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ENVIRONMENTAL SCIENCE

Environmental effects of the Kakhovka Dam destruction by warfare in Ukraine

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The use of water as a weapon in highly industrialized areas in the Russo-Ukrainian war has resulted in catastrophic economic and environmental damages. We analyze environmental effects caused by the military destruction of the Kakhovka Dam. We link field, remote sensing, and modeling data to demarcate the disaster's spatial-temporal scales and outline trends in reestablishment of damaged ecosystems. Although media attention has focused on the immediate impacts of flooding on society, politics, and the economy, our results show that toxic contamination within newly exposed sediments of the former reservoir bed poses a largely overlooked long-term threat to freshwater, estuarine, and marine ecosystems. The continued use of water as a weapon may lead to even greater risks for people and the environment.

Modern warfare strategies have reduced the need for ground-based operations, however, rivers not only continue to be combat barriers but are increasingly used as weapons (*1*). Intentional destruction of dams has occurred repeatedly in Ukraine. In 1941, detonation of the Dnipro Dam occurred, killing thousands (*2*). In 2022, several dams were destroyed along the Irpen, Oskil, and Inhulets rivers (*2*, *3*). The most devastating event occurred on 6 June 2023, when the Kakhovka Dam on the Dnipro River collapsed following repeated attacks (*4*–*9*). In March 2024, Russian missiles destroyed power plants of the Dnipro (3.3 km^3), Kaniv (2.6 km^3), and Novodnistrovsk (3 km^3) reservoirs.

Dams are major components of contemporary human infrastructure on rivers throughout the world. More than 50,000 large reservoir facilities (LRFs) exist worldwide (*10*). Although the risk of failure is low (~1%) (*11*), concern is growing given the state of deterioration of many structures (*12*, *13*). The recent collapse of dams in Libya (*14*) highlights the danger of dam failures in the context of global climatic change. However, human conflict has been overlooked as an aspect of risk partly because the intentional destruction of dams is banned by the Geneva Conventions.

Until recently, the Dnipro River included a cascade of six reservoirs stretching across from Ukraine to the Black Sea and containing ~43.6 km^3 of water (Fig. 1). The Kakhovka LRF (hereafter K-LRF, 18 km^3, Fig. 2A) was at the downstream end of this cascade. Its main purpose was to supply water to a 12,000-km irrigation system for 500,000 hectares (ha) of croplands and to a 400-km-long canal for provision of 85% of Crimea's water (*7*, *15*).

The destruction of the Kakhovka Dam caused catastrophic draining of the reservoir, downstream flooding, and contamination of freshwater and marine environments (*8*). However, access to data on this failure has been hindered by ongoing combat which constrains field research (*4*, *8*, *16*), limiting analysis thus far to early rapid assessment (*6*, *7*). We examine the environmental impacts and scales of the K-LRF catastrophe by linking empirical data from ground-based surveys and remote sensing within an analytical framework encompassing insights from dam removal practices (*17*), hydrodynamic modeling, flood hazard assessment (*18*), and analysis of ecosystem reestablishment (*19*) (Fig. 2, materials and methods, figs. S1 to S10, and tables S1 to S8). We show that (i) large amounts of pollutants accumulated in the reservoir sediment before the catastrophe; (ii) excessive drainage and release of water likely caused massive mortality of benthic organisms and fish; and (iii) a massive freshwater plume was present which undoubtedly affected marine life in the northwestern Black Sea; (iv) the exposed sediment has become a long-term source of contaminants that can be mobilized by floods; and (v) high growth rates of riparian vegetation suggest that conversion of the former lakebed to vegetated floodplain can be accomplished within five years.

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Framework and data

To analyze hazards to humans caused by the Kakhovka flooding, we adopt the US Bureau of Reclamation approach (*18*), which relates loss of human life to values of *DV*, where *D* and *V* are maximum flow depth and velocity, respectively. We extend this analysis by developing an approach to estimate impacts on populations of rodents, which is based on a species-area relation and evaluates population losses as a ratio between the area of danger for swimming animals and the total inundated area. Dangerous areas are identified by critical values of the survival index S_{sw}, which relates swimming abilities of animals (*20*, *21*) to *DV* values (fig. S10).

