Water Security 21 (2024) 100167

Contents lists available at ScienceDirect

Water Security

journal homepage: www.sciencedirect.com/journal/water-security

Synthesis Paper

Water security consequences of the Russia-Ukraine war and the post-war outlook

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ARTICLE INFO

Keywords:
War
Water resources
Water security
Development strategy

ABSTRACT

Russian forces have destroyed one-third of Ukraine's freshwater storage since February 2022 to 2024. Potable, industrial and irrigation water supplies have been cut across the south and east of the country. Overall, social, economic and ecological damages are estimated in the tens of billions of $US, while the loss of Ukraine's economic potential and necessary investments in restoration reach $600 billion. We consider the current eco-economic efficiency of irrigated crops, as well as damage to commercial and recreational fisheries including losses of littoral areas and spawning grounds. Alternative water supplies for the war-torn regions by construction of wells to tap groundwater are presented and justified; various scientific opinions and approaches to ecosystem management and options for the future reconstruction of the Kakhovka Reservoir are discussed; and, finally, strategic development options for the water sector are considered to ensure water security in the post-war development period.

1. Introduction

Throughout history, water resources have been fundamental for social and economic development. When the water fails, so do the societies it supports; and water resources are now stretched to the limit in many parts of the world [1,2]. Water has often been a cause, or excuse, for political and military conflict. As recently as 30 years ago, war between states in the Middle East over the water resources they share was considered highly likely, if not inevitable [3]. With increased population and development, growing enough food required quantities of water that were simply not available. Neighboring states seemed not to hesitate to go to war over other issues, so why not water? And yet, as Shapland [4] has observed, wars over water have not occurred – because it is cheaper and less risky to buy food from abroad than to take up arms to grab local water resources to grow it at home. Provided that the global market can provide that food, and governments can find the foreign currency to pay for it, better by far to reduce the volumes allowed to their farmers and maintain supplies to more profitable sectors (industry, commerce, tourism) and more politically powerful groups (urban consumers). So, *for example,* Egypt now imports *virtual water* [5] equivalent to another Nile – but the leaders do not trumpet this policy and there are always new alarums [6,7].

Ironically, Ukraine, which is a major source of that virtual water, is now the victim of a military assault on the actual water that has been supplying its grain exports. The extensive infrastructure of dams, reservoirs and canals in Ukraine was largely created in the period 1950 to 1980 to supply industry, energy, transport, irrigation and municipal water supply [8]. On the Dnipro River, a cascade of six reservoirs was constructed with a total volume of 43.8 km^3; on other rivers, there are 1,095 smaller reservoirs with a total water volume of 8.6 km^3 and approximately 50,000 ponds with a volume of 3.9 km^3. In the rush for economic development driven by a doctrine of subjugating nature, environmental issues received short shrift [9]. Rivers have been fragmented into cascades of complex techno-natural ecosystems, practically stagnant and subject to chemical, microbial, biological, physical, and radionuclide pollution [10–12].

Even with its engineered water reserves, Ukraine was less well supplied than most of Europe: the internal river flow in Ukraine is approximately 50 km^3, and the available groundwater reserves are only 5 km^3 [13]. With internal renewable water resources of 1,200 cubic meters per person per year, Ukraine ranks 37th out of 50 European countries [14]. Climate change and increased demand would have caused a deficit in some regions by 2050 [15], but Russia's assault has created this situation now (Fig. 1).

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https://doi.org/10.1016/j.wasec.2024.100167
Received 1 December 2023; Received in revised form 21 February 2024; Accepted 11 March 2024
Available online 18 March 2024

The deliberate destruction that has devastated Ukraine's water infrastructure has killed many people, caused severe material losses, flooded large areas, and constitutes nothing less than an ecocide [16–20]. Loss and damage includes complete or partial destruction of the Kakhovka, Oskil'ske, Pechenizke, Karachunivske and Karlivske Reservoirs; municipal water supplies and sewerage to and from Mykolaiv, Kharkiv, Mariupol, Chernihiv, Bakhmut, Severodonetsk, Vugledar, Lysychansk and Avdiivka; and termination or partial loss of function of main channels for water supply to the Kakhovka and North-Rogachytska irrigation systems, and the Dnipro-Donbas, Dnipro-Kryvyi Rih, and North-Crimean Canals [21–23].

