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Natural and Climatic Transformation of the Kakhovka Reservoir after the Destruction of the Dam

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ABSTRACT

As a result of the Russian armed aggression, Ukraine has lost almost a third of its accumulated fresh water reserves worth more than USD18 billion. It has caused a loss of access to quality drinking water for 6 million people in Ukraine and more that 13 million people have a limited access to water for satisfying sanitary and hygienic needs. The situation is complicated due to the destruction of the Kakhovka hydroelectric power station dam which has led to a large-scale man-made disaster, severe negative environmental and socioeconomic consequences, the beginning of natural-climatic transformations of the drained water reservoir. The article presents comprehensive research of the state of the Kakhovka Reservoir functioning before and after the destruction of the hydroelectric power station dam on the basis of the facts and the results of decoded satellite imagery of Sentinel 2, Sentinel-3 and Landsat 8–9. It was found that the water reservoir drainage has caused disruption of microclimatic conditions, an increase in the air temperature by 2.0 °C and more, accelerated evapotranspiration by 1.41–2.04 times, exacerbation of water scarcity in 58.2% of the territory of the drained water area and in the adjacent territories. About 52.0% of the territory of the drained water reservoir has stressful conditions of natural-climatic functioning. The obtained results confirm that the formed aboveground plant biomass of bottom landscapes is not capable of creating appropriate microclimatic conditions which existed in the water area of the Kakhovka Reservoir.

Keywords: Kakhovka Reservoir, normalized difference vegetation index, chlorophyll-a, land surface temperature, evapotranspiration, vegetation health index.

INTRODUCTION

The Dnipro river with the basin area of about 511 thousand km^2, 57.3% of which is located in Ukraine is one of the largest transboundary rivers of Europe. The Dnipro basin covers over 48% of Ukraine's territory and accumulates 80% of its water resources which satisfy food and water needs of more than 70% of the country's population (Pichura et al., 2017). The Dnipro basin is a multi-branched complex with high natural and socioeconomic value. The current state of the river catchment area is characterized by a complicated and acute environmental situation caused by the Russian armed aggression. The aggressor not only claims lives of thousands of people, but also exerts a disastrous pressure on Ukraine's environment, destroying natural landscapes, flora and fauna species, polluting water resources, ruining a fertile soil layer, in addition to poisoning the environment with petroleum products and heavy metals (Vyshnevskyi et al., 2023, Romanova et al., 2024, Hartmane et al., 2024). A negative impact of combat actions on the state of water resources is caused by explosions, flooded machinery, fuel spills, dam damages and destructions, abrasion, bridge destructions and construction of artificial confining layers, fortifications in riparian zones, impairment of floodplain ecosystems, destruction of treatment plants with further discharge of untreated wastewater into natural sources, etc.

Ukraine has lost about a third of its fresh water reserves (approximately 19 km^3) worth more than USD18 billion (Hapich et al., 2024). According to the UNICEF data, as a result of the Russian armed aggression and combat actions, about 6 million people in Ukraine do not have access to quality drinking water, more than 13 million people lack water for satisfying sanitary and hygienic needs. It has caused a fall in the level of ecological security of residential areas, first of all, in the combat zones and occupied territories. The situation in the Dnipro lowland became more complicated after June 6th, 2023 when the dam of the Kakhovka hydroelectric power station was destroyed (Vyshnevskyi et al., 2024, Hapich et al., 2024). The dam destruction has led to a man-made disaster having environmental, economic and social consequences. According to the UNO data, Ukraine's losses caused by the dam destruction are over USD14.0 billion.

Since the beginning of the Russian large-scale invasion of Ukraine's territory, there have been over 1000 ecological crimes, 15% of them concerns water resources. The war has caused more than $56.4 billion in damage to the environment (Hryhorczuk et al., 2024). The consequences of military actions are transboundary migration of pollutants through the air and water, including the Black Sea and the Azov Sea. It should be highlighted that, according to the resolution of the General Assembly of the UNO No. 64/292 dated June 28th, 2010 (United Nations, 2010), the aggressor country violated the right of Ukrainians to safe water and hygiene as a basic human right that is crucial for full-fledged life and protection of all other rights. Therefore, the full-scale Russian aggression causes transformation of the Dnipro catchment area that determines necessity of thorough investigation of its state aimed at searching for efficient methods for restoring ecosystems, taking measures for optimizing nature management and integrated management of the Lower Dnipro subbasin in a post-war period. The river bed system in the lower course of the Dnipro river has become a natural-hydrological battle line of active military actions, therefore, field research of transformations of natural ecosystems is impossible. Application of the technology of remote sensing on the basis of comprehensive decoding of Sentinel and Landsat satellite imagery is an effective and efficient tool for researching ecosystems in dangerous and hard-to-reach areas. The purpose of the research was to perform a thorough spatio-temporal analysis and identify the patterns of the functioning of the Kakhovka Reservoir after the destruction of the hydroelectric power station dam.

MATERIAL AND METHODS

Research scheme and materials

The research scheme of spatial patterns of the functioning of the Kakhovka Reservoir and the adjacent territories includes six successive blocks (Fig. 1). The values of the near surface air temperature (T, °C), precipitation (P, mm) and reference evapotranspiration (ET_o, mm/day) were established on the basis of the of the Climatic Research Unit of the University of East Anglia (https://crudata.uea.ac.uk/cru/data/hrg/) and the data of NASA POWER (https://power.larc.nasa.gov/data-access-viewer/). The source of actual satellite imagery for decoding and calculating necessary indices was the data of the Sentinel 2 L2A, Sentinel-3 SLSTR L1B, Landsat 8–9 spacecrafts available at Copernicus Browser and EO Browser.

Characteristics of the research territory

The Kakhovka Reservoir was constructed in 1955–1958 (Fig. 2), that caused flooding of 2.8

1. Analysis of practical use of the reservoir

2. Analysis of the consequences on the first days of the dam destruction

3. Investigation of regularities of the formation of aboveground biomass in the drained water reservoir, the seasons of 2023: Normalized Difference Vegetation Index, Chlorophyll Sensitive Index, Chl-a_{CSI}

4. Investigation of the climatic conditions and the change in the microclimatic conditions and evapotranspiration processes of the drained water reservoir and the adjacent territories for 2020-2023: near surface air temperature (T,), Land Surface Temperature (LST), evapotranspiration (ET_{LST})

5. Investigation of the scenario of phyto-climatic functioning of the drained water reservoir, September, 2023

6. Analysis of natural-climatic transformation of the drained water reservoir and adjacent territories in 2023: Vegetation Condition Index (VCI), Temperature Condition Index (TCI), Vegetation Health Index (VHI)

Figure 1. Structural-logical methodological scheme of the research of the Kakhovka Reservoir and the adjacent territories

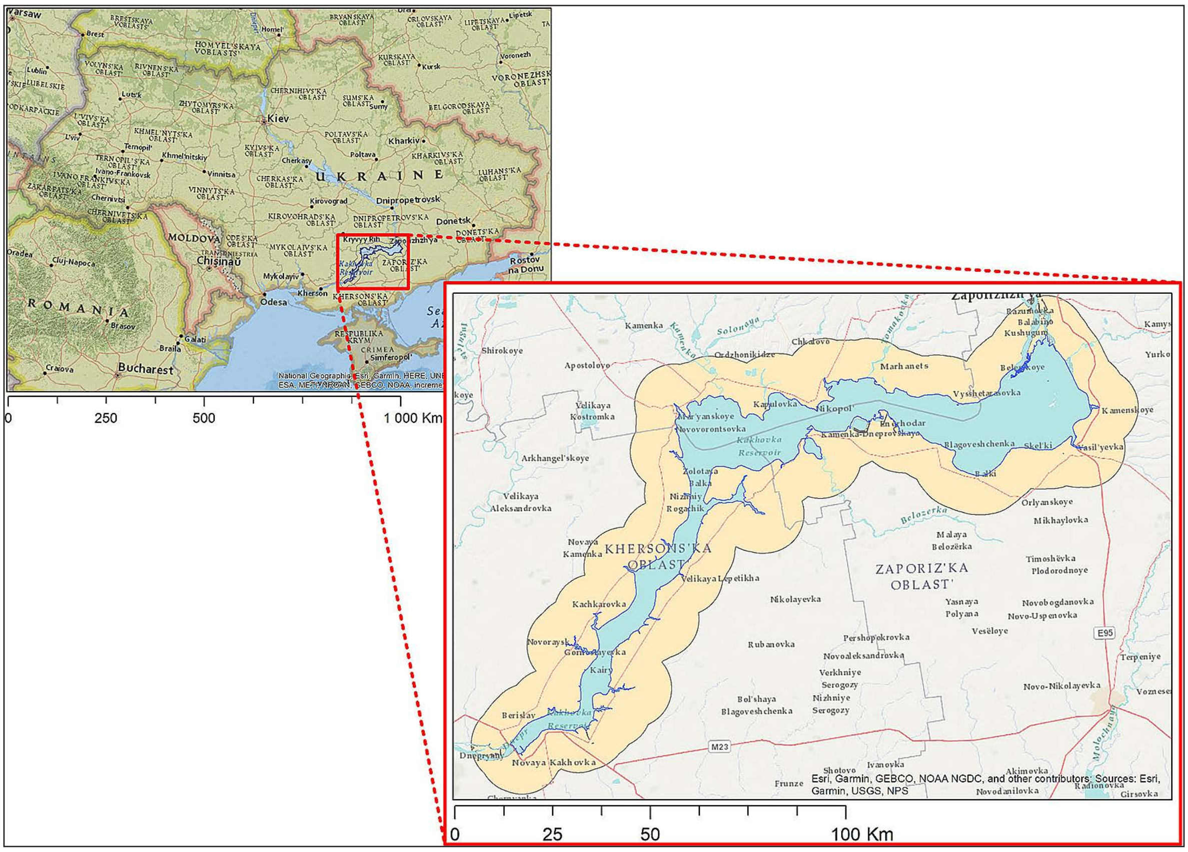

Figure 2. Spatial location of the Kakhovka Reservoir (a blue color) and the research buffer zone of 10 kilometers (a pink color)

thousand hectares of arable lands, 36 thousand hectares of pastures, over 90 settlements, about 37.0 thousand people were relocated, tens of villages, the Nikopol and Kamianka-Dniprovska cities were flooded (Lukhtanov and Chernyavsky 1959). In total, 221.3 thousand hectares of farmlands and forested lands were meant for the water reservoir (Kovpak 2003).

The flooded water areas in Dnipropetrovsk, Zaporizhzhia and Kherson regions amounted to 2155 km^2. The reservoir water area in the period of its functioning had the following characteristics: the total capacity – 18.2 km^3, the active capacity – 6.8 km^3; the normal storage level – 16.0 m, the dead storage elevation – 12.7 m, the maximum depth of the water body – 32.0 m, the average depth – 8.5 m, seasonal fluctuations of the water table 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 shoreline – 869.0 km; the multiyear discharge varied from 28.3 to 61.7 km^3/year. The capacity of the hydroelectric power station (HPS) was 329.0 thousand kW, the maximum discharge capacity of HPS amounted to 2600 m^3/s. In order to maintain the necessary minimum level of discharge in the lower course of the Dnipro, the flow rate of HPS had to be 1000 m^3/s, but its critical level reached 400–500 m^3/s in low water seasons with active water use. The Kakhovka Reservoir was an important source of electric power, providing irrigated agriculture in the Steppe zone which is characterized by the deficit of natural moisture. It was also a source of water supply for settlements, fisheries, recreation, etc.

