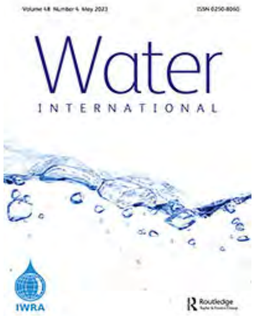

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Viktor Vyshnevskyi[a], Serhii Shevchuk[b], Viktor Komorin[c], Yurii Oleynik[c] and Peter Gleick[d]

[a]National Aviation University, Kyiv, Ukraine; [b]Central Geophysical Observatory, Kyiv, Ukraine; [c]Research Institution 'Ukrainian Scientific Centre of Ecology of the Sea' (UkrSCES), Odesa, Ukraine; [d]The Pacific Institute, Oakland, CA, USA

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Introduction

The Kakhovka hydropower plant on the Dnipro River in Ukraine, its spillway dam and adjoining structures were completely destroyed in the early morning of 6 June 2023 in the course of the Russia–Ukraine War. In the lower reaches of the Dnipro River, four cities and several dozen villages were extensively flooded, killing many people, and destroying or damaging industrial and urban infrastructure. Bacteriological and chemical pollution has been recorded in both the lower Dnipro River and the north-western part of the Black Sea. Water supplies have been cut off for extensive agricultural areas, several large cities and towns, and major energy stations, including the Zaporizhzhia nuclear power plant. Three major consequences of this incident are described here: those on (1) the hydraulic structure itself, (2) the territory downstream from the hydraulic structure and (3) the Kakhovske reservoir formed by the dam and nearby regions. The purpose of this study is to clarify the consequences of the destruction of the Kakhovka hydroelectric plant and dam, as well as to outline the conditions that should be expected in the near future and consider options for restoration.

Methodology and data

The data for this study come from hydrometeorological observations, remote sensing systems, water-quality measurements from water samples in the north-western area of the Black Sea, and on-the-ground observations. Water discharges were obtained for the Dnipro hydropower plant, which is located on the upper border of the Kakhovske reservoir. Water levels were determined from observations at two hydrological stations: Nikopol on the northern bank of the reservoir and Kherson in the lower reaches of the Dnipro River (Figure 1).

The satellite images were provided by the Landsat 8, Landsat 9, Sentinel 1 and Sentinel 2 satellites.[1] Some satellite images of the Modis Aqua and Modis Terra satellites were also downloaded.[2] In addition, Maxar Technology satellite images were used. Similar

CONTACT Peter Gleick pgleick@pacinst.org

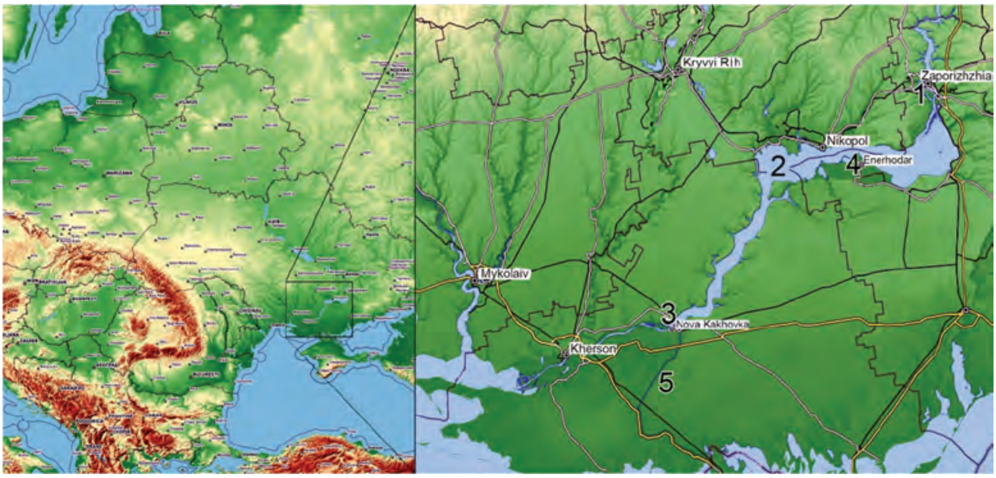

Figure 1. Location of the Kakhovske reservoir and nearby objects on a map of Europe: 1, Dnipro hydropower plant; 2, Kakhovske reservoir; 3, Kakhovka hydropower plant; 4, Zaporizhzhia nuclear power plant; and 5, North Crimean Canal. Source: Modified by the authors from OpenTopoMap.

approaches were used in many previous studies (Al-doski et al., 2013; Fakhri & Gkanatsios, 2021; Garzón & Valánszki, 2020; Shevchuk et al., 2022).

Under the Ukrainian Scientific Centre of Ecology of the Sea's (UkrSCES) guidance, the environmental non-governmental organisation (NGO) 'Let's do it Ukraine' and volunteers collected water samples from the Dnipro River, flooded areas and the Dnipro–Bug estuary. UkrSCES staff also sampled the water and biota in Odesa Bay of the Black Sea. All samples were analysed in UkrSCES laboratories and the data are available.[3]

In addition, wartime events were monitored from official Ukrainian and international sources and from news media.

The Dnipro River and the Kakhovske reservoir

The Dnipro River is one of the largest in Europe, with a length of around 2200 km, a catchment area of 504,000 km^2 and an average natural (unimpacted by human activity) flow at its mouth of around 53 km^3/year. In recent years, water withdrawals from the river, the losses for evaporation from numerous ponds and reservoirs, and increased evaporation due to climate change have reduced its average annual flows by more than 10 km^3. The mean water discharge at the Kakhovska hydroelectric power plant in the period 1956–2020 was 1290 m^3/s, or 40.7 km^3/year (Vyshnevskyi & Kutsiy, 2022).

