SCENARIOS FOR THE FUNCTIONING OF THE KAKHOVKA RESERVOIR TERRITORY

VITALII PICHURA[1]*, LARYSA POTRAVKA[1], NATALIIA STOIKO[2] AND HALYNA DUDYCH[2]

[1]*Kherson State Agrarian and Economic University, Ukraine, 73006, Kherson, Stritens'ka str. 23*
[2]*Lviv National Environmental University, Ukraine, 80381, Dubliany, V. Velykyi str. 1*
**Corresponding author email: pichuravitalii@gmail.com*

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ABSTRACT

The destruction of the Kakhovka hydro-electric power station and the draining of the Kakhovka Reservoir caused several environmental and socioeconomic problems in the southern region of Ukraine. Water supply in these territories has always been an important factor in the formation of settlements. Therefore, this vital function was assigned to the water reservoir. The settlements located nearby entirely depended on the functioning of the water reservoir, and its water was used to meet the economic and sanitary needs of industries and the local population. The study presents exhaustive research and substantiation of three scenarios for the functioning of the Kakhovka Reservoir, which are actively discussed by Ukrainian and international communities. The first scenario means rebuilding the dam of the hydro-electric power station and filling the Reservoir with water; the second scenario involves creating a natural plant ecosystem and restoring the Great Meadow (Velykyi Luh); the third scenario implies the creation of a natural artificial system of the Reservoir partially filled with water and the formation of a quasi-natural environment. The study was carried out using the data of our field research, the data of the State Agency of Water Resources of Ukraine, the global data from the Copernicus Climate Change Service, and the data of remote sensing from the satellites Sentinel 2 L2A, Sentinel-3 SLSTR and OLCI L1B, and Landsat 8-9. The advantages and disadvantages of each scenario for the functioning of the Kakhovka Reservoir territory are discussed. Currently, it is possible to forecast and develop the scenarios for the functioning of these territories only through assessing the ability of Ukrainians to adapt to the conditions formed after the ecocide. The findings are an essential information resource for making objective management decisions on the post-war restoration and sustainable functioning of the regions depending on the Kakhovka reservoir.

Keywords: ecocide, water quality, climate, degradation, irrigation, vegetation, environmental services, sustainable development

INTRODUCTION

On June 6, 2023 the destruction of the dam of the Kakhovka hydro-electric power station (HPS) by the became a national disaster. Today, it is difficult to establish the number of Ukrainians who died since the flooded territories on the Left Bank are still occupied. As for the loss of resources, it was found out that the loss of water resources amounted to more than

17 billion cubic meters, 600 km^2 of the adjacent territories were flooded. There were substantial losses of fishery resources. Flora and fauna were destroyed. The emergency zone included 180 settlements with over 900 thousand people. As a result of the disaster, more than 6 million people lost access to water resources (Vyshnevskyi *et al.,* 2023, 2024a; Pichura *et al.,* 2024a). The losses caused by the dam destruction amounted to more than USD 18 billion (Hapich *et al.,* 2024a). According to the resolution of the UN General Assembly № 64/292 of July 28, 2010, citizens of Ukraine have lost the right to safe water and sanitation, which is a basic human right, the basis for a full life and the provision of all other rights (Pichura *et al.,* 2024b). The negative consequences of the dam destruction include water scarcity, deterioration of the water balance, a reduction in the hydrological functioning of the Dnipro-Buh estuary system, systematic pollution of a part of the Black Sea, deterioration of the conditions of hydro-biological resources, full or partial cessation of the functioning of industrial enterprises, deterioration of the water supply of agricultural enterprises, cessation of the functioning of the hydrological irrigation network, disruption of the hydrological regime in the territory, a decline in the level of groundwater and a lower water table, drainage and desertification of the territories, secondary salinization of irrigated and adjacent lands, an increase in the frequency of dust storms, a decrease in the area of fertile soils and a worsened condition of natural ecosystems, an increase in the volume of dust pollution, and deterioration of health status and quality of life (Vyshnevskyi *et al.,* 2023, 2024a; Pichura *et al.,* 2024a, 2024b; Hapich *et al.,* 2024a, 2024b; Snizhko *et al.,* 2024).

Today, the Ukrainian and international communities are actively discussing three possible scenarios for the post-war functioning of the Kakhovka Reservoir territory: rebuilding the dam of the hydro-electric power station and filling the Reservoir with water (Vyshnevskyi *et al.,* 2024b; Pichura *et al.,* 2024a); creating a natural plant ecosystem and restoring the Great Meadow (Velykyi Luh) (Kuzemko *et al.,* 2024); creating a natural-artificial system of the Reservoir partially filled with water and creating a quasi-natural environment (Vyshnevskyi *et al.,* 2024b; Pichura *et al.,* 2024a). The research that has been conducted so far is local by nature and does not allow for a systemic view of causal relationships. Most publications in the public space are based on assumptions and are not corroborated with actual data. Therefore, a lack of exhaustive research into the actual state of the Kakhovka Reservoir territory, which is related to the limited access to the research area due to active hostilities and a lack of actual information about the state of the entire territory impacted by the disaster complicates the choice of an objective management decision on selecting the scenario for the post-war functioning of the reservoir territory. In this regard, it is essential to use satellite imagery and compare it with the results of the field research conducted in the accessible territories of the Reservoir and decipher them correctly.

The practical application of remote sensing allows tracking the actual state of large areas of territorial systems in hard-to-reach places (Vyshnevskyi *et al.,* 2024b; Pichura *et al.,* 2024a, 2024b; Dovhanenko *et al.,* 2024). However, the remote sensing data are limited by cloud cover and repeated surveys. The satellite Sentinel-2, which provides free access to images with a temporal resolution of about five days and a spatial resolution of 10m×10m per pixel, is a source of actual remote sensing data. The satellite Landsat 8-9 has a spatial resolution of 15 to 60 m per pixel and a frequency of images of 16 to18 days. The satellite Sentinel-3 has a spatial resolution of 270 m×270 m per pixel and the capability to provide pictures daily. They are an additional source of accessible actual data for large-scale research. Sentinel-2 and Sentinel-3 belong to the family of satellites for remote sensing of the European Space Agency (https://www.esa.int/) designed within the framework of the project on the global monitoring for environment and security by Copernicus (https://www.copernicus.eu/). The American satellite Landsat 8-9 was created by NASA (https://www.nasa.gov/) in cooperation with USGS (https://www.usgs.gov/). It was created on the basis of the LEOStar-3 platform by Orbital Sciences Corporation (https://www.northropgrumman.com/). The satellites are designed to monitor land, vegetation, forest, and water resources, and measure water and earth temperature. They are used in disaster relief and for national security.

The purpose of the comprehensive research is to identify the trends in the functioning of the Kakhovka Reservoir territory according to three scenarios created based on field research and the methods of remote sensing. The relevance of the study is determined by the necessity of assessing the suitability of the living conditions for Ukraine's population in the ecocide zone.

MATERIAL AND METHODS

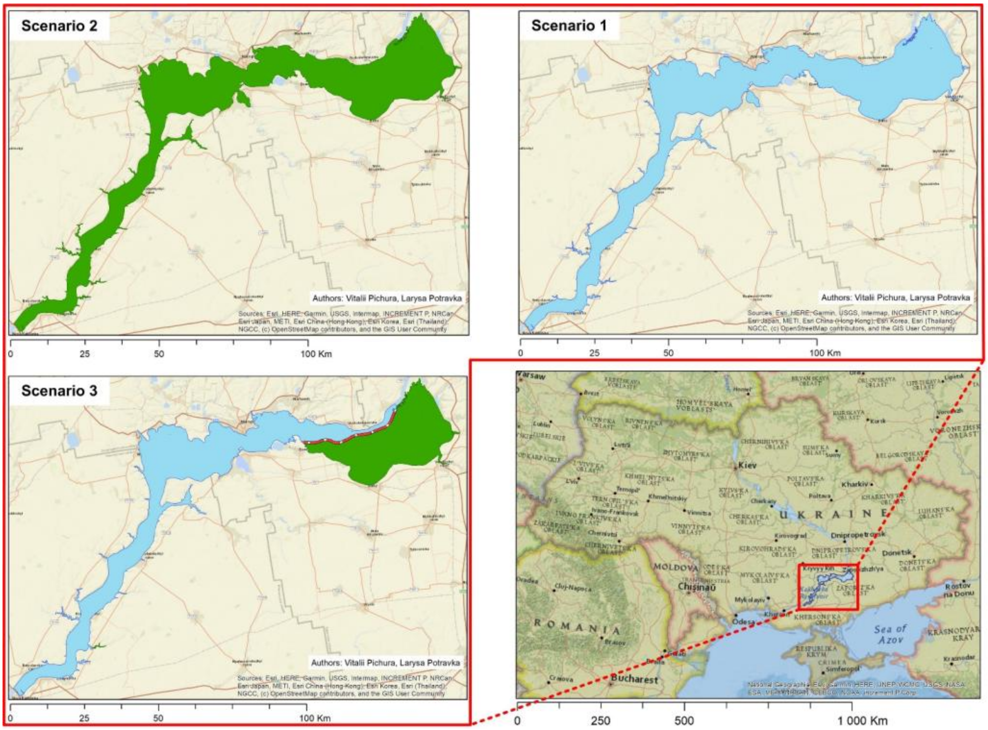
Research scheme and materials

The scheme of the research into the functioning of the Kakhovka Reservoir after the destruction of the dam of the Kakhovka hydro-electric power station includes three scenarios (Fig. 1): Scenario 1 – the restoration of the Kakhovka Reservoir which involves examining the state of the Reservoir before the destruction of the hydro-electric power station dam; Scenario 2 – the creation of natural plant ecosystems which consists in studying the state of the drained Reservoir and the adjacent territories after the dam destruction; Scenario 3 – the creation of a natural-artificial system of the Kakhovka Reservoir which involves investigating the state of the territory partially filled with water and creating a quasi-natural environment.

The Kakhovka Reservoir had an area of 2155 km^2. It was created in the South of Ukraine in 1955–1958 to generate electricity, develop fisheries and recreation, feed plants in water protection areas and nature reserves, provide fresh water to enterprises, irrigation systems, and sanitary needs of about 6 million people. Before the destruction of the hydro-electric power station dam, the water reservoir had the following characteristics: the total volume – 18.2 km^3, the usable volume – 6.8 km^3; the average retention level – 16.0 m, the horizon of the dead volume – 12.7 m, the maximum depth of the water body – 32.0 m, the average depth – 8.5 m, seasonal fluctuations of the water level were 3.3 m; the maximum length of the water area – 230 km, the maximum width – 25.0 km, the average width – 9.3 km, the coastline – 869.0 km; the long-term flow varied between 28.3 and 61.7 km^3/year. The capacity of the hydroelectric powers station (HPS) amounted to 329.0 thousand kW, and the maximum spillway capacity of the HPS was 2600 m^3/s.

To substantiate different scenarios for the functioning of the reservoir territory, the results of our research (Pichura *et al.,* 2024a, 2024b), the data on monitoring and environmental assessment of water resources provided by the State Agency of Water Resources of Ukraine (http://monitoring.davr.gov.ua/EcoWaterMon/GDKMap/Index), the global data on climate research of the Copernicus Climate Change Service *(*https://atlas.climate.copernicus .eu/atlas*),* and the data of remote sensing were used. The data of the spacecraft Sentinel 2 L2A, Sentinel-3 SLSTR and OLCI L1B, Landsat 8-9 from the sites Copernicus Browser and EO Browser were used as a source of the up-to-date satellite imagery for decoding and calculating the relevant indices.

Fig. 1: Scenarios for the functioning of the Kakhovka Reservoir territory
Scenario 1 – rebuilding the hydroelectric power station dam and filling the Reservoir with water. Scenario 2 – creating a natural plant ecosystem. Scenario 3 – creating a natural-artificial system of the Reservoir partially filled with water and creating a quasi-natural environment.



Research methods

The research into the trophic state of surface waters was carried out based on the calculation of the intensity of saturation of floating alga with chlorophyll pigment (Chl-a, μg/dm^3) using Maximum Peak-Height Index (MPHI) (Peppa *et al.,* 2020):

$$MPHI=B5-B4-\frac{(B8-B4)\times(705-665)}{842-665}\Big\} \rightarrow Chl\text{-}a=2223.18MPHI+24.03 \quad (1)$$

where B4, B5, and B8 are the reflectance, and λB4 = 665 nm, λB5 = 705 nm, and λB8 = 842 nm are the central wavelengths of the corresponding bands of Sentinel-2 L2A. The MPHI values varied between -1.0 and 1.0. The value above MPHI = 0.004 indicates the presence of Chl-a in the algae of the water surface layer.

The content of phosphates (P, mg/dm^3) was calculated based on the established dependence (Pichura *et al.,* 2024b):

$$P=0.0102Chl\text{-}a^{0.6995}, \quad r^2=0.984 \quad (2)$$

Turbidity of surface waters (Tu, NTU) was determined using the formula (Zhan *et al.,* 2022):

$$\text{Turb}=194.79\left(\text{B5}\times\left(\frac{\text{B5}}{\text{B2}}\right)\right)+0.9061 \quad (3)$$

where B4, B5, and B8 are the reflectance bands of Sentinel-2 L2A.

Total Suspended Solids (TSS, mg/dm^3) were calculated based on the established dependence (Nurjaya et al, 2019):

$$\text{TSS}=3.4216\text{Turb}, \quad r^2=0.987 \quad (4)$$

The surface water quality was determined using the classification presented in Table 1 (Romanenko *et al.,* 1998).

