FEATURES

LAID TO WASTE

Ukrainian scientists are tallying the grave environmental consequences of the Kakhovka Dam disaster

By **Richard Stone**, *in Kyiv and Odesa, Ukraine*

In the predawn hours of 6 June 2023, a pair of explosions rocked the Kakhovka Dam, a 3-kilometer-long hydropower facility on the Dnipro River in southern Ukraine. Waking up that morning to the unfolding catastrophe, "I couldn't believe it," recalls Volodymyr Osadchyi, director of the Ukrainian Hydrometeorological Institute (UHMI). "I thought it had to be fake news." But footage captured by a Ukrainian military drone showed water from one of Europe's largest reservoirs gushing through a gaping breach in the dam.

Over the next 4 days, 18 cubic kilometers of water surged downstream, inundating more than 620 square kilometers and affecting 80 settlements. Scores of people died, and many more are unaccounted for. Up to 1 million people lost access to drinking water. In October, the Ukrainian government pegged the cost of the disaster, which it blames on Russia, at roughly $14 billion. Nearly half that figure—$6.4 billion—is an estimate of lost ecosystem services due to chemical pollution and habitat destruction along the Dnipro, one of Europe's largest rivers.

Assessing environmental harm in the midst of a war in which the Dnipro itself delineates more than 300 kilometers of the front line is not easy. But Osadchyi and other Ukrainian researchers have been sobered by what they've found so far. The toll includes heavy damage to a unique sturgeon breeding facility, flooding of nature reserves and agricultural land, and a death blow to countless organisms adapted to brackish estuaries near the confluence of

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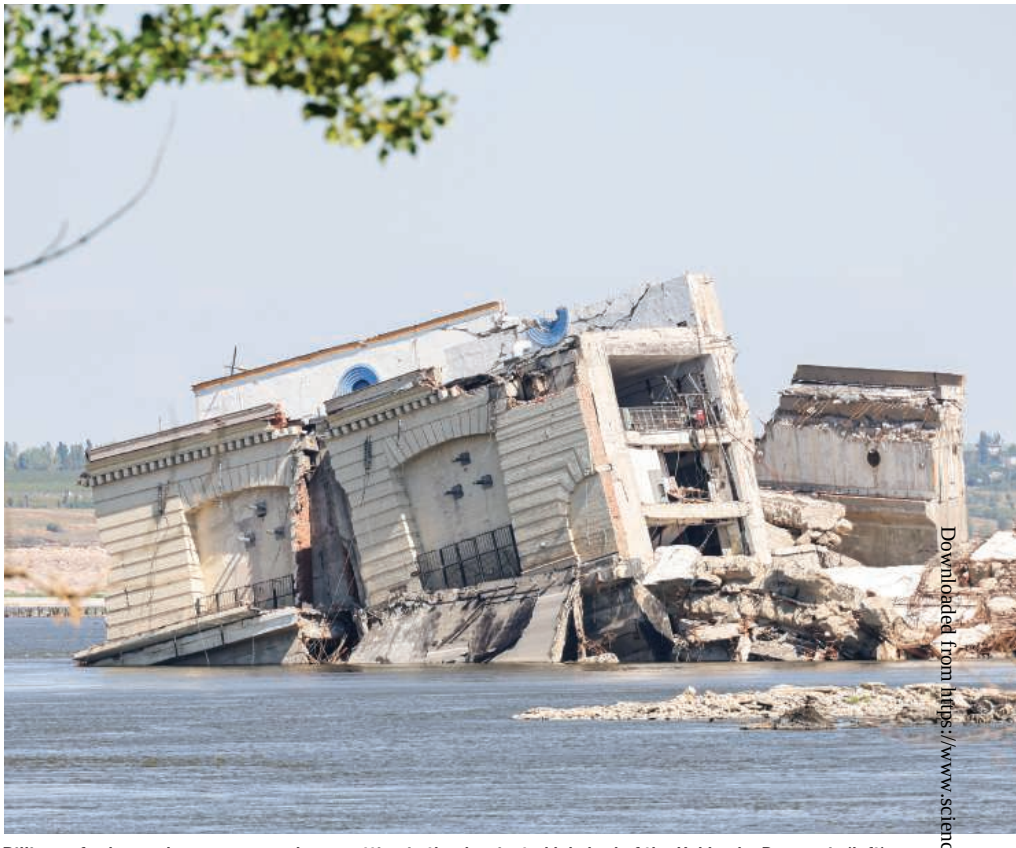


Billions of zebra and quagga mussels are rotting in the dessicated lakebed of the Kakhovka Reservoir (left), which largely emptied after explosions tore apart the Kakhovka Dam in June 2023, unleashing a destructive flood.

