NATURAL PROCESSES IN THE AREA OF THE FORMER KAKHOVSKE RESERVOIR AFTER THE DESTRUCTION OF THE KAKHOVKA HPP

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ABSTRACT

The results of the studies devoted to the consequences of the Kakhovka dam destruction on June 6, 2023 in the course of the Russia-Ukraine war are presented. After the accident, the Kakhovske reservoir, which was the largest by volume on the Dnipro River, practically disappeared. It has turned into the network of river branches and lakes that do not compare with the former reservoir.

Currently, the conditions on the territory of the former reservoir have approached those observed in natural conditions. To some extent, they depend on the water discharge of the Dnipro River, more exactly, on the water discharge of the Dnipro HPP located upstream. In the conditions of large water runoff, the large part of the former Kakhovske reservoir is covered with water.

An unusual natural phenomenon of the area of the former reservoir is very rapid overgrowth, primarily by willow. A year after the accident, its height in places which is rich in organic sediments exceeded 4 meters. At the same time, the size of the trees on the bottom covered by sands is much smaller. Today, a large area of the former reservoir looks like a dense forest.

Keywords: Kakhovske reservoir; Dnipro River; overgrowth; willow

INTRODUCTION

The processes observed in the reservoirs are the subject of various studies, such as thermal regime, water quality, algal bloom, biodiversity, human use, etc. Among these studies there are a few ones, devoted to the consequences of the water level decrease.

Interesting results on the overgrowth of the area after water level decrease in the reservoir located in Czech Republic, are published in articles (Maděra & Kovářová, 2004; Maděra *et al.*, 2009). It was found that after the water level lowering, the area without water was quickly covered by white willows and black poplars. It is important that decrease of water level occurred at the beginning of July, that is, much later after the flowering of trees and the seed ripening. This fact showed the high viability of white willow seeds in water. The average seedling density at the end of the first year after the water level lowering was about 30 seedlings per 1 m^2. This study also found that the ratio of white willow to black poplar depends on inundation. In case of summer floods, the significant part of black poplars dies.

A similar process of the water level decrease was observed in the large cooling pond of the former Chernobyl NPP. A few years after the disaster, it was decided to stop pumping water in it. After water level decrease, the artificial planting was carried out, but the main role in the overgrowth of cooling pond played the natural processes (Dyachenko *et al.*, 2022).

A decrease in the water level followed by overgrowth occurred during the ongoing Russia-Ukraine war with the Oskilske reservoir, located in eastern Ukraine. During the first year after dam damage, the area without water was covered with vegetation, but the features of this process remain unknown duo to the proximity of hostilities (Gleick *et al*., 2023).

Varies studies were carried out as to the Kakhovske reservoir, which was the largest by volume on the Dnipro River. The features of thermal regime of the reservoir before and after the accident were described in the papers (Vyshnevskyi & Shevchuk, 2021; Vyshnevskyi & Shevchuk, 2024). It has been found that an important factor, affecting the thermal regime of the former Kakhovske reservoir, was deep-water Dniprovske reservoir located upstream. Besides, the surface water temperature of the former Kakhovske reservoir greatly depended on wind impact.

After the destruction of Kakhovka HPP, the network of river branches and lakes was formed in the area of the former Kakhovske reservoir. The plum of cool water in the main river branch downstream of Dnipro HPP in spring and summer is observed at a distance of more than 100 km (Vyshnevskyi & Shevchuk, 2024).

The features of water quality in the former Kakhovske reservoir were described in the articles (Vyshnevskyi, 2020; Zhezheria *et al*., 2022). It was shown that water in the Kakhovske reservoir was very reach in inorganic phosphorus. Moreover, during the last decades, the concentration of inorganic phosphorus had the tendency to increase. At the same time, the concentration of nitrogen compounds was rather stable. As a result, the N/P ratio in the water of the Kakhovske reservoir was the smallest (about 5) among other reservoirs of the Dnipro Cascade.

The accident at the Kakhovske reservoir, that happened on June 6, 2023, occurred unique in human history. In a few weeks after explosion, the great reservoir practically disappeared. It has turned into network of river branches and lakes which cannot be compared with the former reservoir. In one's term, the operation of many water intakes, which were used for irrigation, industrial and domestic drinking water supply, was stopped. At the same time, the area of the former reservoir began to overgrow. Varies consequences of the dam destruction are described in many articles (Dovhanenko *et al*., 2024; Gleick *et al*., 2023; Harada *et al*., 2022; Kuzemko *et al*., 2024; Magas *et al*., 2023; Nepsha *et al*., 2024; Pichura *et al*., 2024; Spears *et al*., 2024; Starodubtsev & Ladyka, 2023; Vyshnevskyi & Shevchuk, 2024; Vyshnevskyi *et al*., 2024). Besides, the events of the current Russia-Ukraine war are mentioned in papers (Harada *et al*., 2022; Rawtani *et al*., 2022).

In the paper (Nepsha *et al*., 2024) it is stated that after the dam destruction, the vast majority of living organisms, such as fish, mollusks, various species of dipterans, which inhabited the Kakhovske reservoir, have died. Before the accident, there were no less than 43 species of fish, of which 20 species were of industrial importance with annual catch was up to 2.6 thousand tons.

In the study (Pichura *et al*., 2024) it was shown that the disappearance of the reservoir has caused the changes of microclimatic conditions, an increase in the air temperature and the evapotranspiration. Some attention in the study was also paid to the overgrowth of the reservoir. It was stated, that the dam destruction and the drainage of the Kakhovske reservoir is the greatest man-made disaster of our time.

The study (Dovhanenko *et al*., 2024) based on remote sensing data, is devoted to clarification of the bottom sediments of the former Kakhovske reservoir. It was clarified that in the upper part of the former reservoir (mainly in the vicinity of old river branches) dominate the sandy sediments. Simultaneously, the sediments in deep south-western part of the reservoir contain many small particles. According to this study, the overgrowth of the bottom was held in the direction from the coastline towards the central area. In the upper part of the reservoir (closer to the city of Zaporizhzhia a "center of overgrowth" was formed. This was mainly due to the presence of large groups of higher vegetation on the shore of the reservoir. The greatest increase in vegetative cover was observed from the end of August to the end of September of 2023, when the surface of reservoir's bed was characterized by moderate moisture. According to (Dovhanenko *et al*., 2024), the vegetative season in 2023 ended in November.

