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REVIEW ARTICLE
10.1029/2023EF003910

Rivers and Water Systems as Weapons and Casualties of the Russia-Ukraine War

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Key Points:

- Rivers and water systems have been used as weapons, casualties, and triggers of conflict in the past
- Numerous instances of the use of water in war have occurred in the Russia-Ukraine war since February 2022, especially involving water infrastructure on the Dnipro River
- The international community, including legal, political, and military entities, must work to reduce the risks of water-related conflicts

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Citation:
Gleick, P., Vyshnevskyi, V., & Shevchuk, S. (2023). Rivers and water systems as weapons and casualties of the Russia-Ukraine war. *Earth's Future*, *11*, e2023EF003910. https://doi.org/10.1029/2023EF003910

Received 21 JUN 2023
Accepted 31 AUG 2023

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Abstract The geophysical, hydrological, and ecological consequences of the Russia-Ukraine war for the major rivers and water infrastructure in Ukraine are addressed here, focused on the dams and reservoirs of the Dnipro (Dnieper) River and major tributaries, up to and including the destruction of the Kakhovka Dam in June 2023, using remote sensing systems, on-the-ground reports, and official sources. The rivers have long played a role as physical barriers during conflicts, but in the current war, water and built water systems have also been targeted for attacks and used as both offensive and defensive weapons. Among the consequences of the conflict have been both direct and indirect effects on civilian populations, agriculture, military operations, water supplies and quality, and natural ecosystems. An historical review shows that such attacks have occurred in the past, but the extent and severity of the current violence appear unprecedented, raising important questions of international law and how international legal and scientific communities should respond.

Plain Language Summary The Ukraine-Russia war has led to extensive attacks on water resources and water infrastructure. Using remote sensing, media reports, on-the-ground observations, we review the types and history of violence against water systems in Ukraine from the start of the conflict. Among the most serious impacts are a series of attacks on dams in the Dnipro river watershed, with severe impacts on humans, ecosystems, energy, water supply, and irrigation, including the destruction of the Kakhovkha dam, one of Europe's largest. This review raises important questions about how the international community should respond to water-related conflicts.

1. Introduction

In 2014, Russia occupied Crimea and portions of eastern Ukraine and then on 24 February 2022 launched a large-scale invasion of the rest of Ukraine, initiating a major conflict that continues as of this writing, in mid-2023. In addition to the immense human, economic, and political consequences of the war, there have been extensive impacts for the region's natural resources, including agriculture, industry, and especially water resources and water systems.

There is a long history of violence associated with water resources worldwide. As tracked by the Pacific Institute's open-source database, the Water Conflict Chronology, water conflicts can be traced back more than 4,500 years in three key forms: water scarcity or disputes over water access and control have *triggered* violence and conflict; water and water systems have been used as offensive and defensive *weapons* during conflicts; and water and water systems can be *casualties* or targets of conflict. An assessment of worldwide trends in the data shows a substantial increase in the number of such events in recent decades (P. H. Gleick & Shimabuku, 2023).

The current Russia-Ukraine war is the most significant armed conflict involving major powers in Europe since World War II, when water and water systems were also involved in military operations. In 1940, for example, the Netherlands used water as a defensive weapon when they flooded the Gelderze Valley to create a barrier to advancing German troops (P. H. Gleick et al., 2009; Information and Documentation Center for the Geography of the Netherlands (IDG), 1996). In 1941, during the offensive of German troops on the eastern front, the Irpin River on the western outskirts of Kyiv was turned into a defensive frontier. In August of that year, the retreating Soviet Army intentionally destroyed the Dnipro hydroelectric power plant (HPP) on the Dnipro River near the city of Zaporizhzhia in order to delay advancing German forces—an example of the use of water systems as both a target/casualty of war and as an offensive weapon. The breaching of that dam and the massive downstream flooding reportedly killed tens of thousands of people downstream (P. H. Gleick et al., 2009; Swain, 2001; Vyshnevskyi, 2011).

