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Impact of war on natural and climatic transformation of territories in the irrigation zone of Ukraine

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Abstract
The area under irrigation in Ukraine as of 2020 amounted to 551.4 thousand hectares. After the full-scale russian military invasion, 18% of the irrigated area remained under the control of Ukraine. Using remote sensing methods to analyze data from Sentinel-2 and Sentinel-3 satellites allowed us to identify the consequences of the cessation of farming practices and the Kakhovka reservoir's drainage. It was found that the lack of irrigation caused the impairment of hydrological conditions on the left bank of Kherson region, which resulted in water scarcity and drainage of water bodies in these territories. The destruction of crop production and soil exposure led to an increase in soil surface heating by 1.45–1.72 times and accelerated evaporation of soil moisture in 80% of the territory. Droughts and active hostilities caused fires in the summer and autumn of 2024 on an area of more than 200 thousand hectares. Droughts and strong winds of 20–30 m/s led to the loss of topsoil (more than 600 t/ha), with storm epicenters covering 100–3000 hectares. It was proved that military operations, the cessation of farming practices, the Kakhovka reservoir's drainage, and the destruction of irrigation caused water stress, negative consequences of natural and climatic transformation, and desertification in the irrigation zone of Ukraine.

Highlights

- The impact of war on ecosystems in the irrigation zone.
- Using satellite imagery data to study the condition of territories in the former irrigation zone.
- The consequences of lack of irrigation for steppe soils have been investigated.
- The impact of climate change on ecosystems in the former irrigation zone.
- Substantiating three scenarios for the functioning of the Kakhovka reservoir in the post-war period.

Keywords Kherson region, Kakhovka reservoir, Soil management, Occupation, Climate, Water stress, Desertification, Ecocide

1 Introduction

Over the past century, the accelerated impact of anthropogenic factors has caused an increase in the frequency of abnormal climatic events, which has affected the functioning of ecosystems [1, 2]. A decrease in moisture content has become a sign of these impacts. Water scarcity is a serious problem since water is a crucial abiotic factor for the existence and survival of flora, fauna, and humans [3, 4]. About 19% of the world's population suffers from water shortages, and 35% of irrigated land requires additional water supply [5, 6]. Water shortages are the reason for ecosystem degradation and a decrease in crop yields, which has a negative impact on the rate of social and economic development of territories [7, 8]. Negative manifestations of desertification and the increasing frequency of dust storms cause wind erosion, soil coarsening, sandiness of soil texture, and its transfer outside the deflation patches, the loss of fertile soil layer, a reduction in soil productivity, and increased environmental degradation [9, 10]. In particular, dust emissions from soil into the atmosphere caused by wind erosion result in serious problems with human health [11].

Under conditions of a steady increase in air temperature, uneven seasonal distribution of precipitation, and a decrease in its amount [12], conserving and restoring natural ecosystems (wetlands, vegetation cover, and water resources), moistening and maintaining artificial ecosystems (agrocenoses, artificial forests and windbreaks, pastures, and water bodies), ensuring the necessary level of land use and the standard of living are relevant directions. Under such conditions, irrigation for land reclamation is of paramount importance [13, 14]. By 1990, Ukraine's area under hydraulic reclamation amounted to 2.29 million hectares [15]. Over the next 25 years, the area under irrigation decreased by 75%. Between 2014 and 2020, the irrigated area varied between 460.0 and 551.4 thousand hectares [14, 16]. Climate change necessitates an increase in the area of irrigated farmlands to 20 million hectares in Ukraine [17]. However, with water shortages constantly worsening, it is impossible to achieve this figure. Therefore, the primary task will be to restore irrigated areas to the level of 2021, and the desired task will be to reconstruct irrigation systems and revive irrigation to the level before 1990. In the zone of climate-driven risky farming, irrigation is a primary condition for growing vegetables and melons, and maintaining orchards, vineyards, and berry gardens. Irrigation in the Steppe zone contributed to more than a twofold increase in gross crop yields [18–20].

Since the 60s of the 20th century, the Kakhovka reservoir was the primary source of irrigation in Southern Ukraine. The water surface area of the Kakhovka reservoir amounted to 2155 km^2, its total volume was 18.2 km^3, and its usable volume was 6.8 km^3. The reservoir was constructed in 1955–1958 in the lower course of the Dnipro River to generate electricity, establish fisheries and recreation facilities, feed plants in water protection zones and natural protected areas, provide fresh water for enterprises, irrigation systems, and supply water to 6 million people [21, 22]. The construction of the reservoir was necessitated by droughts and the famines of the 1920s, 1930s, and 1946–1947 s [23]. The reservoir's water reserves were meant to irrigate over 1 million hectares [24]. Over 400 thousand hectares were in Kherson region, more than 350 thousand hectares were in Crimea, 200 thousand hectares were in Zaporizhzhia region, and over 100 thousand hectares were in Mykolaiv and Dnipro regions. Until 1990, water intake from the Kakhovka Reservoir amounted to more than 12 billion m^3 per year. Between 1990 and 2021, the area irrigated by water from the Kakhovka reservoir decreased to

450 thousand hectares. The main reason for this was the lack of adequate funding and technical deterioration of the water management complex. The reservoir supplied water to the remote cities of Melitopol, Berdiansk, and adjacent settlements of Zaporizhzhia region. Moreover, the reservoir served as the only source of water supply for the cooling pond of the Zaporizhzhia nuclear power plant [25].

The introduction of irrigation changed the conditions for the functioning of the natural environment. After the Republic of Crimea was occupied by russian troops, between 2014 and 2021, the total volume of water intake from the Kakhovka reservoir amounted to 1.21–1.34 billion m^3 per year [26]. In particular, water intake for agricultural activities through irrigation canals amounted to 800–950 million m^3. 65–70% of this volume was used for auxiliary activities in crop production, and 30–35% was used immediately for growing crops [14, 16, 17]. The moisture supply resulted in a change in soil formation and hydrological processes in irrigated, adjacent, and remote territories, a reduction in temperature pressure, and an increase in moisture content in the territory. Irrigation contributed to a 1.7-fold increase in the bioclimatic potential of agricultural lands, which determined a 2.5-fold rise in crop yields [3, 20]. These findings proved the stable functioning of the agricultural sector in the area of significant water scarcity.

Russia's full-scale invasion of Ukraine on February 24, 2022, caused the impairment of the irrigated zone. According to the State Ecological Inspectorate of Ukraine (https://www.dei.gov.ua/), environmental losses exceed USD 72.9 billion, including land pollution and soil contamination, the damage to the nature reserve fund and protected ecosystems, air pollution, water pollution, and the impact of war on climate change. The most affected types of infrastructure during the first three months of the armed conflict included dams and water reservoirs, underground mines, municipal water supply, and sewage treatment systems [27]. Within the combat zone, the content of oil products and heavy metals in the soil exceeds the norms by 15–30 times [21, 22], which makes it impossible to use these lands for growing agricultural products since they are considered potentially unsafe for consumption. According to the Association of Deminers (https://www.uda.org.ua/en/), about 4.8 million hectares of agricultural land in Ukraine are mined, and 13.6 million hectares need to be surveyed for mines. About 26% of Ukraine's territory remains occupied. The area of irrigated lands, which are under the control of Ukraine, is 100 thousand hectares, which is 18% of the area identified in 2021.

On June 6, 2023, Russian troops destroyed the Kakhovka dam, which caused the reservoir's drainage—the destruction of the primary source of irrigation in Southern Ukraine [28–30]. The large-scale anthropogenic disaster caused the intensification of negative environmental and socioeconomic consequences, the beginning of natural and climatic transformations of the drained reservoir. The disaster resulted in a sharp drop in water levels, an abnormal increase in the speed and turbulence of the current, disruption of bottom sediments, flooding and inundation of the shoreline territories, settlements, bank abrasion, diffuse pollution of waterbodies and watercourses, disruption of the functioning of the delta-lake system of the Lower Dnipro, pollution of the Dnipro-Buh Estuary and the Black Sea, the loss of human lives, aquatic and plankton animals, and terrestrial flora and fauna. The flood affected 110 thousand people, killing 84 people [31]. Shellfish weighing up to 500 thousand tons died [32]. During the first three days of the disaster, more than 70 fish species, including 18 Red Data Book species, died in the lower reaches and the delta-lake system of the Dnipro River. In particular, from the

Kakhovka reservoir [33], 42 fish species with a total weight of over 11,000 tons disappeared, causing losses of commercial catches of about 2 585 tons per year estimated at USD 5.4 million. According to additional calculations [34], these losses are much higher. In particular, 85 fish farms were destroyed, and the losses of fishing infrastructure are estimated at USD 270 million [33]. 150 official cases of dolphin deaths in the Black Sea have been recorded. The water hammer and rapid rise in the water level in the Lower Dnipro caused the death of most terrestrial invertebrates and vertebrates. In particular, 70% of the habitat of the Nordmann's mouse and up to 50% of the habitat of the thick-tailed three-toed jerboa were flooded [35]. The populations of the copperhead, venomous snake, yellow-red snake, Sarmatian snake, and other Red Data Book species were affected. The flooded territories were home to about 20 thousand wild animals. As a result of flooding and waterlogging, more than 50 objects of the nature reserve fund suffered, and 80 thousand hectares of the reserves lost their original state [36]. According to the Ministry of Internal Affairs of Ukraine (https://mvs.gov.ua/), 180 settlements were included in the emergency zone. According to Kherson Regional Military Administration (https://khoda.gov.ua/), 118 historical monuments of Ukrainian culture were flooded.

The Kakhovka reservoir's drainage has led to the exposure of bottom sediments containing a total of 83.3 thousand tons of toxic heavy metals (Pb, Cd, Ni) [32]. A decrease in the water level by 4.0 m and more in the area of the lower reaches downstream of the Dnipro HPP dam caused dehydration and drainage of unique floodplains of Lake Khortytsia, leading to the destruction of the habitat of steppe flora and fauna species and the biodiversity loss in lake and floodplain systems [37, 38].

The destruction of the reservoir resulted in the drainage of water bodies, evaporation, and a reduction in the groundwater level, the transfer of salts to the topsoil, an increase in their concentration, and a rise in the area with secondary salinity and salinization [34]. The danger level in these territories is exacerbated by the occupation of the left bank of the Lower Dnipro, where 82% of Ukraine's irrigated land is concentrated. These territories include the Autonomous Republic of Crimea and parts of Kherson and Zaporizhzhia regions. According to the Ministry of Agrarian Policy of Ukraine (http://www.minagro.kiev.ua/), the occupation and the loss of the irrigation source cause land users' annual economic losses equivalent to 4.0 million tons of grain crops (USD 1.5 billion).

To estimate environmental and economic losses caused by the war, it is necessary to research the impact and consequences of military operations and occupation on an ongoing basis. Moreover, the research should examine the territories' suitability for human habitation, economic activity, and the possibility of developing these territories. The research should be based on monitoring the ecological condition and resource potential of the temporarily occupied territories of Ukraine. In particular, the findings of this research are the information basis for substantiating the post-war recovery and functioning of the territories affected by the war.

The research object is the natural and climatic transformation of the irrigation zone in Ukraine under the influence of war, exemplified by the occupied territory on the left bank of Kherson region.

2 Materials and methods

2.1 Characteristics of the research territory

The research was conducted using the data on Kherson region in Ukraine (Fig. 1). The region is located in the southern part of Ukraine on the Black Sea Lowland. Kherson region borders on Mykolaiv region to the northwest, on Dnipropetrovsk region—to the north, on Zaporizhzhia region—to the east, on the Autonomous Republic of Crimea—to the south along the Syvash and the Perekop Isthmus. The region comprises 49 territorial communities (9 urban, 17 semi-urban, and 23 rural) and 5 districts (Beryslav, Henichesk, Kakhovka, Skadovsk, and Kherson). The region includes 656 settlements. As of January 1, 2021, the population amounted to 1016.7 thousand people, including the urban population of 624.7 thousand people and the rural population of 392.0 thousand people. According to the Kherson Region Military Administration (https://khoda.gov.ua/), as of March 2024, about 156 thousand people remained in the region, including the urban population of 68.0 thousand people, which is 6.5 times less than the pre-war population.