In the paper (Kuzemko *et al*., 2024) the results of field studies carried out in the northern bays of the former reservoir on June 30, 2023 and on October 19, 2023 were described. In the second case, 68 species of higher vascular plants were found. The most common habitat type of flora was characterized by the dominance of willow, a hybrid of the native species *Salix alba* and the long-naturalized alien species *Salix fragilis*. During the first visit to the former reservoir, it was observed a very high density of trees – averaging 90 per 1 m^2. In October, in the second surveys, the density of trees significantly decreased but the average plant height increased to 190 cm, with a maximum height of 309 cm. This indicates highly favorable conditions for the formation of this habitat type, with an average daily growth rate of 1.7 cm. Another quite popular habitant, observed in October along the permanent watercourses, was reed. According to this study, the rapid colonization of the newly formed substrates by willows occurred due to the coincidence of the time of the dam destruction and the ripening of the willow seeds. These results are close to those published in the articles (Maděra & Kovářová, 2004; Maděra *et al*., 2009).

As can be seen from these results, the natural processes in the area of the former Kakhovske reservoir have the great scientific interest. Thus, the main goal of this study is to identify modern features on area of the former reservoir and to forecast the natural process in it for the near future.

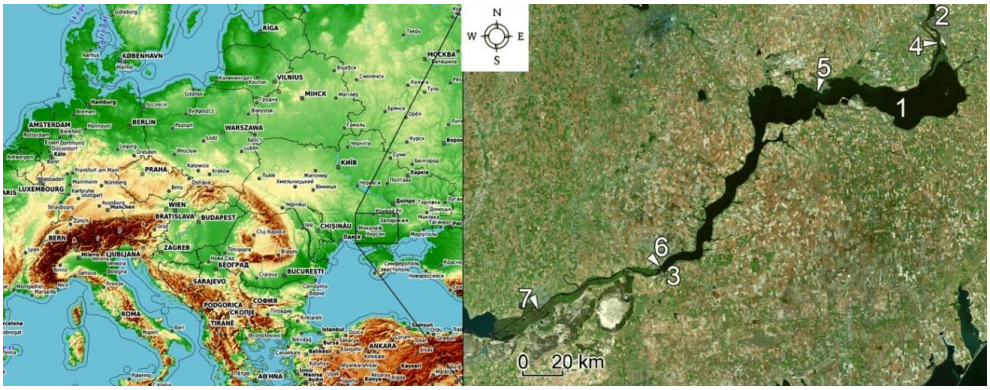
MATERIALS AND METHODS

Study area

The Kakhovske reservoir was created in the lower reaches of the Dnipro River in the 1950s. It was the second reservoir on the river after the Dniprovske one, created upstream, near the city of Zaporizhzhia in 1930s. During the following decades, 4 more reservoirs were created, and the total number of them on the river (the Dnipro Cascade) reached 6.

At a normal retention level of 16.0 m a.s.l., the project area of the Kakhovske reservoir was 2,155 km^2 and the volume was 18.2 km^3. The length of the reservoir was 230 km and the maximum width was 25 km (Vyshnevskyi, 2011) (Fig. 1).

Fig. 1: The location of the former Kakhovske reservoir (1), Dnipro HPP (2), Kakhovka HPP (3) and hydrological stations Rozumivka (4), Nikopol (5), Nova Kakhovka (6) and Kherson (7)



The mean natural (unimpacted by human activity) water runoff at the mouth of the Dnipro River was about 53 km^3 per year. In recent years, the water intake from the river, evaporation from numerous ponds and reservoirs, climate change have led to a decrease in the average runoff by more than on 10 km^3. The mean water discharge at Kakhovka HPP in 1956–2020 was 1,290 m^3/s or 40.7 km^3 per year. The water runoff at Dnipro HPP during the same period was some larger – 1,420 m^3/s or 44.8 km^3 per year (Vyshnevskyi & Kutsiy, 2022). As can be seen, the large volume of water was spent in the Kakhovske reservoir, mainly as a result of water intake and evaporation from the water surface.

The flow regulation significantly impacted the maximum discharges of the Dnipro River. In natural conditions, the maximum discharge in the lower reaches of the river could exceed 20,000 m^3/s. After the creation of the Dniprovske and Kakhovske reservoirs the maximum discharge significantly decreased. The largest discharges at Dnipro HPP and Kakhovka HPP were registered in 1958, when they were 11,100 m^3/s and 9,740 m^3/s, respectively. After the creation of entire Dnipro Cascade, the maximum discharges became some smaller.

Data sources

The most important source of information of this study was the remote sensing data. The greatest attention was paid to the images of Sentinel and Landsat satellites. In total, several dozens of satellite images were analyzed.

The second source of data was observation data at meteorological and hydrological stations. The Nikopol meteorological station is located on the northern outskirts of Nikopol town not far from the northern shore of the former Kakhovske reservoir.

The monitoring of water discharges at Dnipro HPP and Kakhovka HPP was carried out until June 6, 2023. After the explosion of Kakhovka HPP the observations are left only at Dnipro HPP. Besides, the data on the water level of four hydrological stations were used. Three of them (Rozumivka, Nikopol and Nova Kakhovka) were located on the shore of the Kakhovske reservoir and one on the right bank of the Dnipro River in Kherson city. After the accident, the observations are left only at Rozumivka and Kherson stations.

Many years ago, before the creation of the Kakhovske reservoir, the water level and water discharges in the studied section of the Dnipro River were measured at Rozumivka station. The distance of this station from the river mouth was 324 km. In turn, the distance of Nikopol station from the river mouth was 242 km, Nova Kakhovka station was 90 km and Kherson

station was 28 km. These data are used for the study of conditions in the past, which now are similar to those ones, observed before the creation of the reservoir.

The wildfires in the studied region was studied using Fire Information for Resource Management System (FIRMS).

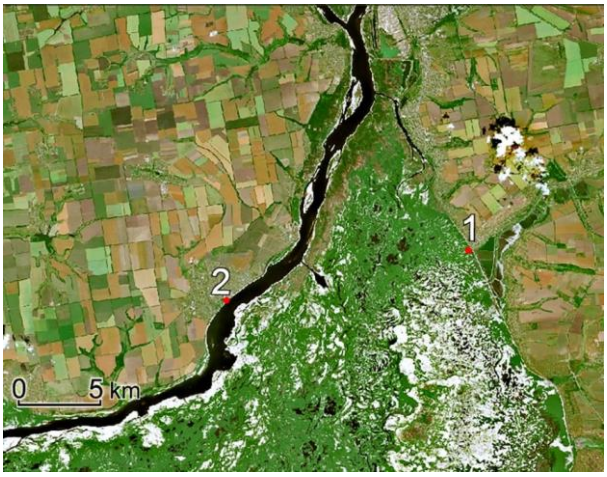
Methods

Surface water temperature in the former reservoir was determined using ArcMap 10 program on the base of satellite images taken by Landsat 9 satellite. For this it was used the data of band B10 and the dependence (("ST_B10" * 0.00341802) + 149.0)-273.16, recommended by the US Geological Service. The territory, which does not belong to water area, was identified by the calculation of Normalized Difference Pond Index (NDPI). This index was calculated according to the equation NDPI = (B6 – B3) / (B6 + B3), in which B3 and B6 are the values of Landsat 9 satellite bands. The territory, which is not a water area, was presented in grey color for better visualization.