In May 1943, the British Royal Air Force bombed dams on the Eder, Möhne, and Sorpe rivers in Germany, killing more than a thousand people and causing massive downstream flooding. In 1944, German troops destroyed dams on the Liri River in Italy, releasing flood waters as a weapon against territory occupied by British troops (P. H. Gleick et al., 2009; Kirschner, 1949).

One of the consequences of the horrors of World War II, 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 explicitly prohibit using water and water systems as a weapon against civilian populations. For example, two provisions of the 1977 Protocols to the Geneva Conventions (Article 56 of Protocol I and Article 15 of Protocol II) 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; P. H. Gleick, 2019b).

Despite these international prohibitions, as noted above, the number of incidents of water-related violence is increasing. In the 2010s and more recently, widespread violence around water resources has been reported, especially in the Middle East associated with the conflicts in Iraq and Syria (P. H. Gleick, 2019a; Hasan et al., 2019). As described below, the Russia-Ukraine war has also involved extensive attacks on rivers and water systems and the use of water as a weapon, and rivers have been used as physical barriers to military operations. Many of these actions deserve to be reviewed and if appropriate, addressed by the International Criminal Court (ICC) or comparable legal authorities. For example, Dannenbaum (2023) raises the possibility that the intentional destruction of the dam almost certainly violates several rules of international humanitarian law and "very likely involves multiple overlapping war crimes" under the jurisdiction of both the ICC and state bodies.

2. Methodology and Data

Over the past several months, new information about the Russia-Ukraine war and its environmental consequences has become available (Harada et al., 2022; Khilchevskyi, 2022; Pereira et al., 2022; Rawtani et al., 2022; Shevchuk et al., 2022; Shevchuk & Vyshnevskyi, 2022; Shumilova et al., 2023; V. Vyshnevskyi et al., 2023; Zheleznyak et al., 2022). In many cases, the main source of primary information about military events was and remains visual observation and local media reports. In recent decades, remote sensing has become more widespread, which is especially relevant in times of war when access by traditional media and other independent sources becomes more challenging (Al-doski et al., 2013; Baumann & Kuemmerle, 2016; Fakhri & Gkanatsios, 2021; Garzón & Valánszki, 2020; Hasan et al., 2019; Shevchuk et al., 2022; Witmer, 2015). We expand upon that work here with an up-to-date analysis of explicit impacts on the rivers and water infrastructure, particularly the Dnipro River, since the expansion of the war in 2022, but we also note that there is a relative lack of information about conditions within Russian-held territory.

An important source of information about water bodies of Ukraine was obtained from the earlier studies of Vyshnevskyi (2011) and Vyshnevskyi and Kutsiy (2022). New data were also developed using images of Sentinel 1, Sentinel 2, and Sentinel 3 (spatial resolution of 10 m), Landsat 8 and Landsat 9 satellites (spatial resolution of 30 m). Correspondent images are available at https://scihub.copernicus.eu and https://earthexplorer.usgs.gov. Measurement of water levels for rivers and reservoirs come from the hydrological gauging stations located on the Dnipro River and its tributaries. Satellite images of Sentinel and Landsat satellites were processed using ArcMap 10. In addition, wartime events and data were obtained from official Ukrainian agencies, including the Ukrainian Hydrometeorological Service and the Ukrainian Scientific Center of Ecology of the Sea, and from international sources and independent news media.

3. Ukraine Rivers and Systems

The analysis here covers major events on Ukraine's rivers, with a special focus on the Dnipro River. The Dnipro is one of the largest rivers in Europe, shared by Russia, Belarus, and Ukraine, and is critical for urban and industrial water supply and for agricultural production in the region. The total length of the river is approximately 2,200 km with a watershed area of 504 thousand km^2. The average flow of water near the river mouth in natural conditions was around 1,690 m^3/s or 53 km^3 per year, though in recent decades, the average water flows have dropped by around 10 km^3 per year due to anthropogenic influences, including water withdrawals and increased evaporation from water bodies (Vyshnevskyi, 2011). The largest river in the east of Ukraine is Siverskyi Donets (Figure 1).