The region's total area is 2846.1 thousand hectares, including farmlands—1971.0 thousand hectares (69.25% of the region's territory), of which arable land is 1777.6 thousand hectares (90.2% of the farmlands). The main soil types in the region are southern black soils, occupying 43.7% of the total area of farmlands, and dark chestnut soils—30.7% [39]. 20% of Ukraine's irrigation systems were designed in the region, their area being 426.4 thousand hectares (21.65% of the area of farmlands in the region). Irrigation was used in 2003–2021 at 250–315 thousand hectares [14]. Three main irrigation systems are located on the left bank of Kherson region: Kakhovka irrigation system—243.1 thousand hectares, Kalanchak and Krasnoznamenka irrigation systems—102 thousand hectares. The Kakhovka reservoir was a source of water intake for these systems. On the right bank of Kherson region, there is a part of the Inhulets irrigation system, which occupies an area of 18.2 thousand hectares and is fed by the Inhulets River (the right tributary of

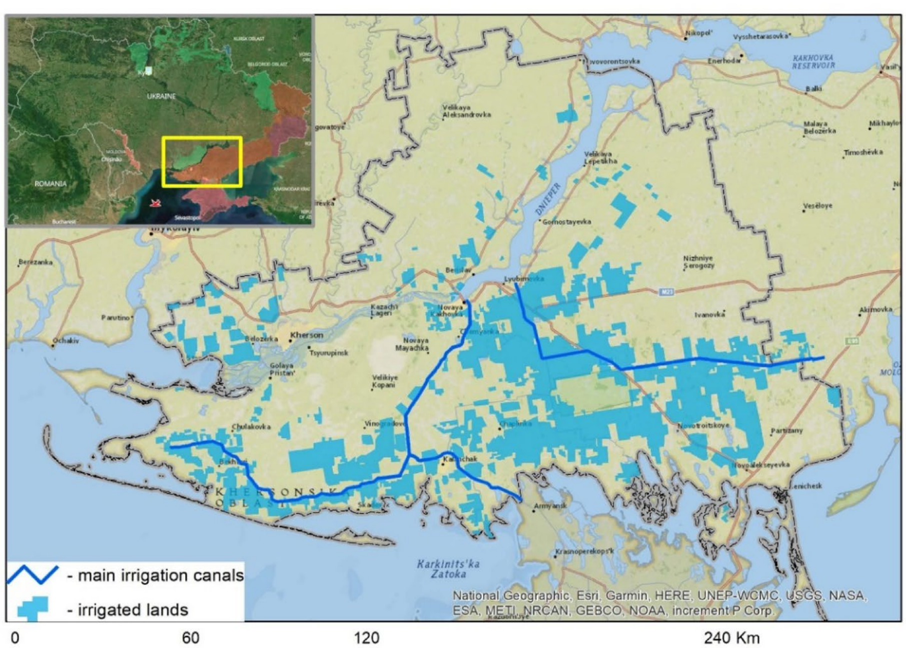

Fig. 1 Research territory—Kherson region, Ukraine (on the map, in the upper left corner, Ukraine's territories occupied by Russia are highlighted in red, the location of Kherson region is highlighted in yellow)

the Dnipro River). Local irrigation systems, with an area of 22.4 thousand hectares and an area of irrigation of 40.7 thousand hectares, were also used in the region. It is noteworthy that rice irrigation systems with an area of 8.1 thousand hectares were located on the left bank of the region [14].

2.2 Hydro-economic value of the Kakhovka reservoir for the agrarian sector

According to the State Agency of Water Resources of Ukraine (https://www.davr.gov.ua/), in 2020, the area under irrigation in Ukraine amounted to 551.4 thousand hectares. 950.34 million m^3 of water was used by agriculture and related services. The largest amount of water was used in auxiliary crop production activities—667.81 million m^3 and for growing cereals (except rice), legumes, and oilseeds—242.93 million m^3. 22.44 million m^3 was used for growing vegetables, melons, and tubers, 8.26 million m^3 was used for growing pome and stone fruits, and 4.34 million m^3 was used in animal husbandry. Water is used in the auxiliary activities of crop production for water-charging irrigation to accumulate moisture reserves in the soil for crops' uptake during the growing season, for crop treatment, crop spraying, and pest control, to operate irrigation equipment, for possible crop reseeding with additional water-charging, rice irrigation and other water use to maintain farmlands in good agricultural and environmental condition. The cost of water in the pre-war period averaged 1.2 UAH/m^3, in particular, in Odesa region—1.8 UAH/m^3, Zaporizhzhia region—1.05 UAH/m^3, and Kherson region—0.94 UAH/m^3. The price fluctuations were determined by the amount of electricity used to transport water from the irrigation source to the water user.

According to the State Statistics Service of Ukraine (https://www.ukrstat.gov.ua/), the area of irrigated lands used to obtain crop yields between 2014 and 2020 tended to expand. In particular, the largest increase was recorded in the area under cereals and legumes, from 102.4 thousand hectares to 188.5 thousand hectares (an increase of 84%). In the structure of crops, the area under wheat was 40%, under corn for grain—31.4%, barley—18.7%, rice—6.0%, millet—2.1%, legumes (mainly peas)—1.5%, and buckwheat—0.3%. The irrigated area under oilseeds amounted to 188.7 thousand hectares in 2020, including soybeans—46.3%, sunflower—38.5%, rapeseed—14.8%, and mustards—0.4%.

The area under vegetables amounted to 22.7 thousand hectares, fruit and berries—10.6 thousand hectares, grapes—3.9 thousand hectares, potatoes—4.5 thousand hectares, and fodder corn—4.4 thousand hectares. The production volume on irrigated lands was as follows: cereals and legumes (except rice)—1055 thousand tons, rice—60.7 thousand tons, oilseeds—531 thousand tons, vegetables—1210 thousand tons, fruit and berries—144 thousand tons, grapes—16.4 thousand tons, potatoes—122.5 thousand tons, and fodder corn—142.4 thousand tons. 76.7% of all Ukraine's irrigated lands were irrigated with water from the Kakhovka reservoir in 2020. The distribution of these lands by crops was as follows: cereals and legumes (except rice)—56.0%, oilseeds—89.8%, vegetables—53.0%, fruit and berries—39.6%, grapes—57.5%, potatoes—55.6%, and fodder corn—72.7%.

The Kakhovka reservoir was an important water supply center for municipal and economic activities in Kherson region. According to the classification of climatic conditions, Kherson region is considered a zone of water scarcity and risky farming. Over the past 20 years, a rise in the average annual air temperature by 2.6 °C (from 9.6 to 12.2 °C), along with uneven seasonal distribution of precipitation, caused a threefold increase in the frequency of adverse climatic events [3, 26]. The average annual precipitation varies between 300 mm and 500 mm. Every second year is characterized by insufficient precipitation (less than 400 mm). The value of evapotranspiration is 2 times higher than the level of precipitation, which determines the low natural bio-productivity of plants growing in non-irrigated areas.

Irrigation provided additional energy for soil formation, determined a high level of plant growth, and contributed to stable crop yields. During the main growing season (from April to October), the amount of precipitation in Kherson region mainly varied between 155 and 330 mm. Precipitation and irrigation provided total water supply for agrocenoses at a level of 345–410 mm, which contributed to an increase in soil formation energy by 335 MJ/m^2 and improved soil bio-productivity. During the growing season of agrocenoses, the total amount of soil formation energy on non-irrigated lands ranged from 265 to 765 MJ/m^2; this amount was 790–910 MJ/m^2 on irrigated lands [20]. On non-irrigated lands, the average yield of winter wheat in Kherson region was 2.4 t/ha, the minimum yield being 0.7–1.8 t/ha and the maximum yield being 2.6–2.7 t/ha. Wheat yields on irrigated lands amounted to 3.8–5.4 t/ha. As of 2021, the reservoir's water was used to irrigate an area of 315 thousand hectares of farmlands in Kherson region, which was 57% of all irrigated lands in Ukraine [14, 20].

It is noteworthy that the Dnipro's irrigation water, which was supplied from the Kakhovka reservoir, was characterized by a low level of mineralization—0.3–0.6 g/dm^3 [40]. In terms of salt composition, the Dnipro's water belongs to the class and category "excellent", and in terms of the level of purity (pollution)—"very clean" [41]. Irrigation with such water contributed to the leaching (washing out and desalinization) of saline soils, which is a factor in increasing soil fertility. It is notable that irrigation of saline areas with such water contributed to the desalinization of mineralized groundwater. The area of saline soils amounted to 20% of farmlands in the region, including 9.6% of slightly saline soils, 7.0% of moderately saline soils, and 3.4% of highly saline soils [14]. These lands were mainly located in the south of Kherson region in the Black and Azov Seas coastal basin.

Soils in Kherson region are subject to a constant deflationary impact. Irrigating soils and forming good agrocenoses cover contribute to reducing the risk of wind erosion. The hydrological and hydraulic discharge of the Kakhovka reservoir's water to the left bank of the Lower Dnipro provided water for 2.5 million hectares of irrigated, adjacent, and remote lands. This improved the microclimatic conditions in Kherson and Zaporizhzhia regions and the Autonomous Republic of Crimea. Additional water supply from the reservoir to wild and cultivated plants in the irrigated area improved their growth, which was manifested in the increased leaf biomass and chlorophyll synthesis and the sequestration (removal from the atmosphere) of 230 million tons of carbon dioxide by plants [26, 42].

2.3 Research scheme and materials

The research scheme included four logical sequential stages:

Research stages	
1.	To establish the spatial hydrological and hydraulic distribution of moisture on the left bank of Kherson region: hydrological distribution of moisture—redistribution of rainwater and irrigation water through thalwegs (watercourses), accumulation and redistribution of moisture in groundwater; hydraulic distribution of moisture—redistribution of irrigation water through a hydraulic network of irrigation channels from the source of water intake to irrigated areas (including irrigated channels and irrigated lands)
2.	To investigate the spatio-temporal transformation of territorial ecosystems in the irrigation zone by the state of vegetation cover in the pre-war period (irrigation)—July 2021 and in the war period (partial irrigation)—July 2022, without irrigation—July 2023–2024. Changes in the plant growth were identified using the Sentinel 2 L2A data based on the indices of decoded satellite images, namely: Bare soil index (BSI), Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI), Detection of Evapotranspiration Levels Composite (DELC), Normalized Difference Moisture Index for Crop Moisture Stress ($NDMI_{STRESS}$)
3.	To determine the spatio-temporal patterns of a change in the Land Surface Temperature (LST) values in the irrigation zone in July 2021–2024 using the Sentinel-3 SLSTR L1B data
4.	To examine the state of water bodies in 2024 using the Sentinel 2 L2A data
5.	To determine the patterns of soil salinization and salinity in the former irrigation zones using the Sentinel 2 L2A data
6.	To identify the level of fire danger in the absence of moisture and hostilities using the Sentinel 2 L2A data
7.	To investigate the manifestations of wind erosion in the former irrigation zone using the Sentinel 2 L2A data
8.	To identify the impact of hostilities and lack of moisture from irrigation on the state of steppe biotopes of the nature reserve fund using the Sentinel 2 L2A data based on the Normalized Difference Moisture Index (NDMI)
9.	To visualize the natural and climatic transformation of the irrigated zone as a result of hostilities and the blockade by the Russian aggressor, a comparison of the satellite images of Sentinel 2 L2A was made for July 2021 and 2024 based on the scenarios of the True color optimized and Normalized Difference Moisture Index (NDMI)

The mapping of the spatial hydrological and hydraulic distribution of moisture on the left bank of Kherson region in the pre-war period of irrigation systems' functioning was done. The hydrological mapping of moisture distribution involved constructing groundwater levels at a depth of up to 5 m and identifying a natural network of thalwegs (watercourses) based on a digital elevation model. The map of a groundwater level was made using data from the Kakhovka hydrogeological-reclamation expedition. To construct a spatial network of thalwegs (watercourses), we applied the SRTM-30 digital elevation model with a pixel resolution of 30 × 30 m. A thalweg is an erosion line of water distribution that connects the lowest areas of a channel bed, valley, gully, ravine, and other elongated landforms. The spatial distribution of the thalweg network was mapped using Hydrology tools of Spatial Analyst Tools of ArcGis 10.6 [43, 44]. The construction of a network of thalwegs (watercourses) includes six successive steps of modeling:

Step 1	Visualizing a digital elevation model (DEM) based on SRTM-30 with a pixel resolution of 30 × 30 m
Step 2	*Filling in incorrect voids* using the Fill function. This function corrects the *DEM* to create a correct cumulative flow grid.
Step 3	*Creating a grid of the flow direction* using the Flow Direction function, which allows for identifying the flow direction based on the structure of relationships between 8 neighboring rhumb lines, which are determined by the morphometric characteristics of the landscape (slope and exposure). In other words, the direction of the maximum slope from the center cell to the centers of 8 neighboring cells is determined.
Step 4	*Creating a cumulative flow grid* using the Flow Accumulation function, which is based on the flow direction grid
Step 5	*Identifying watercourse cells with cumulative flow values higher than the specified value.* At this stage, the procedure of selecting the cumulative flow limit value is performed using the Con tool, which is part of the Conditional toolkit. The Con tool is an important part of the ArcGrid command, which is necessary to determine the correctness of the input data cell values and to control the output data comprehensively.

Step 6	*Determining thalweg (watercourse) links* using the Stream Link function. Thalweg (watercourse) links are separate spatial linear segments of continuous streams that are interconnected by a sequence of outlet nods (points) (the first order thalweg outlet or higher order outlet) with final watershed nodes (points) (mouths of differently ordered thalwegs (watercourses))

The hydraulic mapping of moisture distribution involved making maps of irrigation water distribution through a hydraulic network and actual irrigated lands before the war. The map was created using data from the Kakhovka hydrogeological-reclamation expedition.

The satellite images of Sentinel 2 L2A with a resolution of 10 × 10 m/pixel are the source of up-to-date data on the research into the natural and climatic transformation of Ukraine's hard-to-reach and occupied territories in the irrigation zone. The images were used for decoding and calculating vegetation and moisture indices in July 2021–2024 to identify the state of water resources, fires, and erosion processes. Cloudless periods were investigated.

