UDC 504.064.2:528.8:355.01(477)
DOI: http://doi.org/10.17721/1728-2713.112.15

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MONITORING THE ECOLOGICAL CONSEQUENCES OF WAR USING GEOGRAPHIC INFORMATION SYSTEMS AND REMOTE SENSING

(***Представлено членом редакційної колегії д-ром геол. наук Ксенією БОНДАР***)

Background. ***The study's relevance stems from the catastrophic environmental impact of military operations in Ukraine. Conflicts cause severe degradation of agricultural lands, water pollution, and destruction of forests. With many areas under occupation or in combat zones, field measurements are impossible. Thus, an integrated approach using Remote Sensing (RS) and Geographic Information Systems (GIS) is essential for obtaining objective environmental data. This work aims to study the impact of military actions on soil cover, water bodies, and forests using RS technologies.***

Methods. ***RS and GIS methods were applied to monitor environmental changes. Sentinel-2 and Landsat-8 imagery were used to analyze agricultural degradation in the Zaporizhzhia region via the NDVI index. Forest fires in the Donetsk region (Sviati Hory National Park) were assessed using the NBR index, with damage quantified through ΔNBR (2021 vs. 2024). The MNDWI index helped identify flooded areas and changes in the Kakhovka reservoir's water level (2021–2024). Water turbidity and pollution in the Dnieper-Buh estuary were evaluated using the NDTI index.***

Results. ***In the Zaporizhzhia region, 989 craters were identified on agricultural lands, covering over 70 hectares. NDVI analysis confirmed significant land quality deterioration by 2024 compared to 2021. In the Sviati Hory National Park, NBR calculations revealed extensive damage to forest stands with no signs of natural restoration. MNDWI data confirmed a drastic increase in flooded areas in the Kherson and Mykolaiv regions following the Kakhovka HPP dam destruction in June 2023, while NDTI values indicated a sharp rise in water pollution and turbidity in the Dnieper-Buh estuary.***

Conclusions. ***The study confirms that military operations in Ukraine have a devastating environmental impact. RS and GIS technologies are proven effective for the remote monitoring and quantification of such damage. Key findings include severe soil degradation, extensive destruction of forest resources in the East and North (exacerbated by landmining), and radical changes in hydrological regimes due to the Kakhovka HPP disaster. These changes have led to ecosystem degradation and critical shortages of drinking water, necessitating long-term monitoring strategies.***

Keywords: ***Remote Sensing methods, military operations, spectral indices, natural environment, ecological state***

Background

Armed conflicts always have negative consequences, which not only destroy infrastructure and cause loss of human lives, but also harm the natural environment (Solokha et al., 2024). Today, the Russian-Ukrainian war, which began in 2014 in the Donetsk and Luhansk regions and escalated into a full-scale invasion of the entire territory of Ukraine in 2022, has been the most destructive war in Europe since World War II. Military actions have led to the deterioration of natural resources, namely the degradation of agricultural lands, pollution of water bodies, and the destruction of forests and nature reserves (Makarenko et al., 2022).

With the beginning of the full-scale Russian aggression against Ukraine, a relatively new term, "ecocide", emerged (Certini, Scalenghe, & Woods, 2013). Ecocide is the deliberate infliction of harm to the environment, aimed at the mass destruction of flora and fauna and the pollution of the aquatic environment and atmosphere (Shulha, 2023).

Every day, Russian aggression on the territory of Ukraine commits environmental crimes that have a negative impact on natural resources. Daily shelling, mining of territories and remnants of ammunition, construction of fortifications, destruction of water infrastructure, pollution, and fires all cause long-term consequences for the environment that will take their toll for a long time, even after the end of hostilities (Shevchuk, 2022).

The scientific novelty of the study lies in the development and application of an integrated approach to monitoring the environmental impact of military operations in Ukraine using high-resolution satellite data and multicomponent spectral analysis. Unlike existing studies, which focus mainly on individual aspects of the impact of war (fires, pollution, craters or hydrological changes), the proposed study integrates the analysis of soil, forest, and aquatic ecosystems in a single analytical model.

For the first time, the work simultaneously uses a wide range of spectral indices for regions of active military operations in Ukraine – NDVI, NDMI, NBR, ΔNBR, MNDWI, NDWI and NDTI, which allows for a comprehensive assessment of vegetation degradation, changes in humidity, fire intensity, reduction of the water table, and increased turbidity of the water bodies. The integrated approach provides a multidimensional representation of environmental processes caused by military actions and exceeds the capabilities of traditional single-parameter methods.

The scientific contribution of the work lies in the proposed universal remote monitoring system, which covers various types of natural resources and regions of Ukraine; quantitative assessment of environmental changes using satellite data; and the creation of an environmental monitoring system and assessment of the damage caused during the war.

Armed conflicts cause the greatest damage to land resources, including soil cover, which is the foundation for agriculture and forestry. Minefields, bombings, landslides, scorched earth and destroyed military equipment in the fields lead to long-term environmental degradation. Restoring land resources after war is a difficult and lengthy process that requires a series of appropriate environmental protection measures (Certini, Scalenghe, & Woods, 2013).

Remote sensing (RS) techniques are key to studying soil degradation, NDVI being the most common one, providing information on the state of vegetation cover. For example, Bashir & Ali (2020) successfully combined NDVI and BSI to detect erosion.

Shelestov et al. (2023) used satellite image classification to identify degradation zones, while Solokha et al. (2023) demonstrated the effectiveness of combining remote sensing and field measurements to assess degradation. The GEF report states that the NDVI has been successfully used to assess degradation dynamics on a global scale (Yengoh et al., 2015). Ebrahimi et al. (2024) evaluated the accuracy of remote sensing models for assessing land degradation in the Baluchistan region, Iran. In their study, researchers used data from the Sentinel-2 satellite and analyzed the relationship between surface albedo and five spectral indices: NDVI, SAVI, MSAVI, BSI, and TGSI. Based on these data, a degradation map was created. Mzid et al. (2021) used multispectral satellite data (Sentinel-2 MSI) for three representative agricultural areas in Italy over four years to identify the presence of agricultural bare soil. To distinguish bare soil from that covered by active or dead vegetation on arable land, the researchers used a combination of two indices, NDVI and BSI, which were able to differentiate between bare soil and other soil covers with a confidence level of 95 %.

Nature reserves are important for maintaining biodiversity and ecological balance, but today, a large number of protected areas in Ukraine are under occupation or in the zone of hostilities, which causes their destruction, fires, pollution and disruption of natural processes (Tomchenko et al., 2023). Armed conflicts lead to the physical destruction of natural ecosystems. Shelling, the construction of fortifications, passage of heavy equipment all have a negative impact on the natural environment. It has also been noted that during artillery shelling, toxic substances accumulate in the soil, slowing down the restoration of the vegetation cover (Zavgorodniuk, & Parkhomenko, 2017). In their study, Mao, Li & Shen (2020) emphasized the importance of using remote sensing technologies for mapping and monitoring the dynamics of protected areas. A study by Bai et al. (2019) used remote sensing data from multiple sources (Landsat, MODIS vegetation products and ASTER-DEM) to identify threats to the Wutai Mountain World Heritage Site. Remote sensing data were also used to assess the overall risk of cultural heritage sites in the Paphos area, Cyprus (Agapiou et al., 2015). Reddy, Satish & Rao (2018) analyzed the use of Landsat satellite data to determine the fire hotspots in the Nilgiri Biosphere Reserve, India.