Figure 1. The location of Ukraine, the Dnipro River, and the cities and reservoirs described in the text. The reservoirs of the Dnipro Cascade are numbered on the map: 1—Kyivske, 2—Kanivske, 3—Kremenchutske, 4—Kamyanske, 5—Dniprovske, 6—Kakhovske

Starting in the late 1920s, six hydroelectric power plants were built on the Dnipro River. Dnipro HPP near the Zaporizhzhia city was the first hydroelectric power station built on the river. At the time of its completion in the 1930s it was the largest hydropower plant (560 MW) in Europe. As mentioned above, the retreating Red Army blew up the dam in August 1941, but the station was rebuilt after World War II.

The second HPP built was Kakhovka Dam, completed in 1956, downstream of the Dnipro HPP and about 60 km upstream of the city of Kherson, creating the largest reservoir on the Dnipro River, one substantially larger than the one created by the Dnipro HPP, with a reservoir volume of 18.2 cubic kilometers of water (km^3) at a normal retention level of 16.0 m above mean sea level (a.s.l). In addition to hydropower, the primary purpose of the creation of the Kakhovske reservoir was to provide reliable irrigation water and water supply for the south of Ukraine. In the 1980s, the Zaporizhzhia NPP, the most powerful in Europe, was built on the southern bank of the Kakhovske reservoir near the town of Enerhodar.

Four additional dams and reservoirs, Kremenchutske, Kamyanske, Kyivske and Kanivske, were subsequently built on the Dnipro River to produce electricity and to facilitate water supply, irrigation, shipping, and fishing. The total design volume of all six reservoirs is 43.7 km^3, approximately equal to the annual water flow of the river.

Extensive additional levees and dikes were also built along the margins of the reservoirs to protect populated areas vulnerable to flooding. The total size of the protected area is 2,540 km^2, which exceeds the area of the largest Kremenchutske or Kakhovske reservoirs. In particular, a large part of Nikopol city near Kakhovske reservoir is located in an area with a lower elevation than the normal level of water in the reservoir.

4. Water-Related Implications of the Russia-Ukraine War

Water systems and infrastructure have played an essential role in the Russia-Ukraine war, and have regularly been used as a defensive and offensive weapons, and as targets or casualties of the conflict. On 24 February 2022, following early missile strikes on many facilities in Ukraine, Russia launched a ground attack, with an attempt to encircle and then capture Ukraine's capital, Kyiv. In the first days of the war, the Ukrainian military used rivers and water infrastructure as defensive tools by destroying many bridges over rivers to slow the Russian assault and creating an artificial flood on the Irpin River (the left tributary of the Dnipro River) on the western outskirts of Kyiv. This artificial flood was created by Ukrainians by the destruction of the dam in the mouth of the Irpin River, causing water from the Kyivske Reservoir to inundate the Irpin River floodplain (see item 11 in Figure 2).