PHOTO: ALEXEI KONOVALOV/TASS VIA ZUMA PRESS

the Dnipro and the Black Sea. Billions of mussels are rotting on the former reservoir's desiccated lakebed. And the Kakhovka's destruction has added a new wrinkle to a puzzle that arose earlier in the war: the unexplained deaths of dolphins and porpoises in the Black Sea off Ukraine's southern coast.

Such ecological miseries pale in comparison with the atrocities Russian forces have committed against Ukrainians during a nearly 2-year war that has claimed hundreds of thousands of lives. But when the long and grinding war finally ends, Ukrainians will confront environmental damage that extends well beyond the Dnipro to widespread chemical contamination of agricultural fields and forests from shelling, the wanton destruction of protected areas, and the laying of innumerable mines that experts say will take decades to clear.

"The environmental cost of the war has been immense," says Sergei Mosyakin, director of the M.G. Kholodny Institute of Botany, part of the National Academy of Sciences of Ukraine (NAS). "The ecocide that Russia has inflicted on our country will be studied for generations to come."

Yet as in all wars, nature has found places to thrive when humans are displaced. For instance, because it has been too dangerous to fish in much of the Black Sea, fish stocks are thought to be rebounding. With hunting banned in a wintering ground for migratory birds on the southern steppe, near the Black Sea coast, "the situation for many populations of birds is so much better now," says Vasiliy Kostiushyn, an ornithologist at the I.I. Schmalhausen Institute of Zoology (IZAN), also part of NAS.

The ecological legacy of the Kakhovka disaster is similarly nuanced, as new habitats emerge on terrain scoured by floodwater and in the former reservoir's driedout lakebed. The Ukrainian government has vowed to rebuild the dam after the war. But some experts hope it will change its mind and allow a natural recovery—and perhaps even accelerate efforts to rewild parts of the lower Dnipro Basin.

"Kakhovka is a tragedy," says marine ecologist Galyna Minicheva, director of NAS's Institute of Marine Biology (IMB). "But it is also a huge and unprecedented natural experiment."

ORIGINATING IN RUSSIA, the 2200-kilometer-long Dnipro (the Dnieper, for Russians) flows across Ukraine's northern frontier with Belarus, near Chornobyl, wending through Kyiv and the rest of the country before spilling into the Dnipro-Bug Estuary and the Black Sea. After World War II, Soviet engineers built or refurbished six hydroelectric dams along the river. They completed the Kakhovka Dam, the final and largest one, in 1956.

Soon after Russia launched its full-scale invasion of Ukraine on 24 February 2022, it captured the Kakhovka Dam and Nova Kakhovka, a city on the Dnipro's left bank built for the hydroelectric station's workers. In a TV address that October, Ukrainian President Volodymyr Zelenskyy claimed the Russian military had rigged the dam with explosives and warned that its destruction "would mean a large-scale disaster." At the time, Ukrainian troops were on the verge of recapturing Kherson, a major city downstream on the Dnipro, triggering concerns Russia might blow up the dam to unleash floodwaters that would slow the Ukrainian advance.

It would not have been the first use of water as a weapon during the conflict. In March 2022, the Ukrainian army destroyed a dam on the Irpin River, north of Kyiv, to

