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Thermal regime of the Danube Delta and the adjacent lakes

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Abstract: The Danube Delta is a unique natural object influenced by natural and human factors. According to the available observation and remote sensing data, the features of the water temperature in the Danube Delta, as well as in nearby lakes and the adjacent area of the Black Sea, have been determined. The water temperature in the Danube River was found to be much higher than the air temperature, especially in autumn. Generally, it is also higher than in nearby lakes and the adjacent part of the Black Sea. During 1961–2021 the mean annual water temperature in the Danube Delta increased significantly, especially during the last three decades. It has been determined that water temperature is affected not only by air temperature, but also by water discharge and wind. With a large water discharge the mixing of water is intensified and it causes the decrease of surface water temperature during the main part of the year with the exception of the coldest months. The greatest impact of water discharge on the water temperature is observed in June. The cool breeze in summer months also has some effect on the surface water temperature of the river near the seashore. The results show the potential of remote sensing to track the changes of water temperature along the river and to identify the shallow sections.

Keywords: Danube River; Delta; Danube lakes; Water temperature; Wind; Remote sensing.

INTRODUCTION

Many scientific works are devoted to the thermal regime of water bodies and, in particular, large rivers and lakes. It is common knowledge that water temperature is rising as a result of climate change (Adrian et al., 2009; Basarin et al., 2016; Czernecki and Ptak, 2018; Dokulil, 2014; Graf and Wrzesiński, 2020; Lieberherr and Wunderle, 2018; Lovasz, 2012; Marszelewski and Pius, 2016; Pekarova et al., 2008; Ptak et al., 2018; Ptak et al., 2020; Ptak et al., 2022; Vyshnevskyi, 2020; Vyshnevskyi and Shevchuk, 2021; Webb and Nobilis, 2007; Woolway et al., 2017; Wrzesiński and Graf, 2022). This increase rises when moving from the south-west to the north-east of Europe (Lieberherr and Wunderle, 2018).

In most cases, an increase in water temperature is less than an increase in air temperature (Lieberherr and Wunderle, 2018; Ptak et al., 2018; Vliet at al., 2011; Webb and Nobilis, 2007). But in certain circumstances, this dependence can be the opposite. One possible reason for the larger rise in water temperature compared to the increase in air temperature is the decrease in water discharge. Another possible reason is the discharge of heated effluents into the rivers (Vyshnevskyi, 2020; Webb and Nobilis, 2007).

As a rule, water temperature is higher than the air temperature, but in spring, this ratio can be the opposite (Ptak et al., 2022; Vyshnevskyi and Shevchuk, 2021; Webb and Nobilis, 2007). During the warm period, the surface water temperature decreases with increasing water discharge and mixing of water.

Meanwhile, the attention to the thermal regime of the Danube Delta is relatively small, and it still needs to be better understood. This applies even to the works dedicated to the nature of the Danube Delta (Gastescu, 2009). Much more attention is paid to water discharge and to transport of sediments (Gastescu, 2009; Panin and Jipa, 2002; Vyshnevskyi and Shevchuk, 2022).

In fact, even careful processing of routine monitoring data does not make it possible to determine the spatial features of large water bodies with the complicated thermal regimes. This is one of the reasons for the use of remote sensing. There are quite a few papers devoted to the use of remote sensing to study the thermal regime of lakes, reservoirs and seas (Alcântara et al., 2010; Barsi et al., 2014; Dyba et al., 2022; Lieberherr and Wunderle, 2018; Reinart and Reinhold, 2008; Schaeffer et al., 2018; Sharaf et al., 2019; Vyshnevsky, 2020; Vyshnevskyi and Shevchuk, 2021). Recently, this technology was used, in particular, to study the Dnipro Reservors' thermal regime, located relatively not far from the Danube Delta (Vyshnevskyi and Shevchuk, 2021). The same approach was used to study the surface water temperature of water bodies in Poland (Dyba et al., 2022). In the latter and in other cases, some attention was paid to the measurement accuracy, based on remote sensing. The difference between temperature measured in situ and Landsat 8 band 10 is typically less than 1 °C. The larger error occurs when the distance to the shore is less than 180 m (Schaeffer et al., 2018).

In fact, the potential of using remote sensing to study the thermal regime of large river deltas, in particular the Danube Delta, has not yet been fully exploited. The main aim of this study is to determine the features of the thermal regime of the Danube Delta and adjacent lakes, as well as the influencing factors.

MATERIALS AND METHODS

The Danube River is the second largest river in Europe in terms of the catchment area, length and water flow. At the same time, the Danube Delta is the second largest in Europe after the Volga Delta.

