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MONITORING OF WATER BODIES AND RECLAIMED LANDS AFFECTED BY WARFARE USING SATELLITE DATA

O.V. Vlasova[1], Doctor of Agricultural Sciences, A.M. Shevchenko[2], Ph.D. in Agricultural Sciences, I.A. Shevchenko[3], Ph.D. in Technical Sciences, O.M. Kozytsky[4]

[1] Institute of Water Problems and Land Reclamation of National Academy of Agrarian Sciences of Ukraine, Kyiv, Ukraine; https://orcid.org/0000-0002-1911-4329; e-mail: elena_vl2001@ukr.net;
[2] Institute of Water Problems and Land Reclamation of National Academy of Agrarian Sciences of Ukraine, Kyiv, Ukraine; https://orcid.org/0000-0002-2637-6538; e-mail: monitoring_protect@ukr.net;
[3] Institute of Water Problems and Land Reclamation of National Academy of Agrarian Sciences of Ukraine, Kyiv, Ukraine; https://orcid.org/0000-0002-7401-8786; e-mail: irashef@ukr.net;
[4] Institute of Water Problems and Land Reclamation of National Academy of Agrarian Sciences of Ukraine, Kyiv, Ukraine; https://orcid.org/0000-0002-4459-6331; e-mail: olegkoz@ukr.net

Abstract. *The paper presents the results of monitoring the state of water bodies and reclaimed lands affected by warfare using remote sensing methods and in-situ surveys. On the example of the flooding of the floodplain of the Irpin river by the waters of the Kyiv reservoir as a result of the destruction of the culvert structure, as well as the flooding of the floodplain of the Dnipro river near village Otradokamyanka after the explosion of the Kakhovska hydro power plant (HPP), the change in the area of inundation was calculated based on spectral index maps and surface classification using Sentinel-2 L2A imagery. On the base of Sentinel-2 L2A images, maps of SAVI and NDWI indices were obtained. They revealed the places of soil cover by sediments and the increase of the area of water bodies. Monitoring of reclaimed lands affected by warfare was carried out in the floodplain of the Irpin river on the Irpin Drainage and Moistening System during three time intervals: before the war in 2019; during the fighting in the spring of 2022 and a year after the end of military actions. Studies have shown a significant prevalence of waterlogged areas in the present time, which confirms the destruction of drainage network.*

The calculated values of the NDVI index turned out to be too high for agricultural crops, which indicates that the lands is overgrown with shrubs. Based on the results of the conducted monitoring, the territory was classified according to the degree of its damage by shell craters. Based on the results of the studies, it is recommended to monitor water bodies and reclaimed lands that have been affected by the war using images of different spatial resolution, a complex of spectral indices, a combination of image bands and in-situ surveys.

Key words: *water bodies, reclaimed lands, military actions, satellite images, spectral indices, level of damages*

Relevance of research. Since the beginning of the war with the Russian Federation, Ukraine has faced significant negative consequences of hostilities, which led not only to direct destructions and economic losses, but also affected the environment, in particular, water bodies and land resources. The problems related to the use and ecological condition of reclaimed lands due to their fouling, pollution, damage or destruction of hydraulic facilities, objects of engineering infrastructure of irrigation and drainage systems, etc., have been significantly aggravated. The destruction of the Kakhovska hydro power plant (HPP) dam and, as the result, emptying of the Kakhovska reservoir caused extra damages and losses to both the population and the economy of the country, as well as the environment. Assessing the effects of military actions and large-scale destruction of hydraulic facilities on the environment using in-situ methods is quite difficult. For its practical solution, the development and elaboration of scientific approaches with the use of remote sensing technologies and the application of independent spatially distributed satellite information is relevant. This especially applies to the levels of river floodplains flooding after the detonation of hydraulic facilities and damages to drainage and irrigation systems on reclaimed lands.