The features of the studied area were analyzed also using the historical and navigation maps.

In addition, a short field survey of the overgrowth of the upper part of the former reservoir was carried out on June 21, 2024. In fact, this is the only part where such research can be carried out, given the proximity to hostilities. The first plot of research is located on the left and simultaneously northeastern shore of the former reservoir near the village of Malokaterynivka. This area in the past was located in shallow water, which was far from the main river branch. The second plot is located on the opposite side of the former reservoir near the village of Bilenke. This second plot is located near the place of the former river branch, where water flow was observed even in the conditions of the reservoir (Fig. 2).

Fig. 2: The location of the studied plots on the shore of the former Kakhovske reservoir: 1 – near the village of Malokaterynivka, 2 – near the village of Bilenke



RESULTS

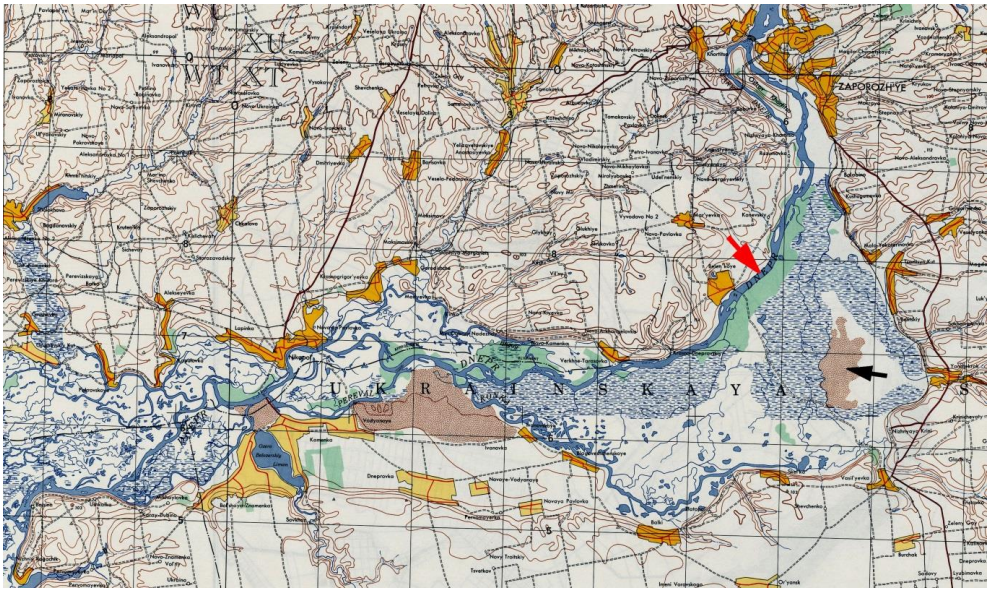
The conditions before the creation of the Kakhovske reservoir

Under natural conditions, downstream Zaporizhzhia city it was the inner delta of the Dnipro River, which had the name Velykyi Luh (Great Meadow). It was the lowland

territory, partly covered by river branches and lakes, partly by meadows and forests. The most popular trees on the banks of the river branches were willow and poplar. According to the old maps, the forest cover was insignificant – about 10 % or even less. The network of artificial forest belts of square shape is visible on the old maps and aerial photos.

In the northeastern part of the inner delta, there was a rather high sandy massif with dunes. The highest point of this massif, which was called Kuchugury, had a height of 20.7 m (Fig. 3).

Fig. 3: The historical map which shows the inner delta of the Dnipro River. The red arrow shows the main river branch in its upper part, the black arrow shows the location of sandy massif Kuchugury



Before the creation of the Kakhovske reservoir, many residents of surrounding towns and villages had vegetable gardens in the studied area. They grew crops of tomatoes, cucumbers and other vegetable crops. This floodplain was also famous for their pastures, where local residents grazed cattle from spring to mid-autumn. Besides, the observed area was very reach in fish, in particular sturgeons (Vyshnevskyi, 2011).

The conditions of this area largely depended on the water discharges of the river. Annually in a spring period, the large part of this territory was flooded. Thus, in the last four years (1951–1954) before the creation of the Kakhovske reservoir, when the water discharge at Rozumivka station (1,400 m^3/s) was close to mean long-term value, the mean maximum water level at Rozumivka station was 16.75 m and the mean minimum water level was 10,57 m. In turn, in these years the mean maximum water level at Nikopol station was 8.63 m a.s.l. and the mean minimum level was 3.69 m a.s.l. In the first case the difference was 6.18 m, in the second — 4.94 m. The historical variation between maximum and minimum level at Rozumivka and Nikopol stations reached 9 and 8 m, respectively.

The annual flooding significantly restricted the settlement in the inner delta. The analysis of old maps did not reveal any villages in this area.

Before the creation of the Kakhovske reservoir, its area was prepared for inundation. According to the historical data, published in paper (Vyshnevskyi, 2011), seven hundred thousand hundred-year-old trees have been cut down inside Velykyi Luh.