The Danube Delta begins about 50 km downstream of Reni hydrological station. In this place, which bears the name Izmail Chatal, there is the first division of the river into two branches: the left – Kiliyskyi, the right – Tulchynskyi. About 17 km downstream of the Izmail Chatal the Tulchynskyi branch forks into two new branches: left – Sulinskyi, right – Georgievskyi. As we approach the sea, the main branches are divided several more times, which determines the existence of a large number of watercourses and islands (Fig. 1).

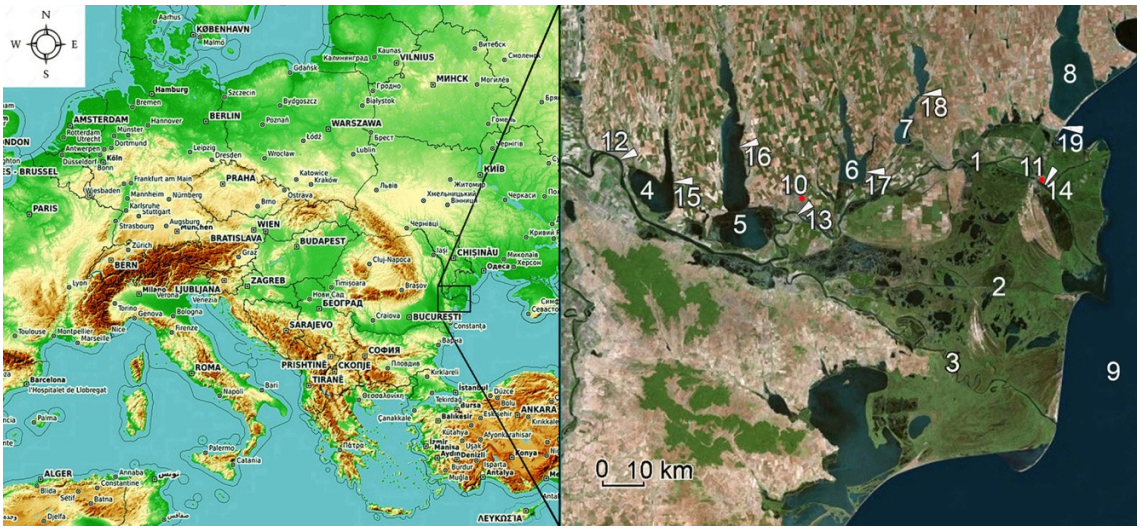


Fig. 1. The location of the Danube Delta and the available network of observations: 1–3 – Kiliyskyi, Sulinskyi and Georgievskyi branches of the Danube River, 4–8 – lakes Cahul, Yalpuh, Katlabukh, Kytai an Sasyk, 9 – the Black Sea, 10–11 – meteorological stations Izmail and Vylkove, 12–14 – hydrological stations on the Danube River: Reni, Izmail and Vylkove, 15–18 – hydrological stations on the lakes: Nahirne, Kosa, Kyslytsa, Chervony Yar, 19 – hydrological station Prymorske.

To the north of the lower course of the Danube River and its delta there are a number of water bodies called the Danube lakes. The largest of these are Cahul, Yalpuh, Katlabukh and Kytai. These lakes, though large, are shallow. The average water depth in only some of them is more than 2 m.

Importantly, the Danube Delta largely preserves its natural conditions, at least much more than the Nile Delta, the Volga Delta, the Ganges Delta and others (Kuenzer and Renaud, 2012; Shumova, 2018). The main part of the Danube Delta belongs to the Danube Biosphere Reserve in the Ukrainian part of the delta and the Danube Delta Biosphere Reserve in the Romanian part. The nearest reservoirs on the river (Jerdap I and Jerdap II) are located at a distance of about 900 km from the delta.

According to the data (Vyshnevskyi and Kutsiy, 2022; Vyshnevskyi and Shevchuk, 2022) the mean annual water discharge on the lower course of the river upstream of the delta at Reni hydrological station during 1921–2020 is 6510 m^3/s. The largest water discharge is observed in April, slightly less – in May. The lowest discharges are observed in September.

Some impact on the redistribution of the river discharge by separate branches has the directing flow dam on the site of Izmail Chatal, built in the early 20th century. As a result of its influence, the share of discharge of the Kiliyskyi branch has decreased significantly. While at the beginning of the twentieth century this share reached 70 %, in past decades it has become about 50% (Vyshnevskyi and Shevchuk, 2022).

The characteristic width of the river near Reni station upstream of the delta is 750–800 m, the average depth is 11–12 m and the maximum depth is 17–18 m. Meanwhile, there are sections with much less depth. The mean flow velocity near Reni station under normal conditions is 0.7–0.8 m/s.

The article used data from meteorological and hydrological stations on both the Danube River and the Danube lakes. In addition, were used the data at Prymorske hydrological station on the seashore. Air temperature at meteorological stations is measured every 3 hours, and water temperature at hydrological stations – at 8:00 and 20:00 local time.