Analysis of recent studies and publications. The most common and unpredictable natural phenomena are floods and man-made disasters that cause great economic losses, harm communities, and affect human lives. Therefore, quick and accurate determination of areas flooded by surface waters is of a great necessity for monitoring the changes that occur within river basins, especially as a result of military actions [1–6]. In this context, multispectral (multiband) satellite images of the Landsat 8 and Sentinel-2 L2A systems can be an accessible and irreplaceable source of information [7–10]. In global practice, based on the difference between spectral reflectance of water, soil, and vegetation covers, spectral indices for water, soil, and vegetation are calculated as the indicators of the natural state of mentioned surfaces [6, 12]. Spectral indices are used to classify a certain type of land cover [13, 14]. The Normalized Difference Water Index (NDWI) is used to identify water bodies on a background of soil and vegetation covers [15, 16], the Normalized Difference Vegetation Index (NDVI) is used for vegetation cover, etc. Recently, the use of various combinations of satellite images' bands has become widespread. For example, we can single out Red8, SWIR1, Red (abbreviated as RSR). This combination of the near, mid-IR bands, and the visible red band makes it possible to clearly distinguish the boundary between water and land, as well as to emphasize hidden poorly visible details when using only a range of visible bands [17–19].

In the literature, the issue of flooded areas identification with the help of multispectral satellite data and spectral indices obtained on their basis is sufficiently covered [20–23]. A lot of attention is paid to the use of SAR images and the determination of catchment area structure, the study of climate changes, soil and climate potential, and the ecological state of river basins [24]. However, practice shows that incorrect or unsuccessful use of calculated spectral indices leads to erroneous results and conclusions. Only the integrated application of indicators such as spectral indices in their certain combination and comparison makes it possible to perform operational monitoring of water bodies and reclaimed lands. In addition, the analysis of the detected changes makes it possible to determine the reasons for the deterioration or improvement of the situation on a certain territory and to plan further actions for its preservation or restoration.

The aim of the research is to determine the optimal set of indicators – spectral indices and combinations of satellite images' bands for monitoring water bodies and reclaimed lands affected by military actions.

Research methods and materials. The essence of technologies for obtaining satellite spatially distributed data is defined by the observation and measurements of energy and polarization characteristics of own and reflected radiation of water, soil-vegetation surfaces, and the atmosphere in various ranges of the spectrum of electromagnetic emission. During the research with the use of satellite data such methods as geospatial analysis, mathematical modeling, systems of experts evaluations, and field surveys were used.

In the course of research, system analysis was applied. The research methodology included the following components:

– search, analysis of available free information and application of required types of satellite data (multispectral, panchromatic with high spatial resolution);

– calculations of spectral indices for vegetation, soil, and water, comparison of bands combinations;

– analysis of the obtained results and changes that occurred with water bodies and reclaimed lands under the influence of military actions.

During the monitoring based on satellite data and field surveys, observations of water bodies, the condition of agricultural lands located on reclaimed territories, their soil and vegetation cover were performed. The research materials were satellite images and in-situ verification information.

Research results and discussion. In the conducted studies, the main attention was paid to the fixation of negative processes and their consequences in the floodplain of the Irpin river, in particular, in the area of the Irpin drainage and moistening system (DMS) within the Bilohorodka territorial community of the Buchanskyi district, Kyiv region, Ukraine, as well as on the territory along the Dnipro and Kozak rivers within Kherson region.