To calculate spatial patterns of *DV*, we developed a hydrodynamic model of the lower Dnipro with a computational domain (mesh size 16×16 m) based on bathymetric data derived from field and photogrammetric surveys and remotely sensed water surface extent during the peak of the flood (fig. S9). A boundary condition, a water discharge of 29,000 m^3s^{-1}, was estimated based on the decrease in water volume in the reservoir through time. Model validation was performed using ground-based observations

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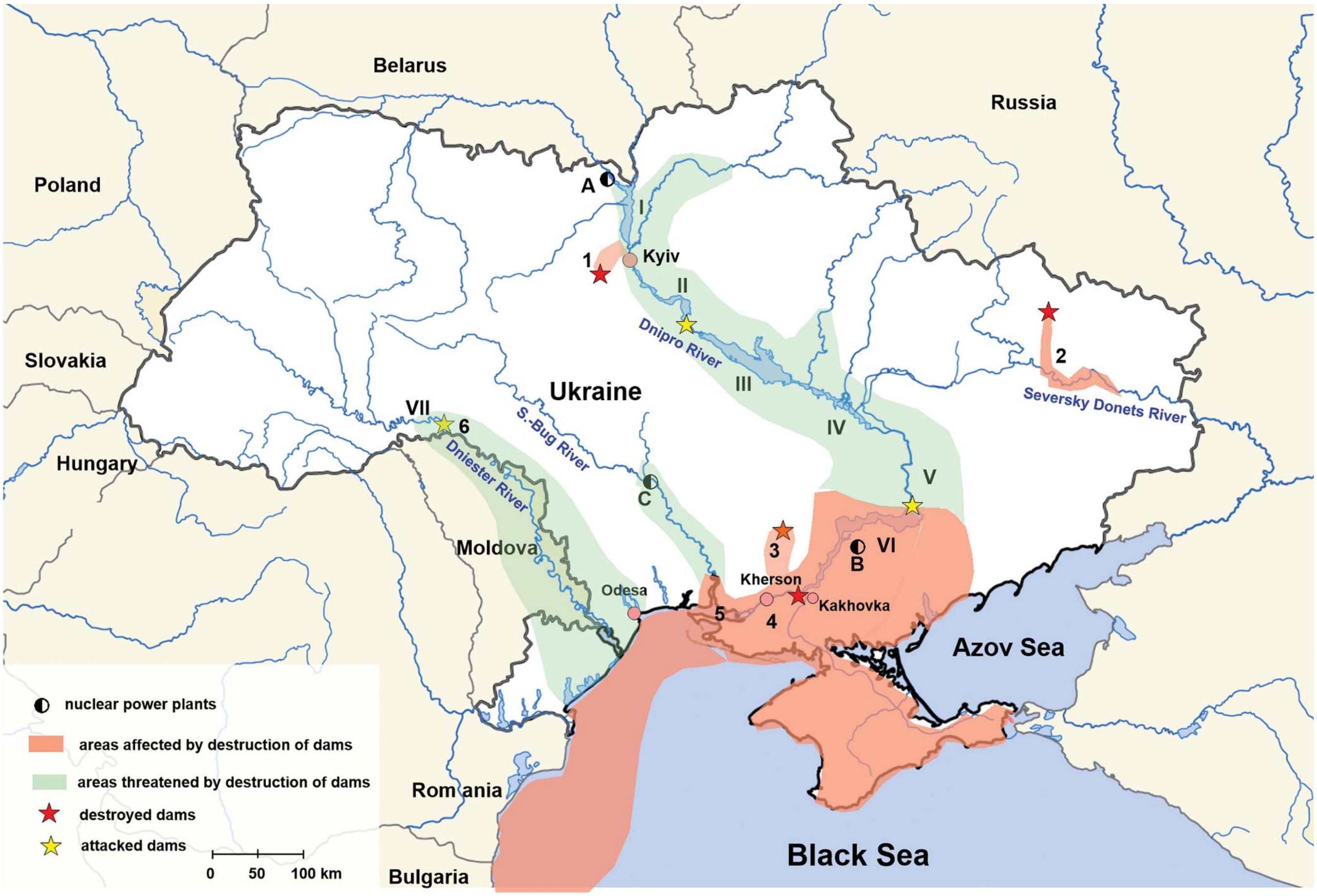

Fig. 1. Areas of Ukraine affected or threatened by dam destruction in military operations. Arabic numbers 1 to 6 indicate rivers: Irpen, Oskil, Inhulets, Dnipro, Dnipro-Bug Estuary, and Dniester, respectively. Roman numbers I to VII indicate large reservoir facilities: Kyiv, Kaniv, Kremenchuk, Kaminske, Dnipro, Kakhovka, and Dniester, respectively. (**A** to **C**) indicate nuclear power plants: Chornobyl, Zaporizhzhia, and South Ukraine, respectively.