Table 1: Classes and categories of surface water quality by ecological classification

Water Quality Classes	I	II		III		IV	V
Water Quality Categories	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Chl-a, μg/dm^3	<2	2-4	5-10	11-30	31-50	51-150	>150
Total Suspended Solids, mg/dm^3	<5	5 - 10	11 - 20	21 - 30	31 - 50	51- 100	>100
Water quality according to cleanliness (pollution)	Very Clean	Clean		Polluted		Dirty	Very Dirty
	Very Clean	Clean	Clean Enough	Slightly Polluted	Moderately Polluted	Dirty	Very Dirty
Trophic class	Oligotrophic	Mesotrophic		Eutrophic		Polytrophic	Hypertrophic

Changes in the microclimatic conditions of the drained water reservoir and the adjacent landscapes were calculated on the basis of the values of Land Surface Temperature – LST, which is an important geophysical parameter about the surface heating energy and the water balance of the land-atmosphere system (Li et al., 2023). To identify differences in the changes of LST values in 2020 and 2023, the spacecraft Landsat 8-9 raster data of thermal channel 10 with a resolution of 75×75 m/pixel were used (the source – EO Browser). The rasters of the LST values were used to clarify the values of changes in the heterogeneity of evapotranspiration distribution depending on spatial changes in the surface heating of the drained Reservoir and the adjacent territories.

The value of evapotranspiration (ET_{LST}) was calculated on the basis of the established dependence (Pichura *et al.,* 2024a):

$$ET_{LST}=1.7658\text{LST}-49.187, \quad r^2=0.77 \quad (5)$$

The research into changes in the landscape structure of the drained reservoir territory, the degree of degradation of floodplain systems, and shoreline vegetation of the protected water area was carried out using the Normalized difference vegetation index (NDVI) (Ashok *et al.,* 2021):

$$\text{NDVI}=\frac{\text{B8-B4}}{\text{B8+B4}} \quad (6)$$

where B4 and B8 are the of thecorresponding bands of Sentinel-2 L2A.

The NDVI values varied between -1.0 and 1.0. Negative values are mainly formed by clouds, water, and snow, and values close to zero (from 0.05 to 0.15) are formed by stones and bare soil. As a result of the field research and calibration of the satellite imagery data, we adapted the classification of NDVI values for the territory of the drained Reservoir. The value above NDVI, from 0 to 0.6, corresponded to the areas without vegetation, covered with shells, takir, sands, and stones. The value above NDVI = 0.6 indicates the presence of vegetation, in particular: 0.60–0.70 – satisfactory vegetation; 0.70–0.85 – good vegetation; 0.85–1.00 – very good vegetation. It was found that the NDVI values from 0.60 to 0.85 were characteristic of meadow and marsh vegetation, and the value of 0.85 indicates the presence of woody plants (mainly willow trees).

The calculation of Above Ground Biomass (AGB) of plants is an important ecological and atmospheric indicator of plant health. This indicator characterizes the total mass of living structures, including stems, leaves, and reproductive organs. AGB of plants is used for monitoring the state of plant biomass and determining the amount of carbon and oxygen production in the process of photosynthesis. Assessment of AGB at relevant scales (local, regional, national, or global) is important for obtaining information on biomass accumulation, calculating and forecasting ecological and atmospheric services of plant biomass, and making management decisions important in terms of nature conservation. Satellite remote sensing is widely used for accurately monitoring the AGB dynamics of natural vegetation. Sentinel-2 images are optimal for monitoring the AGB dynamics in the territories of different scales. AGB is the accumulated sum of daily evaluations of plant biomass production. In particular, it is the sum of accumulated radiation and radiation-use efficiency, the factors of temperature stress and organic nutrition, water availability, etc (Narissara *et al.,* 2018, Hu *et al.,* 2024).

Above Ground Biomass (AGB, t/ha) of plants in the drained Reservoir was calculated using the formula (Narissara *et al.,* 2018, Hu *et al.,* 2024):

$$AGV = \begin{cases} if\ NDVI \geq \text{"0.85"}\ then\ (537NDI45 + 158.45EVI - 353.66) \\ if\ NDVI\ within\ \text{0.60-0.85} then\ 0.35(537NDI45 + 158.45EVI) \\ NDI45 = \frac{B5-B4}{B5+B4}; \qquad EVI = 2.5\frac{B08-B4}{B8+6B4-7.5B2+1} \end{cases} \quad (7)$$

where B2, B4, B5 and B8 are the of the corresponding bands of Sentinel-2 L2A.

The equivalent of the amount of carbon dioxide (CO_2, t/ha) in plants was calculated using the formula:

$$Carbon\text{=0.5AGV} \rightarrow CO_2 = 3.67Carbon \quad (8)$$

The Terrestrial Chlorophyll Index (OTCI) was used to compare the environmental state in the pre-war period (2021) and the war period (2022–2024). The following formula was used (Dash *et al.,* 2010):

$$OTCI\text{=}\frac{(B12-B11)}{(B11-B10)} \quad (9)$$

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

OTCI, the Terrestrial Chlorophyll Index, can 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.

Image processing, mapping, and spatio-temporal analysis were performed using ArcGis 10.6.

RESULTS

SCENARIO 1 – rebuilding the Kakhovka Reservoir

Water quality and eutrophication of the Reservoir. Restoration of the Reservoir involves preserving its social, economic, and environmental importance. Given the ecological aspect, it should be underscored that the large-scale hydroelectric construction in 1934–1976 changed the water regime of large valley and river areas of the Dnipro, which was transformed from a river type into a lake type. This, in turn, caused a slowdown of the circulation of water masses and led to water stagnation (Pichura *et al.,* 2018, 2020). The total area of the water mirror of the cascade of the Dnipro reservoirs was 6981 km^2, which increased the potential of Ukraine's water resources by 43.8 km^3. The reservoirs in the direction of the Dnipro river flow (Fig. 2): Kyiv (filled in 1964–1966, the area – 922 km^2, the volume – 3.75 km^3) → Kaniv (filled in 1974–1976, the area – 675 km^2, the volume – 2.6 km^3) → Kremenchuk (filled in 1959–1961, the area – 2252 km^2, the volume – 13.5 km^3) → Kamianske (filled in 1964, the area – 567 km^2, the volume – 2.45 km^3) → Dnipro (constructed in 1932, restored after World War II in 1948, the area – 410 km^2, the volume – 3.3 km^3) → Kakhovka (filled in 1955–1958, the area – 2155 km^2, the volume – 18.2 km^3).

Despite the great economic importance of the reservoir cascade, it existence has caused several environmental problems related to the disruption of the Dnipro water flow, deterioration of surface water quality, eutrophication (Fig. 2, 3), flooding of shoreline areas, bank abrasion, an increase in the water table, a rise in the volume of the groundwater flow, disruption of soil feeding of rivers, and other processes.

Fig. 2: The cascade of the Dnipro reservoirs and eutrophication of surface waters

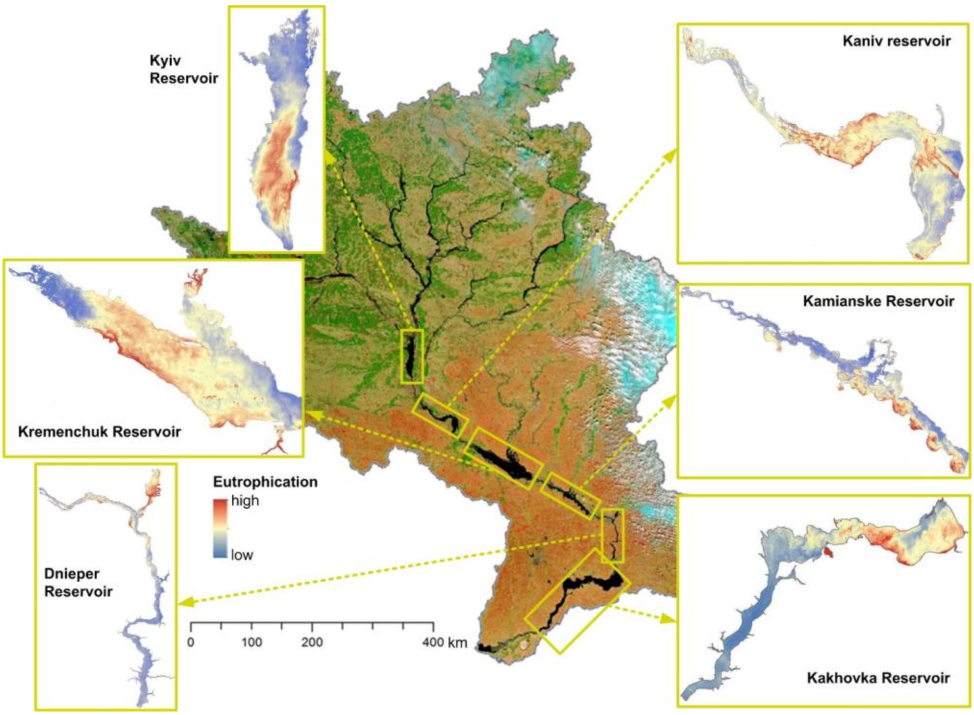
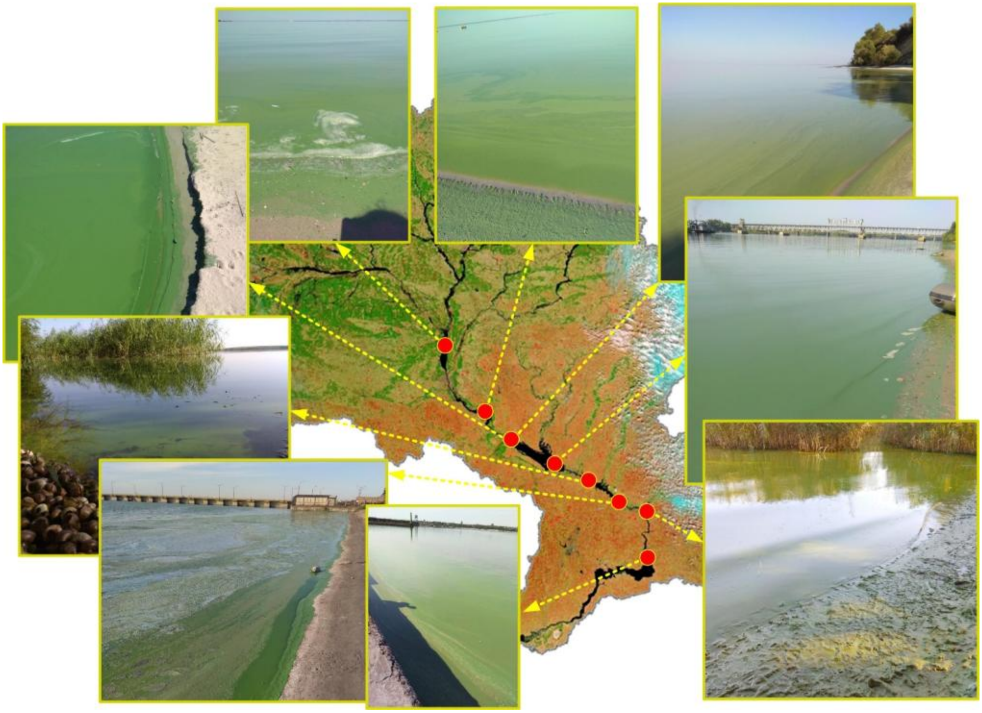


Fig. 3: Cyanobacteria bloom in the Dnipro water in August 2019



During the period of the functioning of the reservoir cascade, the average annual flow (W, m^3/s) in the lower Dnipro fell by 412 m^3/s (from 1670 m^3/s to 1258 m^3/s). In different locations of the riverbed system, the water exchange slowed down by 14–30 times, which caused stagnant zones. This resulted in the disruption of the natural functioning of the catchment area and the riverbed system of the Dnipro river, which resulted from cutting down 30 % of forests, a reduction in the area of windbreaks by 2.3 times, drainage of more than 2.5 million hectares of wetlands, a significant decrease in water protection zones, an increase in the area of arable lands by more than 70 % of the catchment area. An additional factor complicating the hydrological situation is climate change characterized by a fall in precipitation by 40 %, an increase in the average annual temperature by 2.5°C, and acceleration in evapotranspiration by 20 % over the past decade. High anthropogenic pressure and climate change have caused a decrease in the river flow during spring floods by 1.93 times.

Environmental problems were exacerbated due to the intensive development of agriculture and industry. More than 60 % of the domestic industrial production and the largest urban agglomerations were located in the catchment area that caused intensive use of water resources, which were returned to the river in large volumes of polluted water discharge. The total wastewater discharge in Ukraine amounts to 20.6 billion m^3, including 63.9 % from industry, 19.5 % from municipal services, and 16.6 % from agriculture. 900 thousand tons of pollutants enter the water bodies of the basin with wastewater discharge. In Ukraine, there are 5 thousand storage facilities for unusable pesticides and agrochemicals which are mainly located in rural areas. Annually, an average of 120 million tons of soil containing 0.24 million tons of nitrogen, 0.12 million tons of phosphorus, and 2.4 million tons of potassium enter rivers and other water bodies. In the Ukrainian part of the Dnipro

River basin, there are 1310 landfills and other storage and disposal sites, including 160 sites of toxic waste disposal containing materials with content of toxic substances that exceed the acceptable concentration. Untreated municipal wastewater, which enters river waters due to the emergency state of the networks and frequent breakdowns, is also a source of pollution.

Disruption of the hydrological regime and the entry of large volumes of untreated wastewater with a high concentration of biogenic substances to the Dnipro River were the leading causes of the degradation of water quality, the development of planktonic algae, a considerable decrease in water transparency and the decline of the trophic state of the reservoirs. The water body's trophic state is an indicator of the ecosystem's metabolism (energy intake, accumulation, and consumption) and reflects its environmental state. The entry of excessive amounts of biogenic substances causes changes in the functioning of the hydro-ecosystems of reservoirs and accelerates successive processes. The eutrophication of reservoirs depends not only on the load of biogenic substances on water bodies but also on the degree of the development of autotrophic aquatic animals, i.e., on climatic, hydrodynamic, and morphological characteristics of water bodies. The most intensive eutrophication occurs in heated shallow water areas of the reservoirs and in the stagnant zones of the water area, which is characterized by a low flow velocity. The eutrophication process is determined by the disruption of the stability of aquatic ecosystems which fundamentally distinguishes it from the concept of pollution. The indicators of physical, chemical, and biological nature determine the trophic type of a water body.

