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Losses in fishery ecosystem services of the Dnipro river Delta and the Kakhovske reservoir area caused by military actions in Ukraine

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We studied the development of commercial and recreational fishing on the Kakhovske Reservoir (aka Kakhovka) and the Dnipro (aka Dnieper) River lowlands in 2020–2023. The fish assemblage of the Kakhovske Reservoir is under consideration for the period 1956–2021. The dynamics of the fish population transformation, species extinction, and the emergence of new invasive species are given. The losses in Kakhovske Reservoir's ecosystem services as a result of the Kakhovska Hydroelectric Power Plant's (HPP) Dam explosion in June 2023 are analyzed. The states and prospects for local recreational and commercial fishing development are assessed. By field research and monitoring observations of the Kakhovske Reservoir and the Dnipro River lowland using the Earth remote sensing data, it was established that 2 months after the accident, the area of the remained reservoir water surface was ~430 km^2 (about 19% of the initial, including the restored Dnipro River bed). The newly formed shallow waterbodies, which do not have a water connection between each other, occupy an area of about 300 km^2. These areas continue to dry out, shrink, and become overgrown with vegetation. The draining of the Kakhovske Reservoir caused an ecological disaster for about 40 species and subspecies of fish. The total monetary losses of commercial fishing are about $5.5 million annually. Losses in fishery from the vanishing of spawning grounds are estimated at 20,000 tons of fish resources (~$40 million). The negative consequences of the loss of the Kakhovske Reservoir aquatic ecosystems will affect the socio-economic development of the entire South of Ukraine for a long time. Among the major ecosystem services lost is the cessation of water supply. Ukraine's priority issues are the post-war rehabilitation of the country, its degraded lands, territories, and water areas, and ensuring water and food security. One of the urgent problems will be the feasibility of reconstruction of the Kakhovska HPP's Dam and restoration of the Reservoir, renovation of water supply, fishery, navigation, energy, and recreation. Biodiversity is a basis for the efficient and sustainable ecosystem functions that provide many ecosystem services, and it should be considered for the post-war recovery and development of Ukraine.

KEYWORDS

ecosystem services, freshwaters, Dnipro reservoirs Cascade, fish resources, food resources, post-war recovery

1 Introduction

Freshwater ecosystems are key elements in the development and functioning of humankind and the environment. Today, they play a key role in achieving the strategic objectives (No.6) of sustainable development (UN-Water, 2016). Unfortunately, the progressive increase in wars and conflicts threatens the functioning of aquatic systems already depleted from anthropogenic pressures. Water conflicts are categorized into three types (Gleick, 2019a): "trigger", "weapon" and "casualty". According to available information (Water Conflict Chronology, 2024), more than 1,600 conflicts are accounted for in human history. The lion's share (almost 90%) occurred in the foreseeable past, between 2000 and the present (Figure 1). Predominantly, they have occurred between countries of the former Soviet Union (Peña-Ramos et al., 2021), the Middle East (Amery, 2002; Gleick, 2019b), and the African continent (Aston, 2008); a somewhat smaller share occurs in other parts of the world (Gleick and Heberger, 2014; Schillinger et al., 2020). Between 2020 and 2023 alone, 543 conflicts were recorded in which 285 times water

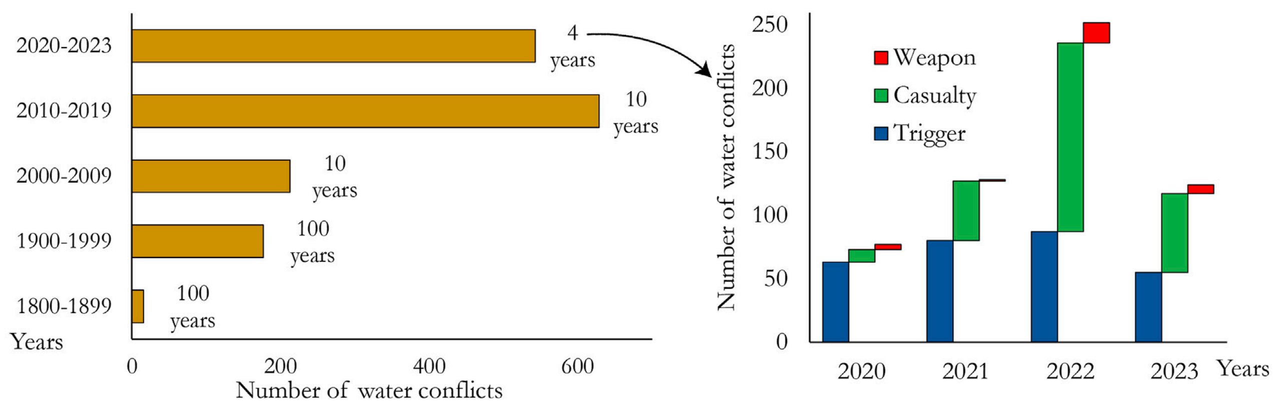

FIGURE 1
World statistics on water conflicts and their forms (according to Water Conflict Chronology, 2024).

