River bed and floodplain of the Dnipro River within the Kakhovka reservoir: before its construction and after the dam blow up in 2023

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SUMMARY

The breach of the Kakhovka Reservoir dam resulted in one of the largest technological environmental disasters of the 20th and 21st centuries, with no parallels worldwide. After a sudden drop in water levels within the reservoir, the floodplain and the course of the Dnipro River, which had been submerged for 68 years, were exposed. Based on available information, including topographic maps predating the reservoir inundation, as well as accessible imagery from Sentinel-2 L2A after the dam's breach, a comparative analysis of the morphology of the riverbed and floodplain microrelief was conducted. The research revealed that during the 68 years underwater, there were no alterations to the riverbed or floodplain microrelief. This phenomenon is primarily explained by the absence of alluvial material inflow due to the presence of an upstream cascade of reservoirs on the Dnipro River. The reservoir mainly received very fine suspended particles, leading to their minimal accumulation at the reservoir's bottom without disrupting the natural morphology of the riverbed and floodplain microrelief. The natural course of the Dnipro River, the floodplain microrelief, and the islands, including their channels and ancient riverbeds, became the main water flow concentrators when the water level in the reservoir decreased to the level of the floodplain after its destruction.

Keywords: Kakhovka Reservoir, Dnieper River channel, floodplain microrelief, riverbed type
Introduction

The blowing up of the Kakhovka Reservoir dam became the cause of one of the largest technogenic environmental disasters of the 20th and 21st centuries, resulting in billions of damages to Ukraine's economy, loss of human lives, and destruction of unique ecosystems. The Kakhovka Reservoir was the sixth in a cascade of reservoirs downstream on the Dnipro River, stretching from Nova Kakhovka to Zaporizhzhia. Its water surface area was 2,155 km², with an 18.19 billion cubic meters volume. The maximum width was 28 km, and the depth reached 36 meters. It was brought into operation in 1955. The reservoir played a crucial role as a water reservoir for supplying irrigation canals in southern Ukraine and Crimea and for cooling the reactors of the Zaporizhzhia Nuclear Power Plant. The explosion of the Kakhovka Hydroelectric Power Station occurred on June 6, 2023, at 2:50 AM Kyiv time, carried out by Russian regular troops. The reservoir completely drained on June 23, and the water level on the submerged territories below the dam finally decreased on June 18. Following the blowing up of the Kakhovka dam and the rapid lowering of water levels in the reservoir, the relief of the Dnipro valley bottom was exposed. Thus, the aim of the research was to study the morphology of the riverbed and micro-relief of the floodplain within the Kakhovka Hydroelectric Power Station's boundaries before the reservoir's creation and after its elimination. Additionally, it aimed to assess the changes during the 68 years of the reservoir's existence. The primary research method employed was the cartographic approach using GIS technologies, including a comparative analysis of existing topographic maps and available imagery from Google Earth and Sentinel-2 L2A.

Methodological Framework

The methodology involves processing and comparing temporal satellite images from Google Earth, Sentinel-2 L2A, and German topographic maps at a scale of 1:300,000 from 1943. The material processing was carried out using the QGIS software. To achieve the set goals, satellite images from Google Earth of the year 2020 were used, depicting the Kakhovka Reservoir as filled. The alignment of the 1943 topographic maps, which portray the natural state of the riverbed and valley prior to the construction of the Kakhovka Hydroelectric Power Station in 1955, was performed. Additionally, Sentinel-2 satellite images with a resolution of 8 m/pixel were utilized for the period of June 20, 2023, when the majority of the water had drained from the reservoir, resulting in distinct outlines of the Dnipro riverbed.