The intensity of cyanobacteria bloom in warm seasons, the concentration of floating algae, and the level of chlorophyll pigment in them (Chl-a, $\mu g/dm^3$) are important indicators for assessing and determining the trophic state of water bodies. Chl-a is a universal characteristic of the development and photosynthetic activity of algae that allows the expression of biomass in the units of this component of a plant cell. There is a direct correlation between biogenic pollution and the development of phytoplankton (its production, biomass, and chlorophyll content in water) in water bodies. The assessment of the trophic state of a water body is usually based on the dependence of water biological productivity on the content of mineral nutrients (nitrogen and phosphorous) in them. Therefore, the level of Chl-a concentration and its change in a water body is an essential criterion of the assessment of reserves and production of phytoplankton biomass, and also an indicator of water pollution.

Chl-a concentration in the Reservoir increased to 270 $\mu g/dm^3$ and higher in July (Fig. 4). In 2020–2022, the water area of the eutrophic varied between 37.0 and 55.0 %, with a polytrophic state – 40.5–48.0 % and a hypertrophic state – 4.1–14.5 %. Throughout the warm spring–summer season, there was a systematic formation of a considerable amount of plankton biomass in the Kakhovka Reservoir that determined the eutrophic state of the Reservoir with a systematic formation of water quality from moderately polluted to very dirty by 81.9–87.2 % of the water area.

According to the data of the State Agency of Water Resources of Ukraine, the degradation of water quality in the Kakhovka Reservoir (Tab. 2) occurred due to the inflow of untreated wastewater from enterprises and undertreated municipal sewage, surface and erosion runoff from farmlands. This caused the accumulation and increase in the concentration of heavy metals by 1.2–2.1 times, biogenic substances by 1.2–2.6 times, and higher biological and chemical oxygen consumption by 2 times in summer. This limited the suitability of water for drinking and fisheries.

Fig. 4: Chl-a concentration (μg/dm³) in the Kakhovka Reservoir in July 2020–2022

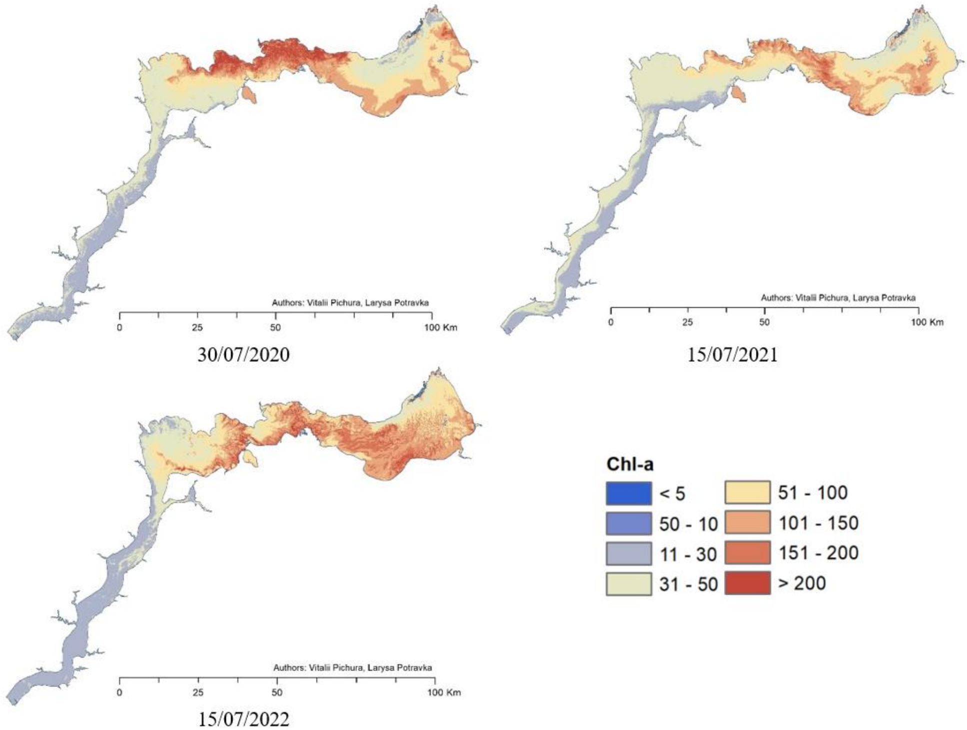


Table 2: Water quality in the Kakhovka Reservoir in 2019–2021

Indicator		Standards of water quality		Month											
		for fishing	for drinking	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Reaction	pH	6.5-8.5	6.5-8.5	8.2	8.2	8.1	8.1	8.2	7.7	7.5	8.5	8.2	8.0	8.1	8.0
Dissolved oxygen, mgO_2/dm^3	DO	>6	>4	10.7	11.3	10.8	9.7	8.5	8.0	7.6	6.6	8.1	9.5	9.0	9.4
Biochemical oxygen demand for 5 days, mgO_2/dm^3	BOD	≤2	≤3	2.2	2.1	2.4	2.1	2.4	2.6	2.7	3.9	3.9	3.1	2.5	2.3
Chemical oxygen demand, mgO_2/dm^3	COD	≤20	≤15	21.3	22.5	35.2	20.6	25.6	29.6	30.9	28.2	27.5	23.0	23.8	25.3
Total Suspended Solids, mg/dm^3	TSS	≤25	≤25	5.2	5.1	6.6	6.0	6.5	6.7	10.1	10.3	10.6	5.3	5.0	5.0
Nitrate nitrogen, mg/dm^3	NO_3^-	≤9.1	≤25	2.5	1.8	0.7	0.9	0.9	1.1	1.1	2.1	2.4	0.8	2.1	3.2
Nitrite nitrogen, mg/dm^3	NO_2^-	≤0.02	≤0.1	0.03	0.04	0.03	0.03	0.03	0.05	0.06	0.07	0.03	0.03	0.03	0.03
Phosphate, mg/dm^3	PO_4^{3-}	≤0.2	≤0.2	0.28	0.24	0.10	0.11	0.09	0.15	0.30	0.52	0.39	0.34	0.36	0.32
Sulphate, mg/dm^3	SO_4^2	≤100	≤150	43.0	46.5	51.3	47.3	52.9	50.3	65.7	54.5	55.1	60.9	61.7	57.5
Chloride, mg/dm^3	Cl^-	≤300	≤200	31.9	33.0	45.7	37.6	37.2	43.9	39.8	37.5	39.4	39.1	39.6	39.4
Iron, mg/dm^3	Fe	≤0.1	≤0.1	0.17	0.16	0.30	0.12	0.14	0.14	0.17	0.21	0.12	0.15	0.18	0.10

– does not meet quality standards
– does not meet quality standards for fishing
– does not meet quality standards for fishing and for drinking

The economic value of the Reservoir. It is noteworthy that the environmental state in the period of the functioning of the Reservoir, in accordance with the indicators of surface water quality, was considered unsatisfactory, but the Reservoir was of crucial socioeconomic importance for water-deficient regions of the Steppe zone of Ukraine. Along with electricity generation, the water reserves of the Reservoir were used for supplying water to more than 140 settlements with a population of over 1 million people. Given all the factors of the Reservoir's impact on the socioeconomic life in Ukraine, the destruction of the Reservoir deprived 6 million people of a source of drinking water, and 13 million people were restricted in satisfying their household needs. Experts have estimated the amount of environmental damage at USD 60 billion. It should be emphasized that the Kakhovka Reservoir was the main source of irrigated agriculture, covering about 800 thousand hectares of farmlands. The main elements of the irrigation system included the Kakhovka Canal, the North Crimean Canal, and the Dnipro – Kryvyi Rih Canal. Over the past pre-war years, the volume of surface water use was 1.21–1.34 km^3, including 4.89–7.98 % for drinking and sanitation needs, 71.15–73.56 % – for production needs, 18.04–23.60 % for irrigation, and 0.36–0.42 % for other needs. The Reservoir was also an artery for navigation and the basis for the functioning of the Nikopol Port, an important center of recreation, fishery, and hydro-resources. In Ukraine, more than 22 % of the fish market was provided by freshwater fish caught in the Reservoir water. The combination of natural and economic conditions was complemented by the tourist hospitality of the southern region that offered new opportunities for the local communities, promoted the development of different businesses, and rooted and strengthened agricultural production.

Water aeration using HPS turbines. Under conditions of flow regulation, the operation of HPS turbines provided aeration that improved aerobic processes of self-purification of transit water masses. Aeration of river water is highly important in summer due to the lack of precipitation and an increase in the days with temperatures above 30°C. The inflow of large amounts of polluted wastewater to surface waters exceeds the hydrological capacity of the Dnipro River for self-purification. Therefore, if the cascade of the Dnipro reservoirs functions, HPS turbines are the main sources of oxygen enrichment of large volumes of transit river water. HPS turbines of the Dnipro cascade are installed at a depth of 14–35 meters, which allows aerating the water layer with the lowest oxygen content at depths of more than 7 meters. It should be emphasized that the lack of oxygen causes water quality degradation due to a higher level of water toxicity, fish kills, a reduction in the number and diversity of bottom invertebrates (mollusks, crustaceans, dragonfly larvae, etc.), which are fish food and also participate in processing organic substances and affect the biochemical cycle of many substances and heavy metals. Therefore, the process of water aeration of transit flows is necessary for the activity of aerobic bacteria and improves the state of hydro-ecosystems and self-purification properties of the Dnipro River.

Activated sludge and its function. Over 65 years of the functioning of the Kakhovka Reservoir, important bottom habitats of activated sludge were formed. They maintained biological treatment of waters through the riverbed from the catchment area of the Dnipro River, with an area of 511 thousand km^2. The transit water treatment process involved utilizing, transforming, and mineralizing organic substances through aerobic fermentation of organic substances by a specific complex of microorganisms and bacteria, algae and protozoa.

The technical functioning of the hydro-structures and activated sludge of the Kakhovka Reservoir improved the surface water quality, ensured the Dnipro's treatment and capacity for restoration, formed appropriate conditions for the existence of hydrophytes and hydro-biota, contributed to a reduction in the inflow of pollutants to the Dnipro-Buh estuary system and the Black Sea. The destruction of the dam of the Kakhovka hydro-electric power station caused a massive anthropogenic and natural-climatic transformation of the territory of the drained Reservoir that hurt the functioning of the Dnipro-Buh estuary system and the Black Sea in general. It caused water scarcity in the southern regions of Ukraine.

Suppose the scenario of rebuilding the dam and filling the Kakhovka Reservoir with water is used. In that case, the environmental and socioeconomic situation in the region of the reservoir's influence will return to its previous state. Before flooding, it is necessary to remove the vegetation and bottom sediment from the reservoir's territory and consider the technical specificity of creating a channel for fish passage when rebuilding the dam. It is also necessary to modernize the treatment systems of enterprises and settlements and transform the structure of the land fund on the basis of basin adaptive landscape anti-erosion principles of spatial planning of the Dnipro catchment area. In turn, this will reduce the negative impact of economic activity on ecosystems and create conditions for the restoration of land and water resources in the Dnipro basin.

SCENARIO 2 – the creation of a natural plant ecosystem. The destruction of the dam of the Kakhovka HPS (Fig. 5) caused a natural-climatic transformation of the drained Reservoir (Fig. 6) and a catastrophic moisture deficit in the southern regions of Ukraine.

Changes in micro-climatic conditions, water scarcity, and an increase in temperature stress. The functioning of the Kakhovka Reservoir was a primary factor of favorable micro-climatic conditions for the adjacent territory. This was due to groundwater and the difference between radiation and heat balances of the water surface and land, which resulted in the local circulation (breezes), which were pronounced in warm seasons.

Fig. 5: The destruction of the dam of the Kakhovka HPS

Fig. 6: The change in the state of the Kakhovka Reservoir in 2023–2024 (the view from Nikopol to Zaporizhzhia NPP)

In the daytime, the breeze circulation occurred as a result of heating and convective flows rising above the land, which were replaced by cooled air flowing from the Reservoir to the lower surface layer. At night, when the landscape surface cooled, reverse circulation occurred. The existence of the Kakhovka Reservoir determined the formation of a horizontal-vertical fast and powerful breeze, which formed a favorable micro-climate on the steppe plains stretching for tens of kilometers from the Reservoir. Therefore, the reservoir drainage disrupted the micro-climatic conditions, causing an increase in the heating temperature on the adjacent landscape (Land Surface Temperature – LST) by 1.0°C and more (Fig. 7). This resulted in an increase in the area with temperature stress by 58.2 %, worsening the problem of water scarcity, acceleration of seasonal evaporation (evapotranspiration – ET_{LST}) up to 50 % and more in 2023.

Degradation of shoreline vegetation. The drainage of the Reservoir, a reduction in the groundwater level, water scarcity, and deterioration of microclimatic conditions resulted in the loss of good vegetative properties in more than 50 % of the shoreline vegetation of the water protection areas.

Degradation of the floodplain systems of the Khortytsia National Reserve. A reduction in the water level by 4.0 meters and more in the area of the lower course below the dam of the Dnipro HPS in September 2023 caused degradation of 78.6 % (550 ha) of unique floodplain systems of the Khortytsia National Reserve. Abnormally favorable winter-spring climatic conditions in 2024 led to an increase in the water level in the lower Dnipro, ensuring a high level of moisture in this period. This contributed to a partial seasonal restoration of 35.1 % of the floodplain systems of Khortytsia Island. However, a reduction in the discharge from the Dnipro HPS and water shortages against the backdrop of high summer temperatures led to catastrophic degradation of floodplain plants in 94.3 % of the area (660 ha) (Fig. 8).

