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THE IMPACT OF THE KAKHOVKA DAM DESTRUCTION ON THE WATER TEMPERATURE IN THE LOWER REACHES OF THE DNIPRO RIVER AND THE FORMER KAKHOVSKE RESERVOIR

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ABSTRACT

The results of the studies devoted to the consequences of the Kakhovka dam destruction and the empting of the Kakhovske reservoir are presented. The water regime of the lower reaches of the Dnipro River was studied, in particular, the water temperature. The remote sensing data on spatial features of water temperature are given. Significant changes in water temperature are shown both in the lower reaches of the Dnipro River and in the former Kakhovske reservoir. In the first days after the destruction of the dam, due to the mixing, the surface water temperature at the mouth of the Dnipro River dropped significantly. Then the water temperature in the lower reaches of the river approached to that one observed before the destruction. In turn, the former Kakhovske reservoir became a network of river branches and lakes that cannot be compared with the former reservoir. The Dniprovske Reservoir, located upstream, affects the water temperature of this territory, especially the largest branch.

Keywords: the Dnipro River, Kakhovka dam, destruction, Kakhovske reservoir, water temperature

INTRODUCTION

There are many scientific works devoted to the thermal regime of water bodies and, in particular, large rivers and their deltas. In general, mean annual water temperature exceeds air temperature. Thus, according to the studies (Vyshnevskyi & Shevchuk, 2023) the mean annual water temperature in the lower reaches of the Danube River at Izmail station is 14.0 °C and the air temperature is 11.7 °C. At some extent this feature depends on the direction of the river flow in its Romanian section from south to north. At the same time, air temperature in spring, mainly in April and May, can be higher than water temperature (Bonacci *et al.*, 2022; Ptak *et al.*, 2022; Vyshnevskyi & Shevchuk, 2023).

It is common knowledge that as a result of climate change, the water temperature is rising (IPCC, 2022; Hannah & Garner, 2015; Graf & Wrzesiński, 2020; Ptak *et al.*, 2020; Ptak *et al.*, 2022; Vyshnevskyi & Kutsiy, 2022; Vyshnevskyi & Shevchuk, 2021; Vyshnevskyi & Shevchuk, 2023; Wiejaczka *et al.*, 2018; Woolway *et al.*, 2017). Thus, the water temperature in the reservoirs on the Dnipro River during 1977–2020 increased in summer period by

0.74 °C dec^{-1}, and during May–October − by 0.65 °C dec^{-1} (Vyshnevskyi & Shevchuk, 2021). An increase of water temperature is also predicted for the future (Hannah & Garner, 2015; Pekarova *et al*., 2023).

Another direction of many studies is the impact of human activity on water temperature. In particular, this concerns the impact of reservoirs on their downstream sections (Long *et al*., 2019; Tao *et al*., 2019; Vyshnevskyi & Shevchuk, 2021; Wiejaczka *et al*., 2018). These studies show the delay of water warming in spring and summer downstream of the dams. As a rule, a significant excess of air temperature over water temperature is observed in the period from April to June. On the other hand, the largest excess of water temperature over air temperature is registered from October to December.

There are many studies of water temperature which are based on remote sensing data (Barsi *et al*., 2014; Dyba *et al*., 2022; Graf & Vyshnevskyi, 2023; Sharaf *et al*., 2019; Vyshnevskyi & Shevchuk, 2021; Vyshnevskyi & Shevchuk, 2023). The obtained results give a good idea of the spatial features of surface water temperature. Simultaneously, these results show a good correlation between measured and calculated data.

The water temperature impacts on fish reproduction. Thus, the start of spawning of silver Prussian carp (*carassius gibelio*), which is one of the most popular in the Dnipro River, is observed when the water temperature reaches 13.5 °C (Bondarev *et al*., 2019). Since the water temperature downstream the reservoirs became lower than in natural conditions, the spawning occurs quite late.

A separate area of research is the war impact on the water bodies. Until recently, such studies focused mainly on the incidents outside of Europe (Al-doski *et al*., 2013; Garzón & Valánszki, 2020; Gleick & Shimabuku, 2023). But the ongoing Russia′s aggression against Ukraine has affected many water objects: some were polluted, some were destroyed. The information about the environmental consequences of this war have been described in recently published research papers (Harada *et al*., 2022; Magas *et al*., 2023; Rawtani *et al*., 2022; Gleick et al., 2023; Shevchuk et al., 2022; Starodubtsev and Ladyka, 2023; Vyshnevskyi *et al*., 2023; Vyshnevskyi & Shevchuk, 2024) and media.

The most dramatic incident with water bodies during the Russia-Ukraine war was the destruction of the Kakhovka dam and the emptying of the Kakhovske reservoir. It was the largest hydrotechnical object destroyed in the whole history of mankind. This accident had the great impact on social, economic and environmental spheres of Ukraine. As a result of the explosion a large area downstream of the dam was flooded. Many people died or went missing. At the same time, the conditions that have been observed for many decades have changed significantly (Vyshnevskyi *et al*., 2023). Thus, the main goal of this study is to find out the impact of the Kakhovka dam destruction on the lower reaches of the Dnipro River, in particular, on the water temperature in it.