Research methods

The research of changes in the landscape structure of the drained reservoir area and regularities of the seasonal formation of plant bio-productivity in 2023 was carried out on the basis of normalized difference vegetation index (NDVI) and the intensity of plant saturation with a chlorophyll pigment using the satellite imagery of Sentinel 2 L2A. Differentiation of the spatio-temporal activeness of plant development was calculated by NDVI (Pichura et al., 2024):

$$NDVI = \frac{B8 - B4}{B8 + B4} \quad (1)$$

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

The NDVI values ranged from -1.0 to 1.0. Negative values are mainly formed by clouds, water and snow, while the values close to zero (from 0.05 to 0.15) – by stone and bare lands. The value higher than NDVI = 0.15 indicates emergence of plants, in particular: 0.15–0.40 – sparse vegetation; 0.40–0.55 – satisfactory vegetation; 0.55–0.70 – thick vegetation; 0.70–1.00 – very thick vegetation. The intensity of plant saturation with a chlorophyll pigment (Chl-a) was calculated by chlorophyll sensitive index (CSI) (Zhang et al., 2022):

$$CSI = 2.5 \times \frac{B8 - B5}{B8 + B8} \times \frac{B2}{B5} \tag{2}$$

where: $B2$, $B5$ and $B8$ are the of the corresponding bands of Sentinel-2 L2A. The value of CSI changes is a dimensionless indicator. Negative values are largely formed by clouds, water and snow, and the values from 0.0 to 0.2 – by stone, sand and bare soil. The value of CSI > 0.2 indicates the presence of vegetation and Chl-a content in plant leaves.

The value of chlorophyll content (Chl-a$_{CSI}$, μg/sm^2) in plant leaves was calculated by the formula (Zhang et al., 2022):

$$Chl\text{-}a_{CSI} = 130.34\,CSI - 25.37 \tag{3}$$

The value of Chl-a$_{CSI}$ ≤ -20 is mainly formed by clouds, water and snow, while the values from -20.0 to 0.0 – by stones, sand and bare soil. The value of Chl-a$_{CSI}$ > 0.0 indicates Chl-a content in plant leaves. Spatio-temporal patterns of changes in microclimatic conditions in the adjacent territories caused by the reservoir's drainage were established on the basis of changes in the values of the near surface air temperature (T, °C), reference evapotranspiration (ET_o, mm/day) for 2020–2022 and land surface temperature (LST, °C) for 2020–2023 using the satellite imagery of Landsat 8–9 and Sentinel-3 SLSTR L1B.

Spatio-temporal differentiation of ET_o in the research territory was determined on the basis of the data calculated by FAO Penman-Monteith method. The ET_o value is calculated on the basis of climatic parameters. It reflects evaporation in a particular region in a certain period of the year. The FAO Penman-Monteith method is maintained as the sole standard method for the computation of ET_o from meteorological data (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \tag{4}$$

where: ET_o – reference evapotranspiration, mm/day; R_n – net radiation at the crop surface, MJ/m^2 day; G – soil heat flux density, MJ/m^2 day; T – air temperature at 2 m height, °C; u_2 – wind speed at 2 m height, m/s; e_s – saturation vapour pressure, kPa; e_a – actual vapour pressure, kPa; e_s - e_a – saturation vapor pressure deficit, kPa; Δ – slope vapor pressure curve, kPa/°C; γ – psychrometric constant, kPa/°C.

The LST value determines radiation temperature on the earth surface obtained from solar radiation. It is an important geophysical parameter related to the surface energy and water balance of the system "earth–atmosphere" (Li et al., 2023). Rasters of the distribution of LST values for 2020–2023 were retrieved from the open sources Copernicus Browser from the data of the device for measuring the temperature of the sea and land surface (Sea and Land Surface Temperature Instrument – SLSTR) Sentinel-3, which has two canals (F1 and F2), designed for measuring LST. Canal F2 with the center wavelength of 10854 nm measures in the thermal infrared range with a resolution of 270 × 270 m/pixel. The rasters were used for determining spatio-temporal patterns of changes in LST values after the Kakhovka dam destruction and the water reservoir's drainage in 2023, in comparison with the average for 2020–2022. In order to thoroughly examine and determine seasonal patterns of changes in LST in 2023 of the drained water reservoir and the adjacent territories, the raster data of the Landsat 8–9 spacecraft of thermal canal 10 with the center wavelength of 10895 nm with a resolution of 75 × 75 m/pixel (the source – EO Browser) were used. The rasters of LST values were used for specifying changes in the distribution heterogeneity of evapotranspiration depending on spatial changes in the surface heat of the drained water reservoir and the adjacent territories. Natural-climatic transformation of the drained territory of the Kakhovka Reservoir was calculated on the basis of vegetation health index (VHI) (Bento et al., 2020):

$$\left.\begin{aligned} VCI &= \frac{NDVI - NDVI_{\min}}{NDVI_{max} - NDVI_{min}} \\ TCI &= \frac{LST_{max} - LST}{LST_{max} - LST_{min}} \end{aligned}\right\} \rightarrow VHI = \alpha \times VCI + (1 - \alpha) \times TCI \tag{5}$$

where: VCI (vegetation condition index) – spatial variability of NDVI, used for determining conditions of vegetation. NDVI – the current value of NDVI in a certain raster pixel, $NDVI_{max}$, $NDVI_{min}$ – the absolute maximum and minimum of *NDVI* in the same period. VCI changes from 0 to 1, high values correspond to favorable conditions for vegetation, low values – to unfavorable conditions.

TCI (temperature condition index) – spatial variability of *LST*, used for determining plant stress related to high temperatures. *LST* – the current value of *LST* in a certain raster pixel, LST_{max}, LST_{min} – the absolute maximum and minimum of *LST* in the same period. High temperatures throughout the vegetation period correspond to unfavorable conditions and probability of droughts, low temperatures mainly testify to favorable conditions. Coefficient *a* – a coefficient determining contribution of *VCI* and *TCI* to the general state of vegetation.

VHI (vegetation health index) – evaluates cumulative temperature conditions and moisture for plant development. VHI ranges from 0 (extreme stress) to 1.0 (the most favorable conditions). VH is useful for early identification of drought, assessment of the area affected by drought, its duration and intensity, and also for monitoring the impact of drought on plants and agricultural crops. For the drained territory of the Kakhovka 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.

The *a*-coefficient should be calculated using the data of zonal climate moisture on the basis of aridity index (*AI*) (Pichura et al., 2023):

$$AI = P_y / ET_{yo}\} \rightarrow a = 0.5AI \quad (6)$$

where: P_y – the amount of precipitation per year, mm; ET_{yo} – the amount of reference evapotranspiration per year, mm; 0.5 – the equilibrium value of the balance of the combination of chlorophyll and moisture content in plants and thermal conditions on the surface.

Normally, the *AI* value lower than 0.5 indicates arid or semi-arid territories, whereas the values over 0.65 indicate wet and hyper-wet zones.

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

RESULTS

Water utilization of the reservoir

The dynamics of the water balance of the Kakhovka Reservoir was affected by anthropogenic-climatic changes in the inflow of water resources from the upper and middle course of the Dnipro and the volumes of utilization of water resources. Using the data of the State Agency of Water Resources of Ukraine, it was calculated that the input of the water balance in the lower course of the Dnipro river (from the dam of the Dnipro Reservoir to the dam of the Kakhovka Reservoir) fell by 46.2% (from 48.92 to 26.33 km^3) in 1989–2021. In particular, the ratio of the output to the input of the water balance reduced from 78.44 to 55.15%, which is primarily determined by a decrease in the activeness of water use and the number of industrial enterprises, a fall in the irrigated areas since 2014 as a result of occupation of the Autonomous Crimean Republic by the Russian aggressor. The average value of the total output of the water balance in 2020–2021 was 14.52 km^3.

In the structure of the output, the water volume of 12.73 km^3 (87.68%) ensured the minimum environmental flow in the outlet section of the Kakhovka Reservoir. 1.22 km^3 (8.36%) of the water resources were taken for drinking water, sanitary, hygienic and economic needs, about 0.42 km^3 (2.92%) of the flow was spent on evaporation, filtration and replenishment, and 0.15 km^3 (1.04%) of the flow was redirected beyond the limits of the calculated water management activities. The amount of the average annual water reserve in the reservoir was 11.81 km^3 in 2020–2021, and the transit flow to the lower part of the Dnipro, given the minimum environmental flow in the outlet section of the reservoir was 24.54 km^3.

The situation in the functioning of the Kakhovka Reservoir changed dramatically on June 6th, 2023 when the Russian aggressors destroyed the hydroelectric power station dam of the Kakhovka Reservoir. The ecocide caused a large-scale environmental disaster in the catchment area of the Lower Dnipro, which resulted in an abnormal increase in the river velocity and turbulence to catastrophic levels in the first days, disruption of the bottom sediments and the flooding of more than 600 km^2 of the lower part of the Dnipro, movement of substantial volumes pollutants through the Dnipro-Buh estuary to the Black sea area, and the reservoir started drying up.

Consequences of the destruction of the Kakhovka HPS dam

The destruction of the Kakhovka Reservoir dam caused disastrous consequences determined by a dramatic water level difference, an anomalous increase in the river velocity and turbulence, disruption of the bottom sediments, the flooding of the riverbanks and settlements, shoreline abrasion, diffusive pollution of water bodies, watercourses, disruption of the functioning of the delta-lake system of the lower part of the Dnipro, death of people, aquatic animals and plankton, terrestrial flora and fauna, the drainage of Kakhovka Reservoir, a reduction in the water level by 2.0 meters and more in the area of the lower reach below the dam of the Dnipro HPS and the drainage of lakes in the floodplain of the island Khortytsia, deterioration of the situation with water supply for the nearby settlements, destruction of the main fresh water source for irrigating farmlands in the territory of more than 800 thousand hectares and other negative consequences. According to the data of the Ministry of Foreign Affairs of Ukraine, 180 settlements with the population of more than 900 thousand people were included in the emergency zone. According to the data of Kherson Regional Military Administration, 118 historical monuments of Ukrainian culture were flooded.

By June 10th, 2023, polluted fresh water runoffs had been transported through the Black Sea area to the mouth of the Dniester river, the polluted area of the water resources being over 7300 km^2. As a result, on June 14th, 2023, (Vyshnevskyi et al., 2023, 2024) in the coastal area of Odesa, there was a reduction in the sea salinity by 2.62 times (from 11.0 g/dm^3 to 4.2 g/dm^3), an increase in the concentration of biogenic substances, phytoplankton content, an excess of the maximum allowable concentration (MAC): copper – by 895 times (MAC = 0.02 mcg/dm^3), zinc – by 44.8 times (MAC = 1.0 mcg/dm^3), arsenic – by 3.02 times (MAC = 0.6 mcg/dm^3), and oil products – by 2.0 times (MAC = 0.05 mcg/dm^3). According to the data of the Institute of Hydrobiology of the National Academy of Agrarian Sciences of Ukraine, in the first three days, the destruction of the Kakhovka dam caused a loss of 346 tons of the total plankton biomass, water flows carried from 24 to 51 thousand tons of micro-algae away, that resulted in an increase of algae biomass to 30 g/m^3 in the lower part of the Dnipro and the Dnipro-Buh estuary. In particular, (Novitskyi et al., 2024) 42 fish species with the total weigh of over 11 000 tons perished in the Kakhovka Reservoir, causing losses of the commercial catches of about 2 585 tons per year costing USD 5.4 million. 85 fish farms were destroyed, the losses of the fisheries infrastructure being USD 270 million. These numbers are too low, 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 tons. 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. In addition, 150 official cases of the dolphin deaths were registered in the Black sea area.

The water hammer effect and a sharp increase in the water level in the lower course of the Dnipro caused death of most terrestrial invertebrates and vertebrates. In particular, 70% of the world population of the Nordmann’s mouse, up to 50% of the blind hare, the ground hare or the common jerboa were flooded. The populations of the common copperhead, the steppe viper, the yell-red snake, the Sarmatian snake and other species from the UCN Red List suffered. Approximately 20 wild animals had lived in the flooded areas. Over 50 objects of the Nature reserve fund suffered from the flooding, in particular, 80 thousand hectares lost their original state.

Historically, the territory of the water reservoir was the center of the functioning of the Great Meadow and historical monuments of Zaporizka Sich: 1564–1593. – Tomakivska Sich, 1593–1630 – Bazavlutska Sich, 1630–1652 – Mykytynska Sich, 1652–1709 – Chortomlytska Sich, 1734–1775 – Nova (Pidpilnetska) Sich. Experts and scientists differ in their opinions on the functioning of the drained territory and the necessity to restore the dam and flood the reservoir territory. Therefore, the conducted research was aimed at thorough examination of the natural-climatic transformation of the reservoir territory resulting from the destruction of the hydroelectric power station dam.