Fig. 7: Patterns of changes in LST (°C) and ET_{LST} (mm/day) in the territory of the drained Kakhovka Reservoir and the adjacent territories (September 2020 and 2023)

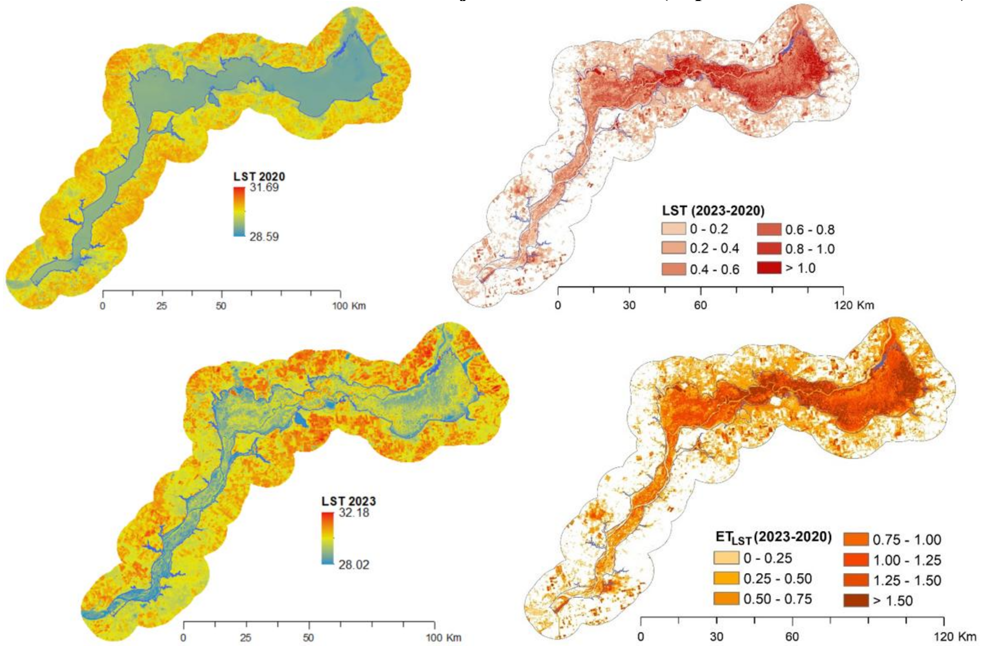
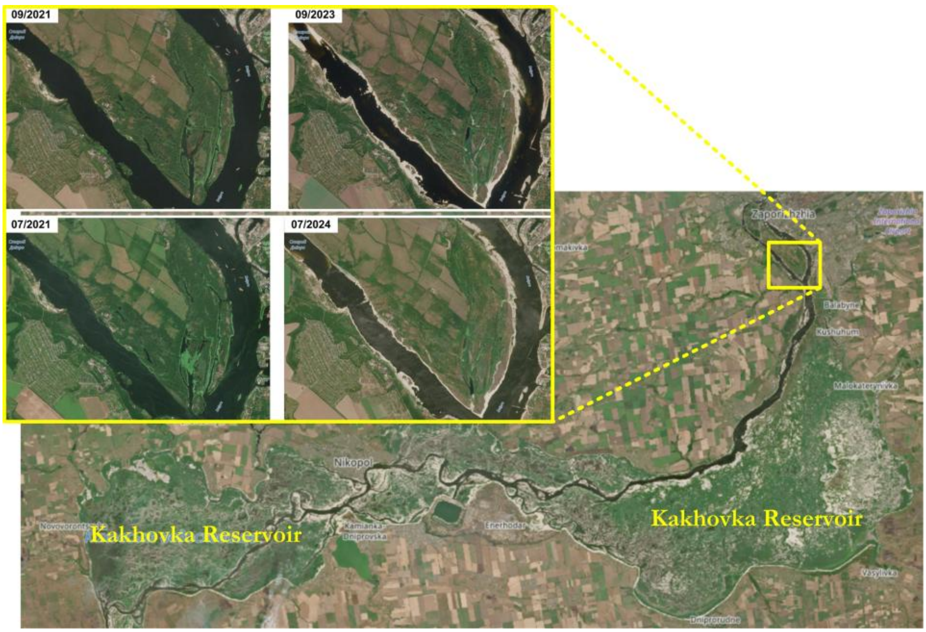


Fig. 8: Floodplain systems of the Khortytsia National Reserve: a – the location and years of comparison of the state of floodplain systems; b – degradation of floodplain systems



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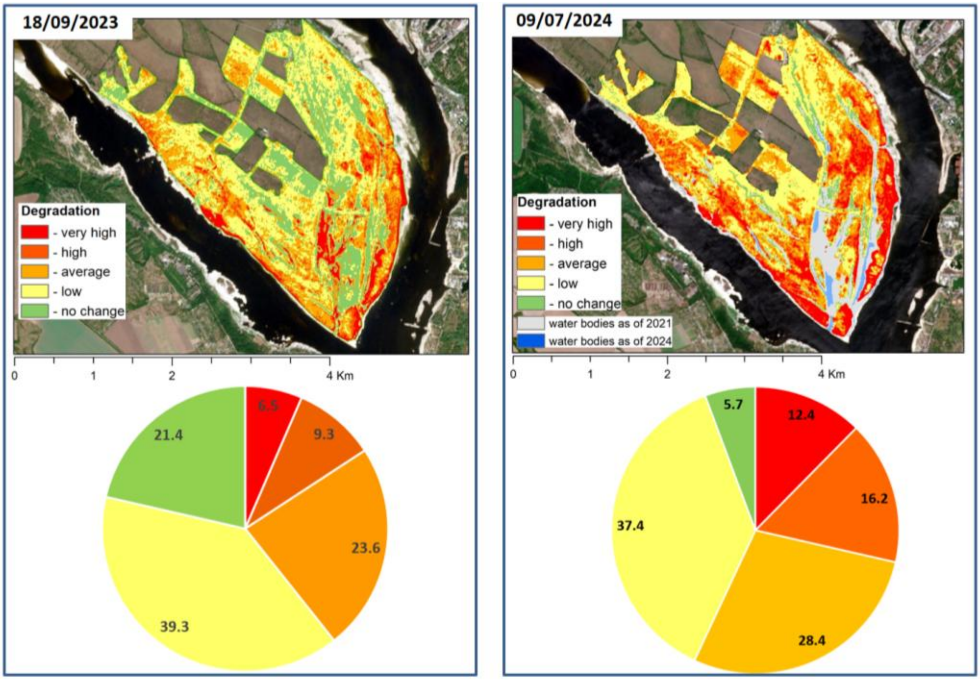


b

A reduction in groundwater levels and a difficult access to water for the population. A reduction in groundwater levels by 8–12 m and more caused the drainage of wells and led to the deterioration of water supply in 140 shoreline settlements. The quality of water from available underground sources for settlements does not comply with the standards for drinking water, and there is no treatment equipment. The content of lacto-positive coliform bacteria in the water exceeds the norms by 9 times, and the water hardness exceeds the norms by 1.5 times.

A lack of agricultural production and irrigation. The gross harvest of crops in the southern regions increased by 50 % and more due to irrigation. Irrigation allowed farmers to grow vegetables and melons and maintain orchards, vineyards, and berry gardens. Hardworking people had high incomes, ensured the food security of the country and the country's competitiveness in the global market. Irrigation affected regional climatic conditions of irrigated, adjacent, and remote areas. This mitigated temperature pressure and increased the moisture content in the area of more than 2.5 million hectares of the territory in the Steppe of Ukraine. In particular, water from the Dnipro River has a low salinity of 0.3–0.6 g/dm^3, contributing to the leaching (washout and desalinization) of saline soils that increase soil fertility. Soil moisture and the formation of good agrocenoses reduced the risks of wind erosion and led to carbon sequestration (removal from the atmosphere) in plant photosynthesis. In addition, irrigation in saline areas contributed to the desalination of mineralized groundwater.

The destruction of the primary source of irrigation for the southern regions caused extreme water shortages, the drainage of water bodies (Fig. 9), evaporation and a reduction in the water table, the transfer of salts to the upper soil layer, and a rise in their concentration, an increase in the area with secondary salinization and salinity (Fig. 10).

Fig. 9: The drainage of waterbodies in the temporarily occupied territories on the Left Bank of Kherson region in 2024

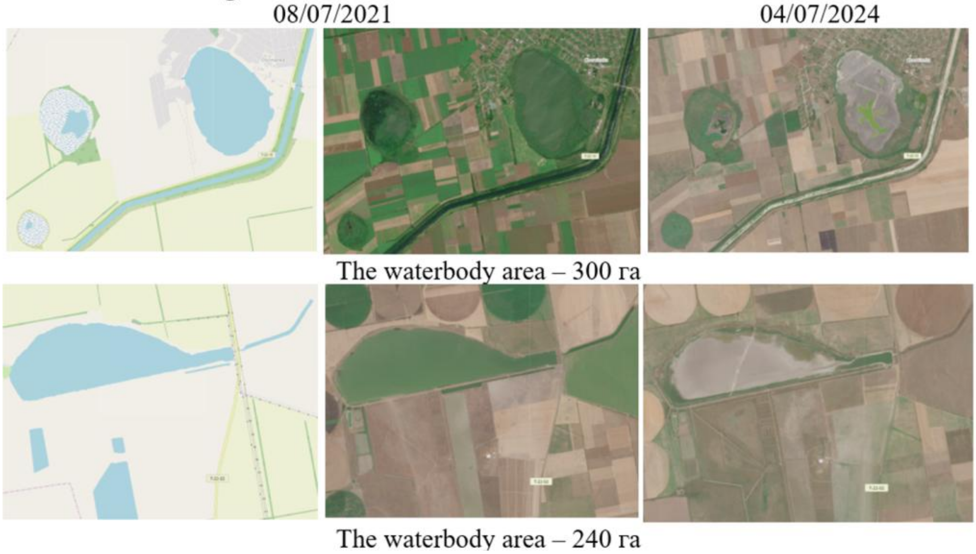
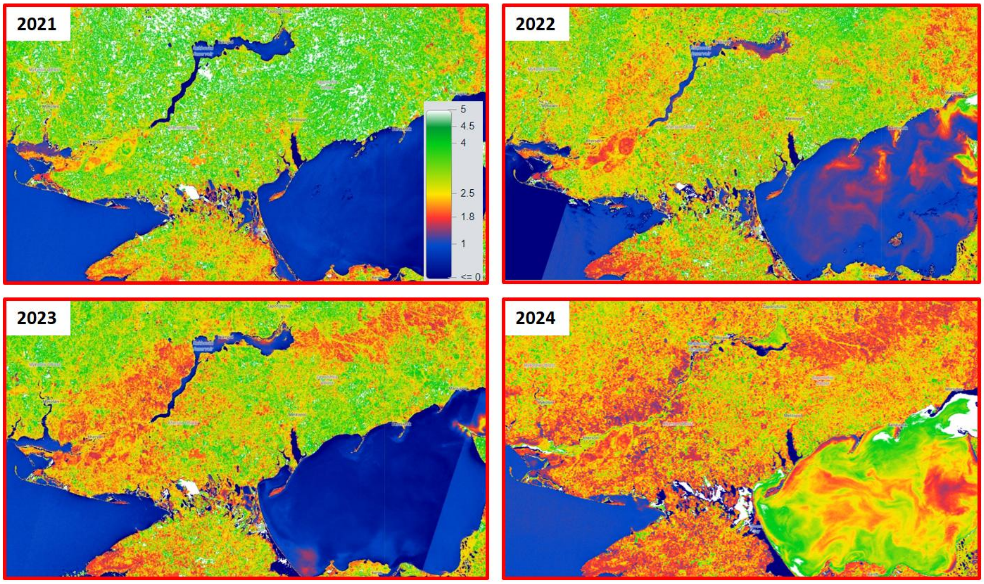


Fig. 10: An increase in the number of saline lands due to a lack of agricultural practices and irrigation in the temporarily occupied territory on the Left Bank of Kherson region (the research territory is 2.1 thousand hectares, the areas of secondary salinization are circled in red)

The lack of irrigation and agriculture has caused an increase in temperature pressure on the land surface, the loss of good vegetative properties of natural vegetation and drying out, the loss of plant biomass and bare soil, acceleration in evapotranspiration, deterioration of physical-chemical properties and soil degradation. Fig. 11 presents a comparison of the environmental state in the pre-war and war periods according to the Terrestrial Chlorophyll Index (OTCI).

Fig. 11: A change in the values of the Terrestrial Chlorophyll Index in the South of Ukraine in May 2021–2024

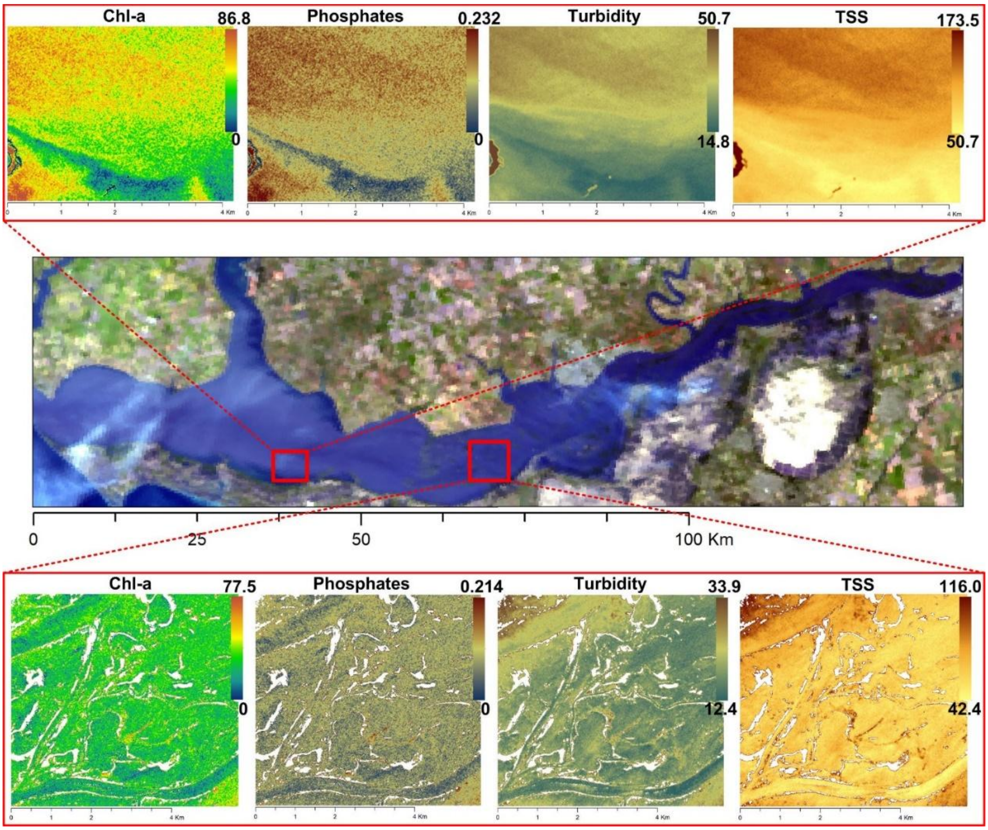


Low OTCI values indicate the presence of water, sand, or snow. The elevated value highlighted in white testifies to the lack of chlorophyll (vegetation) indicating bare soil and stone. Chlorophyll values in the range from red (low chlorophyll values) to dark green (high chlorophyll values) indicate the presence and the corresponding state of vegetation. Within water bodies, white color is characteristic of water areas with high surface water pollution by suspended and organic substances.