(figs. S10 to S12). The model allowed assessment of damage to riparian habitats caused by soil erosion and uprooting of vegetation (figs. S13 to S18).

Drainage of the K-LRF exposed lakebed sediment (Fig. 2, A to C, and figs. S19 to S21), the release of which is a major concern in dam removal projects (*12*, *13*, *17*, *22*). Three concepts developed through dam removal research guided our analysis: (i) Abrupt fall of base level is a key factor controlling mobilization of sediment; (ii) sediment volume, grain size, chemical content, and colonization of sediment by vegetation define the long-term mobilization of toxic substances; and (iii) in highly developed regions, contaminated sediment may require intentional removal. Examples include polychlorinated biphenyls in the Hudson River (*23*) and Agent Orange in the Passaic River (*24*) in the USA. We estimate sediment release using a method of non-erodible velocities (*25*), combined with analysis of remote sensing images and data from water quality monitoring (fig. S18).

Reestablishment of ecosystem biodiversity in the aftermath of dam removal (*12*, *17*, *22*) and levee breaching (*23*, *24*, *26*) is an important aspect of remediation that has been conceptualized in process-based models (*27*, *28*) and recent models of self-organization (*19*, *29*, *30*). We analyze the processes of ecosystem reestablishment using results of field surveys and remote sensing within the context of process-based modeling (Fig. 2D and figs. S1 and S4). We apply our analytical framework to data collected before the dam breach (figs. S5 to S8), during the flood and reservoir draining (figs. S10 to S12, S18, and tables S1 to S6), and over a one-year period following the disaster (table S5 and figs. S23 to S26).

The Kakhovka Dam triggered a toxic "time-bomb"

After construction in the mid-1950s, an increase in nutrient concentration and water temperature in the K-LRF boosted biological productivity (*31*–*33*). Based on field research prior to 2022, we estimate total standing biomasses of 100,000 to 150,000 tonnes for periphyton, 30,000 to 50,000 tonnes for aquatic plants, 200,000 to 500,000 tonnes for macroinvertebrates, and 6000 to 10,000 tonnes for fish. The diversion of water for agriculture and industry decreased the maximum mean water discharge of the lower Dnipro from 3500 m^3s^{-1} to 2000 m^3s^{-1} (fig. S7). The river system downstream of the dam consists of the main channel, a floodplain, and several meandering side channels. The riverine ecosystem was very diverse (*8*, *15*) with more than 70 fish species, of which 18 were protected species (*33*). The floodplain provided habitat for breeding, migration, and wintering for approximately 350 bird species. Mammals included rodents, canids, wild pigs, and deer (*7*, *33*).

Because the K-LRF is located at the downstream end of the Dnipro reservoir cascade, approximately 98% of the sediment load was retained in upstream reservoirs (*15*) (Fig. 2A). Pre-disaster field surveys reveal that the lakebed contained a layer of sediment 0.3 to 1.5 m thick, composed almost entirely of fine silt eroded from the shoreline. Based on the morphology (fig. S6B) and average thickness of the sediment layer, we estimate the total volume of sediment to be approximately 1.3 to 1.7 km^3. Sorption, hydrolysis, settling, and biological consumption