MATERIALS AND METHODS

Study objects

The Dnipro River is one of the largest in Europe, its length is about 2,200 km, a catchment area is 504,000 km^2, and the mean natural (unimpacted by human activity) water runoff at the mouth is 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 1290 m^3/s or 40.7 km^3 per year (Vyshnevskyi & Kutsiy, 2022).

In total, 6 reservoirs were created on the Dnipro River. The Kakhovske reservoir, which is the last in the cascade, was created in the 1950s. By its volume this reservoir was the largest in the cascade. With a normal retention level of 16.0 m a.s.l., the project area of the reservoir was 2155 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. The total length of the dam was 3.2 km, the maximum height was 29 m (Vyshnevskyi, 2011).

Upstream the Kakhovske reservoir is the small, but very deep Dniprovske reservoir, created near the city of Zaporizhzhia. With a normal retention level of 51.4 m a.s.l. its project volume is 3.2 km^3. The maximum depth of this reservoir reaches 62 m (Vyshnevskyi, 2011).

Materials

The military actions in the studied region led to the fact that the most important source of information in this study was remote sensing data. The greatest attention was paid to images of Landsat 8 and Landsat 9 satellites. The available images of Collection 2 Level 2 were downloaded from the site of US Geological Service https://earthexplorer.usgs.gov. The time of survey of the lower reaches of the Dnipro River is around 8:37 GMT, that is almost corresponds to noon of local time. The survey time of the Kakhovske reservoir is similar – 8:31. The spatial resolution of B10 thermal band of satellites is 100 m, the revisit time is 16 days.

The second source of data was the data observation at meteorological and hydrological stations. Air temperature data were used at Nova Kakhovka and Kherson meteorological stations located nearby the Kakhovske reservoir and the Dnipro River. Hydrological station in Nikopol city is located on the northern shore of the Kakhovske reservoir. In turn, the Nova Kakhovka hydrological station is located upstream from the dam near it. Finally, Kherson hydrological station is located at distance of 65 km downstream of the Kakhovka dam and simultaneously 28 km upstream of the Dnipro River mouth (Fig. 1).

Fig. 1: Location of the former Kakhovske reservoir (1), Kakhovka dam (2), the lower reaches of the Dnipro River (3), Nova Kakhovka (4) and Kherson (5) meteorological stations, Nikopol (6), Nova Kakhovka (7) and Kherson (8) hydrological stations

Methods

The main source of information for this study was remote sensing data. In total, about 20 satellite images of Landsat satellites were downloaded. They were processed using ArcMap 10 program. Surface water temperature was determined using the dependence (("ST_B10" * 0.00341802) + 149.0)-273, which is recommended by the US Geological Service.

The territory, which does not belong to water area, was identified using 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 satellites bands. The territory, which is not a water area, was presented in grey color for better visualization. Some small areas covered by clouds (if such cases occurred) were presented in white.

In addition, observation data at meteorological and hydrological stations were processed. The analysis was carried out for the period of 1991–2020 and up to the moment of the accident with the destruction of the Kakhovka dam.

The features of the lower reaches of the Dnipro River channel were analyzed using the navigation maps.

RESULTS

The water temperature in the Kakhovske reservoir and downstream before the explosion

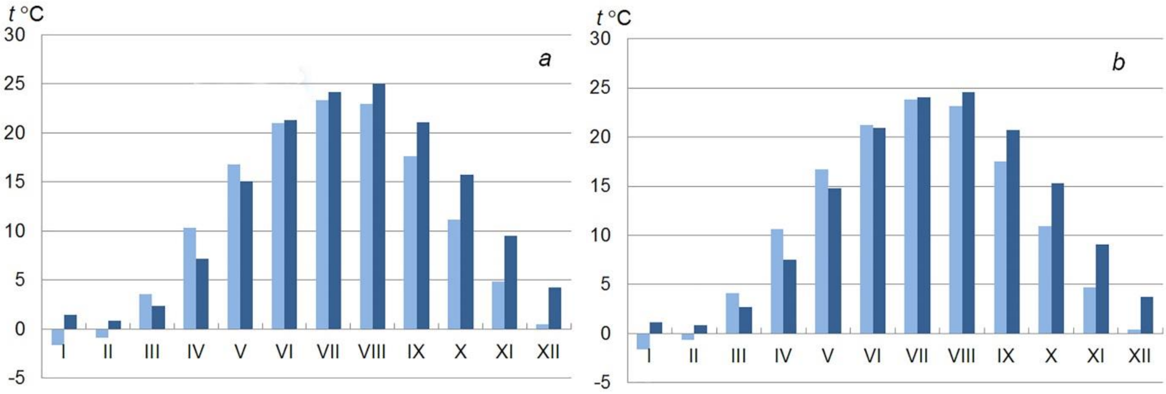
The location of the studied area in the south of Europe results in a fairly high air and water temperature. In general, the highest water temperature is observed in August. The mean water temperature of this month at Nova Kakhovka for the years 1991–2020 was 24.9 °C and at Kherson station it was 24.6 °C.

As can be seen, the water temperature at Kherson station is somewhat lower than at Nova Kakhovka station. The main cause of this feature is the impact of the Kakhovske reservoir located upstream Kherson station. It is important that water is discharged from the bottom layer of the reservoir.