Previous research. Publications on the restoration of a riverbed due to a sudden decrease in reservoir levels are absent, as such a scenario has not occurred in world history. However, there are several articles related to the restoration of a natural riverbed following the dismantling of a dam. For instance, Shuman J.R. (1995) considers dam removal as a means of improving the river ecosystem and reducing environmental impact. He also evaluates the negative effects on the regional energy system and assesses the feasibility of dam removal. In the study by Leisher, C., Hess, S., Dempsey, K., et al. (2022), a social survey was conducted where residents living near the dam provided an assessment of the reservoir's role before and after the dam's removal. The research revealed an increase in the river's significance in the lives of local residents after the dam's dismantling. Researchers Lewis, L. Y., Bohlen, C., & Wilson, S. (2008) evaluated property values before and after dam construction both upstream and downstream. While there are numerous studies concerning dam removal and reservoir drainage, none have been found that specifically address a sudden and rapid decrease in reservoir levels, as well as the restoration of riverbed and floodplain functioning within former reservoir boundaries.

Results

The analysis of the 1943 topographic map within the Kakhovka Reservoir area enabled the identification of two sections with different types of the Dnipro riverbed that existed prior to its creation. The first section exhibits an anastomosing riverbed type, typical for the narrower part of the Dnipro valley, from Kakhovka to Enerhodar. Its length spans over 145 km. Characteristic features of this riverbed include multiple channels, and a significant number of islands within the floodplain area.
These islands are covered by vegetation, with much of their surface being marshy, featuring numerous oxbow lakes, small streams, and floodplains. The most typical segment of the Dnipro riverbed is from Enerhodar to Zolota Balka village, characterized by the highest number of islands and channels. The maximum width of the anastomosing riverbed measures 19.2 km. The significant number of islands within the Dnipro riverbed in this stretch is due to the sharp narrowing of the valley bottom around Zolota Balka village and the change in its direction, leading to the confinement of water and an increase in sediment accumulation. In the vicinity of Zolota Lypa village, the Dnipro riverbed narrows abruptly and changes its direction from northeast to southwest. The valley’s bottom width ranges from 3.78 to 7.42 km. Compared to the Enerhodar - Zolota Balka segment, this section is characterized by fewer islands and channels. The islands are marshy with sparse vegetation, indicating their more frequent inundation during high water levels, primarily due to an increase in water level within the Dnipro riverbed resulting from reduced flow capacity.

The second type of the Dnipro riverbed within the Kakhovka Reservoir area is distinguished in the most expanded section of the valley bottom – from Enerhodar upstream to the southern outskirts of Zaporizhzhia (Fig. 1a). In this segment, the riverbed is elongated predominantly from east to west. This section is characterized by a single-channel, meandering riverbed with isolated islands that locally divide the river into branches. The floodplain on the left bank is well-developed with pronounced micro-relief, featuring numerous oxbow lakes and temporary streams that function as permanent watercourses during higher water levels. The floodplain's elevation increases along the main Dnipro riverbed due to the formation of natural levees. This is clearly identifiable on the 1943 map by the presence of vegetation and the absence of oxbow lakes. As one moves away from the Dnipro riverbed towards the ledge of the left-bank terrace, there is a decrease in the floodplain's elevation, an increase in the number of oxbow lakes, and heightened marshiness.

The lowering of the floodplain's relief in the region of the left-bank terrace's recess is emphasized by the presence of the Konka River, a left tributary of the Dnipro. A significant increase in the floodplain's elevation is observed in its eastern part. Notably, on the 1943 map, substantial sandy elevations are clearly identifiable, acting as local divides within the floodplain between the main course of the Konka River and its right temporary tributary, Kuschugum, which functions as a riverbed during higher water levels (Fig. 1a). Evidence of this is provided by islands locally known as "Kuchugury," which were covered in vegetation and emerged above the water surface of the reservoir after its filling in 1955 (Fig. 1b). A rise in the floodplain's elevation is also observed south of Zaporizhzhia in the area of the floodplain expansion. After the reservoir was filled, this part of the floodplain appeared as a series of islands separated by vegetated channels (Fig. 1b). Some of these islands feature recreational buildings and leisure bases, such as "Meridian." The area of the islands decreases downstream along the course of the Dnipro.

From 1955, the Dnipro riverbed along with its floodplain remained submerged until June 6, 2023, as previously mentioned. After the dam's blow-up, within 17 days, the water almost entirely vanished from the reservoir and returned to the floodplain level, becoming concentrated within the Dnipro riverbed. Throughout the 68 years, both the riverbed and floodplain were underwater; however, during this time, the configuration of the Dnipro riverbed hardly changed in terms of its plan, with islands and floodplain micro-relief preserved (Fig. 2, Fig. 1d, e).