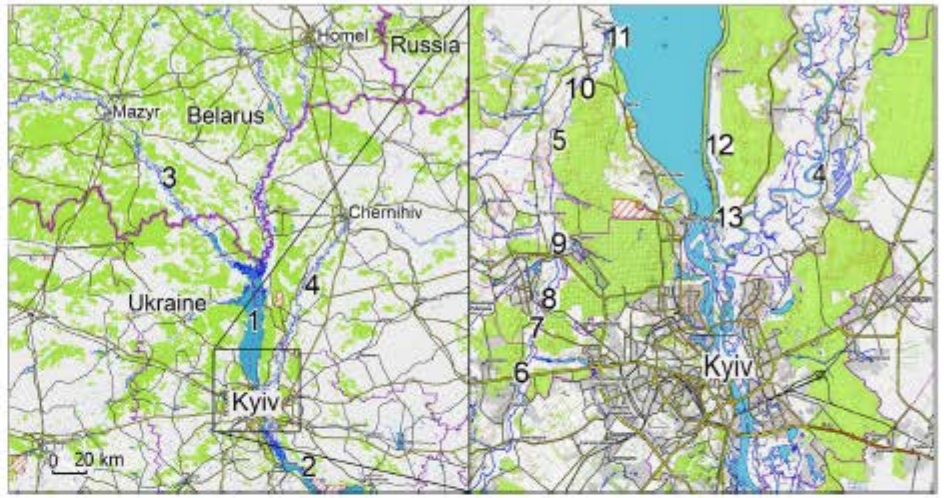

Figure 2. Map showing the location of Kyiv and the main water objects near it: 1–2—the Kyivske and Kanivske reservoirs; 3–5—the Pripyat, Desna, and Irpin rivers; 6–10—bridges across the Irpin River near Hostomel and Demidiv villages, Irpin, Stoyanka, and Romanivka; 11—the levee along the Irpin River near Kazarovichi; 12—drainage canal; 13—bridge over the drainage canal.

The resulting flooding peaked on 18–21 March 2022 and became a serious obstacle to advancing Russian troops from the north and the northwest (Shevchuk et al., 2022). In some places the width of the flooding on the Irpin River exceeded 1 km (Figure 3). These actions were helpful in successfully slowing and ultimately stopping the threat to Kyiv.

The Siverskyi Donets River and its left tributary Oskil River also became an important frontier in the east of Ukraine in early 2022. During the first days of the large-scale invasion, in order to slow Russian troops, the highway over the dam of Pechenigske Reservoir on the Siverskyi Donets River was damaged. In addition, water was released from the Oskilske reservoir to create an artificial flood downstream, significantly increasing the width of the Siverskyi Donets River (Figure 4).

In the months following the release, the volume and area of the Oskilske reservoir were greatly reduced—the first relatively large reservoir to be drained during the war (Figure 5).

Other water infrastructure on Ukraine's rivers has also been targeted for attack during the war. In mid-September 2022, Russian missiles struck a dam on the Inhulets River in the Ukrainian city of Kryvyi Rih, flooding parts of the city (Gettleman, 2022). In May 2023, the Karlivka dam forming the Karlivske reservoir on the Vovcha River around 40 km from Donetsk was destroyed, reportedly by Russian artillery during the shelling of the town of Karlivka (Top War, 2023). A Russian missile attack occurred in October 2022 on the hydroelectric dam at the town of Kremenchuk on the Dnipro River. The above mentioned Dnipro hydroelectric plant near Zaporizhzhia city was attacked in December 2022 and again in February 2023 (BBC News, 2023). Ukraine's urban water-supply and wastewater treatment systems, or the electricity systems needed to run them, have also been regularly destroyed by Russian attacks, cutting access to safe water and sanitation to civilian populations in the cities of Chernihiv, Sloviansk, Severodonetsk, and Lysychansk, among others (Shevchuk et al., 2022).

5. Kakhovka Dam and Reservoir

The lower reaches of the Dnipro River and especially the Kakhovka dam have been an essential focus of conflict since the beginning of the large-scale invasion in early 2022 when the dam and hydropower plant were occupied by Russian forces. In April 2022, the Russians were accused of cutting off the water supply to the city of

a b

Figure 3. Flooding of the Irpin River floodplain on 11 March 2022 (a) and on 18 March 2022 (b). Images from the Sentinel 2 satellite.