Changes in the thermal regime of water bodies for the period 1961–2021 were investigated. Correlation analysis of the available air and water temperature data was carried out for different water bodies: the Danube River, the adjacent lakes and the Black Sea. In particular, the regression analysis was used to study the impact of the river discharge on the water temperature.

In addition to regular monitoring data, remote sensing data have been used. Most of the attention was paid to the images of the Landsat 8 satellite, which was launched in February 2013. The available images of Collection 2 Level 1 were downloaded from the site https://earthexplorer.usgs.gov. In particular, the images of LC08_L1TP_181028 serie cover the entire Ukrainian part of the Danube Delta and the adjacent lakes. The time of the survey of the studied area is 08:50 GMT, that almost corresponds to noon local time. The spatial resolution of B10 thermal band of the Landsat 8 satellite is 100 m, and the revisit time is 16 days. Such resolution for the river with a width of several hundred meters is sufficient for spatial and temporal analysis.

In total, about 30 satellite images were downloaded. They were processed using ArcMap 10 program. The surface water temperature for images obtained by the Landsat 8 satellite was determined by the dependence t = (1321.08 / (Ln (774.89 / ("LC8_B10.TIF" * 0.0003342) +0.1)) + 1))) – 273.15, which is recommended by NASA.

The territory, which does not belong to the water area, was identified using the Normalized Difference Pond Index (NDPI) calculation. This index was calculated by the equation NDPI = (B6 – B3) / (B6 + B3), in which B3 and B6 are the values of the respective Landsat 8 satellite bands. The territory, which is not the water area, was presented in grey colour for better visualization.

RESULTS

Air temperature and its changes

The presence of meteorological stations in the cities of Izmail and Vylkove allows for characterizing the climatic conditions of the Ukrainian part of the Danube Delta and their changes over a long period. The mean annual air temperature at Izmail meteorological station during 1991–2021 was 11.7 °C, and at Vylkove station – 12.2 °C. The minimum mean monthly temperature at these stations is observed in January – minus 0.5 °C and plus 0.4 °C. In turn, the maximum is observed in July – 23.6 °C and 24.1 °C, respectively.

Between 1961 and 2021, the mean annual air temperature in the studied region increased significantly. Its increase at Izmail station is about 0.35 °C per decade, at Vylkove station – 0.37 °C per decade. In the last three decades, namely 1988–2021, there has been much higher growth (Fig. 2).

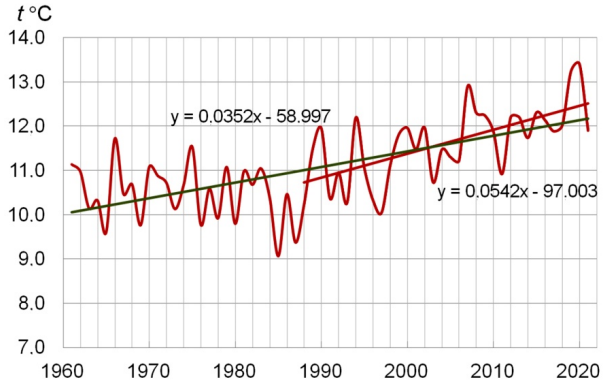


Fig. 2. The changes in mean annual air temperature at meteorological stations Izmail in two periods (1961–2021 and 1988–2021).

This increase in air temperature generally corresponds to the results of previous studies or slightly exceeds the values obtained by other studies (IPCC, 2022; Marin et al., 2014; Ptak et al., 2018; Ptak et al., 2022; Woolway et al., 2017). The main reason of these differences is the high air temperature observed in recent years (especially in 2019–2020).

It is important, that intra-annual increase in air temperature occurs unevenly. The most significant increase is observed in January, July and August. Thus, at Izmail meteorological station during 1961–2021 the increase in July was equal to 0.50 °C, and in August – 0.63 °C per decade.

Water temperature

Features according to the data of observations at hydrological stations

The location of the Danube Delta in southern Europe determines a reasonably high water temperature. The mean annual water temperature at Izmail station during 1991–2021 was 14.0 °C. At Reni station the mean annual water temperature is similar; at Vylkovo station – it is 0.1–0.2 °C lower.

The highest water temperature at Izmail station during 1991–2021 was observed in July and August 25.5 °C and 25.8 °C respectively. Simultaneously the water temperature at Vylkove station in these two warmest months is 0.2–0.3 °C lower than at Reni and Izmail stations. In May and June, the water temperature at Vylkove station is also slightly lower than at Izmail station.

One of the factors influencing the water temperature in the Danube Delta is the direction of the river flow on the Romanian section from the south to the north. In this section, the water temperature has time to rise. Another factor to consider is the location of places of water temperature observation. All hydrological stations in Ukraine on the Danube River are located on its left bank, oriented to the south. This contributes to the fact that the water temperature here can be a few tenths of a degree higher than in the middle of the river.