Sadly, military operations heavily rely on wood, with its uncontrolled logging for military needs being observed in forest areas (Fig. 1.8). Forest resources are used for the construction of fortifications, the arrangement of field structures, heating and other needs, causing massive deforestation (Zibtsev, Soshensky, & Goldammer, 2022). As of February 24, 2022, the total forest area in Ukraine was 10.4 million hectares. According to the Operational Headquarters for Recording Environmental Crimes, 3 million hectares of forests have been damaged by military aggression. The forests in the northern and eastern regions have been most affected by hostilities.

Water is a valuable natural resource on Earth and an important factor in the metabolism of substances laying the foundation of life. Water resources play an important role in industry and agricultural production (Shumilova et al., 2023). Unfortunately, armed aggression has significantly deteriorated the state of water resources, especially in regions where hostilities have taken place or are still ongoing. A study by Vyshnevskyi et al. (2023) analyzed the consequences of the collapse of the Kakhovka hydroelectric power plant dam, the purpose and capacity of the Kakhovka reservoir, the impact on the surrounding areas downstream of the Dnieper, as well as the water quality of the Dnieper-Buh estuary and the northwestern part of the Black Sea. Magas et al. (2023) presented results of their analysis of the hydrological situation in the Dnieper-Buh Estuary area following the destruction of the Kakhovka hydroelectric power plant dam. An assessment was made of the impact of rising water levels downstream of the dam on the water area and coastal zones of the Kherson and Mykolaiv regions. The destruction of industrial enterprises and infrastructure leads to the leakage of toxic substances, heavy metals and oil products into the water bodies, which contributes to the deterioration of water quality and poses a threat to the drinking water supply for the population (Strokal, & Kovpak, 2022). Military attacks and the destruction of reservoirs are the major factors in the environmental disaster caused by the armed conflict (Mao, Li, & Shen, 2020). Monitoring of the satellite images over the past three months has revealed a decrease of 80 % in the area of the reservoir compared to its original size. A significant part of the reservoir does not only contain an insufficient amount of water, but has completely dried up. A high degree of drainage was observed on the left bank of the Kakhovka reservoir. The shoreline in the vicinity of the cities of Nikopol and Energodar has undergone significant drainage (Tomchenko et al., 2023).

The relevance of the study is determined by ongoing active hostilities in Ukraine, which have catastrophic consequences for the country's natural resources. Since some territories are under occupation or are zones of active combat operations, field measurements are impossible to take. Therefore, there is a need to create an integrated approach using remote sensing and geographic information systems to obtain objective information about the state of the environment. The destruction of the reservoir had a serious impact on the natural ecosystems and has changed the shoreline zone, with reservoirs being critical for water supply and irrigation in regions with insufficient moisture (Stakhiv et al., 2025; Hordiichuk, et al., 2024). The destruction of the wetlands due to the armed conflict is of particular concern, since they play an important role in maintaining the ecosystems and natural water purification. Armed conflicts can lead to drainage in these areas due to changes in the hydrological regime, which alters the local microclimate, lowers the groundwater level, and causes land degradation.

The aim of this work is to study the impact of military actions on the natural environment, namely on soil cover, water bodies, forests, and protected areas using remote sensing methods.

Methods

During the study of the military impact on Ukraine's natural resources, methods of remote sensing of the Earth (RS) and geographic information systems (GIS) were used. One of the remote methods is satellite imaging. This requires comparing satellite images of the territory before and after the hostilities and analyzing the changes that have occurred, such as craters from shell explosions, burned forests areas, or dug fortifications. Using remote sensing methods, it is possible to observe the state of water bodies, such as changes in the coastline and pollution, as well as to monitor the spread of atmospheric air pollution. Satellite images allow for real-time monitoring in natural colors.

The following remote sensing data were downloaded for the study:

Sentinel-2 space imagery has a high spatial resolution (10–20 meters), which allows for the analysis of changes in land cover and agriculture, forestry, and the study of water tables due to hostilities (Dataspace, n.d.). Sentinel-2 satellite data for 2021–2024 were downloaded from the Copernicus platform and EO Browser, which made it possible to analyze the state of natural resources before and after the start of the full-scale invasion.

Landsat-8 space imagery has a spatial resolution of 30 meters for multispectral data and 15 meters for panchromatic data and operates in several spectral ranges: visible, infrared, and thermal (Landsat Science, n.d.). These data are used for mapping and monitoring changes in natural resources and were downloaded from the United States Geological Survey (USGS) between 2021 and 2024 to assess the state of natural resources.

To ensure accurate comparisons and minimize seasonal fluctuations, satellite images were selected mainly for the summer period (June–August), when vegetation cover is at its peak, there is no snow cover, and the impact of phenological changes is minimal. This ensured the consistency of the spectral indices used between different years of observations.

In the course of the work, thematic processing of satellite images was carried out, which involves image analysis, including classification of the studied areas, calculation of spectral indices, and detection of changes in the environment caused by hostilities.

Spectral indices used in the course of the work.

Assessment of the state of vegetation in remote sensing is often based on NDVI (formula 1).

$$NDVI = \frac{NIR-RED}{NIR+RED} \qquad (1)$$

where NIR is the near-infrared reflectance; Red is the red spectral channel reflectance.

NDVI represents this difference as a number from -1 to 1. The calculated NDVI values are classified as follows:

- -1 – 0 – dead plants or inanimate objects;
- 0 – 0.33 – weakened plants;
- 0.33 – 0.66 – relatively healthy plants;
- 0.66 – 1 – completely healthy plants.

Water surfaces in satellite images are identified using the NDWI index (formula 2). This tool makes it possible to observe the dynamics of the water surface by analyzing changes.

$$NDWI = \frac{Green-NIR}{Green+NIR} \qquad (2)$$

where Green is the reflectance in the green spectral channel; NIR is the reflectance in the near infrared range.

NDWI uses a numerical scale from -1 to 1 to determine the presence of water. Values greater than 0 (NDWI > 0) are interpreted as water bodies, and values less than 0 (NDWI < 0) are interpreted as land.

The NBR index (formula 3) is used to assess damage caused by fires.

$$NBR = \frac{NIR-SWIR2}{NIR+SWIR2} \qquad (3)$$

where NIR is near-infrared reflectance; SWIR2 is short-wave infrared reflectance.

Healthy vegetation is characterized by good near-infrared reflectance, while areas recently destroyed by fire have good short-wave infrared reflectance.

NBR reflects this difference as a number from -1 to 1, where high values are characteristic of healthy vegetation and low values indicate areas damaged by fire (EOS Data Analytics, 2022).

The Modified Normalized Difference Water Index – MNDWI (formula 4) is used to detect water surfaces in satellite images within urban areas. This index can also be used to detect surface water pollution.

$$MNDWI = \frac{Green-SWIR}{Green+SWIR} \qquad (4)$$

where Green is the reflectance in the green spectral channel; SWIR is the reflectance in the short-wave infrared range.

MNDWI represents this difference as a number from -1 to 1, where MNDWI > 0 indicates the presence of water, MNDWI < 0 indicates the presence of land (Xu, H., 2006).