Rasters for distributing the Land Surface Temperature (LST) [45] values were obtained from open sources of Copernicus Browser using the data of the Sea and Land Surface Temperature Instrument—SLSTR and Sentinel-3 SLSTR L1B, which has two channels (F1 i F2), designed to measure the LST. Channel F2, with a central wavelength of 10,854 nm, measures temperatures in the thermal infrared range with a resolution of 270 × 270 m/pixel. Ratsers were used to determine the spatio-temporal patterns of changes in the surface heating in the irrigation zone located in the occupied territory.

2.4 Methods for decoding satellite images

Bare soil index (BSI) was used to identify soil without vegetation in the corresponding bands of Sentinel 2 L2A [46]:

$$\mathrm{BSI} = 2.5\frac{(\mathrm{B11} + \mathrm{B04}) - (\mathrm{B08} + \mathrm{B02})}{(\mathrm{B11} + \mathrm{B04}) + (\mathrm{B08} + \mathrm{B02})} \tag{1}$$

where B02—blue, B04—red, B08—NIR near infrared, B11—SWIR short-wave infrared are the corresponding bands of Sentinel-2 L2A.

The index is multiplied by 2.5 to increase the image brightness. BSI is used to monitor the state of vegetation cover, crops, forests, and droughts and detect landslides or erosion in areas without plants.

The Leaf Area Index (LAI) was used to determine the density of vegetation cover in the corresponding Sentinel 2 L2A bands [47]:

$$\mathrm{LAI} = (3.618\mathrm{EVI} - 0.118) \;\rightarrow\; \mathrm{EVI} = 2.5\frac{B08 - B04}{B08 + 6B04 - 7.5B02 + 1} \tag{2}$$

where EVI—Enhanced Vegetation Index; B02—blue, B04—red, B08—NIR near infrared are the corresponding bands of Sentinel-2 L2A.

The LAI is a dimensionless index, which measures the one-side area of green leaves per unit of land (m^2/m^2). It is visualized from 0 to 3, with higher values indicating higher density and increased leaf mass. The LAI is used to predict future yields by analyzing crop growth and assessing leaf density, vegetation cover, transpiration, and photosynthesis.

The Normalized Difference Vegetation Index (NDVI) was used to assess vegetation cover and plant health in the corresponding Sentinel 2 L2A bands [48]:

$$\mathrm{NDVI} = \frac{\mathrm{B08} - \mathrm{B04}}{\mathrm{B08} + \mathrm{B04}} \quad (3)$$

where B04—red, B08—NIR near infrared are the corresponding bands of Sentinel-2 L2A.

The range of NDVI values is from − 1 to 1. According to the typical NDVI classification, negative values indicate clouds, water, and snow, whereas values from 0 to 0.4 mainly indicate stones and bare soils. The NDVI values higher than 0.4 testify to the presence of plants.

The Detection of Evapotranspiration Levels Composite (DELC) was used to identify areas with different levels of evapotranspiration in the corresponding Sentinel 2 L2A bands [49]. The calculation algorithm was developed by Ramon Suarez (License: Cc by Zero 1.0) for the Copernicus Browser of Sentinel 2 L2A images:

$$\begin{aligned}
&function\ setup()\ \{\\
&\quad return\ \{\\
&\quad\quad input:\ [B11,\ B09,\ B02,\ dataMask],\\
&\quad\quad output:\ \{\ bands\ :\ 4\ \}\\
&\quad \};\\
&\}function\ evaluatePixel\,(sample)\\
&\{\\
&return\ [2.5\ *\ sample.B11, 2.5\ *\ sample.B09, 2.5\ *\ sample.B02,\ sample.dataMask\,];\\
&\}
\end{aligned} \quad (4)$$

The DELC images show different variations of evaporation, ranging from a low level to a very high level. It is noteworthy that the presence of water is characterized by hues from black to dark blue. Buildings are characterized by very light gray to dark gray hues. To analyze evaporation, six levels were determined: (1) dark green areas with very low evaporation, (2) light green areas with low evaporation, (3) bright light green areas with moderate evaporation; (4) red and brown areas with high evaporation, (5) dark yellow areas with very high evaporation, (6) light yellow areas with critical evaporation.

The Normalized Difference Moisture Index for Crop Moisture Stress ($NDMI_{STRESS}$*)* was used to determine the level of moisture stress and identify irrigated areas in the corresponding Sentinel 2 L2A bands. The calculation algorithm was developed by Monja Šebela (https://www.indexdatabase.de/db/si-single.php?sensor_id=96&rsindex_id=56) for the Copernicus Browser of the Sentinel 2 L2A images:

$$
\begin{aligned}
&var\ index\ =\ (B08\ -\ B11)\,/\,(B08\ +\ B11)\,;\\
&if\ \ (index\ <=\ 0)\,\{\\
&\ \ return\ [1,\ 1,\ 1]\,;\\
&\}\\
&if\ \ (index\ <=\ 0.2)\,\{\\
&\ \ \ return\ [0,\ 0.8,\ 0.9]\,;\\
&\}\\
&if\ \ (index\ <=\ 0.4)\,\{\\
&\ \ \ return\ [0,\ 0.5,\ 0.9]\,;\\
&\}\\
&else\{\\
&\ \ return\ [0,\ 0,\ 0.7]\,;\\
&\}
\end{aligned}
\tag{5}
$$

The $NDMI_{STRESS}$ images with a deep dark blue color indicate areas with high moisture content and very good growing conditions for plants. They are mostly irrigated areas. A deep turquoise color indicates areas with good moisture content and plant growth, and a light turquoise color indicates areas with satisfactory moisture content and plant growth. A white color is characteristic of areas with low and critical moisture content and the absence of plants or the presence of deadwood.

The Normalized Difference Moisture Index (NDMI) was used to determine moisture content in plants in the corresponding Sentinel 2 L2A bands [50]

$$
\mathrm{NDMI} = \frac{\mathrm{B08A} - \mathrm{B11}}{\mathrm{B08A} + \mathrm{B11}} \tag{6}
$$

where B08A—VNIR near infrared, B11—SWIR short-wave infrared are the corresponding bands of Sentinel-2 L2A.

The range of NDMI values is from − 1 to 1. Negative NDMI values (close to − 1) indicate infertile soil without vegetation. Values near zero (from − 0.032 to 0.032) correspond to water stress. NDMI values from 0.032 to 0.24 indicate satisfactory moisture content in vegetation cover; values from 0.24 to 0.80 correspond to good moisture content; values above 0.80 testify to high moisture content.

The Terrestrial Chlorophyll Index (OTCI) was used to calculate chlorophyll content in the leaves of plant cover in the reservoir's bed. The following formula was used [51]:

$$
OTCI = \frac{(B12 - B11)}{(B11 - B10)} \tag{7}
$$

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

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

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

3 Results

3.1 Features of natural-artificial moisture redistribution

The territory of Kherson region belongs to the climatic zone of extreme water scarcity and risky farming, hence irrigated agriculture contributed to the development of the left bank territory of Kherson region and settlements. Thus, irrigation should be considered a determining factor in the region's development and the main condition for growing vegetables and melons, as well as for horticulture and berry growing. About 30% of the rural population of Kherson region was employed in agriculture. Due to irrigation, the yields of cereals and oilseeds increased by 2.0–2.5 times, which led to a rise in crop production. In particular, the good moisture content of the territories on the left bank of Kherson region was determined by the redistribution of precipitation by thalwegs and the functioning of the hydraulic and drainage network of irrigation water (Fig. 2).

The profile-horizontal redistribution of water occurred in the direction from the northern to the southern part of the region, which ensured the maintenance of water content in waterbodies and watercourses, an appropriate level of water balance and biological activity of soils, and additional water supply for groundwater from freshwater sources which saturated the wells designed to meet the population's drinking and household needs.

The occupation of 26% of Ukraine's territory and the destruction of the Kakhovka HPS dam in 2023 caused the loss of the primary source of water supply and irrigation, which led to the decline of agricultural production and resulted in a social and economic crisis and ecosystem degradation. Under these circumstances, it is necessary to study the current living conditions of the population in these territories. Plans for the post-war reconstruction are postponed due to the occupation, active hostilities, and large areas

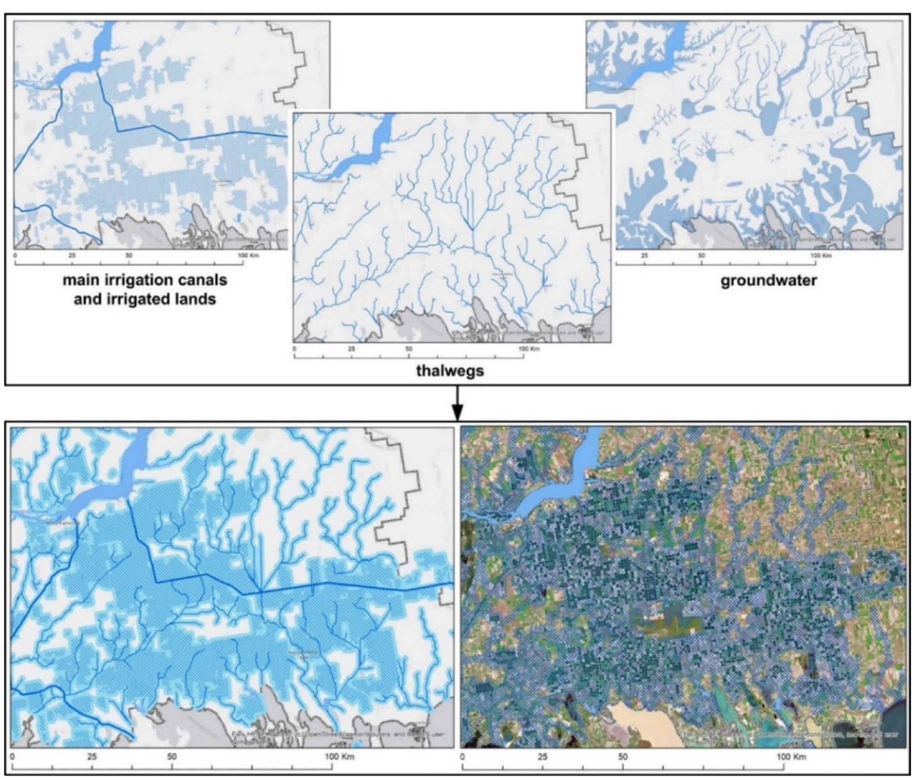

Fig. 2 Hydrological and hydraulic distribution of moisture on the left bank of Kherson region

of mined territories. The deepening social crisis in the occupied territories causes the population's impoverishment, high mortality rates, and degradation of the age structure. As of January 2025, 72.11% of Kherson region, with about 93% of the region's irrigated lands, 425 settlements (65% of their number), and 13 districts (68% of the region's districts) were occupied. Currently, the following districts of the region are occupied: Verkhnii Rohachyk, Velyka Lepetykha, Nyzhni Sirohozy, Hornostaivka, Kakhovka, Ivanivka, Oleshky, Hola Prystan, Skadovsk, Kalanchak, Chaplynka, Novotroitsk, and Henichesk.

3.2 Patterns of change in vegetation cover and moisture content

The invaders' destructive actions in the occupied territories are confirmed by the analysis of the satellite imagery data. Spatio-temporal changes in the vegetation cover in the irrigation zone were examined in the occupied territories on the left bank of Kherson (Fig. 3). The research was conducted using the analysis of indices of changes in plant growth in July 2021–2024.

Based on the result analysis, it was found that, over the research period, July was characterized by the highest surface air temperatures and water stress. In this month, after harvesting winter crops, important phenological stages of the development and flowering of late spring crops under irrigation (sunflower, corn, and soybean) occur. The active growth of late spring crops in July allowed us to identify differences in the spatial distribution and use of irrigated, adjacent, and non-irrigated lands in the conditions of the left bank of Kherson region, in particular:

- **July 2021** (before Russia's full-scale invasion) was characterized by active agricultural production, irrigation, and social and economic activities of the communities in the research territory;
- **July 2022** (Russia's full-scale invasion and the beginning of the occupation) was characterized by a decline in agricultural production, a social and economic crisis, and the devastation of territories and settlements;
- **July 2023** (occupation of the territory)—the destruction of the Kakhovka HPP dam, the reservoir's drainage, ecocide, the destruction of the primary irrigation source, the drainage of the main irrigation canals, water stress, the destruction of agricultural production, and the deepening social and economic crisis;

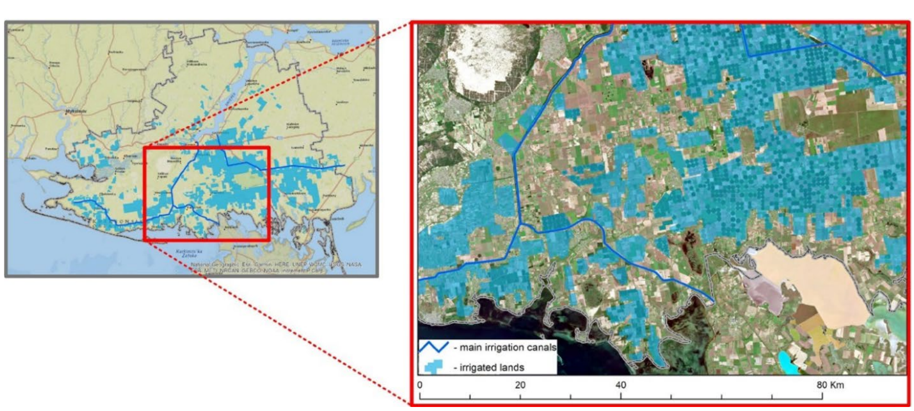

Fig. 3 Research territory on the occupied left bank of Kherson region

- **July 2024** (occupation of the territory)—the lack of irrigation, the destruction of crop production, a five-fold increase in the frequency of abnormally high temperatures, the lack of moisture, the signs of a semi-desert, the drainage of waterbodies, the shallowing of watercourses, stubble burning and the fires of steppe biotopes, a social and economic crisis, the population's impoverishment, high mortality rates, and the degradation of the age structure.