Formation of the aboveground biomass

Dehydration of the Kakhovka Reservoir resulted in the bare bottom sediments and natural-climatic transformation of the drained territory characterized by the indicators of the spatio-temporal differences in the seasonal differentiation of moisture supply and phyto-climatic conditions of the reservoir. Plant biomass is the most important indicator of restoration and further ecological sustainability of the impaired territorial landscapes, manifestations of desertification, moisture accumulation and retention, maintenance of soil regeneration process and characteristics in the bottom sediments accumulated in the reservoir water area over the period of the reservoir functioning. The results of the decoded Sentinel-2 satellite imagery allowed establishing the spatio-temporal patterns of plant biomass formation by the Normalized difference vegetation index (NDVI) (Fig. 3).

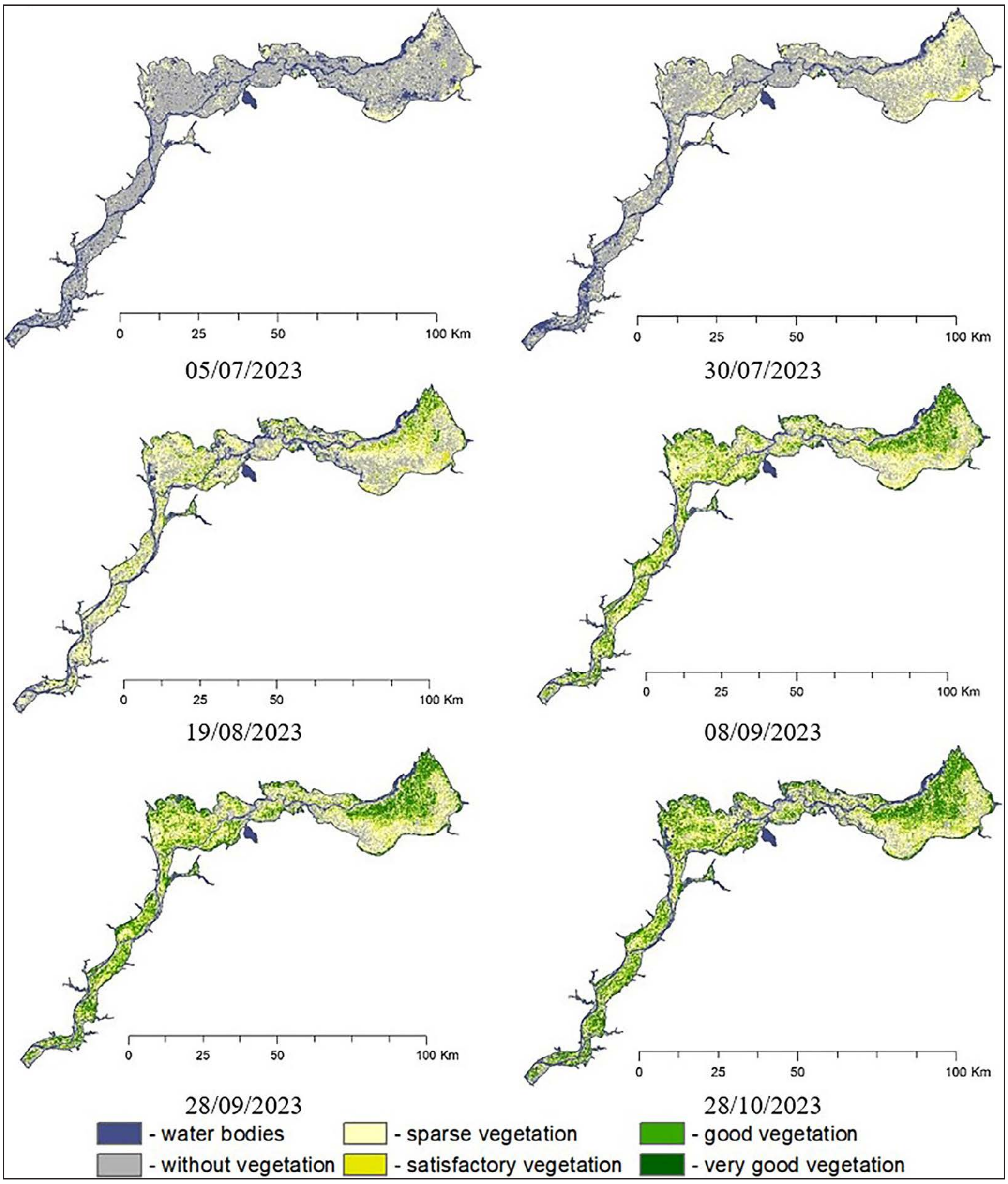

Figure 3. Spatio-temporal dynamics of the plant cover in the territory of the Kakhovka reservoir by normalized difference vegetation index (NDVI)

Seasonal local-differential changes in the vegetation areas in the territory of the drained reservoir were registered. Activeness of growth and development was determined by the patches of water retention and the level of biogenic accumulation in the bottom sediments. The active stage of the beginning of plant development and the formation of aboveground biomass were observed at the beginning of June, 2023, the maximum NDVI value being 0.2 (Fig. 4a), which was characterized by the emergence of sparse vegetation mainly in the upper part of the reservoir and beams. The average seasonal NDVI value in the vegetation period in July–October, 2023 varied between 0.09 and 0.37 (Fig. 4b) The average NDVI value was calculated taking into consideration the entire structure of the landscape type, in particular: water bodies, territories without vegetation, and territories with vegetation. The maximum NDVI values of vegetation largely varied between 0.2 and 1.0. The highest activeness of plant vegetation was registered from September to November, the NDVI of plants in some bottom landscapes reached the maximum possible values – 0.9–1.0. At the September peak of vegetation activeness, mainly throughout the territory of the reservoir, along the natural water course of the Dnipro river, the development of plant biomass was observed, determined by an appropriate level of water accumulation in the bottom sediments. Over the period of active plant vegetation from September to October, the landscape structure of the drained water reservoir by NDVI was formed in the following way (Fig. 4c): the area of water bodies (NDVI < 0.05) including all the water-covered territories, in particular, the main course of the river, wetlands, isolated shallow water, varied between 7.1 and 10.2%; the territory without vegetation (NDVI = 0.05–0.15) including stones, sands, bare bottom areas was 13.8–16.9%; the area with sparse vegetation (NDVI = 0.15–0.40) including territories of water stress with patches of stunted vegetation ranged from 30.9 to

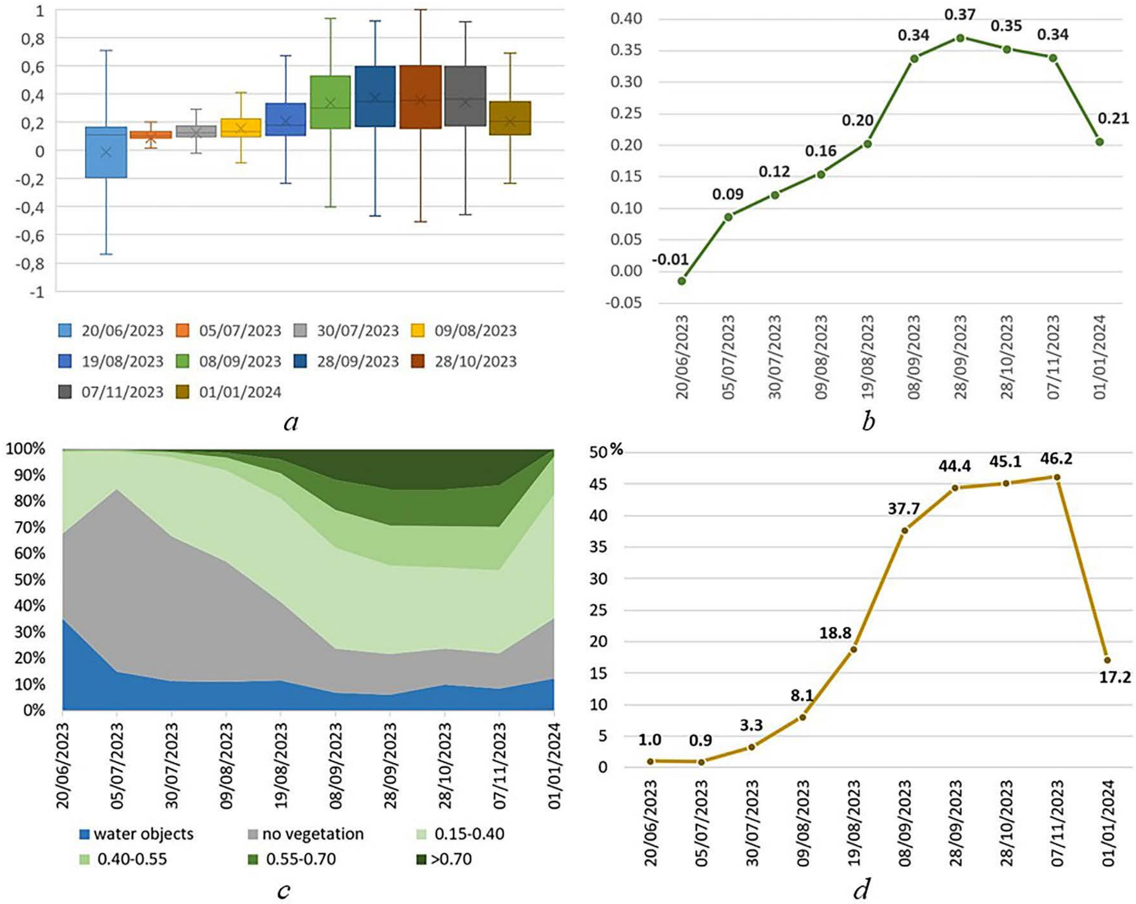

Figure 4. Formation of the structure of the drained territory of the Kakhovka Reservoir by the normalized difference vegetation index (NDVI): (a) differentiation of the NDVI values; (b) the average NDVI values; (c) dynamics of the distribution of the reservoir area, %; (d) a change in the share of the area covered with plants, NDVI > 0.40

38.4%; areas with satisfactory vegetation (NDVI = 0.40–0.55) including territories with appropriate plant density varied between 14.6 to 15.7%; the area with good and very good vegetation (NDVI > 0.55), including well-developed tall plants and shrubs amounted to 23.0–29.5%. The plant area with NDVI > 0.40 varied between 44.4 and 46.2% in the period of maximum vegetation (Fig. 4d).

The key indicator of the plant physiological condition and the main component of the plant pigment apparatus for accumulating solar radiation for photosynthesis is Chl-a. Identification of Chl-a in plants is important for obtaining information about plant development, productivity, water stress and phytocenoses diseases, the formation of density and species composition of the aboveground biomass. Remote sensing is an effective and highly informative means of obtaining accurate and continuous spatio-temporal data on Chl-a content in plant leaves. It is ensured by decoding satellite imagery through identification of the red edge wavelength reflection (680 ~ 750 nm), which rises sharply from the absorption maxima of the red band to the near infrared (NIR) range, and is the most sensitive to saturation of plants with chlorophyll. There are more than ten indices for calculating the Chl-a content, namely: red-edge normalized difference vegetation index (NDVIre), Red-edge ratio normalized difference vegetation index (RERNDVI), red-edge chlorophyll index (CIre), novel inverted red-edge chlorophyll index (IRECI), modified chlorophyll absorption ratio index (MCARI), MERIS terrestrial chlorophyll index (MTCI), transformed chlorophyll absorption in reflectance index (TCARI), Maccioni 2001 (Macc01), modified normalized difference (MND), Datt 99 (Datt99), TCARI/optimized soil-adjusted vegetation index (TCARI/OSAVI), chlorophyll sensitive index (CSI) (Zhang et al., 2022).