Here, we assess the current state of water infrastructure in South-East Ukraine. Restricted access to the front-line and occupied territories does not allow a comprehensive assessment; eye-witness reports from local media remain a primary source of information about military events and their consequences. We also draw on open sources of international and Ukrainian organizations that maintain statistical records and assess losses incurred by the economy [24–26] and interviews in foreign and domestic publications provided by experts in water management, ecologists, economists, and other specialists.

2. Ecosystem services

Recent years have seen a rapid decline in the biodiversity of freshwater ecosystems across Europe [27,28]. This is attributed to the loss of habitat caused by climate change, pollution, and other human impacts on inland waters and wetlands [29]. In Ukraine, the situation has been exacerbated by the Russian invasion that has disrupted almost every natural activity, as well as conservation measures and, inevitably, ecosystem services [30]. Significant damage has been inflicted on more than 16 % of the territory (over 100,000 km^2); access to safe drinking water is restricted for approximately 5 million people; there have been huge economic losses, as well as disruption and total loss of aquatic ecosystems [31,32].

The commercial fish catch has been reduced to less than a half of pre-conflict levels in the Dnipro Reservoir cascade and decreased by over 80 % in the Black and Azov Seas, not to mention recreational fishing [33]. But the most important ecosystem service of Ukrainian reservoirs (especially the Dnipro Cascade) is water storage and regulation for many and various needs: water supply and drainage, hydropower, navigation, irrigation, recreation, self-purification, cooling water for thermal and nuclear power stations, and numerous waste storage facilities and tailings ponds providing the ecosystem service of containing pollutants,

