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ORIGINAL ARTICLE

Assessment of water needs in the lower Dnipro sub-basin following the destruction of the Kakhovka reservoir

Mykhailo Khoriev[1] · **Viktor Karamushka**[1] · **Oksana Huliaieva**[2] · **Brian Kuns**[3]

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Abstract

The paper describes the purposes of the Kakhovka reservoir, which was the final in a series of large reservoirs created out of the Dnipro River in Ukraine. Importantly the paper presents the water consumption balances of the reservoir prior to its destruction on June 6, 2023. This consumption is divided up by economic sector—energy, agriculture, fishing, industry, transport, and household use and also with details on inter- and intra-annual water demand trends and variations (prior to destruction). The water needed to maintain important ecosystems in the reservoir and south of the now destroyed dam is also accounted for. This overview of water consumption is then used as input in an analysis of how prospective water-uses of the Dnipro River, including water needed to maintain important ecosystems, can be met given the situation now where the Dnipro River still exists, but the reservoir and dam, which were important for regulating and maintaining flow-rates and water-levels at different times of the year, do not exist at the moment.

Keywords Kakhovka dam and reservoir · Dnipro River · Water users and consumers · Water balance · Water needs assessment · Reservoir destruction · Ecological flows · Irrigation

Introduction

There is a wide-ranging discussion about the possibility of dam removal to restore rivers or water courses to their original state (Bellmore et al 2017, 2019; Foley 2017; Lejon et al 2009; Tullos et al 2016). Most dam removal projects involve long-term planning and discussion with authorities and stakeholders, including detailed plans on what to do after the removal of the dam to ensure stakeholders are prepared and that ecosystems can be restored. However, some dams fail, i.e. their removal is unintentional, leading to negative consequences for local populations and ecosystems in the form of short-term, but devastating floods and longer-term altered water regimes. There are various reasons for dam failure, but in many cases, it occurs due to extreme and prolonged rainfall events, a failure to plan for risk, and/or poor construction and maintenance (Latrubesse et al 2020; Roulo & Pichuka 2024; Darji et al. 2024; Zhang et al 2016, in particular ch. 4). Though rarer, dams can also be targets of malign actors or, to use Peter Gleick's (2019) terminology, dams can be "casualties of war" and even "weapons of war". In such cases it is important to point out that, while someone certainly intended to destroy the dam, the destruction of the dam was unintentional and unplanned from the perspective of the owner/manager of the dam and from the perspective of the stakeholders, consumers and users of the water provided by the dam.[1]

[1] By comparison the Soviet destruction of the Dnipro dam in 1941 to obstruct the advancing German army was a planned dam removal.

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✉ Viktor Karamushka
vkarama2011@gmail.com

Mykhailo Khoriev
m.khoriev@ukma.edu.ua

Oksana Huliaieva
o.huliaieva@uhe.gov.ua

Brian Kuns
brian.kuns@slu.se

1 Department of Environmental Studies, National University of Kyiv-Mohyla Academy, 2 Skovoroda Street, Kyiv 04070, Ukraine

2 Private Join Stock Company "Ukrhydroenergo", Vyshgorod 07300, Ukraine

3 University of Agricultural Sciences, P.O. Box 7070, 750 07 Uppsala, Sweden

In this paper, we present a case of dam failure due to a deliberate explosion, with catastrophic consequences, that has led to a wide-ranging debate on the desirability of dam reconstruction vs. nature restoration. We are talking about the destruction of the Kakhovka dam in southern Ukraine on June 6th, 2023 (see Glanz et al 2023). The immediate and longer-term consequences of this event have been devastating (KSE 2023; UNEP 2023; UN Ukraine 2023; Vyshnevskyi et al. 2023). What this paper is concerned with is a *post-hoc* discussion that has arisen in Ukraine about what to do with the former reservoir and dam after the war. Should the reservoir be "restored" partially (Stone 2024) or in full (Afanasiev 2023), or should the original, pre-Soviet, wetlands be "restored", by among other things, designating the former reservoir, which indeed appears to now be wetlands in formation (Afanasiev 2023), as a protected area (Vasyliuk et al. 2023). The Cabinet of Ministers of Ukraine has approved a decision (CMU 2023) calling for the rebuilding of the dam and reservoir. However, as this region is an active combat zone today, the implementation of this decision has been suspended until the region is liberated. Thus, the future of the reservoir and dam remains an open question, as it is unclear when it can take place, and how it will be financed.

The amount and availability of water will be one of the main limiting factors in the future development of southern Ukraine. We argue therefore that any plan of restoration should be informed by a discussion of the pre-war water-uses and needs stemming from the reservoir, which is what we set out to do here. The aim of this paper is to provide an assessment of the water-related needs of different actors and branches for whom the Kakhovka reservoir was the main source of water. In particular, we will compare water balances and the hydrological regime of the Kakhovka reservoir and lower Dnipro River under years of low and high-water availability (exceedance), using official pre-war data. This will be compared with data on pre-war water use and consumption by different users and consumers of water from Kakhovka reservoir, plus the water-flow needed to maintain ecological functions in the lower Dnipro River, south of the erstwhile dam. With this baseline information we will be able to show the magnitude of water shortages that can arise in different water availability scenarios when the possibility to store water in a reservoir no longer exists. This will provide valuable information for decision-makers in Ukraine and Europe as they plan for a future with or without the reservoir and dam.

This paper will make various contributions to the discussion on dam removal and catastrophes. First, the literature on dam removal shows that actors who use the water from a reservoir are one of the main stakeholders in discussions on whether or not a dam should be removed (see for example Lejon et al 2009). In mapping out the pre-war water use from the reservoir, and how much water is available without the reservoir under different water availability scenarios, we provide important information for assessing which water consumers will be able to get the water they need, which in turn can feed into the debate among stakeholders about the future of the dam and reservoir. Second, dam failures of the magnitude of the Kakhovka dam destruction are thankfully rare in history (Zhang et al 2016). However, because of their "critical" importance as infrastructural nodes and because such large-scale failures are often unplanned (as defined above), the failure or destruction of such dams causes significant large-scale and long-term damage and require comprehensive consideration when planning for recovery. Despite this, events of this magnitude remain understudied in the literature on dams.

Background

The Kakhovka reservoir served as the main source of water in the southern Ukraine for the water consumers (household sector, industries, irrigation, drinking water supply for population) and water users (fishery, recreation, water transport, energy including cooling water for the Zaporizhzhia nuclear power plant). The reservoir was created in the 1950s when the Kakhovka Hydroelectric Power Plant (HPP) was built on the Dnipro River in southern Ukraine. It resulted in the-flooding extensive wetlands, known as the Great Meadow, along the southern reaches of the Dnipro. While the main reason for the creation of the reservoir was to massively expand irrigation (Kuns 2018; Hapich, Onopriienko 2024), its creation significantly contributed to southern Ukraine's industrialization and economic development in general. Put simply, all water-related infrastructure in southern Ukraine was oriented on and developed in line with the operational parameters of the Kakhovka reservoir. The Kakhovka HPP constituted the southern end of the reservoir, marking the boundary between the reservoir and the remaining unaltered portion of the Dnipro River, which flowed south of the dam. The power plant itself only provided roughly 1% of Ukraine's total electricity (Hapich and Onopriienko 2024). However, the water sluicing through the dam was—as we detail here—important for supporting the normal functioning of ecosystems of the unaltered portion of the Dnipro south of the dam. In sum, the Kakhovka reservoir and HPP, as they functioned in the Soviet period and the period of Ukrainian independence, were arguably the most important structures for the economic and ecological life in the entire southern Dnipro basin in particular and southern Ukraine in general.

The Kakhovka HPP and reservoir were the sixth and southernmost in a series of hydroelectric power stations and reservoirs that were built on the Dnipro River, resulting in the formation of what is called the Dnipro cascade of reservoirs (Baksheev 2008; MEPNRU 2022) (Fig. 1). The reservoir was put into operation in 1956. Its full volume was 18.2 km^3 and its usable storage, i.e. the difference between total storage volume of a water in the reservoir and the remaining volume below the minimum operational level, was 6.8 km^3. The area of the water surface, when a normal retaining water level was observed, was 2155 km^2, and the water surface area of the "dead volume", i.e. the water below all water intakes, was 1930 km^2. The length of the reservoir was 230 km and the maximum and average width was 25 and 9.3 km respectively. The maximum and average depth was 36 m and 8.4 m. The area of shallow waters, up to 1 m, was 44 km^2, and up to 2 m, 110 km^2 (Baksheev 2008).