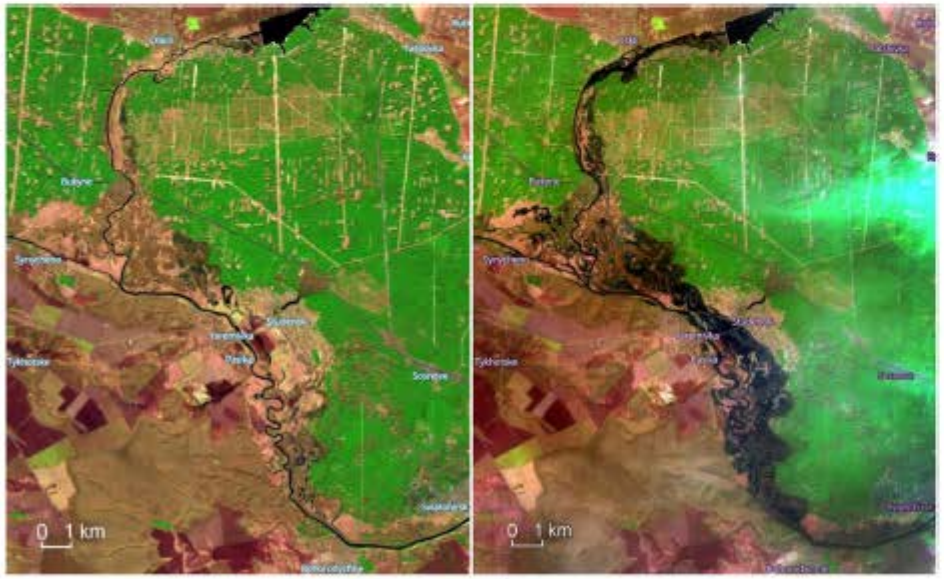

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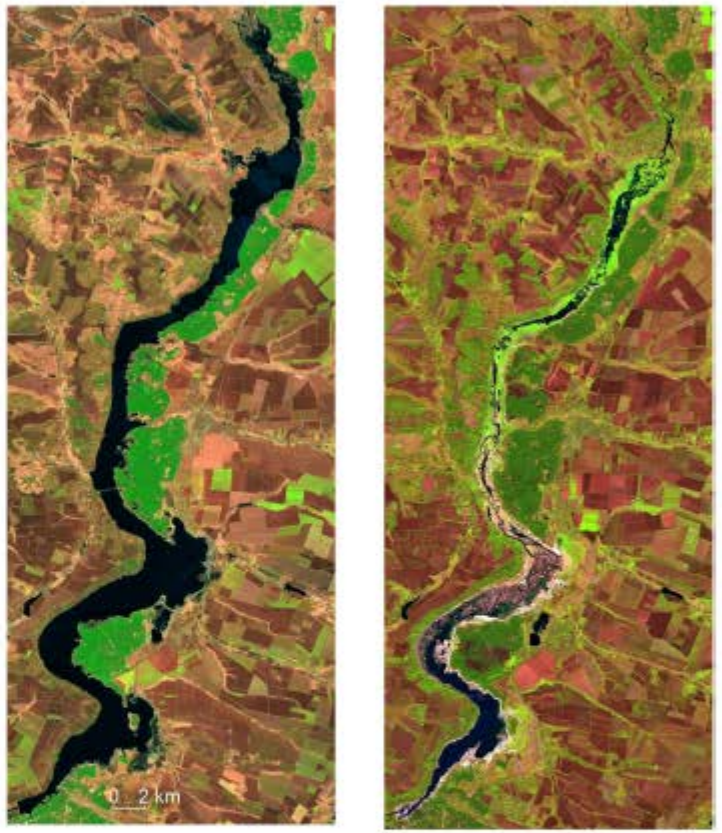
Figure 4. Flooding of the Oskil and Siverskyi Donets rivers on 29 March 2022 (a) and on 1 April 2022 (b). Images from the Sentinel 2 satellite.



a b

Figure 5. The view of the Oskilske reservoir on the Oskil River: (a) on 29.03.2022 and (b) on 18.10.2022. Images from the Sentinel 2 satellite.

Mykolaiv when they advanced to the Dnipro River (Zhuhan & Ibrahim, 2022). In November 2022, the pumping station for the water supply of this city, standing on the right bank of the river upstream of Kherson city, was purposefully destroyed (Kesaieva, 2022).

But the most dramatic situation occurred as a result of destruction of the Kakhovka dam and hydroelectric power plant on 6 June 2023. The Kakhovka hydroelectric complex consisted of four main elements: the left-bank and the right-bank ground dam with a total length of 3.8 km, a concrete spillway with 28 gates (450 m in length), the generator building (150 m), and the shipping lock (18 m). Six generators with a total capacity of about 335 MW were installed at the Kakhovka HPP. Just upstream of the dam on the left bank of the reservoir is the intake for the North Crimea Canal (Figure 6).

On 11 November 2022, the Ukrainian army liberated Kherson city and other settlements on the right bank of the Dnipro River. That day Russian forces destroyed part of the roadway across Kakhovka dam and three sections of spillway near the right bank of the Dnipro River, to prevent Ukrainian forces from crossing the river (Figure 7).