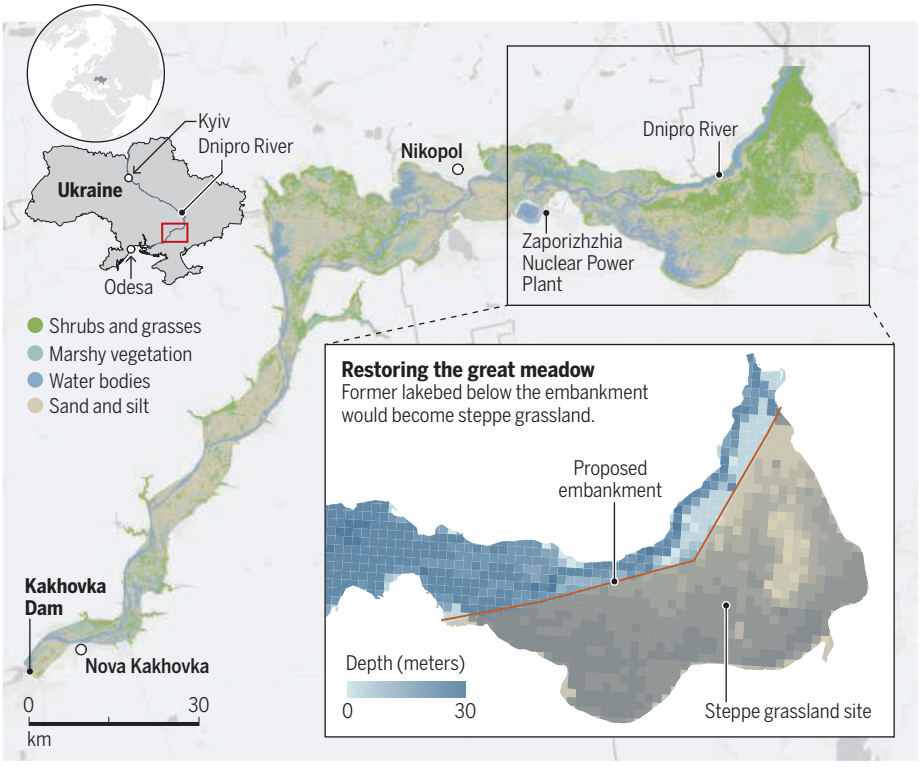
bog down Russian troops marching on the capital. The next month it employed a similar tactic, punching a hole in a dam at the Oskil Reservoir in the Kharkiv region. Then in September 2022, Russia hit a dam on the Inhulets River with cruise missiles, unleashing clayey floodwaters on Kryvyi Rih, Zelenskyy's hometown. Those and other strikes on water infrastructure ruined cropland and wrecked local ecosystems.

But even though Ukraine clawed back Kherson that November, the Kakhovka Dam, still under Russian occupation, stayed intact for another half a year.

The morning of the disaster, Sergiy Afanasyev's first thoughts were for colleagues at the S.T. Artyushchyk Production Experimental Dnipro Sturgeon Breeding Plant. Located southwest of Kherson in Dniprovs'ke, the 40-year-old station annually stocked the Dnipro's reservoirs with some 1.5 million juvenile sturgeons adapted to the region, including the critically endangered Danube sturgeon (*Acipenser gueldenstaedtii*). Ukrainian troops evacuated its staff before a 4-meter wave of turbid, polluted water flooded the station and its breeding ponds. But the sturgeons, which

Reservoir bogs

The Kakhovka Dam breach on 6 June 2023 inundated settlements and unique ecosystems along the lower Dnipro River. Nearly 90% of the reservoir drained, exposing 1870 square kilometers of former lakebed. One proposal for postdisaster recovery calls for building a 50-kilometer-long embankment that would create a narrower, deeper reservoir and allow for the return of steppe grassland.



When the Kakhovka blasts came, they dwarfed the previous attacks. The breach was wider than modeling of an explosion had anticipated. "Something else made everything way worse," says Amin Tavakkoli Estahbanati, a remote sensing specialist at the University of Houston. Analyzing synthetic aperture radar measurements from 2015 to 2023, he and his colleagues reported at the American Geophysical Union meeting in San Francisco last month that the dam had begun to deform months before the blasts, possibly because of faulty operations and poor maintenance.

are acutely sensitive to toxicants, could not be rescued. "There is a very low possibility that any survived," says Afanasyev, director of NAS's Institute of Hydrobiology.

The breach would also have been devastating for the scarce wild sturgeons in the Dnipro. In late spring, the fish swim upriver from the Black Sea to spawning grounds just below the Kakhovka Dam. Early June is peak breeding season, Afanasyev says. "The explosion wiped them out."

