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The Kakhovka Sea Before and After the Destruction of the Kakhovka Dam

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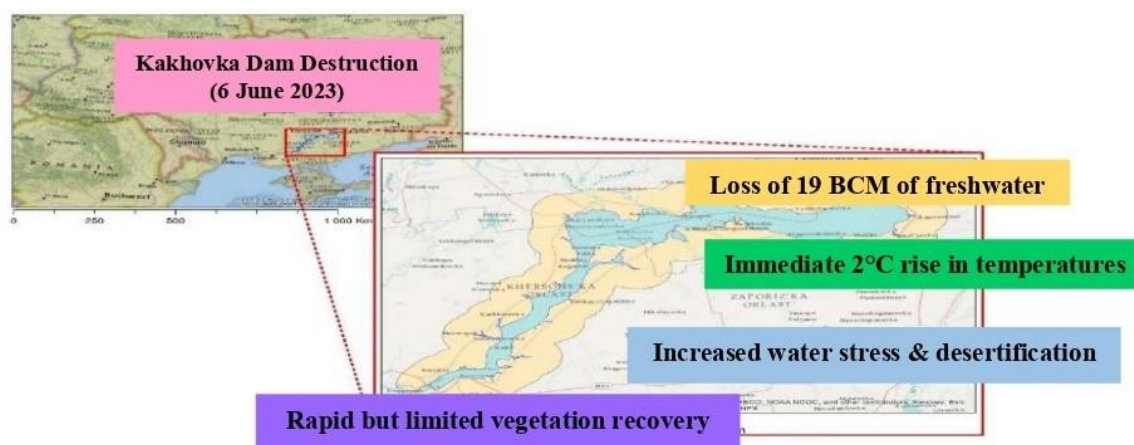
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Graphical Abstract

The destruction of the Kakhovka Dam on 6 June 2023 resulted in the loss of 19 billion cubic metres of freshwater, exacerbating drought conditions and increasing water stress in the affected region. This disaster triggered an immediate 2°C rise in local temperatures, accelerating desertification and limiting vegetation recovery. The environmental impact highlights the vulnerability of ecosystems to human-induced disruptions and underscores the urgent need for sustainable adaptation strategies.



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Abstract: Sabotage of the Kakhovka dam on the Dnipro River eliminated one third of Ukraine's fresh water reserves, clean drinking water for 6 million people and domestic supply for more than 13 million. Opinions differ on whether and how to replace it. Fieldwork is constrained by fighting along the course of the lower Dnipro but we have used remote sensing to examine the natural-climatic transformation of the reservoir and dependent areas, which experienced an almost immediate increase of 2.0°C in the land surface temperature, two-fold acceleration of evapotranspiration, and exacerbation of water scarcity.

Keywords: Kakhovka Reservoir, Hydrology, Temperature, Evapotranspiration, Vegetation health.

Introduction

Russian aggression has claimed the lives of hundreds of thousands of Ukrainians and driven millions from their homes; destroyed natural landscapes, flora and fauna; polluted soil and water with petroleum products and heavy metals from fuel spills, munitions, industrial plant and storage facilities, and untreated sewage from disrupted water infrastructure [1-3]. On 6th June 2023, sabotage of the Kakhovka dam on the lower Dnipro River eliminated one third of the country's fresh water resources – some 19 billion cubic metres (BCM) worth more than \$US18 billion [1]. As a result of Russian military action across the country, six million people in Ukraine do not have safe drinking water and domestic supplies are restricted for more than 13 million and damage to the environment already exceeds \$60billion [4]. Repair and reconstruction require thorough investigation to find effective ways to restore ecosystems and **optimize** the management of natural resources.

Material and Methods

Fieldwork is restricted by active conflict along the course of the lower Dnipro but we have used satellite imagery to establish the status of the Kakhovka Reservoir before and after destruction of the retaining dam (Fig. 1). Data on the flow of the lower Dnipro River over 205 years were taken from Lotsmanska Kamianka within the city of Dnipro up to 1975 [5] and, subsequently, observations of the Kherson hydro-biological station. Values of near-surface air temperature, precipitation, and reference evapotranspiration were provided by the University of East Anglia Climatic Research Unit (<https://crudata.uea.ac.uk/cru/data/hrg/>) and NASA POWER (<https://power.larc.nasa.gov/data-access-viewer/>). Sentinel and Landsat satellite imagery were abstracted from the **Copernicus Browser** at **EO Browser**.

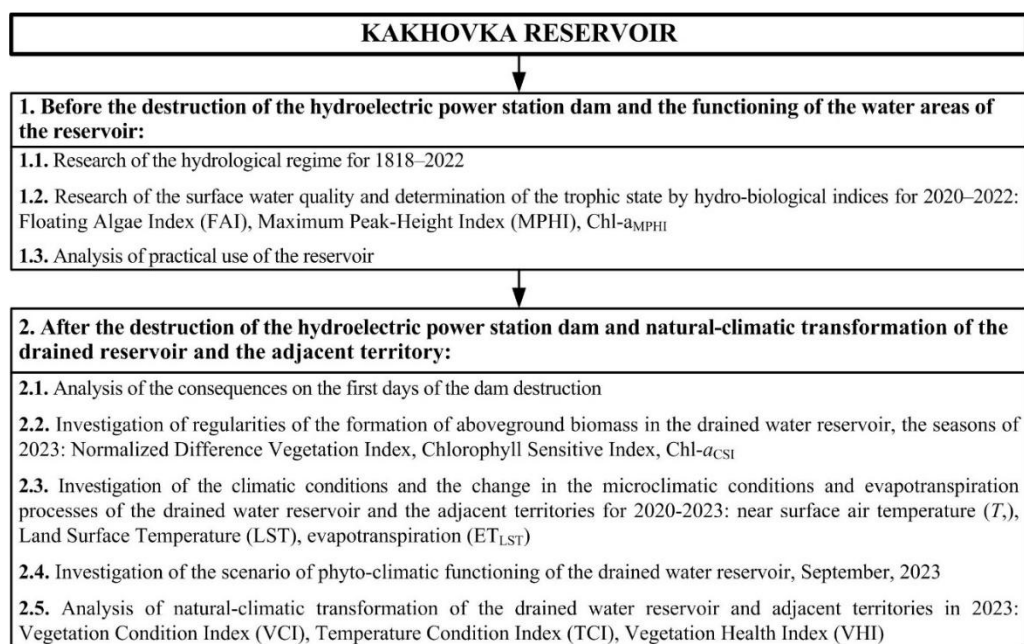


Figure 1. Scheme of research.

Study Area

Historically, the territory of the reservoir was the Velykyi Luh, the Great Meadow, that hosted the fortified Cossack encampments of Zaporizka Sich (1564-93), Tomakivska Sich (1593-1630), Bazavlutska Sich (1630-52), Mykitynska Sich (1652-1709), Chortomlytska Sich (1734-1775), and Nova (Pidpilnetska) Sich. Construction of the Kakhovka dam between 1955 and 1958 (Fig. 2) flooded 2,800 ha of arable land, 36,000 ha of pasture, and more than 90 settlements, including parts of the cities of Nikopol and Kamianka-Dniprovska, to create a reservoir with a total capacity of 18.2 BCM and an active capacity of 6.8 BCM, a normal storage level of 16.0 m and a dead storage elevation of 12.7 m, a maximum depth of 32.0 m and an average depth of 8.5 m, a maximum length of 230 km, a maximum width of 25 km, and an average width of 9.3 km, with a shoreline of 869 km [6]. This transformation significantly altered the social and economic conditions of the local population, affecting settlements, livelihoods, and water management systems in the region [7]. Known locally as the Kakhovka Sea, its area of 2,155 km² was 13 times the size of the Sea of Galilee and one-thirtieth of the Aral Sea at that time. Its hydroelectric power station had a capacity of 329 MW – only one-twelfth of the whole Dnipro cascade. However, power was not its main purpose; rather, it was intended primarily for water supply to the cities and industries of the southern steppes and, in particular, for irrigation.

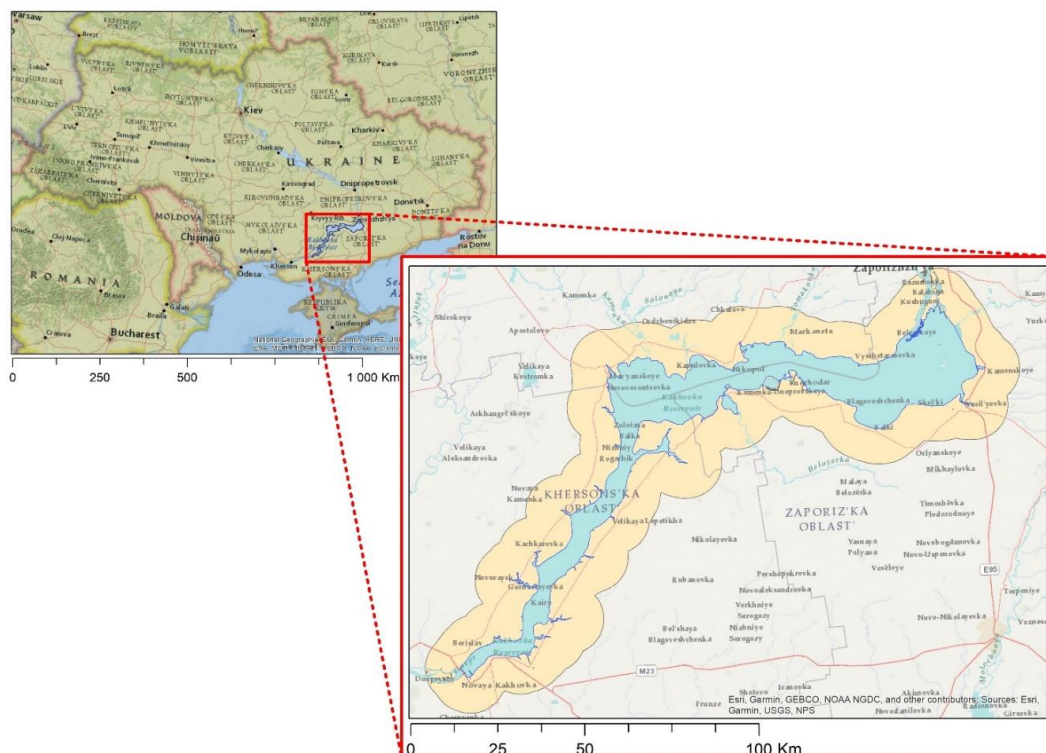


Figure 2. Location: Kakhovka Reservoir (blue) and the 10km buffer zone (cream).

Research Methods

The trophic state of the reservoir and its water quality over the period 2020-2022 was assessed by the activity of algal (cyanobacteria) blooms and the intensity of their saturation with chlorophyll-a, measured by the Floating Algae Index [8]:

$$FAI = B6 - B4 - \frac{(B8 - B4) \times (740 - 665)}{842 - 665} \quad (1)$$

where B4, B6, and B8 are the reflectance of $\lambda B4 = 665$ nm, $\lambda B6 = 740$ nm, and $\lambda B8 = 842$ nm, the central wavelengths of the corresponding bands of Sentinel 2 L2A imagery.

FAI varies between -1.0 and 1.0, where a value greater -0.004 indicates a bloom. Saturation with chlorophyll-a is calculated by the Maximum Peak Height Index (MPHI) [9]:

$$MPHI = B5 - B4 - \frac{(B8 - B4) \times (705 - 665)}{842 - 665} \quad (2)$$

where B4, B5, and B8 are the reflectance, and $\lambda B4$ (665nm), $\lambda B5$ (705nm), and $\lambda B8$ (842 nm) are the central wavelengths of the corresponding bands of Sentinel 2 L2A.