The most obvious features of this impact are observed in spring and in autumn. In April, when the air temperature increases significantly, the mean air temperature at Kherson station in 1991–2020 was 10.6 °C and the water temperature was 7.5 °C respectively. The largest differences between air and water temperature was observed in October. The mean air temperature at this month during 1991–2020 was 10.9 °C and the mean water temperature was 15.3 °C.

The water temperature at Nova Kakhovka station depended on the large volume of former Kakhovske reservoir which heating and cooling was very slow. The water temperature at this station also depended on the reservoirs located upstream. As noted, upstream the Kakhovske reservoir exists the very deep Dniprovske one. Besides, there are four more reservoirs. As a result, the water temperature in the Kakhovske reservoir in spring was much colder than air temperature. Another peculiarity was observed in autumn, when the water temperature was much warmer, than air temperature. The mean air temperature at Nova Kakhovka station in October during 1991–2020 was 11.4 °C and the mean water temperature was 15.7 °C (Fig. 2).

Fig. 2: Mean monthly air temperature (left columns) and mean monthly water temperature (right columns) during 1991–2020 at Nova Kakovka (a) and Kherson (b)



Similar to many other rivers and lakes, the water temperature at both stations had the tendency to increasing. The increase of mean water temperature for the May–October during 1981–2020 at Nova Kakhovka was 0.58 °C dec^{-1} and at Kherson station it was 0.59 °C dec^{-1}.

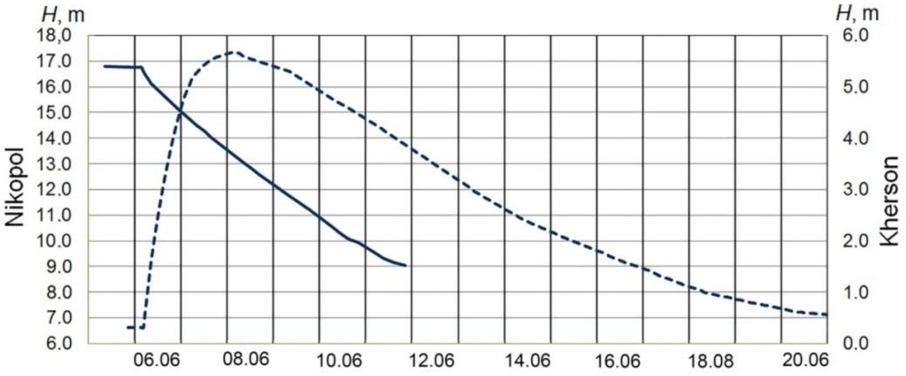
The large area of the former Kakhovske reservoir and the great differences in its depth caused the spatial features of the water temperature. In summer period, the water temperature in the northeastern shallow part of the reservoir was higher, than in deep southwestern part. In autumn and winter, the highest water temperature was observed in deep southwestern part.

The wind also had a certain influence on the thermal regime of the Kakhovske reservoir. The largest impact was observed in May and June, when the difference in surface and bottom temperature was the largest (Vyshnevskyi & Shevchuk, 2021).

The changes of water level after explosion

On the day of the explosion, on June 6, 2023 the Kakhovka HPP was under the control of the Russian troops. The water level at Nikopol station before the explosion was 16.76 m a.s.l. The total volume of reservoir at this level was 19.8 km^3.

Fig. 3: The changes of water level at Kherson (dotted line) and Nikopol (solid line) hydrological stations between June 05–20, 2023

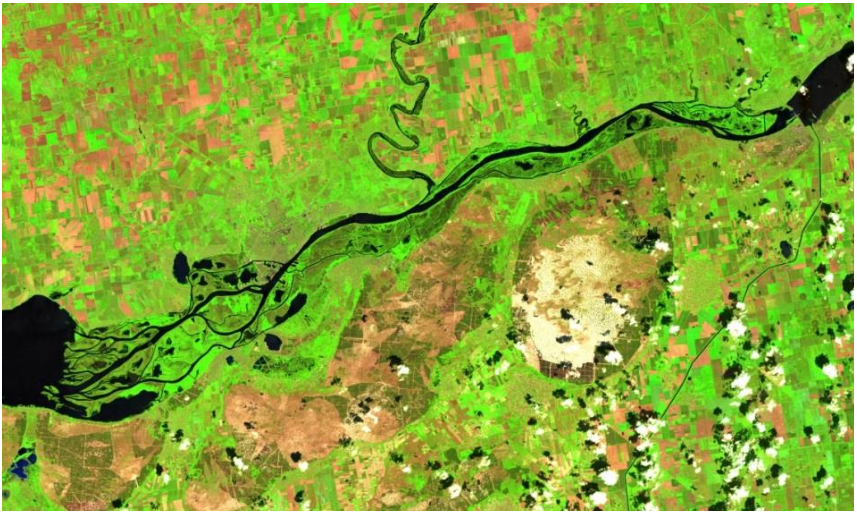


The water level at Kherson station began to rise on June 6, 2023 at 4:20 am, or about one hour and a half after explosion (Magas *et al.*, 2023). On the first day, the increase in the water level reached 20 cm per hour. The highest water level was observed on June 8, 2023 at 3 am. The total rise of water level, which lasted about two days, reached 5.37 m (Vyshnevskyi *et al.*, 2023) (Fig. 3).