Over 500 million m^3 of fresh water is necessary to cover drinking, sanitation, and irrigation needs in the southern regions of Ukraine. Water supply from the nearest Dnipro Reservoir will only partially satisfy these needs. This will cause new environmental problems and water shortages for the users in the region of the Dnipro Reservoir. In particular, the consumption of excessive volumes of water from the Dnipro Keservoir will lead to the disruption of water supply, deterioration of the hydrological regime and ecological sustainability of water ecosystems, worsening the water quality in the lower course of the Dnipro River. Creating a network of wells in the South of Ukraine will partially satisfy the drinking and sanitation needs of the population. The use of groundwater for irrigation will cause accelerated depletion and the replacement of freshwater horizons by saline water from the Black Sea that will create a new wave of water shortages and cause soil degradation and salinization. The application of technologies for desalinating seawater for irrigation in the Steppe zone of Ukraine is not cost-effective or energy-saving and does not meet irrigation needs. In particular, the application of drip irrigation technologies on light chestnut saline soils in the Steppe of Ukraine with a level of mineralized groundwater at a depth of 2–5 meters will cause an increase in the number of soil patches with secondary salinization and the formation of salt marshes. Drip irrigation is used in the system with rainwater on such soils for washing and leaching salt and soil treatment with phosphogypsum for chemical reclamation of saline soils. This system of irrigation agro-technological measures is inefficient and economically unreasonable. Therefore, it is impossible to restore irrigation and satisfy the drinking and sanitation needs of the population in the southern region of Ukraine without rebuilding the Kakhovka Reservoir.

Water quality degradation in the Dnipro-Buh estuary system and the Black Sea. The research was conducted using hydro-biological, biological, and physical-chemical indicators that characterize the water quality and the functioning of the water area. It was established that the destructive consequences of the Kakhovka dam breach manifested in the reservoir drainage, the release of pollutants with a concentration of 1.1–51.8 MPC, and the pollution of water resources in the area of 6800 km^2 of the estuary system, and the Black sea (Fig. 12).

Fig. 12: Water pollution in the Dnipro-Buh estuary system (a) and the Black Sea (b) in the period of 08–24/06/2023



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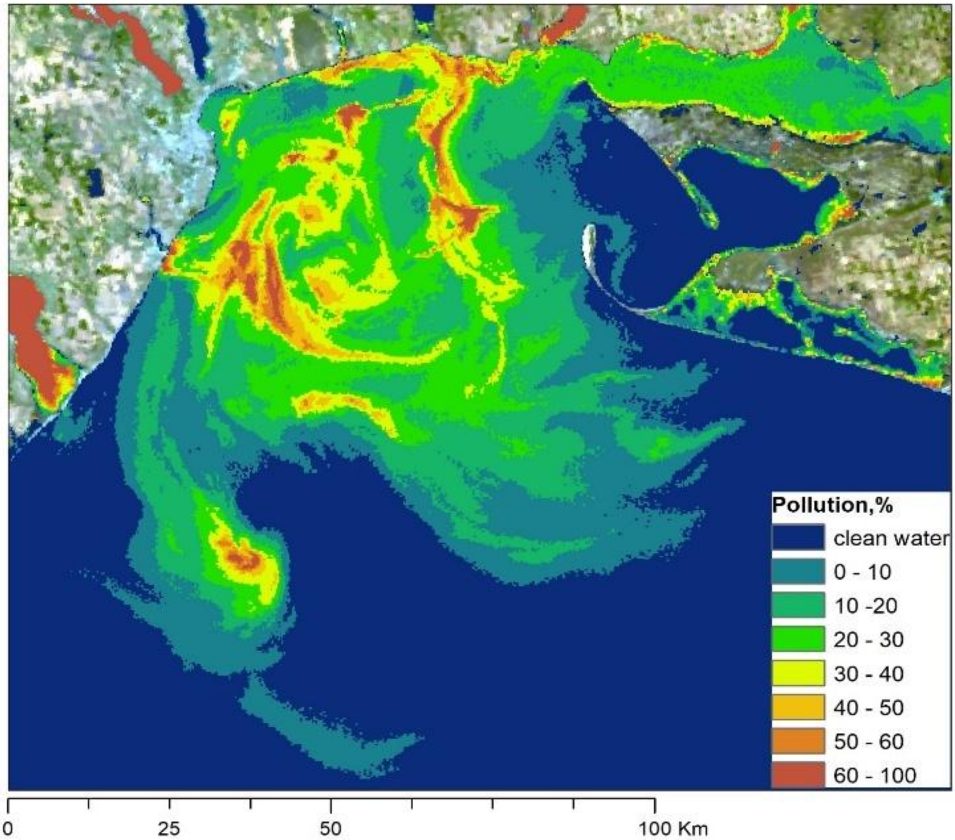
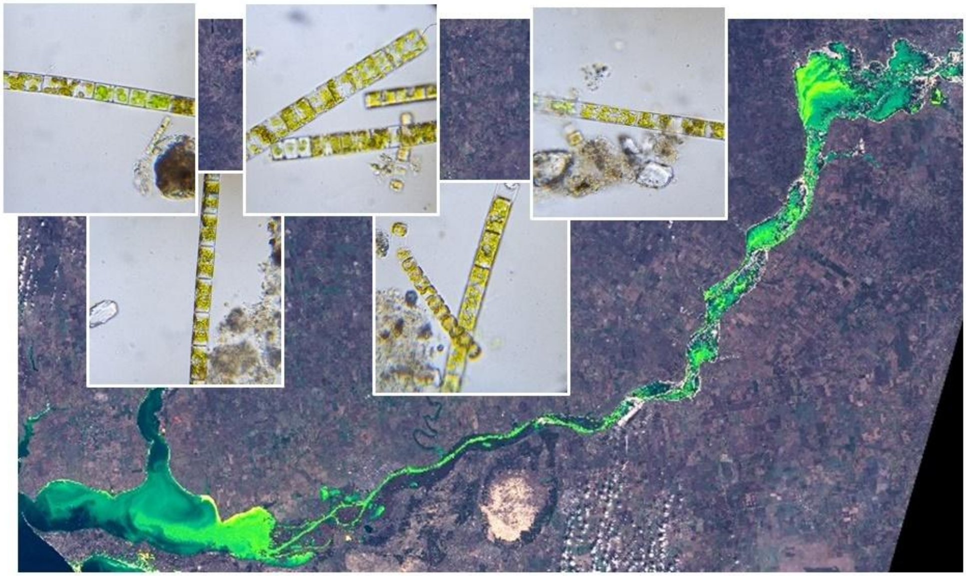


b

After the destruction of the Kakhovka dam, the seasonal characteristics of the hydrological regime of the Dnipro-Buh estuary system deteriorated by 1.42–1.82 times. First of all, the following indicators confirming the negative effect were established: stagnation of water masses, a 2.1-fold increase in the level of the concentration of biogenic substances in the water sources, higher density of algae distribution and a 2.9-fold rise in chlorophyll concentration, more intensive eutrophication and surface water quality degradation to polytrophic (dirty) and hypertrophic (very dirty) levels, deterioration of physical-chemical water properties in terms of turbidity and suspended substances by 4.0 times.

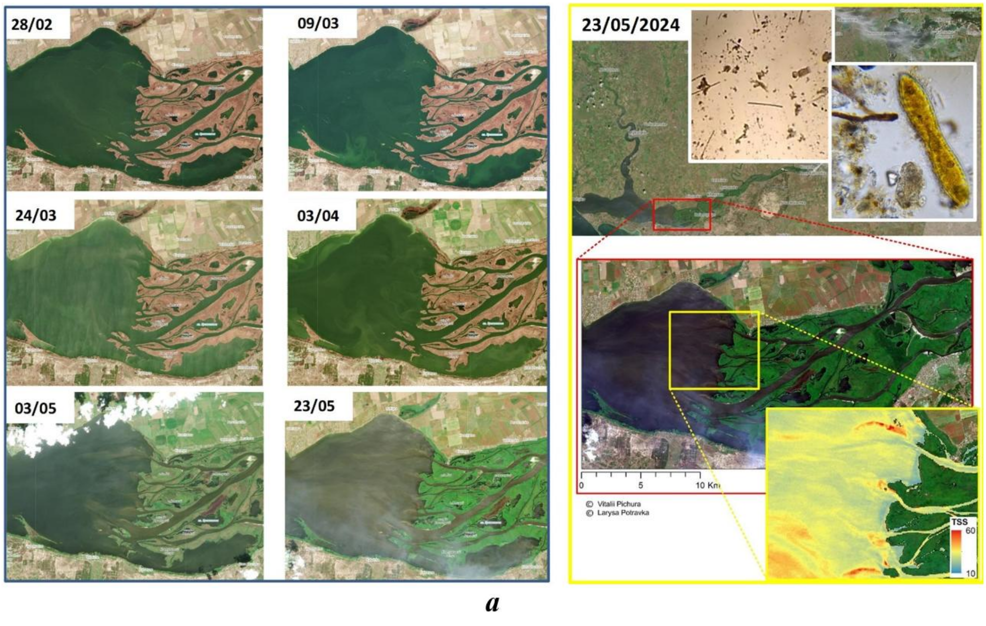
In March–April 2024, there was an abnormal increase in phytoplankton concentration in the waters of the Dnipro-Buh estuary systems. The phytoplankton biomass ranged from 4.17 to 5.23 mg/dm^3 in deep flowing waters of the water area and from 8.12 to 15.43 mg/dm^3 in the shallow shoreline areas. The water quality corresponded to eutrophic and polytrophic conditions regarding biological productivity. An increase in phytoplankton concentration was caused by the movement of microscopic diatomic algae *Melosira varians* (filamentous algae) with the water masses from the territory of the Kakhovka Reservoir. This led to the transfer of colonial diatomic *Melosira varians* by the river flow and increased their share in the Dnipro-Buh estuary system (Fig. 13) from 15.0 to 86.7 %. Being naturally cryophilic (cold-tolerant), these algae formed large volumes of biomass. A slight increase in water temperature to 5°C is a favorable condition for intensive reproduction of *Melosira varians,* whereas the growing season of other algae has not started yet.

Fig. 13: Active reproduction of *Melosira varians* in the Dnipro-Buh estuary system as of March 2024



In the water samples from the Dnipro River taken in the spring of 2024, there was a high concentration of suspended and organic substances, a high density of plant residues, and protozoa remains. Pollutants are carried by the river flow to the Dnipro-Buh estuary and the Black Sea (Fig. 14, 15).

Fig. 14: Pollution of the Dnipro-Buh estuary system: *a* – in February–May 2024; *b* – as of 07/06/2024



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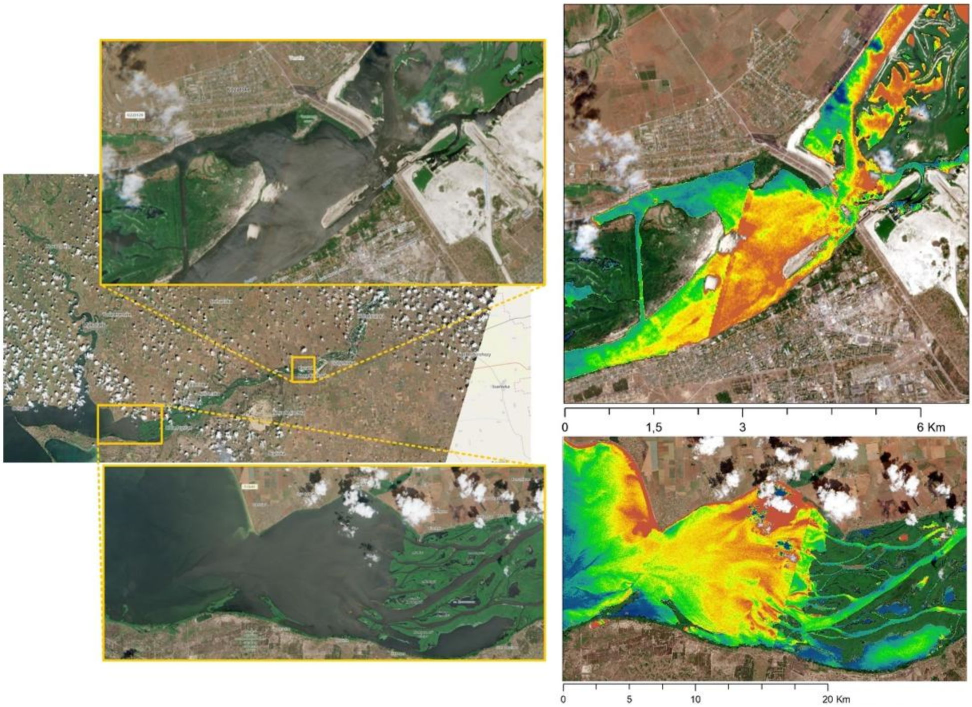
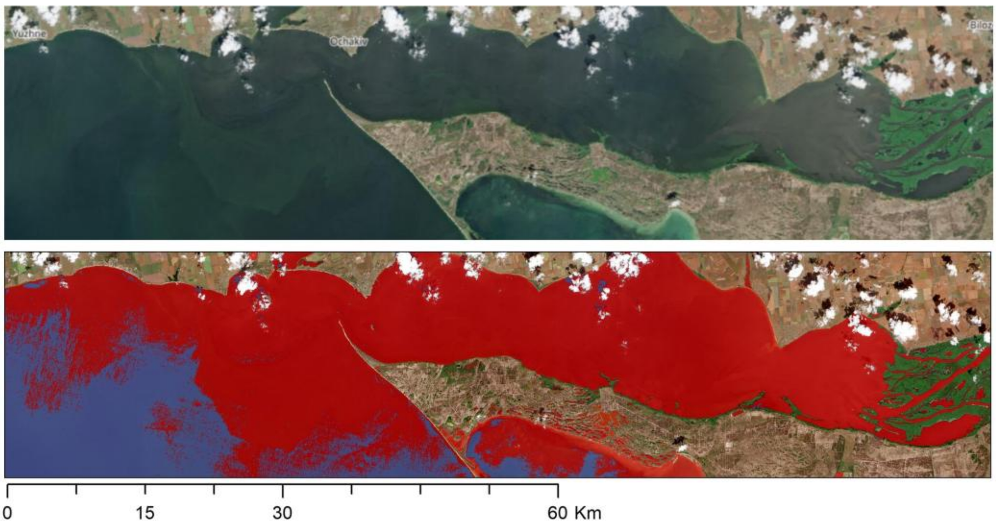