MPHI value varies between -1.0 and 1.0. A value greater than 0.004 indicates presence of Chl-a in the cyanobacteria of the surface water. Chlorophyll content ($Chl-a_{MPHI}$, $\mu g/dm^3$) was calculated by the formula:

$$Chl-a_{MPHI} = 2223.18MPHI + 24.03 \quad (3)$$

Surface water quality was determined according to Chl-a content (Table 1) [10].

Table 1. Ecological classification of surface water quality.

Water Quality Class	I	II		III		IV	V
Water Quality Category	1	2	3	4	5	6	7
Chl-a, $\mu g/dm^3$	< 2	2–4	5–10	11–30	31–50	51–150	>150
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
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Changes in the structure of the exposed bed of the reservoir and seasonal primary productivity in 2023 were measured by the normalized difference vegetation index (NDVI) and the intensity of plant saturation with chlorophyll-a:

$$\text{NDVI} = \frac{B8 - B4}{B8 + B4} \quad (4)$$

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

NDVI ranges from -1.0 to 1.0. Negative values reflect cloud, water and snow; values close to zero (0.05-0.15) indicate bare ground; higher values vegetation. The intensity of plant saturation with Chl-a was calculated by the Chlorophyll Sensitive Index (CSI) [11]:

$$\text{CSI} = 2.5 \times \frac{B8 - B5}{B8 + B5} \times \frac{B2}{B5} \quad (5)$$

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

CSI is dimensionless: negative values indicate cloud, water and snow; values from 0.0 to 0.2 bare ground; $\text{CSI} > 0.2$ indicates vegetation. Chl-a content in plant leaves ($\text{Chl-a}_{\text{CSI}}$, $\mu\text{g}/\text{m}^2$) was calculated by the formula:

$$\text{Chl-a}_{\text{CSI}} = 130.34 \text{CSI} - 25.37 \quad (6)$$

Spatio-temporal changes in microclimate caused by drainage of the reservoir were established on the basis of changes in near-surface air temperature (T , $^{\circ}\text{C}$), reference evapotranspiration (ET_0 , mm/day) for 2020-22, and land surface temperature (LST, $^{\circ}\text{C}$) for 2020-23 using Landsat 8-9 and Sentinel 3 SLSTR L1B imagery. ET_0 was determined according to the Penman-Monteith method [12]:

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad (7)$$

where, ET_0 is reference evapotranspiration, mm/day; R_n is net radiation at the crop surface, $\text{MJ}/\text{m}^2/\text{day}$; G is the soil heat flux, $\text{MJ}/\text{m}^2/\text{day}$; T is air temperature at 2m, $^{\circ}\text{C}$; u_2 is wind speed at 2m, m/s; e_s is saturation vapour pressure, kPa; e_a is actual vapour pressure, kPa; $e_s - e_a$ is the saturation vapour pressure deficit, kPa; Δ is the slope of the vapour pressure curve, $\text{kPa}/^{\circ}\text{C}$; and γ is the psychrometric constant, $\text{kPa}/^{\circ}\text{C}$.

LST relates to the surface energy and water balance of the earth-atmosphere system [13]. Raster values for 2020-23 were retrieved from the [Copernicus Browser](#) from the Sea and Land Surface Temperature Instrument of Sentinel 3 which measures LST with a central wavelength of 10854nm (thermal infrared) at a resolution of 270×270m. Seasonal patterns of LST across the reservoir bed and adjacent territories in 2023 were investigated using raster data from the Landsat 8-9 thermal channel with the central wavelength of 10895nm at a resolution of 75×75 m retrieved from the [EO Browser](#).

Natural-climatic transformation of the drained reservoir bed was characterized by the Vegetation Health Index (VHI) [14]:

$$\left. \begin{aligned} \text{VCI} &= \frac{\text{NDVI} - \text{NDVI}_{\min}}{\text{NDVI}_{\max} - \text{NDVI}_{\min}} \\ \text{TCI} &= \frac{\text{LST}_{\max} - \text{LST}}{\text{LST}_{\max} - \text{LST}_{\min}} \end{aligned} \right\} \rightarrow \text{VHI} = \alpha \times \text{VCI} + (1 - \alpha) \times \text{TCI} \quad (8)$$

where, VCI (Vegetation Condition Index) represents the spatial variability of NDVI.

TCI (Temperature Condition Index) represents the spatial variability of LST, determining plant stress related to high temperatures. High temperatures throughout the growing season correspond with the likelihood of drought.

α – a coefficient determining contribution of VCI and TCI to the general state of vegetation.

VHI evaluates cumulative temperature and moisture for plant development, ranging from 0 (extreme stress) to 1.0 (the most favourable condition). For the drained territory of the reservoir, values lower than 0.50 indicate extreme drought and bare ground; 0.50-0.58, high surface heat, water stress with patches of stunted plants; 0.58-0.63, moisture deficit with low plant biomass and considerable heat stress; 0.63-0.73, satisfactory moisture and plant biomass; greater than 0.73, a high level of moisture, low surface heat, visible vegetation. Coefficient α should be calculated [15] on the basis of the Aridity Index, AI [16]:

$$\text{AI} = P_y / \text{ET}_{y0} \rightarrow \alpha = 0.5 \text{AI} \quad (9)$$

where, P_y is annual precipitation, mm; ET_{y0} is annual reference evapotranspiration, mm; 0.5 is the equilibrium value of the balance of the combination of chlorophyll and moisture content in plants and thermal conditions on the surface.

AI considers both physical phenomena (precipitation and evaporation) and biological processes (transpiration). An AI value lower than 0.5 indicates arid or semi-arid conditions, values greater than 0.65 humid conditions.

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

Results

Prior Hydrological Regime

Major engineering over the period 1934-1976 transformed the lower Dnipro to a cascade of reservoirs that multiplied Ukraine's accessible water resources but restricted their circulation – leading to stagnation, eutrophication, and a raised water table [17]. Figure 3 shows a decrease in the average annual flow in the lower Dnipro by $2.0\text{m}^3/\text{s}$ per year; over 205 years of observations:

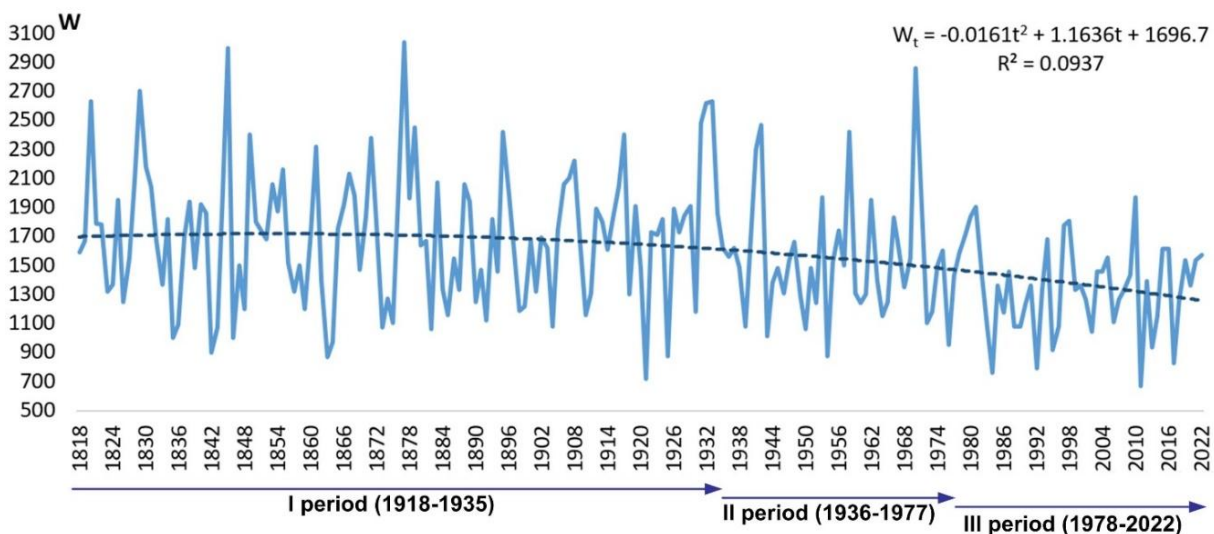


Figure 3. Average annual flow (m^3/s) in the lower Dnipro River, 1818-2022.

Mean annual flow diminished from 1670 to $1258\text{m}^3/\text{s}$. In high-water years, the maximum value ranged from 1970 to $3,040\text{m}^3/\text{s}$, in low-water years from 670 to $1,050\text{m}^3/\text{s}$. The multiyear norm was $158,9\text{m}^3/\text{s}$ with the variance of 28 per cent.

We can recognize three periods: I (1818-1935) more-or-less-natural flows that ranged from 1328 to $1,965\text{m}^3/\text{s}$ in 90% of cases (Fig. 4a), the mean was $1,704\text{m}^3/\text{s}$, variance 27%; II (1936-1977) the creation of the reservoir cascade that dampened the average annual flow from $1,704$ to $1,530\text{m}^3/\text{s}$, varying between $1,248$ and $1,665\text{m}^3/\text{s}$; III (1978-2022) its functional operation during which the average annual value of the flow fell to $1,344\text{m}^3/\text{s}$, varying between $1,093$ and $1,562\text{m}^3/\text{s}$.

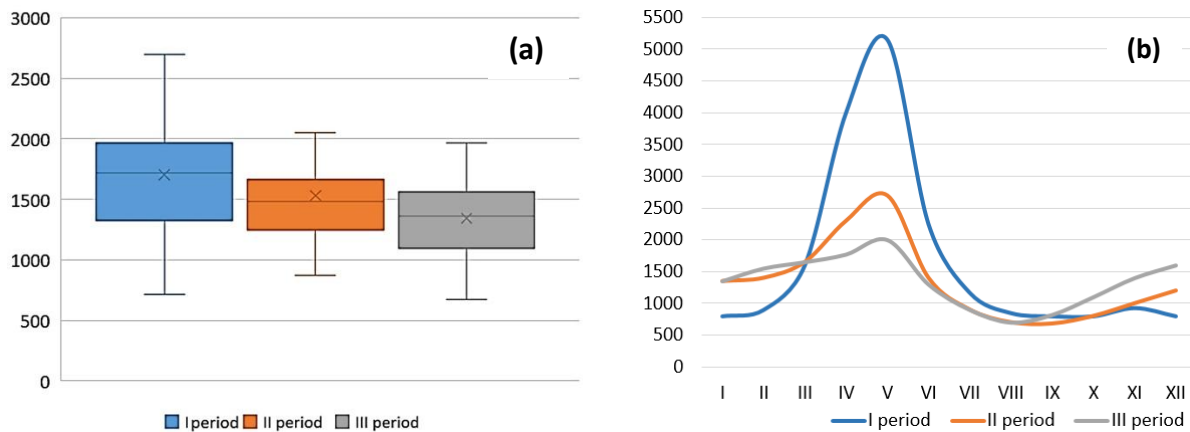


Figure 4. Periodic change in the flow (W , m^3/s) in the lower Dnipro lower course 1818-2022: (a), mean annual values; (b), mean monthly values.