Chlorophyll sensitive index (CSI) has a certain advantage over other indices due to high sensitivity to the Chl-a content in plants and 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. It allows clearly distinguishing between the territories with water, bare territories without vegetation and the territories covered with plants with different accumulation of the Chl-a content. In particular, scientists developed a mathematical function (Formula 3) for calculating the Chl-a content in the values μg/sm^2 on the basis of a correlation between *CSI* and field measurements ($R^2 = 0.88$) (Zhang et al., 2022). Using the results of the decoded Sentinel-2 satellite imagery, a seasonal pattern of Chl-a$_{CSI}$ accumulation in the aboveground biomass of the drained water reservoir was established (Fig. 5), that allows distinguishing a change in the area of water bodies, bare areas of bottom sediments, as well as areas with sparse or stunted vegetation or well-developed vegetation. At the end of June, after the water receded, the presence of Chl-a$_{CSI}$ was registered in 18.8% of the drained reservoir area in 90% of cases in the range of 5–30 μg/sm^2 (Fig. 6a), the weighed average against the overgrown area was 5.6 μg/sm^2 (Fig. 6b) that is determined by phytoplankton residues, which were dried at the beginning of July and lost their photosynthetic properties. The beginning of the development of the aboveground biomass in some areas was observed at the end of July, the weighed average of Chl-a$_{CSI}$ was 6.7 μg/sm^2, the area with sparse or stunted vegetation (Chl-a$_{CSI}$ < 30 μg/sm^2) was 16.8%, with good biomass (Chl-a$_{CSI}$ ≥ 30 μg/sm^2) – 4.9% of the territory of the water reservoir. In the second decade of August, active plant development was observed in the upper part of the drained territory and beams, the areas with well-developed vegetation being 13.9% (Fig. 6c), the areas with sparse or stunted vegetation being 23.0%. At the September peak of vegetation activeness, there was a maximum level of the Chl-a$_{CSI}$ content in the entire territory of the water reservoir with an increase in its content in the aboveground biomass from the drained part of the lower area of the Dnipro river to the destroyed dam of the Kakhovka HPS. Over this period, Chl-a$_{CSI}$ accumulation in 90% of cases varied between 22.0 to 68.0 μg/sm^2 with the local peak level of over 120 μg/sm^2. The weighed average was 44.4 μg/sm^2, characterizing good conditions for the formation of the aboveground biomass in 44.2% of the territory, the share of the area with sparse or stunted vegetation was 22.0%. About 30% (Fig. 6d) of the vegetation area of the drained water reservoir accumulated Chl-a$_{CSI}$ ≥ 50 μg/sm^2, which allowed identifying well-developed tall plants or shrubs in these territories.

The research established that, in terms of the Chl-a$_{CSI}$ content, the share of the water bodies in the territory of the water reservoir after the dam destruction in the period of summer-autumn stabilization of the landscape structures varied between 17.5 and 22.1%, the bare bottom sediments – 16.3–18.9%, the territory with sparse or stunted vegetation (water stress) – 22.0–27.0%, and the

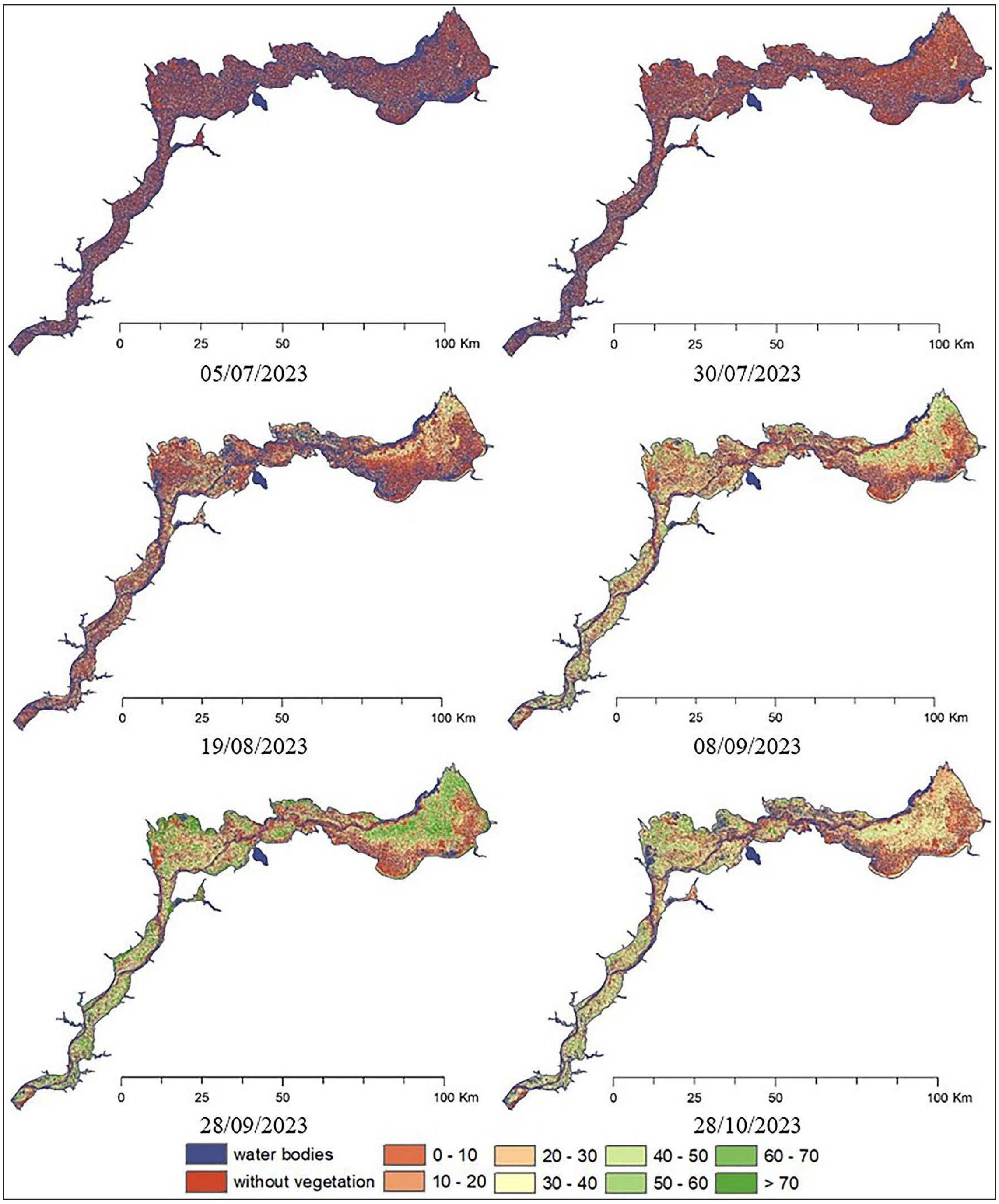

Figure 5. Spatio-temporal dynamics of chlorophyll (Chl-a_{CSI}, μg·cm^{-2}) in the leaves of plant cover in the territory of the Kakhovka Reservoir

area with good vegetation – 15.3–22.0%, the area with very good vegetation – 13.8–28.9%.

Climatic, microclimatic conditions and evapotranspiration

The destruction of the Kakhovka HPS dam caused the beginning of natural-climatic transformations of the drained territory of the water reservoir. Under such conditions, climate is the most determining abiotic factor. It is noteworthy that the system of relationships between natural and anthropogenic factors has undergone considerable changes, which resulted in an increase in the frequency of abnormal climatic manifestations and exacerbated risks of their negative impacts on the conditions of the functioning of natural ecosystems. The main characteristic of these changes is a reduction in moisture supply against the backdrop of significant warming.

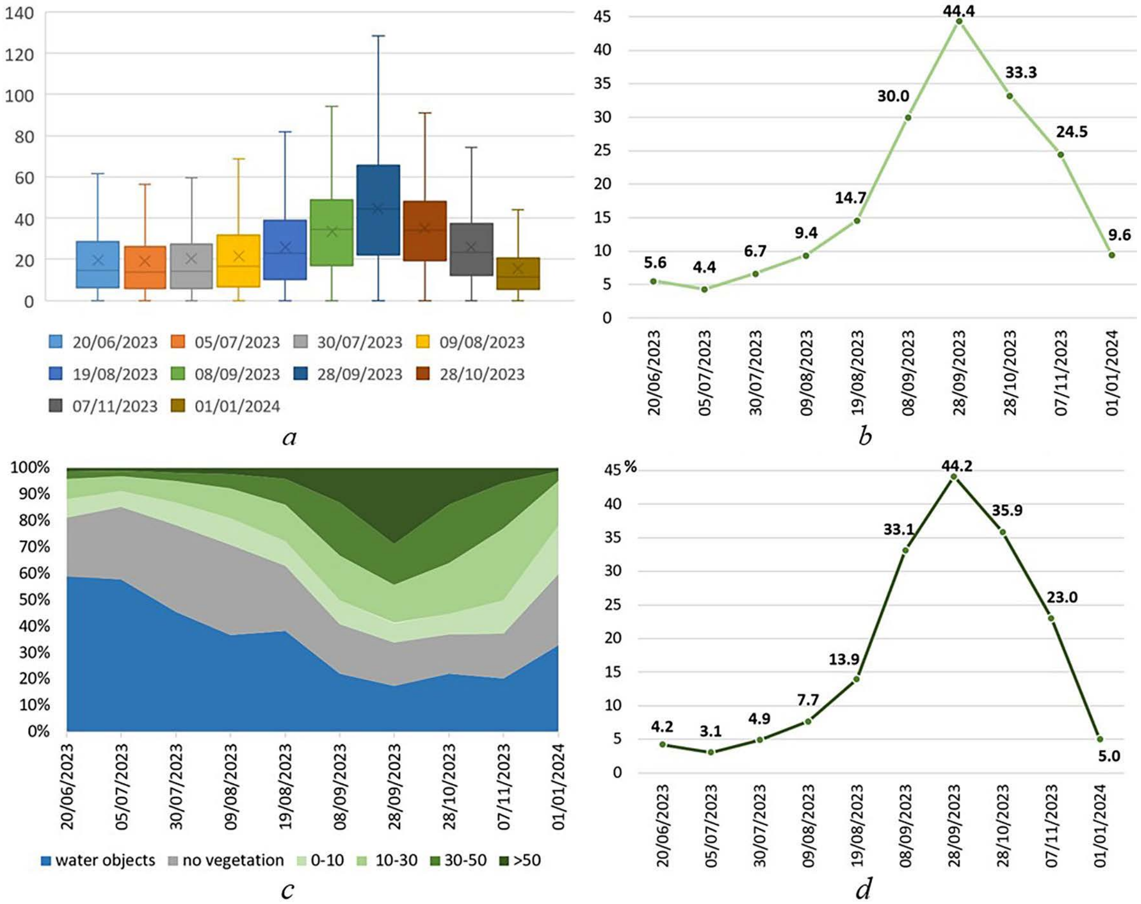

Figure 6. Formation of the structure of the drained territory of the Kakhovka Reservoir by Ch-a$_{CSI}$ (μg·cm^{-2}): (a) differentiation of the Chl-a$_{CSI}$ values in plant leaves; (b) the weighed average of Ch-a$_{CSI}$ against the maximum overgrown area (28/09/2023); (c) dynamics of distribution of the reservoir areas, %; d – change in the share of the area covered with plants, Chl-a$_{CSI}$ > 30 μg·cm^{-2}

Moisture has become a limiting factor of all soil-climatic zones. In particular, in the Steppe zone of Ukraine, in 1945–2019, there was an increase in the frequency of abnormal climatic manifestations by 3 times that caused a rise in the average annual temperature by 3.5 °C. The amount of annual precipitation ranged from 186 to 778 mm with a level of variation of 27.2%, its decrease being 40% over the past 20 years – to 500–300 mm and there was an increase in the frequency of heavy rainfalls in the spring-summer period. Forecasting allowed determining a tendency for abnormal climatic manifestations with a stable trend-cyclic increase in the average annual air temperature by 0.06 °C per year and a decrease in the average annual precipitation by 62.0 mm per year (Pichura et al., 2022). It determined a rise in the solar radiation reaching the earth surface by 18.7% and decrease in climatic expenditures on soil formation by 26.0%, which reduced the rate of natural capacity for soil fertility reproduction. In particular, natural bio-productivity of plants has reduced by 62.0% and it is likely to decrease by 20% later. Over the past 20 years, the natural moisture coefficient has fallen by 66.4% and it is likely to decrease by another 20%. The obtained results (Pichura et al., 2022) confirm significant climate changes and their negative signs that manifest themselves in a decrease of the bio-climatic potential in the zone of the functioning of the drained reservoir, an increase in the volumes of evapotranspiration, deterioration of moisture supply, suppression of natural-climatic functions of self-regeneration of the degraded and transformed landscape structure.

