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Climatic and hydrological conditions for the formation of vegetation cover in the drained Kakhovka reservoir's territory

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ABSTRACT

Today, scientists focus on studying the state of natural vegetation cover in the drained Kakhovka reservoir's territory. In this regard, our research aims to establish the patterns of plant growth and the stability of vegetation cover depending on the current climatic and hydrological conditions in the drained Kakhovka reservoir's territory. The results were obtained and the conclusions were drawn in the course of conducting comprehensive field research, calibrating and decoding the satellite images of Sentinel 2 L2A in 2023–2024. At the end of September 2023, the area covered with plants was 52.4 thousand hectares. The winter-spring period of 2024 was characterized by favorable climatic conditions, which contributed to spring floods that submerged up to 70% of the drained reservoir's territory. This led to substantial moisture accumulation in the bottom sediments, contributing to the rapid growth of plant biomass and active chlorophyll synthesis in leaves. At the end of September 2024, the vegetation cover area in the former reservoir's territory increased twofold. The maximum area of the reservoir's overgrown bed amounted to 135 thousand hectares in 2023–2024, including 48 thousand hectares with woody plants (willows and poplars); 87 thousand hectares were largely covered with marsh and meadow plants with shrub patches. The lack of precipitation and the abnormal increase in the air temperature in July to the historical maximum (+40.5–42.0 °C) for the examined area provoked an acceleration in evapotranspiration and depletion of moisture reserves in the drained reservoir's territory. This caused a deterioration in plant growth, drying out, and partial degradation. It was found that at the end of September 2024, 75.3% of vegetation cover was characterized by varying degrees of growth disturbance. A significant disturbance was observed in 43.5% of the area. The premature plant drying caused a loss of good properties of chlorophyll synthesis in 72.8% of the area. Negative processes led to a decrease in the area of healthy vegetation by 26.3 thousand hectares. It was proved that an increase in the frequency of climatic anomalies and a reduction in the discharge volumes from the Dnipro hydroelectric power plant into the former Kakhovka reservoir's territory is a cause of the complication of plant survival conditions.

Keywords: Kakhovka reservoir, plants, climate, hydrology, NDVI, NDMI, NDWI, OTCI.

INTRODUCTION

The Kakhovka reservoir's dewatering (Vyshnevskyi et al., 2023, 2024a, Pichura et al., 2024a) caused the exposure of the bottom sediments and a natural climatic transformation of the drained territory, which is characterized by the indicators of spatio-temporal differences in the seasonal differentiation of the moisture supply and phyto-climatic conditions of the reservoir. Plant biomass is an important indicator of the restoration and formation of ecological stability of the disturbed territorial landscapes, manifestations of desertification, moisture accumulation and storage, and the maintenance of soil regeneration processes and properties of bottom sediments of the drained reservoir's bed (Hapich and Onopriienko, 2024, Pichura et al., 2024b). Therefore, scientists' attention mainly focuses on studying and establishing patterns in the formation of natural vegetation cover in the drained reservoir's territory (Pichura et al., 2024a, Kuzemko et al., 2024, Vyshnevskyi and Shevchuk, 2024b). These studies are primarily local, and a comprehensive approach to examining the state of the Kakhovka reservoir's territory has not been used. This is primarily due to the limited access to the research territory, which is determined by active hostilities. In this regard, using satellite images, comparing them with the results of field research conducted in the accessible territory of the drained reservoir, and decoding these images accurately are deemed relevant.

In particular, Dovhanenko et al. (2024) used the satellite images of Sentinel 2, Landsat 8 and 9 to established that the spatial heterogeneous structure of the soil cover in the reservoir's drained layer consists of four soil types: 1) eutric relict gley fluvisols, 2) eutric fluvic fluvisols, 3) eutric fluvic-gley gleysols, 4) eutric fluvic subaquatic gleysols. Eutric gley fluisols prevail in the reservoir's bed. The soils are characterized by different granulometric compositions (sands, loamy sands, loams, and clays) with varying levels of moisture. The impact of the granulometric composition and soil moisture content on the intensity of plant overgrowth in the reservoir's bed was determined. Overgrowth could be found from the shoreline towards the central part of the reservoir's territory. Scientists highlighted that the shoreline was overgrown with taller plants. An increase in the vegetation cover was observed from the end of August till the end of September 2023, when the reservoir's bed surface was characterized by good moisture content. Active plant growth was observed until early November 2023.

The paper (Kuzemko et al., 2024) presents the results of the field research into the formation of vegetation cover in the gullies of Kamianka and Milove located on the right bank of the Kakhovka reservoir in the National Nature Park "Kamianska Sich". Scientists found that from June 30 to October 19, 2023, the number of vascular plants in the gullies, represented by 68 species, increased almost sevenfold. The vegetation was characterized by the dominance of the willow, a hybrid of the local species *Salix alba* and the naturalized alien species *Salix fragilis*. In October, the average tree height was 190 cm, with an average daily increase of 1.7 cm. The maximum tree height was recorded at 309 cm. Scientists think that the rapid colonization of the newly formed substrates by willows occurred due to the coincidence of the dam destruction and the period of willow seed maturation.

Vyshnevskyi and Shevchuk (2024b) recorded similar patterns of the formation of vegetation cover and willow growth. On June 21, 2024, the scientists conducted a field survey of the upper part of the former reservoir in two shoreline areas near the village of Malokaterynivka and the village of Bilenke. It was found that good moisture contents in the reservoir's bed, favorable weather conditions from July 2023 to June 2024 contributed to the rapid willow growth on sandy sediments – 1.2 cm/day and on organic sediments – 2.0 cm/day. The average willow height on organic sediments as of 21/06/2024 was 4.5 meters. The diameter of young trees at a height of 1.5 m was about 25 mm, and the density of willow overgrowth reached 30–40 pcs/m^2. Scientists maintain that in the future, climate change, low moisture content in the bottom sediments, and intraspecific competition of trees will cause a decrease in the growth rates of trees, provoke an increase in the proportion of poplars and a reduction in willow areas, and contribute to partial suppression of vegetation and the shoreline plants' drying out. In particular, the situation is aggravated by hostilities that result in fires. Scientists use satellite images to monitor the state of vegetation in the former reservoir's territory.

Reconstructing the historical map, which reflects the territory before the construction of the Kakhovka reservoir, allowed us to establish that the forest cover in the Great Meadow (Velykyi Luh) territory was not more than 10% (Vyshnevskyi and Shevchuk, 2024). In other words, the forest cover in the territory was insignificant under favorable natural climatic conditions of the Great Meadow's functioning, which refutes the assumption about the possibility of the formation of large forest areas in the reservoir's bed. In this regard, the research aims to establish the patterns of plant growth and the stability of vegetation cover depending on the current climatic and hydrological conditions in the drained Kakhovka reservoir's territory.

MATERIAL AND METHODS

Research schemes and materials

The research scheme included four logical successive stages (Fig. 1). The source of up-to-date data for examining the state of vegetation cover in the former reservoir's territory (Fig. 2) included field observations in the accessible area of the Kamianka gully in the right bank part of the Dnipro River, the data of the aerial reconnaissance in the section of the village of Respublikanets → the city of Beryslav in Kherson region. The satellite

Research stages

1. Examining mosaic heterogeneity of the gullies in the Reservoir's territory based on field observations and the data of Sentinel 2 L2A: *NDVI*

↓

2. Examining the climatic and hydrological conditions of the formation of vegetation cover in the Reservoir's bed according to the data of Sentinel 2 L2A and Sentinel-3 OLCI L1B: *NDVI, NDWI, OTCI*

↓

3. Determining spatio-temporal patterns of the formation of vegetation cover in different areas of the Reservoir's bed according to the data of Sentinel 2 L2A and Sentinel-3 OLCI L1B: *NDVI, NDMI, NDWI, OTCI*

↓

4. Examining the stability of vegetation cover according to the data of Sentinel 2 L2A and Sentinel-3 OLCI L1B: *NDVI, OTCI*

Methods for decoding satellite images: *Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), Normalized Difference Water Index (NDWI), Terrestrial Chlorophyll Index (OTCI)*