Water turbidity is determined using the normalized differential thermal index NDTI (formula 5). It reflects how well light passes through the water, and its increase may indicate pollution.

$$NDTI = \frac{Red-Green}{Red+Green} \qquad (5)$$

where Red is the reflectance in the red spectral channel; Green is the reflectance in the green spectral channel.

NDTI values are interpreted in the range from -1 to 1. Positive values (NDTI>0) indicate an increase in water turbidity, while negative values (NDTI<0) indicate relatively clear water (SMARTAFRIHUB, 2023).

Remote sensing data can be used to estimate the amount of moisture in vegetation and soil using the NDMI index (formula 6).

$$NDMI = \frac{NIR-SWIR1}{NIR+SWIR1} \qquad (6)$$

where NIR is near-infrared reflectance; SWIR1 is short-wave infrared reflectance.

NDMI represents this difference as a number from -1 to 1. Classification of NDMI calculation values:

- -1 – 0 – low moisture in vegetation cover;
- 0 – 0.4 – moderate moisture in vegetation cover;
- 0.4 – 1 – sufficient moisture in vegetation cover (EOS Data Analytics, 2023).

Manual digitization was used to identify craters caused by explosions, as well as to display changes in the water body boundaries. Digitization was performed using Sentinel-2 and Landsat-8 satellite images in the ArcGIS environment with the formation of separate polygonal layers. Based on the created shapefiles, the areas of damaged sites, the areas and diameters of the formed craters, as well as changes in the water level of the Kakhovka Reservoir were calculated in the attribute table using the Geometry Calculation tool, which made it possible to quantitatively assess the scale of the impact of hostilities on the landscape.

Results

The ongoing military operations in Ukraine have devastating effects both on people and the environment. One major problem is the degradation of land resources and soils caused by armed aggression.

During shelling, shell explosions have highly dangerous and destructive impacts on the territory of Ukraine. After the explosion, shells leave behind damaged soil with large amounts of toxic substances and particles of the metal from which the ammunition is made. As a result, the atmosphere, soil, groundwater, and water bodies of the shelling areas are contaminated.

In the shelling zone, a crater, or funnel, is created, which is a depression forming in the soil or hard rock when explosives in the ammunition detonate and cause soil compaction, a process by which soil particles are pressed together and the space between their pores decreases.

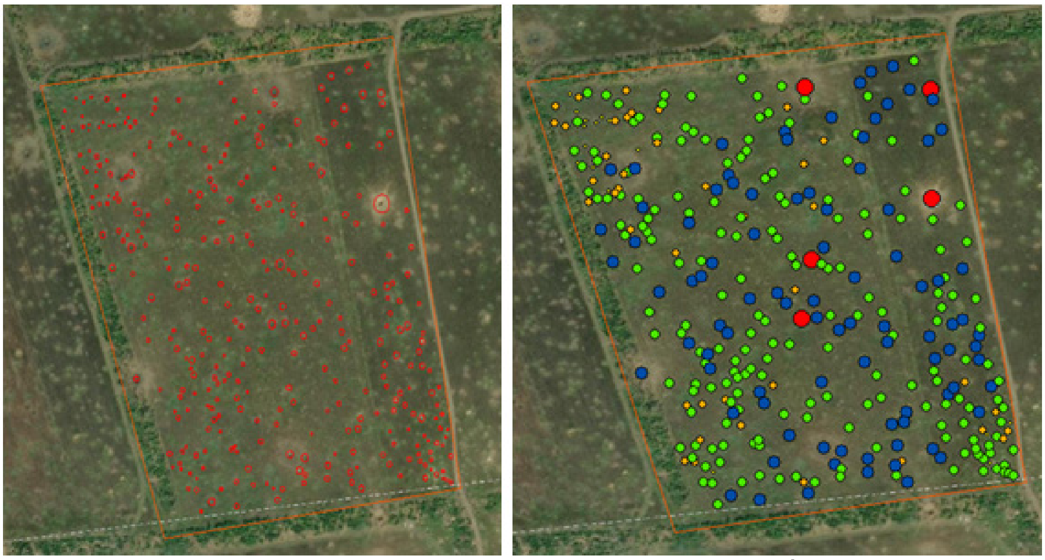
Craters formed during the explosion mix soil horizons, and compaction limits the ability of plants to adapt to climate change, drought, and insufficient moisture in the area (Fig. 1).

a b

Fig. 1. Sentinel-2 satellite image of the study area:
a – 2021; b – 2024

The study area, which included agricultural lands in the Zaporizhzhia region where hostilities took place, was selected in order to identify craters formed and degradation of land resources and to assess their condition.

To identify craters formed by shell explosions, two study sites were selected (Fig. 2). The area of each site was calculated using ArcGIS software and classified according to size.



a b

Fig. 2. Site No. 1:
a – identified craters; b – classification of craters by size

On this site of 16.75 hectares, 336 craters from explosions of various types of shells were found. We classify them as follows:

- diameter 1.1–1.9 m, formed by a 120 mm mortar shell (16 craters, highlighted in yellow);
- diameter of about 2–2.7 m, formed by a 122 mm artillery shell (39 craters, highlighted in orange);
- diameter of about 2.8–4 m, formed by a 152/155 mm artillery shell (185 craters, highlighted in green);
- diameter of about 4.1–7.9 m, formed by a 250 kg aerial bomb (91 craters, highlighted in blue);
- diameter approx. 8+ m, formed by a 500 kg aerial bomb (5 craters, highlighted in red).

A statistical analysis was conducted for this study site, which includes the total area, number of craters, average crater area, minimum and maximum area, diameter, density of crater distribution on the site, and total area of damaged zones, shown in Table 1.

Table 1

Statistical analysis of study site No. 1

Indicators	Value
Total area	167,500 m²
Number of craters	336
Minimum crater area	1.12 m²
Maximum crater area	237.8 m²
Average crater area	16.4 m²
Minimum crater diameter	1.2 m
Maximum crater diameter	16.9 m
Average crater diameter	4.25 m
Total area of damaged zones	5,510.4 m²
Density	≈ 20 ctaters per 1 ha

On the second study site covering an area of 54.5 hectares, 653 craters from explosions of various types of shells were found. We classify them as follows:

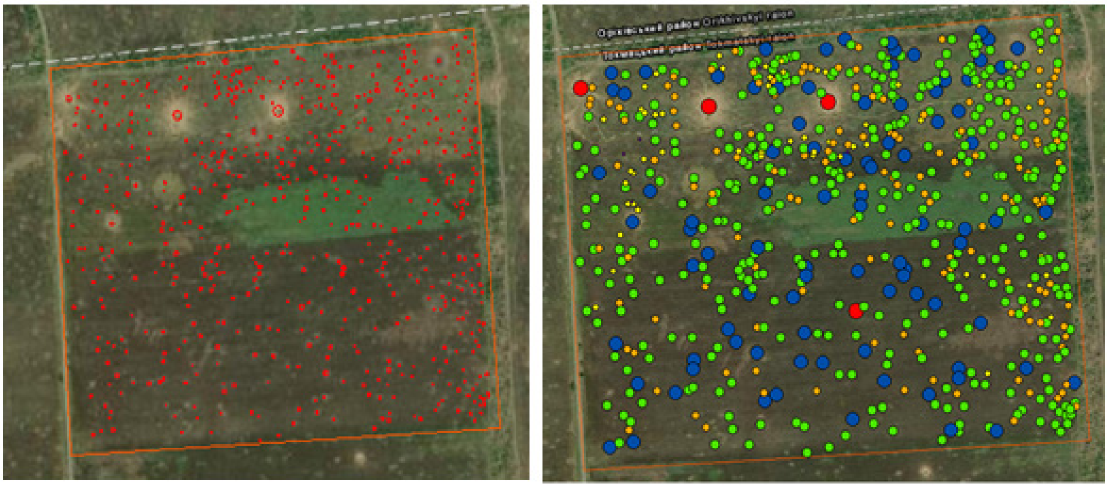
- diameter 0.5–1 m, formed by an 82 mm mortar shell (7 craters, highlighted in purple);
- diameter 1.1–1.9 m, formed by a 120 mm mortar shell (55 craters, highlighted in yellow);
- diameter of about 2–2.7 m, formed by a 122 mm artillery shell (141 craters, highlighted in orange);
- diameter of about 2.8–4 m, formed by a 152/155 mm artillery shell (356 craters, highlighted in green);
- diameter of about 4.1–7.9 m, formed by a 250 kg aerial bomb (90 craters, highlighted in blue);
- diameter approx. 8+ m, formed by a 500 kg aerial bomb (4 craters, highlighted in red).

The results of the research are presented in Fig. 3.

A statistical analysis was also conducted, as for the previous site, with the values given in Table 2.

To monitor the quality of agricultural lands in the study areas, a Landsat-8 image of the United States Geological Survey (USGS) for the Zaporizhzhia region was downloaded for two periods: July 15, 2021 and July 15, 2024. The NDVI vegetation index was calculated (Fig. 4).

Analysis of the spatial distribution of NDVI showed a significant deterioration in the condition of vegetation cover and land in 2024 compared to the pre-war period. In 2021, NDVI values ranged from –0.076 to 0.61, which corresponds to predominantly healthy and stable vegetation cover. In contrast, in 2024, the index range decreased to –0.024 – 0.53, indicating a decline in plant photosynthetic activity and a general weakening of ecosystems.



a b

Fig. 3. Site No. 2:
a – identified craters; b – classification of craters by size

Table 2

Statistical analysis of study site No. 2

Indicators	Value
Total area	545,000 m²
Number of craters	653
Minimum crater area	0.22 m²
Maximum crater area	244.2 m²
Average crater area	11.45 m²
Minimum crater diameter	0.5 m
Maximum crater diameter	17.6 m
Average crater diameter	3.52 m
Total area of damaged zones	7,476.85 m²
Density	≈ 12 craters per 1 ha

ISSN 1728-2713 (Print), ISSN 2079-9063 (Online)

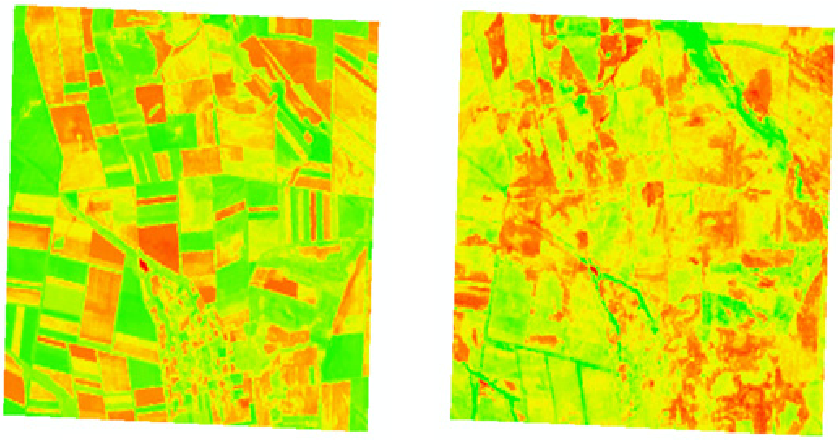


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Fig. 4. The result of applying the NDVI index for Zaporizhzhia region:
a – 2021; b – 2024

The largest drop in NDVI was recorded in areas with a high density of explosion craters and soil damage. In some areas with intensive hostilities, NDVI decreased by 0.15–0.25 compared to the pre-war baseline. This indicates the degradation of agricultural land, loss of soil structure, disruption of root systems, and a decrease in plant biomass. Some areas demonstrate a complete absence of vegetation due to mechanical destruction of the soil and repeated explosive impacts.

Svyati Hory National Nature Park

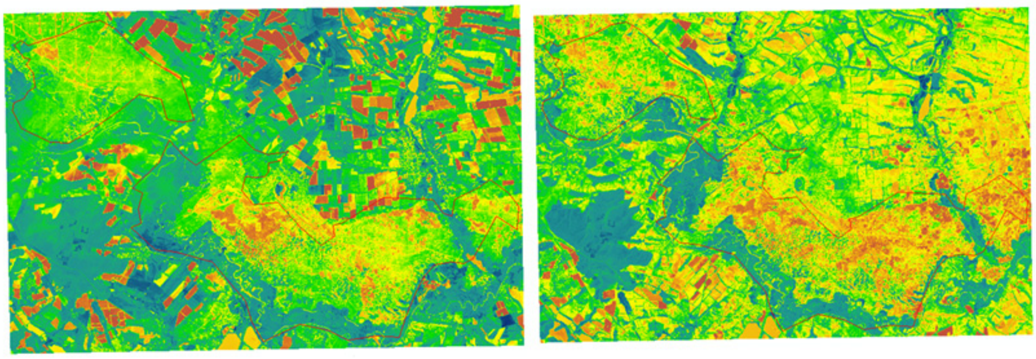
The Svyati Hory ("Holy Mountains") National Nature Park is located in the Donetsk region, representing a unique complex of protected landscapes (Fig. 5).

At the beginning of the full-scale invasion, this nature reserve was the first to be negatively affected by shelling, and the eastern part of the park was occupied. After de-occupation in October 2022, the national park remained with scorched land, instead of the former forest stands.

a b

Fig. 5. Satellite images of the Svyati Hory National Nature Park:
a – 2021; b – 2024

During the study, Landsat-8 satellite images before and after the fire were downloaded and the NBR index was calculated, which can be used to identify burned areas. Contrasting satellite images (Fig. 6) clearly showed the destruction of the forest structure within the Svyati Hory National Nature Park. Although the park was deoccupied a year and a half ago, the restoration of the forest has been complicated by the fact that a large part of the park was mined.



a b

Fig. 6. Calculated NBR indices for the Svyati Hory National Nature Reserve:
a – 2021; b – 2024

The results of calculating the index yielded the following minimum values: –0.23 (2021) and –0.55 (2024), which indicates that the forest stands were damaged as a result of hostilities and have not been restored.

To quantitatively assess the state of the forest, the difference between the NBR indices for 2021 and 2024 was calculated and a thematic map of changes in the forest condition was created (Fig. 7).