The water quality corresponds to III-V levels of pollution – “moderately polluted” (green color), “dirty” (yellow color), “very dirty” (brown color)

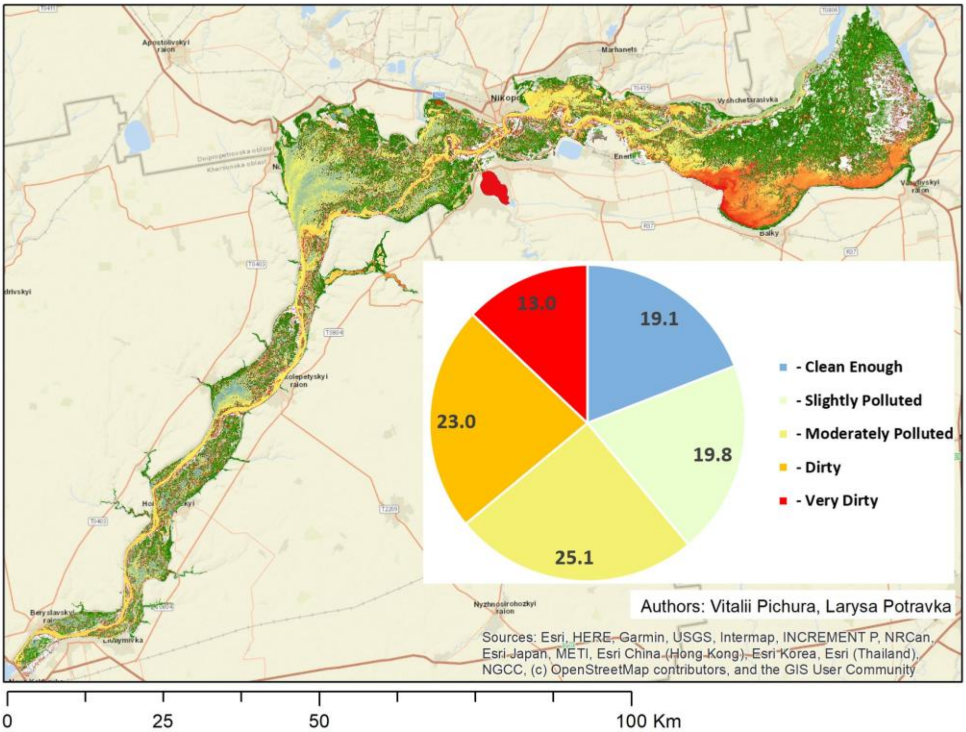
b

Fig. 15: The area of systematic pollution of the Dnipro-Buh estuary and the Black Sea by high concentrations of pollutants (highlighted in red)



Plant residues from the Kakhovka Reservoir are washed away by spring plants and enter surface waters (Fig. 16). In particular, an increase in the number of dead remains and protozoa is caused by washing out by waters from the bottom patches of activated sludge of the drained Reservoir. There was a large number of protozoa, mainly *Oxytricha fallax, Vorticella microstoma, Uronema nigricans, Pseudoglaucoma muscorum*, which are characteristic of a polysaprobic zone (polluted water) with a slow flow and considerable areas of stagnant water masses.

Fig. 16: The Dnipro water quality in the drained Kakhovka Reservoir as of 25/05/2024



It is noteworthy that significant patches of the aquatic ecosystem destruction within the drained Kakhovka Reservoir are shallow water bodies whose area is unstable and depends on the regimes of the river water withdrawal by the Dnipro HPS and additional water discharge from adjacent territories of the local runoff. In particular, the water withdrawal volumes depend on the seasonal accumulation of rainwater masses in the upper and middle parts of the Dnipro River basin. In this regard, the area of shallow water bodies with a depth of 0.5–2.0 m in the research period varied between 307 and 196 km^2. These reservoirs are characterized by poor water quality, accumulation of high concentrations of pollutants, a high level of water heating in hot seasons, intensive development of cyanobacteria, active anaerobic processes, an increase in water toxicity, a lack of dissolved oxygen, and death of aquatic organisms. Such negative processes were largely observed at the end of the spring flood, during the water release from the Reservoir, and during an increase in air temperature. Isolated shallow water bodies became a trap for fish during the spawning season causing the deaths of thousands of tons of fish (Fig. 17).

Fig. 17: Isolated shallow water bodies of the drained Kakhovka Reservoir and fish deaths as of 18–24/06/2024

The research findings indicate considerable degradation of the water quality and exacerbation of the environmental situation in the aquatic ecosystem of the Dnipro River. These processes will occur annually in the future. Therefore, it is essential to repair the hydrological regime of the functioning of the Dnipro River within the Kakhovka Reservoir. It is necessary to create efficient scenarios for the formation of the reservoir's water resources, retaining water during spring floods within the natural Dnipro River course, which will block fish passage to isolated shallow water traps.

Formation of plant biomass in the Reservoir and environmental services. In September 2023, in the period of maximum vegetation development, in the territory of the dried Reservoir, according to the indicators of drought intensity and the NDVI value, there was a distribution of the areas (Pichura *et al.*, 2024a): water bodies (16 %); Type I – areas without vegetation (21 %); Type II – open areas with patches of suppressed vegetation and water stress (18 %); Type III – areas with low plant biomass, water scarcity, and considerable temperature pressure (13 %); Type IV – areas with a satisfactory moisture level and plant biomass (20 %); Type V – areas with a good moisture level and healthy vegetation (12 %). At the beginning of June 2024, the area covered by water was 31.8 %, without vegetation – 31.9 %, with satisfactory vegetation – 7.4 %, with good vegetation – 13.6 %, with very good vegetation – 15.3 % (Fig. 18). About 15.3 % (33.0 thousand hectares) of the territory was covered with willows, the remaining 21.0 % (45.3 thousand hectares) is covered by meadow and marsh vegetation (Fig. 19). Most of the territory without vegetation was covered by shells. It was characterized by bare soils, sand, stones, and shallow water.

Fig. 18: The distribution of the areas of the drained Kakhovka Reservoir as of 09/06/2024

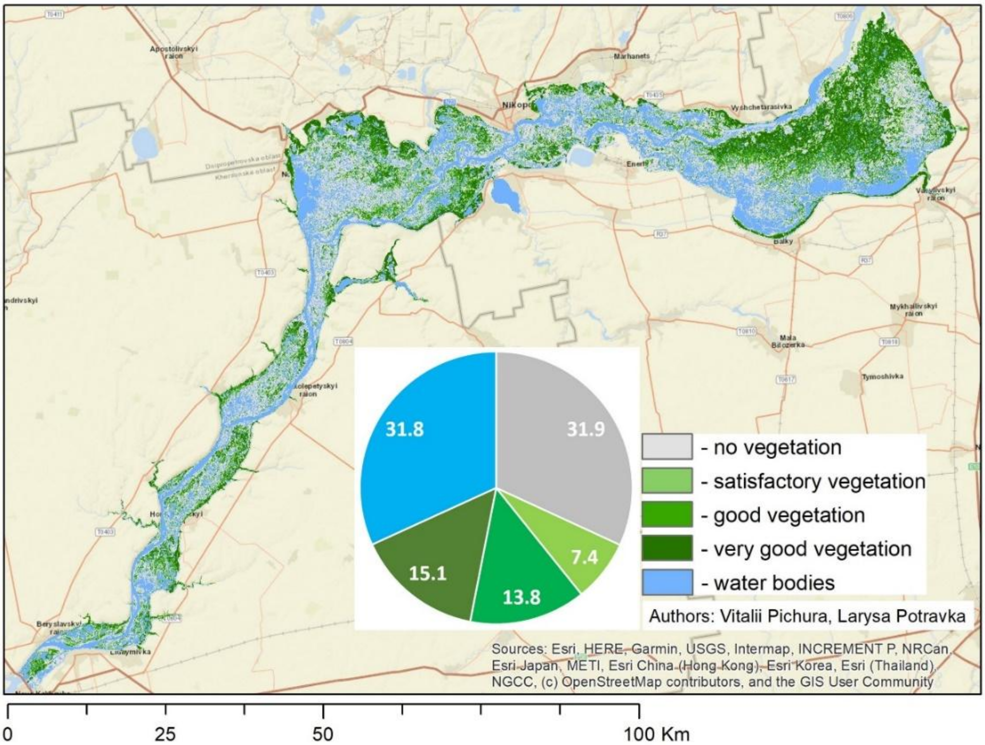
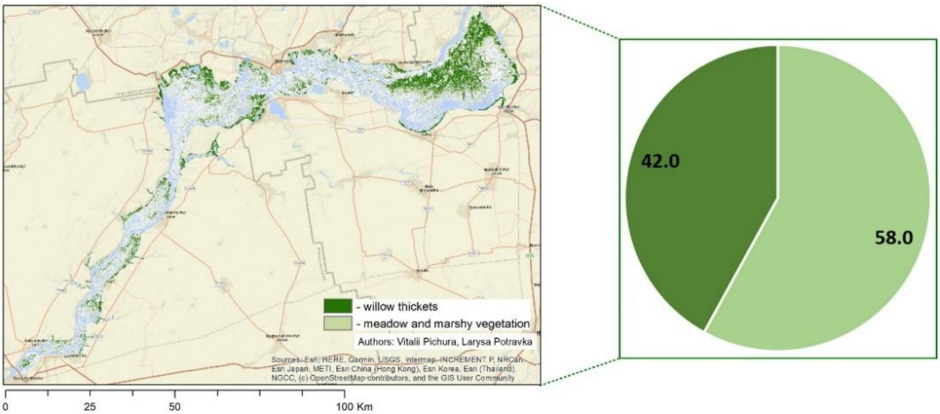


Fig. 19: Mosaic heterogeneity of different areas of the drained Reservoir as of 2024 (the authors' pictures)

The calculation of the Above Ground Biomass (AGB) of plants allowed for establishing that the biomass formed in the area of 78.3 thousand hectares within the territory of the drained Kakhovka Reservoir as of 09/06/2024 (Fig. 20*a*) had the following structure: woody plants mainly represented by willows – 42 %, meadow and marsh plants – 58 % of the territory. About 4.7 million tons of above-ground biomass was formed over the year (Fig. 20*b*). The vegetation patches were uneven, with sparse (0.1 t/ha) and dense (287 t/ha) growth. The average biomass value was 61.3 t/ha. The patches of well-developed woody plants formed more than 40 t/ha of biomass. The biomass of meadow and marsh vegetation ranged from 5 to 75 t/ha. The formation of natural biomass in terms of environmental-atmospheric services is estimated at 8.5 million tons in the total equivalent of sequestration and carbon dioxide reserves (CO_2) (Fig. 20*c*). However, it does not compensate for the volumes of carbon sequestration provided in the past by agrocenoses in an area of 2.5 million hectares of irrigated and adjacent lands. According to our calculations, the equivalent of the total carbon dioxide sequestration provided by agrocenoses amounted to more than 230 million tons.

Fig. 20: Environmental atmospheric services of the plant biomass in the territory of the drained Kakhovka Reservoir as of 09/06/2024: *a* – vegetation structure; *b* – above-ground biomass, t/ha; *c* – equivalent of CO_2 reserves, t/ha



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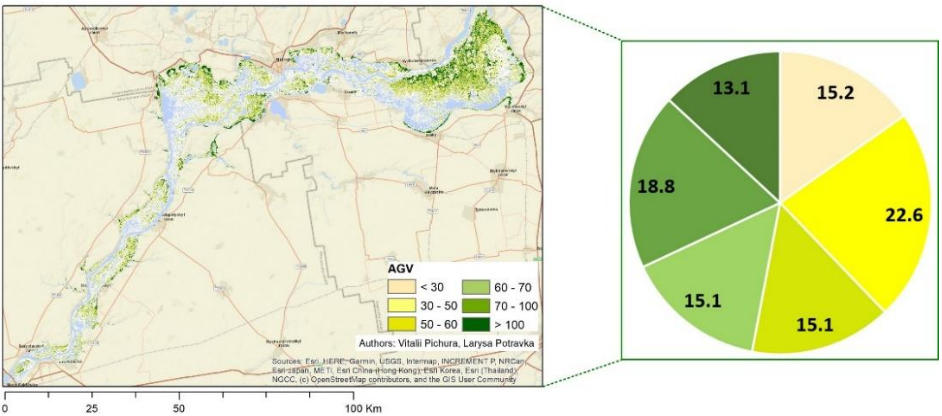