Figure 1. The research scheme of the drained bed of the Kakhovka reservoir

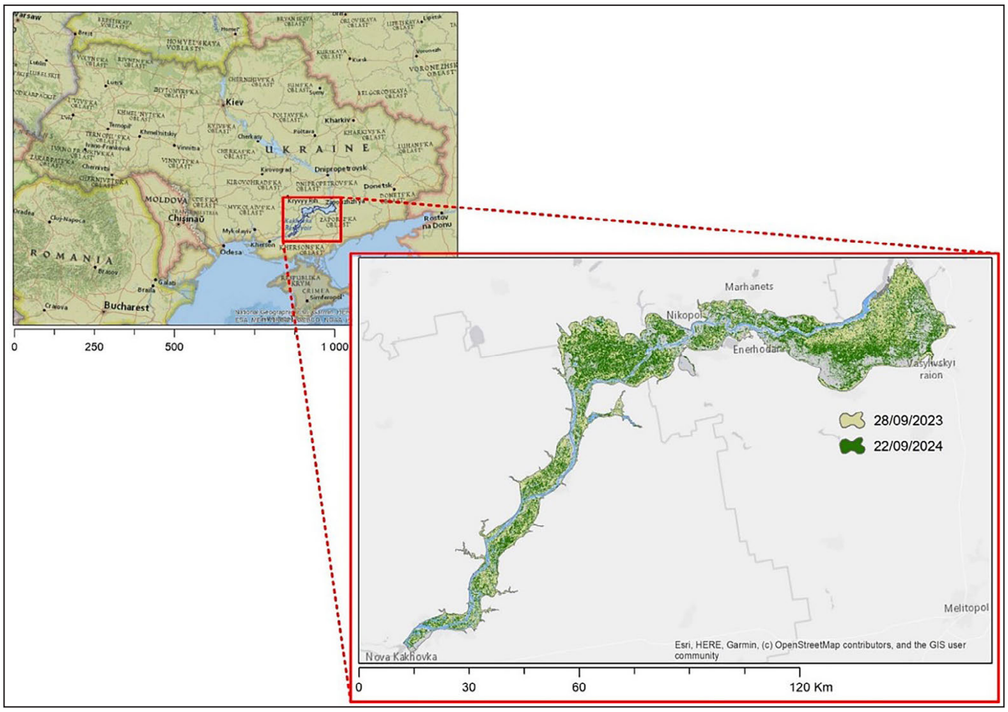


Figure 2. The research territory of the Kakhovka reservoir's drained bed

images of Sentinel 2 L2A and Sentinel-3 OLCI L1B were used to decode and calculate vegetation and moisture indices between 18/06/2023 and 22/09/2024. Cloudless periods were studied.

Methods for decoding satellite images

The normalized difference water index (NDWI) was used to determine the area of water bodies and the former reservoir's bed submerged by spring floods (Gao, 1996, Ahmed and Akter, 2017, Ashok et al., 2021):

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (1)$$

where: *Green* is a green spectral band, and *NIR* is a near-infrared spectral band.

The territories covered with water correspond to the *NDWI* value which is higher than -0.2. The normalized difference moisture index (NDMI) was used to determine the moisture content in plants in the corresponding Sentinel 2 L2A bands (Gao, 1996, Tibangayuka et al., 2025):

$$NDMI = \frac{NIR\text{-}SWIR}{NIR+SWIR} \quad (2)$$

where: *NIR* is a near-infrared spectral band, and *SWIR* is a short-wave infrared spectral band.

The range of NDMI values is from -1 to 1. Negative NDMI values (close to -1) correspond to infertile soil – without vegetation. Values near zero (from -0.032 to 0.032) correspond to water stress. Values from 0.032 to 0.24 characterize satisfactory moisture content in the vegetation cover, values from 0.24 to 0.80 indicate good moisture content, and values more than 0.80 correspond to high moisture content. The NDVI was used to determine the state of vegetation cover and plant health in the corresponding Sentinel 2 L2A bands (Ashok et al., 2021, Pichura et al., 2024c):

$$NDVI = \frac{NIR\text{-}Red}{NIR+Red} \quad (3)$$

where: *NIR* is a near-infrared spectral band, and *Red* is a red spectral band.

The range of NDVI values is from -1 to 1. According to the typical NDVI classification, negative values correspond to clouds, water and snow, and values from 0 to 0.4 mainly indicate stones and bare soils. NDVI values more than 0.4 identify vegetation.

Given the differences between the spectral characteristics of bottom sediments and typical soil cover, we used the field research results to calibrate satellite images that ensure objective recognition of bare and vegetated areas of the former reservoir's bed. In particular, the classification of growth properties and plant structure was based on the NDVI. It was found that NDVI values from 0 to 0.6 corresponded to the territories without vegetation, covered with shells and stones, with takirs and sands. NDVI values over 0.6 indicate vegetation, namely 0.60–0.70 – satisfactory vegetation; 0.70–0.85 – good vegetation; 0.85–1.00 – very good vegetation. It was found that at the peak of plant growth, NDVI values from 0.60 to 0.85 mainly characterized marsh and meadow vegetation with shrub patches; NDVI values more than 0.85 indicated the presence of woody plants (largely willows and poplars).

Seasonal characteristics of plant growth disturbance were calculated using the formula:

$$\Delta NDVI = NDVI_t\text{-}NDVI_{t-n} \quad (4)$$

where: $NDVI_t$ is the state of vegetation on the current date of the research; $NDVI_{t-n}$ is the state of vegetation on the previous date of the research.

The plant growth disturbances ΔNDVI were calculated based on the following conditions: ΔNDVI ≥ 0 – without changes; from 0 to -0.1 – low disturbance; from -0.1 to -0.2 – medium disturbance; from -0.2 to -0.3 – high disturbance; ΔNDVI < -0.3 – very high disturbance. The research was conducted based on decoding the main growth stages of the active formation of vegetation cover, namely 28/09/2023, 09/06/2024, 14/07/2024, 23/08/2024, and 22/09/2024.

The plant growth disturbances $\Delta NDVI_{GV}$ in the drained reservoir's territory were determined as of 22/09/2024 in relation to the $NDVI_{max}$ values (28/09/2023; 09/06/2024; 14/07/2024; 23/08/2024) using the formula:

$$\Delta NDVI_{GV} = NDVI\begin{bmatrix}22\\09\\24\end{bmatrix} - \\ - NDVI[28/09/23; 09/06/24; 14/07/24; 23/08/24]_{max} \quad (5)$$

The terrestrial chlorophyll index (OTCI) was used to calculate the chlorophyll content in leaves of the vegetation cover in the reservoir's bed. The following formula was used (Dash et al., 2010, Kovács et al., 2024):

$$OTCI = \frac{(B12-B11)}{(B11-B10)} \quad (6)$$

where: B10, B11 and B12 are the corresponding bands of Sentinel-3 OLCI L1B.

The OTCI, the terrestrial chlorophyll index, can be used to assess chlorophyll content over land to monitor vegetation condition and health. It is produced globally at 270 m spatial resolution from OLCI data on the Sentinel 3 mission.

Our observations allowed us to classify the chlorophyll content in plants in the Kakhovka reservoir's bed: OTCI values less than 1.8 – very low; 1.8–2.2 – low; 2.2–2.5 – medium; 2.5–3.0 – increased; 3.0–3.5 – high; OTCI values more than 3.5 – very high chlorophyll content. OTCI values less than 2.2 indicate significant water stress in plants; 2.2–2.5 – insufficient moisture content in plants; 2.5–3.0 – satisfactory moisture content in plants; and more than 3.0 – good moisture content in plants. A change in the chlorophyll content in plants ΔOTCI (%) in the reservoir's bed was determined as of 22/09/2024 in relation to the $OTCI_{max}$ values (28/09/2023; 09/06/2024; 14/07/2024; 23/08/2024) using the formula 7: The rasters of the $NDVI_{max}$ values and $OTCI_{max}$ values were calculated using the Cell Statistics of ArcToolbox, ArcGIS. ArcGis 10.6 was applied for image processing, mapping, and spatio-temporal analysis.

$$\Delta OTCI = \left[\frac{OTCI[22/09/24]}{OTCI[28/09/23;\ 09/06/24;\ 14/07/24; 23/08/24]_{max}} - 1\right], \% \quad (7)$$

RESULTS AND DISCUSSION

Mosaic heterogeneity of the reservoir's gullies

In September 2023, the gully systems were characterized by good conditions for vegetation development, with the proportion of vegetation cover in their territories ranging from 30.7% to 60.3% (Fig. 3). The state of the vegetation cover was considered satisfactory, good, and very good. The state of the areas with a medium density of low plants was satisfactory; the state of the mosaic-heterogeneous dense patches of shrubs (mainly willows) up to 1.0-1.3 m high was good, the state of the areas with willows of over 1.3m high was very good. Overall, in September 2023, the total area of the gullies covered with willows was 1193 hectares (36.5%). The area with low plants was 580.8 hectares (17.8%), the area without vegetation was 27.1%, and water bodies covered 18.6%.

Figure 4 shows the Kamianka gully as of April 21, 2024 in different mosaic-heterogeneous areas. Most of the area without vegetation is covered with shells, takirs, sands, stones, and shallow waters. Willows of 1.3–1.8 m high prevail in the vegetation structure. About 15% of the area is covered with willows of 1.8 m high.

It is notable that the total area of gullies is only 3.0% of the drained Kakhovka reservoir's territory. This refutes the possibility of using them as an indicator of favorable natural climatic conditions for the formation of plant biomass in the main territory of the drained reservoir. Therefore, the results of the field research into the state of gullies can be useful for characterizing the species composition of flora and assessing changes in the state of vegetation cover in the adjacent areas. The results of the field research were used for accurate interpretation of satellite images, identification, and distance monitoring of the spatiotemporal mosaic heterogeneity of plants on the bottom landscapes in the entire reservoir's territory with an area of 215.5 thousand hectares.

Climatic and hydrological conditions for the formation of vegetation cover in the reservoir's bed

Based on the results of the field research and decoding of the satellite images of Sentinel 2 L2A, we specified the spectral characteristics of vegetation identification and plant growth, and accurately determined the overgrown areas in the reservoir's bed in 2023–2024 (Fig. 5).