Spring floods were drastically reduced by construction of the six reservoirs – upstream to downstream: Kyiv (filled 1964-6, area 922 km^2) → Kaniv (filled 1974-6, 675 km^2) → Kremenchuk (filled 1959-61, $2,252 \text{ km}^2$) → Kamianske (filled 1964-5, $5,567 \text{ km}^2$) → Dnipro (constructed 1932, reconstructed after World War II in 1948, 410 km^2) → and Kakhovka (filled 1955-8, $2,155 \text{ km}^2$). In Period III, mean annual flow amounted to $1,344 \text{ m}^3/\text{s}$, characterized by low spring floods ($1,680 \text{ m}^3/\text{s}$ on average) and a summer-autumn low water season ($1,090 \text{ m}^3/\text{s}$ on average). At the same time, water exchange was reduced by 24 times.

Trophic State of the Reservoir

Restriction of water exchange led to eutrophication, manifest in algal blooms and a considerable reduction in water clarity in well-heated and well-lit, shallow, stagnant zones. The Floating Algae Index in the period 2020-22 exceeded -0.004 across almost the entire water area in July (Fig. 5a). The greatest intensity was observed in the middle part of the reservoir where FAI reached 0.27 (Fig. 6b) on account of a concentration of living material and metabolites in the surface waters, high temperatures, and a low hydrological capacity for self-treatment.

There is a direct correlation between biogenic pollution and the quantity of phytoplankton in water bodies, so Chl-a concentration is a good indicator of eutrophication. Its concentration increased to more than $270 \mu\text{g}/\text{dm}^3$ in July (Fig. 5b, 6b) and, water quality ranged from moderately polluted to very dirty in 82-87% of the reservoir area over the entire warm spring-summer season (Table 2).

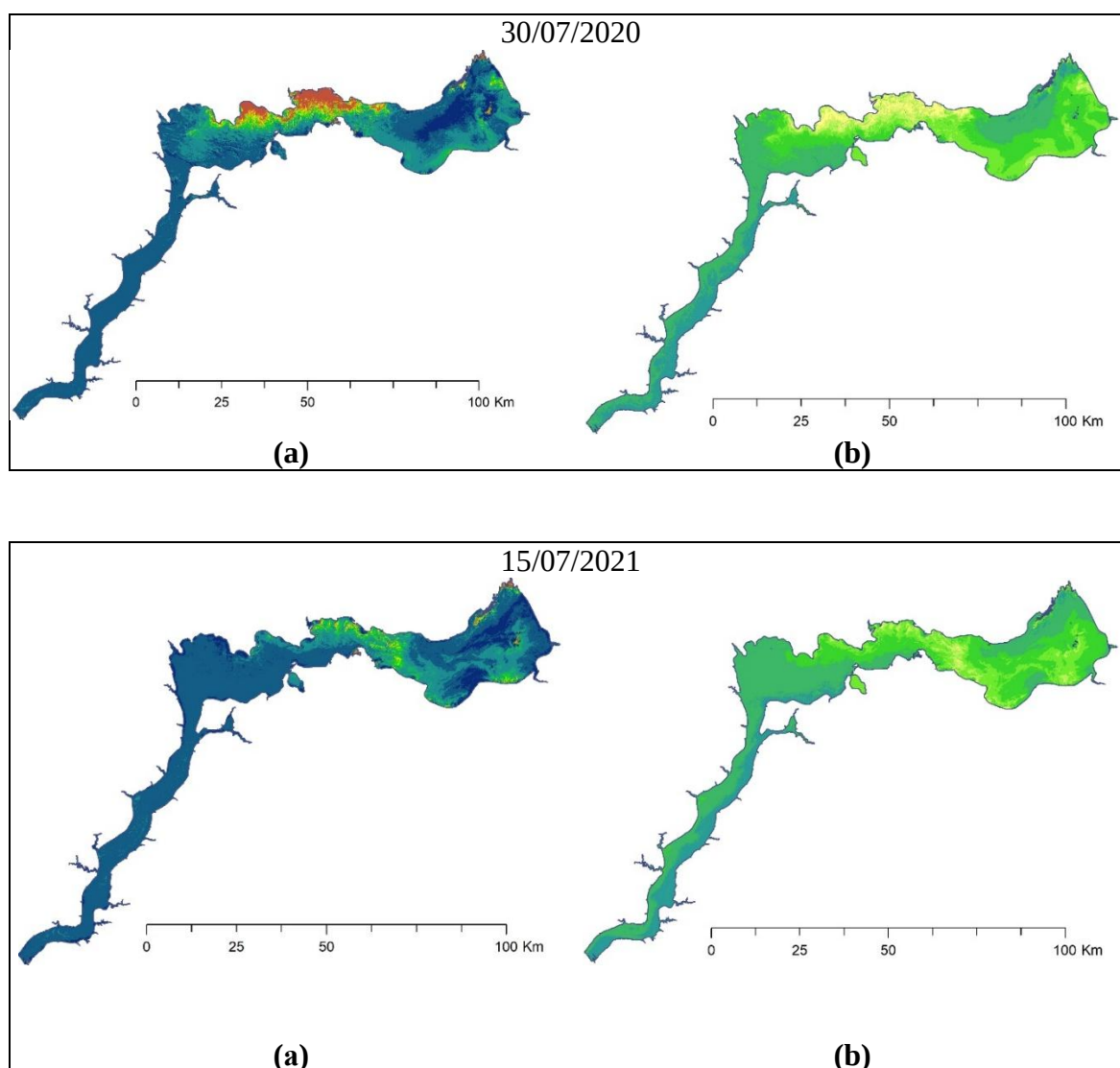
Table 2. Surface water quality in the water area of the Kakhovka Reservoir

Trophic level	Water quality categories	Chl-a, $\mu\text{g}/\text{dm}^3$	30/07/2020	15/07/2021	15/07/2022
Oligotrophic	Very clean	<2	0.36	0.43	0.48

Mesotrophic	Clean	2-4	0.01	0.01	0.01
	Clean enough	5-10	0.05	0.05	0.05
Eutrophic	Slightly polluted	10-30	12.37	12.72	17.57
	Moderately polluted	30-50	33.59	42.21	19.41
Polytrophic	Dirty	50-150	41.43	40.49	47.93
Hypertrophic	Very dirty	> 150	12.19	4.09	14.54

Water Use

The water balance of reservoir was affected by changes in the inflow of water from the upper and middle Dnipro and abstraction from the lower course. Data from the State Agency of Water Resources of Ukraine show that the input of water from the dam of the Dnipro Reservoir to the dam of the Kakhovka Reservoir fell from 48.9 to 26.3BCM in 1989-2021. At the same time, the output to the input ratio fell from 78 to 55% thanks to lesser water consumption by industry and irrigation, notably following Russian occupation of Crimea in 2014 (Table 3).



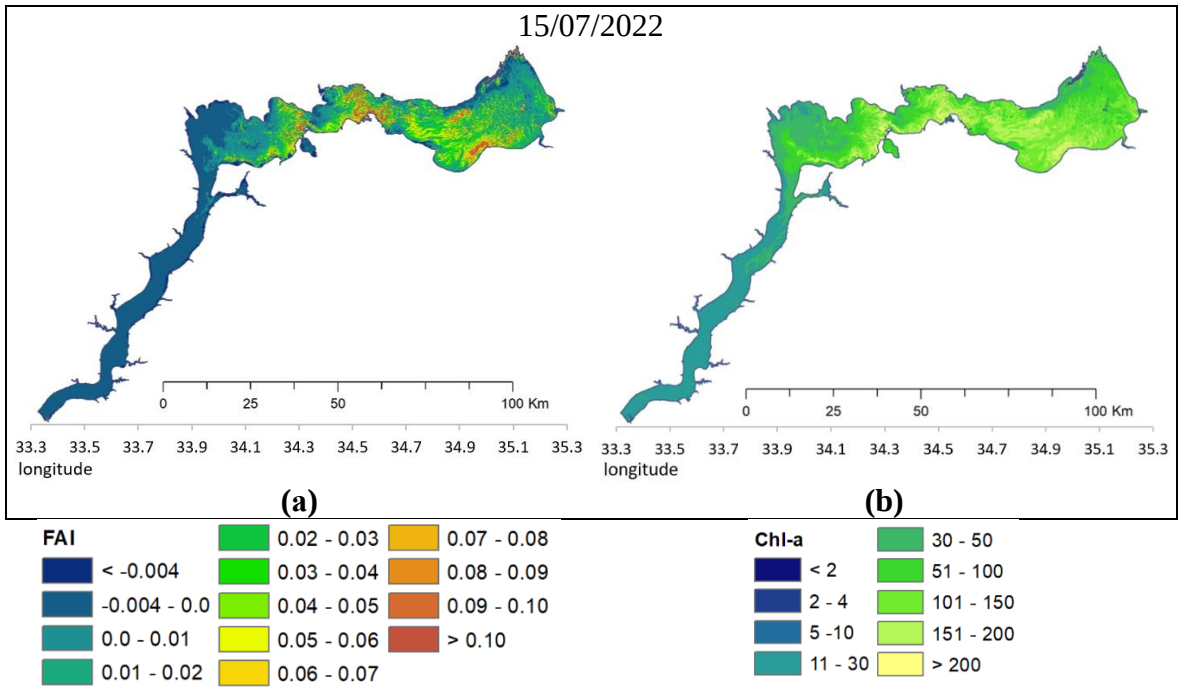


Figure 5. Floating Algae Index (a) and Chl-a (b) – $\mu\text{g}/\text{dm}^3$ in the Kakhovka Reservoir in July, 2020–22 .

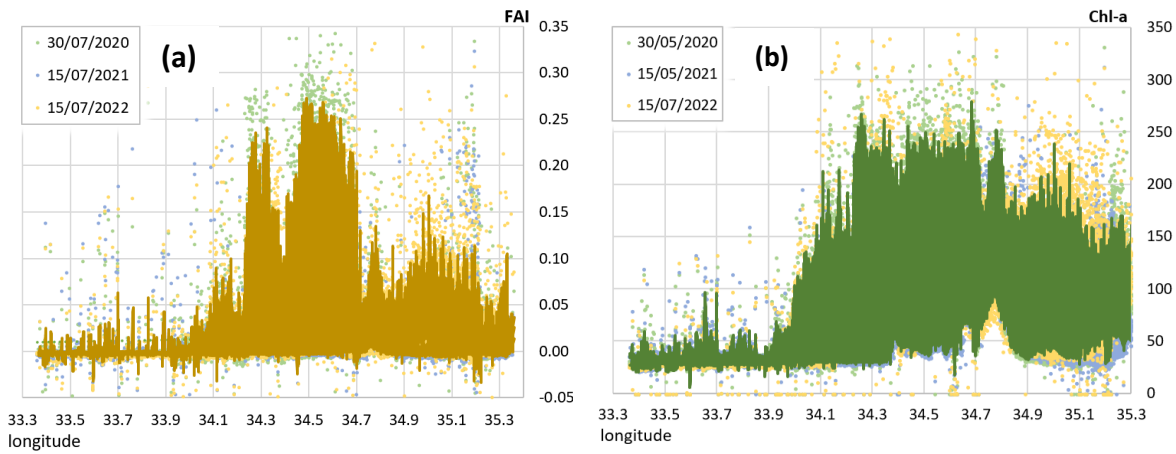


Figure 6. Trophic state of the Kakhovka Reservoir in July, 2020–2022: (a), Floating Algae Index (FAI); (b), Chlorophyll-a content (Chl-a, $\mu\text{g}/\text{dm}^3$).

Table 3. Mean monthly water balance in the lower Dnipro River 2020-21, mln m³.