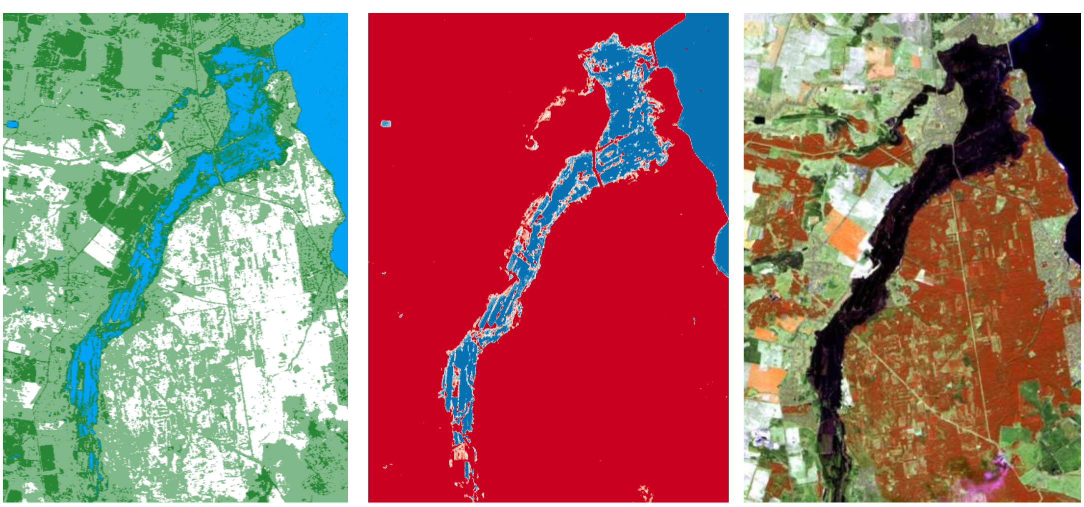
The floodplain of the Irpin river is wide (about 1–2 km), cuted by a dense network of reclamation canals. According to the nature of hydrological regime, the Irpin river and its tributaries belong to the type of rivers mainly fed by snow. Fluctuations in water levels are characterized by a distinct spring flood, low summer-autumn and winter baseflow. Annual short-term rain floods are observed during summer and autumn periods. The peculiarities of river's hydrological regime are caused mainly by the significant regulation of surface runoff, intensive reclamation of the floodplain and the river valley in general, as well as the construction of a polder protective dam at the mouth of the river [25].

During the military actions in the Kyiv region, as a result of the destruction at the end of February 2022 of the culvert structure of the Kozarovytsky protective dam, the floodplain of the Irpin river was flooded by the waters of the Kyiv reservoir in the area of Kozarovychi and Demydiv villages. Later, the flooding reached the outskirts of the villages of Huta Mezhyhirska, Chervone, Moschun, Gorenka, and the settlement Gostomel. We used Sentinel-2 L2A satellite images to assess the impact of the destruction and the scale of the territory flooding. The first image was obtained on March 18, 2022. The flooded area was calculated based on the following indicators: the map of the spectral index – Normalized Difference Water Index (NDWI), which uses reflectance in near-infrared spectrum and visible green light (flooded area was determined on the territory of 17,98 km^2); the map of the Normalized Difference Snow Index (NDSI) (flooded area was determined on the territory of 17/68 km^2); and surface classification with a combination of RSR bands for the separation of land and water bodies (flooded area was determined on the territory of 23/7 km^2) (Fig. 1).

Further, Sentinel-2 L2A images acquired on 07.04.2022, 21.03.2023, 30.05.2023 and Landsat 8 image acquired on 03.06.2022 were used to determine the flooded areas based on the calculated NDWI, NDSI indices, and RSR bands combination. According to the Sentinel-2 L2A image acquired on 07.04.2022 the flooded areas were: NDWI – 17.56 km^2, NDSI – 16.17 km^2, and RSR bands combination – 16.14 km^2. According to the Landsat 8 image acquired on 03.06.2022, the flooded areas were: NDWI – 16.32 km^2, NDSI – snow index was not used during summer period, and RSR bands combination – 19.13 km^2. According to the Sentinel-2 L2A image acquired on March 21, 2023, the flooded areas were: NDWI – 12.74 km^2, NDSI – 11.40 km^2, and RSR bands combinations – 15.03 km^2. According to the Sentinel-2 L2A image acquired on 30.05.2023, the flooded areas were: NDWI – 8.50 km^2, NDSI – snow index was not applied, and RSR bands combination – 14.04 km^2. With the help of this technology, separation of surface water and dry land was carried out, flooded areas were calculated for different dates, and their decrease was recorded. In the course of the study, the Normalized Difference Water Index (NDWI) was used to identify excessively wet areas and the presence of water bodies on the earth surface. For its calculation, reflected near-infrared radiation and visible green range were used.