Climate of the studied region

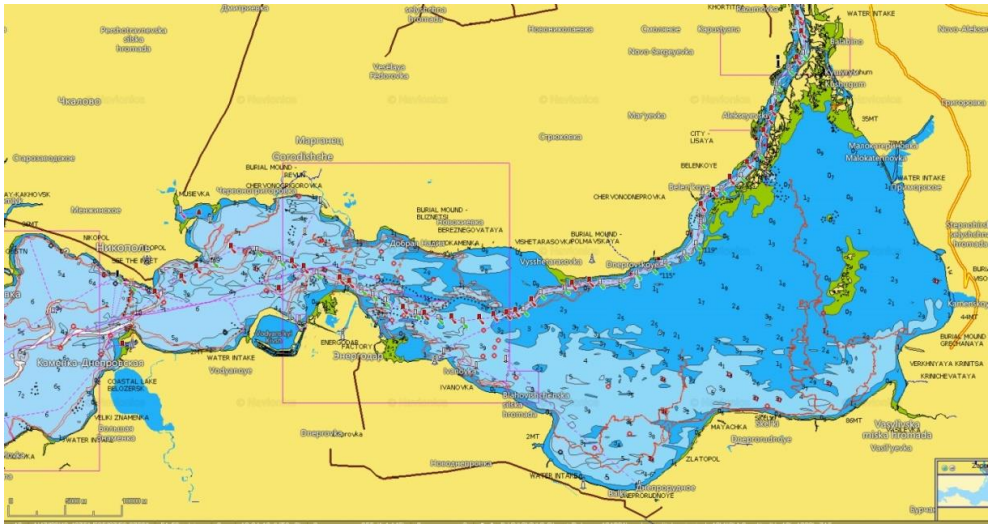
The mean annual air temperature at Nikopol meteorological station during standard period 1991–2020 is 10.5 °C. In previous period (1961–1990), the mean air temperature was lower – 9.4 °C. Currently (1991–2020) the mean air temperature in January, which is the coldest month, is minus 2.4 °C, the mean air temperature in July (the warmest month) is 23.5 °C. The mean precipitation at Nikopol station is 485 mm.

The air temperature in June 2023, when the accident occurred, was close (20.6 °C) to the long-term value (21.2 °C). During the next months the air temperature was warmer than usual. The air temperature in July of 2023 was 23.7 °C, in August it was 24.6 °C, in September it was 19.4 °C, in October it was 12.6 °C. Even in December, the mean air temperature (2.9 °C) was much higher than 0 °C.

The features of the former Kakhovske reservoir

As mentioned, the Kakhovske reservoir was created in the 1950s. Its project normal retention level (16.0 m a.s.l.) was achieved in spring of 1958. The mean depth of the reservoir was 8.5 m. In fact, the depth of the reservoir in its different parts varies greatly, its southwestern part near the dam was much deeper than the wide northeastern part. The depth of the northeastern part in many places was less than 2 m. There was a group of sandy islands remained from the above mentioned sandy massif Kuchugury near the center of the widest part of the reservoir. These islands, covered with bushes and trees, were famous as an ornithological reserve (Fig. 4).

Fig. 4: The navigation map of the former Kakhovske reservoir



Soon after the creation of the Kakhovske reservoir, two negative processes began in it, such as the significant shore erosion and the algal bloom. As a result of the erosion of the shores, their retreat exceeded 100 m in some places. Therefore, the shores were protected for

a long distance – mainly by stones. In general, the total length of protected sections exceeded 200 km (Vyshnevskyi, 2011).

Gradually, the Kakhovske reservoir played an increasingly important role in the economy of Ukraine. In addition to electricity production, this reservoir became the most important source of water for irrigation and water supply in Ukraine. On the basis of the reservoir, three large canals were built: the Dnipro–Kryvyi Rih, the North Crimean and the Main Kakhovskyi Magistral ones. Besides, the North-Rohachytska irrigation system was built on the left and simultaneously southern shore of the reservoir. In addition, Zaporizhzhia thermal power plant and Zaporizhzhia nuclear power plant were built on the shore of the reservoir near the Enerhodar town. It is important that Zaporizhzhia NPP with 6 units of 1 mln kW each is the largest in Europe.

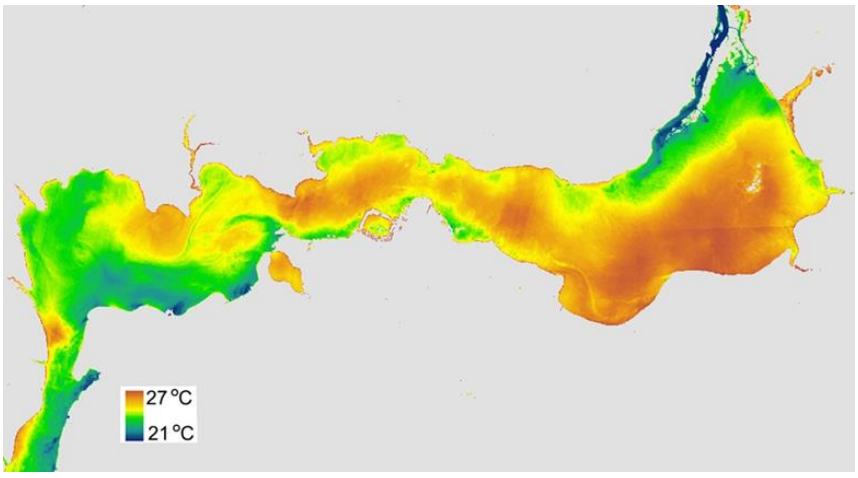
During the existence of the Kakhovske reservoir, the water level in it was close to the designed values. The mean water level at Rozumivka station for the period 1966–2020 was 15.78 m a.s.l., the maximum level (17.63 m a.s.l.) was registered on 02.05.1970, and the minimum (14.32 m a.s.l.) on 12.04.1987. The mean water level at the downstream Nikopol station for the period 1966–2020 was 15.67 m a.s.l., the maximum level (16.46 m a.s.l.) was registered on 26–28.11.1993 and the minimum (14.18 m a.s.l.) on 04.04.1968 (Vyshnevskyi & Kutsiy, 2022).

Compared to natural conditions, the creation of the Kakhovske reservoir caused the increase of the water level at Rozumivka station by approximately 2.5 m, at Nikopol station – by approximately 9.7 m. At the same time, the water level near Nova Kakhovka rose by approximately 15.4 m.

On the eve of the accident, when the Kakhovka HPP was operated by the Russians, the water level in the reservoir was higher than usual. In fact, this level turned out to be higher than during the entire period of operation of the Kakhovske reservoir.

According to data of last satellite image taken by Landsat 9 satellite before the accident on June 2, 2023, the water temperature in the wide part of the reservoir was about 23–25 °C. The coldest water was observed in the area, which is significantly dependent on discharges from the upstream Dnipro HPP. On that day the mean water temperature at Rozumivka and Nikopol stations was 18.7 °C and 23.2 °C, respectively (Fig. 5).

Fig. 5: The surface water temperature of the Kakhovske reservoir in a daytime on June 2, 2023 according to the data of Landsat 9 satellite



As can be seen, there was a fairly good correlation between the actual and calculated water temperature. Some excess of the calculated water temperature over measured one at the hydrological stations can be explained by different time of measurements. The satellite surveying is carried out in a daytime, when the water temperature is warmer that mean daily one.