Soon after explosion, the large territory along the both banks of the Dnipro River downstream the Kakhovka dam was flooded. Four cities and more than dozen villages were flooded (Fig. 4).

Fig. 4: The satellite images of the lower reaches of the Dnipro River taken by Landsat 8 satellite: a – on June 01, 2023, b – on June 09, 2023

(a)



(b)

As can be seen in Fig. 4, the increase of water level was observed not only in the lower reaches of the Dnipro River, but also on its right tributary, the Inhulets River. The increase of water level reached there several meters. Many consequences of this accident, including the pollution of water, are described in papers (Gleick *et al*., 2023; Vyshnevskyi *et al*., 2023; Vyshnevskyi & Shevchuk, 2024).

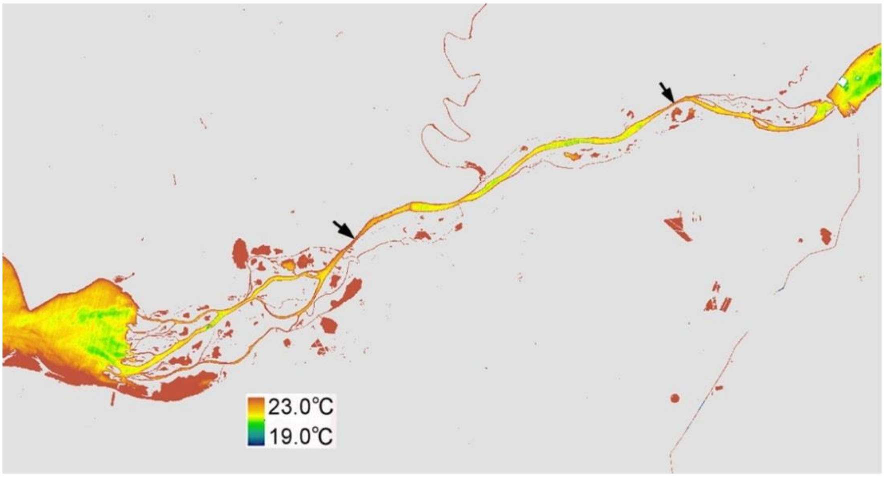
Soon after explosion, the water level in the Kakhovske reservoir began to decrease. By June 11, 2023, this decrease reached almost 9 m. Then the registration of the water level in the reservoir became impossible, partly due to the risk of war actions.

The features of water temperature in the lower reaches of the Dnipro River

The water temperature in the lower reaches of the Dnipro River before the destruction of the Kakhovka dam depended both on weather conditions and on the operation of the Kakhovka HPP located upstream. On June 1, 2023 the mean daily water temperature at Kherson hydrological station was 19.5 °C. Practically the same temperature (19.7 °C) was observed in the last day before the destruction of HPP on June 5, 2023. On the day of the accident, it was 19.4 °C. For several days, starting from June 7, 2023, the registration of water temperature was interrupted.

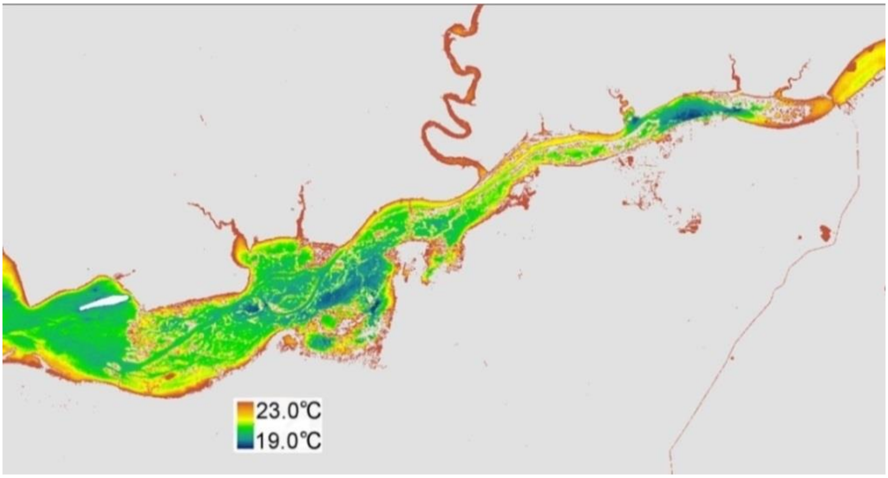
Under these circumstances, remote sensing data became the only source of data. The last satellite image before the accident was taken on June 1, 2023. According to it the water temperature in the lower reaches of the Dnipro River ranged from 19.0 °C to 23.0 °C. The highest surface water temperature was observed in the lakes located on the floodplain. Simultaneously, rather high water temperature was observed in the nearest places of the river, shown by arrows (Fig. 5).

Fig. 5: Surface water temperature in the lower reaches of the Dnipro River on 01.06.2023, according to Landsat 8 satellite data



The next satellite survey of the studied area was carried out during the day on June 9, 2023, or a little later after the highest water level at Kherson station. This time, despite warm weather, the water temperature in the Dnipro River was much cooler than in previous case. The impact of flow from the reservoir was observed even in the Dnipro-Buh lagoon, where the water temperature decreased as well. The highest water temperature was observed in the Inhulets River, where its movement slowed down significantly. High water temperature was also observed in some bays with small mixing (Fig. 6).