In the Enerhodar-Zaporizhzhia segment, the left-bank floodplain of the Dnipro is broad, reaching up to 23 km. The flow of water within the floodplain followed its micro-relief, utilizing former channels, temporary riverbeds, and depressions on the floodplain's surface. According to the 1943 map at a scale of 1:300,000, seven temporary riverbeds are distinctly delineated on the floodplain's surface. In the northern and central parts of the floodplain, they are oriented from north to south, while in the western part, they run from northeast to southwest. During high water levels, these riverbeds functioned as channels, connecting the Dnipro with the Konka River. These and several other minor channels became the primary collectors of water flow when the reservoir's water level decreased to the floodplain level after its destruction (Fig. 3).
The excess water was primarily concentrated in the depressions of the floodplain. Temporary water bodies formed mainly in the eastern part of the floodplain, near the recess of the terrace, which was previously also part of the valley of the Dniipro's right tributary, the Konka River (Fig. 1a). The satellite images (Fig. 1d, e) also clearly delineate all the channels and temporary riverbeds filled with water, allowing the identification of floodplain formation mechanisms. Specifically, a significant portion of the floodplain in the Enerhodar-Zaporizhzhia segment is formed as an anastomosing-type floodplain. However, the satellite images also highlight local areas with segmental-ridge micro-relief, characteristic of floodplains of meandering riverbeds. These areas are particularly evident in the vicinity of "Kuchugury," which is a raised divide between the Konka River and its left tributary, as well as in the areas of Enerhodar, Kapylivka, Babyne, and others.

Figure 1 View of the largest volume portion of the Kakhovka Reservoir before the dam construction, during its operation, and after the dam blew up
(a - 1943 map; b - Kakhovka Reservoir, 2021; c - Sentinel-2 L2A infrared spectrum satellite image, June 20, 2023; d - Sentinel-2 L2A satellite image, June 30, 2023)

Figure 2 The Dnipro riverbed before and after the formation of the reservoir

The absence of vegetation on the surface of the left-bank floodplain of the Dnipro after the reservoir's destruction in the Enerhodar-Zaporizhzhia segment and on the islands of the anastomosing-type riverbed (from Enerhodar to Kakhovka) contributed to the erosion of deposits and a clearer delineation of the channels through which the water flowed when the reservoir's water level reached the levels of their surfaces. The original natural micro-relief of the Dnipro's riverbed, which existed before the reservoir's creation, gained clearer delineation and is well identified in satellite images. It's worth noting that this micro-relief is also clearly identified in Sentinel-2 infrared spectrum satellite images from June 23 to July 30, 2023. These images show that vegetation is present on the elevated elements of the floodplain's micro-relief and islands, indicating the progression of the riverbed's revegetation process - starting from the highest elements that dried up faster and then moving to the lower micro-relief features.
Conclusions

The research has shown that the natural morphology of the Dnipro River channel and floodplain remained unchanged after the filling of the Kakhovka Reservoir in 1955 and its subsequent operation for 68 years. This can be attributed to several factors. At first, the dispersion of water flow within the reservoir virtually prevented alterations to the channel morphology. The large area and shape of the reservoir contributed to an even distribution of water, preventing the formation of strong flow concentrations that could alter the riverbed. This facilitated the preservation of the pre-existing channel form. Secondly, the absence of sediment inflow due to retention in higher upstream reservoirs also influenced the condition of the Dnipro River channel and floodplain. Major reservoirs located upstream along the Dnipro River (such as Kyiv, Kaniv, etc.) act as reservoirs that retain sediments and materials within their boundaries. This impedes the transport and accumulation of material in downstream reservoirs, including the Kakhovka Reservoir. In conclusion, the preservation of the natural relief of the Dnipro River channel and floodplain after the decommissioning of the Kakhovka Reservoir can be explained by the dispersion of water flow within the reservoir and the almost absence of material inflow from higher upstream reservoirs.

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