The Kakhovka reservoir supplied water for the Kakhovka HPP, the Zaporizhzhia nuclear power plant, industrial enterprises, freshwater fisheries, recreation, extensive irrigation systems throughout southern Ukraine, as well as for the Dnipro-Kryvyi Rih and North-Crimean canals. In addition, the reservoir created a deep-water channel that allowed sea vessels to sail up the Dnipro River. The role of the Kakhovka HPP and dam as a regulator of the flow through the cascade of the Dnipro reservoirs was second to that of the Kremenchuk HPP (further north—see Fig. 1). However, from all the waters that were consumed in the Dnipro basin, it was from the Kakhovka reservoir that the most water was extracted and transferred irretrievably outside the basin. In some years, the amount taken from the reservoir could constitute 40% of water used in Ukraine (Vyshnevskyi et al. 2011).

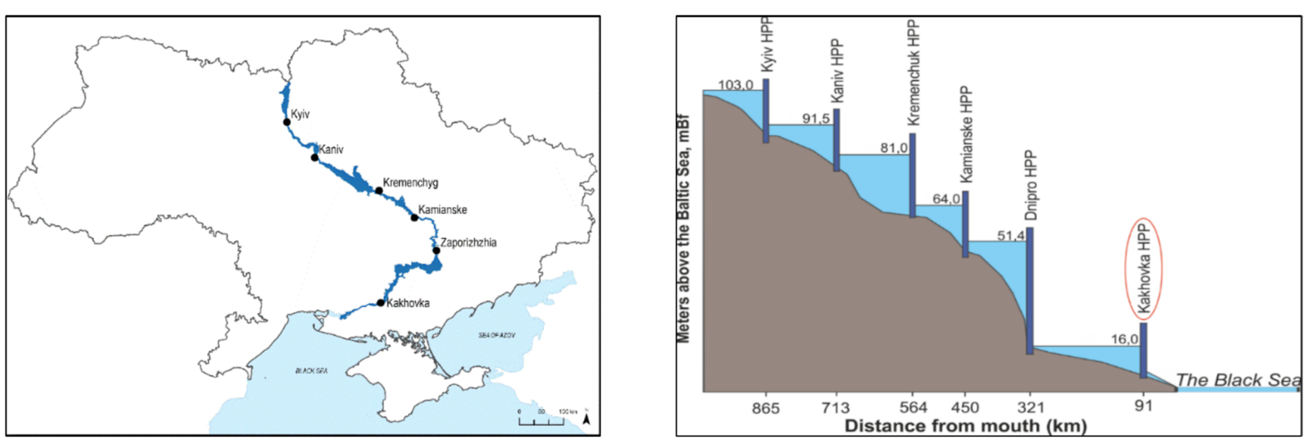
On the 6th of June 2023 at approximately 02:50 AM the dam containing the Kakhovka Hydroelectric Power Plant was demolished in an explosion. A powerful current of water from the reservoir gushed through the resulting opening in the dam into the Dnipro River and continued towards the Black Sea.

According to data from the Ukrainian Hydro-meteorological Institute, as of July 15, 2023, the area of the Kakhovka Reservoir after the explosion of the dam was 261.1 km^2 (NASU 2023). Of this area, 120.9 km^2 included the area of the channel of the Dnipro River. Not included in this area are other water bodies forming in the bed of the reservoir.

Thus, on July 15, 2023, there remained only 12.7% of the general area of the Kakhovka Reservoir. On June 5, 2023, it was at 2065 km^2, somewhat under the standard area noted above (2155 km^2) when a normal retaining water level is observed. Also, on the territory of the reservoir, the main channel of the Dnipro River (re)appeared (Fig. 2).

Unplanned dam removals in an international context

Events like the destruction of the Kakhovka dam, leading to the emptying of one of the largest reservoirs in Europe, are rare in the modern era, but they are instructive. By far, most planned dam removal projects (O'Connor et al. 2015; Magilligan et al. 2017) and unplanned dam failures (Zhang et al 2016) involve smaller dams. The effects of the removal of such dams are geographically constrained, though of course the failure of even a small dam can cause considerable local destruction. The point here is that small dams are not "critical infrastructure" in the same way that a dam the size of Kakhovka was. Critical infrastructure is typically defined as "systems and assets, whether physical or virtual, that are so essential to a nation that any disruption of their services could have a serious impact on national security, economic well-being, public health or safety, or any combination thereof" (Alcaraz & Zeadally 2015, p. 53).



A B

Fig. 1 The map (**A**) and the cascade scheme (**B**) of the Dnipro River reservoirs comprising (from north to south) Kyiv, Kaniv, Kremenchuk, Kamianske (Middle Dnipro), Dnipro, and Kakhovka reservoirs

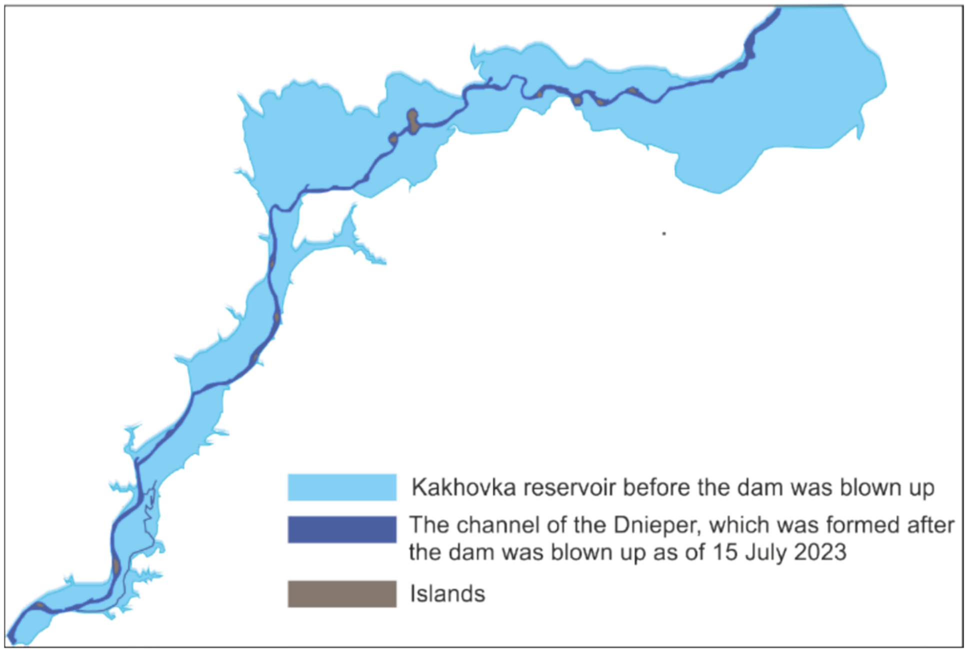


Fig. 2 The map of the Kakhovka reservoir before its demolition, also showing the formation of channel of the Dnipro as of 15 July 2023

In this sense, the Kakhovka dam, as we demonstrate below, ensured important services in water provision, energy generation, river flow regulation, flood prevention, and recreation for all of southern Ukraine. The disruption of these services caused by the dam's destruction will have a serious long-term impact on the future development prospects of the entire region, in which more than 3 million people lived before the war. Events of the magnitude of the Kakhovka catastrophe may be rare, but their effects reach much further in space and time than the removal or failure of small dams. Also, framing the Kakhovka dam as critical infrastructure opens up for discussions, on the hand, of the important services that need to be maintained or replaced now that the dam has been destroyed and, on the other hand, the long-term vulnerability and risk that such large infrastructural nodes carry (Van der Vleuten et al 2013). In mapping out pre-war and current water-balances, we contribute to this discussion.

Since WWII, there has been one comparable event: the failure of the Banqaio dam in China in 1975.[2] The immediate cause of this event was exceptionally high levels of precipitation due to typhoon Nina, but there were a variety of longer-term safety and landscape planning issues that contributed to the wide-spread destruction (Qing et al. 2016). The Banqaio dam was eventually reconstructed, though only 18 years after the initial catastrophe. This suggests that even in the event of a decision to reconstruct the Kakhovka Dam following the end of the war, the different water users and consumers in southern Ukraine will still have to wait a number of years before a new reservoir is in place. This makes our assessment here of water balances and hydrological regimes with and without the dam relevant for the near future, no matter the decision that is made on the dam.

Another point to make here is that, as Magilligan et al. (2017) argue, each dam removal is "complex" with unique historical and geographical circumstances and institutional equities shaping the decision-making process. One potential constant in this complexity is the likelihood of stakeholder conflict between those who want to remove the dam and those who want to retain it, or in the Ukrainian case, those who want to restore the dam and those who want to restore pre-reservoir ecosystems. In this regard, as Tonitto and Riha argue (2016), it is vitally important that proper and exhaustive impact assessments are conducted on the consequences of the dam removal (or dam restoration) decision. We see our work here as contributing to such an impact assessment.