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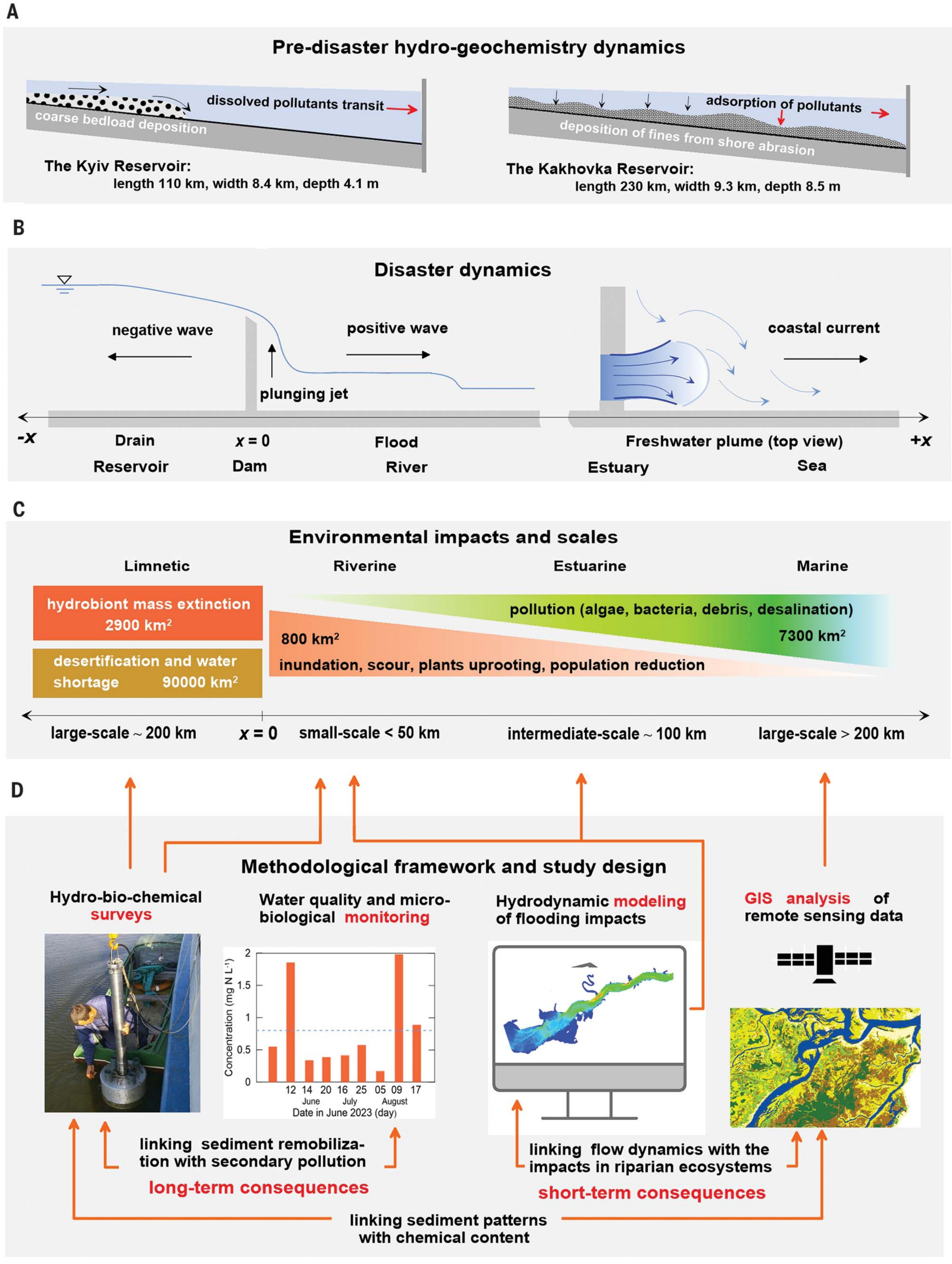

Fig. 2. Conceptual framework of the study. (**A**) Pre-disaster sedimentation dynamics in the Dnipro cascade showing the Kyiv reservoir (upstream) and the Kakhovka reservoir (downstream). (**B**) Schematic of the dam-breaching event (side view on the left) and downstream of the Dnipro-Bug Estuary (top view on the right). (**C**) Environmental impacts and characteristic scale of the Kakhovka Dam disaster. (**D**) Methodology, components, interrelations, and relevance to spatial and temporal scales.

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mediated the adsorption of contaminants from the water column to the sediment (*34*). Contaminants include heavy metals, nitrogen, and phosphorus delivered from industrial and agricultural sources (tables S7 and S8). Within the reservoir, some heavy metals such as Pb and Ni are distributed relatively uniformly (figs. S19 and S20) due to mixing by waves and currents, whereas others such as Zn exhibit locally elevated values at industrial outputs near Nikopol (fig. S19). Nondegradable heavy metals can damage the nervous system, disrupt endocrine system functioning, and cause congenital disorders (*35*).