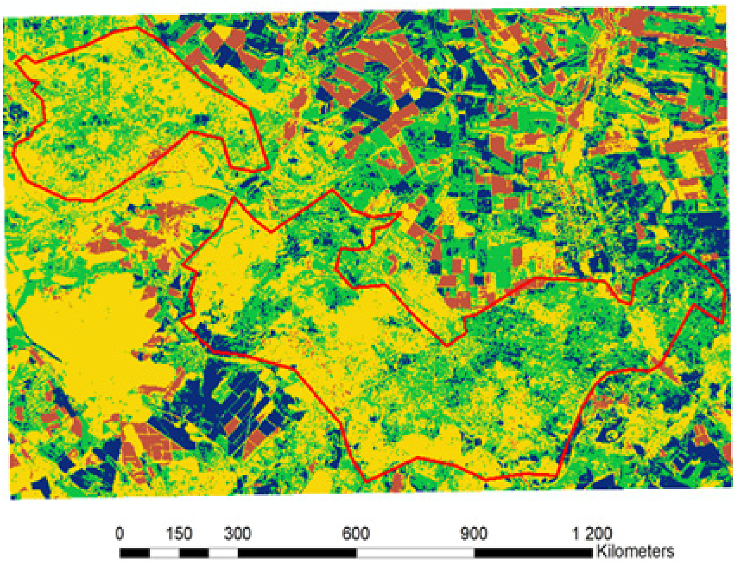


Fig. 7. Changes in forest condition according to the calculated ΔNBR value for the Svyati Hory National Park
The obtained ΔNBR calculation results indicate that most of the area has medium (yellow) and high (green) damage. Also, some areas show severe damage (blue).

Analysis of the consequences of the Kakhovka HPP destruction

The Kakhovka HPP is located in the Kherson region and is the sixth hydroelectric power plant in the Dnieper cascade. It was near the Kakhovka HPP that the largest reservoir was created, which had a complex purpose, among which were: electricity generation, water supply and irrigation, and water transport routes.

At the beginning of the full-scale invasion on February 24, 2022, the Kakhovka HPP was occupied, and in June 2023, it was blown up, which led to the flooding of vast territories of the Kherson and Mykolaiv regions and caused a change in the hydrological regime (Fig. 8).

a b

Fig. 8. Sentinel-2 satellite images of the Kakhovka HPP:
a – July 2, 2022; b – July 2, 2023

The Sentinel-2 satellite images (Fig. 8) show the change in the regime of the Dnipro River in 2022 and 2023. The images demonstrate changes in the reservoir after the explosion of the Kakhovka HPP and their effects on the natural landscapes. To detect flooding of adjacent areas after the explosion of the reservoir, the MNDWI (Modified Normalized Difference Water Index) was used to identify water bodies and the impact of the destruction of hydraulic structures (Fig. 9).

Fig. 9 shows the results of calculating the MNDWI index using the ArcGIS software of Landsat-8 satellite images for 2022 and 2023, confirming a significant increase in the area of water bodies immediately after the dam explosion.

The explosion at the hydroelectric power plant caused large quantities of harmful substances to enter the Dnieper River and then later, with a decrease in flooding, to flow downstream to the Dnieper-Buh estuary.

To assess the state of the Dnieper-Buh estuary following the explosion at the Kakhovka hydroelectric power station, the NDTI index (The Normalized Difference Thermal Index) was used to calculate water turbidity (Fig. 10).

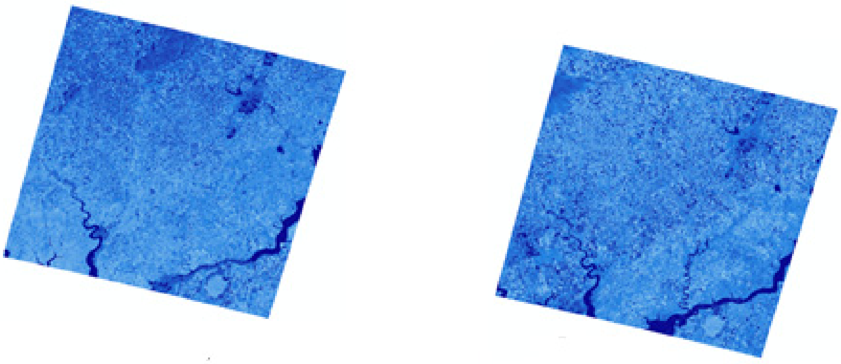


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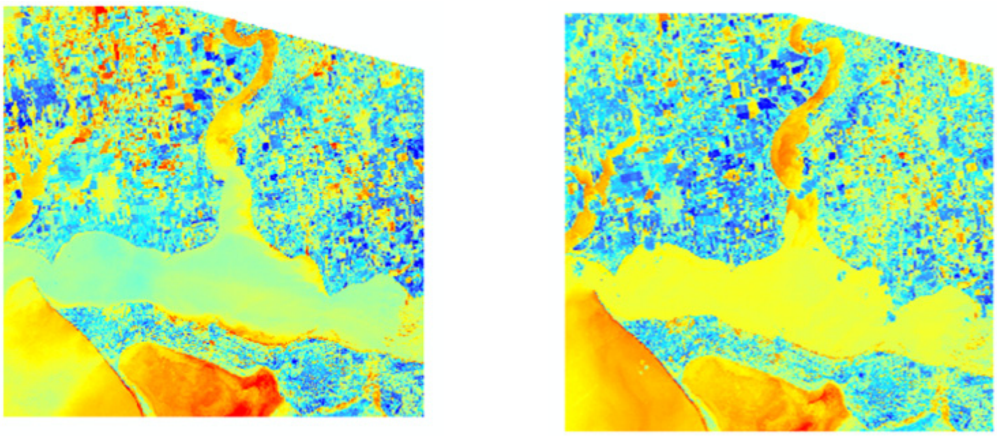
Fig. 9. Calculated values of the MNDWI for detecting flooding caused by the explosion of the Kakhovka HPP:
a – 2022; b – 2023



a b

Fig. 10. Calculated NDTI indices for the Dnieper-Buh estuary:
a – June 9, 2023; b – June 17, 2023

Fig. 10 shows the results of calculating the NDTI index using the ArcGIS software of Landsat-8 satellite images dated June 9, 2023 and June 17, 2023. The calculated values of the NDTI index demonstrate an increase in the maximum values: June 9, 2023 – 0.171; June 17, 2023 – 0.224, which indicate an increase in pollution levels.

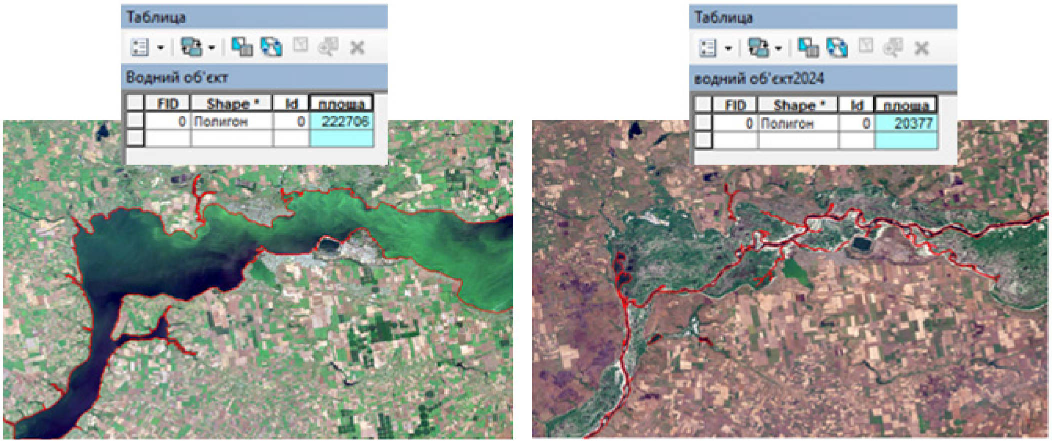
As a result of uncontrolled discharge of water from the Kakhovka reservoir, significant changes occurred in the hydrological regime. A sharp decrease in the water level led to the disappearance of many water bodies, since most of them depended on the reservoir. All this resulted in the degradation of local ecosystems, the death of aquatic flora and fauna, as well as a shortage of drinking water for the population. In addition, the shallowing of the reservoir affected the irrigation systems that supported agricultural activities in this region.