Finally, the consequences of the destruction of the dam go beyond Ukraine. The initial flooding event caused by the destruction of the dam had a tremendous negative effect on the Black Sea, particularly its northern part (Minicheva et al 2023; Tuchkovenko et al 2024; Tuchkovenko & Stepanenko 2023). Even if we can already see that natural processes are restoring natural ecosystems in the Black Sea (Minicheva et al 2023), this process will take a number of years. The relevance for this paper is that whatever post-war solution is chosen for the Kakhovka dam will naturally affect the amount and quality of water flowing from the southern Dnipro into the Black Sea, with long-term implications for ecosystem services and post-war environmental recovery (Hapich et al. 2024).

[2] It was actually a cascade of dam failures caused by the typhoon, but the Banquaio dam was the largest of the dams to fail.

Study area and methods

For a quantitative assessment of water resources and the extent of their use by various industries, the authors have taken into account the actual water balance of the Kakhovka Reservoir from 1989 to 2021, mainly the part, which was consumed or used. The period for analysis is selected based on the characteristics of the climate cycle and includes various stages of economic development affecting demand and use of water resources.

The actual water balance is calculated, using actual data, according to the general formula: ***inflow of water—water use—accumulation = residual***. The inflow to the Kakhovka reservoir consists of surface inflow through the higher Dnipro HPP, the dam in the cascade that is located in Zaporizhzhia immediately to the north of the Kakhovka HPP. Inflow also consists of water pumped into the reservoir from rivers blocked by dams; surface inflow of water into the reservoir from areas not covered by flow measurement (lateral inflow); atmospheric precipitation on the reservoir surface; as well as inflow into the reservoir from industrial and domestic wastewater. The outflow includes water flowing through the Kakhovka HPP (i.e. through hydraulic aggregates, spillways, sluices and filtration); intake of water from the reservoir for irrigation; intake of water from the reservoir for drinking water systems, water losses from evaporation from the surface of the reservoir; and losses from one-way filtration (through soil) from the reservoir.

We use official water balance data in this paper from the Kakhovka Hydro-meteorological Observatory of the Kherson Regional Center for Hydrometeorology. The yearly annual water balance, calculated in monthly time intervals, can be found under "Surface Waters" in the State Water Cadaster (2022). Importantly, while water consumption is usually measured with a volume measurement—for example square meters—we will measure water use or consumption as volume per time unit, in this case seconds. We do this so that we can match water use or consumption with measures of water supply which are generally expressed as water flow in cubic meters per second—m^3/s.

In order to understand the possibility of meeting the water needs of all sectors of the economy of a given territory, it is also necessary to consider the water management balance, which, in accordance with the requirements of the Water Code of the country, is drawn up by the State Water Agency together with representatives of interested executive bodies and organizations. This is a strategic planning tool that lays down the foundations of water resource distribution, analysis, planning, water consumption and drainage norms (SAWRU 2019). The use of the water management balance of a given basin or sub-basin of a river, taking into account different water conditions (50%, 75% and 95% exceedance probability of the supply of water resources), allows a comparison of the real capabilities of the river with the needs of industry, the economy and people as a whole. The development of the water management balance for the part of the Dnipro River between the dam of the Dnipro reservoir (Zaporizhzhia) and the dam of the Kakhovka reservoir is carried out by the Lower Dnipro Basin Agency for Management of Water Resources. The calculation of the water management balance for the Kakhovka water management area (i.e. as mentioned above, between the Dnipro dam and the Kakhovka dam) is carried out in accordance with procedures developed by the Ministry of Environmental Protection and Natural Resources of Ukraine (MEPNRU 2017). The calculated water management balance of the lower Dnipro is presented on the official website of the State Water Agency (SAWRU 2019).

When analyzing the ability to meet the water needs of various sectors of the economy, keeping in mind environmental sustainability, we have also taken into account (1) the requirements for the water level regime of the Kakhovka reservoir in accordance with the rules of its operation (MEPNRU 2022), (2) earlier research on hydrological characteristics and the water balance and management aspects of the Kakhovka reservoir (Baksheev 2008; Vyshnevskyi et al. 2011; Koryagina 2015; Yatsyk et al. 2003; Obukhov 2017) and (3) hydro-ecological research (Oksiyuk et al. 1997; Timchenko 2006).

In sum, we have assessed—in the analysis below—the need for water for different uses: drinking water, irrigation, hydropower, industry, and water transport, keeping in mind the ecological requirements for aquatic ecosystems below the Dnipro hydroelectric dam. Furthermore, we take into account the following conditions:

1) Guaranteed water extractions: we base our assessment on the total hydrograph of water needs, taking into account various scenarios of actual water use in comparison with the water supply.

2) Guaranteed water level: requirements for the minimum water level allowing proper operation of hydraulic structures (various canal and water pipeline intakes and pumping stations at various points on both sides of the reservoir and the dam sluices) of various industries in the pre-war period.

3) Guaranteed volume of water needed to ensure extractions under different scenarios of actual water use and minimum water level limits for hydraulic structures of various industries.

Table 1 Existing water intakes of water consumers of the Kakhovka reservoir. Designed on the base of data from (Timchenko 2006)

Name of the populated area, pump station	Intake design capacity		The minimal possible water level in the water intake zone, m BS*
	th. m^3/day	m^3/s	
Water for drinking and household use			
Marganets city	130	1,50	12,7
Nikopol city	110	1,27	12,7
Pokrov town	150	1,74	14,0
North-Rogachyk	4838	56,0	12,72
Blagovishchenske	172,8	2,00	14,5
Ivanivske	449,2	5,20	14,5
Industrial water intake			
Kryvbasprom—water supply (through the Dnipro-Kryvyi Rih canal)	1979	22,9	13,2

*BS Baltic height system (vertical reference system)

Results

Using and consumption of water resources from the Kakhovka reservoir in the pre-war period

An assessment of the water needs of various water users and consumers and how these needs are satisfied from water coming from the Kakhovka reservoir are presented and discussed below.

Water supply. The primary purpose of the Kakhovka reservoir before the war was to supply water to cities, towns and settlements to meet the needs of households (including drinking water) and industry. The list of water consumers from the Kakhovka reservoir is presented in Table 1.

Estimations at the global level demonstrate that the industrial sector consumes approximately 20% of the available freshwater (Xuemei Han 2024). As it follows from the Table 1, the industrial sector in the region of the Kakhovka reservoir consumes over 25% of water, but the table shows data for Kryvbas area only. The reservoir was also an important source of industrial water supply for the Zaporizhzhia thermal power plant (TPP) and nuclear power plant (NPP), the latter being the largest nuclear power station in Europe. These are two separate power plants that are located next to each other in the occupied city of Enerhodar on the east side of the reservoir. The Zaporizhzhia TPP consumed water through a deep-water intake facility. The estimated water withdrawal was Q = 66 m^3/s (Bosak and Gvozdetskyi 2015). The depth of the intake is about 8 m. The Zaporizhzhia NPP requires its own cooling reservoir, which needs to be regularly replenished due to natural evaporation from the water surface, evaporation and diversion of water from splash basins and cooling towers, partial filtration into the ground water, and regular purges (which have occurred continuously since 2005). This replenishment is carried out through the discharge channel of the Zaporizhzhia TPP connected to the Kakhovka reservoir. The planned volume of purging was 315,360 thousand m^3 at a flow rate of 10 m^3/s.

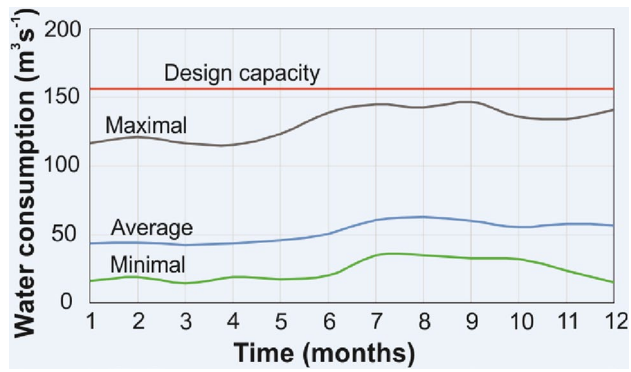


Fig. 3 Multi-year average intra-annual distribution of water consumption (m^3/s) from the Kakhovka reservoir made available to water consumers including the needs of the Zaporizhzhia TPP and NPP and other enterprises and settlements

The throughput capacity of blowdown facilities was 20 m^3/s (Non-technical summary 2016). The critical mark for feeding the cooling reservoir of the NPP from the Kakhovka reservoir was 13.2 m BS (Yatsyk et al. 2003).