Components of water balance	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Input	2517.4	2525.7	2942.0	2958.9	2315.0	2242.8	1569.7	1366.7	1303.1	1799.7	2224.7	2562.6
Output	996.8	2364.584	1145.0	742.9	769.8	682.2	871.0	966.6	1064.3	1137.6	1448.0	2329.6
Including												
Evaporation	0.0	0.0	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	0.0
Seepage	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
Groundwater recharge	0.8	0.8	0.9	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.8
Transfer of part of the flow	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
Intake of surface water	74.0	72.9	80.8	89.9	142.1	114.7	122.8	138.0	120.9	97.6	84.8	75.7
Minimum environmental flow in the outlet section	878.5	2247.4	1015.1	603.9	578.5	518.4	699.1	779.4	894.2	991.0	1314.1	2209.7
Balance												
Reserve of water resources	1520.6	161.2	1797.0	2216.0	1545.2	1560.6	698.7	400.1	238.8	662.1	776.8	233.0
Transit flow	2399.2	2408.6	2812.1	2819.9	2123.7	2079.0	1397.8	1179.5	1133.0	1653.1	2090.9	2442.7

The output comprised 12.7 BCM (88%) environmental flow at the outlet of the reservoir; 1.2 BCM (8%) abstracted for domestic and economic needs; about 0.4 BCM (3%) consumed by evaporation, seepage and groundwater recharge, and 0.15 BCM (1.0%) otherwise redirected. The average annual water reserve in the reservoir was 11.8 BCM in 2020-21, and the transit flow to the lower part of the Dnipro, given the minimum environmental flow in the outlet section of the reservoir was 24.5 BCM.

Natural-Climatic Transformation of the Drained Kakhovka Reservoir and its Environs

Consequences of the Destruction of the Kakhovka dam

Everything changed on June 6, 2023 when Russian forces destroyed the Kakhovka Dam, bringing human, economic and environmental disaster: catastrophic flooding of more than 600km² of the lower part of the Dnipro, scouring the channel and flushing pollutants through the Dnipro-Buh estuary to the Black Sea; and drainage of the reservoir and, thereby loss of water supplies to several municipalities and 800,000 ha of irrigated land. According to the Ministry of Foreign Affairs of Ukraine, 180 settlements with the population of more than 900,000 people were included in the emergency zone and, according to the data of Kherson Regional Military Administration, 118 historical monuments were flooded.

By June 10 2023, polluted runoff had reached along the Black Sea coast to the mouth of the Dniester, the polluted area exceeding 7,300 km². On June 14 in coastal waters off Odesa, salinity was reduced from 11.0 to 4.2 g/l; there was an increased concentration of biogenic substances and phytoplankton, and exceedance of the maximum allowable concentration (MAC) of copper by 895-fold, MAC = 0.02 µg/l), zinc 45-fold (MAC=1.0 µg/l), arsenic 3-fold (MAC = 0.6 µg/l), and oil products 2-fold (MAC= 0.05 µg/l) [1]. One hundred and fifty official cases of the death of dolphins were registered in the Black Sea.

According to the Institute of Hydrobiology of the National Academy of Agrarian Sciences of Ukraine, in the first three days, floodwaters carried away 25-50 thousand tonnes of algae that increased algal biomass to 30 g/m³ in the Dnipro-Buh estuary; losses of bottom-living invertebrates reached more than 10 000 tonnes; more than 70 fish species, including 18 species from the UCN Red List perished in the lower part and the delta lake system of the Dnipro, and 42 fish species in the Kakhovka Reservoir – a loss of the commercial catches of about 2,585 tonnes/year forfeiting \$US 5.4 million/y; losses of the fisheries infrastructure amounting to \$270 million [18]. These are underestimates as they include data only from official sources. According to the calculations of Pavel Kutishchev (expert on aquatic bioresources and Director of the S.T. Artyuschyk Production and

Experimental Dnipro Stout Fish Breeding Plant), in the drained area of the reservoir with an area of only 9,313 ha, losses to the fishery from the death of feed organisms amounted to 2.42 thousand tonnes, from the loss of spawning grounds and future offspring of industrial fish species amounted to 1.07 thousand tonnes. In relation to 1 ha drained shallow waters (≤ 2.0 m), losses of feed organisms reached about 260 kg, fish resources 115 kg. For the drained deep-water areas, which occupied 90% of the water area of the reservoir, these costs are much higher.

Over 50 territories of the Nature Reserve Fund, amounting to 80,000 ha, suffered. The floods drowned most terrestrial invertebrates and vertebrates. In particular, 70% the world population of Nordmann's birch mouse, up to 50% of blind hare and populations of common copperhead, steppe viper, yellow-red snake and Sarmatian snake, and other species from the IUCN Red List.

Colonisation by Vegetation

The exposed bottom sediments of the reservoir were colonized by terrestrial vegetation (Fig. 7). New vegetation was observed at the beginning of June, 2023, the maximum NDVI value being 0.2 (Fig. 8a) with sparse vegetation emerging mainly in the upper part of the reservoir and watercourses. NDVI values in the period July-October, 2023 varied between 0.09 and 0.37 (Fig. 8b), maximum values of vegetated areas varied between 0.2 and 1.0 with the highest values along the course of the Dnipro River (Fig. 8c). Over September-October, the landscape comprised (Fig. 8d): water bodies (NDVI < 0.05), *i.e.* the main course of the river and isolated shallows comprised 7-10%; bare ground (NDVI 0.05-0.15) 14-17%; sparse or stunted vegetation (NDVI 0.15-0.40) 31-38%; areas with NDVI > 0.40 with good and very good vegetation including well-developed tall plants and shrubs varied between 44 and 46% in the period of maximum vegetation (Fig. 8e).

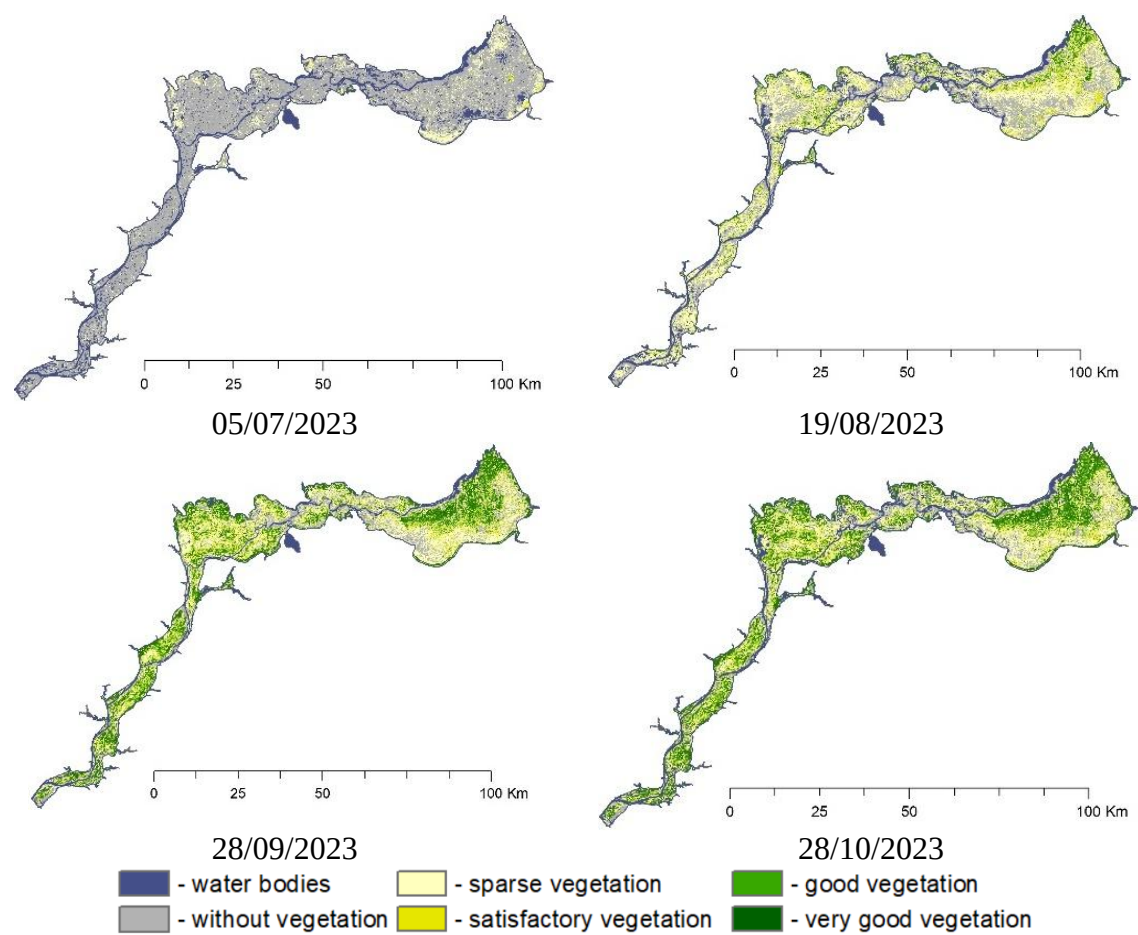
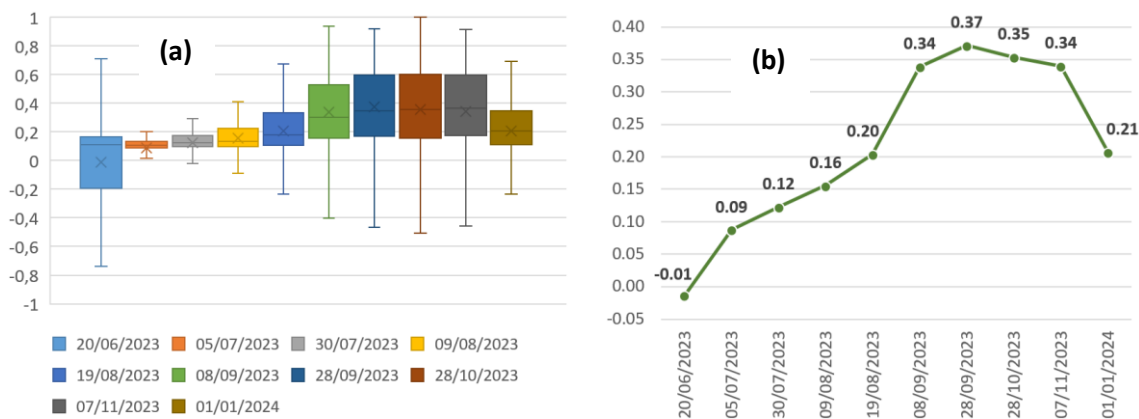


Figure 7. Plant cover in the territory of the Kakhovka reservoir revealed by NDVI.