Sentinel-2 satellite images of the Dnieper River near the city of Nikopol are presented in Fig. 11.

a b

Fig. 11. Sentinel-2 satellite images of the Dnieper River near the city of Nikopol:
a – July 15, 2021; b – July 14, 2024

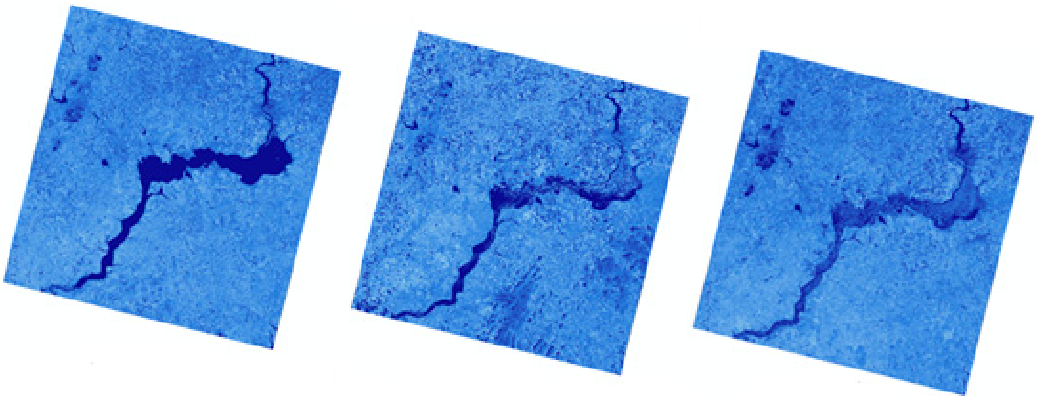
Analysis of its satellite images before and after the explosion shows that the Kakhovka Reservoir has significantly shrunk. ArcGIS 10.04 software was used to calculate the area in order to identify the proportion of water table loss. Figure 12 shows the results of the area calculation, where the area of the water body before the explosion was 222,706 m^2, and after –20,377 m^2.



a b

Fig. 12. Measured areas in m² based on Sentinel-2 images of the Kakhovka Reservoir near the city of Nikopol, Dnipropetrovsk region:
a – July 15, 2021; b – July 14, 2024

To assess the change in the Kakhovka reservoir near the city of Nikopol, the MNDWI (Modified Normalized Difference Water Index) was used, which made it possible to identify changes in the water table. Figure 13 shows the results of calculating the MNDWI index using ArcGIS software from Landsat-8 satellite images for 2021, 2023, and 2024. The data confirm a decline in the water table.



a b c

Fig. 13. Calculated values of the MNDWI index to detect changes in the Kakhovka reservoir caused by the explosion of the Kakhovka HPP:
a – 2021; b – 2023; c – 2024

In 2021 (before the explosion), boundaries of the Kakhovka reservoir with relatively high values are clearly visible, while in 2024 (a year after the explosion), drying up and degradation of the territory with local water bodies can be observed.

On the left bank of the Kherson region, which is currently under occupation, the explosion of the hydroelectric power plant caused the lakes that had formed during its construction to begin drying up as the groundwater level rapidly rose.

These dynamics can be illustrated by Lake Chornyanka, located in the Kakhovka district of the Kherson region (Fig. 14). The area of the water body, measured using the ArcGIS software, was found to be10,646 m².

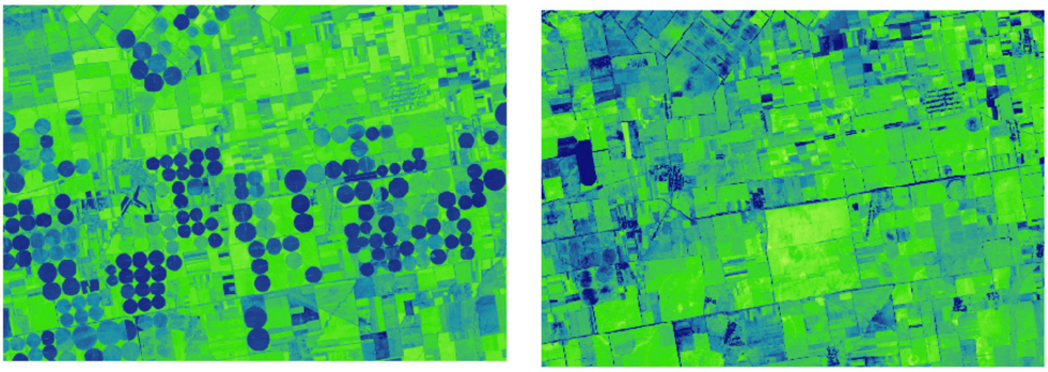
a b

Fig. 14. Sentinel-2 satellite image of Lake Chornyanka:
a – 2021; b – 2024

As a result of the destruction of the Kakhovka HPP in June 2023, Lake Chornyanka dried up as it was connected to the irrigation systems that received water from the Kakhovka Reservoir.

Before the destruction of the Kakhovka HPP, the reservoir supplied water to the irrigation systems in the south. However, after the crime committed by the Russian Federation, agricultural lands began to dry up.

In our assessment of the agricultural lands of the Kherson region, the NDMI (Normalized Difference Moisture Index) was used to evaluate the moisture level of vegetation and the NDVI (Normalized Difference Vegetation Index) to assess the quality of vegetation (Fig. 15).



a b

Fig. 15. Calculated values of the NDMI index for agricultural lands of the Kherson region:
a – 2021; b – 2024

Analysis of the NDMI index showed a significant decrease in vegetation moisture supply in 2024 compared to the pre-war period. In 2021, NDMI varied from –0.35 to 0.41, which corresponds to moderate or sufficient moisture of the vegetation cover and stable functioning of irrigation systems. In 2024, the range of values was reduced to –0.24–0.25, indicating an overall decrease in soil moisture and loss of water balance in the study area. The maximum NDMI values decreased by almost 40 %, which indicates a sharp deterioration in plant water supply conditions.

The maps clearly show the transformation of irrigation infrastructure. In 2021, the boundaries of irrigated systems are clearly visible, which is well expressed by high NDMI values. In 2024, these signs practically disappear, and areas with high index moisture are replaced by areas with consistently low NDMI values. This indicates the cessation of irrigation, a decrease in groundwater levels, and a shortage of water resources after the destruction of the Kakhovka HPP.