It is noteworthy that the functioning of the Kakhovka Reservoir water area created favorable microclimatic conditions in the adjacent territories. It resulted from the differences between the components of radiation and heat balances of water and land surface leading to the creation of local circulation (breezes), which were the most apparent in warm seasons. In particular, the distance of the buffer zone of breeze formation from the water area depends on the area of a water body, a spatial difference of the temperature of water and land surface, the mosaic-landscape and morphometric structure of the adjacent territory. During the daytime, breeze circulation results from heating and convective flows rising above the land, which are replaced by cooled air flows coming to the lower surface layers from the water body. At night, reverse circulation occurs when the landscape is cooled. The large water area of the Kakhovka Reservoir determined the formation of a horizontal-vertical layer fast and powerful breeze which created a favorable microclimate in the steppe landscapes in the territory of tens of kilometers from the water area.

Land surface temperature (LST, °C) is an informative indicator of spatio-temporal changes in micro-climatic conditions. LST is a radiation temperature of the Earth surface, the evaluation of which additionally depends on the ratio of plant cover and soil moisture, and also morphometric characteristics of the area. In particular, LST depends on distribution of energy between soil and vegetation, and also determines the air temperature on the surface (Ghouri and Khan 2022). Therefore, LST is considered to be one of the most important parameters in examination of physical processes of the surface energy and water balance on the national and global scales (Kalma 2008). Evaluation of LST provides information about temporal and spatial variations of the surface condition and is used in different studies on evapotranspiration, climate change, hydrological cycle, plant observation, urban climate and environment, desertification processes, etc.

Against the backdrop of negative zonal climate change and the Kakhovka reservoir drainage, negative consequences for microclimatic conditions in the territory of the water reservoir and in the adjacent territories have been observed. An increase in the surface heat of the drained reservoir territory of 2155 km^2 in area and the 10 km buffer zone of 5657.8 km^2 in area by 2.0 °C and more is also a negative consequence (Fig. 7).

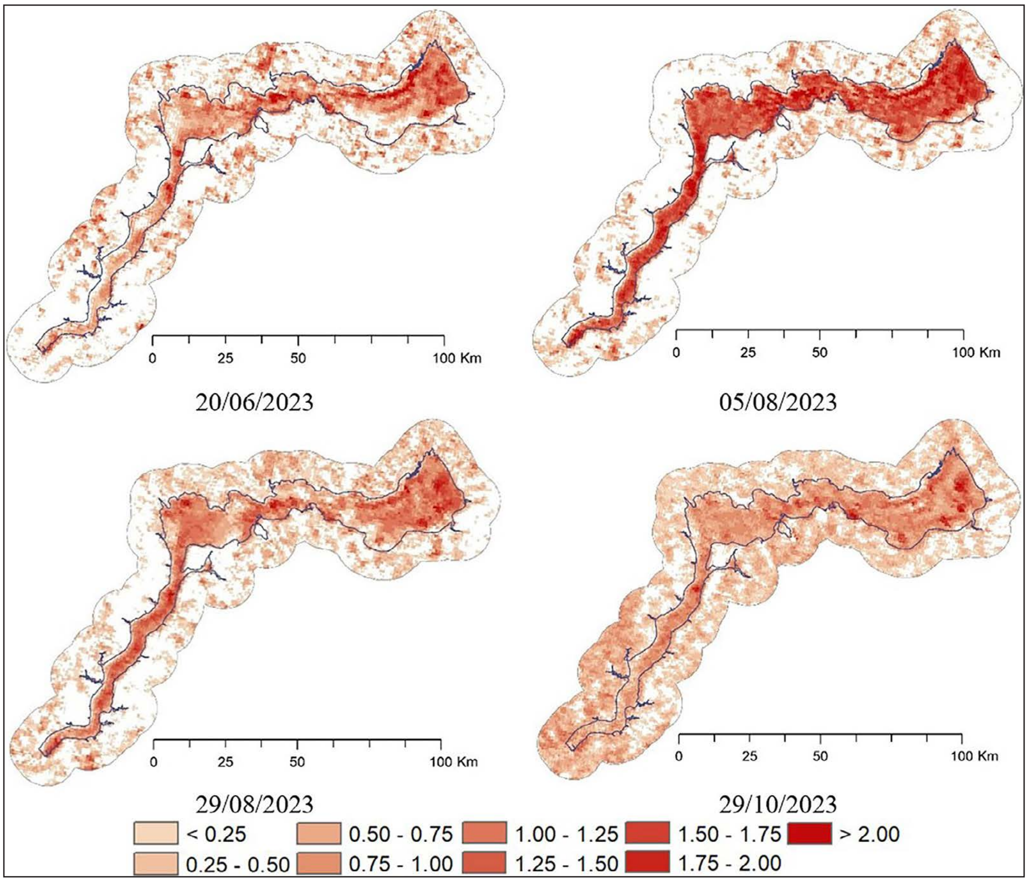

Figure 7. Spatio-temporal changes in the values of the land surface temperature (LST, °C) of the drained Kakhovka Reservoir and the adjacent territories resulting from the dam destruction – calculated on the basis of the difference of LST values in 2023 to the average LST values in 2020–2022

Intensification of negative manifestations of a climate impact started immediately after the water went down which caused seasonal expansion of the areas with a critical increase in LST values. A difference in LST values was calculated on the basis of a difference in raster LST surfaces of the season 2023 to the average value of the corresponding period in 2020–2022. It was established that the reservoir drainage resulted in an increase in the area of the surface heating in the territory of the water reservoir by 85.3–97.9% (Fig. 8a) that caused seasonal-heterogenic deterioration of microclimatic conditions in 48.5–83.2% of the adjacent territory (Fig. 8b). Dehydration and the development of plant biomass in 2023 in the territory of the drained water reservoir did not maintain an appropriate level of water accumulation and the formation of humid microclimate, which was formed in the period of the existence of the water area of the Kakhovka Reservoir. In 2023, it caused an increase in the volumes of evapotranspiration, rapid drainage of bottom-landscape systems and a critical level of soil moisture deficit in the adjacent territories. In order to accurately calculate changes in evapotranspiration processes, depending on seasonal-heterogenic surface heating, functional dependences of the impact of average monthly changes in the surface temperature on the volumes of reference evapotranspiration (ET_o, mm/day) (Fig. 9a), the impact of average monthly changes in the surface temperature on LST (Fig. 9b), the impact of LST on a change in evapotranspiration (ET_{LST}) (Fig. 9c) were established. The established patterns confirm a high correlation of the values of T, ET_o and LST.

A spatio-temporal difference of evapotranspiration processes (ET_{LST}) was specified and calculated on the basis of LST rasters using the

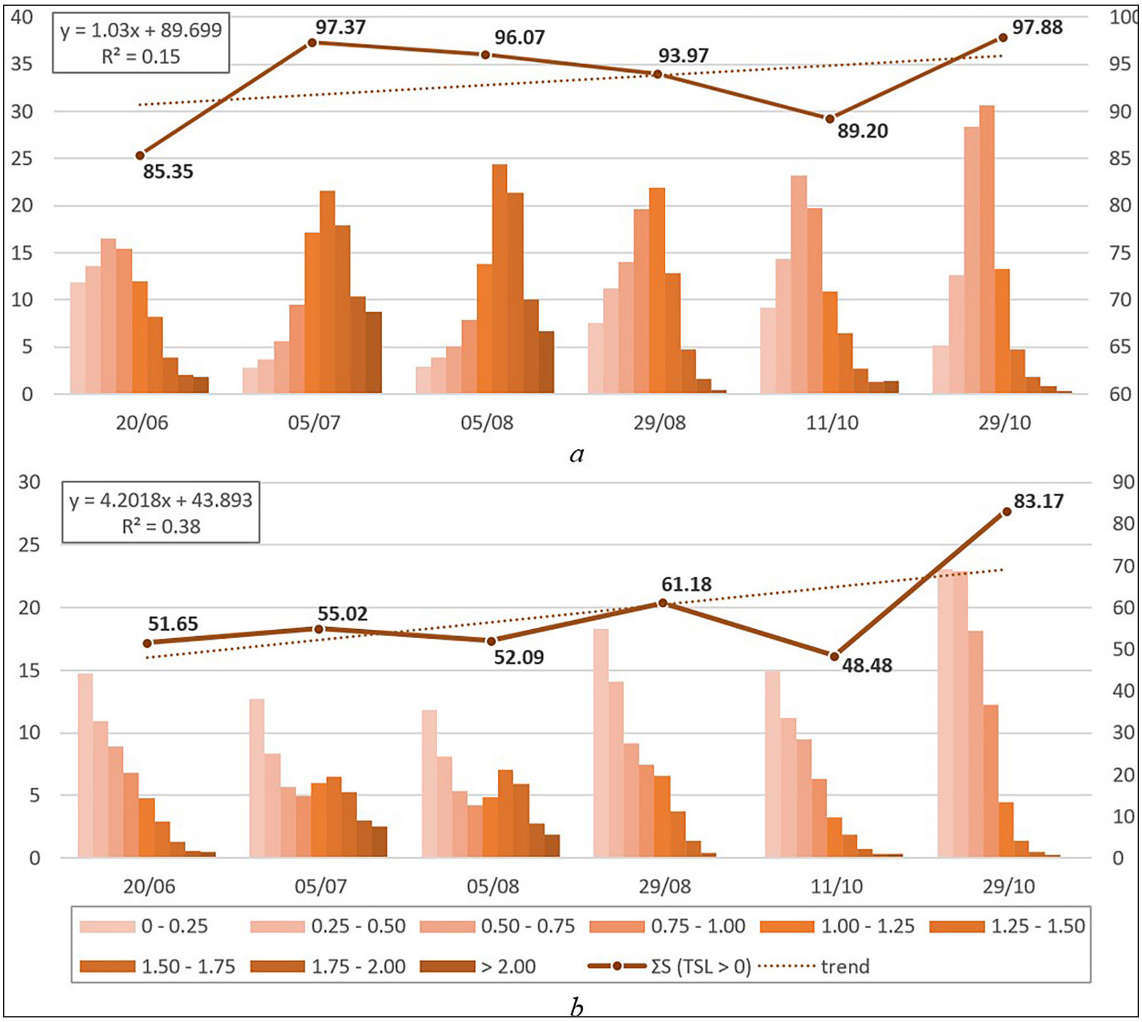

Figure 8. Dynamics of distribution of the areas (%) with different levels of an increase in the land surface temperature (LST, °C) resulting from the dam destruction, 2023: (a) the territory of the drained Kakhovka Reservoir; (b) adjacent territories

developed mathematical functions. It is noteworthy that spatio-temporal variation of evapotranspiration is an important indicator of drought, a change in the water regime, moisture supply of the territorial landscape structures, the level of plant water use, the volume of water footprint, etc. It was calculated that the values of ET_{LST} in the summer-autumn period of 2023 rose to a record level of 4.0 mm/day and more (Fig. 10) in some areas, which determined the intensity of drought manifestations. In 2023, an acceleration in evapotranspiration processes was 50% and more. The total area of the shoreline buffer zone of the drained reservoir with signs of accelerated evapotranspiration varied between 35.4–39.0% and 48.8–77.6% from June to October. In particular, in the adjacent territory, during the warm summer-autumn season, there was an acceleration in evapotranspiration to 10% in the area of 1070.4 km^2 (18.9%), from 10 to 20% in the area of 641.6 km^2 (11.3%), within 20–30% in the area of 355.5 km^2 (6.3%), 30–40% in the