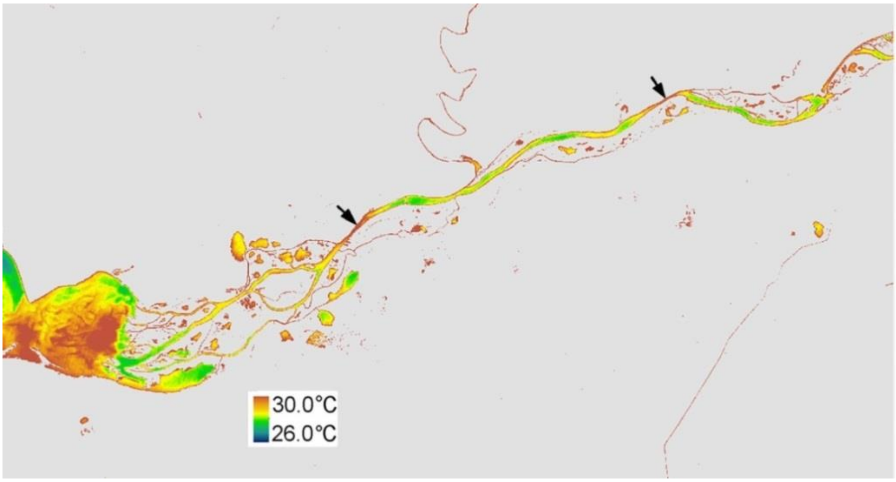
Fig. 6: Surface water temperature in the lower reaches of the Dnipro River on 09.06.2023, according to Landsat 9 satellite data



In a few months after the emptying of the Kakhovske reservoir the water temperature in the lower reaches of the Dnipro River began to depend mainly on the weather conditions. The difference between air and water temperature in spring and autumn became less, than before. Thus, the mean air and water temperature at Kherson station in October 2023 was 14.1 °C and 15.3 °C respectively. In turn, in April 2024 the mean air temperature was 15.1 °C and the mean water temperature was 13.8 °C.

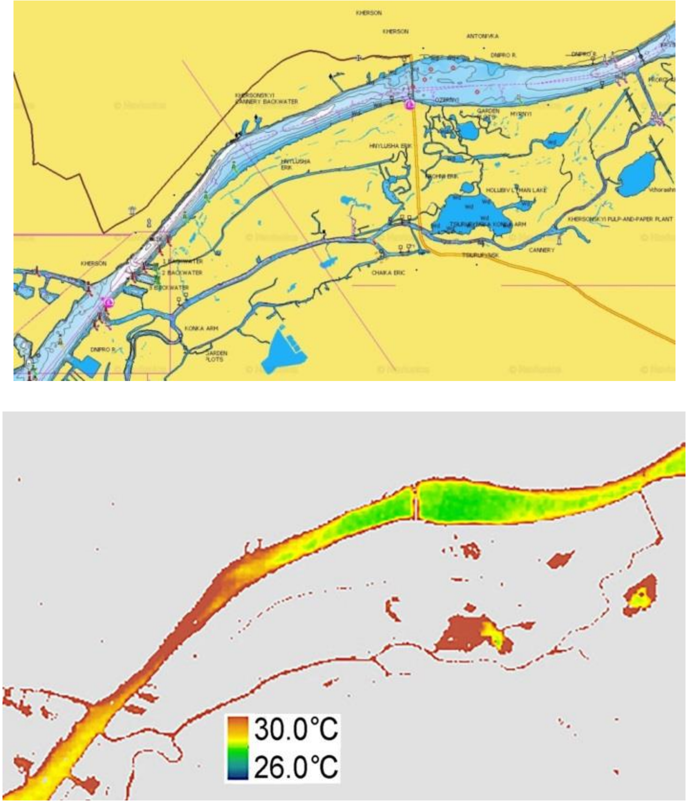
As it was before the accident, the high surface water temperature is observed in the nearest places. At the same time, the water temperature in the wide sections is lower than in the narrow ones (Fig. 7).

Fig. 7: Surface water temperature in the lower reaches of the Dnipro River on 20.08.2023, according to Landsat 8 satellite data



The observed feature can be explained by the different water mixing, which is due to the peculiarities of the river channel. The river depth in the two above mentioned narrow places with high temperature reaches 17–20 m. At the same time, the depth of the wide sections is only 6–7 m (Fig. 8).