The intra-annual distribution of the monthly average water intakes (maximum and minimum values from 1989 to 2021), as well as the design capacity of water intakes are shown in Fig. 3. As follows from this data, water use generally increased in July—September. The maximum average monthly amount of water that was extracted for water consumption to cities and enterprises from the Kakhovka reservoir, and the annual water volumes are presented in Fig. 4. The dynamics of monthly water extraction and annual water volumes (Fig. 4) show a tendency towards a gradual decrease at least during the last thirty years. Both Figs. 3 and 4 are based on the data given in the output portion of the actual water balance (State Water Cadaster 2022).

It should be noted that the Mykolaiv city water intake is located below the Kakhovka HPP on the Dnipro River, the design capacity of which is 9.26 m^3/s (800 thousand m^3/day) (Yatsyk et al. 2003). Compliance with the minimum

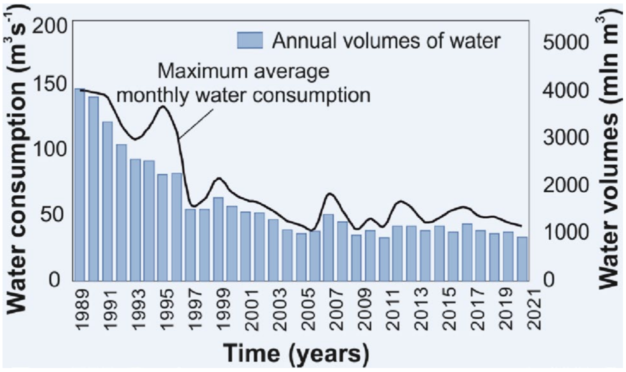


Fig. 4 Annual volumes of water (million m^3) and maximum average monthly water consumption (m^3/s) supplied for the Zaporizhzhia TPP and NPP and other enterprises and cities, from the Kakhovka reservoir

Table 2 Characteristics of the main canals and irrigation systems that consume water from the Kakhovka reservoir

Name of the channel	Power of the main pumping station (MPS), m^3/s	
	Design/installed	Actually used
North-Crimean Canal	294/380	65.9*
Main Kakhovka Canal	530/360	134*/152**

*According to the 2016 data (Gruzinska et al. 2020)

**According to the 2017 data (Khokhlova and Lukashov 2018)

ecological flow release of water at the Kakhovka HPP ensured the normal functioning of this pipeline.

The following section describes water needs and water consumption features by the irrigation sector, the largest water consumer in the region.

Irrigation. One of the main tasks of the Kakhovka reservoir was to meet water needs for irrigation of the arid regions of the Lower Dnipro and Crimea. The main requirement for agriculture was to ensure estimated water extraction during the growing season. The analysis of the average long-term components of the use/outflow part of the actual water balance of the reservoir shows that irrigation accounted for an average of 6.3–6.5% of the total water use. There is not a uniform use of water for irrigation during the growing season. On average, 65% of the total volume of water withdrawal occurred in summer; sometimes this value reached 76%.

Water intake for irrigation was carried out by irrigation systems located on the banks of the Kakhovka reservoir, mostly by water intakes of the North Crimean and Main Kakhovka Canals. In the pre-war period, the latter withdrew more water from the reservoir than the former (Table 2).

The Main Pumping Station was used to supply water to the Main Kakhovka Canal. Water intake was generally uneven during the irrigation season. For example, instantaneous peak flows during 2017 ranged from 6.5 to 152 m^3/s (Khokhlova & Lukashov 2018). The minimum level for the water intake was 14.5 m BS.

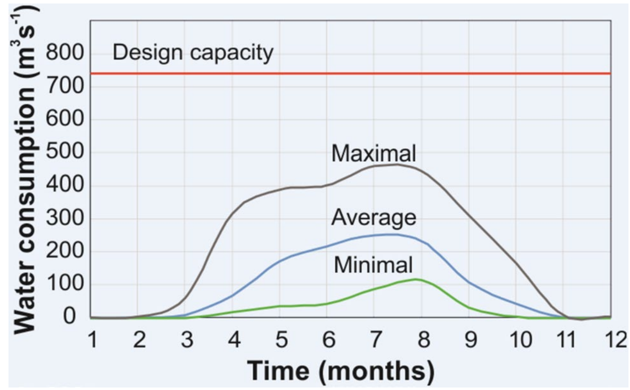


Fig. 5 Supplied for irrigation from the Kakhovka reservoir an average multi-year (1989–2021) intra-annual distribution of water consumption (m^3/s)

Water in the North Crimean Canal flows by gravity on the Ukrainian mainland (water flow is aided by pumping once it reaches Crimea). At a water level of 14.0 m BS in the Kakhovka reservoir, the installed capacity was 380 m^3/s (Baksheev 2008). The intake of water was also uneven with the flow of water into the canal varying both over a 24-h period, and over a period of several months (Honcharuk 2018).

For example, daily water consumption in 2001 ranged from 60 to 205 m^3/s. Water supply to Crimea from this canal was terminated in 2014, after which daily consumption at the main intake facility varied between 11 and 59 m^3/s (Honcharuk 2018). In some publications it was noted that the maximum flow rate reached 65.9 m^3/s (see for example Gruzinska et al. 2020). It should be noted that changes in water level above and below the Kakhovka HPP and in the pressure on gates for the North Crimean Canal in their respective spillways could affect the operation of all downstream structures along the canal, especially the mainland portion (before reaching Crimea) subject to water intake by gravity flow. Usually, an increase in the water level would lead to an increase in water extraction and vice versa.

Figure 5 shows the monthly average distribution of water extracted from the reservoir for the purpose of irrigation (for the period 1989–2021), the maximum and minimum values, as well as the total design capacity of water intakes of the irrigation canals. The graphs are based on data given in the extraction/outflow part of the actual water balance (State Water Cadaster 2022).

The maximum average monthly extraction of water dedicated to irrigation was 459 m^3/s (Fig. 6). During the reservoir's existence, the maximum volume of water extracted for irrigation use reached 6029 million m^3 (in 1990) (Obukhov 2017).

In general, 74% of irrigated land in Zaporizhzhia (204.4 thousand ha), 30% (50.2 thousand ha) of irrigated land in

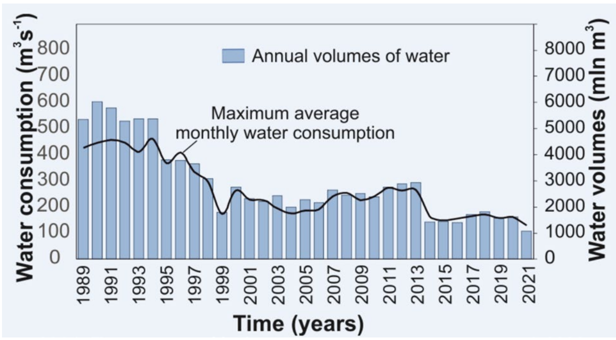


Fig. 6 The maximum average monthly flow of water (m^3/s) and annual volumes of water (million m^3) supplied for the irrigation from the Kakhovka reservoir

Dnipropetrovsk Oblast, and 94% (329.4 thousand ha) of irrigated land in Kherson Oblast (CES 2023) relied on water extractions from the Kakhovka reservoir. As of the second half of 2023, irrigation of these lands has been stopped due to the loss of the water supply source.

The following part describes of the water needs for the main water users in the region.

Hydropower. The use of the Kakhovka reservoir as a water source was to a significant degree regulated by the operations of two hydroelectric facilities: the Dnipro Hydroelectric Power Plant at the north end of the reservoir, located in the city of Zaporizhzhia, and Kakhovka Hydroelectric Power Plant at the south end (MEPNRU 2022). The main task of the Dnipro HPP was to cover the peak loads of Ukraine's power system and use the power generated by the plant to regulate the frequency and daily load schedule. The electricity production of the Dnipro HPP makes up roughly 40% of the Dnipro Cascade hydroelectric power plants-pumped hydroelectric energy storage (HPP-PHES*)* and its reliable operation is a guarantee of the stable operation of the energy system of Ukraine. While delivering this energy, the Dnipro HPP also plays a key role in guaranteeing a water-flow that would ensure proper ecosystem functioning both in the Kakhovka reservoir and south of the Kakhovka HPP. The Dnipro HPP requires an optimal water level both above and below the dam, which is regulated by approved Rules (MEPNRU 2022). The dewatering of the Kakhovka reservoir due to the destruction of the Kakhovka HPP means that the optimal water level can no longer be achieved below the Dnipro HPP. In this regard, the first stage of an experimental project envisages the design and construction of an overflow dam to ensure an adequate water level below the Dnipro HPP (CMU 2023).