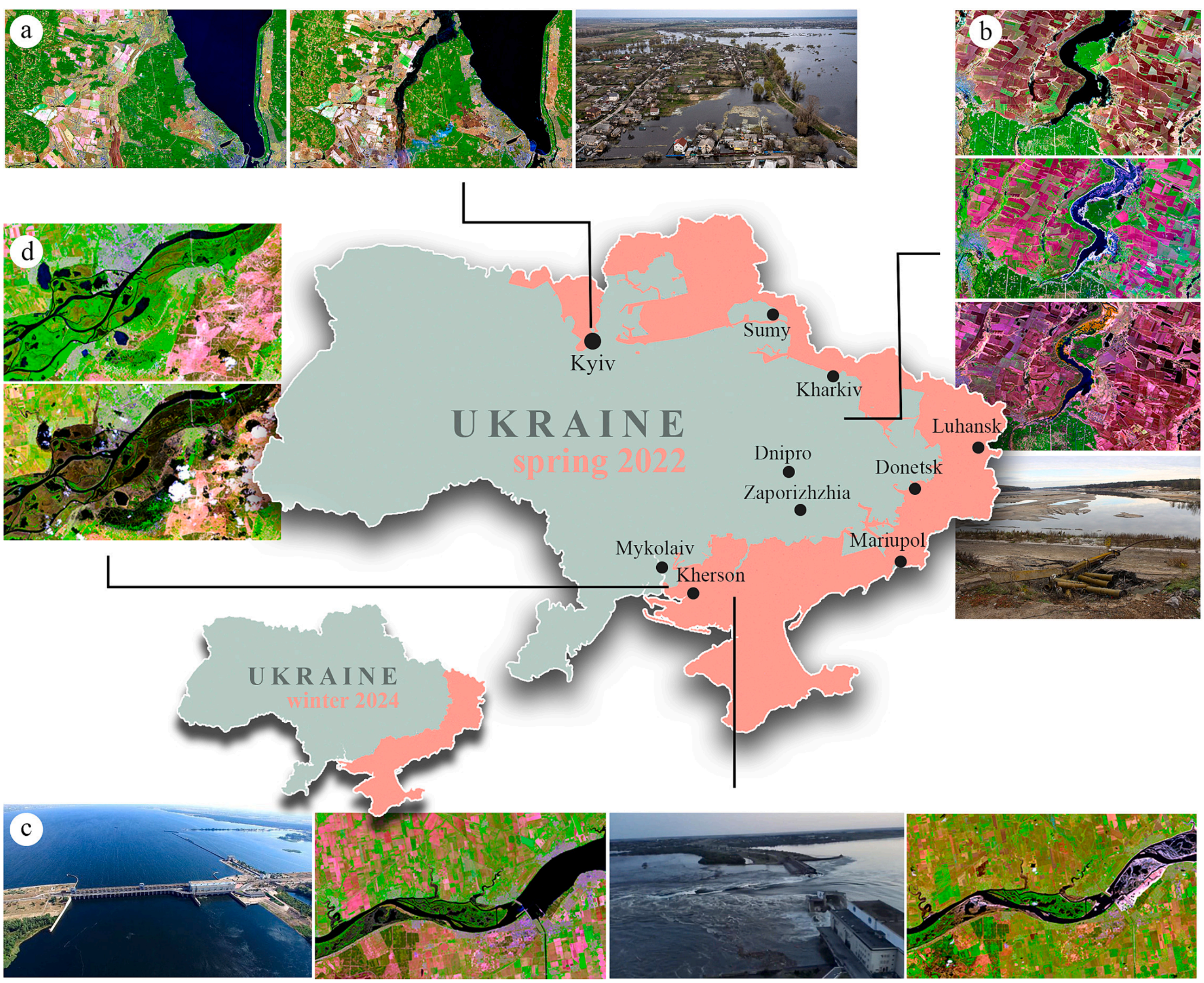

Fig. 1. Consequences of the Russian invasion on water security in Ukraine: a) flooding on the Irpin River (2022); b) destruction of the Oskil Reservoir (2022); c) destruction of the Kakhovka Dam (2023); d) flooding of the Dnipro River delta and the city of Kherson (2023). Sentinel and Landsat images and photos from open internet sources. Extent of areas controlled by Russian forces in pink. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

including radioactivity [34].

3. Water supply and pollution

The total abstraction of water in Ukraine exceeds 8.8 billion m^3, of which 735 million m^3 is from underground sources and 267 million m^3 is mine and quarry water. The largest water consumers are the eastern and southern regions: Dnipropetrovsk, Donetsk, Zaporizhzhia, Kherson and Odesa [35]. Approximately 6 % of total water intake was discharged back into the rivers as wastewater (Fig. 2). The development of these regions as industrial, mining, agricultural and transport hubs with a population before the war of more than ten million was facilitated by a network of canals and pipelines that brought water from the Dnipro reservoirs to the Donbas and Crimea [8,36]. Military action has disrupted or destroyed these water supply systems [37,38]: the operation of dozens of main channels has been terminated; water intakes, pumping stations and pipelines have been damaged or destroyed; and there have been innumerable cases of pollution due to destruction of equipment, fuel leaks, and chemicals from munitions and industrial plants. For instance, more than 450 tons of fuel and engine oil were released into the Dnipro River during the destruction of the Kakhovka Hydropower Station [39,40].

In the early days of the full-scale invasion, the main structure of the North Crimean Canal, the Kakhovka Dam and Hydropower Station and all hydraulic structures regulating the water supply from the Kakhovka Reservoir to the Crimean Peninsula were captured and Russian forces illegally diverted water valued at an estimated $18 million [38,41]. In May 2022, damage to the Raigorodskaya Dam on the Siversky Donets River (Donetsk Oblast) resulted in an uncontrolled discharge of water into the river, lowering the level of the reservoir by 1.5 m at drinking water intakes and disrupting supplies to the Donetsk region; and the shelling of the Vasilkivsky water supply and wastewater treatment plant spilled untreated wastewater into the Dnipro River [22]. More than 30 major water treatment facilities and sewage plants, along with hundreds of smaller structures, have suffered damage totaling about $115 million [37,41].