In total, six reservoirs were created on the Dnipro River. The Dnipro reservoir was the first to be created, formed by the construction of the Dnipro hydroelectric power plant in the early 1930s in the city of Zaporizhzhia. The total volume of this reservoir at normal retention level (51.4 masl) is 3.3 km^3. The spillway of the Dnipro dam was destroyed during the Second World War, but the station was rebuilt in 1947.

At the beginning of the 1950s, the construction of the Kakhovka dam and reservoir, the largest in the Dnipro Cascade, began near Nova Kakhovka town. In this section, the Dnipro River flows through the flat Black Sea lowland. The foundation for the dam was fine-grained silty sand, a contributing factor to the rapid destruction of the hydraulic structure on 6 June 2023.

The Kakhovka dam and hydroelectric plant consisted of four parts: the left bank and the right bank ground dam with a total length of 3.8 km, a concrete spillway dam with a length of 447 m with 28 spillways, a large generator room with six turbines, and a shipping lock with a width of 18 m. The maximum height of the concrete dam was 29 m (Vyshnevskyi, 2011).

The design throughput capacity of the hydraulic structure is 21,400 m^3/s; the hydroelectric plant had a throughput capacity of 2600 m^3/s, capable of producing 335,000 kW of power and an annual production of electricity of 1.4 billion kWh (Figure 2).

The filling of the Kakhovske reservoir began in July 1955 and ended in the spring of 1958. With a normal retention level of 16.0 m, its project area was 2155 km^2, with a storage volume of 18.2 km^3. With a maximum retention level of 18.0 m, its project area was 2222 km^2, with a storage volume of 22.6 km^3. With the dead storage level of 12.7 m (the level at which water use by users became restricted), the area was 1917 km^2 and the remaining reservoir storage was 11.4 km^3 (Vyshnevskyi, 2011).

In addition to the production of electricity, this system provided other benefits, including regional water supply. Almost simultaneous with the construction of the Kakhovka dam, the construction of the large North Crimean Canal began to bring water from the Dnipro River to Crimean agriculture and cities. The canal begins near the dam and stretches almost to the city of Kerch in eastern Crimea, with a total length of 400.5 km. In the second half of the 1980s and early 1990s, annual water flows in the canal from the reservoir reached 3.5 km^3. Subsequently, the transition to a more economical use of water reduced annual water intake to 1.5 km^3, of which 0.5 km^3 were used in the Kherson region and 1.0 km^3 in Crimea. In 2014, after the annexation of Crimea, the supply of water to the peninsula was cut off by Ukraine. In connection with this, the water intake into the North Crimean Canal decreased significantly – to 0.5 km^3 – with this water being used in the Kherson region for the irrigation of about 50,000 ha, partly for growing rice.

Figure 2. Satellite image of the Kakhovka hydrotechnical structure before its destruction. Source: Google Earth, 20 October 2020.

In 1970s, the Main Kakhovka Irrigation Canal was also built to take water from the Kakhovske reservoir. It originates a few kilometres north-east of the beginning of the North Crimean Canal. The length of this canal, which has a predominant direction from west to east, is 129.8 km. In 2020–21, annual water flows into the canal reached 0.9–1.0 km^3, supplying water to around 240,000 ha. Several smaller irrigation systems on both the left and right banks of the Dnipro River were also fed from the Kakhovske reservoir.

In addition to electricity generation and irrigation, the Kakhovske reservoir was widely used for drinking and industrial water supply. The largest facility built in 1957–61 for these needs is the Dnipro–Kryvyi Rih Canal, with a design capacity of 41 m^3/s to provide water to the city of Kryvyi Rih and the nearby Kryvorizka thermal power plant with a capacity of 2000 MWe. In the 1970s, another power plant, the Zaporizhzhia thermal power station, was built near the city of Enerhodar. Its modern capacity is about 1200 MWe. In the 1980s and 1990s, the Zaporizhzhia nuclear power plant was built, with six units with a total capacity of 6000 GWe. This nuclear plant is the largest in Europe. Before the Russia–Ukraine War, it produced 40–42 billion kWh/year of electricity, or a quarter of the total electricity demands in Ukraine. All these energy facilities depended on water for cooling from the Kakhovske reservoir.

The cooling system of the Zaporizhzhia nuclear power plant has three components: a cooling pond, two cooling towers and several basins with fountains. In particular, the cooling pond, built on the edge of the Kakhovske reservoir, has an area of 8.2 km^2 (Vyshnevskyi, 2011).

In addition to Kryvyi Rih, the Kakhovske reservoir provided drinking water supply to several other cities, including Nikopol, Marganets and Beryslav on the right bank, and Enerhodar, Kamianka-Dniprovska and Dniprorudne on the left. The above-mentioned North Crimean and Main Kakhovka Irrigation canals also supplied water to several cities and many villages.

Finally, the Kakhovske reservoir also improved conditions for shipping, in particular for the movement of ships with grain, ore and metals, providing shipping lanes with a depth of 3.65 m, and it was widely used for fish breeding and fishing (crusian carp, roach, bream, silver carp). The total annual volume of catch by commercial entities exceeded 1000 tons (Alymov et al., 2012; Vyshnevskyi, 2011).

The short-term consequences after the explosion

On 11 November 2022, the Ukrainian army liberated Kherson city and other settlements on the right bank of the Dnipro River. That day three sections of the spillway and part of the roadway across the Kakhovka dam near the right bank were destroyed to prevent Ukrainian forces from crossing the river (Figure 3).