As noted in the article (Vyshnevskyi & Shevchuk, 2024), the cool water at Rozumivka station is caused by the water discharge from the bottom layer of deep Dniprovske reservoir, where the water temperature in spring and summer is much colder than in natural conditions of the river.

The conditions after the destruction of Kakhovka HPP

The water level at Nikopol hydrological station before the accident on June 6, 2023 was 16.76 m a.s.l. At this level, the water volume of the reservoir was 19.8 km^3.

After the accident, the water level in the reservoir became to drop rapidly. At 8:00 a.m. that day, it decreased at Nikopol station to 16.13 m a.s.l. On the following days at the same time, the water level was as follows: June 7 – 14.48 m a.s.l; June 8 – 13.05 m a.s.l.; June 9 – 11.74 m a.s.l.; June 10 – 10.42 m a.s.l.; June 11 – 9.35 m a.s.l. On June 11, at 8:00 pm, it dropped to 9.04 m a.s.l. After that, the measurements at Nikopol station became impossible.

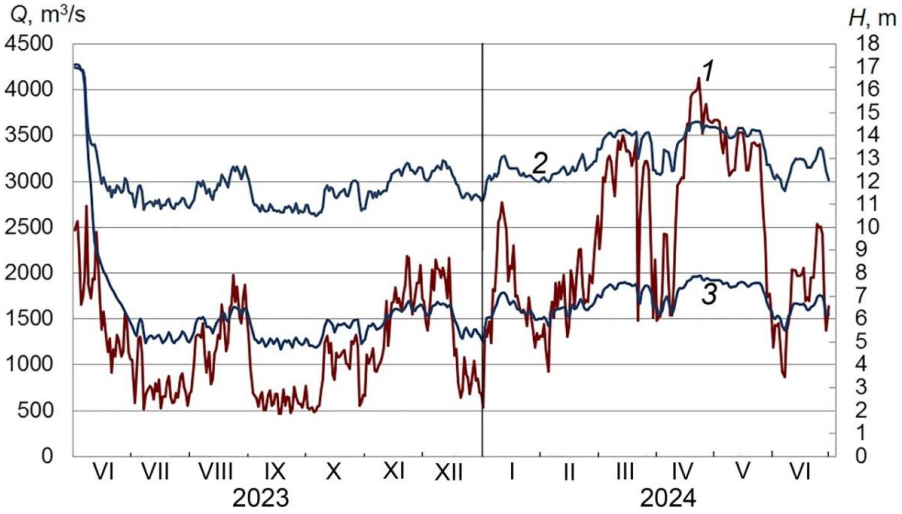
The water level at Rozumivka station before the accident was 16.87 m a.s.l. After that, the water level also started to decrease. On June 6, 2023, at 8:00, it dropped to 16.51 m a.s.l. On the following days at the same time, the water level was as follows: 07.06.2023 – 15.12 m a.s.l; 08.06.2023 – 14.14 m a.s.l.; 09.06.2023 – 13.68 m a.s.l.; 10.06.2024 – 13.60 m a.s.l.; 11.06.2024 – 13.61 m a.s.l. After that, the measurements at the station were interrupted. They were renewed on July 21, 2023.

The complete empting of the reservoir finished at the end of July. The lowest level at Rozumivka station (10.8 m a.s.l.) was registered on July 23, 2023. At that time, the Nikopol station was not working.

According to the satellite images taken by Sentinel 2 satellite, the lowest water level in the main part of the reservoir was registered on 25 July, 2023 and on 30 July, 2023. In those days, the smallest width of main river branch near the village of Bilenke was only 662 m. The smallest width of the main river branch near Nikopol town (322 m) was observed on July 30, 2023.

In the following period, the water level in the area of the former reservoir began to depend mainly on the water discharge at Dnipro HPP located upstream. The small water discharge was observed in September, when its mean value was 626 m^3/s. After that, as a result of rains in the upper reaches of the river, the discharges increased. In October, it was 902 m^3/s, in November – 1,530 m^3/s, in December – 1,360 m^3/s. The highest water level at Rozumivka station (12.91 m a.s.l.) in the second half of 2023 was registered on December 11, 2023. These measured data are shown in Fig. 6. Besides, in this figure is presented calculated level at Nikopol station according to the dependence between discharges and water level in natural conditions.

Fig. 6: The discharges at the Dnipro HPP (*1*) during period from June 1, 2023 till June 30, 2024 and the water level at Rozumivka (*2*) and Nikopol (*3*) stations for the same period



The significant spring flood in form of two waves on the Dnipro River was observed in 2024. The maximum discharge of the first wave (3,500 m^3/s) at Dnipro HPP was registered on March 15, 2024; the peak of the second wave with maximum discharge 4,130 m^3/s was registered on April 23, 2024. At this time, the increase of water level was observed in the area of the former reservoir. The highest water level (14.62 m a.s.l.) at Rozumivka station was observed on April 21 and on April 23, 2024.

The available satellite images show that in the spring of 2024, more than two thirds of the former reservoir area was covered by water. This can be seen on the satellite images taken on April 30, 2024. At that time, the water level at Rozumivka station was 14.35 m a.s.l. (Fig. 7).

The water level a few days earlier than on April 21 and on April 23, 2024 was higher – 14.62 m a.s.l. This means, that maximum inundation in the spring time of 2024 was larger, than it is shown in Fig. 7.

It is obvious that in case of larger discharge, which can reach 7,000–8,000 m^3/s the studied area can be heavily flooded. As noted, this factor limited the use of this area for human needs in the past. The same applies to modern times.

In general, the water runoff of the Dnipro River during the first year after the accident, from June 1, 2023 to May 31, 2024 was larger, than usual. The mean water runoff at Dnipro HPP was 1,730 m^3/s (54.6 km^3). Similar water runoff was during period from June 1, 2023 to June 30, 2024. Such conditions can impact on the overgrowth of the reservoir.

During the period after the destruction of the HPP, the area of the former reservoir was gradually overgrown. This process was monitored using Sentinel 2 satellites images (Fig. 8).

As can be seen on the available satellite images, the overgrowth of the former reservoir began in the second half of July or at the beginning of August of 2023, in fact very soon after its empting. The significant increase in area of green leaves was observed after August 8, 2023 and lasted about two months. The process of overgrowth resumed in March of 2024. As noted in the Introduction, the dominant type of vegetation in the area of the former reservoir is willow.