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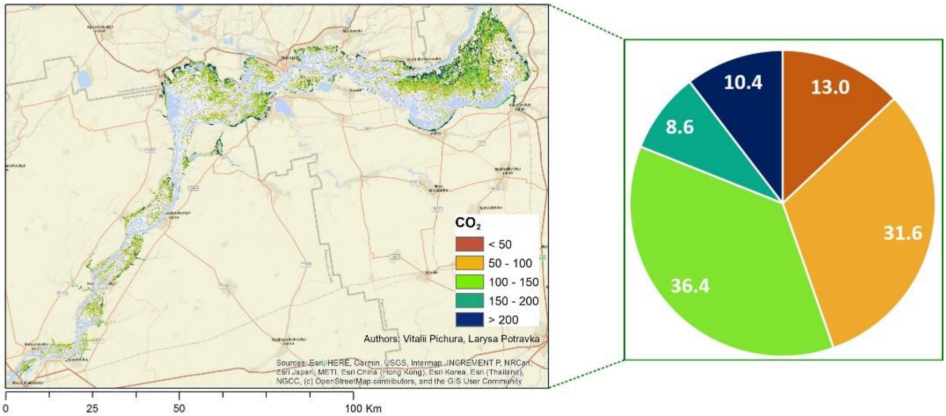
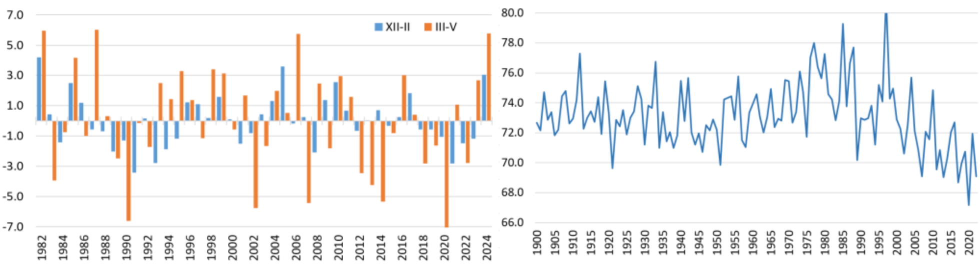


c

A combination of moisture and the availability of nutrients of bottom sediments can explain the rapid growth of plant biomass. Notably, the winter-spring period of 2024 was characterized by favorable climatic conditions, which could be regarded as abnormally favorable in terms of available moisture. In particular, similar conditions were observed in 1982 (Fig. 21*a*). The total value of relative air humidity in the winter-spring period of 2024 exceeded the statistical norm for 1982–2024 by 8.8 %, whereas the excess was 10.1 % in 1982. Abnormally high moisture content was observed in the entire catchment area of the Dnipro River that led to the accumulation of large water volumes in the main river course, good hydrological conditions, and an increase in the frequency of surface water discharges from the Dnipro HPS to the territory of the Kakhovka Reservoir. Therefore, these conditions can be referred to as untypical conditions of Ukraine's Steppe zone, which contributed to plant survival and substantial growth. In particular, over the past 40 years (Fig. 21*b*), there has been a steady decline in relative air humidity by 10–12 %, causing the worsening of water shortages and an increase in temperature pressure on the territorial ecosystems.

Fig. 21: Dynamics of relative air humidity (%) within the Kalhovka Reservoir in 1982–2024: a – deviation from the statistical norm in winter (79.8 %) and spring (68.6 %) periods; b – the average annual value



a ***b***

An increase in the frequency of extreme weather and water shortages will cause vegetation suppression in the future, slow down the development of plant biomass, and lead to the degradation of the plant environment in the territory of the drained Reservoir. The research findings prove the negative impact of the Kakhovka Reservoir drainage on the environmental state of the southern regions, which will have threatening socioeconomic consequences. The necessity of restoring the sources of water supply for the areas under the influence of the Kakhovka Reservoir (settlements, farmlands, etc.) was corroborated.

SCENARIO 3 – the creation of a natural-artificial system of the Kakhovka Reservoir. This scenario is based on the possibility (Fig. 22) of partially filling the Reservoir with water (the territory highlighted in blue) and the creation of a quasi-natural meadow-marsh and forest environment within the territory of the Reservoir (highlighted in green).

The quasi-natural environment is a "second nature environment" that includes all the elements of the natural environment artificially transformed and modified by people. Unlike the natural environment, the quasi-natural environment is not capable of sustaining itself and requires periodical investments of resources. Therefore, an artificial water supply for this territory is necessary for preserving and maintaining the quasi-natural meadow-marsh and forest environment. To create the quasi-natural environment, scientists have proposed the separation of the upper shallow water area occupying 725 km^2 (34 % of the Reservoir's territory) with a dam. Before the Kakhovka dam destruction, this area was mainly characterized by a depth of 0.7–2.5 m (Fig. 23*a*) and contained about 18 % of the Reservoir water volume. 11 % of the water reserves did not participate in flow regulation causing water stagnation and the formation of patches of polytrophic-hypertrophic water masses (Fig. 23*b*), part of which moved downstream.

Fig. 22: The natural-artificial system of the Kakhovka Reservoir

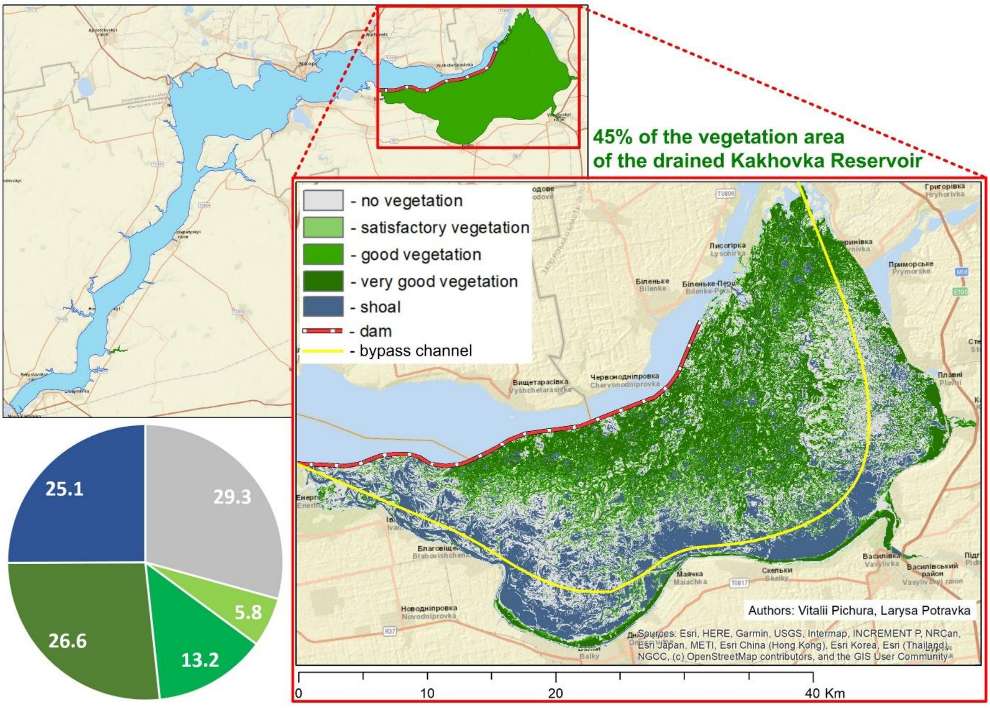
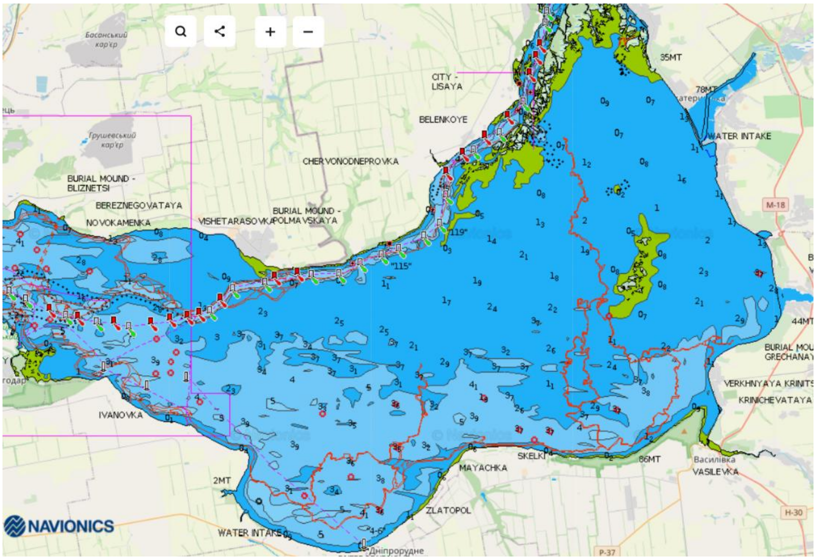


Fig. 23: Bathymetric characteristics and water quality in the territory separated by the Kakhovka Reservoir Dam as of 2022: *a* – depth marks, m (the data source, https://ua.fishermap.org/depth-map/kahovskoe-vodohranilische/#map), *b* – the formation of water quality by hydro-biological characteristics



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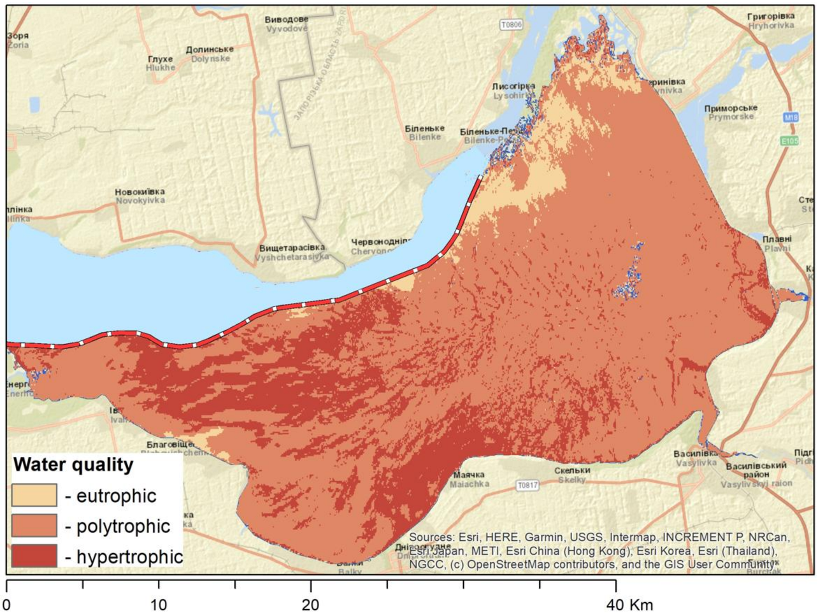


b

Separating the shallow water area by the dam will allow for the preservation of 45 % of the area of vegetation with a total biomass of 2.3 million hectares. 55 % (18.1 thousand hectares) of the area with woody plants and 37% (16.8 thousand hectares) of meadow and marsh plants will be preserved in the structure of plant habitats. It will allow for the preservation of 48 %

of environmental-atmospheric services equivalent to 4.0 million tons of carbon reserves in plants. In particular, the quasi-natural environment will become an essential area for the existence, growth, and preservation of rare protected species of flora and fauna. The functioning of Pan-European Dnipro meridional ecological corridor will be improved.

It is noteworthy that the separation of the shallow water area of the Reservoir by the dam may cause water shortages and the destruction of the quasi-natural environment. Therefore, it is essential to create a bypass channel (Fig. 22 – highlighted in yellow) in this territory to maintain the necessary moisture level in hot seasons to preserve and develop plant biomass. The bypass channel will become an important additional source of water supply to satisfy the population's sanitation needs.

The water-filled territory will cover 66 % (1400 km^2) of the Reservoir area with a water volume of about 15 thousand km^3. It will allow restoring the habitat of bottom activated sludge, which is an important food source for fish, and the biological treatment of surface waters. Separating the shallow water area and narrowing the water area of the upper part of the reservoir will maintain the water flow velocity, which will improve the hydrological functioning of the upper and middle parts of the Reservoir. Where water from the bypass channel flows to the Reservoir, good flow capacity of the reservoir water will be ensured along the shoreline part of the city of Enerhodar and downstream. This will provide additional energy to the flow capacity of the Reservoir water. The restoration of the Kakhovka HPS will lead to turbine aeration of protonated waters, ensuring their oxygenation and providing additional treatment that will improve the surface water quality of the Dnipro-Buh estuary system. Filling the Reservoir with water will ensure relevant water exchange and prevent fish deaths after the spawning season. It will also restore and increase the area of spawning grounds and wintering holes, balance the water content in the low Dnipro, fill with water, and recreate the unique floodplain systems of the "Khortytsia" National Reserve, marsh, and shoreline plants. Breezes will return, which will improve the microclimatic conditions of the shoreline areas. The groundwater level will also rise, which will lead to the return of water to wells in the settlements, provide water for irrigation, and satisfy the sanitation needs of the settlements. It will also result in the return of the population and the revival of the agricultural sector.

DISCUSSION

The issue of water supply has always been crucial for forming human settlements. Cities, towns, and villages were located along rivers. Land use and the development of irrigated agriculture have contributed to the spread of settlements into the Steppe of Ukraine. Therefore, the existence of these settlements depends on the functioning of irrigation systems. Agriculture in the Steppe zone is referred to as a risky farming zone, and its efficiency depends on irrigation. In this context, the scale and damage caused by the destruction of the Kakhovka Reservoir by the occupation forces should be considered in terms of socioeconomic and environmental consequences. Research testifies to the catastrophic nature of the situation. The issue of the ability of the population to live in the territories of ecocide in the future is the primary one requiring the review of the combinations of sustainable development goals in defining the strategies for territorial development by the authorities and local governments. Plans for the post-war recovery are complicated by the ongoing occupation, active hostilities, and large areas of mined territories. The deepening social crisis in the occupied territories cause impoverishment of the residents, high mortality, and degradation of the population's age structure. The invaders' destructive policies toward the local population violate human rights, and daily crimes committed by the representatives of the occupation forces against humanity destroy the lives of thousands of Ukrainians.

Unfortunately, creating the scenario for restoring the territory of the Kakhovka Reservoir is complicated by a considerable amount of unreliable information in the public space from journalists, non-governmental organizations, and scientists from unrelated fields; a lack of reliable information from authorities in the public space. Today, it is necessary to thoroughly study the conditions for the survival and further life of the local population and monitor the environmental state of the territory affected by the ecocide. Therefore, the obtained research results are the basis for choosing the scenario and substantiation of the post-war functioning of the Kakhovka Reservoir.