The Normalized Difference Snow Index (NDSI) is commonly used to establish the spectral differences of snow in the short-wave infrared and visible spectral bands of satellite images. In this case, in the spring, when the ice on the Irpin river began to melt and flooding began, the maps of this index came in handy when calculating the flooded areas taking into account additional water income. The combination of the near, mid-infrared, and visible red RSR bands is taken as the third indicator of flooded areas. This made it possible to clearly distinguish the boundaries between water and dry land, to emphasize imperceptible details when using only bands of the visible range. The usage of a combination of RSR bands was the most effective.

Another water body that was significantly affected by the military actions is the Kakhovsky reservoir. After the explosion of the dam at the Kakhovska HPP on June 6, 2023, significant volumes of water from the Kakhovsky reservoir caused flooding of coastal settlements,



a b c

Fig. 1. Delineation of the flooding zone on March 18, 2022 according to the data from Sentinel-2 L2A: a – NDWI map; b – NDSI map; c – map of the RSR bands combination

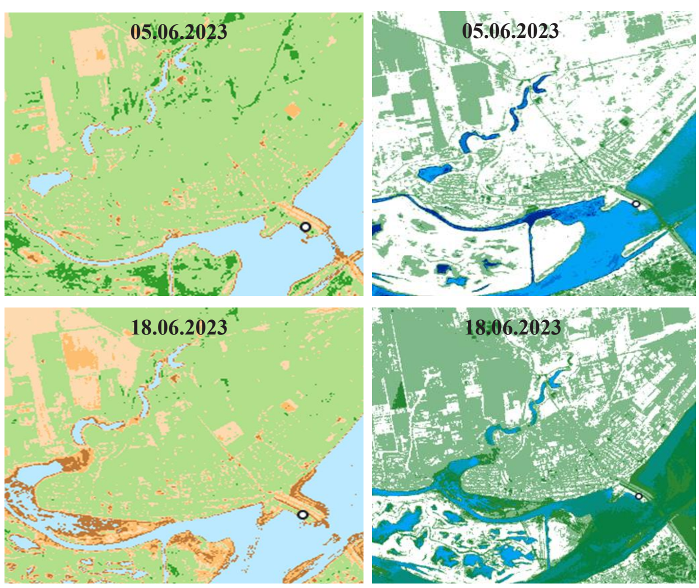
agricultural lands, and conservation areas. A fast waterwave washed up the high right bank of the Dnipro river in the first days after the flooding began, which may continue in the future.

The scale of flooding on the studied area along the Dnipro and Kozak rivers near the village Otradokamyanka (Shylova Balka – an object located on the territory of the Kakhovka district, Kherson region, 2,5 km up north from the village Vesele was established using Sentinel-2 L2A satellite images. Maps of the calculated SAVI and NDWI indices are presented (Fig. 2) in the form of a comparison of the situation before the flood (as on 05.06.2023) and after the flood (as on 18.06.2023).

As a result of the monitoring, the places of soil cover damages by sediments and the increase in the area of water bodies were found. On the maps of the soil index the territories with SAVI = 0–0.1 for different dates had the area from 2.49 km^2 to 5,5 km^2 (dark brown color), with SAVI = 0.1–0.2 – from 4.32 km^2 to 8.74 km^2 (light brown color). The greatest damages have been found on the territory of 7.43 km^2. According to the water index maps, the areas increased with the value: for NDWI = 0–0,1 total area was in the range from 0.40 km^2 to 6.16 km^2 (green color of water), for NDWI = −0,3–0 – from 2.98 km^2 to 7.95 km^2 (dark green color of water). The greatest damages have been found on the territory of 10.73 km^2. It should be noted that over time along the coast line, wind erosion can cause migration of heavy metals with the dust.