Based on the decoded Sentinel 2 images (Fig. 4) and using BSI i LAI, we determined a ratio of the areas with vegetation and the areas without vegetation and active growth of agrocenoses.

A bright green color on the BSI images indicates the good growth of agrocenoses, which is determined by a high moisture supply to plants, which is typical for irrigated areas. The darker hues of a green color indicate woody plants, grass steppe biotopes, weeds, and agrocenoses on non-irrigated lands. A red color indicates areas without vegetation. The BSI images show the depletion of vegetation cover, which has been observed since the beginning of Kherson region's occupation. There was a 60% decrease in the crop area in July 2022. As of July 2023, the crop areas decreased by 80% compared to July

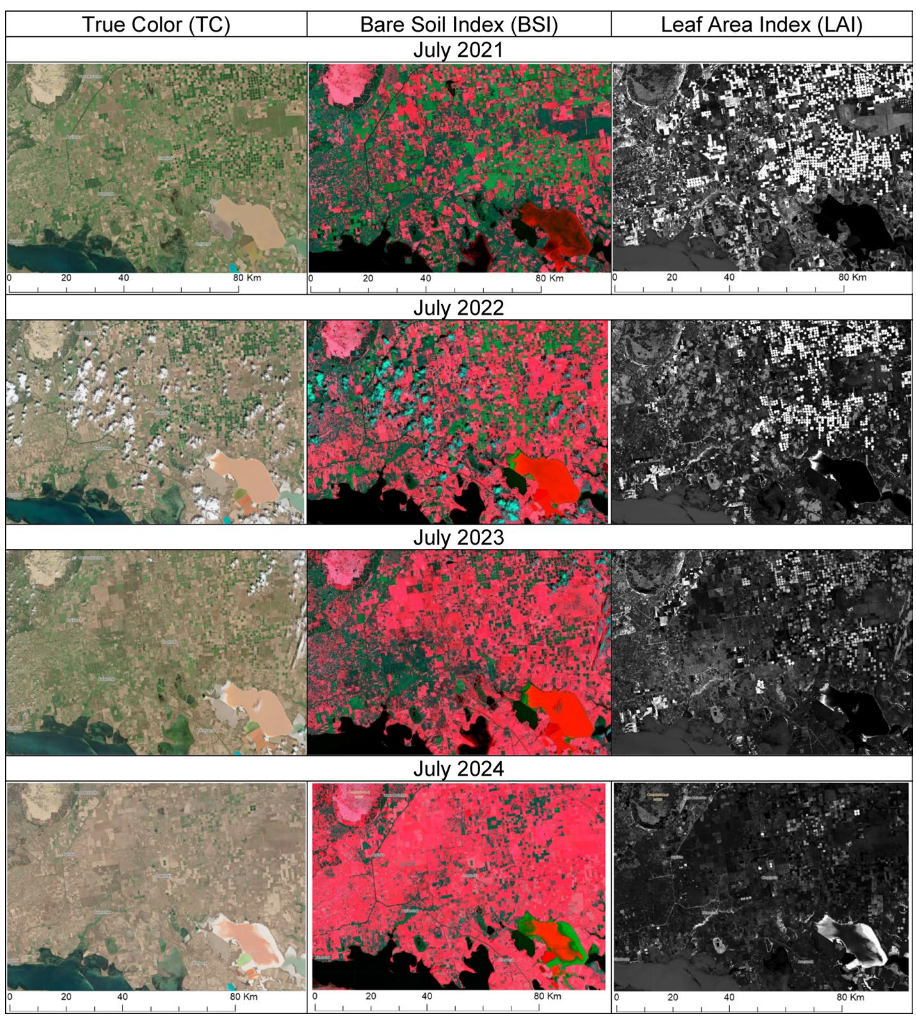

Fig. 4 The state of vegetation cover in the irrigation zone on the left bank of Kherson region in July 2021–2024, according to the Sentinel 2 L2A data

2021. In the south-central and south-western parts of the region, there was a high level of weed infestation, which was confirmed by the BSI image. In 2023, the newly formed weed cover was characterized by heterogeneous dark green boundaries in the image. As of July 2024, only 7% of farmlands was used for growing agrocenoses. Negative manifestations of the decline in agricultural production in the occupied territory is confirmed by the results of the research into the plant LAI. In particular, a white color indicated irrigated agrocenoses, which are characterized by a high moisture supply, assimilation, and active photosynthesis. Grass steppe biotopes and weeds are characterized by a lower level of assimilation in comparison with agrocenoses, hence they are distinguished by a gray color in the images. Dark and black colors indicate areas with dead wood or without vegetation.

The NDVI values obtained from decoding the Sentinel 2 images (Fig. 5) testify to the destruction of crop production and the impairment of good conditions for the functioning of grass steppe biotopes. The vegetation cover was significantly depleted in 2024. Its

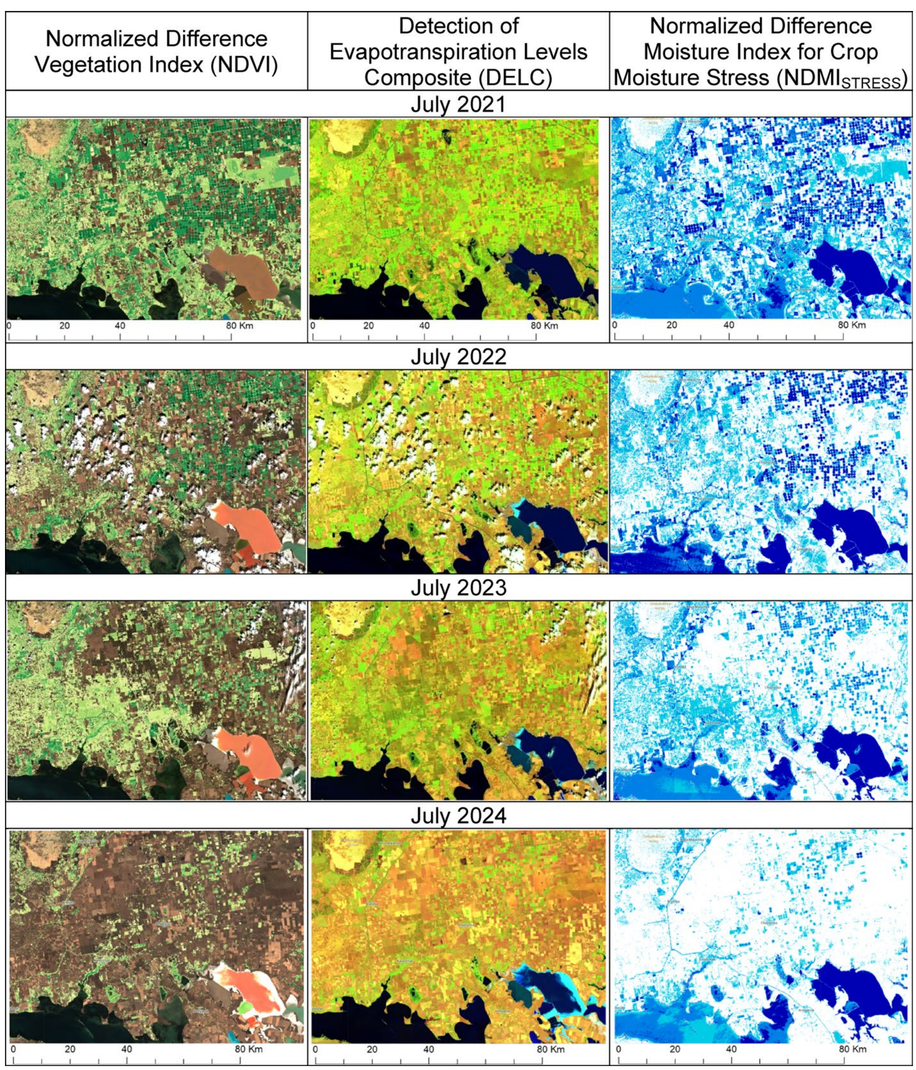

Fig. 5 Changes in evapotranspiration and moisture supply in the irrigation zone on the left bank of Kherson region in July 2021–2024, according to the Sentinel 2 L2A data

share did not exceed 20% of the total area of the occupied territory on the left bank of Kherson region.

Before Russia's full-scale invasion and the destruction of irrigated agriculture in the Steppe zone of Ukraine, the densely formed leaf surface created a plant canopy over the soil surface, thereby reducing the soil surface temperature, the level of evaporation, and the removal of soil moisture, which contributed to the formation of good microclimatic conditions for the aboveground plant layer. The evaporation rate is an indicator of the productivity of steppe landscapes since high transpiration rates or direct evaporation from the soil cause an increase in moisture deficit, the inhibition of plant growth, premature drying of plants, and their reduced productivity. Evapotranspiration is an important indicator of water vapor balance in the atmosphere and moisture retention in the soil. It is determined by the sum of the amount of moisture from evaporation as a result of transpiration from plants and physical evaporation from the soil. Transpiration is an important physiological process of plant growth that provides an efficient means of transporting necessary minerals absorbed by roots. The amount of water that is needed for plant development is 0.01% of the total amount of plants' water uptake [52]. About 95% of the water passes through the plant and is lost through evaporation, which allows it to absorb carbon dioxide to conduct photosynthesis and maintain the necessary balance of plant temperature relative to air temperature, air humidity, and wind speed. Therefore, the depletion of vegetation cover on the left bank of Kherson region has caused a decrease in carbon sequestration and a deterioration in air quality.

Plant transpiration differs from evaporation from soil since the release of water vapor is mainly controlled by leaf resistance, which is a factor in optimizing soil moisture. An increase in bare soil and high air temperatures cause soil droughts, which result in increased air pressure and reduced air humidity, increased resistance to soil water flow to plant roots, higher leaf temperatures, accelerated transpiration, and premature drying of plants. The situation is exacerbated by warm winds leading to increased losses of soil moisture, wind erosion, and the loss of fertile topsoil. According to the analysis of the images of Detection of Evapotranspiration Levels Composite (DELC), in 2021, dense vegetation cover on 80% of the irrigation zone ensured a low or moderate level of evaporation. In 2024, more than 80% of farmlands had a high level of evaporation, and 20% of these territories were characterized by a critical level of soil moisture deficit.

According to the information from $NDMI_{STRESS}$ images in 2021–2024, there was a decline in moisture on the irrigated farmland in Kherson region, which is currently occupied. In 2024, moisturizing and growth of agrocenoses and natural vegetation were observed in small areas, where moisture was provided by aquifers and shoreline areas of small rivers, drained waterbodies, areas along hydraulic canals, and remains of artificial forests and estates.