Fig. 8: The fragment of navigation map of the Dnipro River near and upstream Kherson city (a) and the water temperature in this section on 20.08.2023 (b)



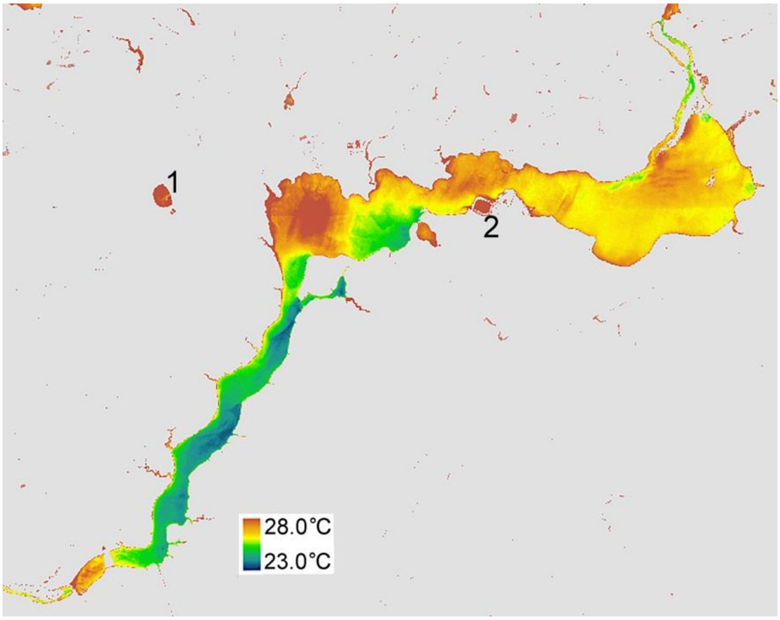
The same feature of surface water temperature, related to the peculiarities of the river channel, was revealed in a study devoted to the thermal regime of the lower reaches of the Danube River (Vyshnevskyi & Shevchuk, 2023).

It can be added, that the emptying of the reservoir led to the termination of the North-Krymian irrigation canal, which can be seen as a red line in the lower right part of Fig. 5, Fig. 6 and Fig. 7. Now this canal has practically run out of water.

The water temperature in the Kakhovske reservoir during its existence and after emptying

The thermal regime of the Kakhovske reservoir during its being was greatly dependent on seasons. As noted, the water temperature in spring and in June was rather low. It was caused by the impact of five reservoirs located upstream. Another important feature of the thermal regime of the former reservoir was related to the large difference in its depth, which was small in the wide northeastern part and significant in the southwestern part. As a result, quite often the water temperature in the shallow northeastern part of the reservoir in April–June was much higher than in the southwestern part. In autumn, when the air temperature was decreasing, the highest water temperature was observed in the southwestern part of the reservoir (Fig. 9).

Fig. 9: Surface water temperature of the Kakhovske reservoir on 15.06.2019, according to Landsat 8 satellite data: 1 – the cooling pond of Kryvyi Rih TPP, 2 – the cooling pond of Zaporizhzhia NPP



It can be added, that high (actually the highest) water temperature before the accident was observed in the cooling pond of Kryvyi Rih TPP and the cooling pond of Zaporizhzhia NPP located near the Kakhovske reservoir.

In the process of the emptying of the reservoir, its thermal regime greatly changed. The shallow northeastern part has partly disappeared, partly turned into the shallow basins and small river channels. At the same time, in the southwestern part of the reservoir, where some of water preserved, its temperature became lower than in the northeastern part (Fig. 10).

It can be added, that after the emptying of the Kakhovske reservoir, the operation of the Rryvyi Rih TPP and Zaporizhzhia NPP became practically impossible. First of all it concerns the Zaporizhzhia NPP which used the large volume of water for its cooling system. After the stop of operation of these enterprises, the water temperature in the both cooling ponds approached natural conditions.

After the disappearance of the Kakhovske reservoir it turned into the network of river channels and lakes. In summer conditions, water temperature in such water bodies with small water exchange is quite high. The coolest water is observed in the main river channel which is under impact of the Dniprovske reservoir located upstream (Fig. 11).

Fig. 10: Surface water temperature of the Kakhovske reservoir on 18.06.2023, according to Landsat 9 satellite data: 1 – the cooling pond of Kryvyi Rih TPP, 2 – the cooling pond of Zaporizhzhia NPP

