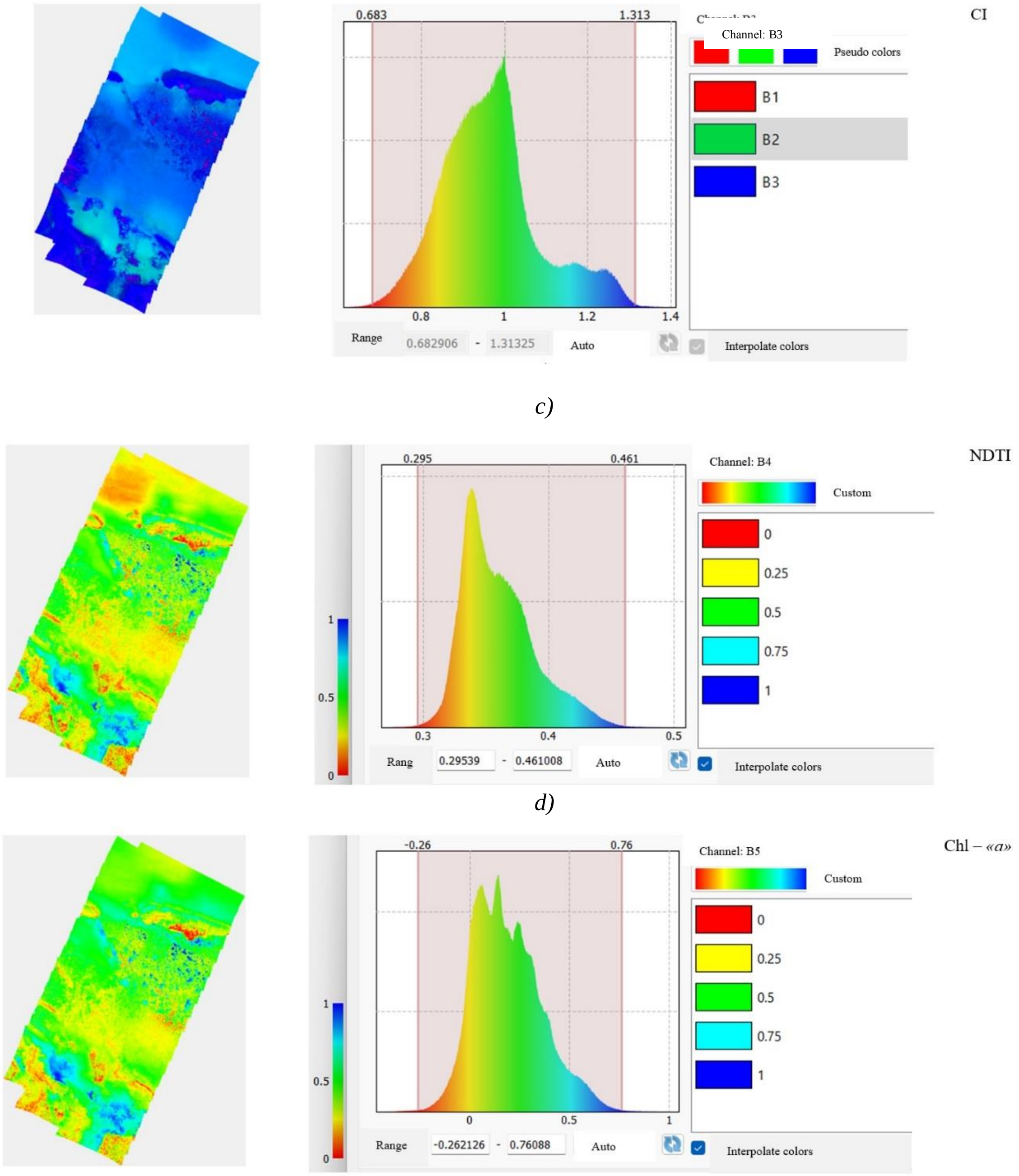
a)

Channel: B2

Range -0.353423 - 0.895112

☑ Interpolate colors

b)



Range 0.682906 - 1.31325

c)

Rang 0.29539 - 0.461008

d)

Range -0.262126 - 0.76088

e)

Figure 5. Spectral indices for assessing the intracity ecosystem of the Yertis river:
a) NDVI, b) NDWI, c) CI, d) NDTI, e) Chl – "a"

In this article, indexes have been identified as the object of research, which can provide basic indicators of damage control of the river ecosystems, with the processing of a multispectral image of the Yertis river exit from the city territory, the data are processed in special programs. The revealed NDVI index (-0.8)-0.48 in the shallow waters of the riverbed, icing and solid waste formation are observed, the NDWI index varies between -0.35-0.89 and reflects the entire development of underwater eutrophication from a decrease in turbulence of the riverbed, according to the water color index CI, the heterogeneity of natural sewage water precipitation, i.e. the water is slightly higher in the middle flowing part of the riverbed, and in peripheral and island environments it turned out to be blurred, the water turbidity index, calculated to increase the accuracy of this criterion, is at the NDTI level of 0.3-0.46, high turbidity values are found in eutrophic coastal hills and on islands with blocked waterways. Possible causes of high turbidity in water include fine inorganic suspended solids and compounds, organic impurities and organisms, and the influence of residual urban water., impurities added to the water after filtration, as shown on the digital map of the Earth. The analysis of Chl–"a" showed that at the level of (-0.26)-0.76 there is an intense change in the flow. The index maps for the Yartis section of the study area show that the largest changes in index values are found in areas with high levels of aquatic vegetation in the water body (island slopes) and in shallow areas with slow water exchange (near shore). Therefore, the turbidity index can be used as one of the indicators for identifying areas of phytoplankton and high plant abundance.

Conclusions. Currently, many spectral indices are used to analyze the state of reservoirs. However, due to the different physicochemical conditions in water bodies and differences in the degree of their eutrophy, it is necessary to empirically select the most reliable information indices for each specific water body, adjust the formulas used to calculate them, and select a measuring scale.

In this article, an inversion study was conducted to assess water pollution with the processing of images taken by the DJI Phantom 4 RTK/Multispectral drone, tracking the ecosystem of the Yertis river, determining some indices NDVI, NDWI, CI, NDTI and chlorophyll "a" (eutrophication). In accordance with the study of the relief and the inversion effect of the multispectral image, the UAV suggests that the use of a multispectral camera may to some extent reflect eutrophication and the degree of pollution of the river, while in accordance with eutrophication and the spread of river pollution, the image shows ways to determine the source of pollution of the river and sources of pollution, the causes of eutrophication of the watercourse.

It was found that the use of multispectral technology with UAVs makes it possible to control eutrophication and water pollution in rivers, lakes and inland waters. In addition, the UAV multispectral imaging data has some disadvantages, such as obstacles associated with the heterogeneity of the landscape, atmospheric noise, the position of the sun, etc., which affect the practical application of multispectral imaging technology. Therefore, when studying eutrophication and water pollution in rivers, lakes and internal water sources, not only for qualitative but also for quantitative studies, the question of how to use UAVs with a multispectral camera and satellite imagery data is relevant. For this reason, calculations of the work performed are not considered a typical approach for all water sources. The results of the study can provide current and forecast data on rivers of the type of the studied object, as well as on environmental protection.

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