The water temperature in the Danube River is much higher than the air temperature. In particular, the mean annual water temperature at Izmail station during 1991–2021 was 2.3 °C higher than the air temperature. The excess of water temperature over air temperature is even greater in autumn and December. The largest difference is observed in October, when the mean air temperature is 11.9 °C and the mean water temperature is 16.1 °C. Even in March–April, when the rapid increase in air temperature is observed, the water temperature in the river is higher than the air temperature (Fig. 3).

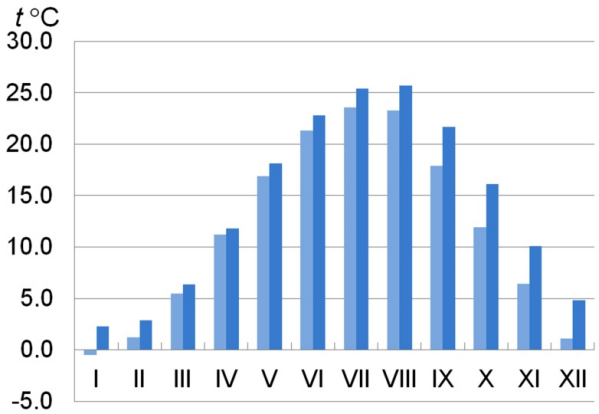


Fig. 3. Seasonal distribution of the air temperature (left columns) and the water temperature (right columns) in Izmail during 1991–2021.

The water temperature in the Danube lakes, compared to the water temperature in the Danube River, is noticeably different: in winter, it is colder. In March–June, it is warmer, and in autumn it is colder. In cold winters, the Danube lakes can freeze.

The water temperature in the Black Sea at Prymorske hydrological station, located near the mouth of the Danube River, also has specific features. Although the water in winter does not freeze here, it is cold at this time. The mean water temperature at Prymorske station in January is usually 2–3 °C. Generally, the sea water temperature in summer is lower than in the Danube River and lakes. The sea water temperature becomes warmer than in the lakes only in autumn, especially with the onset of October.

Overall, the highest water temperature during the year is observed in the Danube River. It is slightly lower in the Danube lakes and much lower in the Black Sea. The relatively high water temperature in the Danube Delta is partly explained by the direction of the river flow in the territory of Romania from the south to the north. In turn, the relatively low temperature in the Black Sea is due to the predominant water movement from the north under the influence of the prevailing wind.

It is important to note that the water temperature, as well as the air temperature, has increased significantly in recent decades. The largest increase is observed in July and August, the lowest in April. In recent years, in particular 2015–2021, the mean water temperature at Izmail station reached 23.2 °C in June, 26.3 °C in July and 26.7 °C in August.

Generally, the observed rise in water temperature corresponds to the increase in air temperature, but the increase in water temperature is somewhat larger, than the increase in air temperature (Fig. 4).

The increase in water temperature is described in many scientific works, but considering the data for recent years (especially 2019 and 2020) is very important, because these years were the warmest. It should be added that water discharge of the Danube in these two years was much less than usual.

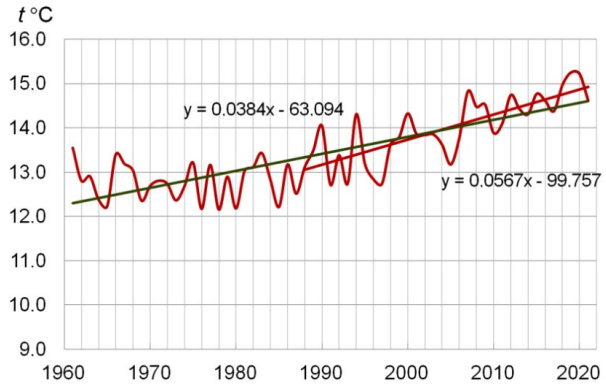


Fig. 4. The increase in mean annual water temperature at Izmail hydrological station in two periods (1961–2021 and 1988–2021).

A close linear correlation exists between the air temperature and the water temperature in Izmail. The correlation between annual means is r = 0.916 in 1961–2021. A slightly lower correlation is observed from May to October (r = 0.906). As for individual months, the closest correlation is observed in August (r = 0.891). On the other hand, the weakest correlation between mean air and water temperature is found in December and January.

According to the linear correlation, the increase in annual air temperature of 2 °C leads to an increase in water temperature of 1.6 °C. It is slightly larger than reported for the section of the Danube River near Budapest, where the same increase in annual air temperature causes an increase of water temperature of 1.5 °C (Vliet et al., 2011).

To some extent, the surface water temperature depends on the water discharge of the Danube River. When the water discharge decreases, the water heating during the warm period increases, in particular, due to the simultaneous decrease in the mixing of water and the depth of the river. On the other hand, when the discharge increases, the heating during the warm period decreases as a result of a simultaneous increase in the mixing of water and the depth of the river.