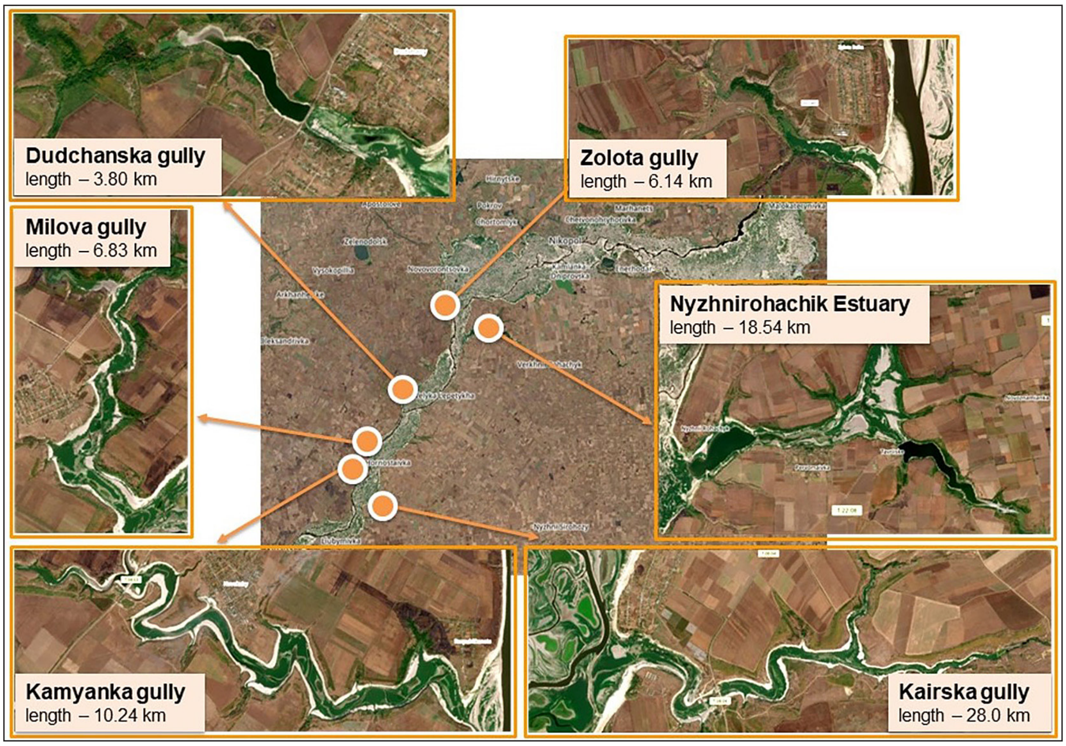


Figure 3. Gullies of the Kakhovka reservoir

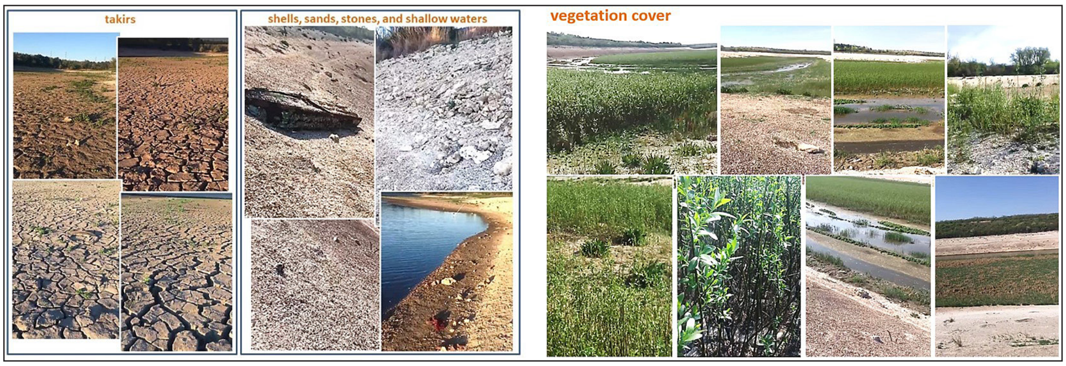


Figure 4. Mosaic heterogeneity of the gullies in the drained reservoir as of April 21, 2024

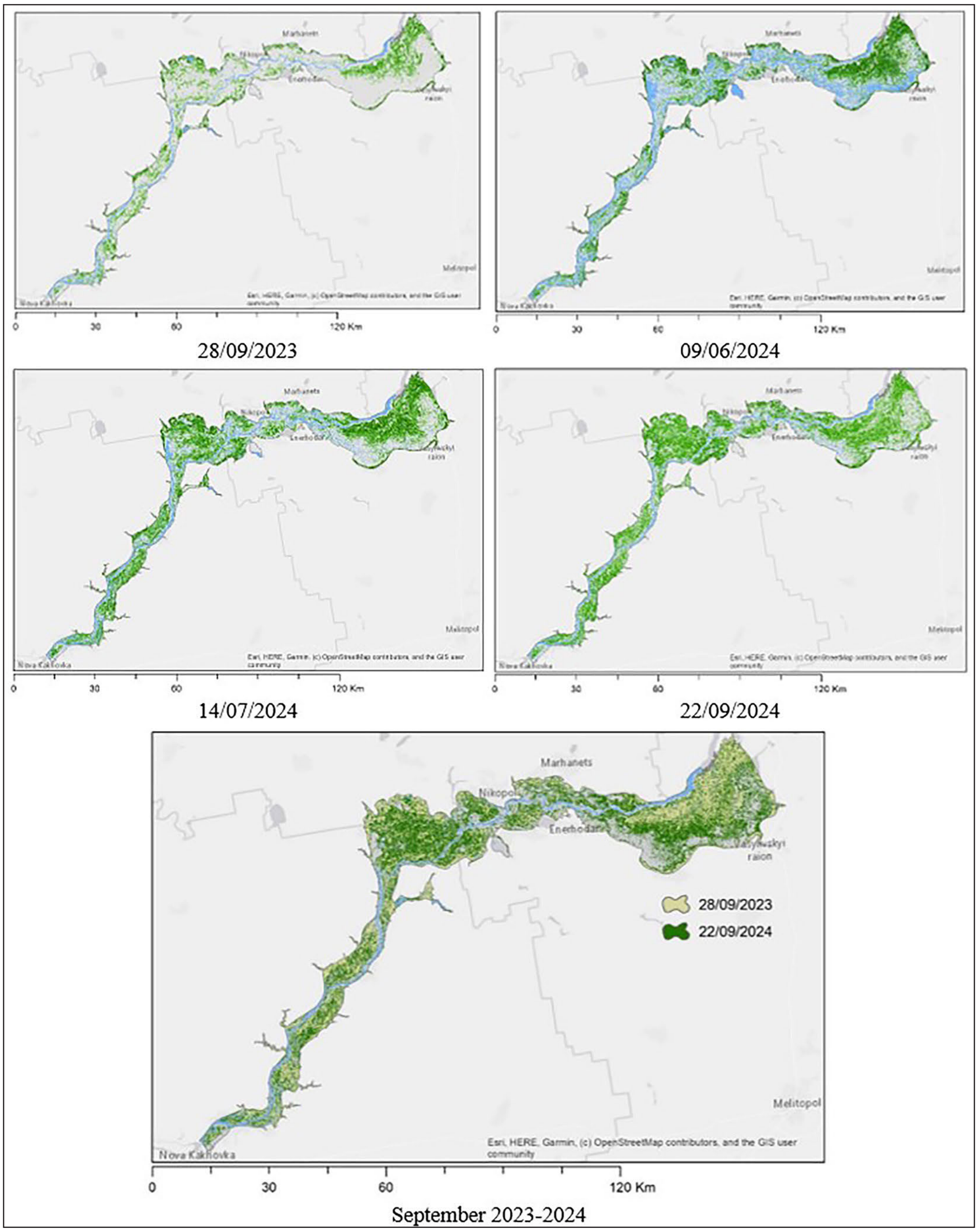


Figure 5. Formation of vegetation cover in the reservoir's bed in September 2023–2024

In particular, based on the data of Sentinel-3 OLCI L1B, the spatio-temporal patterns of chlorophyll formation in plant leaves were identified (Fig. 6). It was found that at the end of September 2023, the plant area was 52.4 thousand hectares: plants covering 37.0% of the area were characterized by satisfactory growth, plants in 46.7% of the area were characterized by good growth, plants covering 16.3% of the area were characterized by very good growth. About 19.1% of plants were at the initial stage of growth, hence they had low chlorophyll content (Table 1). 30.8% of plants had medium and increased chlorophyll content. In particular, 50.1% of plants was characterized by high and very high chlorophyll content in leaves and had good conditions of organic and water nutrition, which contributed to rapid plant growth and the formation of leaf surface density.