Fig. 7: Satellite image of Sentinel 2 satellite taken on April 30, 2024, which shows the flooding area on the territory of the former Kakhovske reservoir during the spring flood

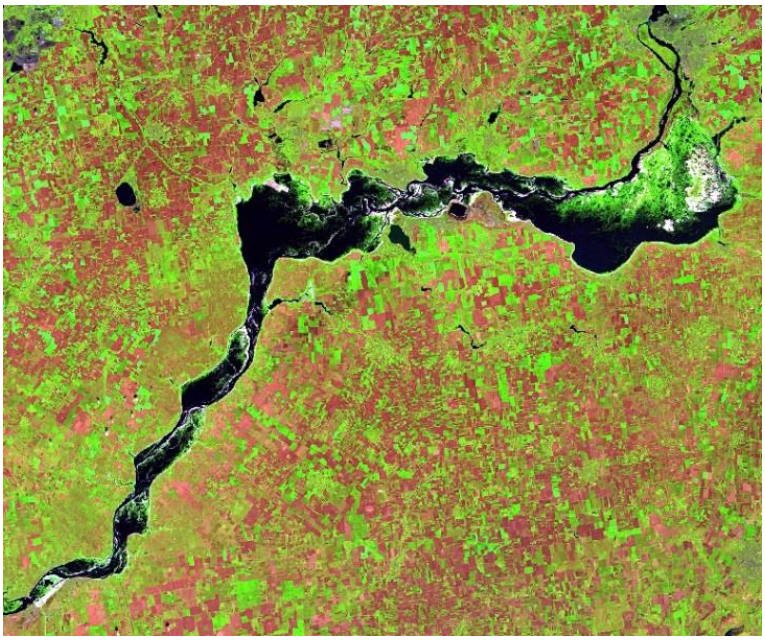
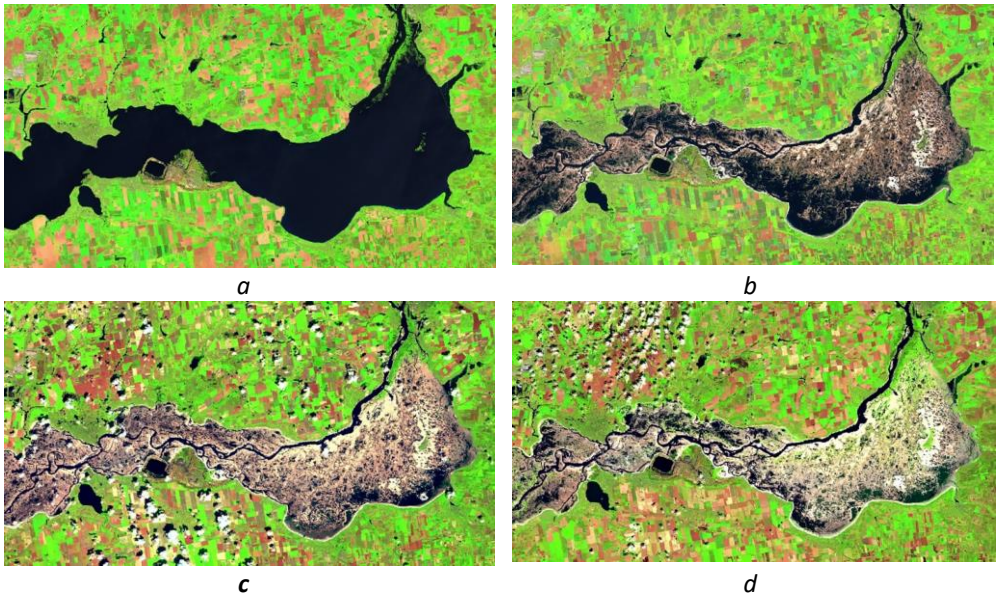
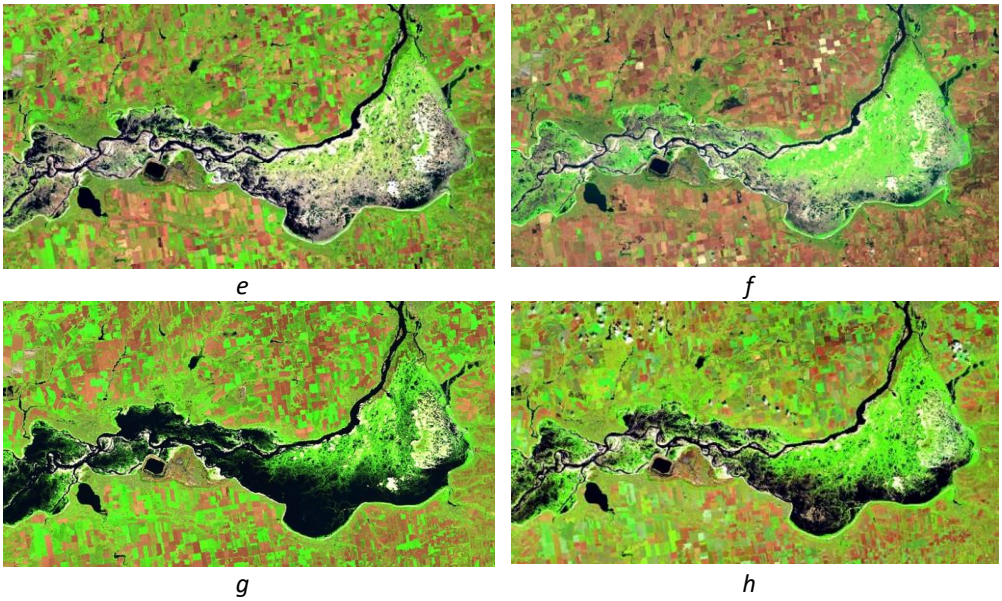


Fig. 8: The state of the wide part of the former Kakhovske reservoir on the different dates: *a* – 05.06.2023, *b* – 20.06.2023, *c* – 15.07.2023, *d* – 09.08.2023, *e* – 19.08.2023, *f* – 03.10.2023, *g* – 05.05.2024, *h* – 09.06.2024



a *b*

c *d*



e *f*

g *h*

In addition to the area covered with plants, on the satellite images can be seen sandbars along the main branches of the river. Similar sandy deposits can be seen around the former islands in the northeastern part of the former reservoir.

The shore near the village of Malokaterinivka has a stone protection. The adjacent strip of shore is covered with sandy deposits. Alongside, a strip of reed (*Phragmites australisis*) is located, and finally, a large area of the former reservoir is covered with willow, more precisely a hybrid of *Salix alba* and *Salix fragilis* (Fig. 9).

Fig. 9: The overall view of the former Kakhovske reservoir near the village of Malokaterynivka, 21.06.2024

The height of the willow trees were measured using a 3 m long leveling rod. Taking into account the age of the trees (about a year), the mean height of the trees turned out to be enormous – about 4.5 m. The diameter of the trees at a height of 1.5 m was about 25 mm. The quantity of willows reached 30–40 per 1 m^2 (Fig. 10).