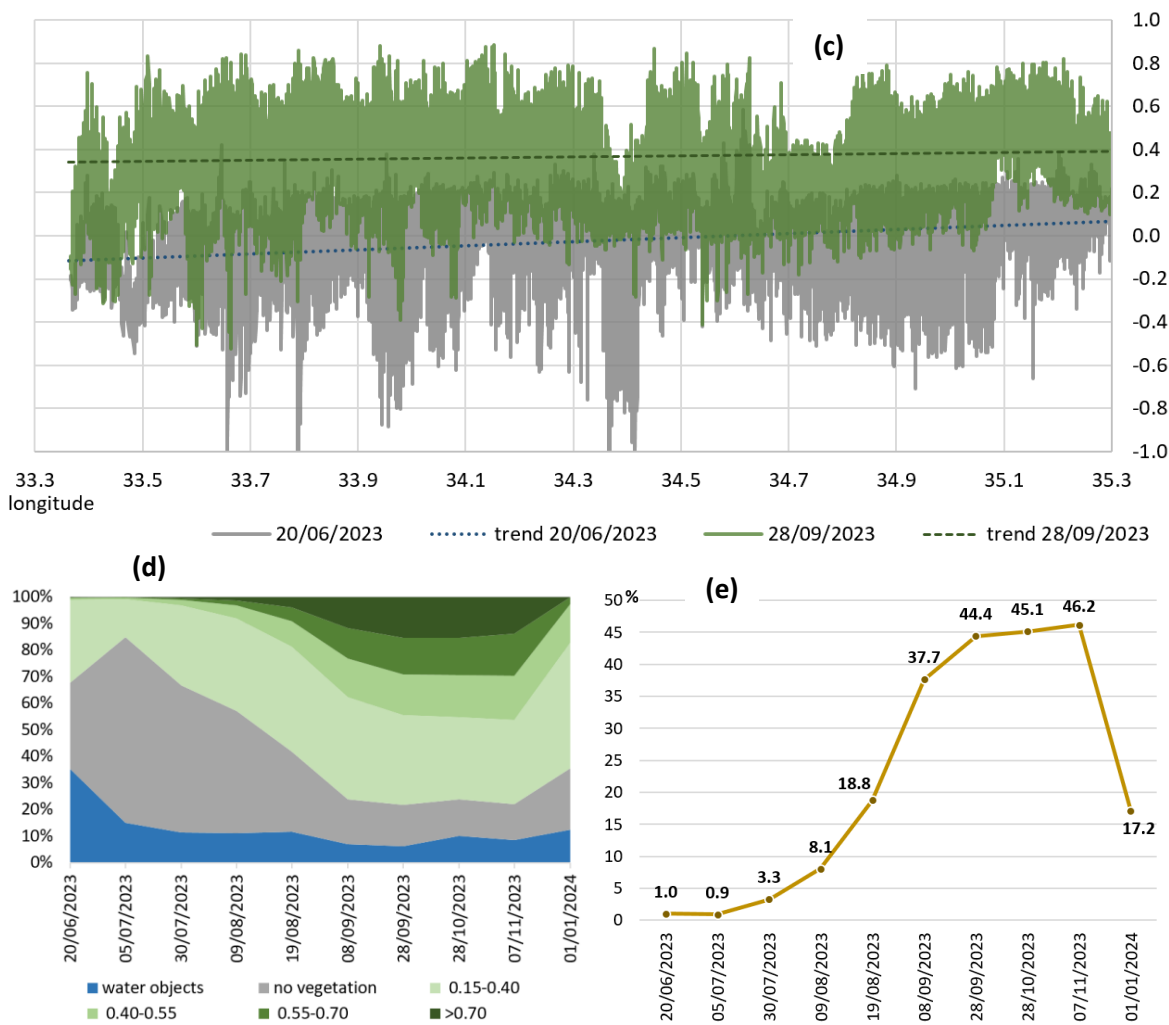


Figure 8. Structure of the drained territory of the Kakhovka Reservoir (a), differentiation of NDVI values; (b), average NDVI values; (c), spatial trends on 20/06/2023 and 28/09/2023; (d), dynamics of the distribution of the reservoir area, %; (e), share of the area covered with plants (NDVI>0.4).

Chlorophyll (Chl-*a*), the key indicator of the plant physiology, may be measured by red-edge wavelength reflection (680 ~ 750nm), which rises sharply from maximum absorption in the red band to the near-infrared. More than ten indices have been proposed for calculating Chl-*a* content [11], amongst which the Chlorophyll Sensitive Index (CSI) has the advantage of high sensitivity to Chl-*a* content in plants, a decrease in the blue spectrum reflection that ensures a reduction in the index sensitivity to the leaf area index and optical properties of the soil background, and a mathematical function (Formula 6) for calculating Chl-*a* content on the basis of a correlation between CSI and field measurements ($R^2=0.88$).

Satellite imagery reveals a seasonal pattern of Chl-*a*_{CSI} accumulation in the aboveground biomass (Fig. 9). At the end of June, after the water receded, Chl-*a*_{CSI} was registered across almost 20 per cent of the drained bed in the range 5-30 $\mu\text{g}/\text{m}^2$, a weighted average of 5.6 $\mu\text{g}/\text{m}^2$, on account of phytoplankton residues (Fig. 10a). These dried at the beginning of July and their chlorophyll was

lost. Aboveground vegetation appeared at the end of July, a range of $5\text{--}30\ \mu\text{g}/\text{m}^2$ (weighted average of $6.7\ \mu\text{g}/\text{m}^2$) reflecting sparse or stunted vegetation. At the September peak (Fig. 10c), Chl- a_{CSI} accumulation varied between $22\text{--}68\ \mu\text{g}/\text{m}^2$ (weighted average $44\ \mu\text{g}/\text{m}^2$) with the local peak of over $120\ \mu\text{g}/\text{m}^2$ representing tall plants and shrubs.

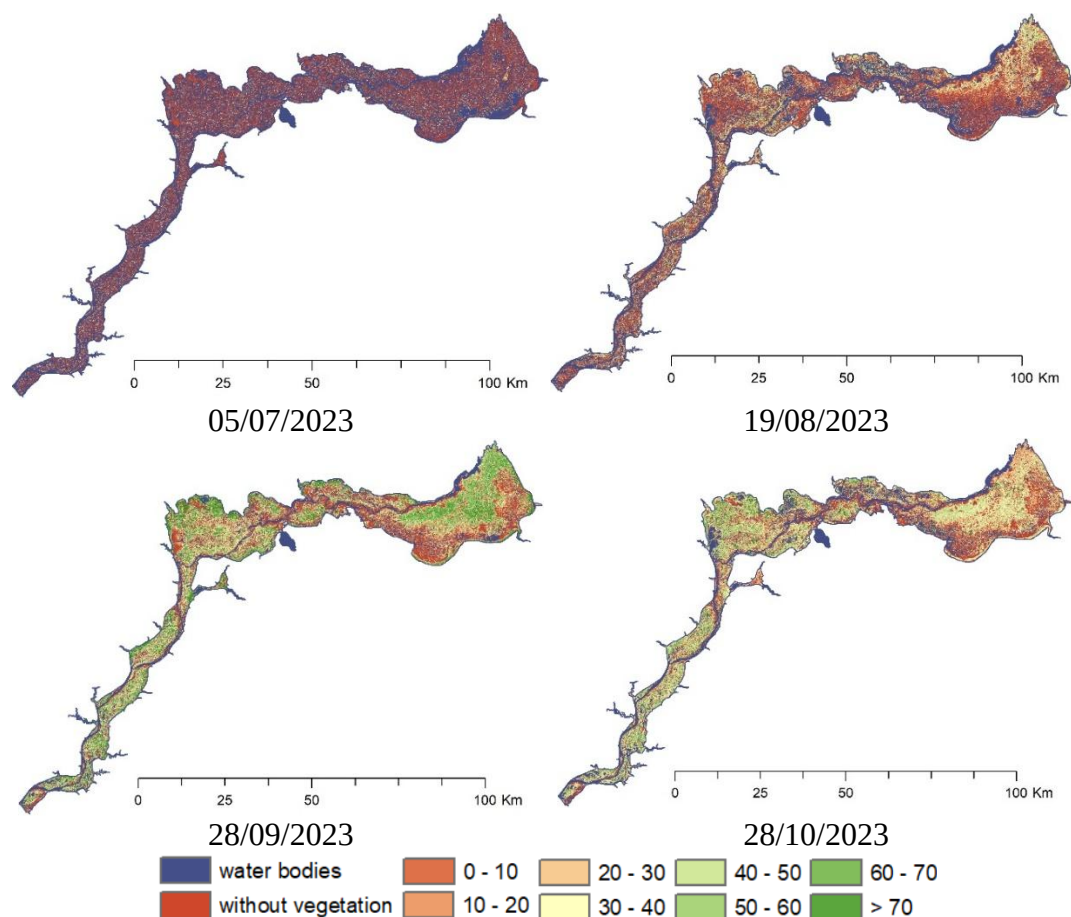
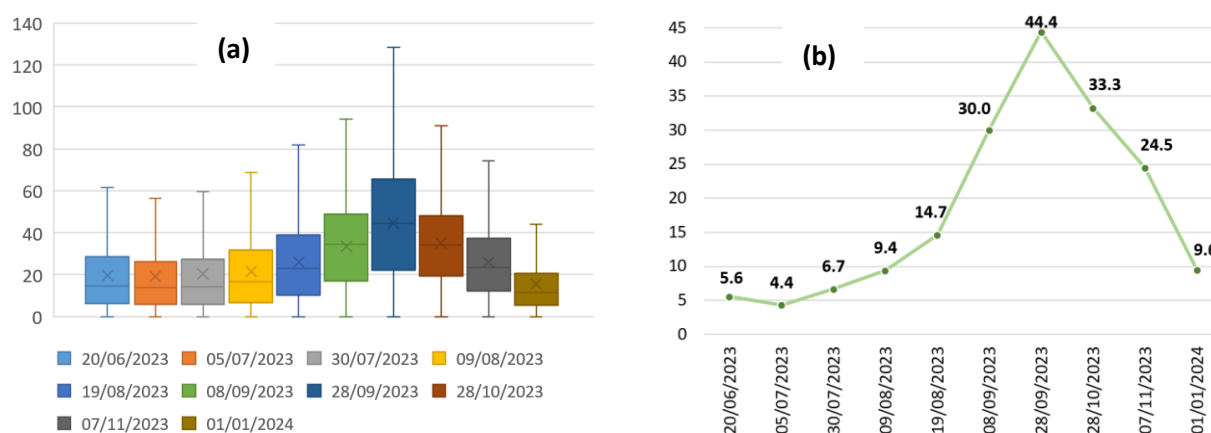


Figure 9. Chlorophyll (Chl- a_{CSI} , $\mu\text{g cm}^{-2}$) in the plant cover of the drained reservoir.