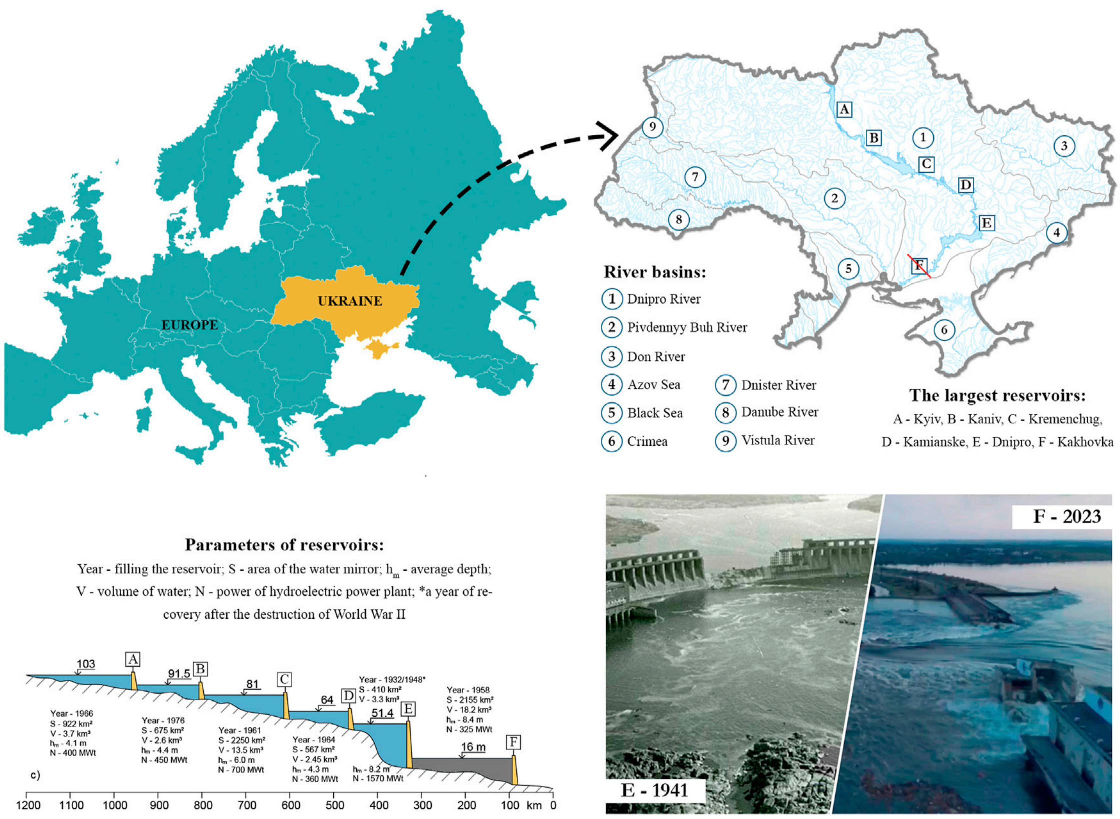

FIGURE 2
An overview map of Ukraine and general characteristics of the Dnieper Reservoir Cascade.

was used as a trigger, 268 times as a weapon, and 28 times as a casualty. The majority of these recorded cases are in the Russian-Ukrainian and Palestinian-Israeli wars.

Since the beginning of February 2022 and throughout the entire period of military operations on Ukrainian territory, critical infrastructure has been subjected to constant missile and artillery strikes. A significant number of hydraulic structures (dams, dikes, canals, water pipelines, pumping stations, etc.) have been destroyed. The total losses of the economy as a result of the war (fall in GDP levels, cessation of investment, labour outflow, additional expenditures on defense and social support, etc.) amount to about $600 billion (Kyiv School of Economics, 2023).

It should be noted that in the history of the Ukrainian state, there has already been a case of destruction of a large hydroelectric facility. To impede the movement of German troops during World War II, the Dnieper Dam was blown up in 1941 (Figure 2). At that time, at the height of the war and during the post-war reconstruction period, the impact of the reservoir's emptying on the loss of ecosystem services and ecological catastrophe for the environment was hardly investigated. The fortunate choice of the location of the hydrosystem site within the canyon-type area did not cause significant flooding in the area compared to other plain-type reservoirs. Industrialisation and rapid post-war development of the country's economy made it possible to rebuild the hydraulic structure and restore the reservoir within a short period of 4 years (1944–1947).

Ukraine is the country with one of the lowest water availabilities in Europe, and rapid climatic changes and anthropogenic pressure on aquatic ecosystems are leading to a decrease in the water volume in rivers and deterioration of water quality there (Hapich et al., 2022a; Chushkina et al., 2024). Today, the total volume and runoff of water resources in the territory of Ukraine is estimated at 55 km^3 per year (Khilchevskyi, 2021). The development and necessity to provide water resources for industries, municipal and household water supply, agriculture, and fishery led to the construction of a large number of reservoirs and ponds in the 20th century. The six largest reservoirs were created on the Dnipro (aka Dnieper) River: Kyivske (aka Kyiv) Reservoir, Kanivske (Kaniv), Kremenchutske (Kremenchuk), Kamianske, Dniprovske (Dnieper) Reservoir, and Kakhovske (Kakhovka) one–the last in the Dnipro Cascade (Vyshnevskyi and Shevchuk, 2021). In June 2023, as a result of the explosive demolition of the Kakhovska Hydroelectric Power Plant (HPP) Dam and hydrodynamic accident, the Kakhovske Reservoir, which provided numerous ecosystem services in the arid territory of southern Ukraine, was completely drained and ~18 km^3 of fresh water was irretrievably lost (Hapich and Onopriienko, 2024). The scale of the disaster as a crime against nature has already been characterized as « ecocide» (Stakhiv and Demydenko, 2023).

The flooding from the Kakhovska Dam washed small islands, areas of floodplain forests and steppes, floodplain meadows, and slopes with all their inhabitants into the Black Sea. The bottom sediments of the Kakhovske Reservoir contain pollutants (Cd, Mn, Fe, and many others) accumulated over decades because of huge industrial emissions (Afanasyev, 2023b; Klitina, 2023). Monitoring stations recorded high levels of heavy metals (Cd, As, and Cu), petroleum by-products, and PCBs in the Black Sea (Stone, 2024). The consequences of sea poisoning will sequentially manifest in the Black Sea region: in Romania, Bulgaria, Turkey, and then in Russia (Klitina, 2023). Bacteriological and chemical pollution has been recorded in both the lower Dnipro River and the northwestern part of the Black Sea (Vyshnevskyi et al., 2023)

As a result of the demolition of the Kakhovska HPP Dam, the near-estuarine zone of the Black Sea has undergone a rapid desalination process. The salinity of water off the Odessa coast was almost 2.7–3.7 times lower than normal for a certain period. Some marine fish and mussels have died, but this amount is not critical to populations (Hubareva, 2023; Stone, 2024). At the same time, the breakthrough of a huge amount of fresh water was disastrous for the few sturgeons living in the Dnipro River, because the beginning of summer is the peak of the breeding season in the spawning grounds downstream of the Kakhovska Dam, where the fish come from the Black Sea. Many Black Sea roaches (Ministry of Agrarian Policy of Ukraine, 2022), the Dnieper barbels (Ministry of Agriculture of Ukraine, 2023), and the Sarmatian bleaks (Brown et al., 2007) appear to have died. The population of estuarine perch (Sander marinus (Havrylenko, 2018)) is highly likely to be extinct (Afanasyev, 2023b; Stone, 2024). Ecological disasters due to the explosion of the Kakhovska HPP Dam may lead to significant changes in the structure of communities not only of fish but also of their parasites. How this may affect the fishery's ecosystem services cannot yet be predicted.

The military actions of the Russian Federation against Ukraine began in March 2014 with the occupation of the Crimean Peninsula and parts of Donetsk and Luhansk regions. During 8 years of the hybrid war, later (24.02.2022) Russian forces invaded the territory of Ukraine. In the 21st century, the Russian-Ukrainian war exceeds all other military conflicts studied in the last 80 years in terms of scale and consequences (Shevchuk et al., 2022). Military actions during war have a significant impact on landscapes and territories, causing diverse long-term negative consequences (Pereira et al., 2022). The war in Ukraine has caused significant damage and worsened the landscapes of more than 16% of natural territories (~104,000 km^2), affected the access of people to quality drinking water, and the loss of many ecosystem services in water bodies (Afanasyev, 2023a). The disruption of many dams as strategic elements of transport connections and structures for the accumulation and retention of water resources has caused significant social and economic losses and caused a certain danger to aquatic ecosystems and their biodiversity (Shevchuk et al., 2022; Novitskyi et al., 2024). In addition to the Kakhovske Reservoir, accidents on the Irpin River (Kyiv Region), the devastation of the Oskolske Reservoir (from the initial water volume of 435 million m^3 only 80 million m^3 remained), damage to the Karachunivske Reservoir, *etc.*, are some other examples of such nature destruction (State Agency, 2023). The volume of commercial fishing in the Dnipro Reservoirs Cascade declined in half, and in the Black and Azov Seas by more than 80%. All this has led to negative consequences in recreational and commercial fishing, and therefore in the food that freshwater ecosystems provide humans as an ecosystem service.