After the damage to the spillway and during the subsequent winter, the water level in Kakhovske reservoir began to drop due to uncontrolled releases of water. By the end of February 2023, water levels had dropped more than 2 m and the shoreline retreated in some places by more than 100 m.

Water levels in the reservoir began to rise again when larger-than-average spring rains and snowmelt increased Dnipro River flows. The largest discharge at the Dnipro hydroelectric power plant on 19 April 2023 reached 6490 m^3/s. Under such conditions, the water level measured at Nikopol gauging station by early May rose to 17.13 masl, the

Figure 3. Satellite image of the damaged spillway of the Kakhovka dam before its destruction. Source: Skysat image from https://twitter.com/planet/status/1666116252090388480/photo/1

highest level recorded since the reservoir was created. Before this the highest water level (16.46 masl) was observed in 1993 (Vyshnevskyi & Kutsiy, 2022).

On the day of the explosion, the Kakhovka dam was under the control of Russian forces and the water level at Nikopol station was 16.76 masl. According to the Operation Rules of the Dnipro Cascade Reservoirs, the total reservoir volume at this level was 19.8 km^3 (Yatsyk et al., 2003).

The explosion, which occurred between 2.30 and 3.00 a.m. on 6 June 2023, caused massive flows of water out of the reservoir and the washing away of major portions of the dam. Large volumes of sediments that had accumulated in the reservoir were flushed downstream as well (Figure 4).

After the destruction of the dam, water levels downstream began to rise rapidly. At 4.00 a.m. on 6 June, the water level at Kherson hydrological station before the increase was 0.31 masl. Four hours later it reached 1.60 masl and by 8.00 a.m. the following day it had risen to 5.29 m. Flood flows eventually peaked at 5.68 m, on 8 June 2023 at 3.00 a.m. Thus, the total increase of the water level reached 5.37 m (Figure 5).

This flood inundated extensive areas below the dam along the both banks of the Dnipro River and nearby, partly flooding four cities: Nova Kakhovka, Oleshky and Hola Prystan on the left bank, and Kherson and several dozen villages along the right bank (Figure 6).

As can be seen in Figure 6, the increase of water level was observed not only in the lower reaches of the Dnipro River, but also on its right tributary, the Inhulets River contributing to the flooding of some additional villages here.

The most severe flooding occurred in Nova Kakhovka city and in the village of Kozatske both located less than 2 km downstream from the destroyed dam. At these locations, the increase in water level began a few minutes after the explosion, in the middle of the night. Most residential buildings in the central part of Nova Kakhovka city have an elevation of 11.5–12.0 masl. Photographs of this area show extensive flooding, including in the square before the Palace of Culture (elevation of 11.5 masl), with

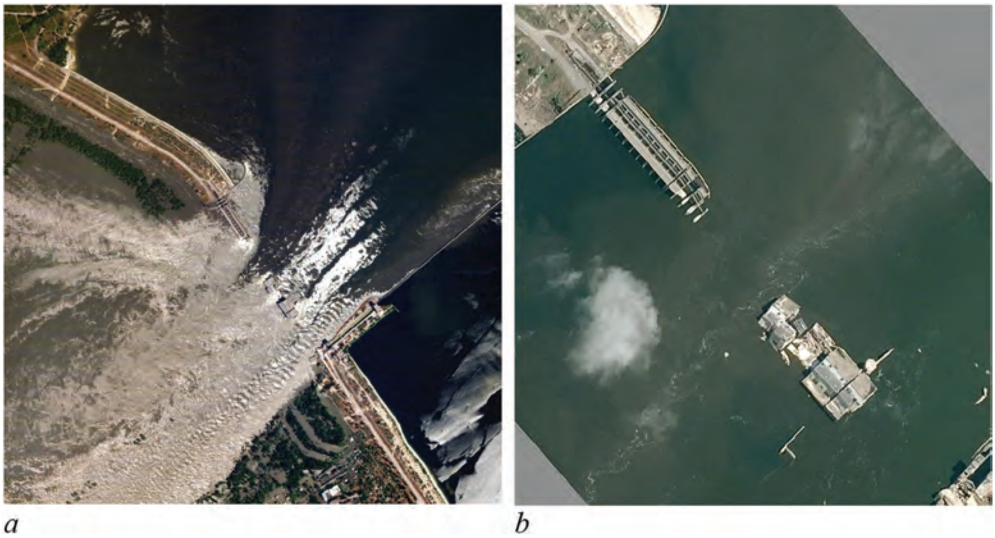

Figure 4. (a) The destroyed Kakhovka hydrotechnical structure soon after the explosion on 6 June 2023; and (b) the dam on 7 June 2023. Source: https://apnews.com/article/ukraine-russia-dam-collapse-before-after-photos-b504eb2ce21e2c30cbcf902fbd718b71

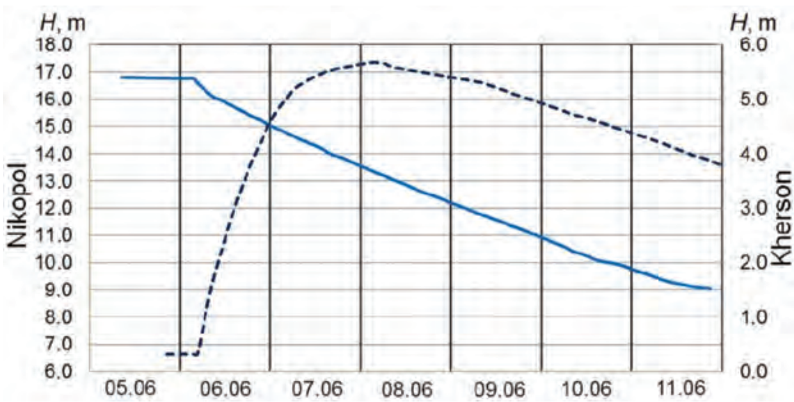

Figure 5. Changes in water level at the Kherson and Nikopol hydrological stations between 5 and 11 June 2023. Source: Data are from the Hydrometeorological Service of Ukraine.

flooding to a depth of around 1 m.[4] From this, we estimate that the water level in Nova Kakhovka city reached 12.5 masl (Figure 7).