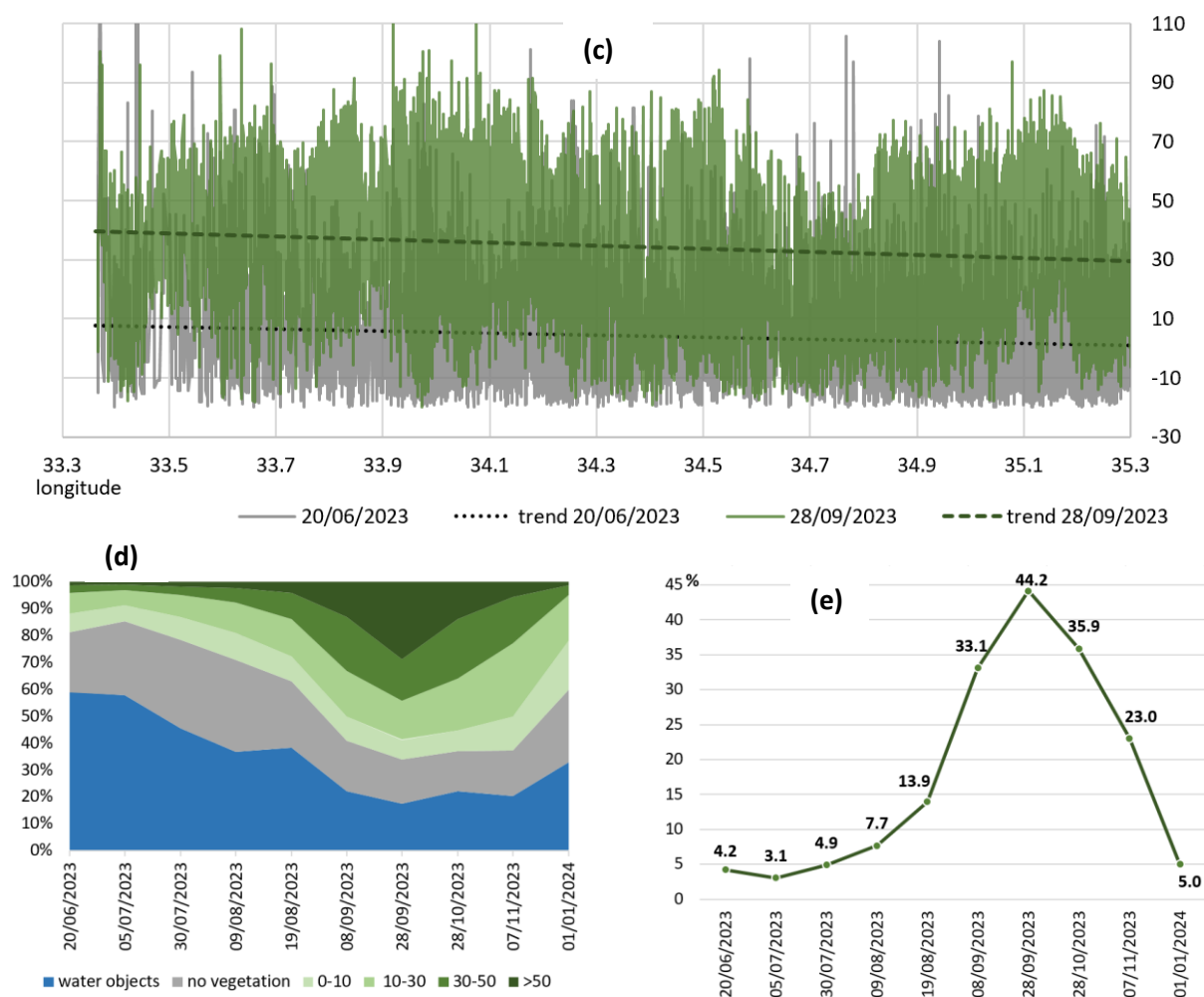


Figure 10. Structure of the drained territory of the Kakhovka Reservoir by Chl-aCS1 ($\mu\text{g}/\text{cm}^2$): (a), differentiation of Chl-aCS1 values in plant leaves; (b), weighted average of Chl-aCS1 against the maximum overgrown area (28/09/2023); (c), comparison of Chl-aCS1 values on 20/06/2023 and 28/09/2023; (d), distribution of the reservoir areas, %; (e), vegetated area, Chl-aCS1 >30 $\mu\text{g}/\text{cm}^2$.

At the end of the growing season, water bodies occupied 17.5-22% of the former reservoir, bare ground 16-19%, sparse or stunted vegetation 22-27%, good vegetation 15-22%, and very good vegetation 14-29%.

Climate, Microclimatic Conditions and Evapotranspiration

Across the Ukrainian steppe, the period 1945-2019 saw mean annual temperatures rise by 3.5°C . Annual precipitation ranged from 186 to 778 mm with 27% variation but decreased by 40% over the last 20 years to 500-300 mm, although with more frequent heavy rain in the spring-summer period. Overall, mean annual air temperature increased by 0.06°C per year and mean annual precipitation decreased by 62 mm per year [19]. There has been an 18.7 per cent rise in the solar radiation reaching the earth surface and a 62% decrease in vegetation productivity that is likely to decrease by a further

20%. Over the past 20 years, the natural moisture coefficient has fallen by 66% and will likely decrease by a further 20%.

Against this backdrop, the reservoir created welcome sea breezes felt tens of km from the water area and its loss has diminished the moisture supply.

Land Surface Temperature (LST, °C) is a radiation temperature of the earth surface. It depends on the ratio of plant cover and soil moisture and, also, landform; it also determines the near-surface air temperature [20,21]. Destruction of the reservoir brought about an almost immediate 2.0°C increase in the LST of the drained territory of 2,155 km² and the 10 km buffer zone of

5,678 km² (Fig. 11) calculated on the basis of a difference in raster LST surfaces of summer 2023 to the average value of the corresponding period in 2020-2022. Drainage of reservoir increased the surface heating of the drained bed (Fig. 12a) and seasonal heating across 48-83% of the adjacent territory (Fig. 12b).

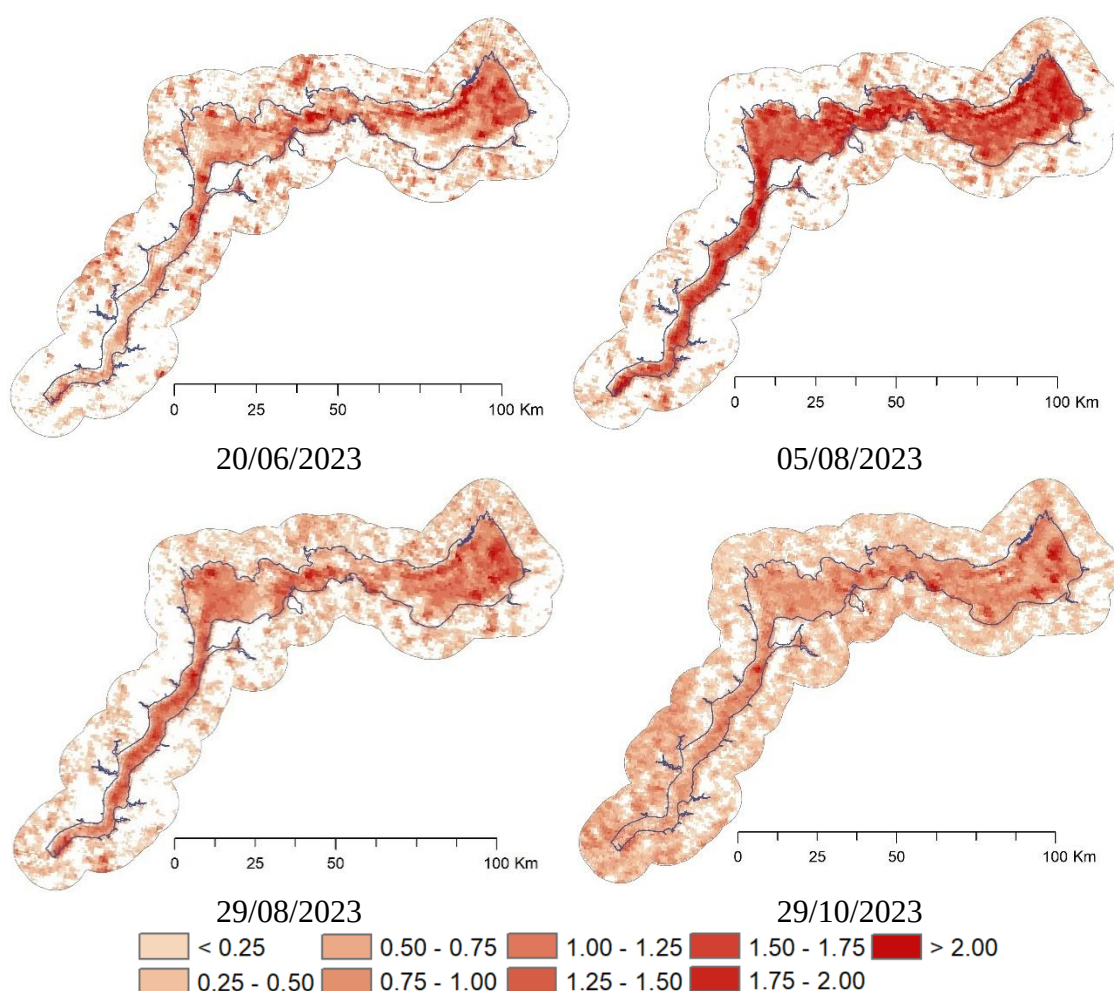


Figure 11. Land surface temperature (LST, °C) of the drained Kakhovka Reservoir and the adjacent territories.

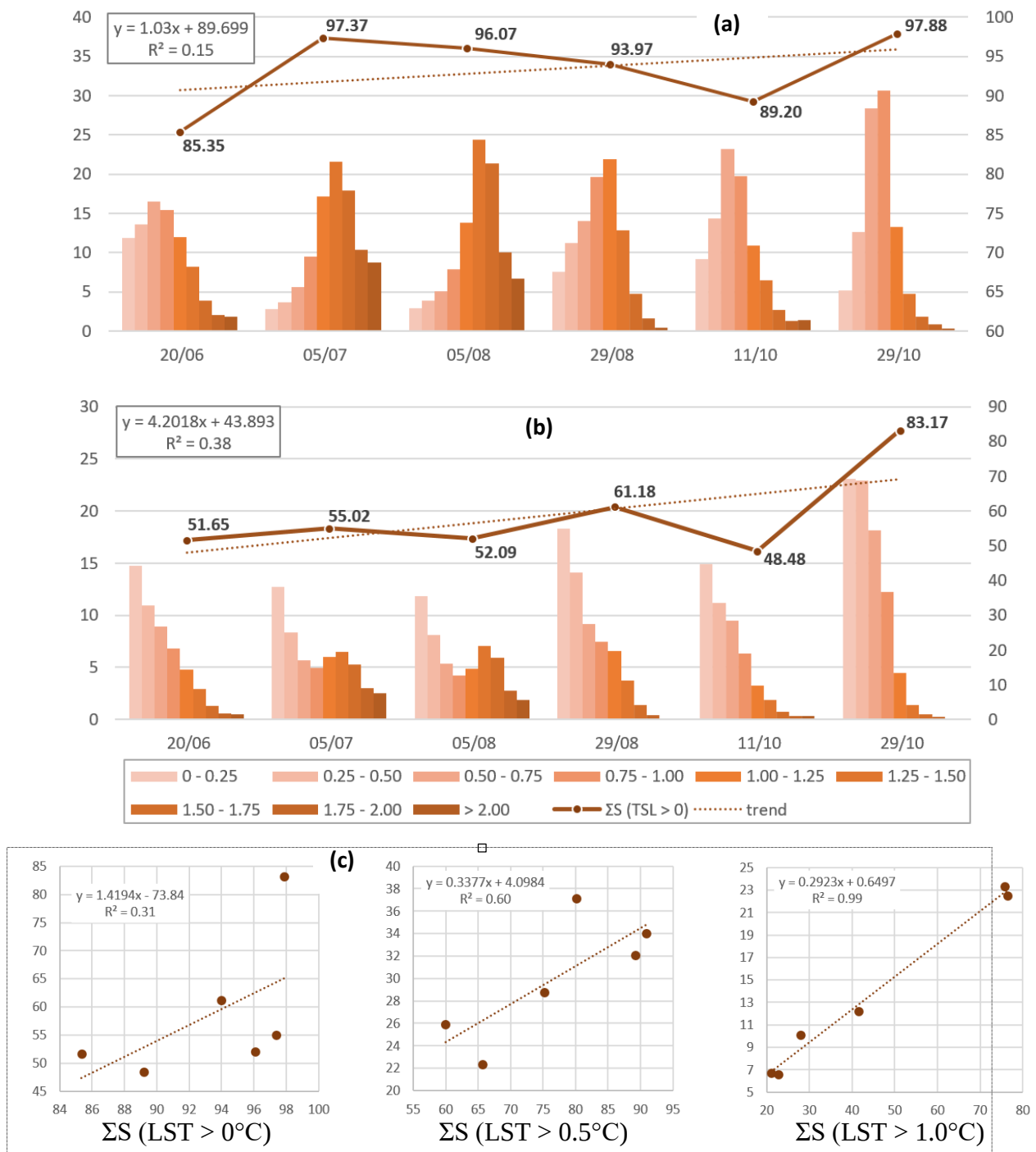


Figure 12. Distribution of the areas (%) with different levels of increase in the land surface temperature (LST, °C): (a), territory of the drained Kakhovka Reservoir; (b), adjacent territories; (c), dependence of the temperature change in the landscape structure of the water reservoir and the adjacent territories.