Scientists note that freshwater biodiversity in Europe is declining at an alarming rate: 37% of freshwater fish species are now threatened with extinction (Reid et al., 2018) and fish numbers in existing populations are declining at a particularly rapid rate (Tickner et al., 2020). Habitat loss due to climate change and anthropogenic modification of river hydrology is recognised as a key stressor affecting biodiversity in freshwater ecosystems (Strayer and Dudgeon, 2010; Ekka et al., 2020; Novitskyi et al., 2023). However, the current negative situation with biodiversity in Europe may get worse due to the emergence of new threats, which are military conflicts and wars (Baumann and Kuemmerle, 2016). During military operations, all environment-oriented, reproduction activities and resource use become more complicated, and ecosystem services are disrupted.

The purpose of our research is to study the consequences of the Kakhovske Reservoir drainage and preliminary assess the loss in fishery and ecosystem services of the Dnipro River Delta and the area of the former reservoir.

2 Materials and methods

In 2020–2023, we studied the development of industrial and recreational fishing in the Kakhovske Reservoir and the lowlands of the Dnipro River. The research was based on theoretical (retrospective review, comparative analysis, mathematical modeling, and forecasting), field, and experimental methods. Official data from the Departments of the State Agency of Land Reclamation and Fisheries of Ukraine (State Agency, 2023) were used.

During the assessment of environmental consequences and economic losses caused to the fishery, the following research methods were used: analytical–a collection of information from official sources of enterprises and institutions that carried out economic activities, control and monitoring observations of the reservoir; hydrobiological–determination of the species composition of fish and other hydrobionts; statistical–qualitative and quantitative assessment of industrially valuable ichthyofauna and the economic losses caused to the fishery; geo-informational–assessment of the modern hydrological regime of the river within the reservoir; to determine the spatial layout, quantitative and qualitative characteristics of water bodies, which were formed after the drainage of the reservoir; predictive–assessment of the potential transformation of the biodiversity in the ecosystems over time under various conditions of further development of the water management industry in Ukraine.

The ichthyological complex of the Kakhovske Reservoir was studied in the period from 1956 to 2021 with an emphasis on the dynamics of the fish population transformation, species extinction, and the emergence of new invasive species. The material was collected according to standard research methods (Arsan et al., 2006; Bonar and Hubert, 2009). Fish protection categories were determined according to the Red List of Ukraine (2021) and the IUCN Red List categories (2023). Systematic names of species are given according to the recent updates (Movchan, 2011; Nelson et al., 2016).

According to the UN document « Millennium Ecosystem Assessment. Ecosystems and Human Wellbeing: Synthesis» (2005) a variety of ecosystem services (ES), that people obtained from the Kakhovske Reservoir and which were lost as a result of its destruction in 2023, were identified.

Research on the state of recreational fishing was conducted in the following directions: a) accounting of recreational fishers (fishing trips); b) collection of information on qualitative and quantitative indicators of catches (Lockwood et al., 1999; Grati et al., 2021; Buzevych et al., 2022). The number of fishing trips was recorded at different times of the day, on weekdays, and on days off in all seasons. The fishers who were fishing simultaneously during the accounting period in the studied area of the reservoir were subject to accounting. Fishers who fish from the shore (bridges, piers, etc.) and watercraft (boats, cutters) were counted separately.

In addition to our observations, the interview method of field survey (Giovos et al., 2018; Novitskyi et al., 2022) was used to collect primary information and study some social aspects of recreational fishing.

The number of fishing trips for a certain period (month, season, year) was calculated according to the average daily indicator for the given period and the number of days in the period Formula (1):

$$\hat{N}_p = \frac{\sum_{j=1}^{k_w} N_{wj}}{k_w} D_w + \frac{\sum_{j=1}^{k_r} N_{rj}}{k_r} D_r = \bar{N}_w D_w + \bar{N}_r D_r, \tag{1}$$

where, $\hat{N}_p$– estimated number of fishing trips for period p (*fishing trips*); N_{wj}–number of fishing trips on a weekday based on the accounting result j; N_{rj}–number of fishing trips on days off based on the accounting result j; $\bar{N}_w$–the average number of fishing trips on weekdays; $\bar{N}_r$–the average number of fishing trips on days off; k_w–number of accountings carried out on weekdays; k_r–number of accountings carried out on days off; D_w–number of weekdays per period; D_r–number of days off per period.

One completed fishing trip corresponds to one recreational fishing effort applied by one recreational fisher and is evaluated in *fishing hours*. One fishing effort covers the time from arrival at the fishing site to departure. Fishing hours reflect the total amount of time in hours spent on fishing by amateur fishers for a certain period on the reservoir (or its area) (Maksymenko, 2015).

The fishing effort of recreational fishing was calculated according to Formula (2):

$$E = \bar{h}\hat{N}_p, \tag{2}$$

where, E–the fishing effort of recreational fishing, calculated for the period p (*fishing hours*); $\bar{h}$–average duration of completed fishing (*hours*).

The assessment of losses in industrial and recreational fishing in the Kakhovske Reservoir due to the complete drainage of littoral areas and the loss of spawning grounds, biotopes for the feeding period of young fish, and feed base for the development of fish farming was carried out according to the following methods. Following the well-described methods (Methodology, 1995), the calculation of spawning productivity for a specific type of fish was made based on the expected industrial return from the ratio:

$$P_{sp} = (B \cdot d \cdot Q \cdot k \cdot r) \big/ \left(F_{sp} \cdot 10\right), \tag{3}$$

where, P_{sp}–fish productivity of spawning grounds by industrial return, kg/ha; B–total industrial stock for 2023, tons; d–coefficient that takes into account the share of breeders in the industrial stock; Q–average fertility, thousands of eggs; k–industrial return from caviar, %; r–share of females in the herd, %; F_{sp}–area of spawning grounds, ha.

Losses in monetary value:

$$N = P_{sp} \cdot F_i \cdot W, \tag{4}$$

FIGURE 3
Drainage of the Kakhovske Reservoir near the city of Zaporizhzhia (12 July 2023, 1 month after the destruction of the HEP dam), *photo by M. Maksymenko*.