Fig. 10: The typical size of willow trees near the village of Malokaterynivka, 21.06.2024

In addition to willow, narrow-leaved ryegrass (*Typha angustifolia*) was observed in the studied area.

The size of the willows on the opposite right bank of the former reservoir on June 21, 2024 was much smaller. The average height of the trees was 2.7 m, the mean diameter at a height of 1.5 m was 13 mm. Poplar trees (*Populus nigra)* were also found in this area (Fig. 11).

Such differences of typical size of trees can be explained by differences in bottom sediments. The trees near the village of Bilenke began to grow on sandy sediments which were well washed by the river flow before the emptying of the reservoir.

Another factor that could affect the rate of overgrowth of the reservoir was the air and water temperature. As noted, the air temperature after the accident was warm, actually warmer than usual. It can be added that the water temperature near the village of Bilenke was colder than in the main area of the former reservoir.

Fig. 11: The typical size of willow trees near the village of Bilenke, 21.06.2024

DISCUSSION

The obtained results have shown that the empting of the Kakhovske reservoir lasted almost two months from June 6, 2023 till the end of July 2023. During this period, the water level at Rozumivka station decreased from 16.87 m a.s.l. up to 10.8 m a.s.l. or about 6 m. The water level at Nikopol station decreased from 16.76 m a.s.l. up to about 5 m a.s.l. or almost 12 m. After this stage (practically simultaneously with it), the overgrowth of the territory of the former reservoir began.

Sufficient soil moisture and warm weather were favorable conditions for flora, primarily for willow. Its average height in the area covered with organic sediments reached 4.5 m by June 21, 2024. Based on these data, it can be calculated the daily growth of trees. If the growing season starts on July 21, 2023, we have a period of 11 months. Period of winter dormancy lasted for about three and a half months. This means that the average daily growth was about 2.0 cm. The daily growth of willow on sandy deposits was about 1.2 cm. In general, these results are similar to those ones obtained in the study (Kuzemko, *et al*., 2024).

Our results are similar also to those ones described in the articles (Maděra & Kovářová, 2004; Maděra *et al*., 2009) which were carried out in Czech Republic. The water level lowering in the Kakhovske reservoir started on June 6 or about one month earlier than in the reservoir in Czech Republic. It is obvious that the flowering of trees and the ripening of seeds near the Kakhovske reservoir due to the warm climate was observed much earlier than in the case described in the papers (Maděra & Kovářová, 2004; Maděra *et al*., 2009).

We predict that the daily growth of trees will decrease in near future, in particular due to the soil moisture decrease. As noted, the water discharge of the Dnipro River in the first year after the accident was larger than usual. With average or less than average water discharge, it will be observed significant soil moisture decrease. Without sufficient light, moisture, space

and nutrition, many willows will die. After all, several dozen adult trees cannot grow on one square meter.

Nowadays, thanks to the presence of 5 reservoirs upstream, the fluctuations of water level and water discharges in the studied area became smaller than they were under natural conditions. This means that the height and duration of floods in the studied area will be less than it was before the creation of the Kakhovske reservoir. In turn, this means that conditions for the trees in spring will be better than in the past before the creation of the Kakhovske reservoir.

Another factor, which can affect the studied area, is climate change. Now the climate in the south of Ukraine is warmer and drier, than it was in the past. This means negative impact on the trees, primarily on willow. In our opinion, the share of poplar on the area of the former reservoir will gradually increase. The ongoing year 2024 also turned out to be warmer than in recent decades.

In any case, in a few years the height of the forest on the bottom of the former reservoir will exceed 10 m.

At the same time, as a result of the water level decrease, the strip of trees which is growing now on the shore of the former Kakhovske reservoir occurred with the lack of water. We predict that part of these trees in the nearest future will die. The same fate is possible as to the hydrophyte vegetation (common reed, cattail) located near the previous water's edge.

Some effect on the studied area has the war activity. Now, the former reservoir is the border between the Ukrainian and the Russian troops. Therefore, the shelling and the wildfires are possible on this area. In fact, the wildfires near and even inside the former Kakhovske reservoir started. These wildfires can be seen using Fire Information for Resource Management System (Fig. 12).

Fig. 12: The wildfires in the upper part of the former Kakhovske reservoir according to data of FIRMS: *a* – on July 27, 2024, *b* – on August 19, 2024

a *b*

In particular, long-term wildfires in the area shown in Fig. 12, lasted from July 9 to July 14, 2024, from July 26 to July 30, 2024, from August 16 to August 21, 2024. In fact, such wildfires were observed in other part of the dried shore of the former reservoir.

Taking into account the climate change, we predict that wildfires will be commonplace in this area in the future.

CONCLUSIONS

The destruction of the Kakhovka dam, which occurred on June 6, 2023, became a unique case in the history of mankind. As a result of the accident, the largest reservoir on the Dnipro River was emptied. In a few weeks, it turned into a network of river branches and lakes.

Simultaneously with the emptying of the reservoir, the process of its overgrowth began. Willow, which occupied the largest area, became the dominant species. The favorable conditions in the first year after the accident caused the abnormal growth rate. This rate depends on soil sediments. In area which is rich in organic sediments, the mean height of trees till June 21, 2024 reached 4.5 m. The size of trees and the growth rate on organic-poor sandy sediments are much less. The warm weather also had a certain impact on the growth of trees. In general, nowadays a large area of the former reservoir looks like a dense forest.

We predict that in future, when the moisture of bottom sediments will decrease, the growth rate also will decrease. The majority of trees will die mainly due to intraspecific competition for light and feeding. At the same time, the ratio between the main species of trees will be changed: the share of willow will decrease while the share of poplar will simultaneously increase. Finally, the conditions in the area of the former reservoir will approach those observed before the creation of the reservoir.

At the same time, the riparian vegetation located near the previous water's edge will be depressed; some of them also will die. The wildfires in the studied region have started and their frequency will increase in future. To some extent, these forest fires will depend on climate change, in particular, on air temperature increase. Currently, these forest fires are observed due to the ongoing Russia-Ukraine war.