The obtained NDMI changes correlate with the hydrological situation in the region: the destruction of the reservoir led to the dehydration of a large part of Ukraine's southern lands, the loss of the irrigation source, the degradation of land reclamation systems, and a corresponding decrease in the moisture content of the vegetation cover. This combination of factors indicates high risks of desertification and a decrease in the productivity of agricultural lands.

Figure 16 shows the results of calculating the NDVI vegetation index using the ArcGIS software of Landsat - 8 satellite images for 2021 and 2024. Analysis of the NDVI vegetation index shows a significant deterioration in the state of vegetation cover after the destruction of the Kakhovka HPP. In 2021, the index values varied from –0.054 to 0.556, which corresponds to predominantly healthy vegetation with high photosynthetic activity. In 2024, the NDVI range decreased to –0.014–0.455, indicating a decrease in biomass, deterioration of the physiological state of plants and degradation of agricultural land. The maximum NDVI value decreased by approximately 18 %, demonstrating a significant weakening of the vegetation cover.

A comparison of the spatial structure of the index demonstrates the disappearance of clear boundaries of irrigation systems characteristic of 2021 (centrifugal fields), which, in 2024, are represented by fragmented areas with low or medium NDVI values. This indicates the cessation of the operation of land reclamation systems after the destruction of the reservoir and the loss of irrigation sources, which directly affected the state of vegetation.

The spread of areas with negative NDVI values in 2024 indicates an increase in the areas of open soil, bare substrates, or completely destroyed vegetation. Such changes are typical of areas of dehydration, degradation, and loss of soil structure. Thus, NDVI indicators confirm a significant deterioration in the state of ecosystems caused by the hydrological and ecological crisis following the demolition of the Kakhovka HPP.

The demolition of the Kakhovka HPP negatively affected the nature reserve areas located nearby. One example is the Big and Small Kuchugury Archipelago, located near the city of Vasylivka, Zaporizhzhia region, on the territory of the Velykyi Luh National Nature Park (Fig. 17).

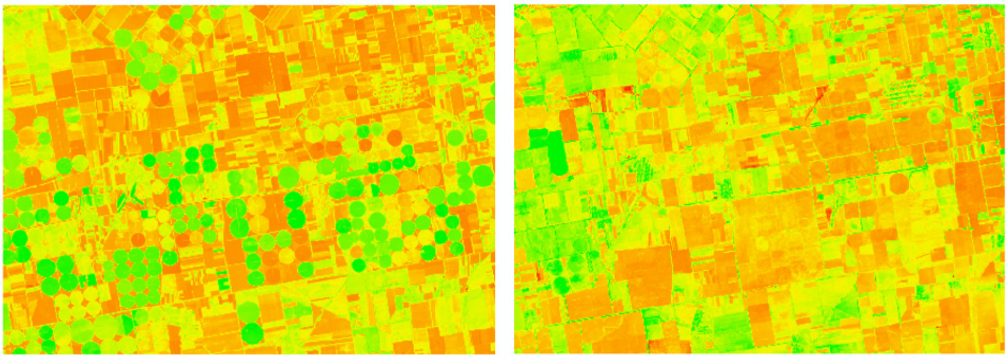
As a result of the collapse of the Kakhovka Reservoir dam, the water level in the Velykyi Luh National Park began to decline, leading to the drying up of the wetlands.

The NDWI index was calculated for the site to identify the loss of water.

A comparison of NDWI maps for 2022 and 2024 demonstrates a significant transformation of wetlands after the destruction of the Kakhovka HPP. In 2022, the index values ranged from –0.47 to 0.18, reflecting the clearly defined boundaries of the water body and the stable structure of the wetland environment. In 2024, the NDWI range expanded to -0.55–0.18, and the spatial distribution of water became fragmented and uneven, indicating the degradation of the hydrological regime.

In 2022, the area with high NDWI values formed a compact water body with a well-defined shoreline. In 2024, these areas disintegrate into numerous small local reservoirs and flooded areas, reflecting the chaotic redistribution of water after the shallowing of the Kakhovka reservoir. The increase in areas with negative NDWI values in 2024 indicates an increase in the proportion of dried or swampy areas where the water surface has lost its integrity.

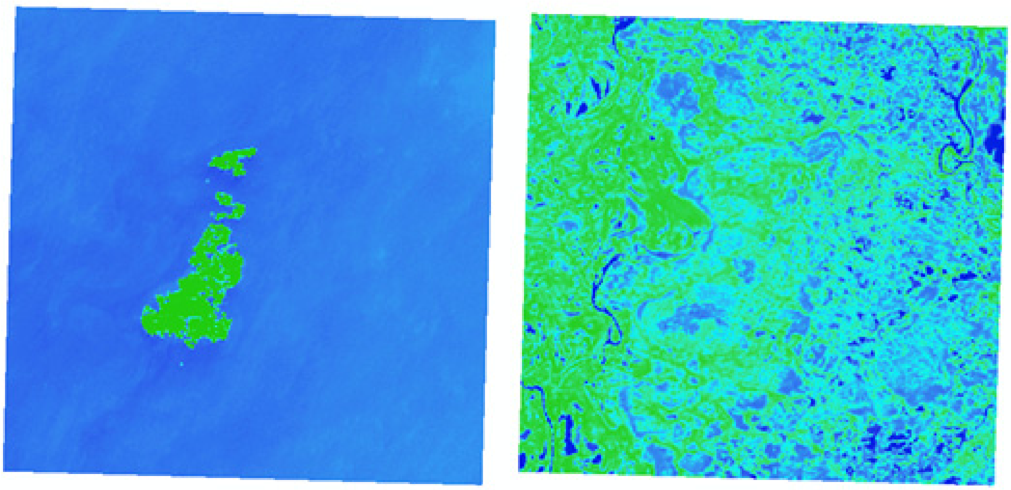
These changes confirm the drastic restructuring of wetland ecosystems: loss of stable water supply, lowering of groundwater levels, and the transition of some areas to a state of seasonal or complete drying. This creates risks of biodiversity loss, degradation of wetland communities, and disruption of natural hydrological processes in the territory of the Velyky Luh National Park.



a b

Fig. 16. Calculated values of the NDVI index for agricultural lands of the Kherson region:
a – 2021; b – 2024

Fig. 17. Created vector layer of the study area



a b

Fig. 18. Calculated NDWI index:
a – 2022; b – 2024

ISSN 1728-2713 (Print), ISSN 2079-9063 (Online)

Discussion and conclusions

The results obtained allow for a comprehensive assessment of the impact of military operations on Ukraine's natural resources, including land, water, and forest ecosystems. Analysis of spectral indices and spatial data demonstrates clear trends in the degradation of natural components, manifested in a decrease in vegetation activity, deterioration of the hydrological regime, destruction of soil cover, and destruction of forest areas.

Although the results are consistent with the general perception of the negative impact of military operations on the environment, the study deepens previous assessments by using several spectral indices simultaneously, detailing changes by year, and applying spatial metrics to quantify the extent of damage. Particular novelties include the mapping of explosion craters and determination of their diameters, areas, and density of distribution in different areas, which allows for an assessment of the intensity of artillery shelling in relation to soil and vegetation degradation. In addition, the calculation of the NDVI, NDMI, NDWI, MNDWI, and NDTI indices in combination offers a comprehensive interpretation of the state of ecosystems, including water balance and water quality.