The water temperature during large discharges can be even lower than the air temperature. For example, in June 2019, the mean air temperature in Izmail was 24.4 °C, and the water temperature was 22.8 °C. This effect was observed when the mean monthly discharge at Reni station was 12500 m^3/s. A similar case was observed in April 2013 (12900 m^3/s) when air and water temperatures reached 13.0 °C and 10.8 °C, respectively. In general, however, there is an inverse relationship between the difference in water and air temperatures ($\Delta t = t_{wat}–t_{air}$) and the water discharge (Fig. 5).

The largest impact of water discharge on the difference between water and air temperature is observed in June. At this time, there is the essential difference between surface and bottom water temperature. In May water is still rather cold from the bottom to surface. In July the water temperature becomes more uniform as a result of heating.

Regression analysis also shows the inverse effect of water discharge on the water temperature for most of the year, except December–February. The corresponding calculation shows that the largest impact of the water discharge on the water temperature is observed in June. With two arguments (air temperature and water discharge) it is possible to obtain a closer relationship between the actual and calculated water temperature than with air temperature only. Such relationships could be used, for example, for filling gaps in water temperature measurements.

The similar results of the impact of water discharge on the water temperature were reported in Pekarova et al. (2008); Vilet et al. (2011), and Wrzesiński and Graf (2022).

Space-time patterns of water temperature determined on the basis of remote sensing data

To study spatial features of surface water temperature of the Danube River and the adjacent reservoirs, remote sensing images from the Landsat 8 were used. Data from B10 thermal band, as well as from the usual monitoring data, show that in spring, namely in April, the warmest water is observed in shallow Danube lakes. At the same time, the lowest water temperature is observed in the Black Sea, which warms up slowly due to its large volume (Fig. 6).

In general, there is a close relationship between the water temperature in the Danube River, which is measured, and the water temperature determined using remote sensing. Thus, the water temperature in the middle of the width of the river, as determined from a satellite image on April 30, 2018, near Reni station was 18.3 °C, near Izmail station 18.2 °C, near Vylkove station 17.8 °C. The measured mean daily water temperature at these stations was 18.5 °C, 18.7 °C and 18.4 °C, respectively. The peculiarities of the places of measurements, differences in the time and the depth of measurements explain the small differences. As mentioned before, the water temperature near the banks could be slightly higher than in the middle of the river. The same result based on remote sensing was obtained in the study (Alcântara et al., 2010).

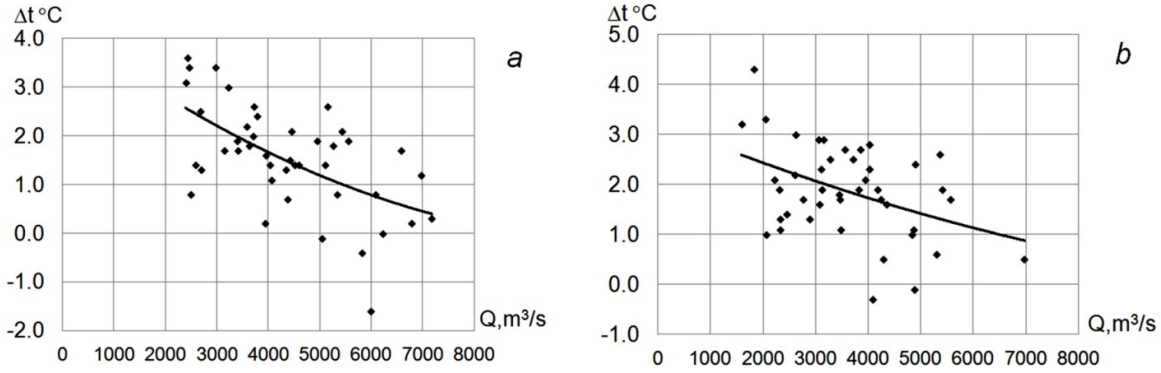


Fig. 5. Relationship between the difference in water and air temperatures ($\Delta t = t_{wat}–t_{air}$) and the water discharge (mean monthly data) in the Danube River near Izmail: *a* – in June, *b* – in July.