According to the analysis of the actual water balance, the share of surface runoff that passed through the Kakhovka HPP's turbines and spillways, i.e. the amount of water filtering through the dam, was 83.3% of the total consumable part of the water balance (State Water Cadaster 2022). Aside from providing electricity, the key direct task facing the Kakhovka HPP in its normal operational regime was to ensure the functioning of aquatic ecosystems in the reservoir and in the Dnipro River below the dam, especially to limit fluctuations in water levels during the fish spawning period.

Water transport. According to the long-term average components of the useable portion of the water balance of the Kakhovka reservoir (State Water Cadaster 2022), water flowing through the locks for lifting and lowering ships for onward movement up or downstream was 0.4% of the water balance. The calculated navigable water level is 14 m. A decrease in the navigable level mark leads to disruptions in the guaranteed depths on the shoal. This is especially important near the city of Zaporizhzhia, where the approach to the sluice from below contains rocks and the depth of this canalized section is 3.2 m, which is lower than the acceptable water level for navigation operations (14 m). The rocky bottom of the ship passage (35 km long) with limited depth continues to Bilenke pier (Yatsyk et al. 2003). Mixed river-sea type vessels have the largest draft with cargo, which is 3.75 m.

Fishing. The Kakhovka reservoir was characterized by a lack of spawning areas. They were under 5% of the area of the water surface at the normal retaining level (NRL), which is two to four times lower than the indicators of other reservoirs of the Dnipro cascade. The main spawning grounds in the Kakhovka reservoir were non-silted or slightly silted areas with depths of up to 2 m, protected from wind and wave influence, with a developed spawning substrate. The spawning grounds most suitable for the reproduction of phytophilic fish species, were concentrated in the northern part of the reservoir (Buzevych et al. 2015). The determinative factor for the normal reproduction of fish stocks in reservoirs is the water level fluctuation. With respect to the Kakhovka HPP, fishing requires limits in the fluctuations of the water level: in the southern area closest to the dam fluctuations should not exceed 0.4 m while the daily water level fluctuations during spawning periods should not exceed 0.1 m (MEPNRU 2022).

Ecological flows. The reservoirs of the Dnipro Cascade are operated in such a way as to ensure the proper functioning of the ecosystems of the reservoirs themselves and the lower Dnipro River (i.e. south of the Kakhovka HPP). The lower Dnipro is, compared to the cascade, a relatively undisturbed portion of the original Dnipro River. The management of the reservoirs is thus a factor in the reproduction of biological resources, the maintenance of the self-purification capacity and the provision of standard quality water to water consumers in the lower Dnipro River. According to the operational regulations of the reservoirs of the Dnipro Cascade (MEPNRU 2022), the following minimal flow rates have been established for maintaining important ecosystems. We call them here ecological flow rates. For the Kremenchuk, Middle Dnipro (Kamianske) and Dnipro HPPs, the flow rates should be at least 400 m^3/s (for the purpose of diluting wastewater). Flows from the Kakhovka HPP should be higher (500 m^3/s); a decrease below 500 m^3/s has been allowed only in special cases (in years of 97–99% of exceedance probability). The exceedance probability of the flow is evaluated using empirical curves of exceedance probability based on long-term series of monthly water discharges. The water flow during drought (corresponding to 97–99% exceedance probability) is extremely low.

During the spawning of aquatic biological resources and with sufficient water content with the priority of filling the Kremenchuk reservoir, water flow from the Kakhovka reservoir to the lower Dnipro can be increased to 1000 m^3/s or more to ensure eco-system functioning (State Water Cadaster 2022). The Kremenchuk reservoir has the second largest water storage capacity of all reservoirs in the Dnipro cascade, and the proper management of its water level is a guarantee that the population, the economy and the environment for large parts of Ukraine will be provided with water resources during dry periods.

The parameters for ensuring functioning of eco-systems in the reservoirs and lower Dnipro were established by the Institute of Hydrobiology of the National Academy of Sciences of Ukraine (Oksiyuk et al. 1997; Timchenko 2006). The main indicators for water quality in the lower Dnipro River are (1) the dynamics of biological oxygen demand (BOD_{tot}) and (2) the processes of the intrusion of salt water wedges into the Dnipro estuary. The regular dynamics of BOD_{tot} from the discharges of the Kakhovka HPP made it possible to determine the maximum permissible ecological water flows in eight established sections of the lower Dnipro, extending from the Kakhovka HPP outlet to the Dnipro-Bug estuary (Timchenko et al. 2000). With regard to the parameters mentioned above, the dependence between discharges from the Kakhovka HPP and the concentration of BOD_{tot} was determined for each of the eight zones of the lower Dnipro from the Kakhovka HPP outlet to the Dnipro-Bug estuary (so-called the Dnipro River mouth zone).

We show nomograms for extreme areas. The nomogram presented in Fig. 7 is used to estimate the minimum ecological flows to maintain acceptable BOD_{tot} levels in the lower Dnipro. The procedure involves: (i) selecting the relevant river reach; (ii) specifying the initial BOD_{tot} concentration based on monitoring data; (iii) defining a target BOD_{tot} threshold corresponding to acceptable ecological status; and (iv) determining the minimum river discharge required to achieve this target. Discharges below 470–490 m^3/s are associated with a rapid deterioration of oxygen conditions and increased ecological risk.

Thus, the quality of the water directly near the HPP (Fig. 7 right, A) depended more on the initial concentration of BOD_{tot}. As Fig. 7A shows, at significant concentrations of BOD_{tot} guaranteeing the functioning of aquatic ecosystems near the HPP could be difficult given high initial pollution indicators (higher BOD_{tot}), i.e. there is no flow rate that can correct for high BOD_{tot} values. However, when approaching the estuary (Fig. 7 right, B) compliance with environmental

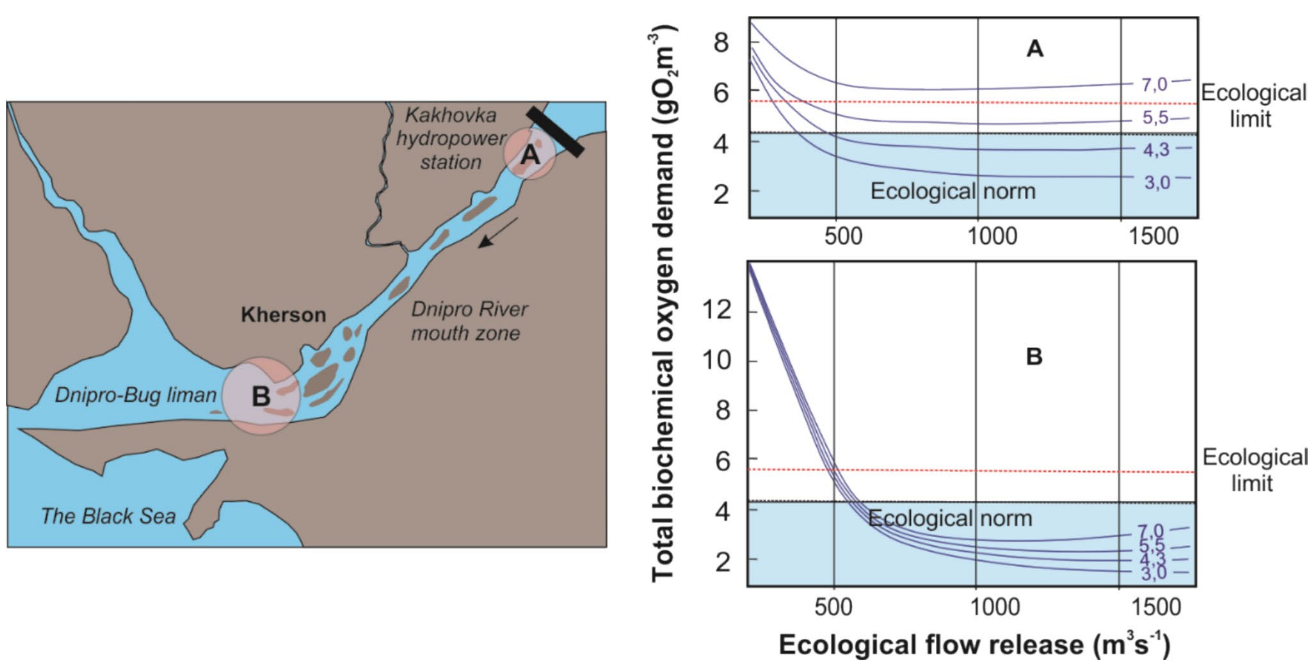


Fig. 7 Map presenting the extreme zones of the lover Dnipro (**A** and **B**, left) and examples of the nomograms for determining ecological flow release in the summer period for the same zones. The numbers on the lines are the initial concentrations of BOD