3.3 Changes in surface soil temperature in the absence of irrigation

We should highlight an increase in the negative effects of climate change. In particular, the maximum daytime air temperature in mid-July 2021 was 37 °C, in 2022—38 °C, in 2023—35 °C, and in 2024—41 °C. According to the Sentinel-3 SLSTR L1B images, in 2021–2024, there were negative spatio-temporal patterns of increasing Land Surface Temperature (LST) in the territories that previously belonged to the irrigation zone (Fig. 6). An approximation of the trend line (shown as a red dash-dotted line in the

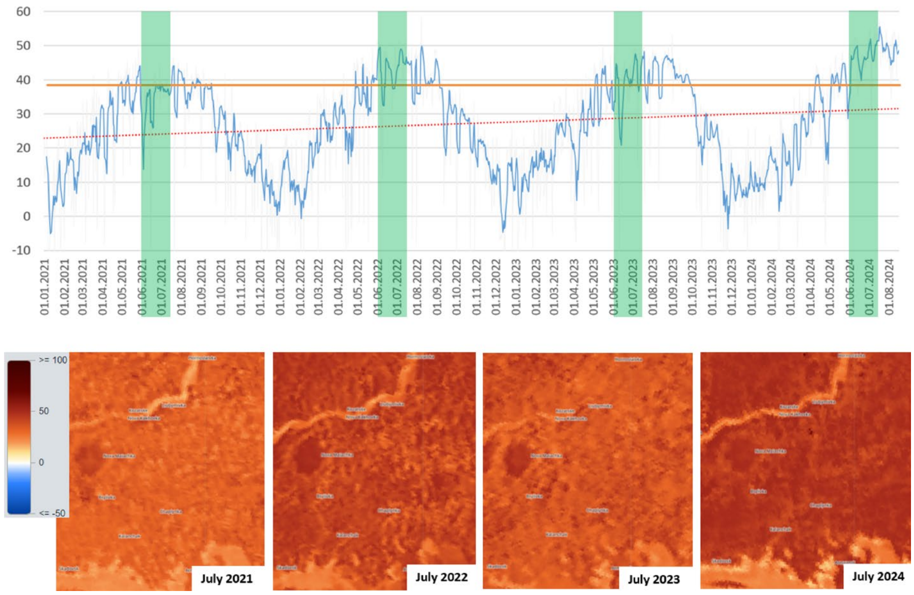

Fig. 6 Changes in Land Surface Temperature (LST) values in the irrigation zone on the left bank of Kherson region in 2021–2024, according to the Sentinel-3 SLSTR L1B data. Notes to the graph: *blue line*: dynamics of LST values; *orange line*: the maximum LST value in 2021, which was characteristic of the summer period of active irrigation and growth of late spring crops; *red dashed line*: linear trend of a change in LST values; *green vertical bars*: period of active irrigation and growth of late spring crops

graph) reflects an average annual increase in LST values by 9.0 °C (by 40%). The period of active irrigation and growth of late spring crops is highlighted in green. The orange line indicates the maximum LST value in 2021, which is 39.0 °C in the period of irrigation and active growth of agrocenoses. The lack of irrigation in 2022 caused an increase in LST to 50 °C or by 28%.

In 2023, before the destruction of the Kakhovka HPP dam, the invaders illegally withdrew and redistributed the reservoir's surface water through the hydraulic network of the occupied left bank of Kherson and Zaporizhzhia regions to supply water to the Autonomous Republic of Crimea [30]. These actions were aimed at filling the reservoir and partial irrigation. This period was characterized by relatively low temperatures and systematic precipitation, which created optimal conditions for moisturizing agrocenoses and contributed to the growth of grass steppe biotopes on the left bank of Kherson region.

In July 2024, the historical maximum air temperature at + 40.5–42.0 °C was recorded, exceeding the statistical norm for the period of 1991–2020 by 12 °C. The LST value was 56 °C, and there were areas with a soil surface temperature of 67 °C, which corresponded to a potential evapotranspiration rate of 12.5 mm/day. The optimal temperature for the development of microorganisms ranges from 25 to 35 °C. Temperatures below + 10 °C slow down biochemical processes and inhibit the metabolism of microorganisms, whereas temperatures above + 40 °C inhibit their activeness and can cause their death. Thus, the abnormal increase in soil temperatures in the areas without irrigation led to catastrophic water stress, which resulted in the disruption of the water balance and worsened soil aeration, caused soil profile compaction, complicated the functioning of microorganisms, inhibited the root system, and was a reason for premature plants' aging and drying. As of July 12–18, 2024, the Climate Shift Index (CSI) value, which indicates the exceptional fifth level of climate change (Fig. 7), was recorded in 80% of

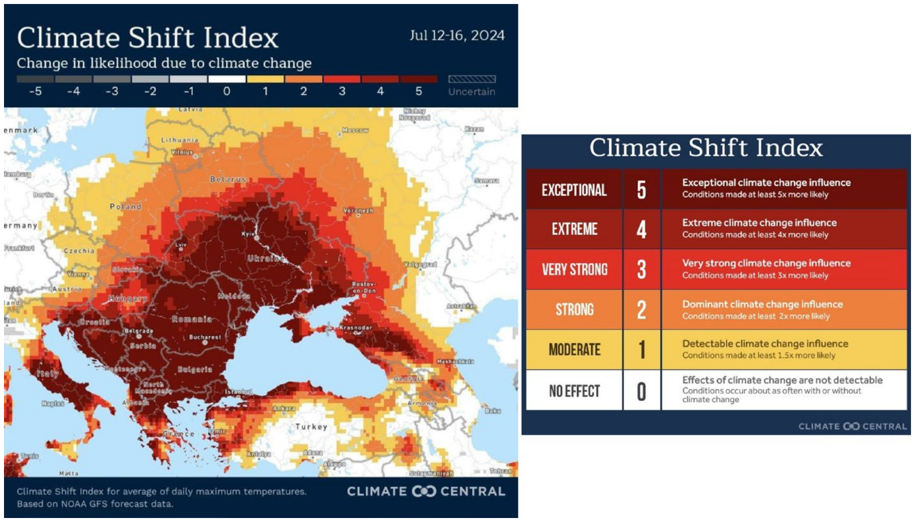

Fig. 7 Air temperature in Ukraine as of July 12–18, 2024, according to Climate Central data

Ukraine's territory, according to Climate Central (https://www.climatecentral.org/climate-shift-index). A five-fold increase in the frequency of abnormally high temperatures was observed in the research area.

3.4 The state of water resources

By 2022, the water fund of Kherson region included 24 small rivers with floodplains totaling 754 km. In addition, there were 693 waterbodies, the Kakhovka reservoir, 22 estuaries (a total area of 10.34 thousand hectares), and the Black and Azov Seas with an area of 470 thousand hectares. The Dnipro is the main river, which crosses the region from northeast to southwest for 200 km. All the rivers belong to the Dnipro River basin, except for the Kalanchak River, which flows into the Black Sea. There are no permanent rivers in the Black Sea area between the lower course of the Dnipro Rivers and the Azov Sea. The region's rivers are fed with surface water at a level of 85–90% and with groundwater at a level of 10–15%.

In 2024, the lack of the Kakhovka reservoir, low precipitation, and abnormally high temperatures caused the drainage of waterbodies and deterioration of river water content on the left bank of Kherson region (Fig. 8). It was found that the Kalanchak River became shallow. The remaining surface water was characterized as "very dirty water" and was unsuitable for water use. According to the information from the residents of the occupied territories, representatives of the occupation forces restricted the population's access to the Kalanchak River.

Representatives of the occupation authorities drilled wells along the drained canals of the hydro-reclamation system and pumped fresh groundwater from the upper horizons. This water was used to satisfy the drinking and technical needs of the occupation forces. Drilling wells and pumping water caused a decrease in groundwater levels, which provoked an increase in salt concentration in water horizons and the depletion and salinization of well water.

Fig. 8 Drainage of waterbodies in the temporarily occupied territory on the left bank of Kherson as of 2024, according to the Sentinel 2 L2 data

3.5 Salinization and soil salinity

The evaporation of mineralized groundwater caused the transfer of salts to the upper soil layer and an increase in their concentration, which resulted in the expansion of the areas with secondary salinity and salinization (Fig. 9). In the images, saline lands are indicated by fuzzy light gray and white contours. The expansion of the areas with saline soils was also recorded. The areas with salt leakage on the soil surface range from one hectare to 400 hectares and more.

Fig. 9 Comparison of the state of lands in the irrigation zone on the left bank of Kherson region as of August 23, 2021, and 2024: salinized and saline lands have fuzzy light-gray and white contours. The observation area in the image is 12.3 thousand hectares, according to Sentinel 2 L2 data

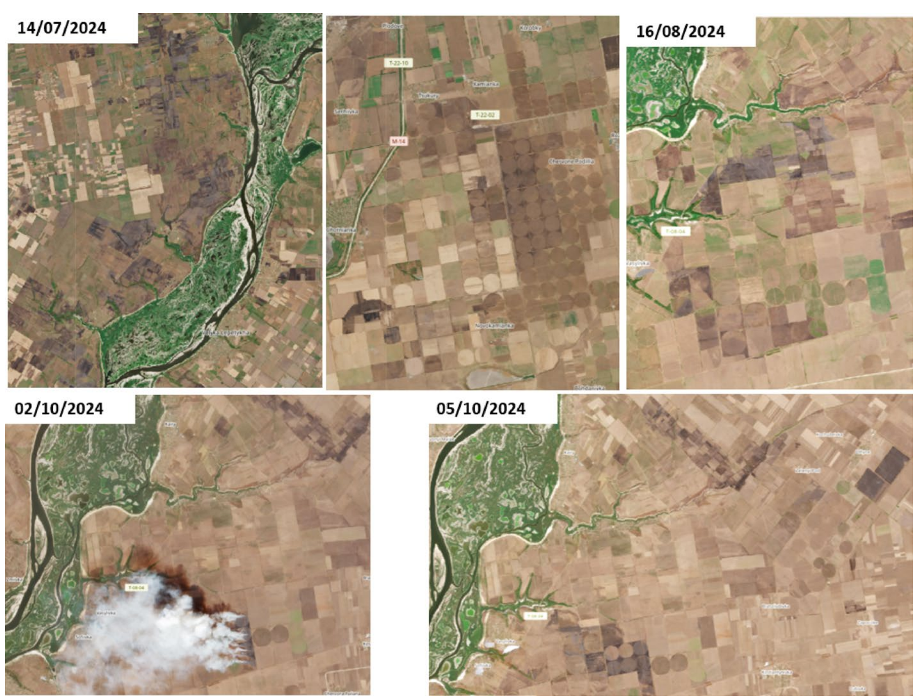

Fig. 10 Fires in the territory of Kherson region in 2024, according to the Sentinel 2 L2A data

3.6 Droughts and fires

In the summer-autumn period of 2024, active hostilities, the concentration of a large number of military equipment, the lack of water in the territories caused by the drainage of the Kakhovka reservoir, and high air temperatures caused fires in the territories of agrocenoses, dry stubble, windbreaks, and steppe biotopes (Fig. 10). Fires were recorded on an area of more than 200 thousand hectares.

3.7 Consequences of droughts and wind erosion

The area of Ukrainian lands in the zone of wind erosion is 6 million hectares (14.0%), 75% with slight erosion and 25% with moderate and severe erosion. The amount of soil losses due to erosion averages 10–15 t/ha per year, and the total amount of the average annual soil losses in Ukraine ranges from 260 million tons to 500 million tons of soil [53, 54]. As a result of wind erosion, up to 24 million tons of humus, 0.96 million tons of nitrogen, 0.68 million tons of phosphorous, and 9.40 million tons of potassium are removed from 6 million hectares of soil. It was found that crop yields on eroded land are less by 20–60%. Erosion processes are intensifying in the steppe soils in the Autonomous Republic of Crimea, Zaporizhzhia, Kherson, part of Mykolaiv and Dnipro regions [15, 55]. In the years with abnormally high temperatures, wind gusts of 20–30 m/s cause soil losses to exceed the norm by 300 times. For instance, in 2007, the above territories became the epicenter of dust storms, which caused soil losses of 10–400 t/ha, which exceeds the speed of soil formation by 10–4000 times [56]. About 95% of the territory of Kherson region is erosion-prone. Droughts, fires, bare soils, and strong winds (20–30 m/s) in 2024 caused topsoil losses of up to 600 t/ha and more (Fig. 11). This level of soil losses was recorded in these territories for the first time. The area of the deflation epicenter on the left bank of Kherson region ranged from 100 to 3000 hectares. The region is dominated by southern black soils (Chernozems Calcis)—the humus horizon reaches 50–55 cm, the upper layer of soils with low humus content contains 3.5–4.0% of humus, and the upper layer of soils with poor humus content contains up to 3% of humus, soil density is 1.2–1.3 g/cm^3; dark chestnut saline soils (Kastanozems Haplik)—the humus horizon reaches 50–55 cm, humus content is 2.5-3.0%, soil density is 1.26–1.42 g/cm^3. The south of the left bank has dark chestnut saline and chestnut saline (Kastanozems Luvic) soils—the humus horizon of dark chestnut soils reaches 50 cm,

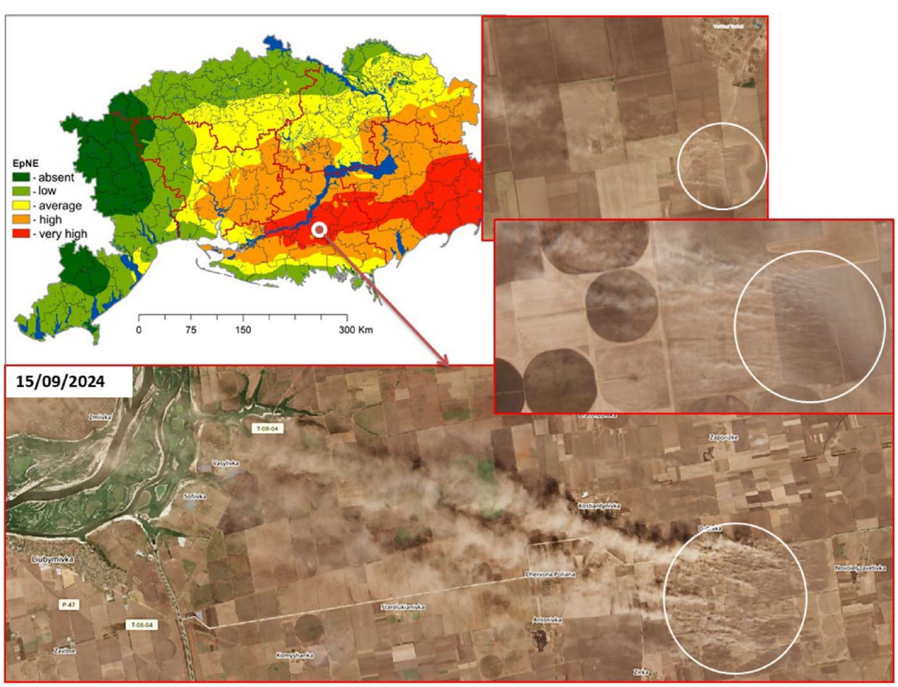

Fig. 11 Consequences of wind erosion on the left bank of Kherson region in 2024, according to the Sentinel 2 L2A data (EpNE—the deflation rate of steppe soils without vegetation)

that of chestnut soils—25–30 cm, humus content is 1.6–2.5%, soil density is 1.29–1.42 g/cm^3 [57].