In general, the destruction of the Kakhovka HPP significantly affected many spheres of Ukraine: economic, social, and natural. Do to the emptying of the reservoir it was became impossible irrigation on the very large territory. The industrial and drinking water consumption occurred restricted. At the same time, the market value of the area on the former reservoir is law. The use of this area was in the past and nowadays is restricted due to flooding. That is why, according to the authors, the Kakhovske reservoir after the war should be restored.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

REFERENCES

Dyachenko, T.M., Zub, L.M., Tomchenko, O.V. (2022). Plant cover transformation in the shallow water habitats of the cooling pond of the Chernobyl NPP as a result of its descent *Hydrobiological Journal*. Vol. 57, Issue 6, 3–16. DOI: 10.1615/HydrobJ.v57.i6.10

Dovhanenko, D.O., Yakovenko, V.M., Brygadyrenko, V.V., & Boyko, O.O. (2024). Characteristic of the dried-up zone formed as a result of the breach of the Kahovka dam. *Biosystems Diversity*. 32(2), 285–295. doi: 10.15421/012431.

Gleick, P., Vyshnevskyi, V., & Shevchuk, S. (2023). Rivers and water systems as weapons and casualties of the Russia-Ukraine war. *Earth's Future*, 11. 10. P. 1–13. https://doi.org/10.1029/2023EF003910

Harada, K.H., Soleman, S.R., Ang, J.S.M., & Trzcinski, A.P. (2022). Conflict-related environmental damages on health: Lessons learned from the past wars and ongoing Russian invasion of Ukraine. *Environmental Health and Preventive Medicine*, 27. https://doi.org/10.1265/ehpm.22-00122

Kuzemko, A., Prylutskyi, O., Kolomytsev, G., Didukh, Y., Moysiyenko, I., Borsukevych, L., Chusova, O., Splodytel, A., Khodosovtsev, O. (2024). Reach the bottom: plant cover of the former Kakhovka Reservoir, Ukraine. *Research Square*. https://doi.org/10.21203/rs.3.rs-4137799/v1

Maděra, P., Kovářová, P., (2004). Primary succession of white willow communities in the supraregional biocorridor in the Middle water reservoir of Nové Mlýny. *Ekológia* (Bratislava), Vol. 23, Supplement 1/2004: 191–204.

Maděra, P., Svobodová, I., Packová, P. (2009). Oecesis of White Willow Communities in the nature reserve Věstonická nádrž reservoir. *Ekológia* (Bratislava), Vol. 28. N. 1. 7–21. DOI: 10.4149/neo_2009_01_7

Magas, N., Khorenzhenko, H., Zamuruieva, K., Beshevets, Yu., Ryndiuk, S., Barkar V., Zamrii, M., Bondar, M. (2023). Analysis of the hydrological situation in the Dnipro-Bug estuary region following the destruction of the Kakhovka hydroelectric power station dam. *Ecological science.* 4 (49). 15–25 (in Ukrainian). doi.org/10.32846/2306-9716/ 2023.eco.4-49.2

Nepsha, O., Hryshko, S., Prokhorova, L., Zavialova, T., Lysenko, V. (2024). Environmental consequences of the explosion of the Kahovsky hydroelectric plant on biodiversity. *Revista de la Universidad del Zulia*. Vol. 15, N 42. P. 163–178. DOI: https://doi.org/ 10.46925//rdluz.42.09

Novitskyi, R., Hapich, H., Maksymenko, M., Kovalenko, V. (2024). Loss of fisheries from destruction of the Kakhovka reservoir. *International Journal of Environmental Studies.* https://doi.org/10.1080/00207233.2024.231489

Pichura, V., Potravka L., Dudiak N., Bahinskyi, O. (2024). Natural and climatic transformation of the Kakhovka reservoir after the destruction of the dam. *Journal of Ecological Engineering*, 25(7), 82–104. https://doi.org/10.12911/22998993/187961

Rawtani, D., Gupta, G., Khatri, N., Rao, P.K., & Hussain, C.M. (2022). Environmental damages due to war in Ukraine: A perspective. *Science of the total environment*, 850, 157932. https://doi.org/10.1016/j.scitotenv.2022.157932

Spears, B.M., Harpham, Q., Brown, E. *et al.* (2024). A rapid environmental risk assessment of the Kakhovka Dam breach during the Ukraine conflict. *Nat Ecol Evol.* 8, 834–836. https://doi.org/10.1038/s41559-024-02373-0.

Starodubtsev, V., Ladyka, M. (2023). Destruction of the Kakhovskaya hydroelectric power plant: the second aspect of the ecological catastrophe. *Proceedings of the XXV International Scientific and Practical Conference: Theoretical foundations of scientists and modern opinions regarding the implementation of modern trends*. San Francisco, June 27–30, 2023. DOI:10.46299/ISG.2023.1.25

Vyshnevskyi, V.I. (2011). The Dnipro River. Interpress Ltd. (in Ukrainian). https://er.nau.edu.ua/handle/NAU/40098

Vyshnevsky, V.I. (2020). Hydrological and hydrochemical regime of the Dnieper reservoirs. *Hydrobiological Journal*, 56, 4, 103–120 DOI: 10.1615/HydrobJ.v56.i4.80.

Vyshnevskyi, V.I., Kutsiy, A.V. (2022). Long-term changes in the water regime of rivers in Ukraine. Kyiv: *Naukova dumka* (in Ukrainian). https://er.nau.edu.ua/handle/NAU/56293

Vyshnevskyi V., Shevchuk S. (2021). Thermal regime of the Dnipro Reservoirs. *J. Hydrol. Hydromech*., 69, 3, 300–310. https://doi.org/10.2478/johh-2021-0016

Vyshnevskyi, V., & Shevchuk, S. (2024). The impact of the Kakhovka dam destruction on water temperature in the lower reaches of the Dnipro River and the former Kakhovske reservoir. *Journal of Landscape Ecology*. 2024, Vol. 17. No. 2. 1–17. 1805-4196. DOI: 10.2478/jlecol-2024-0008.

Vyshnevskyi, V., & Shevchuk, S. (2024). The destruction of the Kakhovka dam and the future of the Kakhovske reservoir. *International Journal of Environmental Studies*. Vol. 81. No 1. P. 275-288. doi.org/10.1080/00207233.2024.2320033

Vyshnevskyi, V., Shevchuk, S., Komorin, V., Oleynik, Yu,, Gleick, P. (2023). The destruction of the Kakhovka dam and its consequences. *Water Inernational*, Vol. 48, Issue 4. P. 1–17. https://doi.org/10.1080/02508060.2023.2247679

Zhezherya, V.A., Zhezherya, T.P., Linnik, P.M. (2022). Nutrients in the water of the reservoirs of the Dnieper Cascade after the Dnieper River regulation. *Hydrobiological Journal*. Vol. 58, Issue 22, 79–97. DOI: 10.1615/HydrobJ.v58.i2.70