After the winter anabiosis and the end of spring floods, at the beginning of June 2024, the area covered with plants was 78.2 thousand hectares, including 20.3% with satisfactory growth, 38.1% with good growth, and 41.6% with very good growth. About 35% of plants was at the stage of growth recovery, hence they were characterized by low chlorophyll content. 12.2% of the vegetation cover had medium chlorophyll content, and 22.9% of plants had increased photosynthetic activity. The remaining 29.9% of plants had significant growth and chlorophyll synthesis

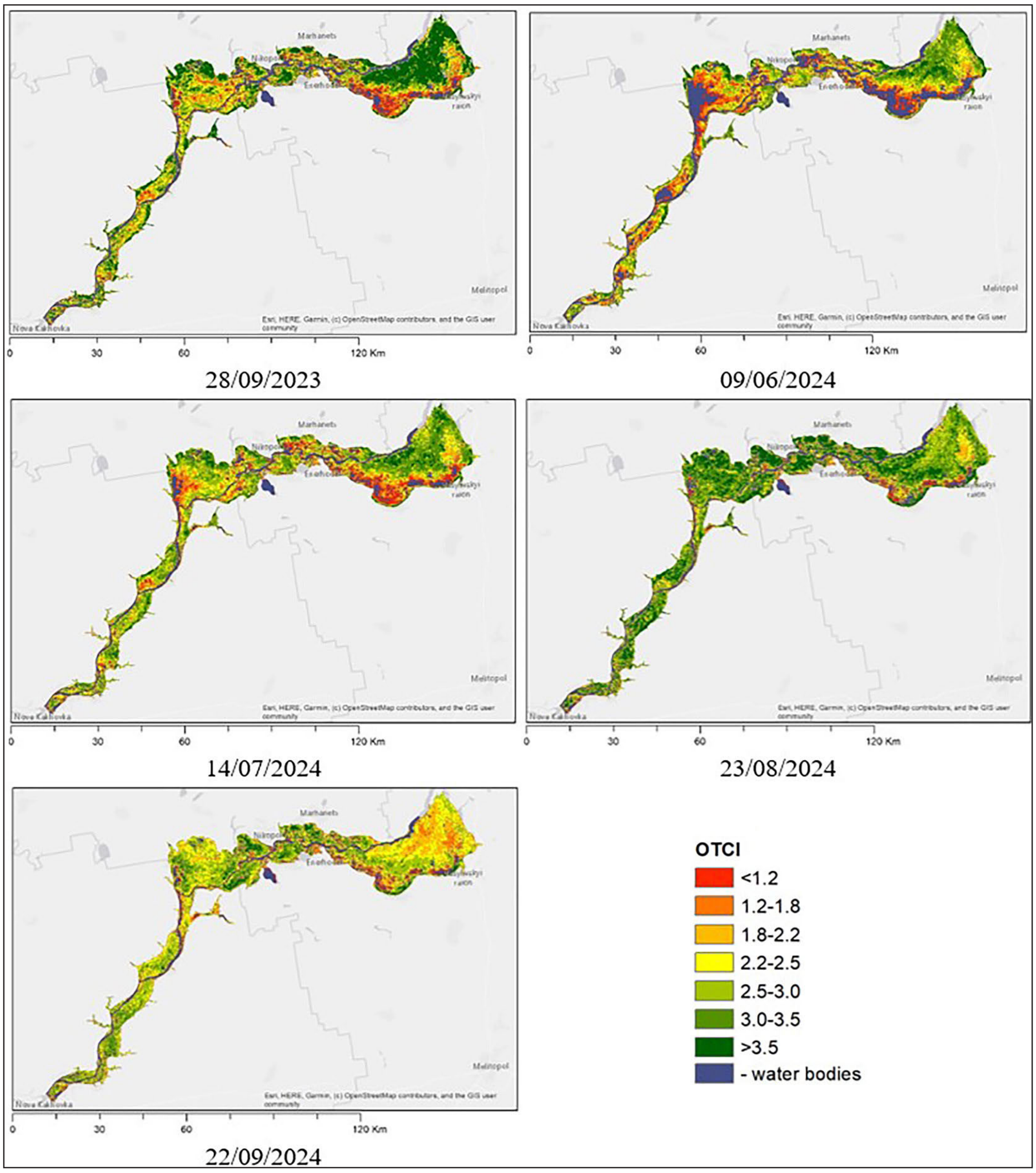
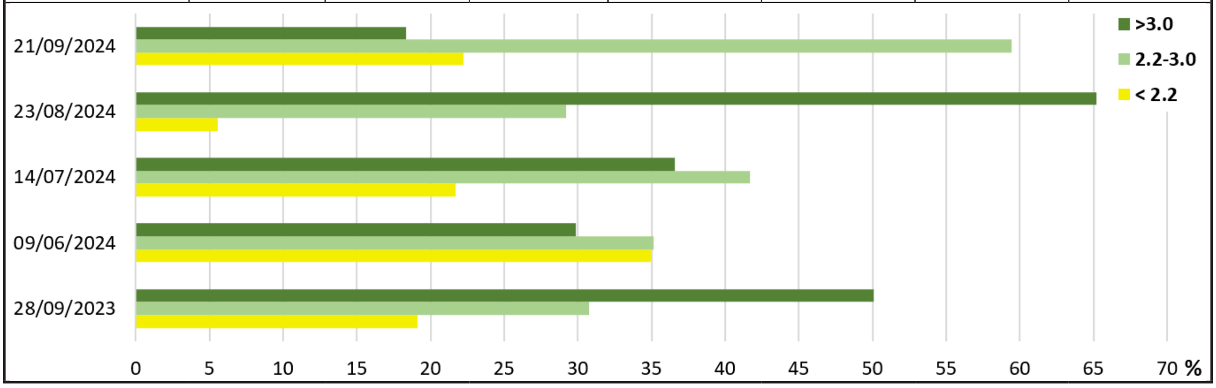


Figure 6. Patterns of plant chlorophyll formation (OTCI) in the reservoir's bed in September 2023–2024

Table 1. Patterns of plant area distribution in the Kakhovka reservoir's bed by chlorophyll content in leaves

Data	Terrestrial chlorophyll index (OTCI)						
	< 1.2	1.2–1.8	1.8–2.2	2.2–2.5	2.5–3.0	3.0–3.5	> 3.5
28.09.2023	2.1	7.4	9.6	11.1	19.7	16.3	33.8
09.06.2024	5.9	16.6	12.5	12.2	22.9	22.0	7.9
14.07.2024	3.1	8.2	10.5	12.5	29.2	28.8	7.8
23.08.2024	0.6	1.5	3.5	5.7	23.5	36.9	28.3
22.09.2024	0.6	4.1	17.5	24.1	35.4	14.5	3.8



in leaves. As of July 14, 2024, the area covered with plants increased by 26% and amounted to 98.5 thousand hectares, including 21.5% with satisfactory growth, 51.2% with good growth, and 27.4% with very good growth. About 21.8% of the vegetation had low photosynthetic properties of chlorophyll synthesis. 12.5% and 29.2% of the vegetation cover were characterized by medium and increased chlorophyll content, respectively. 36.6% of plants had high chlorophyll content in leaves.

The prolonged spring floods resulted in good moisture saturation and retention in the reservoir's bed that led to protracted plant resistance to high summer temperatures and an increase in the vegetation cover in the third decade of August. The area covered with plants was 102.0 thousand hectares, including 26.5% with satisfactory growth, 67.0% with good growth, and 6.5% with very good growth. 11.3% of the vegetation cover was characterized by low and medium chlorophyll content. Increased and high levels of chlorophyll synthesis were characteristic of 88.7%.

At the end of September 2024, the vegetation cover amounted to 110.0 thousand hectares, including 29.6% with satisfactory growth, 64.1% with good growth, and 6.3% with very good growth. The prolonged summer heat, lack of precipitation, evapotranspiration, and depletion of moisture reserves caused a deterioration in the stability of plant biomass and a decrease in chlorophyll synthesis and contributed to the premature drying of the leaf surface. In particular, significant water stress was characteristic of 22.2% of plants, 24.1% of plants had insufficient moisture content, and 53.7% had satisfactory and good moisture conditions.

The rapid growth of plant biomass in 2023–2024 was determined by the combination of moisture and nutrients in the bottom sediments. It is notable that the winter-spring period of 2024 was characterized by favorable climatic conditions, which can be regarded as abnormally favorable in terms of the frequency of moisture manifestations. In particular, similar conditions were recorded in 1982 (Fig. 7). The total value of relative air humidity in the winter-spring period of 2024 exceeded the statistical norm for the period 1982–2024 by 8.8%, and the excess was 10.1% in 1982.

An abnormally high level of moisture content was recorded throughout the entire catchment area of the Dnipro River, which led to a significant accumulation of large water volumes in the main river course, contributed to the formation of good hydrological conditions, and resulted in an increase in the frequency of surface water discharges from the Dnipro hydroelectric power plant into the Kakhovka reservoir's territory. The decoded satellite images of Sentinel 2 L2A allowed us to record the Kakhovka reservoir's filling with water at the beginning of March 2024: 65.0% of the territory was flooded as of March 11, 70.0% – as of March 31, 55.4% – as of April 30, and 47.3% – as of April 25 (Fig. 8).