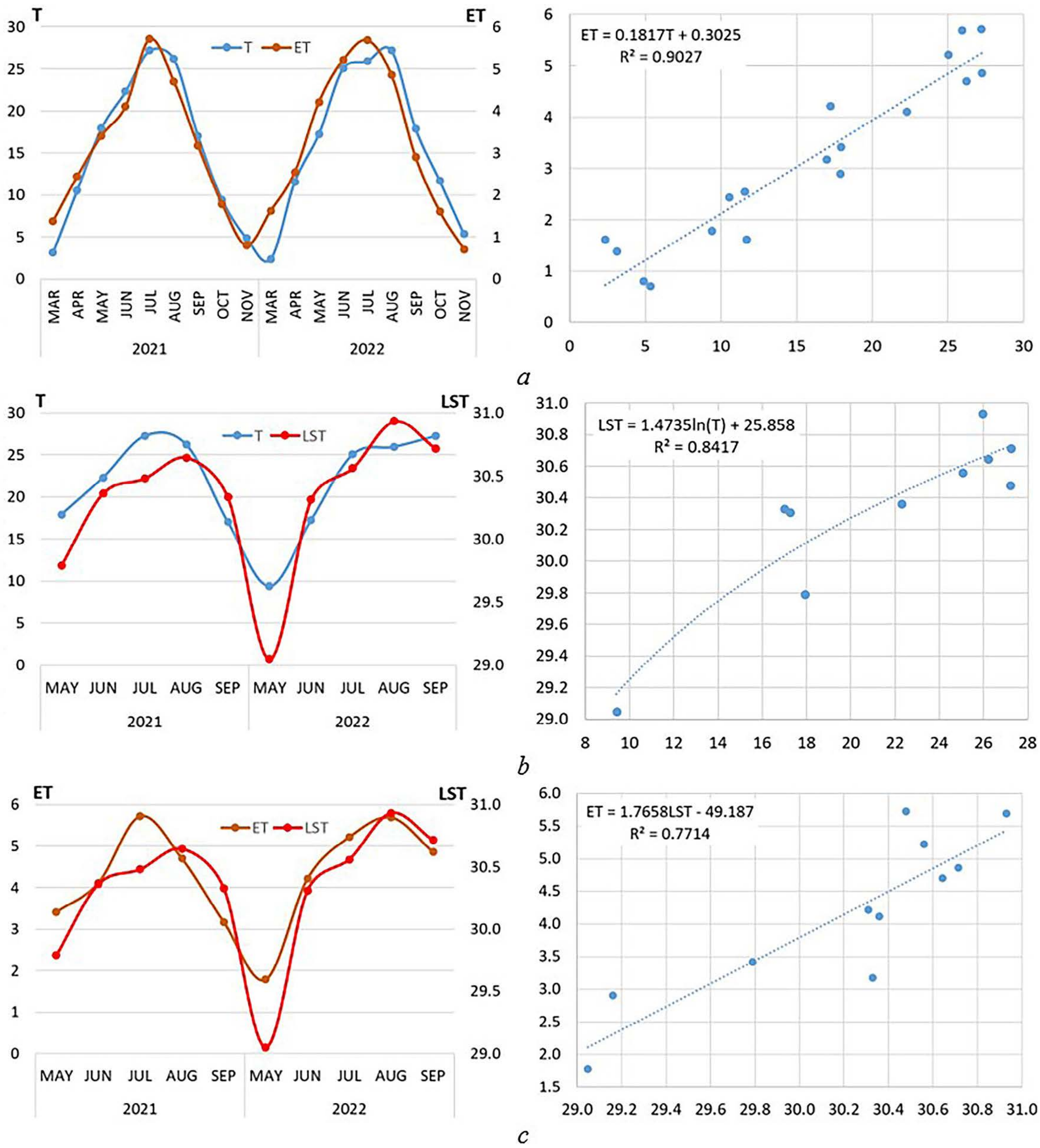

Figure 9. Average monthly patterns of a change in climate-landscape characteristics of the drained Kakhovka Reservoir and the adjacent territories in the warm months of 2021–2022: (a) dependence of reference evapotranspiration (*ET*, mm/day) and the air temperature (T, °C); (b) dependence of the land surface temperature (LST, °C) and the air temperature (T, °C); (c) dependence of reference evapotranspiration (ET, mm/day) and the land surface temperature (LST, °C)

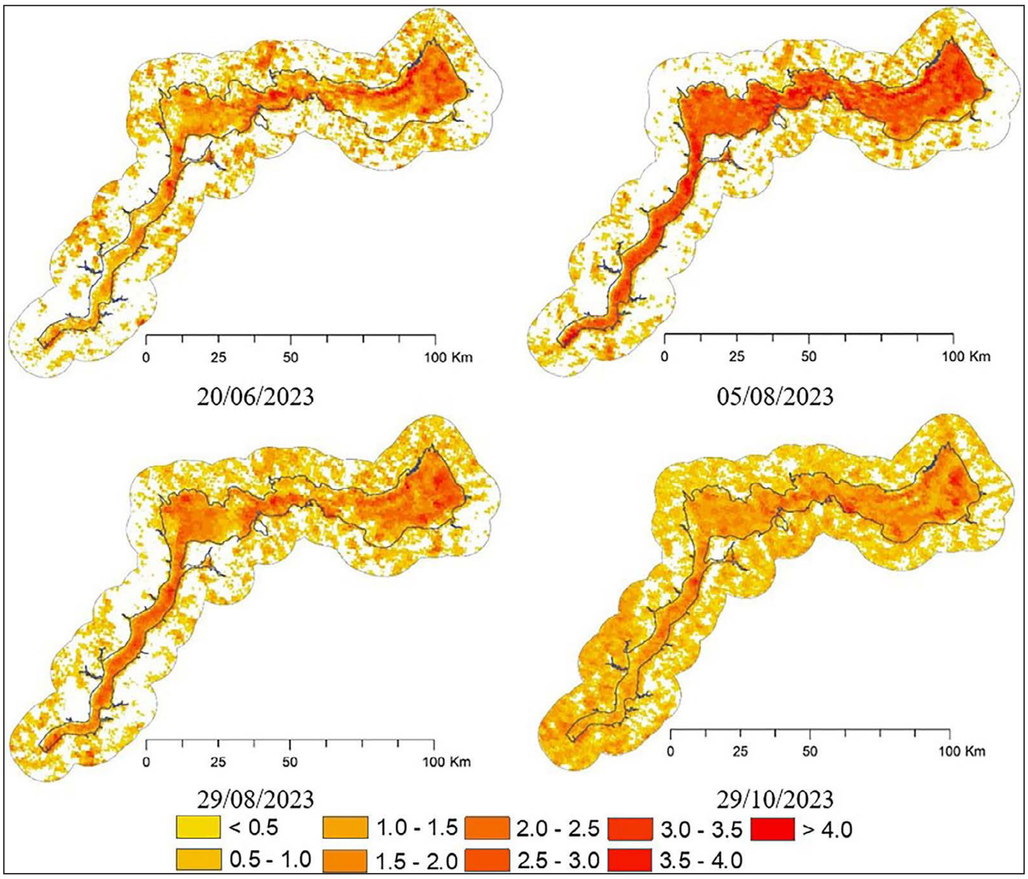

Figure 10. Spatio-temporal changes in the differentiation of evapotranspiration (ET_{LST}) on the surface of the drained Kakhovka Reservoir and the adjacent territories – calculated on the basis of the difference in the ET_{LST} values in 2023 to the average ET_{LST} values in 2020–2022

area of 204.0 km^2 (3.6%), 40–50% in the area of 114.0 km^2 (2.0%), and more than 50% in the area of 190 km^2 (3.4%).

If there is a continuing trend and frequency of climatic manifestations of high surface temperatures, which have considerably increased over the past years, deterioration of the circulation of matter in natural ecosystems and an acceleration in the process of large-scale desertification will occur, which will have disastrous environmental and socioeconomic consequences for the region of the Kakhovka reservoir's impact that is caused by a high level of water scarcity.

Scenario of the phyto-climatic functioning of the drained water reservoir

The scenario was calculated for September 2023 characterized by a typical climatic regime for the Steppe zone, the most favorable level of the formation of plant biomass and the formation of microclimatic conditions in the drained territory of the Kakhovka Reservoir. Comparison of microclimatic conditions was performed in relation to September 2020. The average monthly value of the surface air temperature in September 2020 was 20.6 °C, in 2023 – 7.1 °C, the amount of precipitation was 26.4 mm in 2020, and 20.5 mm – in 2023. In 2020, there was an excess of temperature by 3.5 °C, that characterized, in comparison with 2023, a greater flow of solar radiation reaching the surface of the research territory. No significant differences were registered in the amount of precipitation in September. The LST value (Fig. 11a) in 2020 was 29.83 ± 0.52 °C, in 2023 – 29.96 ± 0.30 °C. Under high air heating, the water area of the reservoir in 2020 considerably mitigated the impact on the land surface reducing evaporation processes from the water surface. The ET_{LST} value in the water area was 2.24 ± 0.19 mm/day in 2020, and the ET_{LST} value was 3.20 ± 0.46 mm/day in the drained territory. This led to a 2.3 – fold increase in the number of cases of high evapotranspiration values from 3.5 to 4.0 mm/day in the adjacent territory in 2023. The Kakhovka Reservoir drainage at the end of

September caused an increase in the LST values by 1.0 °C and more (Fig. 11b) and in the ET_{LST} values – by 1.5 mm/day and more (Fig. 11c). It resulted in deterioration of the water balance and microclimatic conditions, exacerbated water scarcity by 58.2% in the research territory with different levels of climate stress.

According to the official data of the State Agency of Water resources of Ukraine, about 4.72 million m^3 of water resources were spent on evaporation every month from the water areas in warm seasons. The performed calculations allowed specifying that the total evaporation from the water surface was 5.94 million m^3 (Table 1) in September, 2020, and in 2023 this figure from the surface of the dried water reservoir was 12.13 million m^3, which is 2.04 times more. Evaporation from the adjacent territories was 28.56 million m^3 in 2020, in 2023 this figure rose 1.41 times. In 2020, the total evaporation from the entire research area (7812.8 km^2) was 34.50 million m^3, and in 2023–52.36 million m^3. Over the years of research, the conditions for the formation of plant biomass were identical. The average *NDVI* value in the research territory was 0.37 ± 0.17 in the third decade of September in 2020 and 2023.

The obtained research findings prove that, under the most favorable conditions for the formation of plant biomass in the territory of the drained Kakhovka Reservoir, there is an increase in the level of the land surface temperature, a rise in the area of water stress, and increase in the volume of evapotranspiration by 1.52 times. All of will prevent regeneration of the historical Great Meadow.

Natural-climatic transformation

Natural-climatic transformation of the drained territory of the Kakhovka Reservoir was calculated for September 2023 on the basis of VHI. VHI is an integral index and an important indicator showing drought intensity on the basis of plant health and the impact of the land surface temperature. VHI combines the VCI and TCI of landscape systems. TCI is calculated using an equation similar to VCI, but relates the current temperature to its maximum and minimum, since higher temperatures are likely to

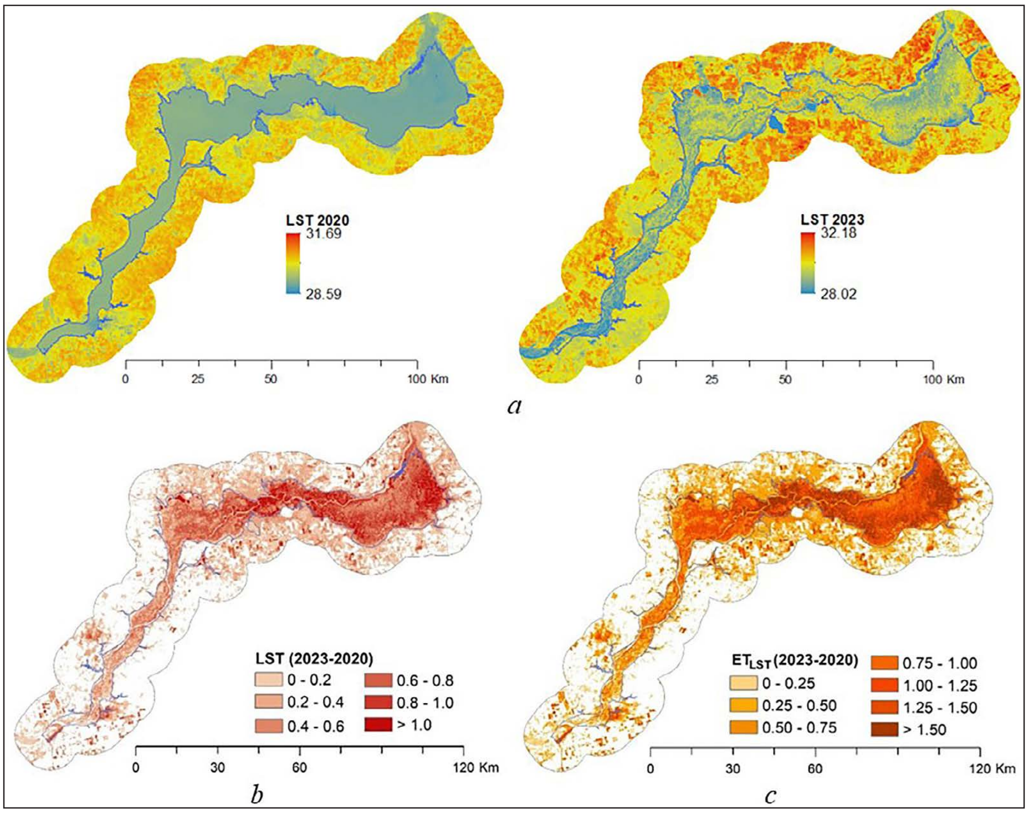

Figure 11. Spatio-temporal patterns of changes in the land surface temperature (°C) and evapotranspiration (ET_{LST}, mm/day) in the area of the drained Kakhovka reservoir and the adjacent territories (September, 2020 and 2023): (a) distribution of LST values in 2020 and 2023; (b) an increase in LST values in 2023, (c) an increase in ET_{LST} volumes from the land surface