Short-term impacts of flood, drain, and plume spread

Hydraulic theory predicts that two waves formed at the breach (*36*), producing surges in both the down- and upstream directions (Fig. 2B). Floodwater surging downstream formed a plume that spread into the Black Sea. The release of ~16.4 km^3 of water continued for two weeks and imposed large-scale impacts on riverine and marine ecosystems (*3*, *7*, *8*).

Modeling indicates that between Kakhovka and Kherson (Fig. 3B), the reach-averaged *DV* was approximately 10 m^2s^{-1}. Along this section of the river, in which 110,000 people and 60,000 buildings were affected by the flood, 84 lives were lost (*7*). Although this flood hazard is classified as medium severity (*18*), public perception was nonetheless elevated, driven mainly by the scale of economic losses rather than loss of life (*7*, *8*).

Predicted flow velocities (figs. S10C and S12E) range between 1 and 4 ms^{-1} on the floodplain and in the main channel. The highest predicted values are close to 5 ms^{-1}, which commonly occur over rapids (*37*). Breaking waves—a distinctive feature of rapids—were unlikely, due to low Froude numbers (fig. S10D). Strong turbulence developed between the main channel and the floodplains (figs. S13 and S14), enhancing riverbed scour and plant uprooting. However, compared with rapids, these turbulent zones reduced swimming risks by directing currents toward slow-moving margins of the flow (*38*). Estimating hazards to floodplain rodents from patterns of the S_{SW} index suggests a 20 to 30% reduction of the total population (fig. S15C). Rodents occupy lower trophic positions in the food web and losses in this population likely affected populations of canids and birds.

Floods can greatly affect ecosystems by mobilizing large amounts of fine particles (*39*). Our results show that flow scoured sediment within a high-speed core immediately downstream of the breach (figs. S16 and S17) and within turbulent shear layers on the floodplains (fig. S14). Flow entrained about 2.97×10^{-3} km^3 of sediment within the core, 1.9×10^{-3} km^3 from a knick zone (fig. S21), and about 1.8×10^{-3} km^3 within shear layers. Using a reconstructed hydrograph (fig.