The rate of deflationary processes and their degree of danger in the Steppe of Ukraine are set according to the main soil types. Namely, for black soils of all types, the rate is 2.5 t/ha; for dark chestnut and chestnut saline soils, the rate is 2.0 t/ha. The cartogram shows the deflation rate of steppe soils without vegetation (EpNE) [55]. High and very high deflation rates (cartogram in Fig. 11) are characteristic of the entire territory of Zaporizhzhia region, about 80% of Kherson region, 40% of Mykolaiv region, and 20% of Dnipro region. High deflation rates are inherent in soils where the normative values of their losses may exceed 30–300 times. A very high rate is characteristic of soils where soil losses exceed 300 times.

They mainly manifest in abnormally hot years. With the continuation of the war, further destruction of forest belts, the lack of irrigation and crop production in the occupied territories with heightened deflation, minimum annual soil losses of 60–75 t/ha are forecasted, which correspond to losses of 0.4–0.6 cm of topsoil per year. In the epicenter of dust storms, soil losses will amount to 4–5 cm per year. In other words, in the epicenter of constant dust storms, the topsoil of 25–50 cm will be lost in 7–11 years.

3.8 The state of the nature reserve fund

The area of the nature reserve fund of Kherson region is 353405.6758 hectares. It includes 83 objects—15 objects of national importance and 68 objects of local importance. The protected area of the region is 10.6%. The total area of the region's ecological network amounts to 575.28 thousand hectares [58]. Currently, 54 objects of the nature reserve fund (65% of their total number) are in the occupied territory. The objects on the right bank of Kherson region are in a high-risk zone since they are subject to constant shelling.

It is notable that the areas of the region's nature reserve fund had additional irrigation moisture due to moisture redistribution in the territories with agrocenoses and natural vegetation. The hydrological redistribution of irrigation water in the upper soil aquifers fed the ecosystems of the Askania Nova Biosphere Reserve named after F. E. Falz-Fein. The reserve was founded by Friedrich Faltz-Fein in 1898. On February 8, 1921, the Decree "On Askania-Nova" was approved, according to which the estate belonging to F. Faltz-Fein, Askania-Nova of the Dnipro district and the adjacent Dornburg estate were declared the State Steppe Reserve of the Ukrainian Socialist Soviet Republic. The Askania-Nova Biosphere Reserve is a nature conservation research institution that ensures the preservation of the largest area of fescue and feather grass steppe in Europe. The reserve is certified as a benchmark of fescue and feather grass steppes on the planet, subject to conservation and investigation under the UNESCO Man and the Biosphere Program (https://askania-nova-zapovidnik.gov.ua/). The area of the natural core zone of the reserve is 11,054 hectares, the buffer zone is 6909 hectares, and the transit zone (the zone of anthropogenic landscapes) is 15,344 hectares (Fig. 12).

The historically formed landscapes of the reserve combine natural and artificial (man-made) ecosystems: flat zonal steppes, meadows, a dendrological park, and a zoo. The depressions, which are characteristic of this area—hollows—are occasionally flooded with meltwater and rainwater. During such periods, meadow plants (rhizome grasses and sedges) are replaced by wetland vegetation, and waterfowl breed here.

Note: green color – natural core zone; yellow color – buffer zone; white color dashed-dotted – transit zone

Fig. 12 Map of the functional zones of Askania-Nova Biosphere Reserve named after F. E. Falz-Fein. Note: green color—natural core zone; yellow color—buffer zone; white color dashed-dotted—transit zone

Before the russian aggressor's full-scale invasion and occupation of Kherson region's left bank, the protected steppe consisted of three massifs: Northern, Southern, and the Great Chapelskyi hollow, and fallow lands where the processes of natural plant recovery were studied. The Great Chapelskyi hollow (4x6 km) is a unique depression that is periodically filled with water. In the deepest part, there were hydrophytes, including one of the rarest species in Ukraine—star water-plantain. Herds of wild ungulates from different continents were kept there in conditions close to natural ones—bison, saigas, European fallow deer, Przewalski's horses, Turkmen kulans, red deer, and Kafr buffaloes lived semi-free throughout the year. In the summer, Watusi cattle, a heard of kanna, wildebeest, and nilgau antelopes, zebra, and gayals from India were moved there. Closer to autumn, many migratory birds gathered in the steppe: different duck species, flocks of thousands of cranes, grey geese, and waders. The wildlife of the protected steppe retained its indigenous (local) fauna. Typical inhabitants of steppe landscapes could be found there: small gophers, steppe marmots, great jerboas, European hares, mouse-like rodents, and medium and small predators: common foxes, steppe polecats, and weasels. The Biosphere Reserve was the largest national center for preserving and reproducing endangered, rare, and valuable species of ungulates and birds. Its collection included more than 100 species with more than 3.5 thousand animals listed in the register of scientific objects of Ukraine's national heritage. The fund of the dendrological park numbered 1600 varieties and species of woody and ornamental flower plants, including 60 species listed in the Red Data Book of Ukraine [59]. According to the staff of the Askania-Nova Biosphere Reserve, the representatives of russian troops organized hunting for local animals, which resulted in mass animal deaths. Some animals were abducted and moved to russia by the occupation authorities. Today, most unique fauna and flora of the reserve have been lost.

It is noteworthy that the vegetation of the ecosystem of the Askania Nova Biosphere Reserve is an important bio-indicator of changes in ecological conditions. The impact of the destruction of irrigation sources, abnormally high temperatures, and high water stress caused vegetation losses and plant drying (Fig. 13).

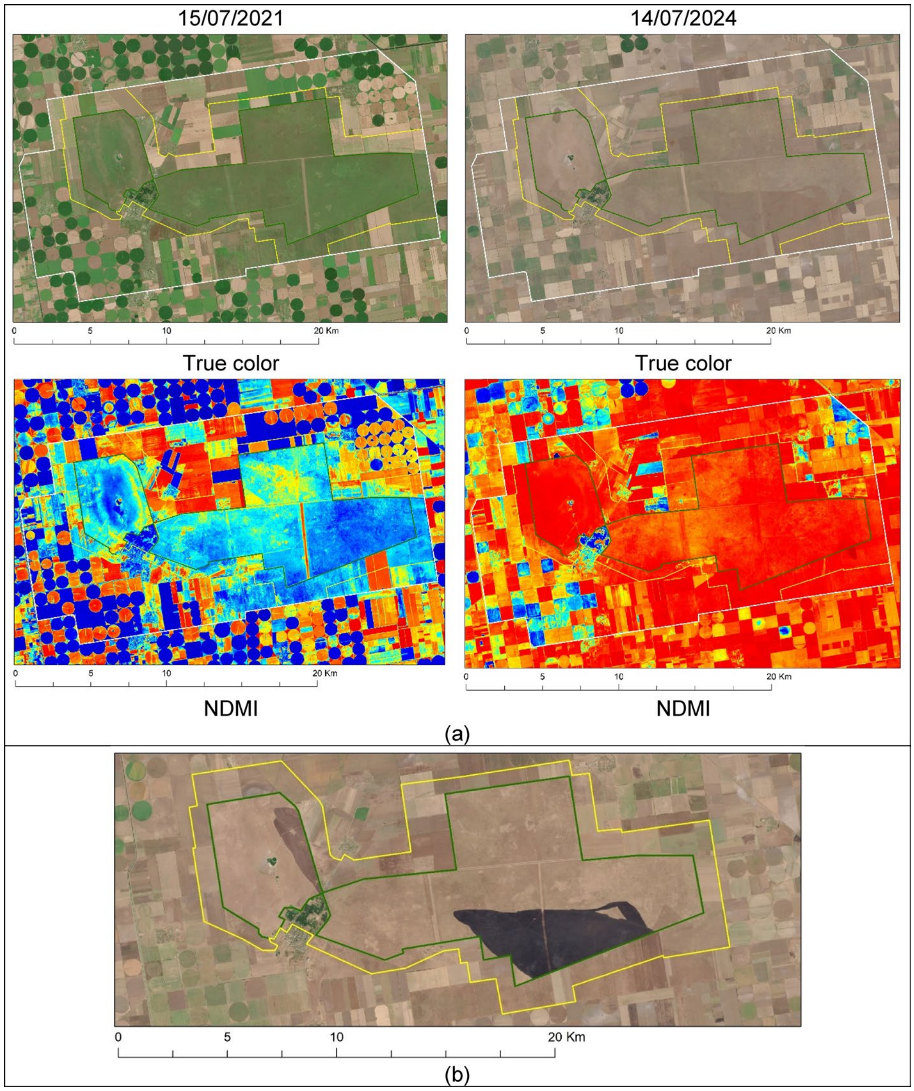

Fig. 13 Moisture content and burnt vegetation cover in the territory of the Askania Nova Biosphere Reserve in 2021 and 2024, according to the Sentinel 2 L2A data: **a** Normalized Difference Moisture Index (NDMI), in the images: a red color—fire-prone areas with water stress, dry plants or no plants; a yellow color—areas with low moisture content and suppression of plant growth; hues of a turquoise color—satisfactory and good moisture content and good plant growth; a blue color—high moisture content and good plant growth; **b** black and dark brown colors in the image indicate the areas with burnt grass steppe biotopes

As of July 15, 2021, the average NDMI value in the territory of the Biosphere Reserve was 0.07 (the NDMI varied between − 0.01 (bare soils and dry plants) and 0.15 (the areas with satisfactory moisture content and vegetation)). As of July 14, 2024, the average NDMI value was − 0.20 (the NDMI varied between − 0.25 and − 0.15 (bare soils and dry plants)). Over 30% of the protected area with plants listed in the Green Book of Ukraine was burnt. The steppe biotopes, which are the main natural value of the Askania Nova Biosphere Reserve and which are considered the standard of feathergrass steppes of the Black sea region, were burnt.

4 Discussion

Hostilities and related activities of the occupation forces caused the drainage of waterbodies, primarily the Kakhovka reservoir, which made it impossible to irrigate farmlands and fill the hydro-reclamation network. In turn, it resu lted in increased temperature pressure on the soil surface, accelerated evapotranspiration, the deterioration of soil properties and their degradation, the loss of good growth characteristics of natural vegetation and plants' drying, fires, soil exposure, and desertification of the territories in the irrigation zone. As of July 15, 2021, the average NDMI value was 0.12 (variation between −0.14 (bare soils) and 0.4 (areas with good moisture content and vegetation)) in the irrigation zone on the left bank of Kherson region (Fig. 14). As of July 14, 2024, the average NDMI value was −0.13 (variation between −0.26 (bare soils and dry plants) and 0.0 (areas with water stress and dry plants)).

Today, the Ukrainian and international communities are actively discussing three possible scenarios for the post-war functioning of the Kakhovka reservoir's territory (Fig. 15): Scenario 1—reconstructing the dam of the hydroelectric power plant and filling the reservoir according to the conditions of its previous functioning [16, 24, 26, 27, 29, 32, 42, 60]; Scenario 2—creating a natural plant ecosystem [61, 62]; Scenario 3—creating a natural-artificial reservoir system partially filled with water and creating a meadow-marsh and forest environment in the reservoir's upper part using modern technologies [16, 26, 27, 32, 42].