Table 1. Change in the volumes of evapotranspiration (ET_{LST}, mm/day) from the surface of the drained Kakhovka Reservoir and the adjacent territories caused by the destruction of the hydroelectric power station dam

Statistical	Data		
	09/2020	09/2023	2023÷2020
Territory of the Kakhovka Reservoir			
Min	1.29	1.80	1.40
Max	4.07	5.08	1.25
Mean	2.24	3.20	1.42
Std dev.	0.19	0.46	2.42
Var,%	8.48	14.42	1.70
Sum_1 per month	593592.702	1212512.160	2.04
Adjacent territory (the buffer zone of 10 km)			
Min	1.49	1.67	1.12
Max	6.77	7.35	1.09
Mean	3.97	4.35	1.10
Std dev.	0.57	0.42	0.74
Var,%	14.36	9.66	0.67
Sum_2 per month	2856163.79	4023687.96	1.41
Total per month (Sum_1 + Sum_2)	3449756.49	5236200.12	1.52

cause deterioration of conditions for vegetation. In particular, a reduction in VHI indicates bare landscapes or unfavorable conditions for vegetation and high temperatures, that means stressful conditions for vegetation and manifestations of drought intensity.

According to the results of the VHI calculations, it was established that the territory of the drained Kakhovka Reservoir was distributed by manifestations of drought intensity and the vegetation health index as of September 2023 (Fig. 12) in the following way: 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%.

It should be emphasized that the main course of the Dnipro river (Pichura et al., 2020, Potravka et al., 2022) is fed by waters of the upper (the mixed forest zone) and the middle (Polissia zone) parts (91.4%), whereas it is fed by the local water (the Steppe zone) of the lower part of the Dnipro river bed and the drained territory of the Kakhovka Reservoir only at the level of 1.8%. Therefore, provided that there is a high level of solar radiation and sufficient local moisture in the territory of water stress and water scarcity, a mosaic landscape structure with low biomass, signs of desertification and its exacerbation will be formed.

Vegetation is characterized by satisfactory and good health in the territories where there is a hydrological connection with surface runoffs of the of the main course of the Dnipro river, remnants of accumulated moisture in the bottom landscapes, with areas of water-erosion entry of soil residues from farmlands, with accumulation of sediments and phytoplankton remains. These areas have favorable phyto-climatic conditions for the formation and functioning of the aboveground biomass. These territories include: beams (Fig. 13), the lower part of the territory of the drained water reservoir with a well-developed hydrological network of the natural Dnipro river channel system, the upper part of the water reservoir with a good level of the riparian moisture accumulation and substantial accumulation of the patches of organic residues.

It is noteworthy that two months after the dam destruction, isolated shallow water bodies with the total area of 307.0 km^2 continued to shrink because of evaporation and drainage. At the end of September, the territory of isolated shallow water bodies reduced by 36.1% being 196.2 km^2. Shallow water bodies isolated from the main course of the Dnipro undergo considerable climatic pressure and belong to the territories with unstable moisture supply. They will be filled in the period

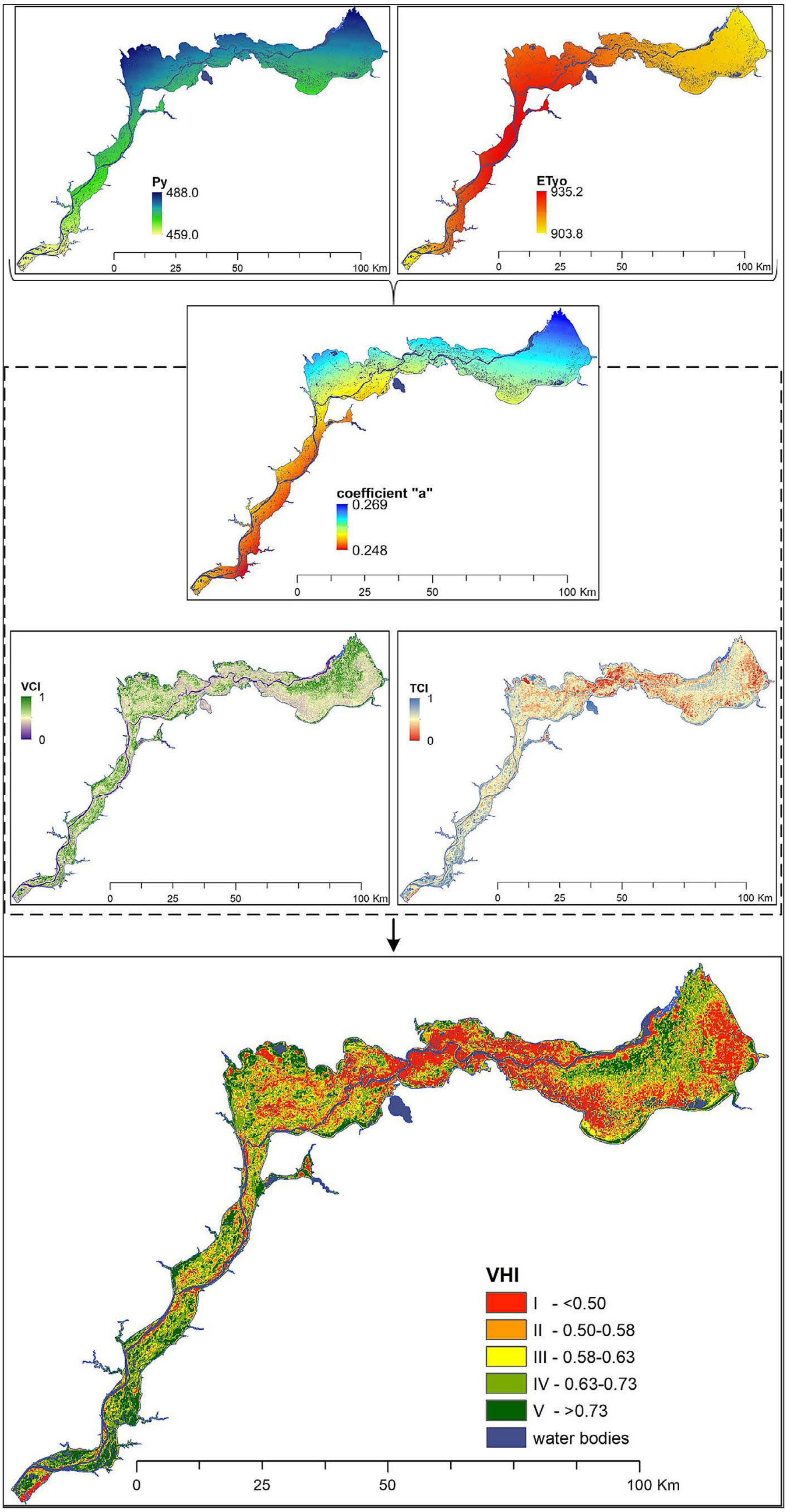

Figure 12. Natural-climatic transformation of the drained territory of the Kakhovka Reservoir in September, 2023; P_y – the average amount of precipitation in 2020–2023; ET_{yo} – the average amount of reference evapotranspiration in 2020–2023; coefficient *a* – the coefficient of contribution of VCI and TCI; VCI – the vegetation condition index; TCI – the temperature condition index; VHI – the vegetation health index

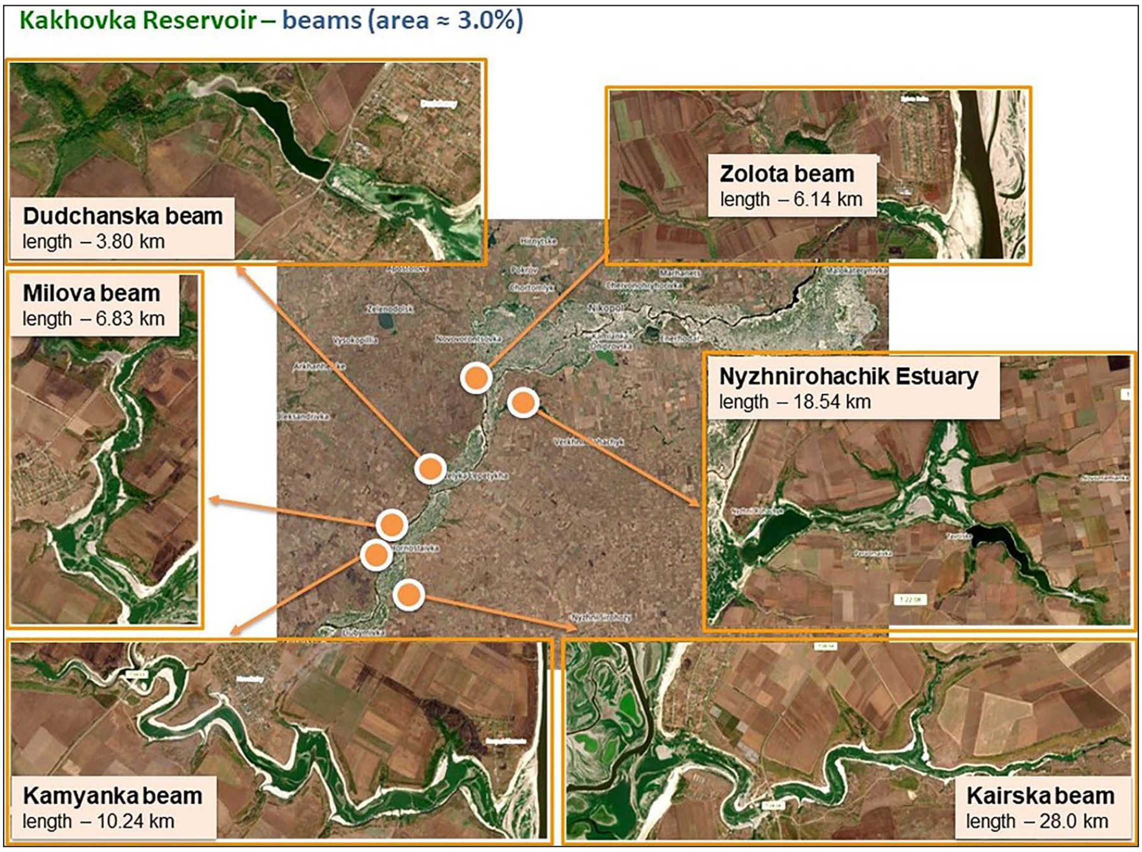

Figure 13. Beams of the Kakhovka Reservoir

of spring flood from the upper and middle pars of the Dnipro catchment and additional discharge from the adjacent territories and the local runoff (Fig. 14). It will determine a seasonal spring increase in the water surface area of stagnant zones, with further drainage in the summer-autumn low water season. About 136.6 km^2 of water bodies and water courses in the drained territory of the water reservoir are functionally stable and ensure the conservation of water resources.