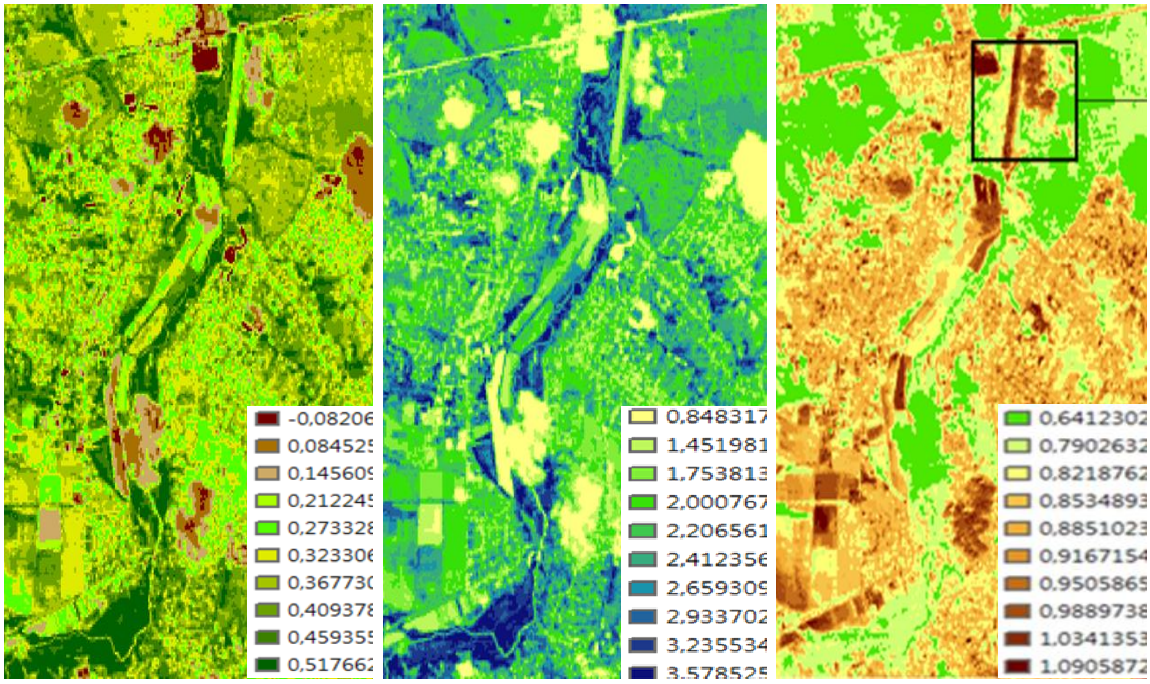
Monitoring of reclaimed lands affected by military actions was carried out in the basin of the Irpin river. The research was conducted at the Irpinska DMS within the Bilohorodka territorial community during three time intervals: before the war – the growing season of 2019 (according to Landsat 8 satellite data), in the spring of 2022, when military actions were actively taking place, and in the summer of 2023 (according to data from the Sentinel-2 L2A satellite). On the base of the image dated 2019, a working area with coordinates was distinguished and classes of the surface were established, which was confirmed by field surveys. The researched plot with a total area of 466 ha includes fields of agricultural crops (cereals, oilseeds, fodder, root crops), hayfields, pastures, gardens, locally built-up areas, and peats burn by the fires, as well as the lands that are not currently in use. All the lands are characterized by different requirements for water regime and moisture supply conditions. Based on the 2019 Landsat 8 image three spectral indices were calculated and the maps were obtained for the NDVI index, which acts as an indicator of the state of vegetation cover, the ir/r ratio, which made it possible to single out overmoistened areas, and the iron oxide index (IO), which is used to estimate soil fertility (Fig. 3).

As of 2019, the NDVI vegetation index had high values from 0.21 to 0.51, which indicates a developed vegetation and a satisfactory condition of agricultural crops. However, high values of the ir/r ratio in the range of 3.5–4.0 indicate that the existing drainage system does not cope with the removal of excess moisture along the Irpin river



a b

Fig. 2. Maps of calculated indices based on Sentinel-2 L2A images to compare the situation on different dates: a – soil index SAVI, b – water index NDWI.



a b c

Fig. 3. Maps of calculated spectral indicators based on the Landsat 8 image in 2019:
a – vegetation index NDVI; b – ir/r ratio; c – index of iron oxide IO

and does not ensure a good (quality indicator) conditions of the territory in general. The values of the IO index on the plot are 1.03–1.09, which indicates a sufficient supply of soil with nutrients. In general, the situation was satisfactory.