Moreover, the developing vegetation did not maintain the same level of humidity as the former open water, so evapotranspiration increased, creating a soil water deficit (Fig. 13). In the summer-autumn period, ET_{LST} rose to a record level of more than 4.0 mm/day (Fig. 14); there was an acceleration in

evapotranspiration of up to 10% across 1,070 km² (19%), from 10-20% across 642 km² (11%), 20-30% across 356 km² (6%), 30-40% across 204 km² (4%), 40-50% across 114 km² (2.0%), and more than 50% across 190 km² (3%).

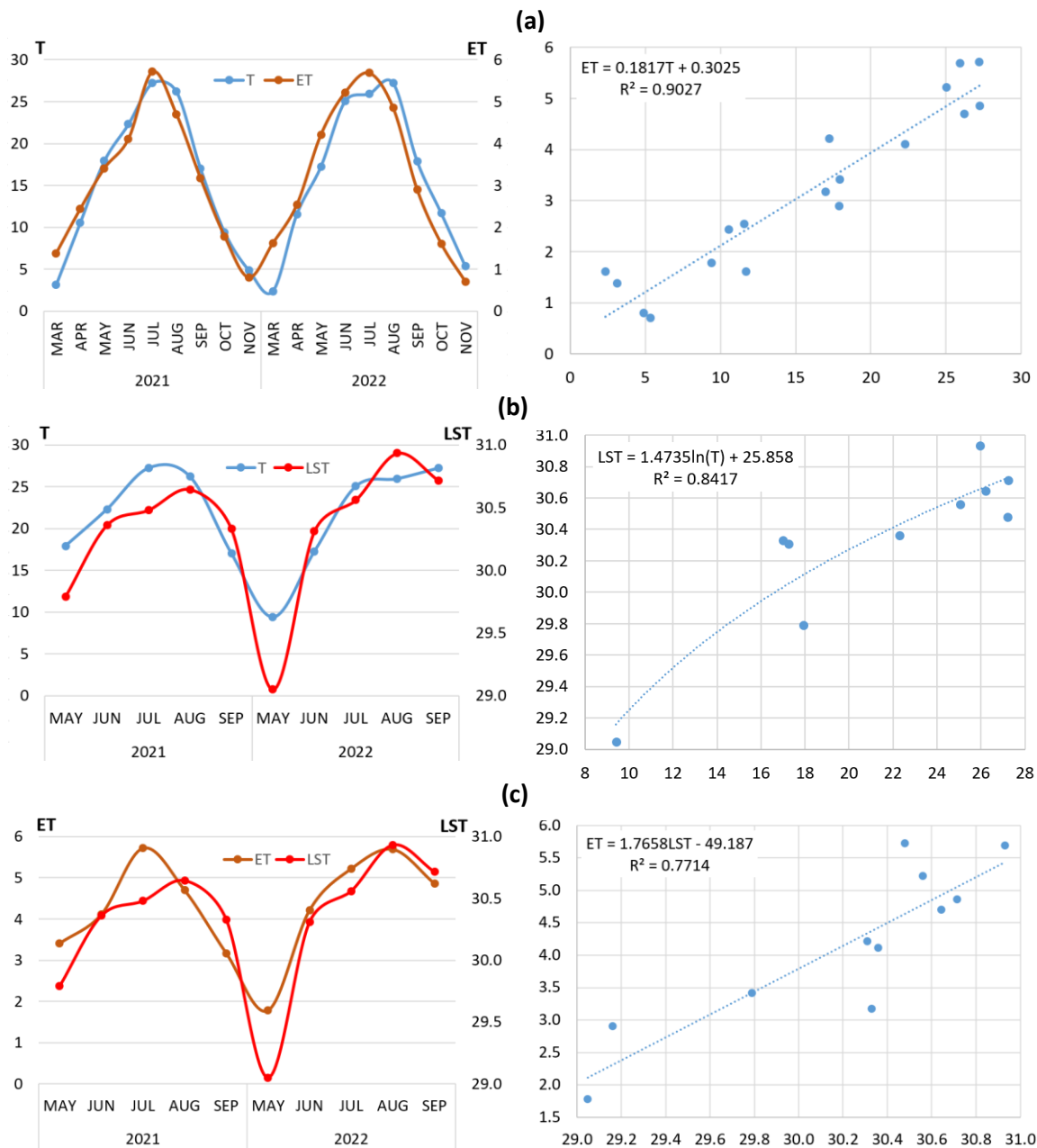


Figure 13. Monthly change in climate-landscape characteristics of the drained Kakhovka Reservoir and the adjacent territories in the warm months of 2021-2022: (a), dependence of reference evapotranspiration (ET, mm/day) and the air temperature (T, °C); (b), dependence of the Land Surface Temperature (LST, °C) and the air temperature (T, °C); (c), dependence of reference evapotranspiration (ET, mm/day) and Land Surface Temperature (LST, °C)

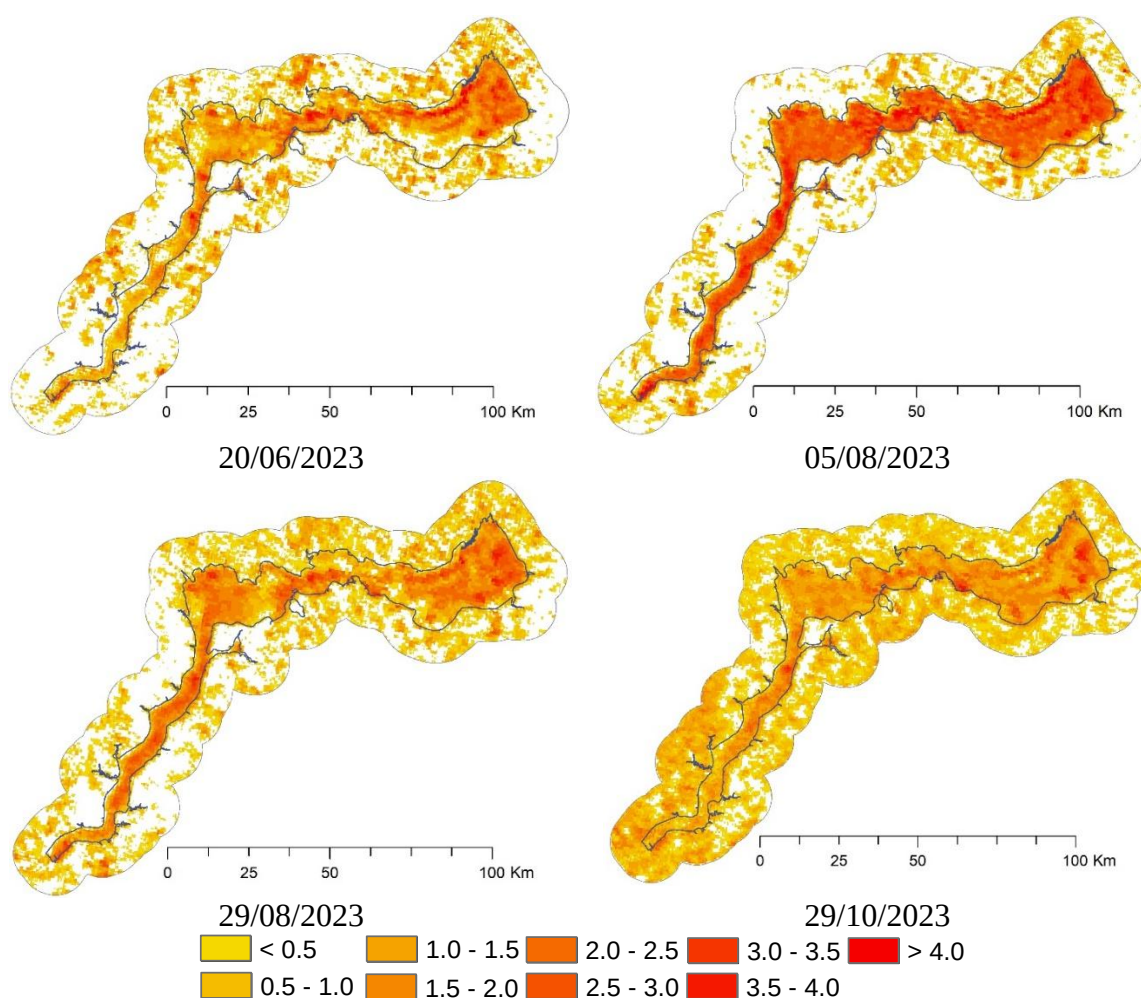


Figure 14. Increase of ET_{LST} on the bed of the Kakhovka Reservoir and adjacent territories, calculated as the difference in the ET_{LST} values in 2023 to the average ET_{LST} values in 2020-2022.

The new world of the drained reservoir

Severe environmental and socio-economic consequences have already been foreseen by Mulvey P&F, Dmytruk, et al. [22]. Our scenario was calculated for September 2023 which was characterized by typical steppe conditions and maximum vegetation cover. Comparison of microclimatic conditions to those for September 2020 showed increased solar radiation reaching the ground surface but no significant difference in rainfall. LST in 2020 was $29.83 \pm 0.52^\circ\text{C}$; in 2023, $29.96 \pm 0.30^\circ\text{C}$. But in 2020 the reservoir moderated evaporation from the water surface: ET_{LST} across the water area was $2.24 \pm 0.19 \text{ mm/day}$ in 2020, and $3.20 \pm 0.46 \text{ mm/day}$ in the drained territory. In 2023, loss of the water body more than doubled the cases of high evapotranspiration values from 3.5 to 4.0 mm/day in the adjacent territory. At the end of September, drainage of the reservoir had caused an increase in the LST values by more than 1.0°C (Fig. 15a) and in the ET_{LST} values by more than 1.5 mm/day (Fig. 15b), exacerbating water scarcity by 58% in the research territory.

According to the State Agency of Water resources of Ukraine, monthly evaporation from the open waters of the lower Dnipro basin during the warm season amounts to 4.72 million m³ (Table 3). By our calculations (Table 4), total evaporation from the water surface was 5.94 million m³ in September 2020; in 2023 the potential evaporation from the dry bed of the reservoir was 12.13 million m³ – more than double. Potential evaporation from the adjacent territories was 28.56 million m³ in 2020, in 2023 this figure rose by 1.4 times. In 2020, potential evaporation from the entire research area (7,812.8 km²) was 34.50 million m³; in 2023, 52.36 million m³. Over the research period, vegetation cover across the buffer zone was comparable with an average NDVI value of 0.37 ± 0.17 in the third decade of September in 2020 and 2023. All of which suggests that the increased land surface temperature, greater water stress, and increased evapotranspiration will prevent regeneration of the historical Great Meadow.