Video and satellite images taken after the destruction of the dam show thousands of buildings were flooded and many completely destroyed.[5]

The drop in elevation in the lower reaches of the Dnipro River is very small. The water level of the tailwater of the Kakhovka dam is rather small as well. With a mean long-term water discharge of 1490 m^3/s, the water level in the tailwater was 0.20 masl. There are no data about water level in this place at the time of the explosion, but they can be estimated on the basis of the discharge data in the Dnipro hydroelectric power plant. Water discharge at this facility on 4 June 2023 was 1660 m^3/s, and on 5 June 2023 was

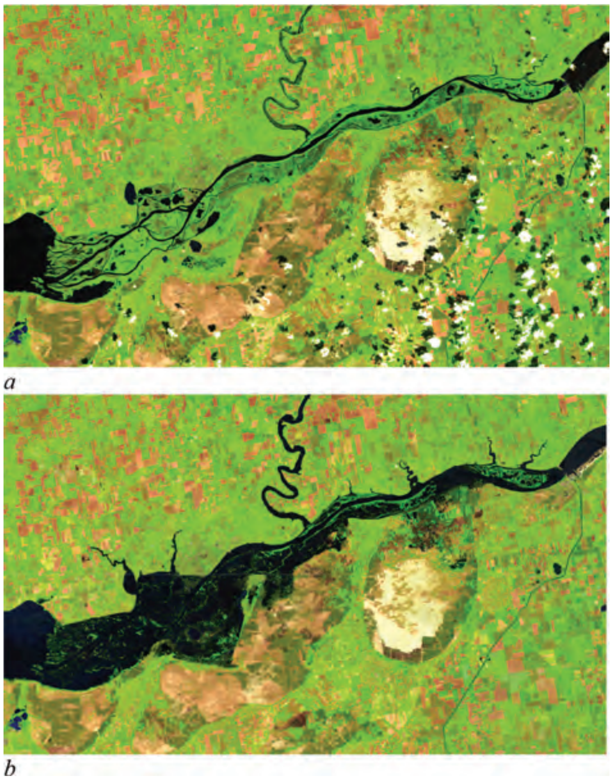

Figure 6. Satellite images of the lower reaches of the Dnipro River taken by Landsat 9 satellite on (a) 1 June 2023 and (b) 9 June 2023. Source: https://earthexplorer.usgs.gov/

Figure 7. The flooded square before the building of the Palace of Culture in Nova Kakhovka. Source: https://focus.ua/uk/voennye-novosti/571041-u-zatoplenij-novij-kahovci-chuli-zvuki-strilyanini-roszmi-video

1750 m^3/s. Under the same discharge from the Kakhovka dam, the tailwater level is about 0.35 masl. This means that the total increase of the water level in Nova Kakhovka city exceeded 12.0 m, double the level of the increase downstream in Kherson city.

The flood also led to a temporary increase in the water level of the north-western part in the Black Sea. The highest level in Odesa seaport was observed on 10 June 2023, and this was 5–10 cm higher than before the destruction of the dam.

According to the Ministry of Internal Affairs of Ukraine, around 50 people were killed or missing on the right bank of the Dnipro River. No information on the human toll on the left bank of the river was available at the time of writing (beginning of July 2023). At the same time, considering the features of the settlements' location, it is possible that the number of victims on the left bank is much larger than on the right bank of the river.

Other consequences of the destruction of the dam include the human and ecological impacts of that flooding, bacterial and chemical contamination, and the longer term disruption of water supply and irrigation systems that had been dependent on water availability in the Kakhovske reservoir.

The pollution of water

The destruction of Kakhovka also caused extensive pollution of the Dnipro–Bug estuary and the north-western part of the Black Sea. On 8 June 2023, pollution reached Odesa, and by June 10 it reached the mouth of the Dniester River. On 17 June, river water containing both chemical and biological contaminants from the sediments previously stored behind the dam and from flooded industrial facilities, landfills, sewage plants and petroleum stations, reached the mouth of the Danube River and covered an area of more than 7300 km^2 (Figure 8).[6]

Water sampling in Odessa Bay by the UkrSCES revealed a significant increase of phytoplankton content, which corresponded with the emergence of green patches of microalgae in seawater near the beaches of Odesa starting from 14 June 2023 (Figure 9).

Observations also showed a noticeable drop in the salinity of the sea following the incident. Before the accident, the salinity averaged around 11 g/l. Between 13 and 14 June 2023, the salinity dropped significantly to a range of 4.2–4.4 g/l (measured as practical salinity unit – psu). As flood flows started to decrease, a corresponding increase in salinity was measured, leading to a full recovery by the end of June (Figure 10).

The influx of fresh and polluted water affected the chemical composition of the seawater and high levels of biogenic substances were measured, including nitrogen (N) and phosphorus (P) compounds. In most cases the highest concentrations were observed on 14 June 2023, that is, simultaneously with the lowest water salinity (Figure 11).