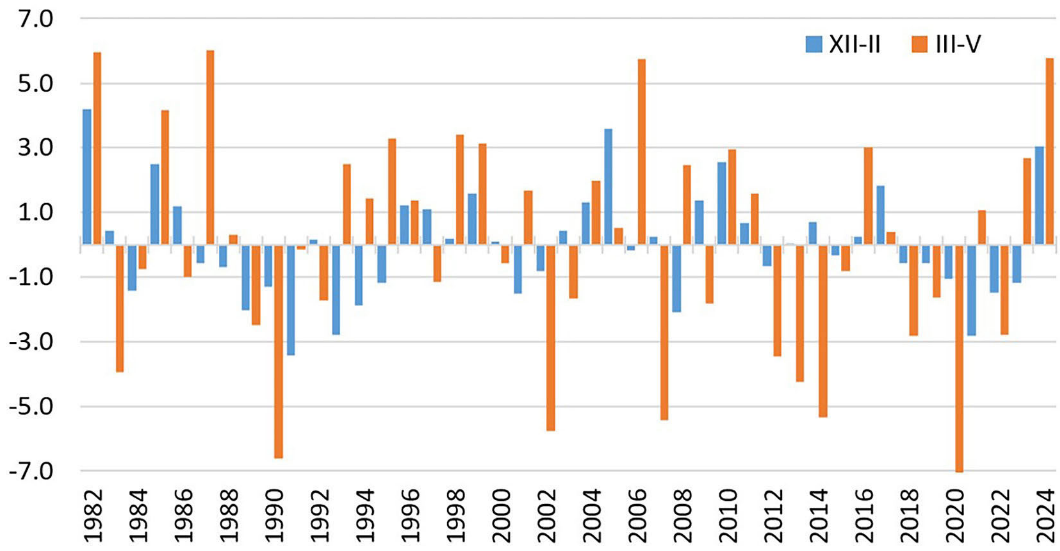


Figure 7. Dynamics of relative air humidity (%) in the Kakhovka reservoir in 1982–2024: deviations from the statistical norm in winter (79.8% of moisture content) and summer (68.6% of moisture content) periods

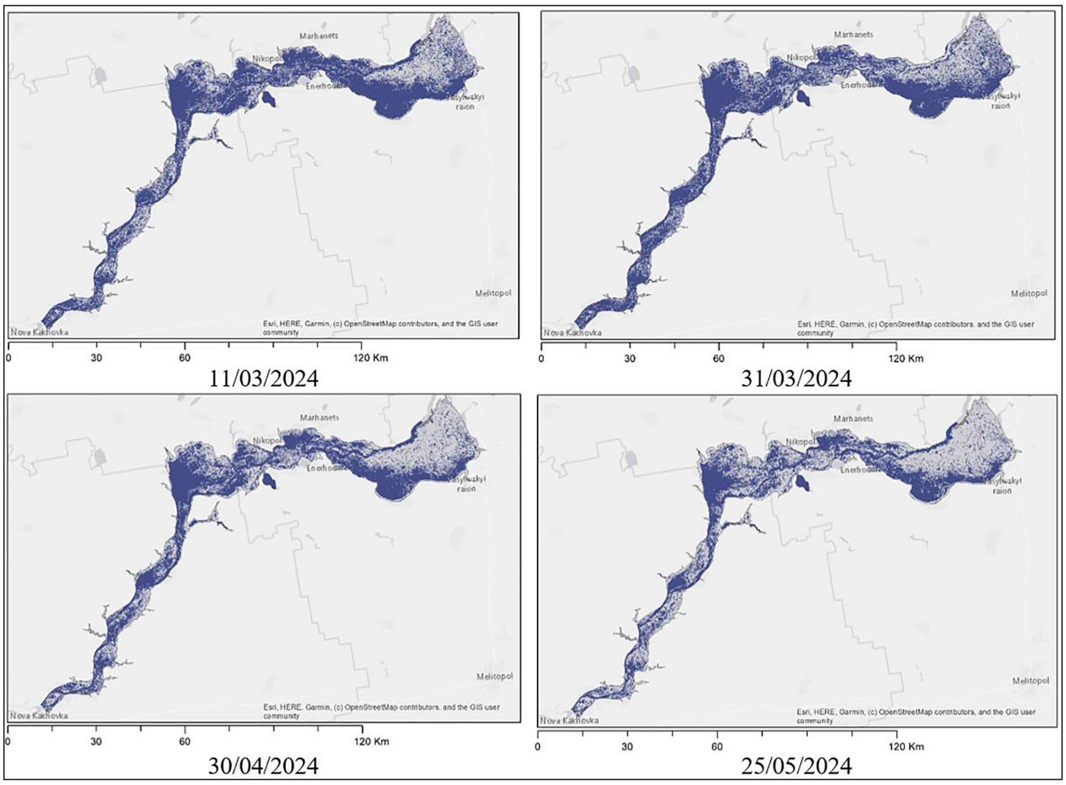


Figure 8. Spring floods in the Kakhovka reservoir's territory in 2024

During the spring floods, there were (Vyshnevskyi and Shevchuk 2024b) two waves of maximum water release through the Dnipro hydroelectric power plant: the first wave was recorded on 15/03/2024 with values of 3500 m^3/s, the second wave was observed on 23/04/2024 with a value of 4130 m^3/s. In particular, the water flow rate in the lower course of the Dnipro River from June 1, 2023 to June 30, 2024 was higher than usual. The average flow rate of releases through the Dnipro hydroelectric power plant was 1730 m^3/s (54.6 km^3). Therefore, these conditions can be considered atypical conditions for the Steppe zone of Ukraine, which contributed to survival, significant biomass growth, and plant overgrowth in the reservoir's bed.

Spatio-temporal patterns of the formation of vegetation cover in different areas of the reservoir's bed

To identify spatio-temporal patterns of the formation of vegetation cover from June 18, 2023 to September 22, 2024, we selected three sites of the former reservoir (Fig. 9), which differ in hydrological network densities and organic residues in the bottom sediments. We presented the dynamics of the weighted average of the NDMI and the NDVI at three observation sites. In particular, a close correlation between the NDMI and NDVI values was established. This allowed us to track the chronology of plant growth depending

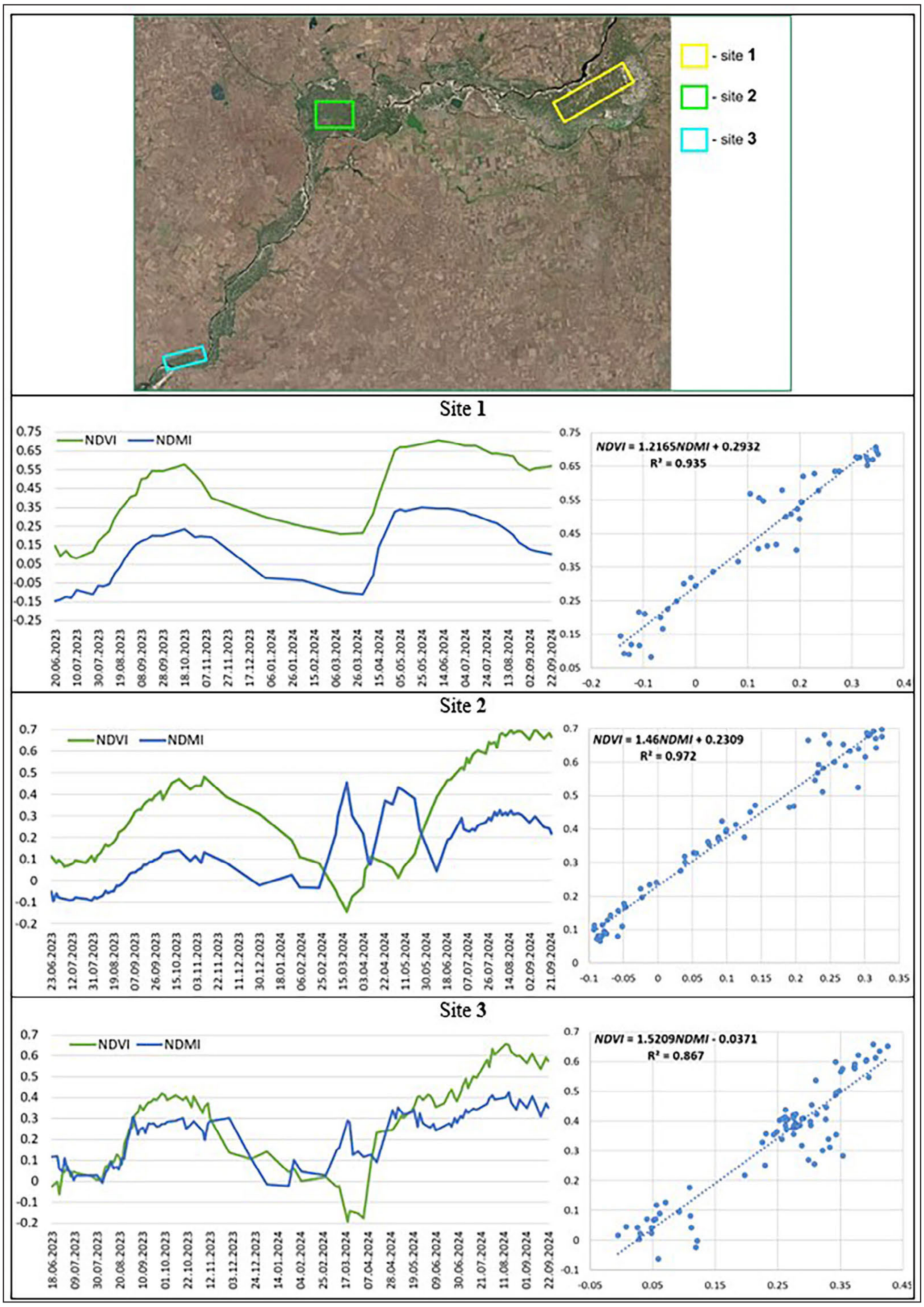


Figure 9. Spatio-temporal patterns of moisture content and plant growth in the drained Kakhovka reservoir's territory

on spatial differences in the moisture conditions in different parts of the reservoir. It is notable that in 2023, a high level of moisture reserves in the bottom sediments was recorded at all observation sites, which stimulated rapid growth and a good level of plant development until early November. At the beginning of the first wave of the spring flood (15/03/2024), plant growth recovery was observed in open areas throughout the entire territory of the reservoir's bed.