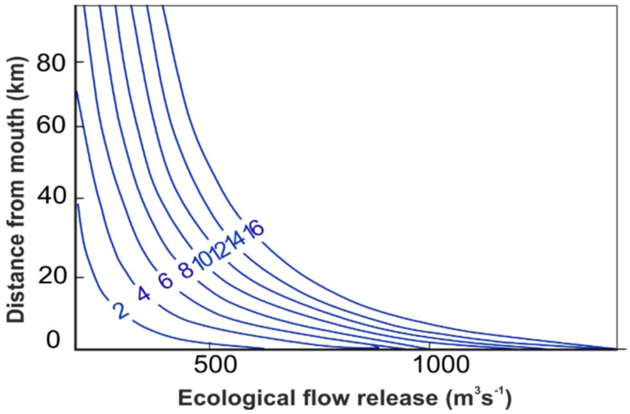


Fig. 8 Nomogram for determining the length of the wedge of salt water in the Dnipro estuary (km) at different water flow rates (m^3/s) and initial salinity concentration (‰, numbers on the lines). Based on the data from Oksiyuk et al. 1997

standards is more optimally achieved with an increase in the water residence time in the system and thus less dependent on the initial concentration, though higher water flow is required (Oksiyuk et al. 1997). The minimum ecological flow should be at least 470–490 m^3/s.

Another factor that contributes to the determination of ecological flow rates is the phenomenon of saltwater intrusion into the lower reaches of the Dnipro. It was observed even before construction of the hydro power station. This phenomenon can be observed several times a year and last from five to 15 days. The main factors that affect saltwater intrusion are runoff and its intra-annual distribution, as well as storm surges and reverse surges that depend on hydrometeorological conditions. Figure 8 presents a nomogram linking river discharge to the upstream penetration of the salt wedge in the Dnipro estuary. The nomogram is applied by selecting representative marine salinity conditions and corresponding river discharge values, from which the upstream extent of saltwater intrusion is determined. Reduced river discharge results in increased penetration of saline water, posing risks of salinization, freshwater habitat degradation, and stress to aquatic biota. The threshold value for maintaining an ecological flow was set at 500 m^3/s, at which the probability of saltwater penetration is insignificant (Fig. 8).

Nevertheless, even with water flows of less than 1000 m^3/s, under various conditions, saltwater can still penetrate into the Dnipro delta. The latter can lead to a decrease in the content of dissolved oxygen in the water, an increase in the content of hydrogen sulfide, fish fatigue, soil salinization, etc. It requires a water release from the Kakhovka HPP with a flow rate of more than 1,500 m^3/s to completely eliminate the possibility of saltwater wedges appearing in the mouth of the river. However, according to research from the Institute of Hydrobiology, Kyiv (Dubnyak et al. 2018), the probability and scale of salt wedge penetration into the lower Dnipro has increased significantly since the 1980s. In 2018, for example, with flow rates from the Kakhovka reservoir close to ecological thresholds, the salt wedge reached the city of Kherson.

The *general requirements* for the minimum water level needed for the proper operation of different hydraulic structures (e.g., dams, channels, spillways, flumes, fishways, etc.) that provide water for various industries in the pre-war period are presented in Fig. 9.

For obvious reasons, the water level is now under these minimum levels, which creates problems for multiple water users and consumers. At present, the priority is the search for alternative water supply for cities. The issue of providing water to all water-intensive sectors of the economy and establishing the operation of related hydrotechnical facilities has not been resolved at the moment and will emerge as an acute problem during post-war reconstruction period.

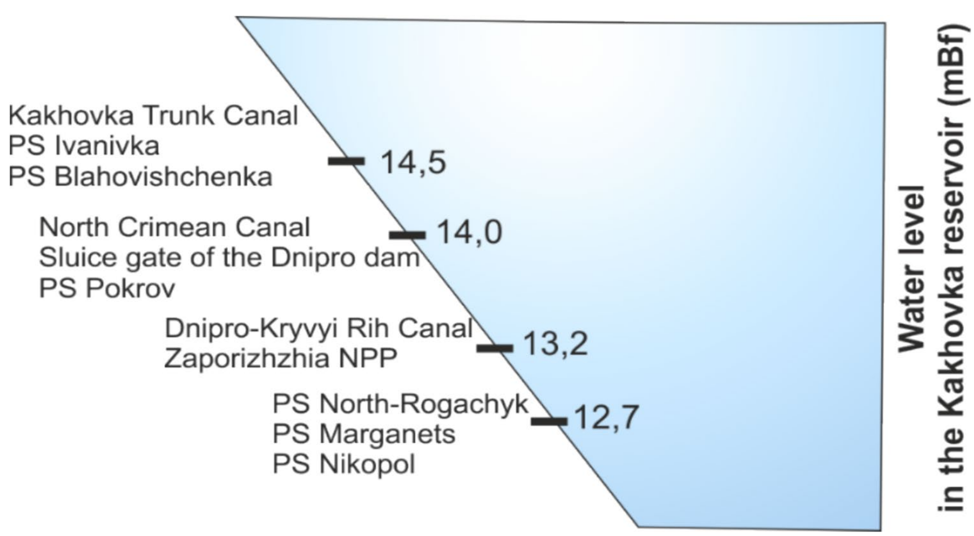


Fig. 9 Minimal level of water needed for the proper operation of different hydraulic structures, such as irrigation canals and water intakes for various consumers in the pre-war period. Based on data from Yatsyk et al. 2003. *PS* pumping station

Water inflow to the studied area of the Dnipro River

The water management balance acts as one of the sources of initial information in the planning and operation of water management facilities. The income related part of the water management balance has been developed for years with 50%, 75%, and 95% exceedance probability on a monthly basis. According to the State Agency of Water Resources (SAWRU 2019), the average annual flow of water entering the water management area of the Kakhovka reservoir under these different water conditions is 1250 m^3/s, 999 m^3/s, and 837 m^3/s respectively (Table 3). The intra-annual distribution is uneven, with minimum monthly water flow rates in July–October. In low-water years with 95% of exceedance probability the average monthly minimum flow decreases to 503–510 m^3/s. Figures 10 and 11 show the intra-annual distribution of flow rates based on the different exceedance rate scenarios, as calculated by the State Agency of Water Resources (SAWRU 2019).

Meeting prospective water needs based on the current situation taking into account the water content of the Dnipro River

When assessing how to satisfy prospective water needs, three scenarios were considered, which were based on the actual pre-war water demand – minimum, average and maximum. According to the above analysis, water demand usually starts to increase with the start of the irrigation season starting in April and ends in October. A separate important component of the outflow/use part of the water balance equation is the provision of appropriate eco-system functioning in the lower reaches of the Dnipro (i.e. south of the Kakhovka HPP, see section on ecological flows above).

Our estimates of the possibilities for providing water to various water users and consumers, taking into account the need to ensure functioning of aquatic ecosystems under different water conditions The estimates are based on the data provided in Table 3. Thus, for water use and consumption, we have added the water needed by urban and regional populations and industry (see Fig. 3), water for irrigation (see Fig. 5), and water needed for ecological flows (see section above on ecological flows). Figures 3 and 5 show minimum, average and maximum use over the year, and these have been added together here to produce overall minimum, average and maximum use. To account for maintaining ecological flow (as explained above), we have added a threshold of 500 m^3/s to each of the estimates on minimum, average and maximum water use. If we juxtapose these estimates of pre-war water use over the supply of water based on scenarios of river flow exceedances of 50%, 75% and 95%, we see that it will almost always be necessary to reserve some water to

Table 3 The income related part of the water management balance for years with runoff of 50%, 75%, and 95% exceedance probability on a monthly (1–12) basis

Exceedance probability of the flow	Water inflow, m^3s^{-1}												
	1	2	3	4	5	6	7	8	9	10	11	12	Avg
50%	1409	1565	1650	1714	1294	1295	873	758	746	1002	1284	1434	1250
75%	1123	1247	1314	1365	1032	1033	698	607	598	801	1024	1143	999
95%	940	1044	1098	1142	864	865	586	510	503	672	858	957	837