Data compiled by the UkrSCES shows a decline in the concentrations of biogenic substances at the end of June and a reduction in the risk of an ongoing water bloom, however counterbalanced by a concerning increase in other pollutants. Specifically, seawater near Odesa on 14 June 2023 recorded concentrations of copper (Cu) at 17.9 μg/l, zinc (Zn) at 44.8 μg/l and arsenic (As) at 1.81 μg/l, all significantly above their reference levels of 0.02, 1.0 and 0.6 μg/l, respectively, as per European Union (EU) Directive 2013/39/EU and the supplementary list of priority substances from Annexe XII.1.2 of the Final Scientific Report EMBLAS of 4 November 2020. The concentration of oil products stood at 0.10 mg/l, higher than its reference level of

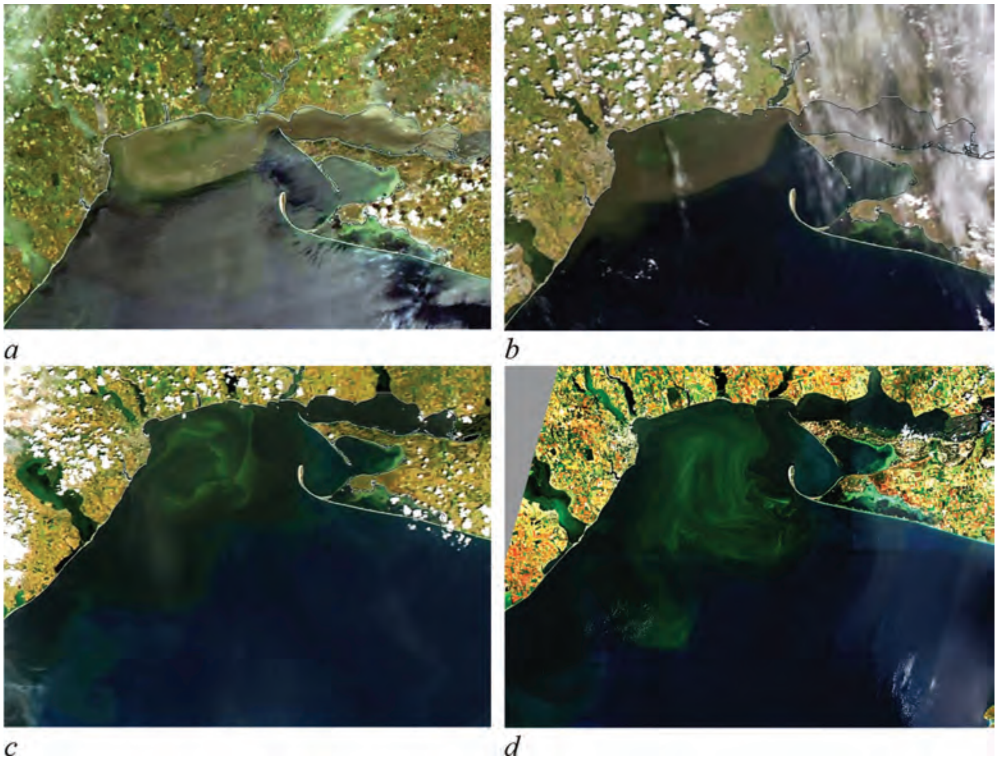

Figure 8. Satellite images of the north-western area of the Black Sea on (a) 9 June 2023, (b) 10 June 2023, (c) 17 June 2023 and (d) 23 June 2023. Sources: https://worldview.earthdata.nasa.gov (a, b), https://scihub.copernicus.eu (c, d).

0.05 mg/l. In contrast, the cadmium (Cd) level at 0.56 μg/l was below its reference standard of 1.5 μg/l. These maximum permissible concentrations are drawn from the aforementioned documents, further supplemented by data from the NORMAN Ecotoxicology Database. The substances for biological entities are determined according to Commission Regulation (EC) No. 1881/2006. Ordinarily, within this region of the Black Sea, pollution levels do not exceed these maximum permissible concentrations. In connection with the increase in water pollution, swimming on the beaches of Odesa was prohibited for several weeks.

Water samples taken from the Dnipro River near Kherson, in the Dnipro–Bug estuary and in the Black Sea near Ochakiv showed a similar surge in pollution. At all stations, concentrations of oil products, toxic metals (such as Zn, Cu and As) and certain chlororganic compounds (such as lindane and polychlorinated biphenyls – PCBs) were found to exceed the maximum permissible concentrations. These pollutants are known to be toxic to many species of aquatic organisms at high concentration levels (Zaynab et al., 2022), affecting the reproductive, growth and other biological processes in marine organisms. Even if individual species can tolerate high levels of Cu and Zn, if the pollutants remain mobilized in the water or are easily available in the food chain, heavy metals can accumulate, leading to even higher concentrations in organisms at the top of the food chain, such as marine mammals or humans. People who eat seafood or

Figure 9. Seawater sample taken in the Gulf of Odessa on 20 June 2023. Photo: Oleksandr Lepyoshkin.