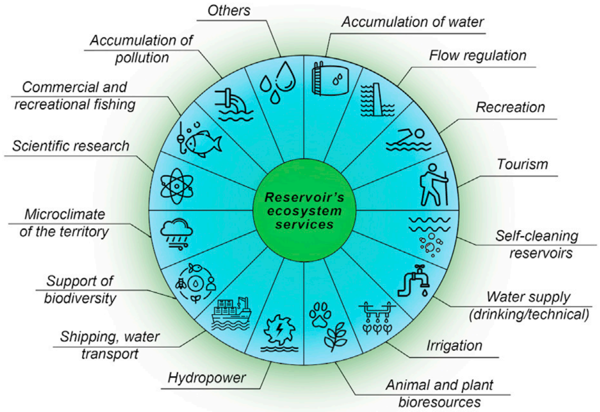

FIGURE 4
Main losses of ecosystem services in the former Kakhovske Reservoir.

where, *N*–loss in fishery, $; F_i–damage area of spawning grounds, ha; *W*–cost of 1 kg of fish at market prices in the region in June 2023. The calculation was based on the condition that $F_i = F_{sp}$

Indicators of limits and forecasts of permissible special use of water bioresources of national importance in the Kakhovske Reservoir for 2023 were used as primary fish data for damage calculations (On the approval, 2022). At the same time, it was taken into account that in 2023 the amount of permissible catch was set as 30% of the formed industrial stock. The share of breeders in the commercial herd was determined following the norms of bycatch of immature fish (Rules for commercial fishing, 2023) and was accepted as d = 0.8. Biological indicators for the ichthyofauna in the Kakhovske Reservoir were determined as previously described (Methodology, 2004). Data processing and analysis (Zar, 2010) were made with Statistica 10.0 (Statsoft Inc.).

It should be noted that today the continuation of military activities in the southern and eastern parts of Ukraine, on the left bank of the Dnipro River within Kherson and part of Zaporizhzhia regions and in the Dnipro River's estuary, which are under Russian occupation, is the limiting factor for the field research. It makes having direct access to the entire water area and conducting thorough comprehensive research impossible.

3 Results

3.1 General information about the Kakhovske reservoir

The Kakhovske Reservoir was built and filled with water in 1955–1958. In the Dnipro Reservoirs Cascade, it was the second largest (after Kremenchutske one) with an area of 2,155 km^2 and more than 18 km^3 of fresh water. The throughput capacity of the Kakhovska HPP was 2,600 m^3/s. In the 1960s–1990s, water exchange of the reservoir occurred 2–3 times a year. As a result of current climate change, global warming, and low water in the rivers of Ukraine, the recent water exchange of the Kakhovske Reservoir in some years was less than 1 time per year.

On 6 June 2023, the Kakhovska HPP Dam was destroyed. According to the Ukrainian Hydro-meteorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine (Kakhovske Reservoir, 2023) on 17 June 2023, the total water surface area of the remained shallow areas in the Kakhovske Reservoir together with the restored watercourse of the Dnipro was 655.9 km^2 (31.8% of its initial area). On 18 June 2023, the complete emptying of the reservoir and the full stop of further intensive discharge of water through the destroyed Kakhovska HPP was recorded.

The use of the *LandViewer* of the *EOSDA* portal allowed us to monitor the water area of the Kakhovske Reservoir and the lowlands of the Dnipro River employing Earth remote sensing data (RSE). It was established that 2 months after the accident, the area of the remained water surface of the reservoir was ~430 km^2 (about 19%) from the initial, including the restored watercourse of the Dnipro River (Figure 3). At the same time, a significant part of it falls on disconnected water bodies of the former reservoir, which occupy an area of about 300 km^2 and continue to decrease, and vegetation is actively developing in the reservoir bed.

3.2 Ecosystem services of the Kakhovske reservoir and their losses

In 2005, the UN published a report « Millennium Ecosystem Assessment. Ecosystems and Human Wellbeing: Synthesis», where the expanded concept of "ecosystem services" (ES) is given. Ecosystem services were recognized as advantages and benefits that people get from ecosystems–obtaining resources, drinking water, food, regulatory services, support services, cultural, and other tangible and intangible benefits. The document outlines four ES categories: supporting, regulating, provisioning, and cultural (Millennium Ecosystem, 2005).

The most important ecosystem service of the Kakhovske Reservoir (as a large technical-natural reservoir) is the accumulation of water for

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Genus	Types of fish	[1] until 1956	[1,2] 1960-1991	[3,4] 1992-2021	Type of nutrition	Environmental group
Acipenseridae	*Huchen *Huso huso ponticus*	-	-	-	A, B	Rheophile
	*Sterlet *Acipenser ruthenus*	+	-	-	A	Rheophile
	*Russian sturgeon *Acipenser gueldenstaedtii*	-	-	-	A	Rheophile
	*Starry sturgeon *Acipenser stellatus*	-	-	-	A	Rheophile
	*Fringebarbel sturgeon *Acipenser nudiventris*	-	-	-	A	Rheophile
Clupeidae	Black Sea sardelle *Clupeonella cultriventris*	+	+	+	C	Limnophilus
	Danube shad *Alosa caspia nordmanni*	+	-	+	C	Limnophilus
	Black Sea shad *Alosa pontica*	+	+	+	C	Limnophilus
Cyprinidae	*Dace *Leuciscus leuciscus*	+	+	+	A	Rheophile
	European chub *Leuciscus cephalus*	+	+	+	B, F	Rheophile
	Don chub *Leuciscus borysthenicus*	+	-	-	D	Limnophilus
	*Ide *Leuciscus idus*	+	+	+	D	Rheophile
	Roach *Rutilus rutilus*	+	+	+	A	Limnophilus
	*Kutum *Rutilus frisii*	-	-	-	A	Rheophile
	Rudd *Scardinius erythrophthalmus*	+	+	+	D	Limnophilus
	*Andermouth *Chondrostoma nasus*	+	+	+	E	Rheophile
	*Pontian shemaya *Alburnus sarmaticus*	+	-	-	F	Rheophile
	Bleak *Alburnus alburnus*	+	+	+	D	Limnophilus
	Owsianka *Leucaspius delineatus*	+	+	+	C	Limnophilus
	Vimba *Vimba vimba*	+	+	+	A	Rheophile
	White bream *Blicca bjoerkna*	+	+	+	A	Limnophilus
	Common Bream *Abramis brama*	+	+	+	A	Limnophilus
	Whate-eye bream *Abramis sapa*	+	-	-	A	Rheophile
	Blue bream *Abramis ballerus*	+	+	-	C	Limnophilus
	Asp *Aspius aspius*	+	+	+	B	Rheophile
	**Silver carp *Hypophthalmichthys molitrix*	-	+	+	G, H	Limnophilus
	**Spotted silver carp *Aristichthys nobilis*	-	+	+	C, H	Limnophilus
	Sablefish *Pelecus cultratus*	+	+	+	B, C	Rheophile
	Amur bitterling *Rhodeus amarus*	+	+	+	D	Limnophilus
	**Stone moroco *Pseudorasbora parva*	-	+	+	C, D	Limnophilus
	Gudgeons *Gobio gobio*	+	+	+	A	Rheophile
	*Dnepr barbel *Barbus barbus borysthenicus*	+	-	-	A, D	Rheophile
	**Grass carp *Ctenopharyngodon idella*	-	+	+	I	Limnophilus
	Common carp *Cyprinus carpio*	+	+	+	A, D	Limnophilus
	*Crucian carp *Carassius carassius*	+	+	+	A, D	Limnophilus
	**Golden carp *Carassius gibelio*	-	+	+	A, D	Limnophilus
	Tench *Tinca tinca*	+	+	+	A	Limnophilus
Anguillidae	*Common eel *Anguilla anguilla*	+	-	+	B	Rheophile
Cobitidae	Spiny loach *Cobitis taenia*	+	+	+	A	Limnophilus
	Loach *Misgurnus fossilis*	+	+	+	A	Limnophilus
Ictaluridae	**Channel catfish *Ictalurus punctatus*	-	-	+	B	Limnophilus
Siluridae	European wels *Silurus glanis*	+	+	+	B	Limnophilus
Esocidae	Pike *Esox lucius*	+	+	+	B	Limnophilus
Lotidae	*Freshwater cod *Lota lota*	+	+	+	A, B	Limnophilus
Atherinidae	**Black Sea big-scale sand smelt *Atherina boyeri pontica*	+	+	+	J	Limnophilus
Gasterosteidae	Three-spined stickleback *Pungitius platygaster*	+	+	+	F	Limnophilus
	Southern nine-spined stickleback *Gasterosteus aculeatus*	+	+	+	F	Limnophilus
Syngnathidae	Pipefish *Syngnathus abaster*	+	+	+	D	Limnophilus
Centrarchidae	**Sunfish *Lepomis gibbosus*	-	-	+	B	Limnophilus
Percidae	European pikeperch *Sander lucioperca*	+	+	+	B	Limnophilus
	*Volga zander *Sander volgensis*	+	+	+	B	Limnophilus
	Perch *Perca fluviatilis*	+	+	+	B	Limnophilus
	*Percarina *Percarina demidoffii*	-	+	+	B	Limnophilus
	*Don ruffe *Gymnocephalus acerinus*	+	-	-	A, B	Limnophilus
	European pikeperch *Gymnocephalus cernuus*	+	+	+	A	Limnophilus
Gobiidae	Longtail dwarf goby *Knipowitschia longecaudata*	-	+	+	A	Limnophilus
	Round goby *Neogobius melanostomus*	+	+	+	A	Limnophilus
	Big-headed goby *Neogobius kessleri*	+	+	+	A	Rheophile
	Monkey goby *Neogobius fluviatilis*	+	+	+	A	Rheophile
	Goad goby *Neogobius gymnotrachelus*	-	+	+	A	Rheophile
	Toad goby *Mesogobius batrachocephalus*	+	+	+	B	Limnophilus
	Tube-nosed goby *Proterorhinus marmoratus*	+	+	+	A	Limnophilus
	*Starry goby *Benthophilus stellatus stellatus*	+	+	+	A	Limnophilus
15	63	48	48	51	← Total	