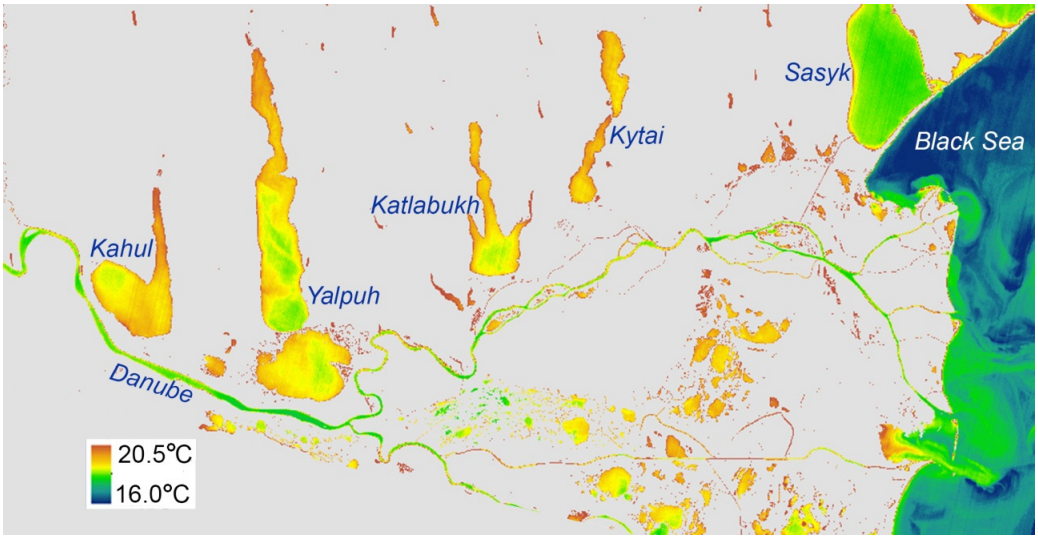


Fig. 6. Spatial features of surface water temperature in the Danube Delta and the adjacent reservoirs on April 30, 2018, according to Landsat 8 satellite data.

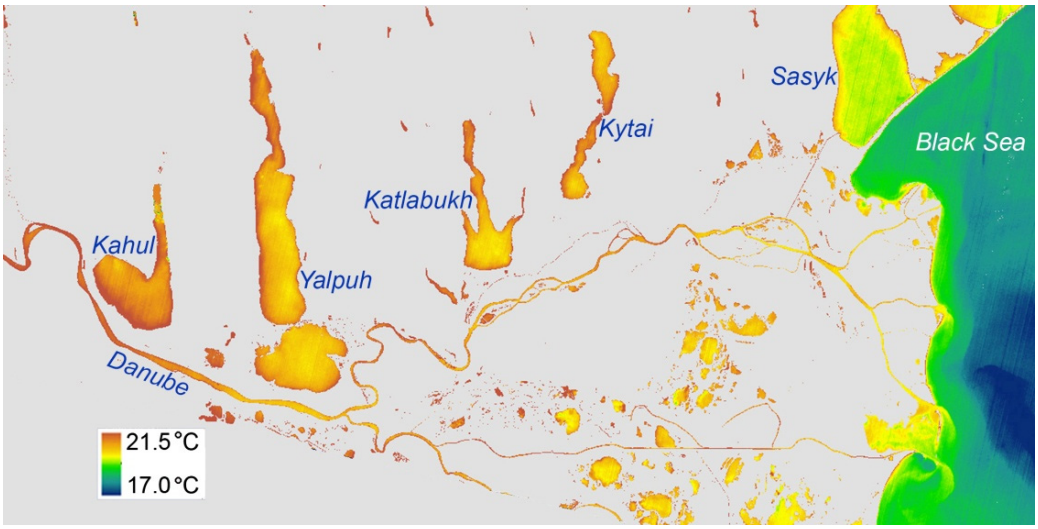


Fig. 7. Spatial features of surface water temperature in the Danube Delta and the adjacent reservoirs on June 01, 2018, according to Landsat 8 satellite data.

Similar to remote sensing results, the registered water temperature in the Danube lakes on April 30, 2018 was slightly higher than in the river. At Cahul–Nahirne station it was 20.0 °C, at Yalpuh–Kosa station – 20.4 °C, at Katlabukh–Kyslytsa station – 18.4 °C and at Kytai–Chervony Yar station – 19.7 °C. The coldest water was observed in the Black Sea at Prymorske station – 16.1 °C.

It is obvious that in the summer period, the water temperature increases. In some cases, available satellite data reveal not only seasonal features but also the effects of flow regime on the water temperature. The satellite image dated June 01, 2018 is indicative in particular. At that time there was a decrease of water discharge. Its value at Reni station on 30.05.2018 was 6860 m^3/s, on 31.05.2018 – 6820 m^3/s, on 01.06.2018 – 6710 m^3/s. As a result of water discharge decrease, the cool water was observed near the sea, where the water discharge was the largest (Fig. 7).

It can be added that on June 01, 2018 at 12:00 at Izmail meteorological station, there was an eastern wind at a speed of 5 m/s, at Vylkove meteorological station – similar speed wind, but from the northeast. This may be an additional factor that caused relatively cool water in the surface layer of the river near the sea. The same can be said about the neighbouring Sasyk lake.

The effect of water discharge decrease on water temperature in the lower course of the Danube River can be observed in many satellite images, taken on 21.09.2018, 10.09.2020, 25.06.2021, etc. Notably, in all these cases, even small changes in water discharge in the range of 10 % had an impact on the surface water temperature.