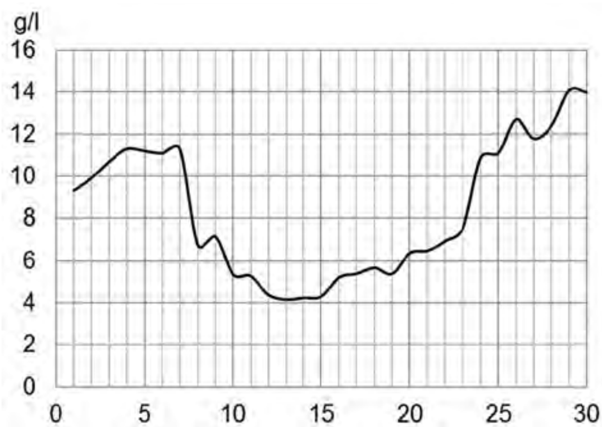

Figure 10. Changes in water salinity at the seaport of Odesa in June 2023. The x-axis are dates in June. Source: Data are from the Hydrometeorological Service of Ukraine.

drink water containing high levels of Cu or Zn can experience various health problems, including issues with the liver, heart, kidneys or nervous system.

Impacts on the Kakhovske reservoir

The downstream flooding was accompanied by a rapid decrease in the water level in the Kakhovske reservoir. The water level measured by the Hydrometeorological Service of Ukraine at the Nikopol gauging station before the explosion was 16.76 masl. After the destruction of the dam in the early hours of 6 June, it decreased to 16.13 masl by 8.00 a.m. At 8.00 a.m. the following day, the reservoir level had dropped to 14.48 masl. By 8.00 p.m.

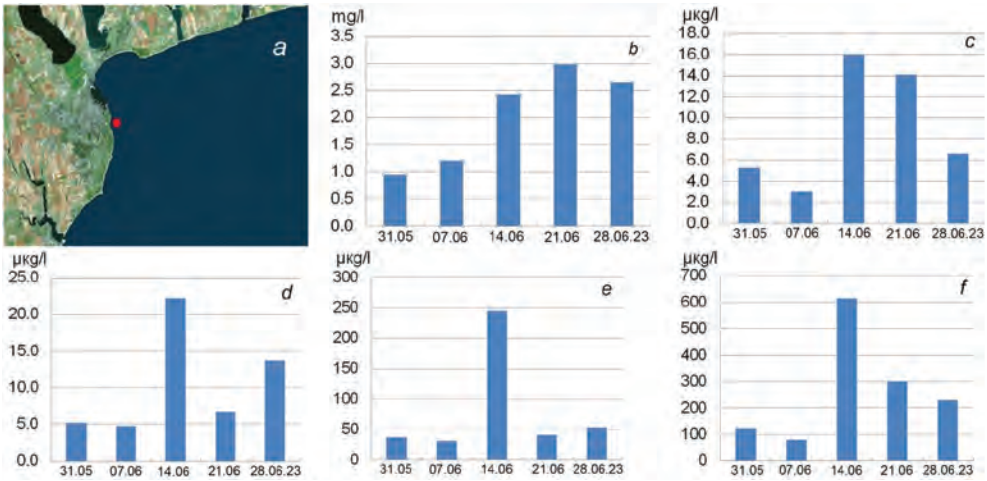

Figure 11. Location of sampling (a) and concentrations of biogenic substances: (b) BOD5, (c) $P(PO_4)$, (d) $N(NO_2)$, (e) $N(NH_4)$ and (f) $Si(SiO_4)$ in the Black Sea near the yacht club of Odesa city. Source: Data are from the Ukrainian Scientific Centre of Ecology of the Sea (UkrSCES).

on 11 June 2023, it decreased to 9.04 m and the main part of the reservoir volume was completely lost. At this point, the monitoring station at Nikopol was no longer able to record (Figure 5).

At the same time, a significant decrease in the water level was observed in the upper part of the Kakhovske reservoir in the city of Zaporizhzhia. On the eve of the incident, the water level in the tailwater of the Dnipro dam was 17.05 masl. On 10 June 2023, it dropped to 14.42 masl; on 15 July 2023, it dropped to 13.40 masl; and on 20 June 2023, the water level stabilized at about 12.60 masl for a total drop in water level of almost 4.5 m.

Satellite images taken on 9 and 16 June show the gradual disappearance of the reservoir (Figure 12).

At the end of June 2023, the Kakhovske reservoir had almost completely disappeared and the original network of branches of the river re-emerged at the site of the former reservoir (Figure 13).

Medium- and long-term consequences of the Kakhovka hydroelectric powerplant's destruction

In addition to the short-term consequences of the Kakhovka dam destruction described above, medium- and long-term consequences are anticipated in both the territory below the hydraulic structure and in the region of the lost Kakhovske reservoir. Ecological consequences in the Dnipro–Bug estuary and the north-western part of the Black Sea are likely to include the death of most of the living organisms lost from the Kakhovske reservoir and the lower Dnipro River. Some of these organisms will settle to the bottom, some will end up on the water's surface. In the first case, we should expect a decrease in the concentration of dissolved oxygen in the bottom layer of the sea and an increase in the level of the water layer saturated with hydrogen sulphide (H_2S). To some extent, this will also happen due to