Upstream of the dam, nearly 90% of the Kakhovka Reservoir drained, exposing 1870 square kilometers of former lakebed, including dense beds of zebra and quagga mussels that once filtered and cleansed the reservoir's water. Now, as much as 500,000 tons of dead bivalves are rotting in the desiccated lakebed. It could take a few years for the soft body parts to decompose fully, and their shells much longer, says Volodymyr Yuryshynets, a parasitologist at the Institute of Hydrobiology.

Normally, Afanasyev would have immediately dispatched scientists to assess the Dnipro's health. But because of the "extreme danger of such investigations" along the war's front line, he says, his institute first enlisted volunteers—fishers and others who remained along the river—to report on fish stocks and send water samples to Kyiv for analysis. Those samples enabled the scientists to verify that sediments swept downstream were laden with manganese and other heavy metals, and long-lived organic compounds such as polychlorinated biphenyls (PCBs) that had accumulated over decades in sediments behind the dam. "The colloidal particles were quite toxic," Afanasyev says.

To bring the picture into sharper focus, however, the scientists knew there was no substitute for seeing the disaster area for themselves.

AROUND 9 A.M. on 4 October, Osadchyi and Grygorii Derkach wriggled under a barbed wire fence meant to keep civilians out of a death zone along the Dnipro near Kherson, less than 1 kilometer from Russian forces on the opposite bank. Ukrainian army officers urged the UHMI hydrologists to secure their precious samples of river water quickly, before the Russians began their daily shelling. "We were in a sour mood," Osadchyi says—a lingering disquiet from the previous day, when the duo had driven through the ruined village of Chornobaivka.

As the pair edged toward the Dnipro that cool, sunny morning, they heard what sounded like a motorbike engine. "Hit the ground!" a soldier shouted. Osadchyi dove under a tree as a Russian reconnaissance drone swooped in, just 20 meters overhead. "It was terrifying," he says. The drone departed, and the rattled scientists scrambled to fill their 40-liter plastic jug. Lugging it back to their car in Kherson's River Port District, they heard shells explode near the area they'd occupied moments earlier.

Back at their laboratory, the UHMI researchers learned new details about water quality in the Dnipro. Although the nasty compounds in the reservoir sediments have largely washed out of the water column, the river is still freighted with nitrogen, phosphorus, and toxicants from sewage and

GRAPHIC: D. AN-PHAM/*SCIENCE*

agricultural runoff. "The amount of wastewater pouring in is the same as before," says Osadchyi, who notes that determining pollutant concentrations is a "complex and meticulous task." Compounding that bad news is the loss of mussels that filtered the water. "To a great degree, they purified the reservoir" when alive, Afanasyev says. Until the mussels rebound, wastewater entering the Dnipro above Kakhovka Dam will wash downstream largely unfiltered.

The emptied reservoir itself might also be creating a health threat. There, the Dnipro now wends through a mucky patchwork of about 9000 newly formed small lakes and ephemeral ponds. Scientists worry these wetlands are incubating disease-transmitting mosquitoes and other blood-sucking insects, populations of which could explode next spring, Yuryshynets says. "It's a potential danger for the region."

Days after Russia launched its full-scale invasion in 2022, Galyna Minicheva risked conducting fieldwork in the highly saline Kuialnyk Estuary near Odesa, Ukraine.

DOWNSTREAM IN THE lower Dnipro Basin, the surge of polluted floodwaters from the breach pummeled rare habitats, including Oleshky Sands National Nature Park, an 80-square-kilometer preserve east of Kherson. The second largest expanse of sand in Europe, it is home to the endangered sandy blind mole-rat (*Spalax arenarius*). "Many surely drowned," says IZAN zoologist Oleksiy Vasylyuk, who also leads the nonprofit Ukrainian Nature Conservation Group.

Other exceptional endemic species—including Nordmann's birch mouse (*Sicista loriger*), a tree-dwelling ant (*Liometopum microcephalum*), a sand gadfly, two species of pearl knapweeds, and a rare birch (*Betula borysthenica*)—inhabit nearby ecosystems, including the 900-square-kilometer Black Sea Biosphere Reserve that's now in Russian hands. Vasylyuk fears some of those populations are now extinct. But it's too dangerous, he says—and in Russian-held areas, impossible—to get out into the field and check.