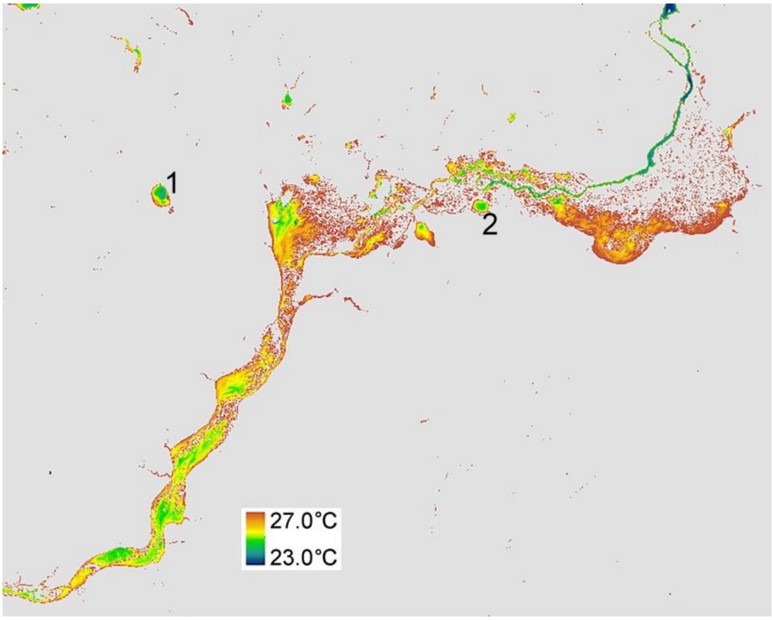
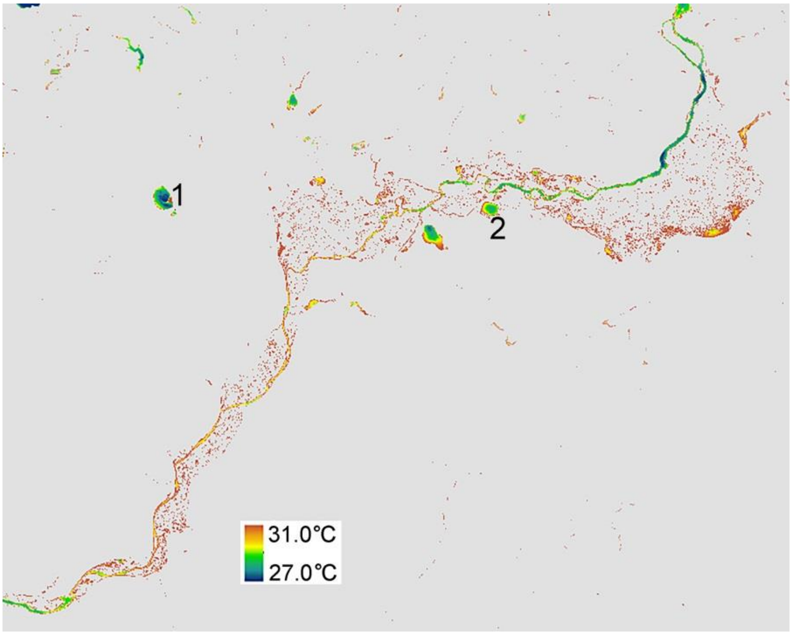


Fig. 11: Surface water temperature on the territory of the former Kakhovske reservoir on 05.08.2023, according to Landsat 9 satellite data: 1 – the cooling pond of Kryvyi Rih TPP, 2 – the cooling pond of Zaporizhzhia NPP



The analyses of old maps shows, that this main branch existed in natural conditions more than 70 years ago before the creation of the reservoir. Nowadays the water temperature in this branch greatly depends on the Dniprovske reservoir which is located upstream. During warm season the water temperature in this river branch is the coldest. This feature can be explained by the water discharge from the bottom layer of deep Dniprovske reservoir located upstream. The length of this section with cold water is about 100 km (Fig. 12).

Fig. 12: Surface water temperature in the wide part of the former Kakhovske reservoir on 05.08.2023, according to Landsat 9 satellite data

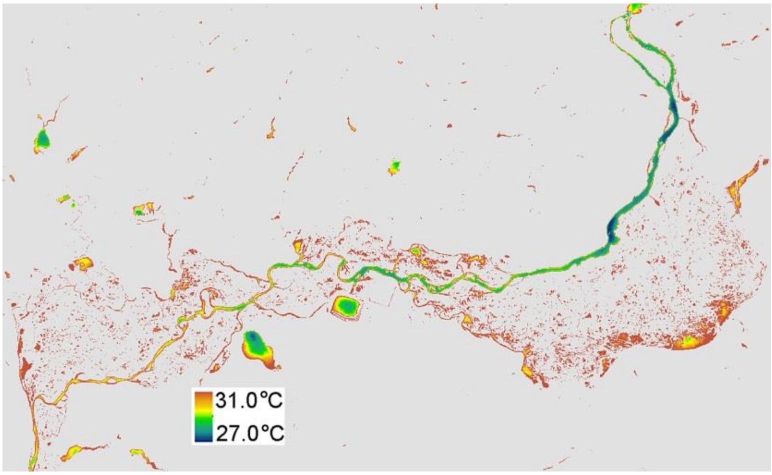
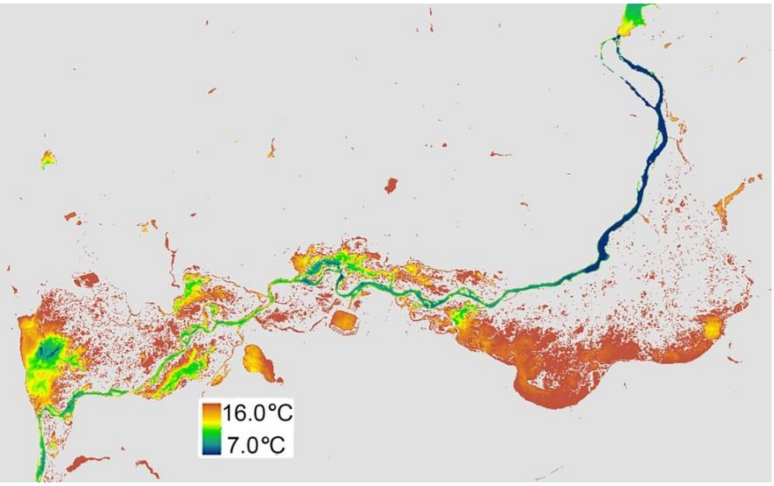


Fig. 13: Surface water temperature in the wide part of the former Kakhovske reservoir on 09.04.2024, according to Landsat 8 satellite data



The main river branch on the place of the former Kakhovske reservoir is much more visible in the spring period, when the water temperature in the bottom layer of deep Dniprovske reservoir remains cold. The length of section with cold water in this case reaches 150 km or even more. The difference in the water temperature of water discharged from the Dniprovske reservoir and the temperature in the neighboring water bodies can reach 10 °C (Fig. 13).