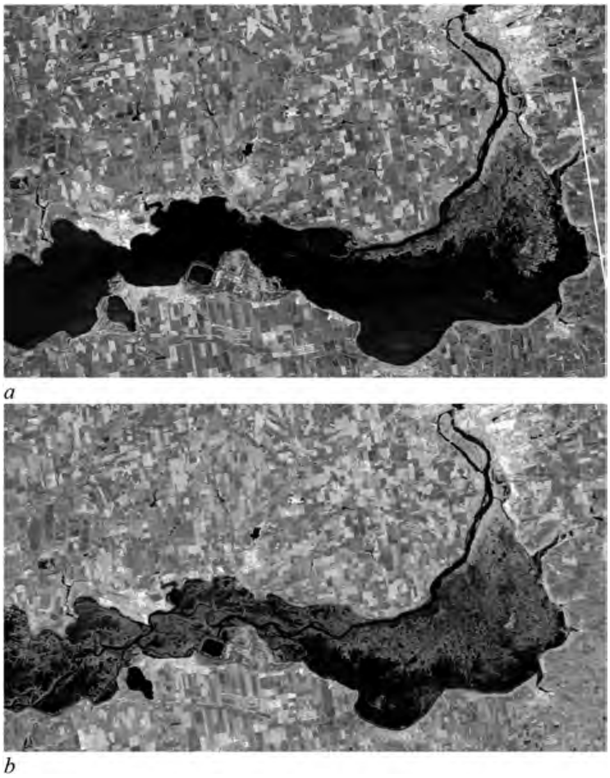

Figure 12. Satellite images of the Kakhovske reservoir taken by the Sentinel 1 satellite on (a) 9 June 2023 and (b) 16 June 2023. Source: https://scihub.copernicus.eu/dhus/#/home

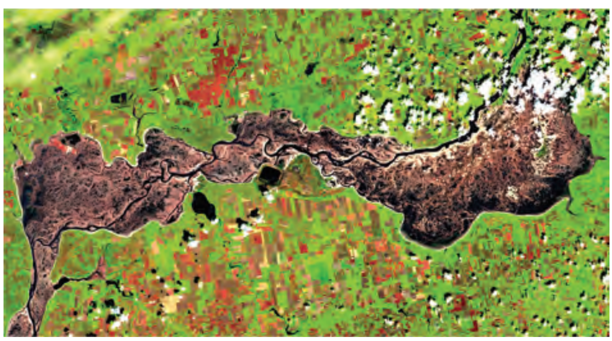

Figure 13. Satellite image of the Kakhovske reservoir taken by the Sentinel 2 satellite on 30 June 2023. Source: https://scihub.copernicus.eu/dhus/#/home

a decrease in water transparency. In turn, the appearance of dead organic matter on the sea surface will contribute to the food base of birds. However, their numbers will stabilize during next two years.

Most of the bottom of the former reservoir will gradually (by the end of summer 2023) be exposed to the surface. This soil will dry out and mostly become covered with cracks. In some months, but mostly in the spring of 2024, thinned vegetation will appear on the former bottom of the reservoir, possibly with a large proportion of invasive species because of their ability to outcompete native species.

The water level at the site of the former river branches will return to pre-construction conditions. Before the creation of the reservoir in the 1950s, the normal water level of the Dnipro River measured at the Nikopol gauging station was about 6.0 m. Thus, the total decrease of water level near the city will be about 10 m. In fact, this has already been observed. The loss of the reservoir is also likely to affect the microclimate of the surrounding territory, which is dry and hot in summer.

Significant economic impacts are also expected. Without the restoration of the reservoir, none of the three water-supply canals mentioned above will work. Accordingly, irrigation will be greatly reduced or completely eliminated with a particularly negative impact on the driest Kherson region in Ukraine, where the irrigated area on the eve of the war reached 300,000 ha. In addition, irrigation in the Zaporizhzhia and Dnipropetrovsk regions will decrease as well by an estimated 50,000 ha. The drinking water supply for several major cities will deteriorate significantly and alternative sources of supply will have to be found, including transporting drinking water by motor vehicle to dozens of settlements.

Without the Kakhovske reservoir, industrial water supply will become significantly more difficult. The available water in the cooling pond of the Zaporizhzhia nuclear power plant will last at most for a year. However, there is a factor that allows this problem to be alleviated. The above-mentioned cooling pond was partially built on the site of the former branch of the Dnipro River. That is why the water here receded only a few tens of metres, providing an opportunity to build a pumping station here to resupply water to the cooling pond.

Consequences for the Black Sea

The flow of oil products and other toxic substances into the Black Sea could lead to the death of many aquatic organisms, especially at sensitive stages of development such as larval. The change in salinity in the Black Sea is expected to add stress in the marine ecosystem, which is adapted to a certain level of salinity. The longer term consequences of the flow of water polluted with biogenic substances include the possibility of large areas with hypoxic and anoxic conditions in the bottom layer, which will further affect the resilience of the ecosystem (Komorin, 2021). We also anticipate the following long-term consequences for marine ecosystems:

- Secondary pollution from the release of toxic substances from the sea bottom sediments will affect ecosystems over a prolonged period.
- Oil products and other toxic substances will accumulate in biological organisms living in the water and on the seabed, leading to long-term effects on their health and lifecycles.
- This disaster can affect the resilience of the sea's ecosystem, as well as cause the appearance of secondary negative effects, such as loss of biodiversity, landscape changes and destruction of biotopes (Komorin, 2021).

Prospects for restoration of the Kakhovske reservoir

After the end of the Russia–Ukraine War there may be several options for restoring the dam and the Kakhovske reservoir. The first consists of restoring the same structure that existed before the destruction. However, this is undesirable for several reasons. First, the Kakhovka hydropower plant was built at a time when there was a relatively small Dnipro reservoir upstream. In connection with this, a large spillway dam was built at Kakhovka, the capacity of which was never even half used. The maximum discharge recorded here in 1958 was 9740 m^3/s (Vyshnevskyi & Kutsiy, 2022).

In addition, a significant mistake was made in the original Kakhovka project: the installation of only six hydropower units capable of passing only 2600 m^3/s, and periodic repairs meant that often only five units were capable of operating. At the same time, the flow capacity of the Dnipro dam located upstream is almost twice as large at 4950 m^3/s. Under these conditions, this hydroelectric plant often operated off-peak, but for much longer, producing electricity when its value decreased. Periodically, the limited capacity of the Kakhovka plant determined the need to discharge water through spillway dam without any economic benefit.