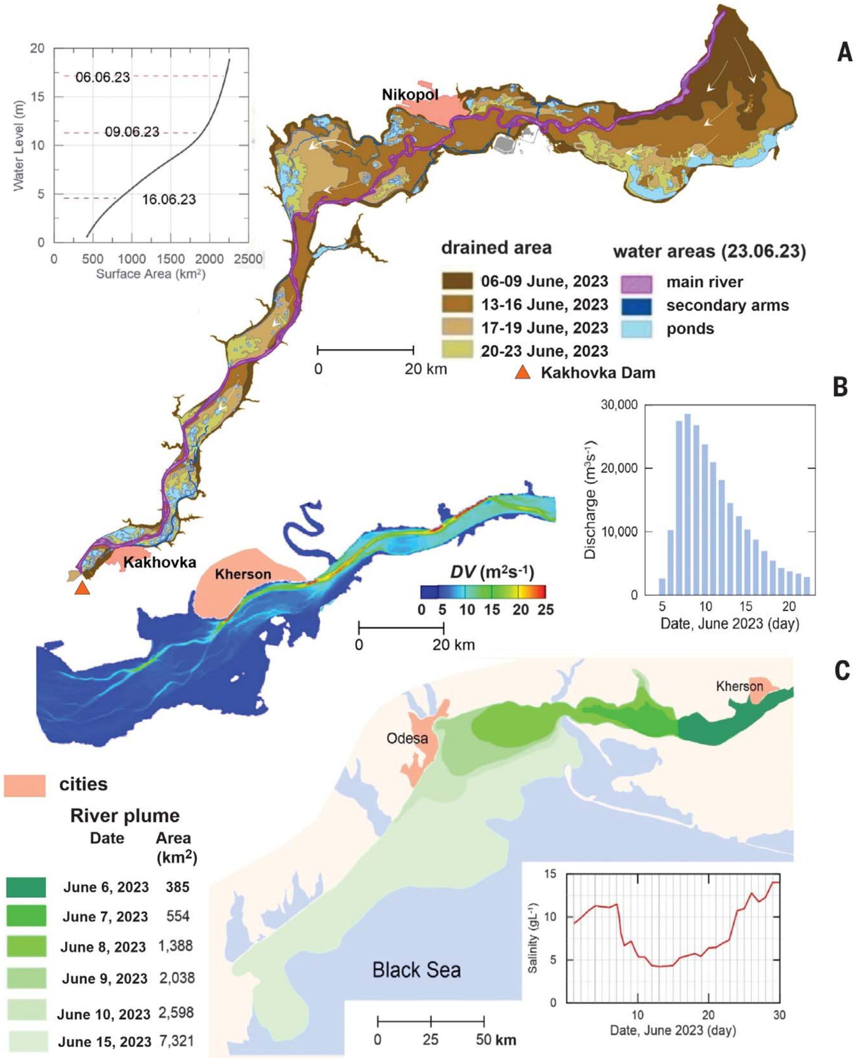

Fig. 3. Dynamics of the dam-breach catastrophe on the Dnipro river, Dnipro-Bug Estuary, and the northern part of the Black Sea. (**A**) Draining of the K-LRF (inset shows how surface area relates to water level of the reservoir; white arrows show the direction of propagating drained land front). (**B**) Modeled depth-average values of *DV* downstream of the K-LRF at maximal water stage (inset shows water discharge at Kherson). (**C**) Dynamics of the river plume in the north shelf of the Black Sea reconstructed from remote sensing data [inset shows measured salinity at Odesa after (*6*)].

S22A) and extrapolating measured suspended solids concentrations (fig. S22B), we estimate that reservoir drainage released about 0.78×10^{-3} km^3 of contaminated fine sediment. Destruction of the Kakhovka power plant and flooding of retail gas (petrol) stations released about 450 tonnes of oil products (*7*).

The first week after the dam breach, the reservoir released 9000 to 17,000 tonnes of phytoplankton per day (fig. S18A). Turbidity increased by a factor of nearly 50, concomitant with a rise in toxicity (fig. S18 and tables S1 to S5), resulting in the probable loss of 10,000 tonnes of macroinvertebrates, considering data on standing biomass prior to the breach. Most likely the entire 0+ juvenile fish stock was lost as the flood occurred immediately after spawning. Floodplain grasses were buried by sediment, destroying habitat for amphibians, birds, and mammals.

Drainage of the reservoir exposed 1944 km^2 of the reservoir bottom (Fig. 3A and figs. S21 to S23) and based on this area we estimate that ~80% of the reservoir biomass was lost. The river returned to its historical course, but large ponds appeared on the floodplain (Fig. 3A). As exposed sediment dried out, it formed patterns composed of regular slabs separated by cracks (*40*, *41*) (Fig. 4C, inset).

The river flood affected water quality in the Dnipro-Bug Estuary and in the northern part of the Black Sea (Fig. 3C and table S1 to S5). The river plume, visible from high levels of turbidity in remote sensed imagery, reached