There was already significant physical and moral wear-and-tear on sewerage facilities: 30–40 % of them are in emergency condition or barely perform basic functions. On average, there are more than 2–3 accidents per km of water supply and sewer network every year [42] and the lack of access for water management staff to damaged infrastructure in conflict zones, along with new daily accidents, exacerbates environmental and water safety hazards. At the time of writing (winter 2024), destruction of reservoirs and the shutdown of canals, pipelines, and pumping stations have taken 18–20 km^3 of the available reserves of fresh water – ***one third of all fresh water reserves in the country,*** valued at $18 billion if supplied to consumers at an average price in Ukraine of $0.80–0.90 per cubic meter.

4. Irrigation

During the 1950–1990 period, irrigation and land reclamation schemes were extended to 2.3 million ha of the country, the largest located in the southern steppes [43,44]. Fifty to seventy-years on, most of them are run down; excessive unproductive water losses and inefficient management raided any profits [45–48] and the irrigated area had contracted to about 300,000 ha in 2022 (Fig. 3). At the same time, the application of manure and fertilizers also decreased and, so, have gross agricultural production and quality.

Livestock production had also been actively developed in the mid-20th century, using various crop rotations [49] and producing plenty of farm manure. But stockbreeding crashed and the global demand for grains and other cash crops led to the adoption of short rotations, or even monocultures, of wheat, sunflower, corn, rapeseed and soya that depend

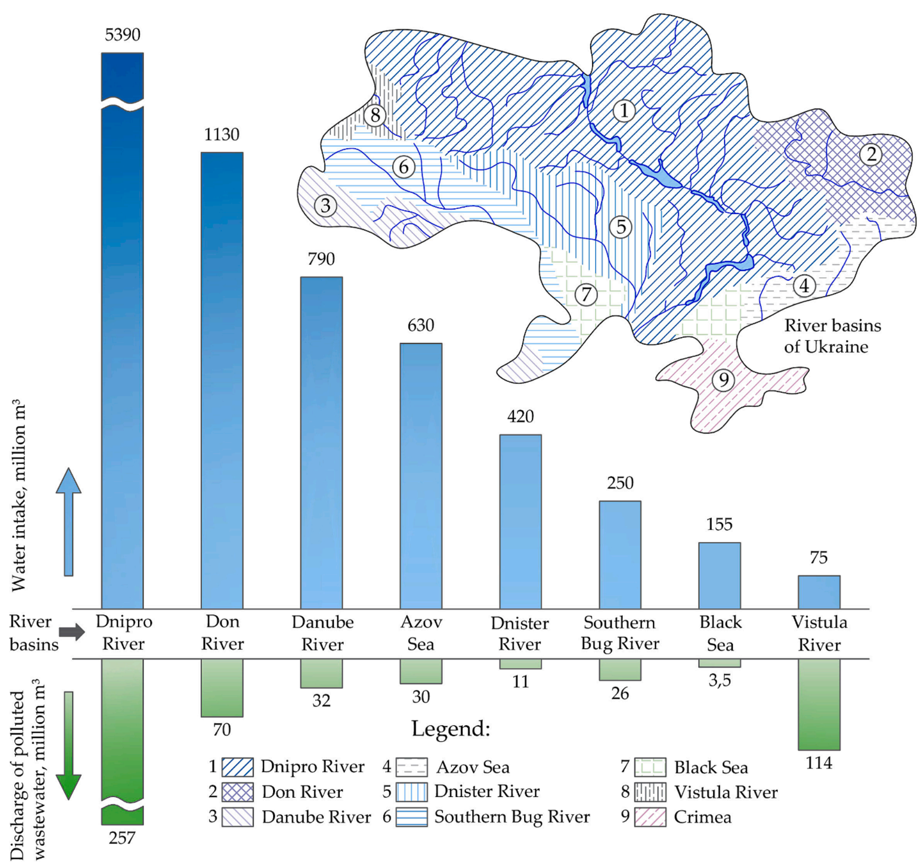

Fig. 2. Water supply and wastewater disposal in Ukraine's river basins [35].