Legend: A - bentophage; B - predator; C - zooplanktonophage; D - euryphagus; E - periphytophagus; F - zoophagus; G - phitoplanktonophage; H - detritophagus; I - phytophagous; J - planktophagous

Rheophile; Limnophilus; *species listed in the Red Book of Ukraine (2021); **alien species and self-displaced people (from the sea); + existence; - nothing; fish species are valuable for commercial fishing; do not represent value for industrial fishing

References: [1] Shcherbukha et al., 1995; [2] Movchan, 2005; [3] Buzevych, 2012; [4] Novitskyi et al. 2022

FIGURE 5
Structural and functional characteristics of fish assemblage in the former Kakhovske Reservoir.

various needs. Water supply is the most important service for the wellbeing of people and various sectors of the economy, provided by river (reservoir) ecosystems. The second ES of the reservoir is the ability to regulate the flow in general and flooding in particular. Regulating the flow led to the emergence and operation of another service–the improvement of shipping conditions (transportation conditions). Many other services are important, for example, regulation of water levels and erosion, self-cleaning, and accumulation of pollutants, including radioactive ones (Rudakov et al., 2023). Recreation and ecotourism are the most valuable cultural services.

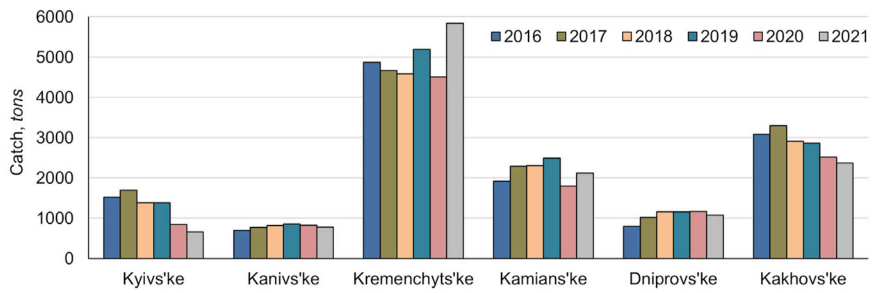

FIGURE 6
Harvest of aquatic biological resources in the Dnipro Reservoir Cascade.

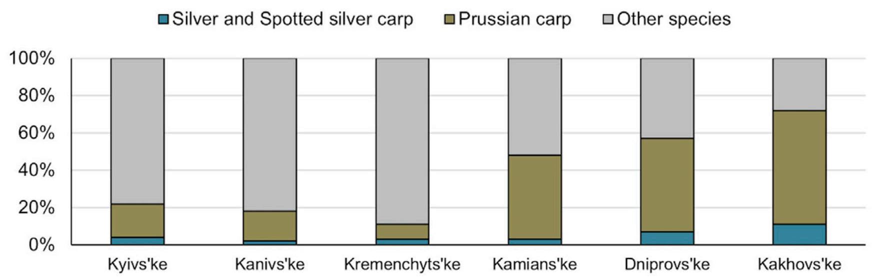

FIGURE 7
Average long-term share of Golden carp and herbivorous fish in the commercial catches at the Dnipro Reservoir Cascade.

According to recent research (Uzunov and Protasov, 2019; Protasov and Uzunov, 2021), Kakhovske Reservoir provided an important ES for delivering drinking and technical water to more than five million people by filling the North Crimean Canal, the Dnipro-Kryvyi Rih Canal, and the Kakhovka and North Rohachynsk irrigation systems with a total area of ~750,000 ha. In addition, the reservoir provided a cooling service for the condensers of Zaporizhzhia NPP (6 GW) and Zaporizhzhia TPP (3.6 GW). For all reservoirs of the Dnipro Cascade, and the Kakhovske in particular, it is possible to note the services of plankton (production and destruction of organic matter, increasing the food base for fish), services of benthos (due to filter mollusks, a significant potential for self-cleaning of reservoirs is achieved), services of periphyton (production of hundreds of thousands of tons of oxygen per season), nekton services (food for fish, biological resources). After the catastrophic drainage, the Kakhovske Reservoir lost almost all the ecosystem services that people obtained from the reservoir as benefits (Figure 4).