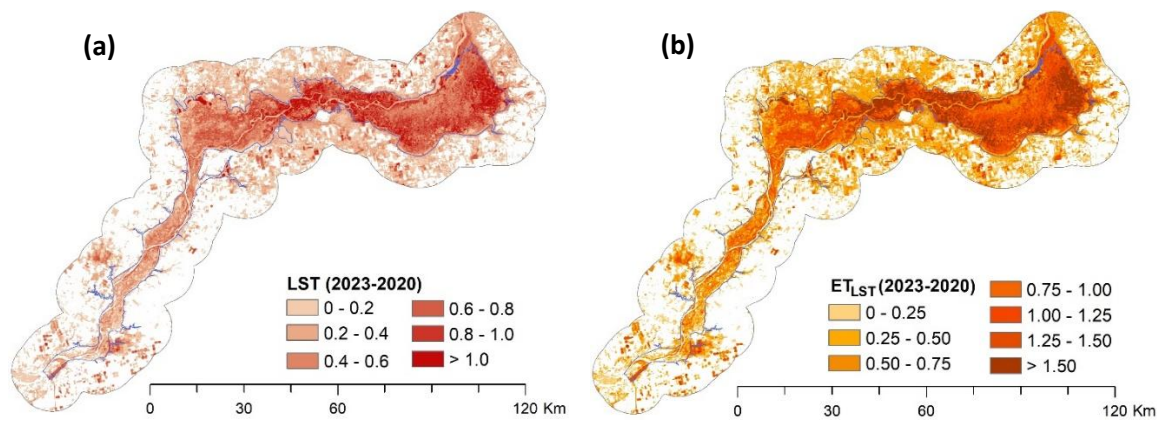


Figure 15. Changes in land surface temperature (LST, °C) and evapotranspiration (ET_{LST}, mm/day) across the drained Kakhovka reservoir and the adjacent territories, September 2020 and 2023: (a), increase in LST values in 2023; (b), increase in ET_{LST} volumes from the land surface.

Table 4. Evapotranspiration (ET_{LST} , mm/day) from the surface of the drained Kakhovka Reservoir and the adjacent territories before and after the destruction of the retaining dam.

Statistic	Data		
	09/2020	09/2023	2023÷2020
Territory of the Kakhovka Reservoir			
Min	1.29	1.80	1.4
Max	4.07	5.08	1.3
Mean	2.24	3.20	1.4
Standard deviation	0.19	0.46	2.4
Variance, %	8.48	14.42	1.7
Sum1 per month	593 592	1 212 512	2.0
Adjacent territory (the buffer zone of 10 km)			
Min	1.49	1.67	1.1
Max	6.77	7.35	1.1
Mean	3.97	4.35	1.1
Standard deviation	0.57	0.42	0.7
Variance, %	14.36	9.66	0.7
Sum2 per month	2 856 164	4 023 688	1.4
Total per month (Sum1 + Sum2)	3 449 756	5 236 200	1.5

Natural-Climatic Transformation

Natural-climatic transformation of the drained territory of the Kakhovka Reservoir was calculated for September 2023 on the basis of the Vegetation Health Index (VHI) which combines the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI) of the landscape. TCI is calculated using an equation similar to the VCI but relates the current temperature to its maximum and minimum, since higher temperatures are likely to be unfavourable.

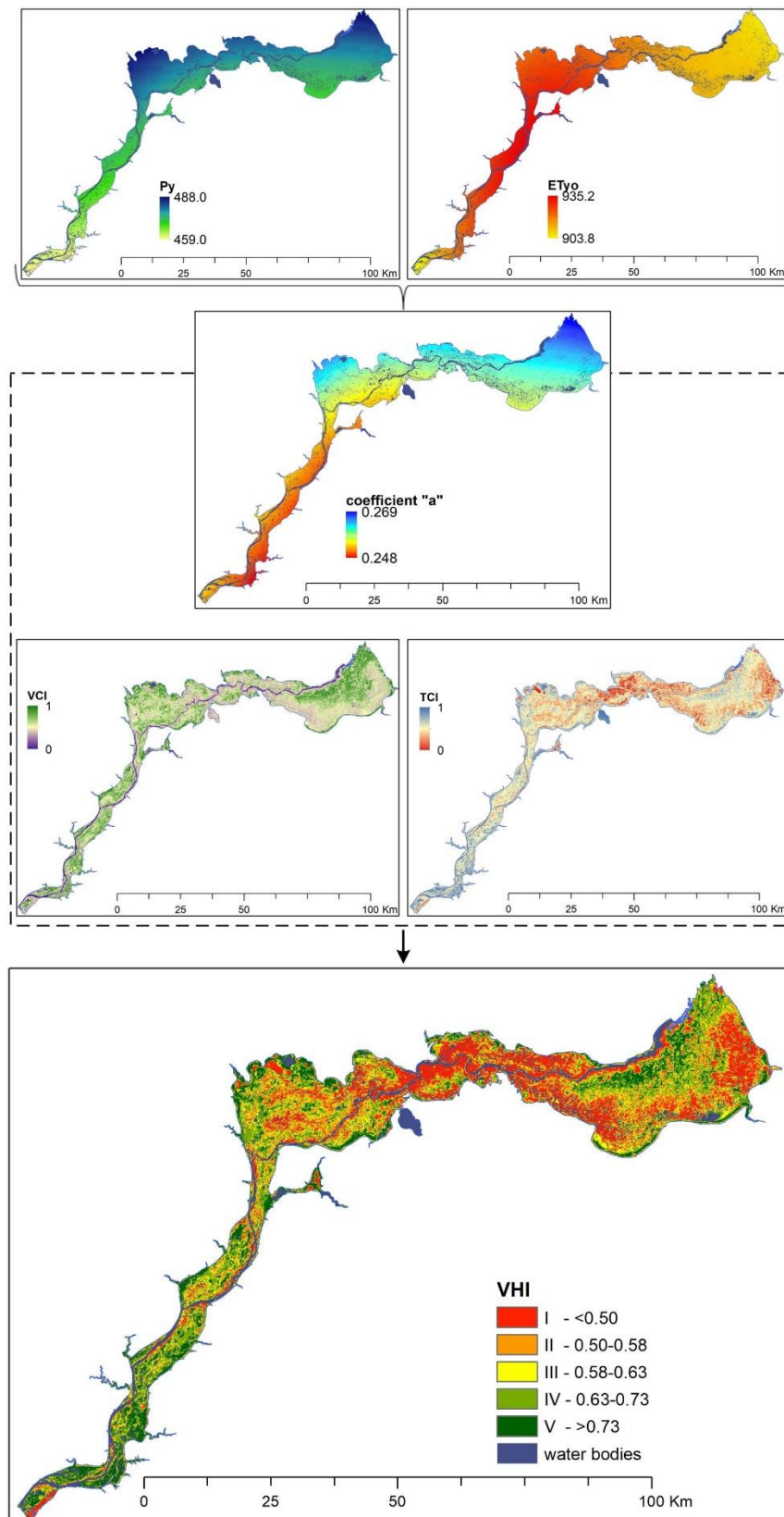


Figure 16. Natural-climatic transformation of the drained territory of the Kakhovka Reservoir in September 2023: P_y , mean annual precipitation 2020-2023; ET_{yo} , mean reference evapotranspiration in 2020-2023; a , coefficient of VCI and TCI; VCI, Vegetation Condition Index; TCI, Temperature Condition Index; VHI, Vegetation Health Index.

Figure 16 shows that, as of September 2023, the territory of the drained Kakhovka Reservoir is composed of: water bodies, 16%; I – bare ground, 21%; II – open landscapes with patches of stunted vegetation, 18%; III – sparsely vegetated land suffering water scarcity and significant temperature pressure, 13%; IV – landscapes with a satisfactory moisture level and plant biomass, 20%; V – a good level of moisture with healthy vegetation 12%. Vegetation is in good health where there is a hydrological connection with overflow from the Dnipro River, residual moisture in bottomland, and runoff from farmland. Two months after the destruction of the dam, isolated shallow water bodies covered 307km² but shrank to 196 km² by the end of September. Some will be filled by the spring flood and about 137 km² of water bodies and water courses in the drained territory of the water reservoir are functionally stable. The Great Meadow must have relied on seasonal flooding from the Dnipro River which is fed mainly from beyond the steppes and only 1.8% by local drainage from drained territory of the Kakhovka Reservoir. That flooding is now constrained by the remaining cascade of reservoirs.

Discussion

The Kakhovka Reservoir was hugely important to the southern steppe of Ukraine. It provided water for more than one million people in more than 140 settlements including Kryvyi Rih (population over 600,000), Nikopol (100,000) and several others, and for 800,000 ha of irrigated land via the Kakhovka Canal, the North Crimean Canal and the Dnipro-Kryvyi Rih Canal [7]. In total, 1.21-1.34BCM: 5% for domestic use, 8% for industry, and 74% for irrigation. Although the environmental condition of the reservoir was unsatisfactory, it was important for recreation and commercial fishing, providing 22% of the national catch. And it was an artery of navigation serving the port of Nikopol.

Destruction of the Kakhovka Dam was a catastrophe, terminating industries and livelihoods built up over 65 years, cutting off water for irrigation, setting in train desertification of the southern steppes. How great the damage might become may be envisioned in the example of the disappearance of the Aral Sea which gravely damaged ecosystems, public health, life security, and the quality of the national and regional development in neighbouring Uzbekistan [23,24]; its dry sea bed now the Aralkum Desert, salt flats subject to frequent dust storms; the number of days above 40oC has more than doubled; the biological productivity of the whole region has shrunk ten-fold and many Red Book species are lost.

The condition of the ecosystems and the territory impacted by the Kakhovka reservoir requires comprehensive, systematic monitoring, and exhaustive research to develop a better future than that for the south of Ukraine. Although the emergent vegetation is not capable of recreating a microclimate that will allow natural regeneration of the former Great Meadow, its beginnings have

been constrained by the available seed bank and raw, polluted soil parent materials. Things will improve as a new ecosystem develops with more fully developed soils and adapted, deep-rooted perennial vegetation. When we have peace, recovery of natural ecosystems and regenerative agriculture, not only on the former reservoir bed but across the southern steppes, may draw upon Europe-wide expertise, careful land preparation, introduction of adapted native species, and new farming systems including controlled flooding to combat heat and drought. We might call it The Great European Plan for working with Nature.

Conclusion

Construction of the Dnipro Reservoir cascade created a new hydrobiology: almost halving the flow of the Lower Dnipro but greatly increasing accessible water reserves. The Kakhovka Reservoir generated electricity, provided fresh water to more than one million people, heavy industry, irrigation of 800,000 ha, was an artery of navigation and an important centre of recreation and fishing. Stagnation of the retained water resulted in eutrophication and cyanobacterial blooms; water quality ranged from moderately polluted to very dirty in 81-87% of the reservoir area.

Destruction of the Kakhovka dam caused a 2°C increase in land surface temperatures and accelerated evapotranspiration across the drained area and the adjacent territories in 2023. Evapotranspiration in September (at maximum vegetation cover in the drained bed of the Kakhovka reservoir) increased two-fold and by 1.4-times across the 10km zone of adjacent land, *exacerbating water scarcity in almost 60% of the territory*.

At the maximum vegetation development in 2023, only 32% of the former reservoir bed supported lush vegetation. This cannot recreate the microclimatic conditions maintained by the reservoir, potentially increasing the frequency of droughts and water scarcity in the Steppe zone of Ukraine. We must do better.

Acknowledgments

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Geolocation

Polygon coordinates: 35.360596,47.71088; 33.333068,47.71088; 33.333068,46.72388; 35.360596,46.72388; 35.360596,47.71088

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