Site 1 in the upper part of the reservoir is characterized by a high level of organic matter in the bottom sediments. Before the Kakhovka Dam destruction, this reservoir's territory had a water area of 0.7–2.5 m deep and contained about 18% of the reservoir's water volume. 11% of water reserves did not participate in flow regulation, which provoked water stagnation and algal blooms, a high level of organic matter accumulation and the formation of patches of polytrophic and hypertrophic water masses. Site 1 does not have a direct hydrological connection with the main course of the Dnipro River. The moisture content in the area depended on moisture reserves after the dam destruction and spring floods. In 2024, the water of spring floods flowed to Site 1 through a natural hydrological arm near the city of Enerhodar (the left-bank part of the reservoir), and then surface waters flowed to the lower part of the drained reservoir's bed opposite the city of Dniprorudne, and the bed was flooded with significant water volumes. The width of the flooded bed from the shoreline of the city of Dniprorudne to Site 1 was over 14 km.

Along the shoreline, the water spilt for 65 km – from the city of Enerhodar to the village of Plavni, Vasylivka district, Zaporizhzhia region. This ensured good plant nutrition in the upper part of the reservoir. From March 15 to April 30, 2024, significant plant growth was observed at Site 1. The large volumes of surface water releases from the Dnipro hydroelectric power plant at a rate of 3500–4130 m^3/c (110.5–130.3 km^3) contributed to the maintenance of a high moisture content and an increase in the intensity of plant growth by 1.6 times (the NDVI – from 0.41 to 0.65). The willow growth was 2.0 cm/day. From April 30 to June 9, a high moisture content and an increase in the NDVI value from 0.65 to 0.71 were observed at Site 1. At the end of June, the willow height reached 4.5 m and more.

After the spring floods, on July 9, 2024, water from the upper part of the reservoir was discharged back to the Dnipro River's main course,

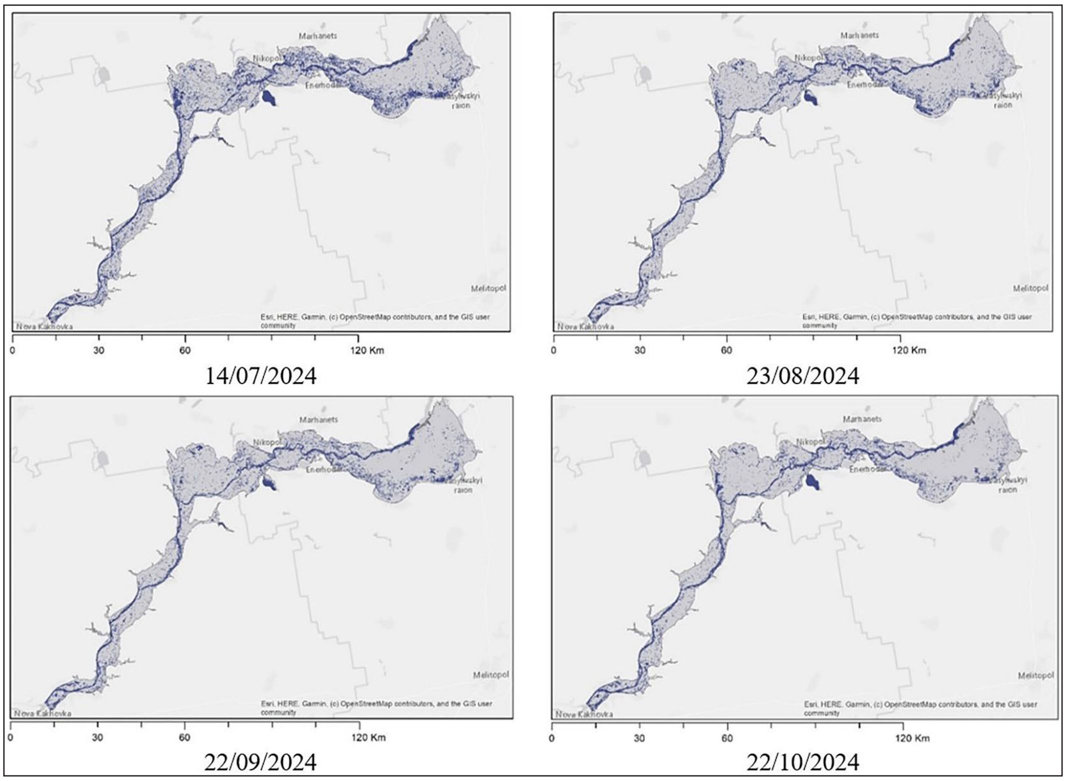


Figure 10. Distribution of the areas covered by water in the former Kakhivka reservoir' s territory in the summer-autumn low-water season of 2024

which reduced water nutrition of plants in the main territory of the reservoir's bed. During the summer-autumn low-water season, the proportion of areas covered by water in the former reservoir (Fig. 10) was 24.3% as of July 14, 2024, 18.2% – as of August 23, 16.2% – as of September 22, and 16.3% as of October 22.

The lack of precipitation and water releases from the Dnipro hydroelectric power plant, abnormally high air temperatures and the lack of a hydrological connection between Site 1 and the main course of the Dnipro river caused moisture depletion and a deterioration in plant growth. Thus, a slight decrease in the NDVI from 0.71 to 0.68 was recorded by July 14, 2024. A rise in the air temperature in July, which reached a historical maximum of +40.5–42.0 °C, and a fivefold increase in the frequency of abnormally high temperatures in the summer period for the research area caused an acceleration in evapotranspiration, depletion of moisture reserves in the reservoir's bed, an accelerated deterioration in plant growth and drying out. The average NDVI value decreased by 21%, from 0.68 to 0.54. Large patches of plants completely ceased their growth. From July 27 to August 19, fires in the upper part of the reservoir swept an area of 320 hectares (Fig. 11).

Site 2 in the middle part of the reservoir was characterized by good and stable moisture content. This part of the reservoir's bed has a good hydrological network and accumulation of spring flood waters of the Dnipro River. In particular, this territory is additionally fed from water of the Bazavluk River, which is 157 km long and has a catchment area of 4.2 thousand km^2. The river flows in Krynychanka, Sofiivka, and Nikopol districts of Dnipropetrovsk region and is a right tributary of the Dnipro Rriver.

Site 2 was covered by water during the spring flood of 2024. After May 20, after the water gradually descended to the main course of the Dnipro River, plants resumed growth in this area. The long flooding period ensured a high level of moisture saturation in the bottom sediments. In particular, additional moisture was provided by the water of the Bazavluk River. This stimulated good growth and high stability of the plant cover during the summer heat. Stable plant growth was observed until the third decade of August. The average NDVI value in July was 0.58–0.60, and it reached 0.70 in mid-August. A slight deterioration of plant growth was observed at the end of September, and the average NDVI value decreased from 0.70 to 0.65. It is notable that Site 2 is characterized by relatively stable moisture content and organic nutrition of the bottom sediments, which contributed to stable conditions of the formation of vegetation cover in 2023–2024.