In the period from the Dam construction (1952–1956) according to different research, the fish assemblage in the Kakhovske Reservoir had got from 42 (Buzevych, 2012) to 56 species (Shcherbukha et al., 1995). A recent study (Novitskyi et al., 2022) registered 39 species of fish (Figure 5). Fish are known to play an important role in nutrient and energy cycling at different trophic levels by regulating aquatic ecosystem food net dynamics (McManamay et al., 2011). They also contribute to food and livelihoods for millions of people worldwide (Lynch et al., 2016).

The catch and sale of aquatic bioresources from the Kakhovske Reservoir in the pre-war period provided no less than 22% of freshwater fish harvest (Novitskyi and Horchanok, 2022) on the market of Ukraine. In terms of commercial fish catch, the Kakhovske Reservoir took second place in the overall harvest in the Dnipro Reservoirs Cascade (after the Kremenchutske Reservoir) (Figure 6).

Commercial fishing (fishery) was based on 20 industrially valuable fish species, among which the main share of Golden carp and herbivorous fish–Silver carp and Spotted silver carp (Figure 7).

Following the above-mentioned methods of loss calculating in the fishing industry, it was established that the average long-term commercial catch of fish in the Kakhovske Reservoir was in the range of 2,500–3,000 tons per year. Taking into account the current prices for fresh fish in Ukraine in 2023, the total loss in monetary value amounts to about $5.5 million per year. Losses of fisheries from the disappearance of spawning grounds are estimated at 20,000 tons of fish (~$40 million).

Recreational fishing is known to be a type of ecosystem service (Kaemingk et al., 2022; Lennox et al., 2022). Active water recreation (boating, swimming, fishing, etc.) provides many psychosocial advances and generates corresponding economic outcomes, providing important health benefits (Venohr et al., 2018). At the same time, recreational fishing is a powerful factor influencing aquatic ecosystems, fish assemblages, and plant communities (Wortley, 1995). Novitskyi (2015) calculated the taking out of aquatic bioresources from the reservoirs of Ukraine as fishery (commercial fishing) that averaged 30%–35%, recreational fishing–40%–45%, and illegal fishing–at least 25%–30% of the total harvest.

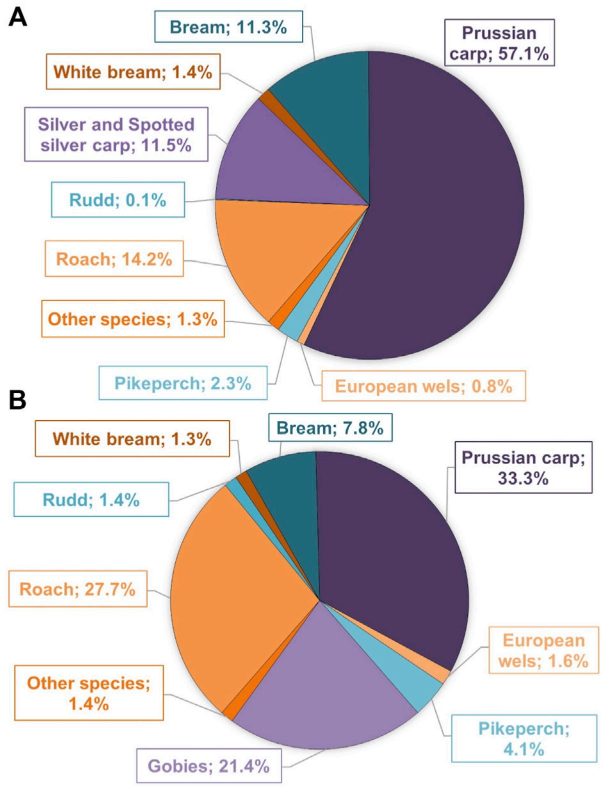

FIGURE 8
Main fish species in the catches at the Kakhovske Reservoir: **(A)** commercial catch, **(B)** recreational fishing.

Thus, recreational fishing is a powerful factor to be considered in nature management, competing with industrial freshwater fishing in Ukraine. Our study notes that recreational fishers caught 34 species in the Kakhovske Reservoir. The ratio of the main commercial fish species in commercial and recreational fish catches is presented in Figure 8. Golden (Prussian) carp was found as dominant in amateur catches.

The total annual catch of fish by recreational fishers at the Kakhovske Reservoir within the boundaries of the Zaporizhzhia region (47.2% of the total water area of the reservoir) was about 586 tons or 6.93 kg/ha of the water area in 2017–2021. Goby species dominated in the total catch in terms of specimen number (Figure 9), and Golden carp (179.6 tons)–in terms of catch weight. The catch volume of the roach was 95.3 tons, and the common bream was 52.9 tons. The total share of predatory fish species (pike, European chub, asp, wels catfish, pikeperch, and perch) was 69.96 tons. The pike perch (43.6 t of the total catch) and wels catfish (21.4 t) are dominant among predators. At the same time, over the entire Kakhovske Reservoir, the total catch was estimated at 747 tons or 3.5 kg/ha (Maksymenko, 2015; Novitskyi et al., 2022).

According to the obtained data on the upper and middle parts of the Kakhovske Reservoir, the largest number of fishing trips per year is concentrated in the 1 section of the reservoir (41%) and floodplains (35% of the total number of trips). The upper part of the Kakhovske Reservoir is up to 28% of the reservoir water surface area, but this part of the reservoir has the largest number of fishing trips–53% of the total accounted number (3.2 fishing trips/ha). The lowest number of trips falls on the lower part of the reservoir–19%, or 1.1 fishing trips/ha.

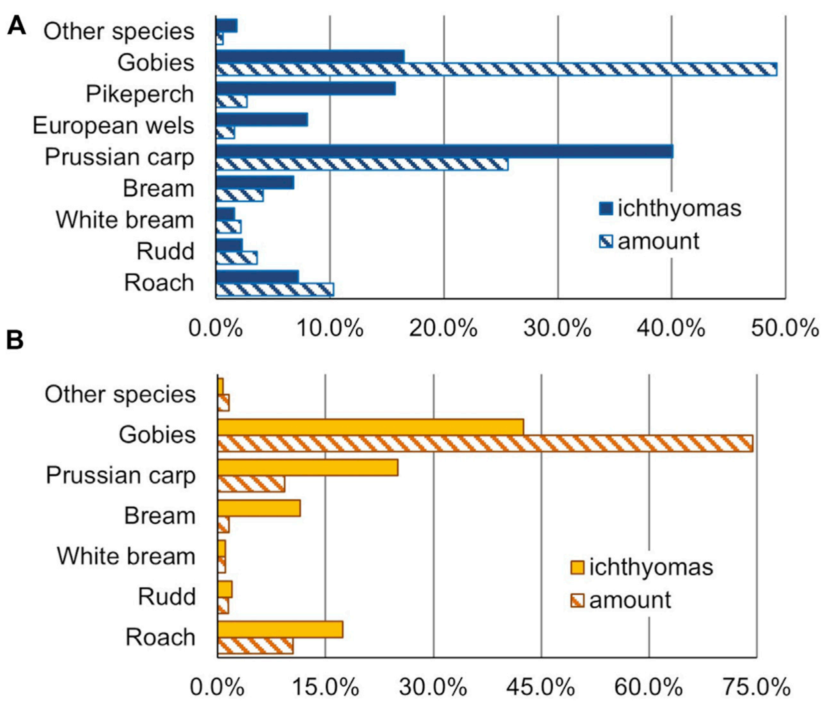

FIGURE 9
Proportion of catch of main fish species in the Kakhovske Reservoir: **(A)** commercial catch, **(B)** recreational fishing.