When the pulse of sludge-choked freshwater reached the Dnipro-Bug Estuary, it hammered fish species adapted to brackish water. Taking heavy losses, according to forecasts by Afanasyev's team, were the Black Sea roach (*Rutilus frisii*), the Dnieper barbel (*Barbus borysthenicus*), and the Sarmatian bleak (*Alburnus sarmaticus*). Particularly heartbreaking, he says, is the presumed demise of the estuarine perch (*Sander marinus*). The species had vanished from the region's watersheds until 2016, when fishers in the Dnipro-Bug Estuary reported its surprising reappearance. "It's very sensitive to toxicants and lower salinity," Afanasyev says. "Now it only exists in a museum."

ULTIMATELY THE FLOODWATERS reached the sea. On a warm September day, 4 months after the breach, sunbathers lolled on Odesa's beach and swimmers frolicked without fear in the Black Sea thanks to a metal net strung between piers that prevents Russian mines from drifting into shore. On a hillside patio overlooking the beach, however, Minicheva's team was all business. An IMB marine biologist in a wetsuit examined a basket of mollusks and other sea creatures. A colleague labeled a glass jar of seawater that will be analyzed for dissolved oxygen and salinity. If it weren't for the war, a more salubrious place to do science would be hard to imagine. "We have a saying," Minicheva said with a smile. "In Kyiv, science is academic. In Kharkiv, it's applied. In Odesa, science is *shikarna*. Luxurious."

For more than a year, Ukraine's military deemed research in Black Sea waters too perilous to undertake. But measurements close to shore in Odesa Bay, where the Dnipro-Bug Estuary meets the Black Sea, showed that the flood caused salinity to drop from 15 parts per million to 4 parts per million—"practically freshwater," Minicheva says. Monitoring stations in the bay run by the Ukrainian Scientific Centre of Ecology of the Sea (UkrSCES) then recorded high concentrations of metals—including cadmium, arsenic, and copper—and toxicants such as petroleum byproducts and PCBs.

The double punch dealt a devastating blow to marine life that couldn't swim away from the flood. Mollusks and other near-shore sedentary creatures in the bay were wiped out en masse, Minicheva says. The surge of nutrients also ignited massive blooms of short-lived cyanobacteria, commonly known as blue-green algae. Then, bacteria that consume the algae rapidly depleted dissolved oxygen, choking coastal waters.

In August 2023, Ukraine's military relaxed restrictions on Black Sea research, hoping to glean evidence for war crimes charges. IMB scientists now have permits to dive at four locations in Odesa Bay. They are chronicling what Minicheva expects to be a prolonged period of ecosystem recovery. And they are warily eying an invasive sea snail, the veined rapa whelk (*Rapana venosa*). The predator from the western Pacific Ocean first appeared in the Black Sea in the 1940s and in recent years has become a major pest in Ukrainian waters, where it dines on endemic oysters and other mollusks. "I worry that *Rapana* could be the big winner" as creatures vie to recolonize marine habitats damaged by the freshwater surge, says IMB marine biologist Mikhail Son.

Researchers are also hoping the marine measurements shed light on a mystery. In March 2023, in a stunning claim that received widespread press coverage, a Ukrainian ecologist asserted that at least 50,000 dolphins died over 6 months in 2022, primarily because of underwater mine blasts and acoustic damage from high-energy submarine sonar. Other experts dismissed that figure as a wild exaggeration—"simply crazy," says UkrSCES acting Director Viktor Komorin.

The truth looks less alarming. In 2022, about 900 porpoise and dolphin stranding deaths were photo verified in the western Black Sea—roughly twice the annual average recorded from 2018 to 2021, says IZAN mammalogist Pavel Goldin. But in 2023 there were only a handful. And necropsies he and UkrSCES zoologist Karina Vishnyakova performed on several of those dead animals have revealed no obvious links to pathogens or toxicants released by the floods or oil spills. They also did not

PHOTO: GALYNA MINICHEVA

find internal hemorrhaging—a hallmark of exposure to loud sonar soundings or underwater explosions. Further tests are underway at the University of Padua and the University of Veterinary Medicine Hannover. But so far, "The cause of the deaths is not straightforward," says Goldin, who has been sharing the results with Ukrainian prosecutors investigating possible war crimes.