Over the time, namely in April 2022, shell craters were recorded on the Airbus image. A Sentinel-2 L2A image from June was used to compare the situation one year later and to find out what damage the warfare has done to the territory. According to the combination of RSR bands, wetted and dry areas were estimated, as well as a map of the vegetation index NDVI was obtained, which proves the restoration of the experimental plot (Fig. 4 d). On the RSR map the overwetted areas are predominate, which indicates the destruction of the drainage network. On the NDVI map (Fig. 4 e), the values of the vegetation cover indicator are too high for agricultural crops – from 0,8 to 0,9, which indicates that the land is overgrown with shrubs.

In order to verify the satellite data, on-situ surveys within the studied plot of the Irpin DMS were carried out (Fig. 5). The photos show large craters from the shells, which over time become overgrown with grass. Therefore, it is necessary to carry out such surveys in a timely manner, because the landscape changes with time. The photos show the destruction of the drainage network and the fragments of the tile drainage.

According to the results of the analysis of high spatial resolution images acquired on March 21, 2022 and April 15, 2022, and field surveys within the studied plot, the territory was classified according to the damage caused by explosive craters, which made it possible to build damages maps (Fig. 6). We have proposed a separate degree of the territory damages by the percentage of the area of craters within the plots: 0–10 % – slightly affected, 10–30 % – moderately affected, more than 30 % – strongly affected area.

As a result of the conducted monitoring, it was determined that on the image dated April 21, 2022, the area of severe damage is 130 hectares, which is 28 % of the total area of the research plot; the area of moderate damage is 139 hectares, which is 29 % of the plot; the area of slight damage is 197 hectares, which is 43 % of the plot. On the image dated April 15, 2022, the area of severe damage is 229 hectares, which is 49 % of the plot; the moderate affected area is 237 hectares, which is 51 % of the plot.

So, it can be noted that the determined necessary set of indicators – spectral indices and the combination of RSR bands is an effective mean of assessing the state of water bodies and reclaimed lands that have been affected by military actions. The proposed approach can be further developed into a separate methodology for monitoring water bodies and reclaimed lands.