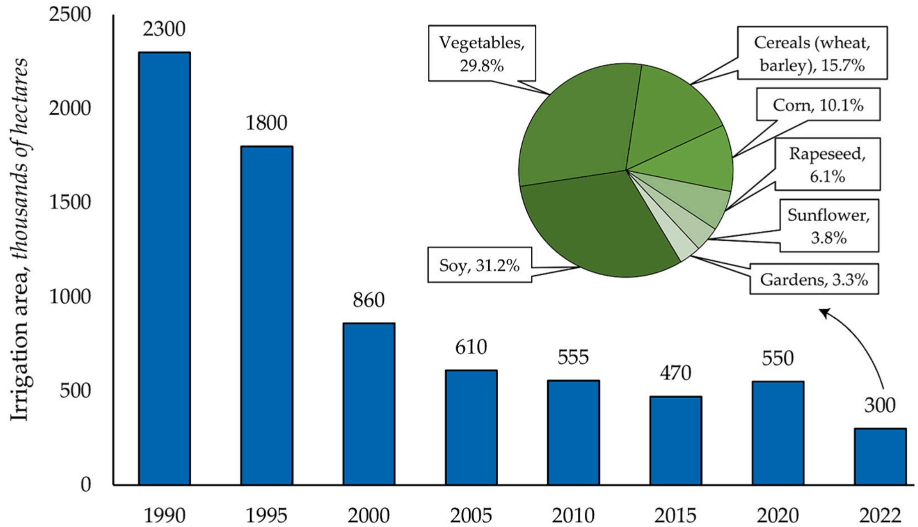

Fig. 3. Changes in irrigated area and the structure of agricultural production in Ukraine.

on industrial fertilizers, herbicides, and pesticides and, in the steppe zone, produce well only under irrigation [50–52].

As of February 2024, Russian forces occupy the following formerly-irrigated areas: Kakhovka system (260,000 ha) North Crimean Canal (280,000 ha, also designed to supply water to the Crimean Peninsula), North-Rogachitsa (102,000 ha), and Krasnoznamyanska (96,000 ha). Furthermore, the destruction of the Kakhovka Dam on the Dnipro River cut off water to the Dnipro-Kryvyi Rih Canal that supplied over 500 million m^3 water/year to the city of Kryvyi Rih, and 100 million m^3 for irrigation. At the same time, the blockade of the Black Sea ports has disrupted exports of agricultural products so the agricultural sector operates at a loss [53,54].

Analysis of previous studies [55] indicates that irrigated grains and soybeans are now unprofitable although, with good weather and minimizing water application, rapeseed and sunflower break even. Vegetables, berries, orchard crops, and vineyards remain profitable, but require upfront capital investment and yield a profit only after 5–7 years [56]. The development of human capital in the southern and eastern regions of the country is also challenging. Many local people fled and most of those who remain have been deprived of their livelihoods by the destruction of the Kakhovka Reservoir.

5. Fisheries

Fish are an important component of the diet in Ukraine, but annual consumption of 9–12.5 kg per person in 2015–22 [24,57] is 4–5 times lower than the European average. The long-term share of the Kakhovka and other destroyed reservoirs in the freshwater catch was 20–25 % [58]. The ichthyo-complex of reservoirs in the south-eastern regions of Ukraine comprises 42 fish species, of which 20 are of commercial value and 34 recreational [39,57,58]. In 2022, the Institute of Fisheries of the National Academy of Agrarian Sciences of Ukraine [59] estimated the stocks in the Kakhovka Reservoir for the year 2023 at about 11 400 tonnes. Most commercial fish species are phytophagous (carp, bream, ide, roach, catfish, perch) and spawn in shallow-water vegetation that is now completely lost. Direct losses to the Ukrainian fisheries, are estimated at $24.5 million and, according to Buzevich's calculations [60], losses to the fisheries from the loss of offspring exceed $242 million.