A fuller picture of the harm inflicted on the Black Sea will only come into focus after hostilities cease. On the eve of the full-scale invasion, UkrSCES had been gearing up for the most ambitious Ukrainian expedition in years to monitor the Black Sea environment. The war scuttled that voyage, and a missile strike on Odesa's port in July 2022 damaged its research vessel—the *Belgica*, donated by Belgium in September 2021 and renamed the *Borys Aleksandrov* after IMB's previous director, who perished in a fire at the institute in 2019. Restoration work must wait until after Ukraine's victory, says Komorin, who has already begun to plan an expedition with Ukraine's Black Sea allies: Bulgaria, Georgia, Romania, and Turkey.

After a centurieslong absence, wild asses called kulans are thriving in a Ukrainian reserve.

PHOTO: REWILDING UKRAINE

SCIENTISTS ARE ALSO awaiting a final decision on whether the Kakhovka Dam will be rebuilt. For the Ukrainian government, a paramount concern is economic recovery. Reimpounding the reservoir could entice residents back to abandoned homes, weekend dachas, and fishing boats along the former shoreline. And it would ease concerns about a future restart of the Zaporizhzhia Nuclear Power Plant, which drew cooling water from the reservoir and, since the dam's destruction, has had to rely on hastily dug wells for water to cool its reactor cores and spent fuel.

Osadchyi, who is part of an expert group from NAS that is assessing options for future water infrastructure there, says a failure to rebuild the reservoir "would be another disaster." Refilling it would allow mussels to reestablish themselves and begin to filter the water again and provide timely water releases for downstream needs such as supplying municipalities, irrigating crops, and sustaining ecosystems.

Afanasyev favors an option he calls "build back better." It would involve creating a narrower and deeper reservoir by repairing the Kakhovka Dam and confining the water within a 50-kilometer-long barrier (see graphic, p. 20). The rationale is that much of the Kakhovka Reservoir was less than 2 meters deep. "It was essentially stagnant," Afanasyev says. Fish kills, he says, occurred frequently: in summer, when water temperatures in the shallow basin soared, and in winter, when ice cover suffocated fish.

This approach also offers "a chance to right an historical wrong," Osadchyi says. When Soviet engineers impounded the reservoir, he notes, they inundated a swath of steppe and wetlands known as the Velykyy Luh, or Great Meadow—an area prized by Cossacks who have lived in southern Ukraine for centuries. A smaller reservoir would spare some of that prized territory, preserving native willows, poplars, and other vegetation that are now colonizing hundreds of square kilometers of the drying basin.

Climatologist Svitlana Krakovska, head of the Ukrainian delegation to the United Nations Intergovernmental Panel on Climate Change, is skeptical of plans to reclaim the old lakebed. Before the disaster, she notes, climate modeling forecasted that the lower Dnipro Basin would become much drier. Evaporation at the Kakhovka Reservoir would have mitigated local warming, she says. Without a reservoir, "The region will only get hotter and drier."

Krakovska also anticipates that the willows and poplars emerging in the former reservoir's lakebed will wither as the water table recedes. "Sure, there will be a different ecosystem," she says. "But I'm afraid it's impossible to go back to what it was like there in the middle of the 20th century."

Still, some experts would prefer to try to rewind the clock even further. "I don't think the dam should be rebuilt," Vasylyuk says. Instead, he and others see great potential in letting nature take its course. "My dream is that the lower Dnipro watershed will be the next hot spot for rewilding," says Igor Studennikov, executive director of the Centre for Regional Studies. As a model, he points to a recent effort to restore the Tarutino Steppe, southwest of Odesa near the Danube delta region. A decade ago, Oleg Diakov, an ecologist with Rewilding Ukraine, and colleagues began to restore native grasses and animals such as kulans (*Equus hemionus*)—a native wild ass that disappeared from the Ukrainian steppe centuries ago—to a 5200-hectare sanctuary.

After the war, Diakov says, similar reserves could be established around areas in the lower Dnipro Basin where extensive minefields will deter agriculture and other land uses for years to come. "We'd already identified this area before the war as having the greatest potential for large-scale ecological restoration," he says. But those aspirations—and a full accounting of the environmental cost of the war—will remain unfulfilled, Mosyakin says, until after Ukraine reclaims territory under occupation.

"The sooner the war is over," Goldin says, "the sooner our ecosystems will get a chance to recover." ■

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Laid to waste

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