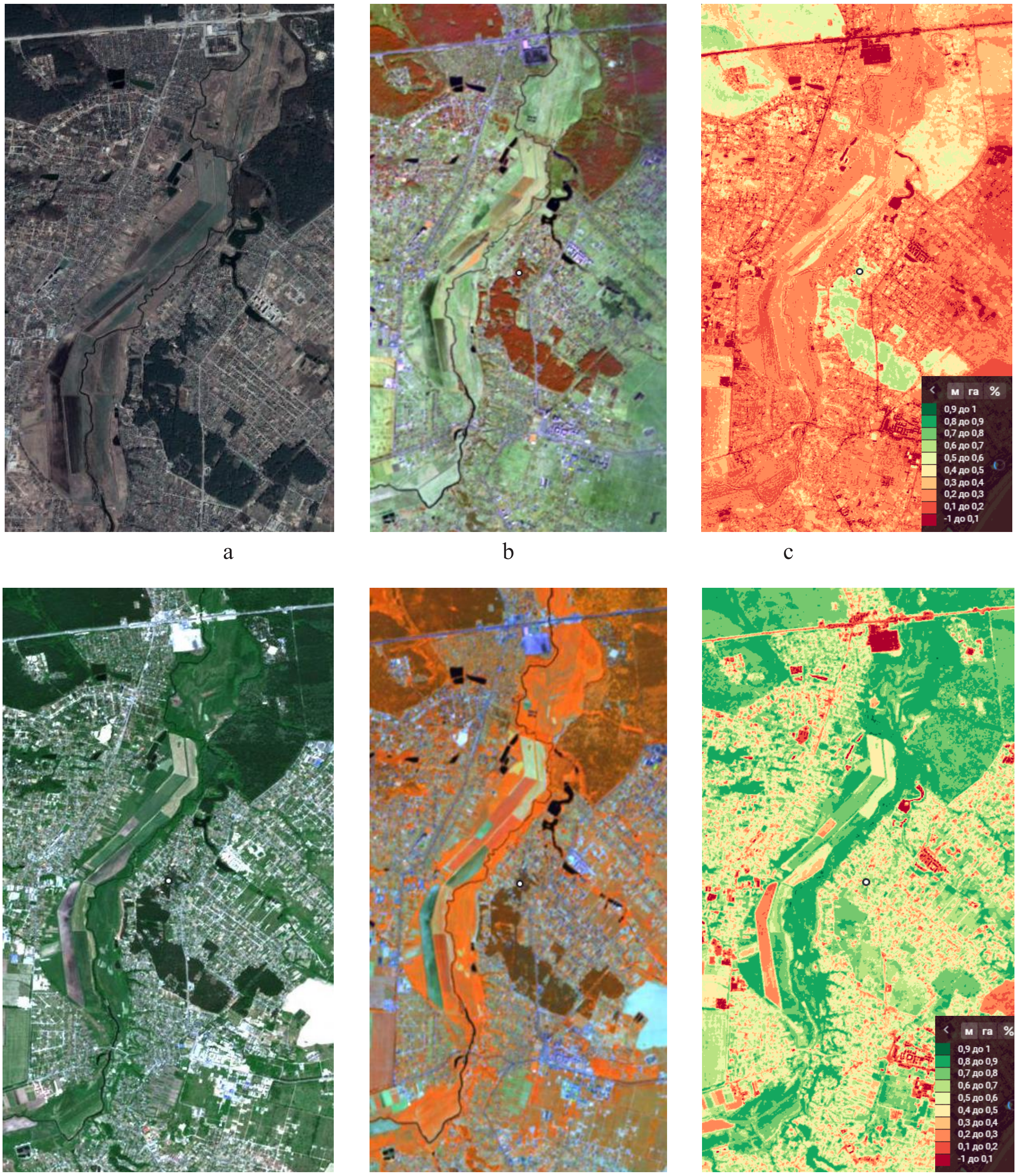


Fig. 4. Airbus image and maps of calculated spectral indices based on Sentinel-2 L2A images: a – Airbus image dated 04.15.2022 with shell craters, b – combination of RSR bands of the Sentinel-2 L2A image (23.03.2023), c – NDVI vegetation index (March 23, 2022); d – Sentinel-2 L2A image of plot restoration (01.06.2023), d – Sentinel-2 L2A RSR bands combination (01.06.2023), e – Sentinel-2 L2A NDVI vegetation index (01.06. 2023)


a


b


c


d

Fig. 5. Consequences of military actions in the area of the Irpinska DMS:
a – a crater from a shell, shown on a satellite image (see Fig. 4 a); b – grass overgrowth of the craters over time; c – closed drainage network damaged by explosions; d – fragments of tile drainage (photos by A. Shevchenko)

a

b

Fig. 6. Maps-schemes of the area of the Irpinska DMS that was damaged in the result of military actions: a – due to the conduct of military actions, b – overgrowth of the area with vegetation

Conclusions. It was established that the integrated application of spectral indices in their certain combination and comparison makes it possible to monitor water bodies and reclaimed lands. The comparison of processed satellite data (images) at different moments of time made it possible to follow the progress of flooding of the floodplain of the Irpin river, which was caused by the destruction of the hydraulic facility in Kozarovichi village. The applied method makes it possible to solve a number of problems, in particular, to quickly diagnose the flooded area, to quantify the areas that are flooded or polluted by sediments, to predict the possible consequences of the impact on reclaimed lands.

A comparative analysis of the state of reclaimed lands before and after military actions using high-resolution satellite images makes it possible to determine the extent of damage of the territory by shells, mines, and aerial bombs, and to create maps-shemes based on the degree of damage of reclaimed lands, which indirectly indicate the degree of destruction of canals, closed drainage networks, etc.