The opposite situation with the increase in water discharge was observed on July 27, 2021. At that time, the water discharges at Reni station were as follows: on 25.07.2021 – 4950 m^3/s, 26.07.2021 – 5040 m^3/s, and on 27.07.2021 – 5110 m^3/s. At the same time, relatively cold water reached the Izmail Chatal and several kilometres downstream but did not reach Izmail station. The measured water temperatures on July 27, 2021 were: Reni station – 27.2 °C, Izmail station – 27.5 °C, and Vylkove station – 27.6 °C (Fig. 8).

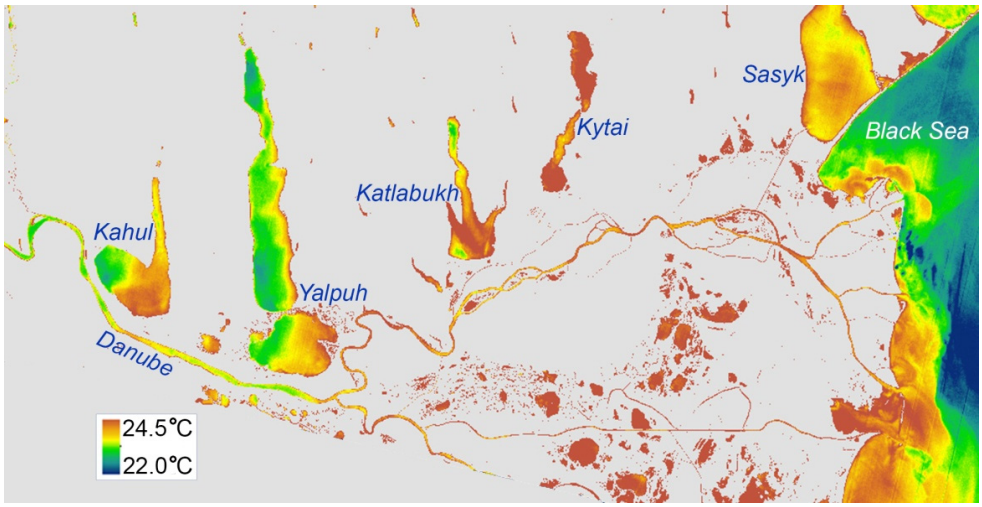


Fig. 8. Spatial features of surface water temperature in the Danube Delta and the adjacent reservoirs on July 27, 2021 according to Landsat 8 satellite data.

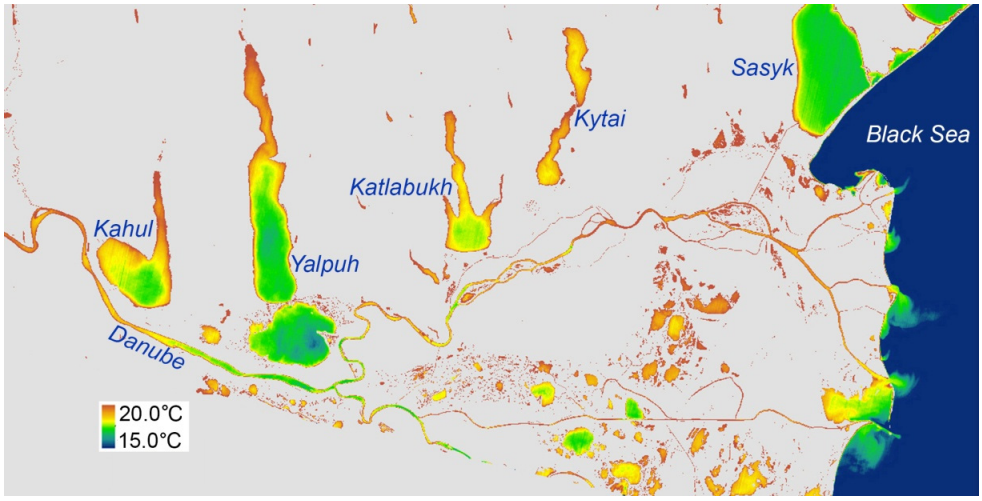


Fig. 9. Spatial features of surface water temperature in the Danube Delta and the adjacent reservoirs on June 06, 2020, according to Landsat 8 satellite data.

Specific conditions on July 27, 2021 was observed on the Danube lakes. The water temperature at Cahul–Nahirne station reached 28.4 °C, at Yalpuh–Kosa station – 27.8 °C, at Katlabukh–Kyslytsa station – 28.4 °C and at Kytai–Chervony Yar station – 27.1 °C. To some extent, such high temperature, which exceeded the observed in the Danube River, was caused by the wind impact and the movement of warm water toward the eastern shore of the lakes, where there are the hydrological stations. At the same time, at Prymorske station on the seashore, the water temperature was only 20.4 °C.