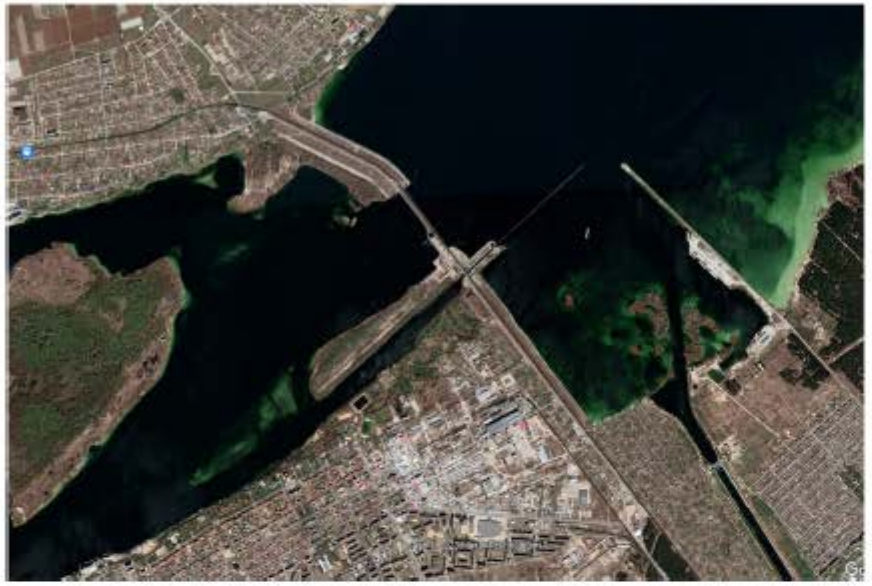


Figure 6. The Kakhovka hydroelectric dam before its destruction on a satellite image. The intake for the North Crimea Canal is in the bottom right of the image (Source: Google Earth Pro, 20.10.2020).

After the damage to the spillway and during the subsequent winter months, waters 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, leading to fish kills and retreat of the shoreline in some places by more than 100 m.

With spring snowmelt and rainfall, reservoir levels began to rise again in all Dnipro reservoirs, including Kakhovske, and by early May, water levels measured at the Nikopol gauging station reached 17.13 m a.s.l., the highest level since the reservoir was created in the late 1950s. On the night of 6 June 2023, the dam at Kakhovka, still under the control of Russian forces, was destroyed by an explosion, leading immediately to massive flows of water out of the reservoir and the washing away of major portions of the dam (Figure 8).

Soon after the explosion the water level downstream in Kherson began to rise. At 4:00 a.m., on June 6th, the water level at the Kherson gauging station was 0.31 m a.s.l. At 8:00 a.m. it reached 1.60 m a.s.l. By 8:00 a.m. the following day it had risen to 5.29 m before peaking at 5.68 m, on 8 June 2023 at 3:00 p.m. Thus, the total increase of the water level in the city of Kherson reached 5.37 m (Figure 9).

Water pouring out of the reservoir inundated extensive areas below the dam along the 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 smaller villages on the right bank. Other consequences of the destruction of the dam include the human and ecological impacts of that flooding, and bacterial and chemical contamination downstream from pollutants released from flooded industrial sites, landfills, sewage plants, and petroleum stations. The loss of the reservoir also means the loss of water supply for urban centers and for agricultural lands dependent on water from the reservoir (Figures 10a and 10b).

The flow of pollutants into the northwestern part of the Black Sea contributed to a large algal bloom, increased measurements of heavy metals, and the closure of swimming beaches near Odesa (V. Vyshnevskyi et al., 2023).

According to the Ministry of Internal Affairs of Ukraine on 18 June 2023, around 50 people were reported killed or missing on the right bank of the Dnipro River (Knight, 2023). No information on the human toll on the left

Figure 7. Satellite image of the damaged Kakhovka dam showing the damage to the roadway and dam on 11 November 2022 (Source: https://twitter.com/Maxar/status/1591158455808954368/photo/2).

bank of the river under the control of Russian forces was available at this time of writing, but given 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.