Considering the predominant role of the Kakhovka hydroelectric structure for land reclamation and water management, the main attention during the restoration should be given to these components, because without the reservoir, about 350,000 ha of land cannot be irrigated. In addition, water supply for such cities as Kryvyi Rih, Nikopol, Marganets, Beryslav, Enerhodar, Kamianka-Dniprovska and many villages has been disrupted, as has water supply for the Zaporizhzhia nuclear power plant and several other large industrial enterprises.

A quick solution to the existing problem might be construction of a temporary dam near the site of the destroyed dam, permitting some filling of the reservoir. While maintaining an ecologically reasonable downstream discharge (500 m^3/s), it would be important to fill the reservoir to a minimum of 12.7 m as soon as possible, to permit water to be provided to all consumers though not for hydropower and shipping. This disadvantage is limited, however, because the electricity production capacity at the Zaporizhzhia nuclear powerplant, Kryvyi Rih thermal powerplant and Zaporizhzhia thermal power plant far exceeds that of Kakhovka hydropower plant by more than an order of magnitude. It should be possible to reach a storage level of 12.7 m and a volume of 11.4 km^3 in just one year.

At the same time, the construction of a new hydropower plant can be started, but with a larger number of units (at least eight) and discharge capacity of at least 4000 m^3/s.

It is important that a restored dam provide a water level in the reservoir of 12.7 m, not only to provide water to most consumers but also to safely pass the flow of a large flood that may occur. In the latter case, part of it can be stored in the restored reservoir and part discharged through repairs or reconstruction of the spillway. Over time, depending on how the hydroelectric power station is built, the water level in the reservoir can be increased.

Epilogue: a historical and legal context

Many examples of attacks on water infrastructure during war are known from history, including many from the Second World War. In August 1941, the retreating Soviet Army destroyed the spillway of the Dnipro hydroelectric power plant on the Dnipro River near the city of Zaporizhzhia in order to delay advancing German forces. The breaching of the dam and the massive downstream flooding reportedly killed tens of thousands of people (Gleick et al., 2009; Swain, 2001; Vyshnevskyi, 2011). In May 1943, the British Royal Air Force (RAF) bombed dams on the Möhne, Sorpe and Eder rivers in Germany, killing more than 1000 people and causing massive downstream flooding. In 1944, German troops destroyed several dams on the Liri River in Italy to flood territory occupied by Allied troops (Gleick et al., 2009; Kirschner, 1949).

One of the consequences of the horrors of the Second World War, and especially its impacts on civilians, was the development of international humanitarian laws of war, including the Geneva Convention of 1949 and its 1977 Additional Protocols. Among many other provisions in these laws, several now explicitly prohibit using water and water systems as a weapon against civilian populations. For example, Article 56 of Protocol I and Article 15 of Protocol II of the 1977 Protocols to the Geneva Conventions prohibit attacks on infrastructure 'containing dangerous forces' including explicitly 'dams' and 'dykes' if such attacks 'may cause the release of dangerous forces and consequent severe losses among the civilian population' (Dannenbaum, 2023; Gleick, 2019).

The war launched by Russia against Ukraine in 2014 and massively expanded in 2022 has been accompanied by the destruction of extensive urban, industrial and physical infrastructure, significant human casualties, and a negative impact on all components of the environment. New data and information on some of the environmental consequences of this war have been described in recent research papers, media reports and assessments from non-governmental sources (e.g., BBC News, 2023; Gettleman, 2022; Gleick & Shimabuku, 2023; Harada et al., 2022; Kesaieva, 2022; Khilchevskyi, 2022; Knight, 2023; Pereira et al., 2022; Rawtani et al., 2022; Shevchuk et al., 2022; Shevchuk & Vyshnevskyi, 2022; Shumilova et al., 2023; Top War, 2023; Zheleznyak et al., 2022). But the destruction of the Kakhovka hydropower plant and the Kakhovske reservoir is now the largest hydrotechnical facility to be destroyed during a war in human history.

Notes

1. See https://scihub.copernicus.eu and https://earthexplorer.usgs.gov.
2. See https://worldview.earthdata.nasa.gov.
3. Available at https://database.blackseadb.org.
4. See https://focus.ua/uk/voennye-novosti/571041-u-zatoplenij-novij-kahovci-chuli-zvuki-strilyanini-roszmi-video; and videos https://www.youtube.com/watch?v=V9hp3Z_OKKw.
5. Video (https://www.youtube.com/watch?v=aeB27ZcKUOA, https://www.youtube.com/watch?v=laWSfzJg7JM), satellite images (https://news.obozrevatel.com/ukr/society/zatopleno-velichezni-teritorii-novi-suputnikovi-znimki-naslidkiv-rujnuvannya-grebli-kahovskoi-ges.htm) and other resourses (https://apostrophe.ua/ua/news/society/2023-06-07/kak-vyiglyadit-zatoplennyiy-herson-s-vyisotyi-ptichego-poleta-foto/298562).
6. This section includes new data and findings from the UkrSCES investigations. These data are available at https://sea.gov.ua/index.php/2023/06/27/ges_explosion_conseq/.

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ORCID

Viktor Vyshnevskyi http://orcid.org/0000-0002-2900-1598
Serhii Shevchuk http://orcid.org/0000-0001-5844-4980
Viktor Komorin http://orcid.org/0000-0002-4847-0496
Yurii Oleynik http://orcid.org/0000-0001-8116-512X
Peter Gleick http://orcid.org/0000-0001-7232-9284

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