4.1 Scenario 1

According to Scenario 1, the environmental and socioeconomic situation in the regions dependent on the reservoir will return to its previous state [16, 24, 26, 27, 29, 32, 42, 60]. Therefore, to prevent the negative consequences of surface water quality degradation

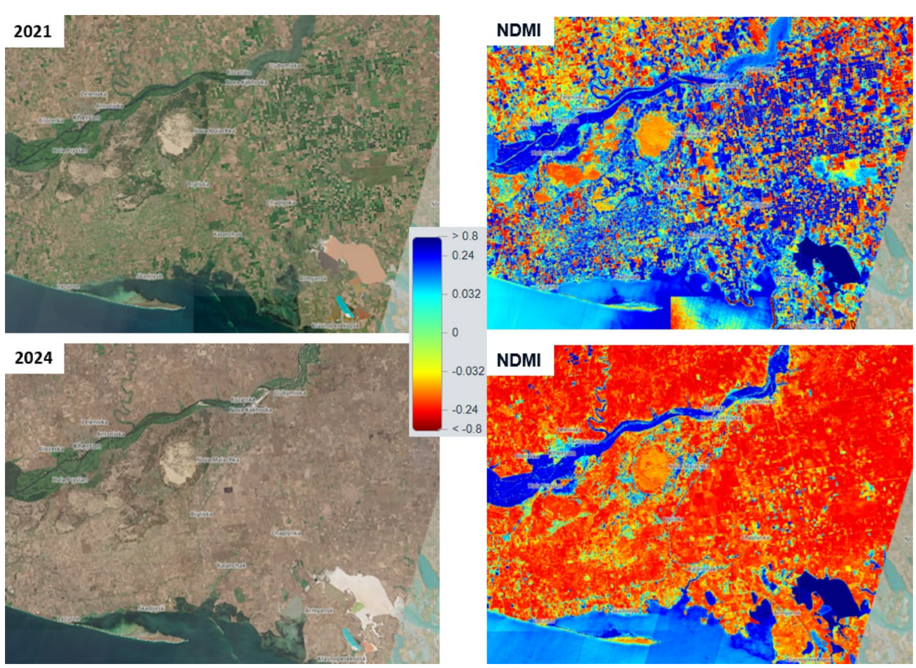

Fig. 14 Natural and climatic transformation of irrigated lands in Kherson region caused by military operations; comparison of the Sentinel 2 L2A images for July 2021 and 2024: images on the left—True color; imahes on the right—Normalized Difference Moisture Index (NDMI)

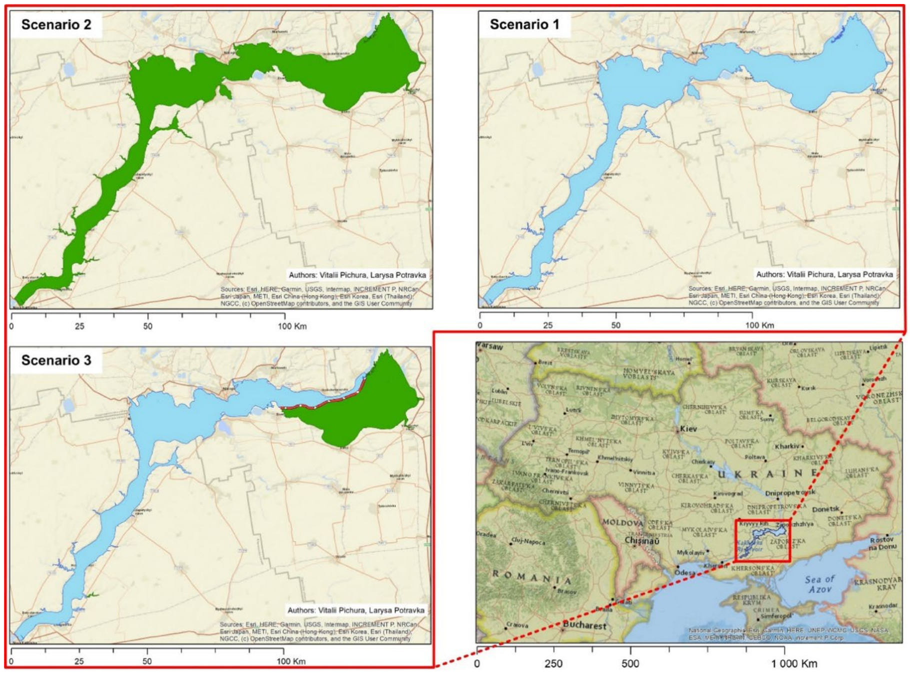

Fig. 15 Scenarios for the functioning of the Kakhovka reservoir's territory

and eutrophication, it is necessary to remove vegetation cover and bottom sediments from the reservoir's territory before its flooding. To ensure spawning and preserve the diversity of aquatic life, it is necessary to consider the technical features of creating a fish passage channel when constructing a dam. In addition, to reduce the inflow of large volumes of untreated wastewater, it is necessary to modernize the water treatment systems of enterprises and settlements, protect shorelines, and restore water protection zones of the Dnipro River and its tributaries, and to carry out erosion control on farmlands based on basin principles of nature management [63–66]. In turn, this will reduce a negative effect of agriculture on aquatic ecosystems and create preconditions for balanced water and land use. The negative consequences of Scenario 1 will involve flooding shallow areas with depths of 0.7–2.5 m, which make up more than 30% of the reservoir's territory. These areas are mainly located in the reservoir's upper part. Their waters were not used in regulating the reservoir's flow, which caused stagnation, accumulation of pollutants, good water heating in the summer, eutrophication, and the formation of polytrophic-hypertrophic water masses, which gradually moved to the reservoir's middle part.

4.2 Scenario 2

In turn, Scenario 2 for creating natural plant ecosystems in the form of the Great Meadow is being actively discussed in scientific circles and public space [61, 62]. Based on our previous research into climatic and hydrological conditions for the formation of vegetation cover in the territory of the drained Kakhovka reservoir [42], we established that the winter-spring period of 2024 was characterized by favorable climatic conditions, which contributed to spring floods resulting in the flooding of 70% of the drained reservoir's territory. This led to substantial moisture accumulation in the bottom sediments, which promoted a rapid increase in plant biomass and active chlorophyll synthesis in the leaves. In 2023–2024, the area of the reservoir's bed covered with plants amounted to

135 thousand hectares, including 48 thousand hectares covered with woody plants (willows and poplars); 87 thousand hectares mainly covered with meadow and marsh plants with patches of shrubs. However, the lack of precipitation and an abnormal increase in the air temperature in July 2024 to the level of the historical maximum (+ 40.5–42.0 °C) for the research area provoked an acceleration in evapotranspiration and depletion of moisture reserves in the drained reservoir's territory. This caused a deterioration in plant growth and premature drying, which led to a loss of good properties of chlorophyll synthesis in an area of 72.8%. Negative processes caused a reduction in the area with healthy vegetation by 26.3 thousand hectares. The spring-winter period of 2025 was characterized by a short period of snow cover and the lack of proper moisture, which led to a water shortage in the Dnipro River's catchment area, further accumulation and storage of the needed amount of water in the Dnipro reservoir's cascades to support the life functioning in Ukraine's regions. This resulted in restricted discharge volumes from the Dnipro HPP, lack of floods, and the Dnipro River's shallowing within the former Kakhovka reservoir's territory, which complicated the recovery of spring growth of vegetation cover. In particular, according to the National Oceanic and Atmospheric Administration (https://www.noaa.gov/climate/climate-news-and-stories), soil moist ure reserves in Ukraine at the beginning of 2025 significantly differ from the previous periods. Namely, in January–February 2024, soil moisture reserves exceeded the average value of this indicator for the past 40 years by 25–35%. As of the beginning of 2025, there was a decrease in soil moisture reserves by 10–32% in the 1.6 m soil layer. A reduction in soil moisture increased water stress and intensified negative impacts on ecosystems.

Figure 16a illustrates the curves of the recovery of spring growth and chlorophyll synthesis in plants in the territory of the former Kakhovka reservoir in April 2024 and 2025. At the end of April 2024, the vegetation cover in the former reservoir's territory was considered good, with high chlorophyll content in plants. At the end of April 2025 (Fig. 16b), the vegetation cover was characterized by significant water stress and low chlorophyll content in plants. At that time, only 20% of plants regained satisfactory growing conditions.

The increasing frequency of climatic anomalies and decreasing volumes of water discharges from the Dnipro reservoir to the territory of the former Kakhovka reservoir are complicating conditions for plant survival. In the future, this will cause a decrease in the density of plants with good growth, increase the area with degraded vegetation cover and dead wood, raise the frequency of fires, lead to a loss of stability of the newly created ecosystem, and cause the destruction of vegetation patches. These negative patterns are confirmed in the studies by Vyshnevskyi and Shevchuk [60].

Notably, the reservoir was the final recipient of the inflow, sedimentation, and biological treatment of polluted water with activated sludge, a place for aeration and oxygenation of flowing water by the turbines of the hydroelectric power plant's dam. Currently, the lack of these processes has caused a four-fold degradation of the surface water quality in the Dnipro-Buh estuarine system [посилання на мою статтю]. In particular, water masses from the drained reservoir wash out plant remains and bottom sediments containing toxic substances and metals. Then, they move with the flow and accumulate in the lakes of the Dnipro Delta, the Dnipro-Buh Estuary, and the Black Sea. This has led to sustainability impairment and ecological regression of freshwater and marine aquatic ecosystems [30, 67]. Therefore, Scenario 2 for preserving the newly created plant

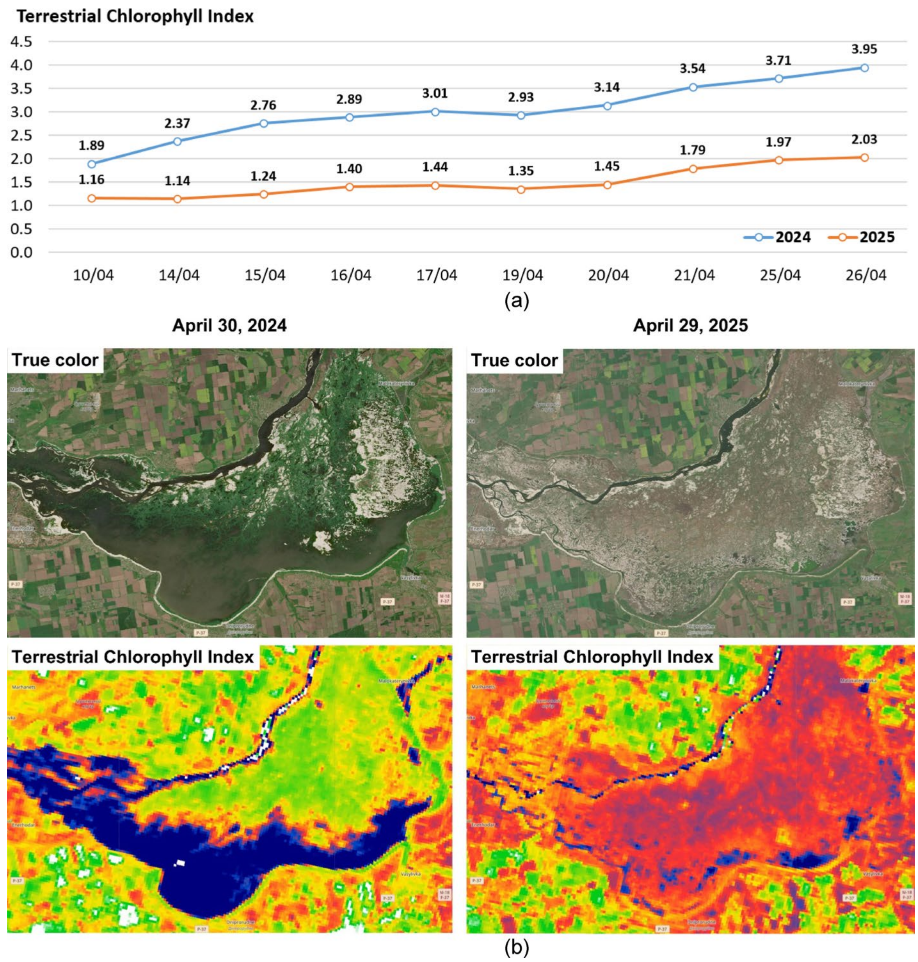

Fig. 16 Recovery of spring growth (**a**) and chlorophyll synthesis (**b**) in plants in the territory of the former Kakhovka reservoir in April 2024 and 2025

ecosystem will not have an appropriate environmental and socioeconomic effect discussed in studies [61, 62].

The Terrestrial Chlorophyll Index (TCI) satellite images present the characteristics of chlorophyll synthesis in plants. The color range shows its fluctuations from blue-red and red (low chlorophyll values) and yellow (medium chlorophyll values) to green and dark-green (heightened and high chlorophyll values). The blue color indicates territories covered with water. The white color indicates rocks, clouds, and plants with abnormally high chlorophyll content. For water bodies, the white color testifies to a high concentration of organic matter or exposed bottom sediments.

We should underscore that more than 500 million m^3 of freshwater per year is needed to cover drinking and sanitary needs in southern regions of Ukraine. An additional 700 million m^3 of water is needed for the auxiliary activities in crop production. After the Kakhovka reservoir's drainage, scientists expressed different opinions [16, 62, 68] about the possibility of covering water shortages in southern Ukraine with a total volume of more than 1200 million m^3 of freshwater per year:

- *The first vision* of scientists was based on the possibility of covering water shortages with the reserves of the Dnipro reservoir, which is located closest to the territories with water supply from the former Kakhovka reservoir. The reservoir covers an area of 410 km^2 and has a volume of 3.32 km^3, which is 5.5 times less than the Kakhovka reservoir's volume. The normal retaining level is 51.4 m. The dead volume level is 48.5 m with a reservoir filling volume of 2.47 km^3. This means that the maximum level of water use should not exceed 850 million m^3. According to the State Agency of Water Resources of Ukraine (https://www.davr.gov.ua/), before the war, the transit of runoff from the Kamianka reservoir's dam to the Dnipro reservoir's dam through the downstream area to the Kakhovka reservoir's dam, given the minimum environmental flow in the closing section of the Dnipro HPP, was 28.22 km^3. More than 60% of the annual runoff occurs during the winter-spring period, the main period for water accumulation in reservoirs to cover summer-autumn water shortages for water users. Before the war, the total discharge of the Dnipro reservoir amounted to 15.63 km^3, 94.9% of which was used to maintain the minimum environmental flow of the River in the closing section through the Dnipro HPP. Local water users use 700–800 million m^3 from the Dnipro reservoir, including 72% for industrial needs, 19.5% for irrigation, and 8.5% for domestic needs. Therefore, based on the hydrological calculations of water use, we can conclude that the Dnipro reservoir's reserves cannot cover the water shortage of the Kakhovka reservoir's water users due to a natural and climatic increase in water shortages. In our opinion, excessive water use from the Dnipro reservoir will cause a reduction in the reservoir's water level below the dead volume level, depletion, the formation of large shallow areas, an increase in eutrophication and water pollution, and water shortages for local water users. In addition, there will be consequences of disrupting the hydrological regime and ecological sustainability of the Dnipro River aquatic ecosystems downstream of the Dnipro HPP.