DISCUSSION

The environmental condition in the period of the functioning of the Kakhovka Reservoir was of unsatisfactory quality by the indicators of the surface water quality, but the water reservoir was of economic and socioeconomic importance for the regions of the Steppe zone of Ukraine with water scarcity. Along with electricity generation, the water reservoir was used for providing water for

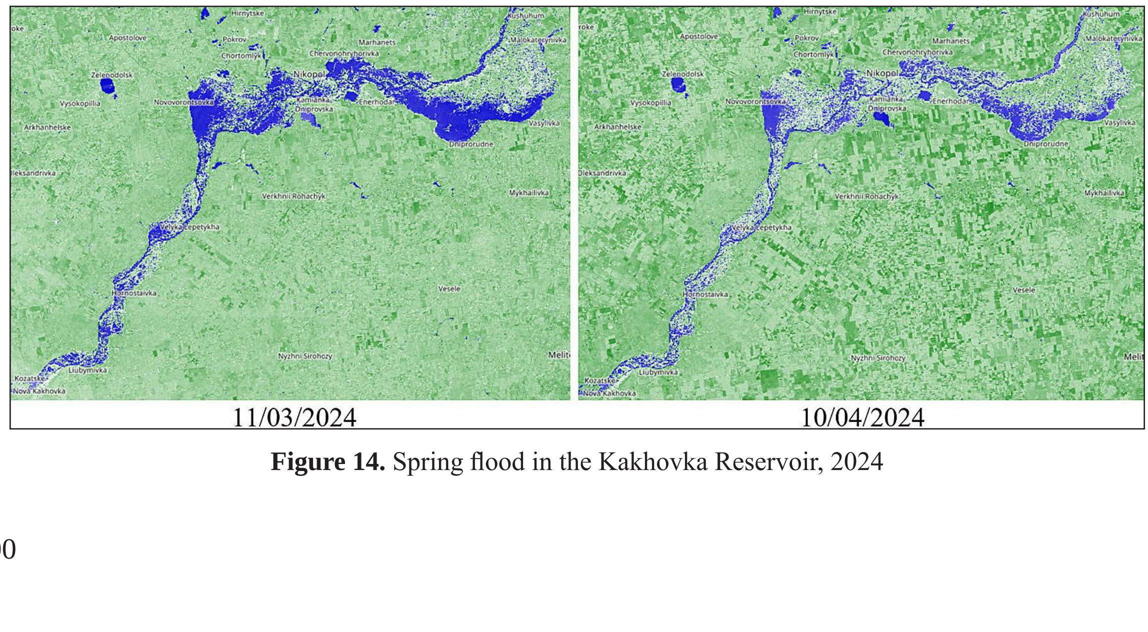

Figure 14. Spring flood in the Kakhovka Reservoir, 2024

more than 140 settlements with over 1 million people, in particular, Kryvyi Rih – the largest among them (with population over 600 thousand people), Nikopol (more thane 100 thousand people), Marhanets (about 40 thousand people), Dniprorudne (about 18 thousand people), Enerhodar (about 50 thousand people) and others. The reservoir was the main source of irrigated agriculture covering irrigated lands of about 800 thousand hectares. The major pathways of the irrigation system were: the Kakhovka Canal, the North Crimean Canal and the Dnipro-Kryvyi Rih Canal. The volume of surface water use was 1.21–1.34 km^3, including for drinking and sanitary-hygienic needs – 4.89–7.98%, for industrial needs – 71.15–73.56%, for irrigation – 18.04–23.60%, and for other needs – 0.36–0.42%. The water area of the reservoir was an artery of navigation and the basis for the functioning of the port Nikopol, an important center of recreation and fishing and the existence of hydrological resources. In Ukraine, 22% of the needs of the fish market were satisfied by catching freshwater fish in the water area of the reservoir.

The conducted research proves that the destruction of the Kakhovka HPS dam by the Russian aggressor caused a large-scale man-made disaster in the Steppe zone of Ukraine and marked the beginning of natural-climatic transformation of the drained water reservoir. It resulted in the impairment of microclimatic conditions, a rise in temperature pressure, a considerable increase in the area with temperature stress and an acceleration in seasonal evapotranspiration. The formed aboveground plant biomass of the bottom landscapes is not capable of creating appropriate microclimatic conditions on the level of the existence of the Kakhovka Reservoir water area. The identified trends do not allow complete natural regeneration of the Great Meadow (Fig. 15), exacerbate negative environmental and socioeconomic consequences in the area of the reservoir's impact.

In particular, the negative consequences include water scarcity, disruption of the water balance and the reduced energy of the hydrological functioning of the Lower Dnipro, destruction of the modern industrial system of productive forces which formed over 65 years, worse water supply for enterprises and population, a reduction in the number and deterioration of hydro-biological resources, termination of the hydro-technical irrigation network, violation of the hydrological regime of the territory and a reduction in the water table, drainage, desertification and the beginning of sodification and salinization of irrigated lands, destruction of agricultural production and farming activity, an increase in the frequency of dust storms, smaller areas with fertile soils and deterioration of the condition of natural ecosystems, a rise in the volume of dust pollution, worse health and quality of life. Water scarcity is a serious problem affecting more and more people

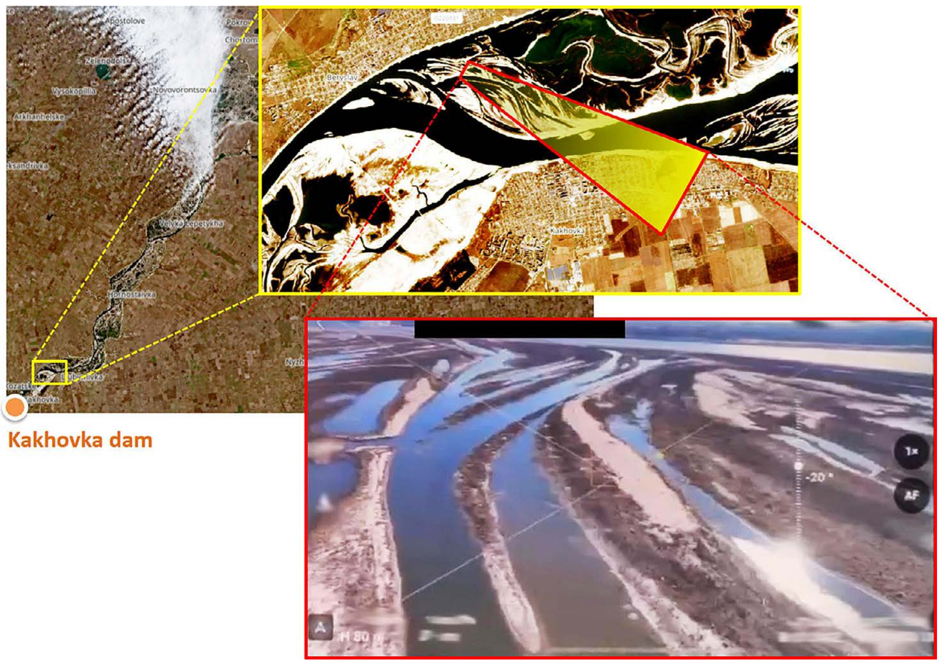

Figure 15. Bare bottom sandy landscape and hydrological network on the territory of the Kakhovka Reservoir, as of 22/03/2024, photo taken at a height of 80 meters

around the world. In the 2000s, severe water scarcity impacted two-thirds of the world population, equivalent to 4 billion people (Mekonnen and Hoekstra 2016). In the period from 1970 to 2010, water scarcity exacerbated, mainly in the lower part of the world's major river basins, that worsened the living conditions of over 60% of the world population (Huang et al., 2021). It was established that in the period from 2012 to 2016, 19% of the world population and 35% of irrigated crop yields depended on 10% of the world's river basins with the most severe water scarcity (Tao et al., 2023). Important factors increasing water scarcity on a global scale include population growth, rising demand on food products, higher standards of living, industrial expansion, climate change, and the sea level rise in combination with inappropriate use of water resources, pollution of water sources, deterioration of the condition of the water supply system. In particular, exacerbation of the problems related to water scarcity is forecasted because of intensification of natural and anthropogenic factors (Rich et al., 2023).

Similar disastrous consequences of the disruption of the functioning of water bodies, decreased river flows and an increased climate impact in the territory of India in 2016 resulted in a large-scale drought sweeping about 10 states and affecting approximately 330 million people, causing economic losses of USD100 billion. For instance, the tendency towards a decrease in daily flows over 41 years (1971–2010) in the Sutlej river, which is important for India, had significant negative consequences for generation of electricity at hydroelectric power stations and agriculture (Goyal and Surampalli 2018). A rise in the air temperature and destruction of natural objects causes the heating of the environment leading to a reduction in productive precipitation, increased evaporation, thereby exacerbating a shortage of surface and ground waters (Kanwar and Singh). The Kakhovka Reservoir was the main freshwater source used for irrigation in the Steppe zone of Ukraine. Water resources in arid regions play an important role and form 70% and more of crop yields (Ingrao et al., 2023). Irrigation improves bioclimatic conditions of farmlands by 1.7 times that determines an increase in crop yields by 2.5 times ensuring the stable functioning of the agrarian sector in the zone of significant water scarcity (Pichura et al., 2021). It was found that availability of the irrigation infrastructure effectively mitigates both direct and indirect climate impacts, and negative spatial side effects of water scarcity at a distance of up to 300 km from the objects of the irrigation system (Marbler 2024).

Water scarcity in China caused impairment of the people's life security, ecosystem evolution and socioeconomic development, affected the quality of the national and regional development (Wei et al., 2023, Li et al., 2024). In particular, the Aral Sea's drying up has a similar negative impact on the population of Uzbekistan, which caused an increase in the frequency of dust storms which are determining factors in the spread of the population's respiratory diseases (Zhupankhan et al., 2021). Therefore, the dam destruction and the drainage of the Kakhovka Reservoir constitute the largest man-made disaster of the present. The condition of the ecosystem and the territory impacted by the reservoir requires comprehensive systematic monitoring and exhaustive research, since it is the basis for establishing environmental and socioeconomic consequences of the disaster for Ukraine. This will ensure the development of objective scenarios of the post-war restoration and stabilization of the functioning of the territorial landscape systems damaged by the war.

CONCLUSIONS

The state of the functioning of the Kakhovka reservoir after the dam destruction was thoroughly analyzed. The water reservoir was of socioeconomic importance for the regions of the Steppe zone of Ukraine, in particular, it generated electricity, provided fresh water to more than 140 settlements with the population of over 1 million people, allowed irrigating more than 800 thousand hectares, was an artery of navigation and the functioning of Nikopol port, an important center of recreation and fishing, and the availability of hydro-resources.

The destruction of the Kakhovha HPS dam caused a large-scale man-made disaster, new negative environmental and socioeconomic consequences, the beginning of natural-climatic transformations of the drained water reservoir. There was disruption of microclimatic conditions, an increase in the temperature pressure in the drained water area and the adjacent territories by 2.0 °C and more, which resulted in a considerable increase in the area with temperature stress and an acceleration in seasonal evapotranspiration in 2023. The total volume of evapotranspiration in September in the period of the most favorable level of the formation of plant biomass and microclimatic conditions in the drained territory of the Kakhovka reservoir rose by 2.04 times, in the adjacent buffer zone of 10 km – by 1.41 times. Such manifestations of negative phenomena caused deterioration of the water balance and microclimatic conditions, exacerbation of water scarcity in 58.2% of the research territory with different levels of climate stress and the formation of a new mosaic heterogeneous structure of the bottom landscapes. In the territory of the drained water reservoir, the share of water bodies fell to 16%, more than half of them belong to the water areas with unstable moisture supply. There is about 39% of bare bottom landscapes and landscapes with significant sparseness of stunted vegetation, 13% of landscapes with low plant biomass, water scarcity and considerable temperature pressure, 20% of landscapes are characterized by a satisfactory level of moisture and vegetation, and 12% of the territory has good conditions of the natural-climatic functioning.

The obtained results confirm that the formed aboveground plant biomass of the bottom landscapes is not capable of creating microclimatic conditions which existed in the water area of the Kakhovka Reservoir. Therefore, dehydration of the water reservoir against the backdrop of climate change had a negative impact on microclimatic conditions of the functioning of landscape systems characterized by a rise in the air temperature and evaporation, potentially increasing the frequency of droughts, exacerbating water scarcity in the Steppe zone of Ukraine.

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