TABLE 1 Indicators of recreational fishers visits to the Kakhovka Reservoir in 2000–2021.

Indicator	Year			
	2000 (Drobot et al., 2003)	2002–2006 (Maksimenko, 2011)	2013 (Maksimenko and Rudyk-Leuska, 2013)	2021 (Novitskyi et al., 2022)
Area of the water surface **S**, thousand ha	215.5			
Estimated number of fishing trips **N**, thousand	568.3	278.3 ± 46.9	356.7	256.4
The average duration of completed fishing **h**, hours	5.0 ± 0.0	5.8 ± 0.2	5.6 ± 0.0	4.9 ± 0.1
Estimated annual indicator of fishing effort **E**, thousands of fishing hours	2,855.8	1,620.8 ± 425.6	1980.2	1,256.4
Estimated annual indicator of density N_S, fishing trip/ha per day	2.6	1.3 ± 0.2	1.7	1.2
Loading E_S, fishing hour/ha	13.3	7.5 ± 1.3	9.2	5.8

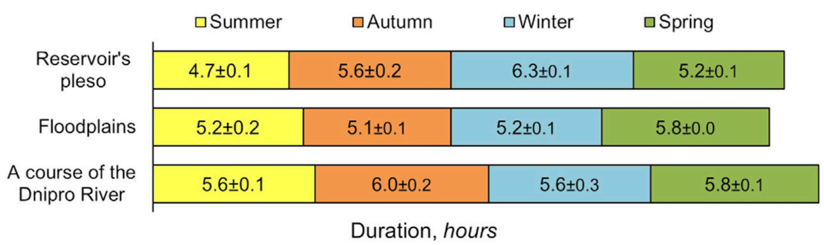

FIGURE 10
The average duration of completed fishing at the Kakhovske Reservoir depending on the season and place.

In Table 1 the averaged data on visits to the Kakhovske Reservoir by recreational fishers in 2000–2021 are presented. The visitation is related directly to the amount of anthropic impact on the shores and water area of the reservoir. The duration of completed fishing indicates directly the prospects of a certain section of the Kakhovske Reservoir for successful fishing. The average duration of completed fishing in the water area of the reservoir, depending on the season and fishing location, varied from 4.7 to 6.3 h (Figure 10).

The destruction of the Kakhovske Reservoir Dam in June 2023 caused an ecological disaster for about 40 species and subspecies of fish. In general, more than 11,000 tons of fish were lost due to the impact of sudden drainage, and estimated losses from disruptions of ecosystem services reach about $270 million (State Agency, 2023).

In Figure 11, data on the ecological losses in the Kakhovske Reservoir from the destruction of the fishery, forage base of fish, and spawning grounds, including in financial terms are presented.

It should be noted that the research covered shallow water areas of 9,313 ha throughout the reservoir, which ensures their high reliability and representativeness. Thus, the obtained results can be extrapolated to the entire water area of the reservoir and partly to the Dnipro River Delta.

4 Discussion

After the Dam destruction, the significant water flow velocity during dewatering resulted in flooding of the lower sections of the reservoir from Kherson, Oleshki, Gola Prystan, and further to the Dnipro estuary. On 9 June 2023, the rate of water level decline in the upper section of the Kakhovske Reservoir allowed many fish to respond to the change in hydrological regime and mostly leave the shallowed areas. However, the majority of limnophilic species groups moved downstream, to the Dnipro estuary, or got to the newly formed floodplains beyond the former shoreline. The fauna of the reservoir, carried away by the flow of water into the floodplains formed below the Kakhovska HPP dam, mostly died with the further lowering of the "flood" wave and washing ashore. Unlike fish, which could move actively and migrate downstream, benthic organisms, primarily mollusks, remained on the drained bottom of the Kakhovske Reservoir. According to the estimates of the Institute of Hydrobiology of the National Academy of Sciences of Ukraine, headed by Professor Serhii Afanasiev, in the first days of the disaster, no less than 500,000 tons of bivalve mollusks were found on land and died (Afanasiev, 2023b). He also claims that the sudden desalination of significant water masses in the Dnipro estuary could contribute to the destruction of rare species populations protected by the Red List of Ukraine and the IUCN, in

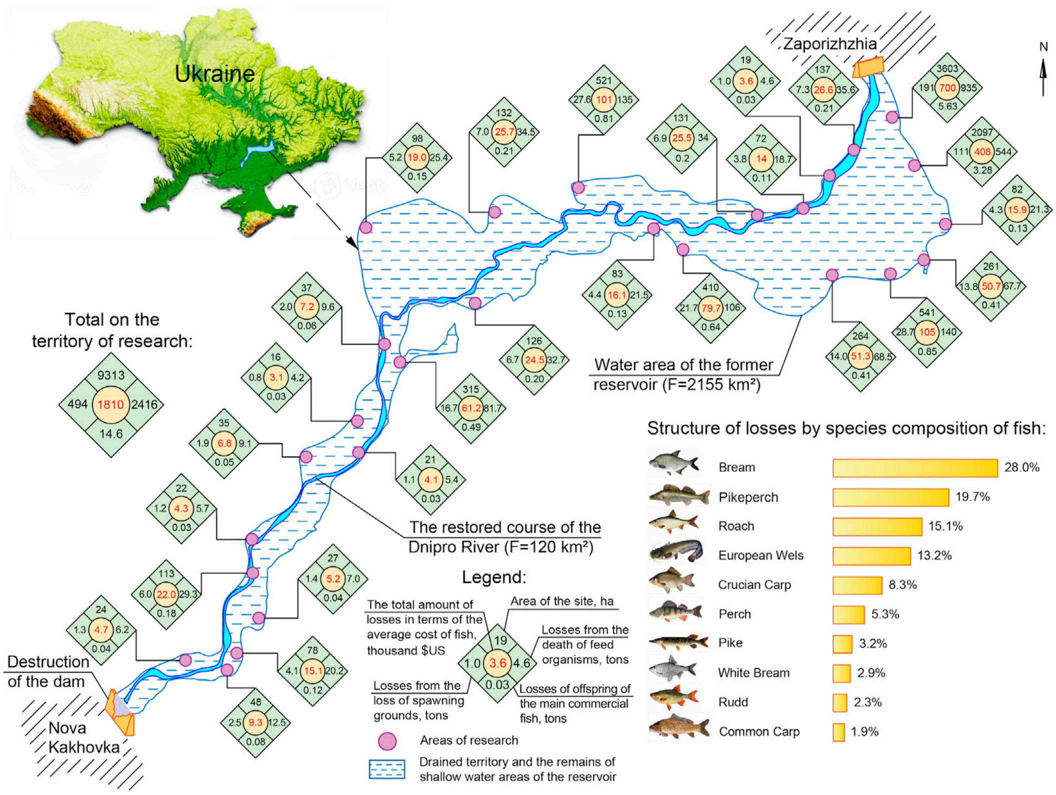

FIGURE 11
Summarized data on ecological losses in the fishing at the Kakhovske Reservoir.