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МОНІТОРИНГ ВОДНИХ ОБ'ЄКТІВ І МЕЛІОРОВАНИХ ЗЕМЕЛЬ, ЩО ЗАЗНАЛИ ВПЛИВУ БОЙОВИХ ДІЙ ЗА СУПУТНИКОВИМИ ДАНИМИ

О.В. Власова, докт. с.-г. наук, А.М. Шевченко, канд. с.-г. наук, І.А. Шевченко, канд. техн. наук, О.М. Козицький

[1] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-1911-4329$ e-mail: elena_vl2001@ukr.net;
[2] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-2637-6538$ e-mail: monitoring_protect@ukr.net;
[3] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid.org/0000-0002-7401-8786$ e-mail: irashef@ukr.net;
[4] Інститут водних проблем і меліорації НААН, Київ, Україна;
https://orcid. org/0000-0002-4459-6331$ e-mail: olegkoz@ukr.net;

Анотація. *У статті викладено результати спостережень за станом водних об'єктів і меліорованих земель, які зазнали впливу бойових дій, за допомогою супутникових знімків різного просторового розрізнення, комбінації їх каналів та натурних спостережень. Визначення оптимального* *набору показників – спектральних індексів та комбінацій каналів супутникових знімків для ведення моніторингу водних об'єктів і меліорованих земель, які зазнали впливу бойових дій, є метою досліджень. На прикладі затоплення заплави р. Ірпінь водами Київського водосховища унаслідок руйнування водопропускної споруди підраховано зміну площі затоплення на основі карт спектральних індексів NDWI, NDSI та класифікації поверхні за знімками Sentinel-2 L2A при комбінації каналів Red8, SWIR1, Red (RSR). За цією методикою було вирішено актуальне завдання з виокремлення поверхневих вод і суходолу та фіксації зміни площі затоплення протягом періоду березень 2022 р. – травень 2023 р. Інше масштабне затоплення після підриву греблі на Каховській ГЕС 6 червня 2023 р. було досліджено на території вздовж річок Дніпро та Козак біля с. Отрадокам'янка в Херсонській області. На основі знімків Sentinel-2 L2A отримано карти індексів SAVI та NDWI, за якими виявлено місця ураження ґрунтового покриву наносами та збільшення площ водних об'єктів за період 05.06 – 18.06.2023 р. Необхідно зазначити, що з часом вздовж узбережжя вітрова ерозія може спричинити міграцію важких металів з пилом. Моніторинг меліорованих земель, що зазнали впливу бойових дій, проведено у заплаві р. Ірпінь на Ірпінській осушувально-зволожувальній системі у межах Білогородської територіальної громади Бучанського району Київської області протягом трьох часових інтервалів: до бойових дій у 2019 р. (використано NDVI, коефіцієнт ir/r, індекс оксиду заліза IO), навесні 2022 р. та після боїв у 2023 р. (використано RSR, NDVI). У першому випадку встановлено задовільний стан меліорованих земель, у другому – зафіксовано вирви від снарядів та руйнацію дренажної системи. Було виявлено, що протягом третього періоду превалюють перезволожені ділянки. Це підтверджує руйнацію дренажної мережі. Розраховані значення індексу NDVI виявилися занадто високими для сільгоспкультур, що вказує на заростання угідь чагарником. За результатами проведеного моніторингу здійснено класифікацію території за ступенем її ураженості вибуховими воронками з виокремленням: (0–10 %) слабо уражених, (10–30 %) середньо уражених і сильно уражених (понад 30 %) ділянок. Запропонований підхід у подальшому може бути розвинуто в окрему методологію ведення моніторингу водних об'єктів і меліорованих земель. Оцінювання стану водних об'єктів і меліорованих земель, які зазнали впливу бойових дій, рекомендовано здійснювати за комплексом спектральних індексів, комбінації каналів знімків та натурних спостережень.*

Ключові слова: *водні об'єкти, меліоровані землі, бойові дії, супутникові знімки, спектральні індекси, ступінь ураження*