Site 3, opposite the village of Novoberyslav and the town of Beryslav, is located on the Neogene limestone strata in the lower part of the reservoir and is characterized by a good hydrological connection with the surface runoff of the main course of the Dnipro River, a high density of shallow water zones, a considerable portion of sandy areas, and a low level of organic matter. Therefore, the intensity of plant growth mainly depends on the water level of the river's main course, which affects the water supply of Site 3. After the beginning of the spring floods, there were good

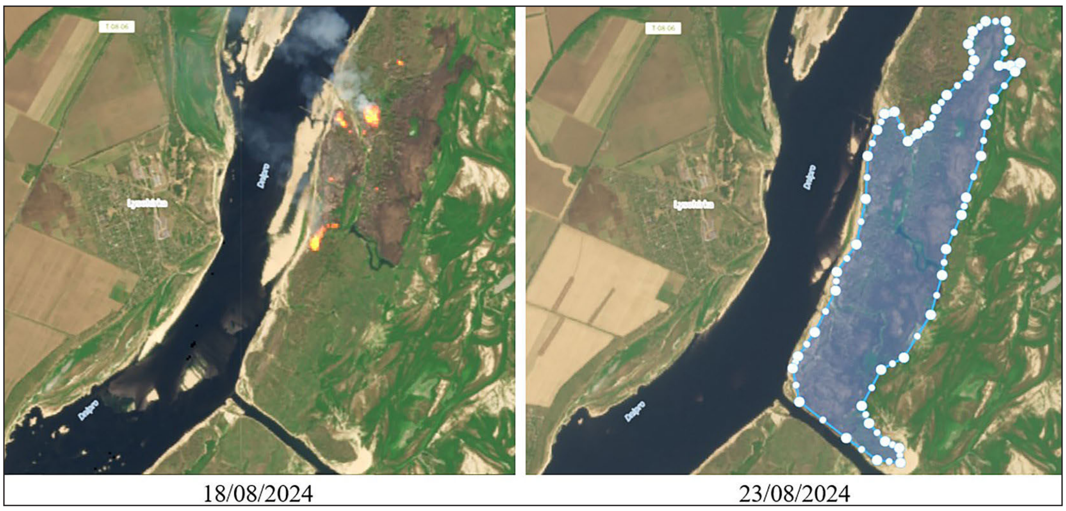


Figure 11. Fires in the upper part of the drained Kakhovka reservoir, according to the data of Sentinel 2 L2A

moisture conditions in this area. In particular, the gradual discharge of water reserves from the upper and middle parts of the former reservoir determined the systematic water nutrition of plants in its lower part. Therefore, stable conditions for plant growth and the formation of vegetation cover were observed from mid-April to mid-August. The average NDVI value increased by 2.9 times – from 0.23 to 0.66. The lack of precipitation and water discharges from the Dnipro hydroelectric power plant caused a decrease in the water level in the main course of the Dnipro River. The shallowing and the partial drying of the river's arms in the hydrological network of the lower part of the drained reservoir caused plant stress at Site 3. This was a cause of a decrease in the average NDVI value from 0.66 to 0.56 between August 13 and September 15. Short-term rainfall on September 20 contributed to a partial resumption of plant growth, but after September 22, a deterioration in plant growth was observed.

The spatio-temporal differences in the climatic and hydrological conditions for the formation of vegetation cover led to heterogeneity of the photosynthetic process of chlorophyll synthesis in different areas of the Kakhovka reservoir's bed (Fig. 12). After the reservoir was drained, in July 2023, there was an increased level of chlorophyll synthesis in aquatic plants, which caused their drying out. Subsequently, new biomass of meadow-marsh and woody plants was formed. The highest intensity of chlorophyll synthesis in plants was observed at Site 3, which was well supplied with organic matter and moisture. However, the high intensity of plant growth and plant density in the upper part of the reservoir's bed caused the rapid depletion of growth resources, which, against the backdrop of high temperatures in July 2024, led to plants' accelerated ageing and premature drying out. At Sites 2 and 3, the intensity of chlorophyll synthesis was lower, which caused a lower intensity of plant growth and development and resulted in sparse foliage. This made it possible to save growth resources at these sites and prolong good growing conditions until the third decade of August 2024.

Research into the stability of vegetation cover

Given the manifestation of negative climate change and artificial regulation of releases from the Dnipro hydroelectric power plant, it is important to examine the stability of plant growth and the formation of vegetation cover in the former Kakhovka reservoir's territory. In this regard, the NDVI values were used to calculate the seasonal plant growth disturbances in September 2023–2024 (Fig. 13).

Calculations were carried out for the important periods of the formation of vegetation cover. The boundaries of vegetation cover were determined at the beginning of each research period. Based on the research results, we identified spatio-temporal characteristics of the disturbances of vegetation biomass depending on the current climatic and hydrological conditions of the drained reservoir.

It was found that plants had the most significant water and temperature stress in the periods 09/06–14/07/2024 and 14/07–23/08/2024. During the first period, the spring floodwater receded

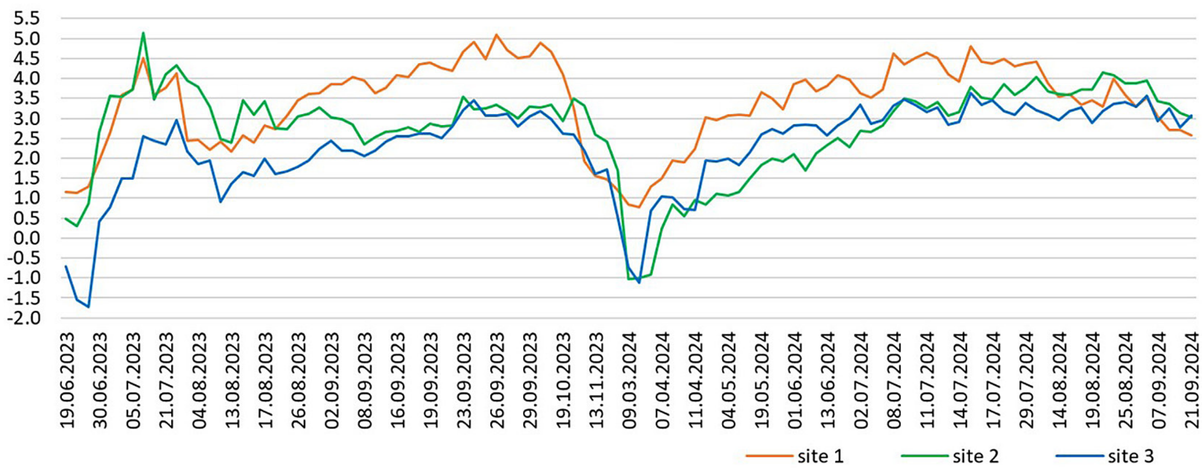
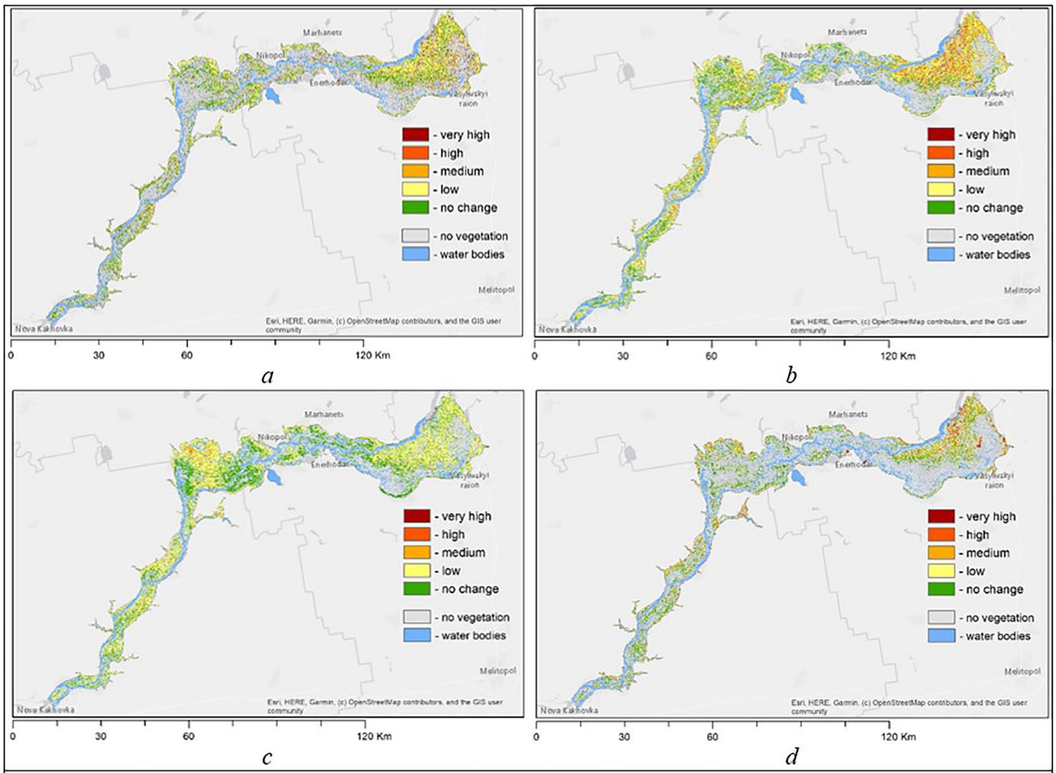


Figure 12. Spatio-temporal heterogeneity of the formation of plant chlorophyll (OTCI) in the reservoir's bed in 2023–2024



Disturbances of vegetation cover in relation to the area of the previous period						
Period	Area, thous. ha	Disturbances of vegetation cover, % share				
		no changes	low	medium	high	very high
09/06-14/07/2024	78.2	33.7	39.3	11.5	5.3	10.1
14/07-23/08/2024	98.5	27.9	46.8	17.6	5,2	2.4
23/08-22/09/2024	102.0	39.4	54.9	5.1	0.5	0.1
28/09/2023-22/09/2024	52.4	45.2	28.5	15.3	5.6	5.3