6. Discussion and prospects for restoration of the Kakhovka Reservoir

Preliminary assessments suggest that, in peacetime, complete restoration of water infrastructure will cost more than $5 billion. Reconstruction of the Kakhovka Reservoir, alone, will cost $1–1.5billion and take ten years [40,61,62].

Neither nature nor society will wait. The ecosystems of water-deprived territories will gradually adapt to the new conditions, as they have done repeatedly in the last 70 years. Inevitably, this will mean the loss of some rare species [63]. Society will seek alternative farming systems with broadacre farms reverting to rainfed crops, and specialist growers turning to modern water and energy efficient technologies such as drip and subsurface microirrigation, which also facilitate application of fertilizers and plant protection products with irrigation water [64,65].

For the south-eastern regions (left bank of the Dnipro River), groundwater may be an alternative to water supply from the Kakhovka Reservoir. This will require well-drilling to tap aquifers of varying depths and water qualities [36,66]. However, groundwater dynamics will be changed by the loss of hydrostatic pressure from the Kakhovka Reservoir; and most aquifers in southern Ukraine are brackish [67]. Therefore, there is a need for a comprehensive review of existing water consumption norms and regulations and technological upgrading of production cycles to reduce water consumption. In addition to investing in drilling and equipping wells, there will be a need for pretreatment or mixing of water from various sources to bring it to the required quality standards [68]. The cost of water to consumers will increase; several local authorities and regional water supply and drainage providers have already declared an average 50 % price increase for municipal consumers to $1.3/$m^3$ during 2024.

The Institute of Water Problems and Land Reclamation of Ukraine [69] predicts that, under present climatic trends and without irrigation, almost half of the cropland in Ukraine will be unsuitable for field crops by 2050; By 2100, the proportion may reach two thirds. Every year, without irrigation, Ukraine will lose about 13.5 million tonnes of cereals and technical crops and 11 million tonnes of fruits and vegetables. Therefore, Ukraine should draw on the experience of other countries in managing and ensuring the water supply from sources other than surface water.

Currently, two tracks are open for debate: 1) whether to rebuild the dam and reservoir to their former size and volume, or 2) maintain the river regime downstream without flooding an area of 2155 km^2. The first path is advocated by engineers in the hydropower complex who support the complete restoration of the reservoir [61] and academician Mykhailo Romashchenko [70,71] and others who argue for the restoration of the reservoir, although somewhat smaller than before, to restore the water supply of cities and towns, industry, navigation, irrigation, fishing, and recreation. However, elsewhere in the EU, large dams are now unwelcome for ecological reasons [72,73], and restoring the enormous Kakhovka Reservoir for the needs of a population that will be 2–5 times smaller than before February 2022 and without the demand for its water by heavy industry is hardly economically justified. Dam construction and the filling of the reservoir and recreation of the entire hydro-ecosystem will take many years: the ecosystem services of the reservoir are needed now. And will the 5–7 % share of electricity for Ukraine which the Kakhovka Hydropower Station would again provide be significant for the country's energy sector?

Redevelopment foregoes the second option of a tract of potential agricultural land, forest, and a floodplain that could be included in the Emerald Network [74,75] within the concept of maintaining European biological and landscape diversity. Considering the scale of this nature regeneration, it would need to be a pan-European project within the master plan to restore the naturalness of 25,000 km of EU rivers by 2030.

Arguably, restoration of the Great Meadow ("*Veliky Lug*" – the floodplain of the Dnipro River before the construction of the Kakhovka Reservoir) would provide more benefit to the economy and natural landscapes than the construction of a new reservoir [76]. Academician Yakiv Didukh [77] estimates the ecosystem services of floodplain areas of the former reservoir at an average of $260,000/ha while the electricity generated by hydroelectric plant accounts for only 13–15 % of this value – but electricity was never the main purpose of the Kakhovka Dam.