FIGURE 12
Fish mortality in the Kakhovske Reservoir near the village of Lysogirka, Zaporizhzhia district (15 June 2023, on the 10th day after the HPP destruction), *photo by M. Maksymenko*.

particular, the pike *Sander marinus*, which lived there and in the Dnipro-Buh estuary ecosystem in general.

On 18 June 2023, the complete emptying of the reservoir and ending of further intensive evacuation of water through the Kakhovska HPP was recorded. The death of hydrobionts continues in the newly-formed isolated lakes: part of the Balabinsk Bay, lakes in the Khortytsia Island floodplain, parts of the rivers Sukha Moskovka, Mokra Moskovka, Yanchekrak, Konka, Karachekrak and others (Figure 12).

In this study, we did not calculate and assess the vegetation loss in the Kakhovske Reservoir, the reserves of which in the reservoir are significant and amounted to about 50,000 tons in air-dry mass (Spesivyi, 2006). Phytoplankton biomass values according to the seasons made it possible to assign the Kakhovske Reservoir to the category of reservoirs with high nutrition (forage). Due to the production of phytoplankton, it was possible to ensure a potential increase in the ichthyomass of planktonophagous fish in the range of 62–112 thousand tons (Report, 2001), which increases significantly the number of potential losses of fish farming in the Kakhovske Reservoir.

Calculations of feed base losses in the reservoir may also be underestimated because it is impossible to calculate the exact amount of zoobenthos species loss. In 1996–2000, the reservoir was classified as medium or highly nutritious in terms of the level of forage zoobenthos development. The average fish capacity in the Kakhovske Reservoir assessed by zoobenthos was 632.7 kg/ha (Report, 2001).

The catastrophic devastation of the reservoir led to the appearance of a lotic hydroecosystem as it was in the early 1950s. In fact, the Dnipro River from the city of Zaporizhzhia to the Dnipro River estuary (340 km) is no longer regulated. Hydrological changes are taking place in the Dnipro-Buh estuarine region, where the lack of fresh water is gradually being compensated by filling the shelf zone with salt water from the Black Sea. Reducing the flow of the Dnipro and increasing salinity will change significantly the conditions of the existence of hydrobionts, especially self-displaced and alien species (Semenchenko et al., 2015; Novitskyi et al., 2019; 2023). These species can displace native flora and fauna, leading to a loss of natural local biodiversity. A significant social-economic problem of increasing water salinity in the water system of the Dnipro-Buza estuary region may cause a change in the water management status of the Dnipro outflow.

According to the annual reports of the Department of Ecology and Natural Resources in the Kherson region, on average, about 1,035 million m^3 of Dnipro water is used for drinking, sanitary and hygienic, production, agricultural and other needs (Korzhov and Kucheriava, 2018). Water from the outflow of the Dnipro is ly used for water supply in more than 30 settlements, together with Kherson and Mykolaiv.

Before the draining, the reservoir was characterized by a small percentage of shallow waters with depths of up to 2 m (5%), which was always a significant adverse factor limiting the number of phytophilous fish in the reservoir (Report, 2001). Currently, the Kakhovske Reservoir has lost all spawning grounds, which makes it impossible for the effective reproduction of phytophiles in river conditions in the near future. Increased mortality due to the loss of protected biotopes (locations) is one of the reasons for the decline of mature (adult) fish populations (Arthington et al., 2016; Hermoso et al., 2016). According to forecasts (State Agency, 2023), it will take at least 10–12 years to restore stocks of the main commercial aquatic biological resources to the state that preceded the disaster.

According to the reports of recreation fishers, only 8 species of fish (Golden carp, Common bream, Roach, Common carp, Bleak, White bream, Perch, Round goby) were caught in the Dnipro water course (Zaporizhzhia city) in August-September 2023. The status of predatory piscivorous fish downstream of the Dnipro remains uncertain. It is known that a change in the number and diversity of large predatory fish causes the launch of trophic cascades on the scale of the entire hydroecosystem (Fox et al., 2012), which have detrimental consequences for the further functioning and sustainability of ecosystems, as well as human livelihoods (Dudley, 2008).

In this study, special attention is paid to such an ecosystem service of the Kakhovske Reservoir as recreational fishing, which is a type of active recreation on the water and is also a powerful factor in nature management. The scale of recreational fishing in the water area of the Kakhovske Reservoir and the lowlands of the Dnipro can be evidenced by the following fact: before 24 February 2022, about 55,000 small-sized fleet vehicles (boats and cutters) were registered in the state registration authorities in the Zaporizhzhia region.

Before the explosion of the Kakhovska HPP dam, recreational fishers caught 800–1,100 tons of fish annually in the Kakhovske Reservoir (Novitsky, 2015), which was at least 25%–33% of the commercial fishery. The draining of the Kakhovske Reservoir will make it impossible or reduce drastically recreational fishing, swimming, diving, underwater hunting, and yachting for almost 800,000 fishers in the Zaporizhzhia, Dnipropetrovsk, and Kherson regions. These annual losses of fishery ecosystem services can reach millions of dollars.

The negative consequences of the loss of the reservoir water ecosystem will affect the socioeconomic development of the southern region of Ukraine for a long time. Water and food security in Ukraine are the main components of national security in the context. The loss of water supply is also a key one among ecosystem services (Hapich et al., 2024b). Unfortunately, the qualitative and quantitative indicators of water resources of small and medium-sized rivers in this region are not able to satisfy fully the needs of industry and the population with fresh water (Hapich et al., 2022b). Irrigated agriculture, where water is the limiting factor for development, will also stop (Hapich et al., 2023).

The post-war restoration of Ukraine, its degraded lands, territories, and water areas, and ensuring food security are today's top priority issues. One of the urgent problems will be the reasonability of rebuilding the Kakhovska HPP Dam and restoring the Kakhovske Reservoir, reviving water supply, fishery, energy, recreation, and irrigation (Report, 2001; United Nations, 2023; Hapich et al., 2024a).

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

RN: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing–original draft. HH: Conceptualization, Formal Analysis, Methodology, Validation, Visualization, Writing–original draft. MM: Investigation, Visualization, Writing–original draft. PK: Conceptualization, Investigation, Methodology, Visualization, Writing–review and editing. VG: Conceptualization, Formal Analysis, Methodology, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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