Figure 13. Seasonal characteristics of plant growth disturbances in the Kakhovka reservoir's bed in September 2023–2024: *a* – period 09/06–14/07/2024; *b* – period 14/07–23/08/2024; *c* – period 23/08–22/09/2024; *d* – period 28/09/2023-22/09/2024

and the reservoir's territory was drained. This caused the first manifestations of stress and a loss of good growing conditions for plants in the upper part of the reservoir. In turn, this led to the disturbance of vegetation cover from medium to very high levels. The second period was characterized by abnormally high air temperatures and extreme levels of plants' water stress. This caused a deterioration in the growth of more than 70% of plants in the reservoir's bed. A high level of plant growth disturbances was observed in an area of 25 thousand hectares on the bottom soils, which did not have hydrological feeding from the main course of the Dnipro River. During the third period, 23/08–22/09/2024, plants gradually lost good growth characteristics, which caused their premature drying out. It is notable that in 2023, plants were characterized by active growth until early November. To identify the actual situation of the formation of vegetation cover's structure and area and calculate the disturbances of plant growth, we systematized a raster model of vegetation with the $NDVI_{max}$ values (Fig. 14*a*) based on the NDVI rasters as of 28/09/2023, 09/06/2024, 14/07/2024, and 23/08/2024. This allowed us to establish the boundaries of the reservoir's bed covered with plants in September 2023–2024. The vegetation area amounted to 135 thousand hectares, including 48 thousand hectares with woody plants (willows and poplars) and 87 thousand hectares with marsh and meadow plants with shrub patches.

The calculation of plant growth disturbances $\Delta NDVI_{GV}$ (Fig. 14*b*) was carried out as of 22/09/2024 in relation to the raster of the $NDVI_{max}$ values. It was found that 24.7% (33 thousand hectares) of the vegetation cover was not disturbed, and 75.3% (102 thousand hectares) of the territory had a varying degree of plant growth disturbances. A significant growth disturbance was recorded in 43.5% (58.7 thousand hectares) of the

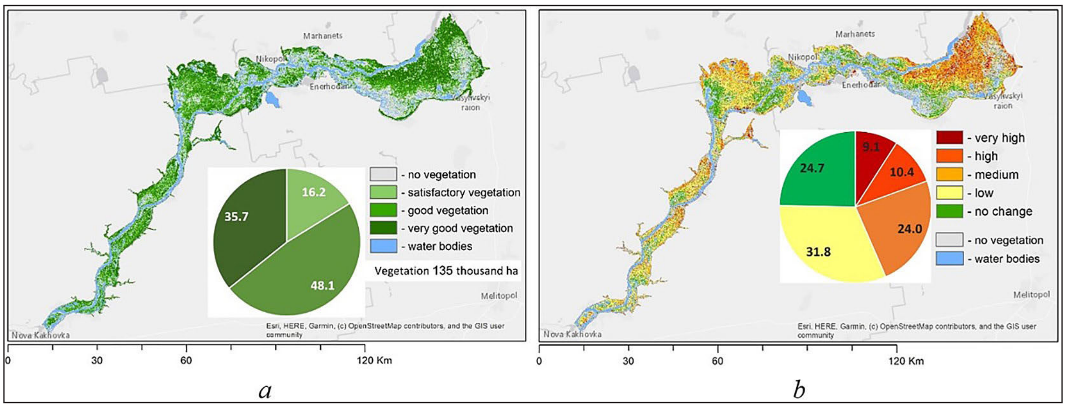


Figure 14. Vegetation cover in the Kakhovka reservoir's bed in September 2023–2024: *a* – the structure of vegetation cover under the most favorable growing conditions, $NDVI_{max}$; *b* – the disturbance of plant growth, $\Delta NDVI_{GV}$

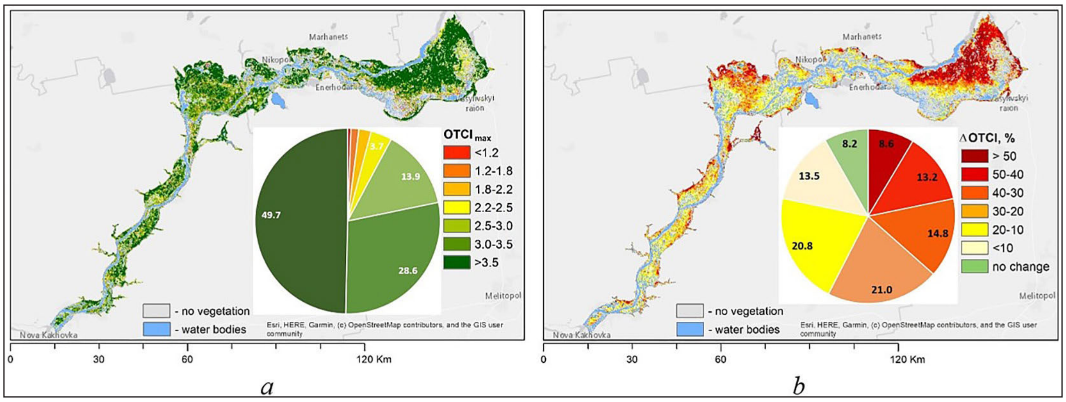


Figure 15. Changes in chlorophyll in the plants of the Kakhovka reservoir's bed in September 2023–2024: *a* – the most favorable conditions for chlorophyll accumulation, $OTCI_{max}$; *b* – a change in chlorophyll content, $\Delta OTCI$

area, including 19.5% (26.3 thousand hectares) of the degraded vegetation and on the verge of destruction. Based on the results of the calculation of chlorophyll synthesis (Fig. 15), we established that as of 22/09/2024, 21.7% of plants maintained relatively stable photosynthesis; 20.8% of plants lost 10–20% of the capabilities of chlorophyll synthesis; 21.0% of plants lost 20–30% of chlorophyll; 28.0% of plants lost 30–50% of photosynthetic properties; 8.6% of plants had more than a 50% reduction in chlorophyll.

It is notable that over the past 40 years, there has been a steady decline in the relative air humidity by 10–12%, which indicates the aggravation of water shortages and increased temperature pressure on the territorial ecosystems. In particular, according to global climate research data from the Copernicus Climate Change Service (https://atlas.climate.copernicus.eu/atlas), in 2024 the air temperature in Ukraine increased by 2.07 °C in comparison with the statistical norm of 1850–1900. By 2100, the average annual value is predicted to exceed the norm by 7.91 °C. The most considerable fluctuations in the temperature increase are expected to be in summer and winter periods from 2.52 °C to 10.34 °C in 2024–2100. The intensification of negative climatic anomalies and artificial regulation of small discharge volumes from the Dnipro hydroelectric power plant causes a significant water shortage, instability and growth disturbances of the newly formed plant ecosystem in the Kakhovka reservoir's bed.

CONCLUSIONS

Based on the results of comprehensive field research and remote satellite sensing, we identified the patterns of plant growth and stability of vegetation cover depending on the current climatic and hydrological conditions of the drained Kakhovka reservoir's territory, in particular:

The proposed methods and classification of plant conditions based on the NDVI, NDMI, NDWI, OTCI and decoded satellite images are adapted and tested for research into the condition of the meadow-marsh and forest environment in the reservoir's bed. It was found that at the end of September 2023, the area of vegetation cover amounted to 52.4 thousand hectares. The winter-spring period of 2024 was characterized by favorable climatic conditions. These conditions contributed to a high level of moisture accumulation in the bottom sediments, the rapid growth of plant biomass and chlorophyll synthesis in plants. During the spring floods, 70% of the reservoir's territory was submerged by flood water. By the end of September 2024, the area of vegetation cover in the former reservoir's territory had increased twofold.

We identified significant variability in plant growth in different parts of the reservoir. This was determined by the heterogeneous characteristics of the hydrological network and moisture redistribution, the connection with the surface runoff of the Dnipro's main course and different levels of organic matter in the bottom sediments. The maximum overgrown area of the reservoir's bed in 2023–2024 amounted to 135 thousand hectares, including 48 thousand hectares with woody plants (willows and poplars) and 87 thousand hectares with marsh and meadow plants with shrub patches.

The lack of precipitation and an abnormal increase in summer air temperatures in the research region caused the acceleration in evapotranspiration and the depletion of moisture reserves in the drained reservoir's territory. This led to a deterioration in plant growth, drying out, and partial degradation. It was established that at the end of September 2024, 75.3% of the vegetation cover had varying degrees of growth disturbances. A significant growth disturbance was observed in 43.5% of the area, including 19.5% of the area with degraded vegetation and on the verge of destruction. The premature plants' drying out caused a loss of good properties of chlorophyll synthesis in an area of 72.8% of plant biomass. In particular, in the upper part of the reservoir, there were fires on plant patches with an area of 320 hectares. These negative processes resulted in a decrease in the area of healthy vegetation by 26.3 thousand hectares. It was proved that stable trends in increasing negative climatic anomalies and artificial regulation of small discharge volumes from the Dnipro hydroelectric power plant into the former Kakhovka reservoir's territory complicate the conditions for plant survival. In the future, this will cause a decrease in the density of plants with good growth, increase the area of degraded vegetation cover and dead wood, raise the risk of fires, lead to a loss of stability of the newly formed ecosystem, and cause the destruction of vegetation patches.

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