The study has a number of limitations that may affect the interpretation of the results:

1. Satellite data depend on weather conditions, in particular cloudiness, which sometimes reduces the number of available scenes for a single site or season.
2. The spatial resolution of the images of 10–30 m does not allow to fully capture small objects, such as minor craters, local channels, or smaller streams or brooks.
3. The lack of ground validation in most areas due to military operations makes it difficult to verify the accuracy of the results obtained and limits the ability to calibrate spectral indices.
4. The use of images solely from the summer period minimizes seasonal differences, at the same time ignoring changes that occur in spring or autumn, when contrasts in vegetation and moisture may be more pronounced.

Thus, the results obtained should be considered taking into account the spatial and technical limitations of remote sensing data.

The interpretation of spectral indices tends to involve a certain degree of uncertainty. A decrease in NDVI can be caused not only by vegetation degradation, but also by drought, changes in agricultural practices, or seasonal features. NBR indicators may drop in dark or shady areas, which does not always mean vegetation burnout. NDWI and MNDWI values may be distorted in urban areas due to the presence of bright artificial surfaces. An increase in NDTI may not point to pollution – instead, it might be associated with natural siltation or increased sediment transport caused by rains or floods.

Therefore, the results of the indices should be interpreted taking into account the accompanying environmental, climatic and landscape factors.

The results obtained are of significant practical importance for state and international structures. Maps of soil damage, forest degradation, and changes in the water balance can be used to:

- assess the extent of environmental damage and plan measures for the restoration of territories after de-occupation;
- prepare appropriate materials to hold the aggressor accountable for environmental crimes;
- justify the need for international assistance to restore irrigation systems, forests, and water resources;
- assess risks for the local population, including access to water and agricultural opportunities.

In the long term, the results demonstrate the systemic degradation of natural resources, which can affect food security, biodiversity, ecosystem resilience, and the recovery potential of the regions.

The study confirmed that military operations in Ukraine have an extremely negative impact on the natural resources. The use of remote sensing (RS) and geographic information systems (GIS) methods proved to be an effective tool for monitoring and quantifying the damage caused.

In the Zaporizhzhia region, 336 craters were detected on an area of 16.75 hectares and 653 craters on an area of 54.5 hectares. The calculated NDVI vegetation index showed a deterioration in the quality of agricultural lands in 2024 compared to 2021, which indicates their degradation. Forest stands in the Sviati Hory National Nature Park have suffered significant damage. Analysis based on the NBR index showed that most of the park has suffered medium to high damage, and forest restoration is complicated by mining of the territories. The explosion of the Kakhovka HPP in June 2023 led to significant ecological changes. The calculation of the MNDWI index confirmed a significant increase in the area of the water bodies in the Kherson and Mykolaiv regions. In addition, the NDTI index showed an increase in water pollution and turbidity in the Dnieper-Buh estuary. The destruction of the hydroelectric power plant resulted in the drying up of the Kakhovka reservoir near Nikopol and other water bodies, such as Lake Chornyanka. This resulted in ecosystem degradation, loss of flora and fauna, and water shortages in the occupied territories. Overall, the findings of the study demonstrate the long-term and devastating effects of military operations on the environment of Ukraine, emphasizing the need for further monitoring and environmental protection measures.

Authors' contribution: Mykola Bialyi – conceptualization, formal analysis, methodology, writing (original draft); Anna Andriievska – conceptualization, data validation, writing (reviewing and editing); Iryna Stakhiv – data validation, writing (reviewing and editing); Tetiana Pastushenko – writing (reviewing and editing).

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Отримано редакцією журналу / Received: 01.12.25
Прорецензовано / Revised: 02.01.26
Схвалено до друку / Accepted: 18.02.26
Опубліковано / Published: 27.02.26

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МОНІТОРИНГ ЕКОЛОГІЧНИХ НАСЛІДКІВ ВІЙНИ ЗА ДОПОМОГОЮ ГЕОІНФОРМАЦІЙНИХ СИСТЕМ ТА ДИСТАНЦІЙНОГО ЗОНДУВАННЯ

Вступ. ***Актуальність дослідження зумовлена катастрофічним впливом військових дій на довкілля України. Конфлікти спричиняють серйозну деградацію сільськогосподарських угідь, забруднення водойм та знищення лісів. Оскільки багато територій перебувають під окупацією або в зоні бойових дій, проведення польових вимірювань є неможливим. Отже, інтегрований підхід із використанням дистанційного зондування (ДЗ) та геоінформаційних систем (ГІС) є необхідним для отримання об'єктивних даних про стан довкілля. Метою роботи є дослідження впливу військових операцій на ґрунтовий покрив, водні об'єкти та ліси за допомогою технологій ДЗ.***

Методи. ***Для моніторингу екологічних змін було застосовано методи ДЗЗ та ГІС. Супутникові знімки Sentinel-2 та Landsat-8 використовувалися для аналізу деградації сільськогосподарських земель у Запорізькій області за допомогою індексу NDVI. Лісові пожежі в Донецькій області (Національний природний парк "Святі Гори") оцінювалися за допомогою індексу NBR, а ступінь пошкоджень визначався через ΔNBR (2021 проти 2024 р.). Індекс MNDWI допоміг ідентифікувати затоплені території та зміни рівня води в Каховському водосховищі (2021–2024 рр.). Забруднення та каламутність води в Дніпровсько-Бузькому лимані оцінювалися за допомогою індексу NDTI.***

Результати. ***У Запорізькій області на землях сільськогосподарського призначення виявлено 989 вирв загальною площею понад 70 гектарів. Аналіз NDVI підтвердив значне погіршення якості земель у 2024 р. порівняно з 2021. У НПП "Святі Гори" розрахунки NBR виявили масштабні пошкодження лісових масивів без ознак природного відновлення. Дані MNDWI підтвердили різке збільшення площ затоплення в Херсонській та Миколаївській областях після руйнування греблі Каховської ГЕС у червні 2023 р., а значення NDTI вказали на різке зростання забруднення та каламутності води в Дніпровсько-Бузькому лимані.***

В и с н о в к и . ***Дослідження підтверджує, що військові дії в Україні мають руйнівний вплив на навколишнє середовище. Технології ДЗЗ та ГІС довели свою ефективність для дистанційного моніторингу та кількісної оцінки таких збитків. Ключові висновки включають значну деградацію ґрунтів, масштабне знищення лісових ресурсів на сході та півночі (що посилюється мінуванням територій) та радикальні зміни гідрологічного режиму внаслідок катастрофи на Каховській ГЕС. Ці зміни призвели до деградації екосистем та критичного дефіциту питної води, що потребує стратегій довгострокового моніторингу.***

К л ю ч о в і   с л о в а : ***методи дистанційного зондування, військові дії, спектральні індекси, навколишнє природне середовище, екологічний стан.***

Тетяна Пастушенко є членом редколегії видання, тому не брала участі у рецензуванні та прийнятті рішення щодо публікації цієї статті.
Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.
Tetiana Pastushenko is the a member of the journal editorial board, therefore did not take part in the peer-review process or in the decision to publish of this article.
The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; in the decision to publish the results.