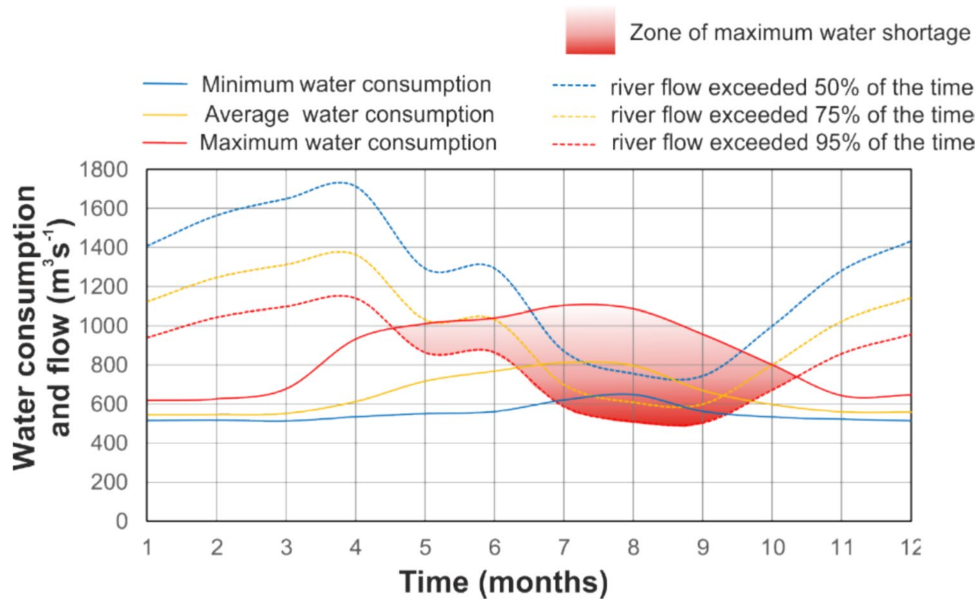


Fig. 10 Intra-annual distribution of water inflow (m.^{3}/s) to the Kakhovka reservoir for years taking into account scenarios with different levels of water availability in and different needs from the reservoir, and the need to support aquatic ecosystems south of the reservoir (i.e. south of the Kakhovka HPP)

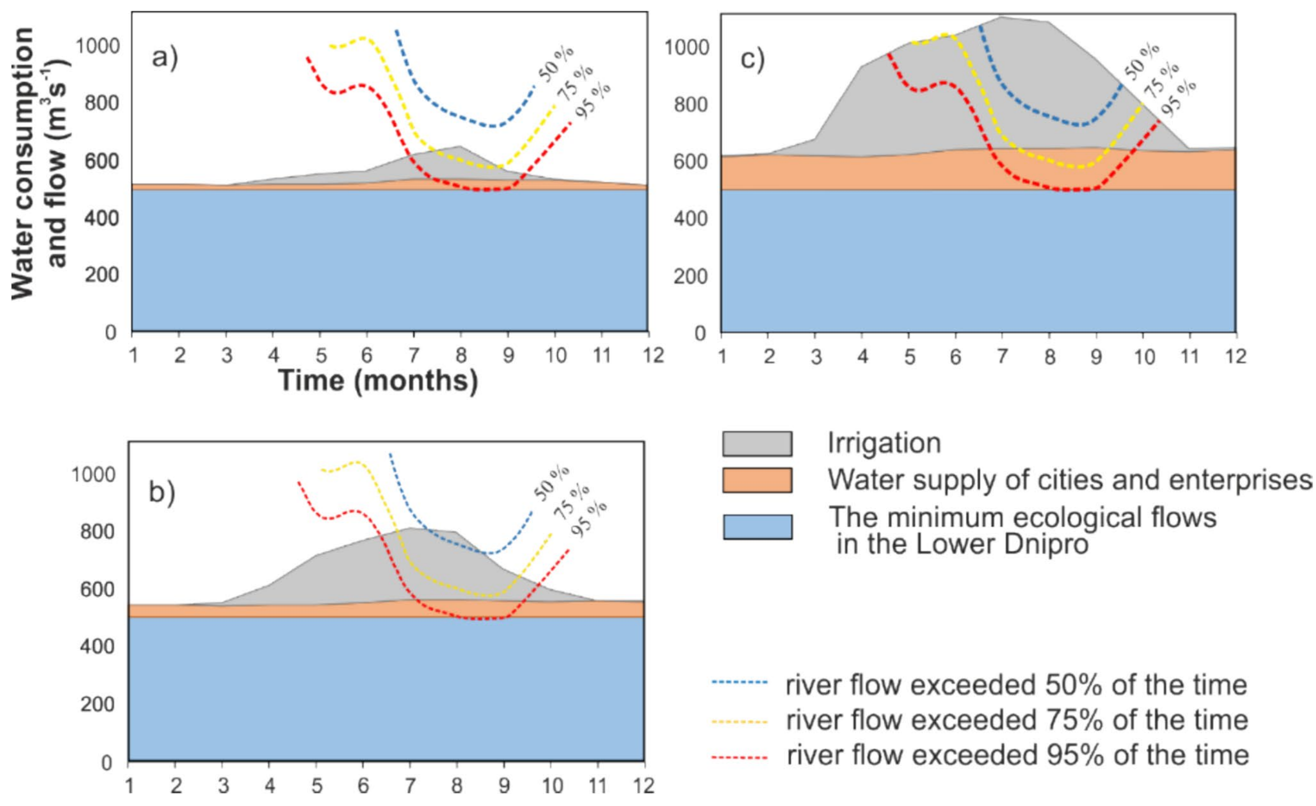


Fig. 11 Intra-annual distribution of water supplied to or consumed by different actors, taking into account scenarios with different water inflow (m^3/s) into the Kakhovka reservoir for years with 50, 75, and 95% exceedance probability and taking into account the need to maintain aquatic ecosystems south of the reservoir

satisfy all water users and consumers, i.e. there would arise a need to store water in for example a reservoir. Depending on the minimum, average and maximum water use at 95% exceedance probability, the volume of water that would need to be reserved to satisfy all water users and consumers, can vary widely from 632 million m^3 to 5355 million m^3. With more favorable water availability, these values are smaller. A water deficit is absent only under the condition of minimal water demand in years with 50% exceedance probability (i.e. the solid blue line in Fig. 10—water use—is under the dotted blue line which indicates water availability). However, it should be noted that these calculations of the required volume of water do not include water losses, such as evaporation or one-way filtration, and we do not take into account restrictions on use that would arise from for example the water intakes now being far above the water level (see Fig. 9).

Figures 10 and 11 illustrate the relationship between available river discharge and aggregated water demands under different hydrological conditions. Each inflow curve represents a specific discharge exceedance probability (50%, 75%, and 95%), defining the upper limit of water availability in a given month. Water demand curves represent minimum, average, and maximum pre-war water use, including domestic, industrial, irrigation, and required ecological flows. Water deficit zones occur in months where total water demand exceeds available river discharge, i.e. where demand curves are located above inflow curves. The vertical distance between these curves represents the instantaneous flow deficit (m^3/s), which, in the absence of reservoir storage, cannot be compensated. Deficits are most pronounced during the summer–autumn low-flow period, when natural discharge is minimal while irrigation demand and ecological flow requirements remain high. Under pre-war conditions, such seasonal deficits were offset by regulation from the Kakhovka and upstream reservoirs; under current conditions, these deficits directly translate into unavoidable trade-offs between water uses and consumptions.

Discussion

Given the above, it is important to consider three aspects when assessing the needs of water users and consumers for water from the Kakhovka reservoir.

1. Water use in the channel of the lower Dnipro (downstream from the dam) meeting the needs of water users and consumers in the region. When analyzing water needs, we used the monthly interval of actual water use for the possibility of comparing it with the water management balance. Depending on the scenarios of water use and water runoff of the year, water shortages of various magnitudes occur. With average volumes of water use to meet regulatory requirements, the water deficit in the summer-autumn period can reach up to 286 m^3/s, (the difference between the yellow line and water consumption in July–August as shown in Fig. 11 b) with maximum volumes—up to 577 m^3/s (the difference between the red line and max water consumption in in July–August as shown above in Fig. 11 c). If we consider a different time interval, for example daily, the instantaneous maximum extraction of intake water for irrigation can increase by 20–25% compared to the maximum monthly value, which for example happened in 2017 (Khokhlova & Lukashov 2018; Honcharuk 2018). However, in an extremely low flow period, the daily minimum natural water flow of the Dnipro can decrease by up to 200–300 m^3/s (Tomiltseva et al. 2017). At particular and short-term points in time, this can increase the area of the daily water deficit, which we would not necessarily see when looking at monthly averages (as in Figs. 10 and 11).