- *The second vision* of scientists was based on the possibility of taking water immediately from the Dnipro River course, which passes through the valley of the drained Kakhovka reservoir. It is impossible, according to hydrological calculations. In the years with low precipitation, water intake from the natural Dnipro River course will not provide even the minimum required water use to cover the water shortage in southern Ukraine in the summer and autumn. In the years with medium precipitation, the River's water supply will not cover the medium and maximum levels of the local population's water needs. In the years with high precipitation, with the maximum level of the population's water use, the level of water supply from the Dnipro River will satisfy only 40–50% of the water needs (Fig. 17).
- *The third vision* was based on the possibility of creating a network of wells in southern Ukraine for groundwater abstraction. In our opinion, the excessive use of strategically important groundwater reserves to cover the shortfall in water use will lead to their accelerated depletion, the replacement of freshwater horizons with saline seawater from the Black Sea and the Azov Sea, which will cause a new wave of water shortages, soil compaction, degradation, and salinization.
- *The fourth vision* of scientists is based on the possibility of desalinating and using saline water from the Black Sea and the Azov Sea. In our opinion, applying this technology is economically inefficient and energy-consuming and cannot satisfy freshwater needs. In particular, the reduced water use and application of drip irrigation technologies on chestnut saline soils in southern Ukraine will cause an increase in the patches with secondary soil salinity and the formation of solonchaks,

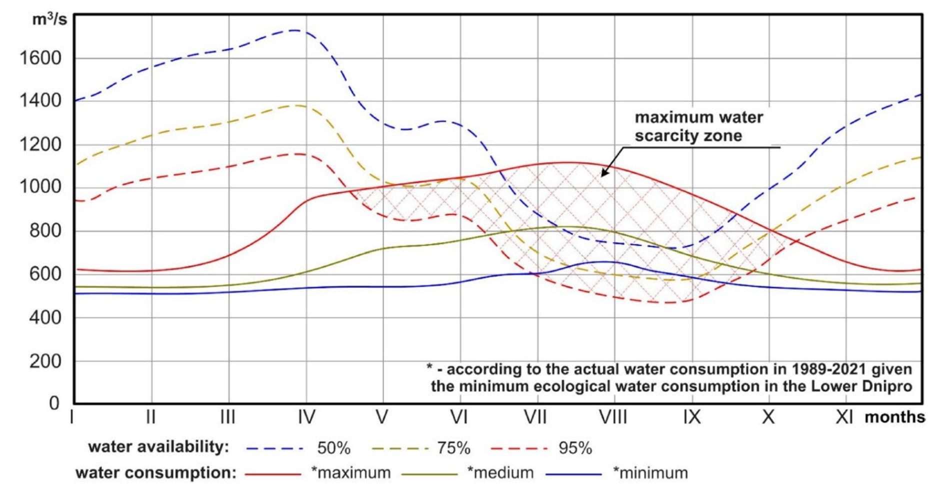

Fig. 17 Model of water supply for southern regions of Ukraine depending on the actual water availability in the Dnipro riverbed in 1981–2021

which excludes the possibility of approving such projects. In particular, the cessation of crop production and lack of irrigation have already caused secondary salinity of soils that will need comprehensive reclamation in the post-war period. The reclamation of soils with secondary salinity aims to remove salts accumulated in the soil and maintain groundwater at a level that does not lead to secondary salinity. It involves the following practices: chemical reclamation of irrigation water and soil; soil flushing; restoring drainage systems; water-balanced and soil-protecting irrigation modes and methods; phytoremediation, selecting crops resistant to adverse changes; implementing soil-protecting, intensive or short crop rotations; soil-protecting tillage; improving fertilization systems through localized fertilization, fertigation, green manure, and micro-fertilization.

4.3 Scenario 3

Resuming irrigation and water supply is possible if the Kakhovka reservoir is restored. In this context, Scenario 3 (Fig. 18) for the functioning of the Kakhovka reservoir's territory deserves our attention. For this purpose, we propose to separate the upper shallow part, covering 725 km^2, or 34% of the reservoir's territory, with a dam. Separating the shallow part with a dam will allow for the preservation of 45% of vegetation cover with a total biomass of 2.3 million hectares. In the structure of plant biotopes, 55% of the area with woody plants and 37% of meadow and marsh vegetation will be preserved. In particular, the preserved vegetation area will be important for the existence, increase, and preservation of rare protected flora and fauna species. The functioning of the Pan-European Dnipro meridional ecological corridor will be improved. The technological decision regarding the separation of the vegetation patch with a dam requires creating a bypass channel (highlighted in yellow in Fig. 18) in this territory. The channel will maintain the required moisture content in hot seasons of the year for the preservation and development of plant biomass. Moreover, the channel will become an important additional source of water supply to satisfy the local population's sanitary needs.

The territory filled with water will cover 66% (1400 km^2) of the reservoir area with a water volume of about 15 km^3. This will allow for restoring the biotope of bottom activated sludge, which is an important food base for fish and biological treatment of surface

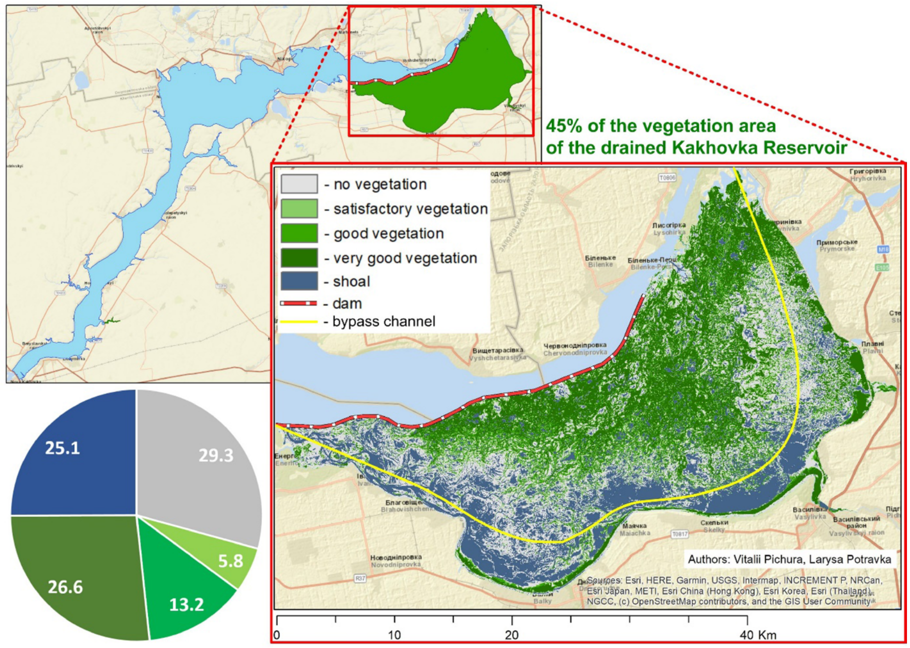

Fig. 18 Scenario 3—Natural-artificial system of the Kakhovka reservoir

waters. Cutting off the shallow part of the reservoir and narrowing the upper part of the reservoir will maintain the water flow rate, which will improve the hydrological functioning of the upper and middle part of the reservoir. Parts of the reservoir's bed should be prepared for filling with water according to Scenario 1. The removed reservoir's bottom sediments can be used after refinement and treatment to restore degraded war-affected soils.

According to the forecast of the Institute of Water Problems and Land Reclamation of the National Academy of Agricultural Sciences [24], half of Ukraine's arable lands without irrigation will be unsuitable for crop cultivation until 2050 and two-thirds—until 2100, which corresponds to annual losses of 13.5 million tons of cereals and industrial crops and 11 million tons of fruits and vegetables at current yields. Therefore, given the water needs for utilities, industry, and the energy sector (including the Zaporizhzhia nuclear power plant), scientists [24] believe that restoring the Kakhovka reservoir is essential.

According to scientists from the Institute of Hydrobiology of the National Academy of Sciences (IH NAS) of Ukraine, flooding the reservoir will mitigate the problem of heavy metal spread [32] from bottom sediments and contribute to the region's economic recovery. Scientists have proposed a compromise to reduce the reservoir area by constructing a 50-kilometer dam [69], according to Scenario 3. The dam will separate the upper northeastern part of the Kakhovka reservoir (where the territory of the Great Meadow used to be) from the rest of the water area.

In the post-war period, restoring irrigation will require implementing up-to-date resource-saving technologies optimizing water use for crop cultivation in the face of climate change. We believe that it is necessary to take mixed approaches of spatially adapted irrigation technologies considering natural moisture, soil and climate characteristics of the territory and crop rotations. We share the opinion of the researchers [24] regarding the mixed application of the systems of fine-dispersed sprinkling technology, sprinkler irrigation with low pressure and low intensity, and drip irrigation, including subsoil irrigation with intermittent water supply. To reduce infiltration losses and evaporation, water can be transported to fields through closed pipelines, and the use of open channels can be limited. In addition to restoring irrigation, the affected territories will require spatial-differentiated implementation of comprehensive agro-technological and forest reclamation erosion control practices [24, 63–66].

5 Conclusion

The natural and climatic transformations of the territories in the irrigation zone of Ukraine caused by military operations and occupation were thoroughly investigated. The destructive consequences of the hostilities and related activities performed by Russian armed forces were recorded. The drainage of the Kakhovka reservoir as a primary source of irrigation caused the disruption or destruction of natural and artificial ecosystems, which led to the social and economic crisis in the occupied territories.

1. We recorded a decline in the ecosystem resilience in 2024, which was caused by water scarcity. The lack of irrigation led to the impairment of hydrological conditions on the left bank of Kherson region, which manifested itself in moisture deficit and the drainage of waterbodies. The Kalanchak River became significantly shallow, and the remaining surface waters are unsuitable for water use.
2. The destruction of crop production and the impairment of suitable conditions for the functioning of grass steppe biotopes caused an 80% loss of vegetation cover, which led to soil exposure and an increase in the soil surface heating by 1.45–1.72 times. In July 2024, the surface soil temperature was 56–67 °C, which caused evaporation of soil moisture in 80% of the territory.
3. The destruction of irrigation, the depletion of upper freshwater horizons, and additional evaporation of mineralized groundwater provoked the transfer of salts to the topsoil and increased their concentration, which contributed to the expansion of areas with secondary salinity and salinization. The areas with salt leakage on the soil surface range from one hectare to 400 hectares.
4. Water scarcity, dry vegetation cover, and military operations caused fires in the summer-autumn period of 2024 in an area of more than 200 thousand hectares. It was found that droughts, fires, soil exposure, and strong winds (20–30 m/s) led to topsoil losses (600 t/ha). The epicenters of deflation in the former irrigation zone were 100–3000 hectares. Plant growth cessation, drainage, and fires were detected in 30% of grass steppe biotopes of the Askania Nova Biosphere Reserve.
5. Restoring the Kakhovka reservoir in the post-war period, according to Scenario 3, will satisfy the population's needs for water, preserve the diversity of plant and bottom biotopes in natural-artificial ecosystems, contribute to achieving sustainable development goals and balanced nature management in Southern Ukraine. Restoring irrigation will require implementing modern resource-saving technological and erosion control practices.

Military operations, the Kakhovka reservoir's drainage, and the destruction of irrigation cause water stress and desertification in Kherson region. The research findings are proof of the ecocide and genocide committed by Russian troops against Ukraine and Europe. Further transformations of ecosystems and the territories dependent on the

Kakhovka reservoir require additional comprehensive systematic monitoring and in-depth research since they are indicators of adverse changes in the ecological conditions and social and economic crisis in the occupied regions.

The research results are important for substantiating the direction of social and economic revitalization and environmental rehabilitation of the affected territories in Ukraine in the post-war period. Today, the post-war restoration of the affected territories can be considered in the context of their suitability for human habitation.

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Author contributions
Vitalii Pichura—research concept and design, collection and assembly of data, data analysis and interpretation, writing the article, final approval of the article. Larysa Potravka—collection and assembly of data, writing the article, critical revision of the article, final approval of the article.

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Data availability
The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

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