The downstream flooding was accompanied by a rapid decrease in the water level in Kakhovske reservoir. Before the explosion the water level at Nikopol station was 16.76 m a.s.l. and the total reservoir volume was extraordinarily high, at an estimated 19.8 km^3. After the destruction of the dam in the early hours of June 6th, it decreased to 16.13 m a.s.l. by 8:00 a.m. At 8:00 a.m. the following day, the reservoir level had dropped to 14.48 m a.s.l. By 8:00 p.m. 11 June 2023 it decreased to 9.04 m and the main part of the reservoir volume was lost. After that date, local gauges were no longer able to measure water levels. Satellite images obtained in July and August of 2023 (Figure 11) show the disappearance of what was once the largest reservoir on the Dnipro River.

There will be other long-term consequences of the use of rivers and water system as a casualty of war in Ukraine. The Kakhovske reservoir provided extensive water supply for regional cities, the Zaporizhzhia NPP, and irrigation water for Ukraine's agricultural lands. According to the Ukrainian Ministry of Agriculture, tens of thousands of hectares of agricultural land have been lost to flooding below the dam, and upstream as much as 580,000 ha may no longer be irrigable in the near future, threatening even greater losses to Ukrainian harvests than have occurred over the past year (Jayanti, 2023), with knock-on consequences for global food supply and prices. Additional impacts will be felt in Crimea, which relied heavily for water supply from the North Crimea Canal. That supply will now be cut off.

Figure 8. The destroyed Kakhovka facility on 6 June 2023 a few hours after the explosion (Source: https://twitter.com/GianlucaMezzo/status/1666097052269559816).

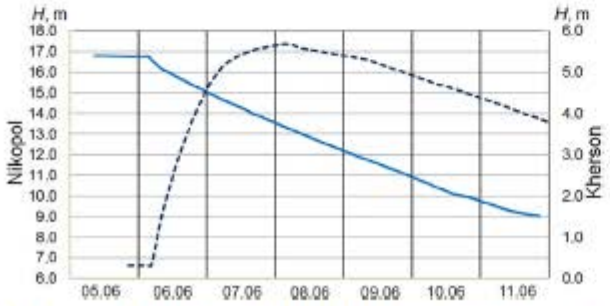


Figure 9. The changes of water level at Kherson (dotted line) and Nikopol hydrological gauging stations (solid line) between 05 and 11 June 2023. In meters above mean sea level.

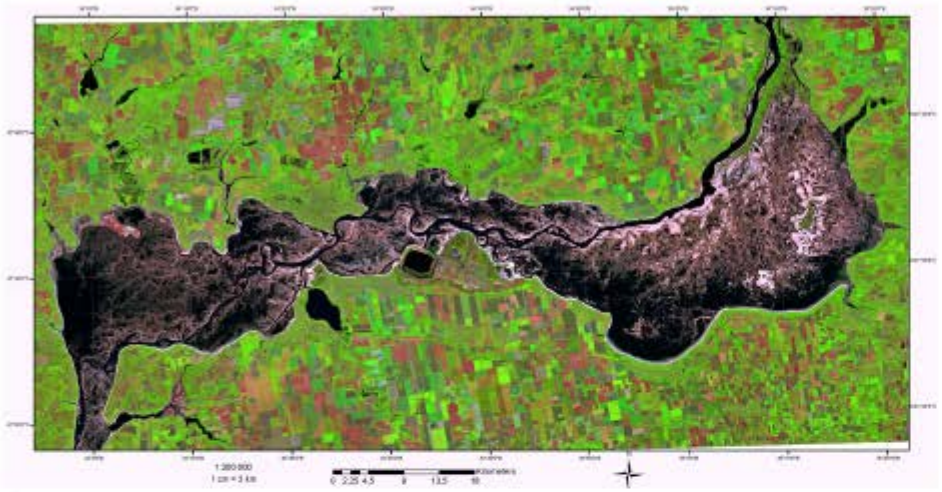
a

b

Figure 10. The floodplain below the Kakhovka dam on the lower reaches of the Dnipro River (a) on 3 June 2023 (image from the Sentinel 2 satellite) and (b) after the dam was destroyed, 9 June 2023 showing the extensive flooding (Image from Landsat 9 satellite).