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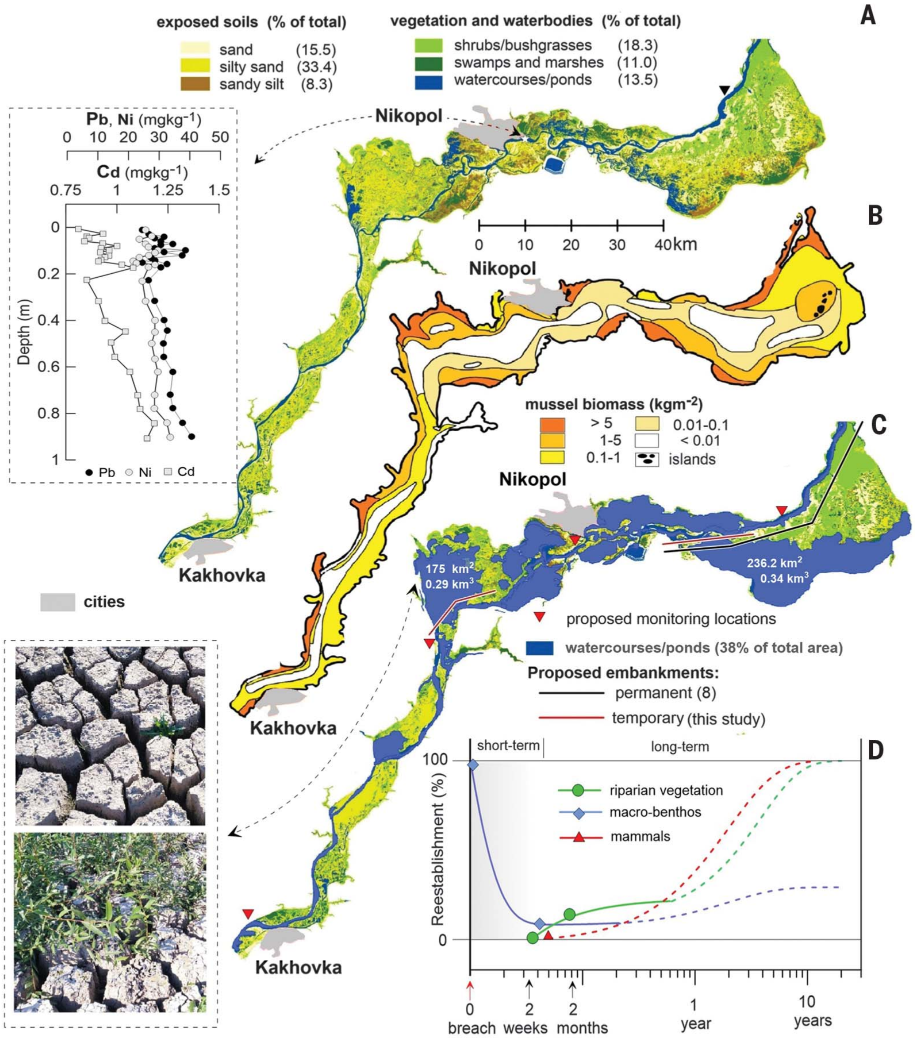

Fig. 4. Development of the area of the former Kakhovka LRF. (**A**) Land cover based on Sentinel-2 satellite images (19 August 2023; resolution 10 m pixel^{-1}; inset shows concentration of heavy metals in the sediment of K-LRF (mg kg^{-1} dry weight) sampled in 2020, dashed arrow line indicates sampling location). (**B**) Spatial pattern of zebra mussels biomass reconstructed from field surveys in the period from 2000 to 2021. (**C**) Extent of inundation of the floodplain by a seasonal flood in March 2024 (inset shows slabs separated by cracks on the former lakebed after drainage and after colonization by plants, above and below, respectively). (**D**) Predicted ecosystem reestablishment on the former lakebed (solid lines indicate observed and dashed lines predicted trends).

the Danube Delta on 17 June 2023, covering ~7300 km^2. Because of restricted vertical mixing, the freshwater formed a layer 10 m thick over underlying saline water. At Odesa, salinity decreased from 11 gL^{-1} to 4.2 gL^{-1} (Fig. 3C), concomitant with five- to tenfold increases in concentrations of nitrogen and phosphorus (table S3). Low salinity and high toxicity caused declines in mussel populations at some locations by as much as 50%. Debris from dislodged plants and entrained rubbish was dispersed along 250 km of coastline. The total biomass of plants transported by the flood amounted to 1600 tonnes with detrital material stranded on beaches at a density of 0.1 kgm^{-2}.

Long-term pollution threat and ecosystem reestablishment trends

The greatest effects of the breach occurred in the former reservoir where the water-surface elevation decreased by 86.4%. Full recovery of the reservoir ecosystem requires rebuilding of the dam (*7*), an unlikely scenario given the ongoing conflict. Therefore, environmental threats and ecosystem responses must be framed within the context of extant conditions. The breach of the dam has produced two main long-term threats: (i) exposure of large areas of contaminated sediment, and (ii) a shortage of water for irrigation. Here we discuss the first threat, while details on the second are provided in (*7*).

Our results show that draining of the reservoir exposed lakebed sediment cumulatively containing around 83.3 thousand tonnes of highly toxic heavy metals (Pb, Cd, Ni) (Fig. 4A, and tables S6 and S8), of which <1% was likely released during the drainage. Remaining heavy metals can affect human populations in the region because river water is widely used by households to compensate for shortages in municipal water supply (*2*, *3*, *42*). Heavy metals in bottom sediment enter the river through erosion of sediment by surface runoff and by seasonal floods. In August 2023, surface runoff rapidly increased levels of turbidity and nutrients in water sampled at Kherson (fig. S18). In March and May 2024, spring floods inundated up to 888.5 km^2 (Fig. 4C), increasing contaminant concentrations (tables S4 and S5).