The comparison of Fig. 12 and Fig. 13 shows, that in the last case the quantity of water on the territory of the former reservoir is larger. This is caused by the spring flood.

DISCUSSION

The destruction of the Kakhovka dam had the significant impact on the national wealth of Ukraine. First of all, this accident destructed the Kakhovka HPP, which had the power about 335,000 KW of installed capacity and produced 1.4 billion kilowatt-hours of energy per year. As a result of the accident, the roads on the dam (both for cars and for trains) were also destructed. After the disappearance of the Kakhovske reservoir, the operation of the Zaporizhzhia NPP, which is the most powerful in Europe, became impossible. The total power of this station, on which 6 power units are installed, is 6 million kW. Moreover, after the accident, the operation of the Zaporizhzhia TPP, located near the Zaporizhzhia NPP, was stopped. The work of Kryvorizka TPP, which used water from the Kakhovske reservoir, was also interrupted. The total capacity of these power stations, except the Kakhovka HPP, is more than 8 million kW. Before the war, these stations produced a third of all electricity in Ukraine.

In addition to energy production, the Kakhovske reservoir was widely used for irrigation and water supply of some cities and dozens of villages. Before the accident, the area of irrigated land using the reservoir exceeded 300,000 hectares. Before the beginning of the Russian aggression in 2014, when the operation of the North Crimean Canal was stopped, the irrigated area exceeded 500,000 hectares.

For several decades the Kakhovske reservoir was the main source of water for many cities, such as Kryvyi Rih, Nikopol and some others. In addition, water was supplied to dozens of villages. Until 2014, the North Crimean Canal, which started from the reservoir, supplied some cities and many villages of Crimea.

After the destruction of the Kakhovka dam, the use of a very long section of the Dnipro River as a transport artery became impossible. Before the accident, the guaranteed depth on the shipping route was at least 3.65 m. Using this route, Ukraine exported many agricultural products, iron ore and many other goods.

According to (Novitskyi *et al*., 2024), the Kakhovske reservoir was an important source of freshwater fish in Ukraine. Annual losses of industrial catch are estimated at 2,585 tons worth up to 5.4 million dollars. Almost all spawning grounds and feeding areas have been destroyed.

In general, the destruction of the Kakhovka dam caused damages amounting to tens of billions of euros.

Nowadays the former Kakhovske reservoir is gradually overgrown with willow and poplar. These tree species are not great commercial value.

Now the study of the processes on the territory of the former Kakhovske reservoir is restricted as a result of war. Under these circumstances, the use of remote sensing is very useful. The correspondent data show that thermal regime of water bodies on the territory of the former reservoir, except main river channel, approached to the natural one. This especially applies to the section of the Dnipro River below the destroyed dam. It is possible to predict that downstream the destroyed dam the water temperature will increase in spring and will decrease in autumn. These changes can impact on other components of nature, in particular the fish. In our opinion, in the near future the spawning on the lower reaches of the Dnipro River will be observed earlier than before. In the absence of the dam, an increase in the population of sturgeon species of fish, which was in significant numbers before the construction of the Kakhovka dam, will probably be observed. The various conditions at the place of the former reservoir are likely to be favorable for birds. Species of plants and animals that were common downstream of the dam can be predicted to spread upstream.

In our opinion, despite these natural processes, after the end of the war the Kakhovka HPP and the Kakhovske reservoir should be restored. In this case, the fish pass should be built, which was absent in the past. Taking into account the presence of five reservoirs upstream and more economical use of water, the normal retention level in the restored reservoir can be lowered from previous 16.0 m a.s.l. to 15.0–15.5 m a.s.l.

CONCLUSIONS

During some decades of being of the Kakhovske reservoir, its thermal regime depended on season, weather conditions, the depth in the different parts and the water discharges from the Dniprovske reservoir located upstream.

The destruction of the Kakhovka dam which happened on June 6, 2023 greatly changed the situation. The large flow of water in the first days after the destruction caused the significant increase of water mixing and the decrease of water temperature not only in the lower reaches of the Dnipro River, but in the Dnipro-Buh lagoon as well. Simultaneously, the slowing of flow in the Inhulets River (the last significant tributary) caused the water temperature increase.

After the accident the former Kakhovske reservoir became the network of river branches and lakes in which the water temperature mainly depends on weather conditions. Simultaneously, the significant impact on the largest river channel on this territory has the Dniprovske reservoir, located upstream. This impact is the largest in spring season, when the water temperature in the bottom layer of the Dniprovske reservoir is cold. As a result, the plum of cool water can be observed at a distance of about 150 km or even more.

Nowadays, the water temperature of the lower reaches of the Dnipro River downstream the damaged dam approached to natural conditions.

Unfortunately, the destruction of the Kakhovka dam and the emptying of the Kakhovske reservoir caused significant social, economic and environmental damage to Ukraine.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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