Forecasting is complicated by the unpredictability of many factors: natural, anthropogenic and, most importantly, geopolitical [78]. We can be sure that the territory of the former Kakhovka Reservoir will not return to its semi-natural ecology of a century ago due to degradation of the soil cover, reduced water flux due to the regulation of the Dnipro River and others upstream by a system of reservoirs, ponds, and canals, let alone climate change; but there is a need to consider advantageous alternatives to reinstatement of the reservoir to quickly satisfy the needs of the state and the population. This issue is firmly in the political arena where the desire to acquire funds reflects the scientific justification and a strategic vision of effective water and land resource management. Perhaps it was this political and scientific dissonance that prompted the Government of Ukraine to suspend the use of the lands occupied by the Kakhovka Reservoir [79].

7. Conclusions

Water resources have been weaponized. Simultaneously, they have become victims and instruments of aggression. The information provided here pertains to a two-year timeframe encompassing the period of military operations from winter 2022 to 2024, during which Ukraine has lost one third of its accumulated freshwater reserves; and scores of reservoirs, pumping stations, main canals, and pipelines have been destroyed, causing significant damage and pollution to the river and reservoir water ecosystems. Estimates of loss and damage (decline in GDP, cessation of investments, outflow of workforce, additional expenses for defense and social support, *etc*.) range from $500–600 billion and will continue to grow [80].

At the time of writing (March 2024), the war goes on. Mine fields and active combat complicate efforts to accurately assess the extent of damage and the restoration requirements. This underscores the need for novel methodologies and criteria for comprehensive research, as well as the potential for implementing comprehensive remote monitoring. Whatever its conclusion, the conflict offers valuable insights for researchers around the world, enabling them to mitigate and prevent the adverse impacts of military conflicts on water ecosystems and security in the years ahead.

Occupation of the southern and eastern regions of Ukraine and destruction of the Kakhovka Reservoir have all but terminated irrigation. Irrigated cereals and technical crops are now unprofitable, even where practicable – not least because of the difficulty of selling and exporting the produce. The strategic development of irrigation should be based on optimal technology to minimize water costs and redesign cultivation systems, for example, by drip irrigation, diverse crop rotations and focus on vegetable farming, orchards, and viticulture.

The destruction of reservoirs has killed precious aquatic populations. The direct loss to the fish catch from destruction of the Kakhovka Reservoir is estimated at around $24.5 million but restoration of spawning grounds and ecosystem services would cost ten times this amount.

Ensuring water supply for 7–10 million people, restoring irrigation on a project area of over 1 million ha, restoring aquatic bioresources, and developing other ecosystem services of reservoirs in the Kherson, Zaporizhzhia, Dnipropetrovsk and Mykolaiv regions, as well as in Crimea, requires new technical, technological, and socio-economic paradigms and post-war investment of tens of billions of dollars. The management of Ukraine's water resources after the war needs to be decided at the state level today, considering all the pros and cons.

Finally, repairing the consequences of war will require the combined efforts of ecologists, hydrologists and hydraulic engineers, economists, and a raft of other professional managers. In our opinion, a new concept of water security and the Ukrainian state strategy should be based on comprehensive legislative measures for the conservation, restoration and rational use of water resources and the natural landscapes of wetlands and, in the creation of this new framework, it is essential to include and assess the eco-economic efficiency of ecosystem services.

CRediT authorship contribution statement

Hennadii Hapich: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Roman Novitskyi:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Dmytro Onopriienko:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis. **David Dent:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Hynek Roubik:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Roman Novitskyi reports financial support was provided by Ministry of Education and Science of Ukraine. Hynek Roubik reports administrative support and writing assistance were provided by Czech University of Life Sciences Prague. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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