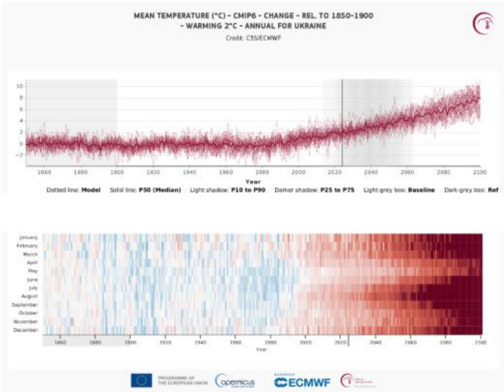
It should be underscored that the ability of the population to adapt in the post-war period is largely determined by the environment and resource factors, mainly by the availability of water resources. According to the preliminary results of the social survey, 75 % of the population in the southern regions of Ukraine supported restoring the Kakhovka HPP and filling the Reservoir with water.

In the context of global climate change and abnormally high temperatures, the southern regions of Ukraine are characterized by a catastrophic level of water scarcity. According to the global research data from the Copernicus Climate Change Service *(*https://atlas.climate.copernicus.eu/atlas*),* in 2024, in the territory of Ukraine (Fig. 24*a*), the air temperature increased by 2.07°C in comparison with the statistical norm of 1850–1900. The average annual value is predicted to exceed the norm by 7,91°C by 2100. It is expected that the most significant fluctuations in a temperature increase from 2.52°C to 10.34°C will occur in the summer and winter seasons of 2024–2100. In July 2024, the historical maximum air temperature of +40.5–42.0°C was reached in the southern regions of Ukraine (Fig. 24*b*). The temperature on the soil surface reached 67°C that corresponded to the potential evapotranspiration at a level of 12.5 mm/day. The temperature exceeded the statistical norm of 1991–2020 by 12°C and more. The previous temperature record of +36.4°C was registered in 1959. According to the data of Climate Central on the Climate Shift Index value (CSI) as of July 12–18 2024, an extreme fifth level of climate change was recorded in 80 % of Ukraine's territory (Fig. 24*c*). A five-fold increase in the frequency of abnormally high temperatures was recorded for the examined region.

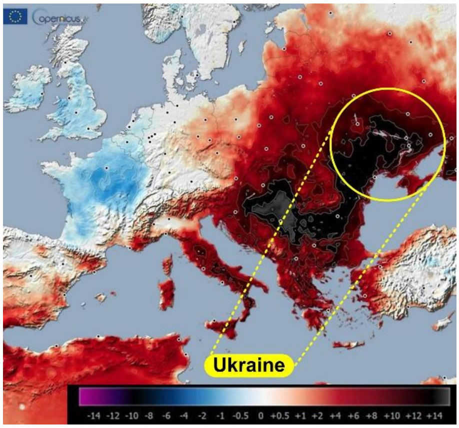
A decrease in productive precipitation, local heavy rainfalls, a rise in evapotranspiration, and desertification accompany an increase in the air temperature in the South of Ukraine (Vyshnevskyi *et al.,* 2024b; Pichura *et al.,* 2024a). The Kakhovka Reservoir played an essential role in accumulating, storing, and redistributing freshwater to satisfy the necessary household and sanitation needs in the southern regions. Water storage essential in the years with low water content, which additionally ensured minimal environmental flow and proper water quality in the Lower Dnipro. About 98 % of the river water reserves are formed in the upper (the zone of mixed forests) and middle (the Forest Steppe zone) parts of the Dnipro catchment area. In the lower course, the local water catchment is only 2.0 %, which cannot meet the local population's needs for water (Pichura *et al.,* 2018, 2020). Therefore, providing these territories with water is an essential national task to create survival conditions for Ukrainians.

Ukraine's government is currently considering the scenario for restoring the Kakhovka dam and filling the Reservoir with water. According to Ukrhydroenergo's data, the estimated cost of the construction of a new Kakhovka HPS will be USD1.0–1.2 billion, and the reconstruction will last about seven years. It is essential to emphasize the necessity of considering the general changes in the Dnipro's state under climate change and taking into account the faults of the Reservoir's functioning in the past.

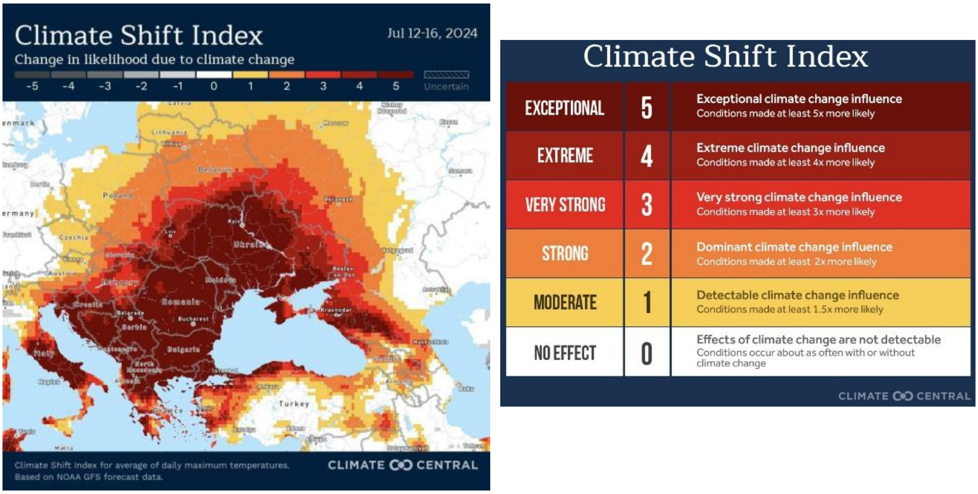
Fig. 24: Changes in the air temperature in Ukraine: *a* – average annual and seasonal changes in the temperature in relation to the statistical norm of 1850–1900; *b* – the air temperature as of June 12–19, 2024, in relation to the statistical norm of 1991–2010; *c* – Climate Shift Index as of July 12–18, 2024



a



b



c

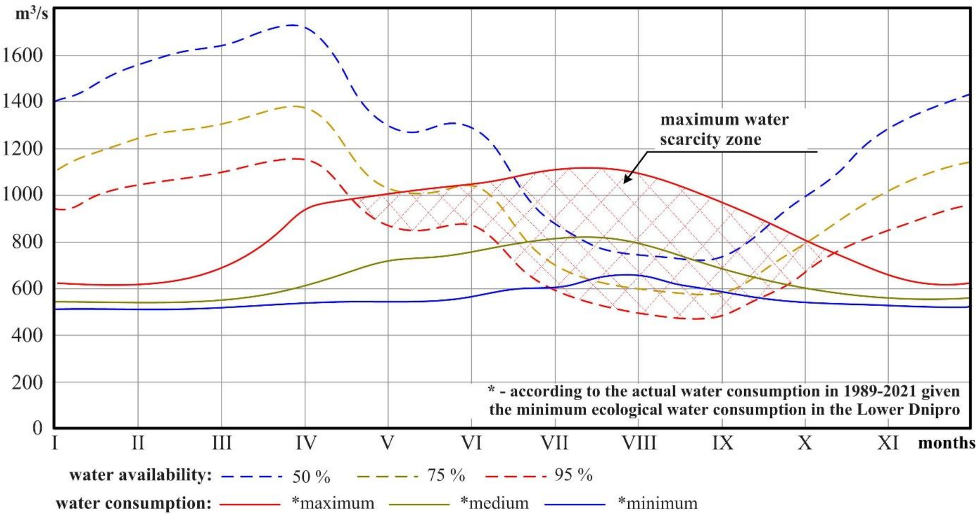
In turn, scientists and the general public are actively discussing the scenario for creating natural plant ecosystems in the form of the Velykyi Luh (Great Meadow) (Vasyliuk *et al.,* 2023; Hapich *et al.,* 2024b; Kuzemko *et al.,* 2024) where the monuments of the Zaporizhzhia Sich are preserved and where rare animals and plants exist. Referring to “The EU biodiversity strategy for 2030: bringing nature back into our lives”, the community considers implementing this scenario to be the main obstacle to global change in these territories as an important part of the European continent. According to the main objectives of the strategy, at least 30 % of the land and 30 % of the sea should be protected areas; at least 10 % of farmlands should not be cultivated and should be restored to the state of natural ecosystems, the application of pesticides should be reduced by 50 %; at least 25 thousand kilometers of rivers should be restored to the state of free-flowing rivers. Scientists highlight that in July 2023, the European Parliament adopted the Nature Restoration Law, which provides for the return of 20 % of the landscape to the category of natural areas by 2030. Therefore, scientists consider the restoration of the Great Meadow to be an exemplary project.

It is possible to achieve these goals provided that the risks are taken into account and the actual capacity of the territories for natural recovery is determined. The post-war restoration of the territories requires scientific substantiation of the projects and programs based on the principles of balanced nature management and aimed at achieving sustainable development goals. Given the results of our research into the state of the drained Kakhovka Reservoir, the implementation of the scenario for creating natural plant ecosystems (restoring the Great Meadow) will not have a desirable environmental, socioeconomic effect under the current anthropogenic and climatic conditions. The formed above-ground plant biomass within the drained Reservoir covering an area of 78.3 thousand hectares cannot substitute for environmental-atmospheric services at the level of agrocenoses biomass on the irrigated and adjacent lands whose functioning depended on the Kakhovka Reservoir. In particular, a lack of water caused the disruption of the micro-climatic conditions and a decrease in the groundwater level that led to the loss of good growing conditions and plant degradation in the water protection areas and unique steppe floodplain systems with a total area of more than 20 thousand hectares. The Reservoir was the final recipient of the inflow, sedimentation, and treatment of contaminated wastewater with activated sludge, the place of aeration, and oxygenation of flowing water by the dam of hydro-electric power plant. Currently, the absence of these processes has led to a four-fold degradation of surface water quality causing an increase in the pollution of the Dnipro-Buh estuary system and the Black Sea (Vyshnevskyi *et al.,* 2023; Pichura *et al.,* 2024b). Therefore, in the absence of the Kakhovka dam, hydrological regulation of discharges from the Dnipro HPSP is necessary for restraining water from the main channel in the period of spring floods. This will cut water pollution by dead plant residues and dried bottom sediments of activated sludge, reduce the area of the shallow water mirror, and separate shallow water from fish passage and spawning.

Experts (Khorev, 2023) have created a model for supplying water to the southern regions of Ukraine depending on the actual availability of water in the Dnipro riverbed for the period of 1981–2021. The model reflects water availability in the river without the volume of the water accumulated in the Kakhovka Reservoir. In other words, the minimum required level of water consumption would not be satisfied in summer and autumn in the absence of the Reservoir and direct water withdrawal from the Dnipro in the years with low water content (Fig. 25 – red curve, 95 % of water availability). In particular, the available water could not satisfy medium and maximum demands for water in the territories depending on the Reservoir in the years with medium river water content (blue curve, 50 % of water availability). In the years with high precipitation and the maximum water use by the population, the level of water supply from the Dnipro River will meet only 40–50 % of the needs. Therefore, the existence of the Kakhovka Reservoir is an essential condition for the survival of the southern region, especially in the years with the expected steady increase in the air temperature and a decrease in the amount of productive precipitation.

It should be highlighted that the direct water withdrawal from the Dnipro riverbed will cause a sharp reduction in its water content, deterioration of the hydrological regime and river regulation, an increase in the concentration of pollutants, significant water pollution, and the death of aquatic bio-resources.

Fig. 25: The model of water supply in the southern regions of Ukraine (m^3/s) depending on the actual water availability in the Dnipro riverbed in 1981–2021



Therefore, it is necessary to start implementing the goals of "The EU biodiversity strategy for 2030: bringing nature back into our lives" and the Nature Restoration Law to solve the problems of the upper and middle parts of the Dnipro catchment area. These measures should involve the restoration of wetlands and forests, erosion control of farmlands, expansion of water protection zones, reconstruction or additional construction of treatment systems for enterprises and settlements, seasonal regulation of water use, creation of fish passages in the dams of hydro-electric power plants, balanced regulation of the Dnipro water content and runoff with the cascade of the Dnipro reservoirs depending on the season and moisture conditions of the year. Against the backdrop of intensive anthropogenic disturbance of the Dnipro water catchment area, the inflow of large volumes of pollutants, unbalanced artificial regulation of water content and runoff, abnormal climate change, catastrophic freshwater scarcity, degradation of the existing natural environment, and the destruction of the critical water resource for the functioning of labor resources in the southern regions of Ukraine, the scenario for creating natural plant ecosystems in the territory of the dried Kakhovka Reservoir is not efficient. Without the required water supply, the natural plant ecosystem will undergo degradation, as exemplified by the floodplain systems of the Khortytsia National Reserve.

The scenario for creating a natural-artificial system with the Kakhovka Reservoir partially filled with water and creating a quasi-natural meadow-marsh and forest environment deserves attention. First, it will satisfy the population's need for water, preserve the biodiversity of habitats of natural-artificial ecosystems, and contribute to achieving sustainable development goals and balanced nature management in the southern regions of Ukraine. The restoration and efficient exploitation of the territory of the Kakhovka Reservoir and adjacent territories should be based on adaptive landscape anti-erosion principles of spatial planning of the Dnipro catchment area. This will allow optimizing the structure of land funds, restoring water protection zones, reducing risks of environmental destruction of land and water resources, and improving the ecological situation in the area depending on the Kakhovka Reservoir. Therefore, the issue of choosing the optimal scenario for the post-war restoration and functioning of the territories in the southern region and assessing the ability of Ukrainians to adapt to new conditions remains relevant for Ukraine today.

CONCLUSIONS

Comprehensive research into the consequences of the dam destruction and the drainage of the Kakhovka Reservoir for the southern water-dependent regions of Ukraine was carried out. Three scenarios for the functioning of the Reservoir territory having both positive and negative environmental and socioeconomic consequences were substantiated. Therefore, choosing the scenario that will ensure a positive regional cumulative effect according to the global sustainable development goals is important. The results obtained are the basis for making objective management decisions for the post-war restoration and maintenance of the sustainable functioning of the regions depending on the Kakhovka Reservoir. Finding ways to restore the damaged territories and creating social and environmental conditions for the return of people require further scientific research into the environmental consequences and social issues and actualizing the scientific substantiation of the directions of socioeconomic recovery. It is possible to predict and create scenarios for the functioning of these territories only through assessing the ability of Ukrainians to adapt to the current conditions.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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