In the pre-war period, water deficits in the Dnipro were covered by the main flow regulator of the Dnipro Cascade—the Kremenchuk reservoir, and by the flow compensator—the Kakhovka reservoir. The capacity of the Kremenchuk reservoir to cover the deficit of the Kakhovka reservoir was 200–210 m^3/s. This deficit can be covered by the Kakhovka reservoir, but in this case the water level in it will decrease by 1 cm. The dispatch schedules of the Kakhovka and Kremenchuk reservoirs were considered together, and the work of these reservoirs, especially in low-water years, was focused on ensuring the necessary water extractions and water levels for different water users and consumers, also taking into account the ecological flow requirements of the sites of the four HPPs. However, in the event of extremely low water levels, the priority of ensuring water provision to the population and for irrigation could necessitate allowing the flow of water in the lower Dnipro to fall below the ecological threshold values that we indicated above. This is according to the decision of the Interdepartmental Commission on Harmonizing the Modes of Operation of the Dnipro and Dniester reservoirs under the State Water Agency. Thus, in 2015, for several months, water flow was allowed to go down to 300 m^3/s (Tomiltseva et al. 2017), i.e. under the 500 m^3/s threshold value for ecological flows. However, under conditions of water deficit, first priority should be assigned to drinking and domestic water supply for the population, followed by the maintenance of ecological flows required to sustain riverine, deltaic, and coastal ecosystems. Other water uses, including irrigation and hydropower generation, are subordinate to these priorities and may be substantially constrained during low-flow periods.

It should be noted that the impact of climate change on the state of water bodies (especially non-flowing ones) should be taken into account when estimating natural water quantity, timing, duration, and fluctuation of inflow. Manifestations of climate change in the southern regions of Ukraine have their own characteristics (Karamushka et al. 2022), and the impact of climate drivers' impact on water bodies can be significant (Boychenko et al. 2022; Kuchma and Boychenko 2022; Romashchenko et al. 2025). Thus, according to various climate scenarios, the Dnipro will see a moderate decrease in river flow by 18–24%, with the exception of the period from January to March, when a slight increase of up to 7% is possible (Didovets et al. 2020).

2. Guaranteed water level—requirements for the highest possible minimum water level for the proper operation of

various water intakes and other water structures of various industries in the pre-war period. In addition to the specified levels within the drained Kakhovka reservoir (Fig. 9), maintaining guaranteed water levels may become acute for other reservoirs, especially for the Kremenchuk reservoir as the main flow regulator, which has its own requirements for maintaining water levels for its own water intakes. In addition, from the point of view of ecosystem functioning, the Kremenchuk reservoir is quite sensitive to intensive summer operation (Timchenko 2006), which unfortunately might now be necessary due to the dewatering of the Kakhovka reservoir. Substantial draining of its shallow water areas will cause intensification of oxidative processes and deterioration of water quality in the Kremenchuk reservoir.

Another aspect for guaranteeing water supply will be the maintenance of stable levels in the tailwater of the Dnipro HPP, i.e. the part of the Kakhovka reservoir bordering on the Dnipro HPP, for water intakes and fisheries during the spawning period. In the river sections, the release waves have more pronounced parameters and can spread over fairly significant distances, which will lead to greater daily fluctuations of water levels, compared to the backwater. In part, this problem can be solved with the help of a cofferdam (Timchenko et al. 2000).

It should be noted that the Kakhovka reservoir in the summer-autumn period was limited in operation to a level of 15.3 m above the Baltic Sea level (Yatsyk et al. 2003), since maintaining this level is necessary for the operation of the North Crimean Canal. At the same time, there are other estimates of the limit parameters in the literature (Baksheev 2008).

It is important to keep in mind that the entire cascade of dams on the Dnipro River works as one system, meaning that significant perturbations to one part of that system—in our case the lowest reservoir (Kakhovka)—have significant upstream consequences that impact water users and consumers throughout Ukraine.

3. Guaranteed volume of water to ensure instantaneous consumption in various scenarios of actual water use and minimum water level limits for hydraulic structures of various industries. This characteristic requires more information on projected water needs and water level of reservoir at which unrestricted water needs will be met. In addition, when determining the volume of the reservoir, it is necessary to estimate the loss (evaporation and filtration of water) depending on the climatic characteristics, the area of the reservoir and the characteristics of the underlying soils in terms of water absorption (saturation).

Conclusion

Many different sectors of the economy and society in southern Ukraine consumed or required varying but still large amounts of water. The very large storage capacity of the Kakhovka reservoir was a necessary condition for the regular use of water on the part of these actors. The Kakhovka reservoir can be considered critical infrastructure on which all water users and consumers in southern Ukraine depended on – in one way or another. In the absence of the Kakhovka reservoir, the flow rate in what is now the main channel of the Dnipro River south of the Dnipro HPP that is needed to meet pre-war levels of water use in the summer period would, depending on the scenario, have to be in a range from 649 to 1100 m^3/s (i.e. minimum and maximum water use in the summer according to the Fig. 11, a and c). Achieving such a flow-rate in low-water years is no longer possible. Assuming that post-war water consumption approximates pre-war use, Ukraine faces a very stark and unpleasant choice in low-water years: it can either divert water to consumers, such as farms and industrial concerns and cities, and let aquatic ecosystems in the southern Dnipro River and estuary deteriorate, or it can curtail water for the various water consumers, to preserve the quality of aquatic ecosystems in the lower Dnipro River and estuary. Under conditions of water deficit, first priority is assigned to drinking and domestic water supply for the population, followed by the maintenance of ecological flows required to sustain riverine, deltaic, and coastal ecosystems. Other water uses, including irrigation and hydropower generation, are subordinate to these priorities and may be substantially constrained during low-flow periods.

As noted above—where we described the only comparable instance of such a large dam failing, the Banquaio event in China in 1976—even if a decision is made to reconstruct the dam, it can take many years before such a dam is in place (not even taking into account that the zone is still an active front in an ongoing war). It is clear that for the short to medium term, all water planning for the Kakhovka reservoir region has to proceed from the assumption that there is no dam and reservoir to balance the needs of the various water consumers with the importance of maintaining ecological functions of the lower Dnipro River and estuary. This article does not propose operational water management methodologies, but establishes the hydrological limits, demand structure, and ecological thresholds that must be taken into account in any subsequent planning or real-time management framework.

No doubts that the amount and availability of water will be one of the main limiting factors in the future development of southern Ukraine. Aside from the important issue of water availability there is a separate issue concerning the possibility of reconstruction in general, and more specifically, the reconstruction of hydroengineering structures at certain water level marks. As it was described above all water intake structures, which were used to deliver the water from the Kakhovka reservoir to the various water consumers, were built assuming the presence of a reservoir. The baseline information on water needs, the possibility of reconstruction of water intake structures, as well as the comprehensive approach to the analysis of water resources provision in the south of Ukraine proposed in this article, can serve as a basis for specialized water management calculations in the future. Determining the feasibility or impracticability of restoring the reservoir(s), and decisions on the optimal volume and operational level should also take into account climatic changes, water transformation, hydrological characteristics and all losses depending on hydro morphometric parameters.

The question regarding the future of the reservoir and dam remains open at least till the deoccupation of the southern Ukraine. It is unclear when it can take place, however, the decision to restore (completely or partially) or to refuse the dam and reservoir restoration will obviously be made taking into account the results of the assessment of the situation that will be formed at that time, and certainly taking into account the water needs of key water users and consumers in the region. While the question of restoring hydraulic structures under specific water level conditions remains open, the integrated assessment of water demand, hydrological availability, ecological constraints, and institutional priorities presented here provide a necessary basis for future, site-specific water management and infrastructure reconstruction studies.

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Author contributions K.M., K.V., H.O. designed the study. K.M., H.O. collected the information on the water balances; K.V., K.B. collected the information on the Kakhovka reservoir functions and restoration scenarios. H.O. and K.V. produced figures presented in the manuscript. K.M. and H.O. wrote initial draft paper in Ukrainian.

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Data availability The data that support the findings of this study are available from the corresponding author, Viktor Karamushka (vkarama2011@gmail.com), upon reasonable request.

Declarations

Conflict of interest The authors report there are no potential conflict of interest to declare.

Ethical approval We declare herein that our paper is original and unpublished elsewhere. This manuscript complies to the Ethical Rules applicable for this journal.

Consent to participate All of the authors consent to participate in this research work.

Consent for publication All of the authors consent to publish this work.

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