Heavy metal pollution can be mitigated by bioremediation methods, including biostimulation of uptake by microorganisms (*43*) and phytoremediation (*44*). For the K-LRF, phytoremediation may be the only available strategy over short timescales (2 to 10 years). We analyze the dynamics of riparian vegetation establishment by combining conceptual models of dam removal (*28*, *45*), remote sensing data, and ground observations to gain a comprehensive understanding of self-organizing ecosystem processes driven by flow-soil-plant interactions (*19*, *40*). By mid-August 2023, pioneer riparian vegetation had become established over 18% of the new floodplain area (Fig. 4A). Although rapid colonization of bare ground is usually attributed to dispersal by wind (*41*), our analysis indicates that wind contributed only 25% to recolonization (*46*) and water played the major role (75%), amplified by self-organization processes in soils (*40*) (figs. S24 and S25). Before breaching, seeds of willows and poplars were dispersed on the water surface by wind over distances of ~200 to 300 m from shorelines (*47*), and were deposited at margins of the ebbing water over distances of 3 to 5 km during drainage of the reservoir (Fig. 3A). Moist cracks that developed in the drying sediment trapped seeds (Fig. 4E), ensuring access to wet soil (fig. S24). The next phase of ecosystem self-organization, the emergence of patterns in initially randomly seeded vegetation, involved flow-plant interactions during spring floods (Fig. 4C). Flow is strongest over soil cracks during the rising and falling stages of floods (*40*), leading to erosion that increases the wetted area of the cracks and enhances releases of contaminants. Over time these erosional processes also uproot plants and form erosional channels, thereby increasing the complexity of riparian habitats (*29*).

Using remotely sensed data on ecosystem conditions in the former reservoir after dam breaching (Fig. 3A and Fig. 4, A and B), we parameterized conceptual models of biomass growth for plants and organisms as indicators

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of ecosystem reestablishment (Fig. 4D). Initial conditions are 0% for terrestrial species whereas values for aquatic species correspond to 100% at breaching and reduce to 13.5% for remaining aquatic areas (Fig. 4A). Upper limits of the timescale for reestablishment of terrestrial species equaled those for fully grown willow trees with an average life span of 30 years (*41*). Our results suggest that reestablishment equivalent to 80% of an undammed ecosystem is expected within five years. Field observations in spring 2024 documented colonization by canids and wild pigs (fig. S26). Restored connectivity among marine, estuarine, and riverine environments supports the expectation (*48*) that biodiversity of the riverine environment will increase within two years (Fig. 4D).

Scales and perspectives

Our work highlights the far-reaching environmental consequences of the K-LRF destruction and raises concerns not only about the use of water as a weapon, but also about risks posed by aging dams around the world. As the war continues, discussions have begun among decision-makers, scientists, and practitioners about the future of the Kakhovka Dam. Opposing opinions exist about whether to rebuild the dam (*8*). Environmentalists argue that the river ecosystem is quickly reestablishing its pre-dam state but neglect threats posed by releases of heavy metals and their accumulation in food webs. Impounding the reservoir might mitigate this problem and promote economic recovery in the region. As a compromise between these two options, scientists have proposed to "build back better" (*8*) by constructing a 50-km-long barrier that would separate a large boggy area in the upper part of the drained reservoir from the lower reservoir (Fig. 4C). Reconstruction of the dam and construction of the barrier would require years of effort during which the release of contaminants would need to be reduced. We suggest that contaminant release can be effectively controlled by constructing two 15-km-long temporary barriers separating the main channel from the two largest areas of bogs (Fig. 4C). Any plans for the recovery of Ukraine's conflict-damaged water ecosystems require the war to end, but considerable risks persist for new missile attacks on dams in the Dnipro and Dniester cascades. If more dams are targeted, the human toll and environmental damage could be cataclysmic as revealed by the collapse of the Kakhovka Dam. Protection of dams in military zones should be a priority concern for international law given the potential of conflict-related breaches to produce large-scale and long-term environmental impacts.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
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MDAR Reproducibility Checklist

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