6. Conclusions

Water resources and infrastructure in Ukraine and, in particular, the major systems on the Dnipro River, have played an important role in the Russia-Ukraine war, adding to a long history of water conflicts. But these recent attacks on water infrastructure have been unprecedented in recent history in extent and severity (P. H.



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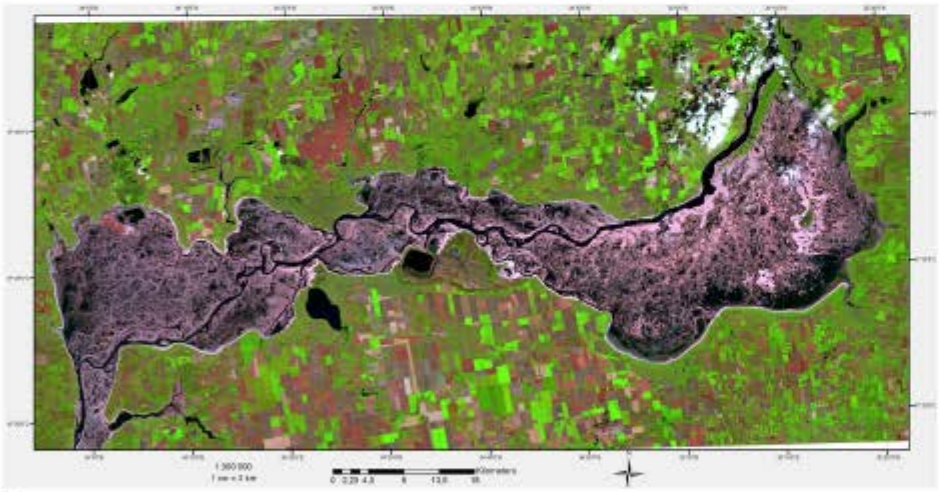

b

Figure 11. The Kakhovske reservoir (a) on 20 June 2023 and (b) on 05 July 2023 showing the draining of the reservoir. Images from the Sentinel 2 satellite.

Gleick, 2019a; P. H. Gleick & Shimabuku, 2023), including especially the destruction of Kakhovka dam and the loss of the largest reservoir on the Dnipro River, leading to downstream flooding of a very large territory with several major cities and dozens of smaller villages; extensive pollution of the lower reach of the Dnipro River, the Dnipro-Bug estuary, and the Black Sea with chemical and biological contaminants; and ecological effects likely extending toward the territories of Romania and Bulgaria along the Black Sea (V. Vyshnevskyi et al., 2023). A range of socio-economic impacts are also beginning to manifest, including the cutoff of water supplies to large urban centers and extensive acreage of agricultural lands that depended on water from the reservoir. Of particular concern in the near term are the human health effects of the loss of reliable clean water and sanitation systems in the region, and the larger-scale global implications for food availability and prices from the loss of Ukrainian food production. These impacts are just beginning to be evaluated, and we anticipate other research and other researchers will be able to shed light on them as additional data becomes available.

Efforts to address these impacts are underway, though the full scope of the long-term effects remain to be seen. As information from the scientific community on these events becomes available, it may help provide information and evidence useful to any future response from the international legal community. Debate is underway—and should be expanded—in the global community about how to apply international humanitarian laws of war, and how to prevent these kinds of attacks on river and water systems in the future. In particular, the Geneva Convention and its Protocols, and other international agreements protecting civilian populations, infrastructure, and the environment from war and conflicts need to be more aggressively enforced by the International Criminal Court and other bodies with jurisdiction.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No new data was used for this review. Long-term historical data on water conflicts are archived and available in P. Gleick and Shimabuku (2022).

Acknowledgments
No funding was received to assist with preparation of this manuscript and for conducting this study. We thank two anonymous reviewers for their helpful comments.

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