Another case with an impact of wind on the surface water temperature occurred on June 6, 2020. At that time, a wind of 7 m/s from the south-south-east caused warm water to move to the northern shores of the lakes. Moreover, relatively warm water was observed in the northern sections of the river and slightly colder in the southern ones (Fig. 9).

It can be added that on June 6, 2020, the water temperature in the sea was much colder than in the lakes and in the river. The main reason is the slow heating of the large volume of seawater.

It is important that even light east wind can cause visible changes in water temperature not only in the lakes, but also in the river. That was the case on July 29, 2016 in the eastern wind. As in many other cases, this was because water and air temperatures over the sea are relatively low in summer (Fig. 10).

Fig. 10 shows that the spatial changes in water temperature in the watercourse system of the Kiliyskyi branch are more significant than those of the Sulinskyi branch. This is due to its larger size, and the presence of its own delta, which the Sulinskyi branch does not have.

These examples of water temperature distribution show the impact of wind on the water bodies, in particular, in the Danube River and the lakes. It is well known that the wind speed near the seashore is larger than at the distance from it. It can be added that the water temperature in the Black Sea in warm periods is much colder than in the river and lakes. It means that the wind from the sea causes a cooling effect. As shown by satellite imagery, the water temperature of Lake Sasyk, which is close to the sea, is much lower than that of the lakes much further away. To some extent, this concerns the water temperature in the section of the Danube River near the sea. As mentioned above, the regular monitoring data also show that water temperature at Vylkove station in summer is slightly less, than at Izmail station.

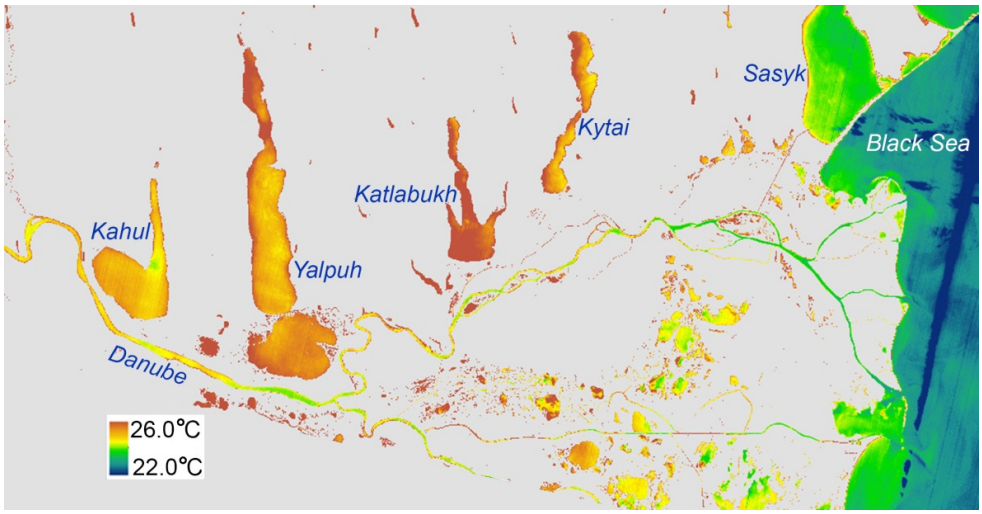


Fig. 10. Spatial features of surface water temperature in the Danube Delta and the adjacent reservoirs on July 29, 2016, according to Landsat 8 satellite data.

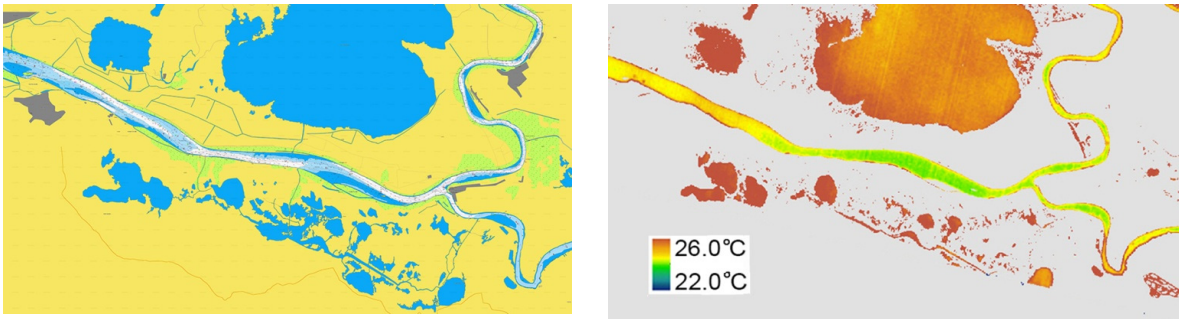


Fig. 11. The fragment of navigation map of the Danube River near the Izmail Chatal (*a*) and the water temperature at this section, according to Landsat 8 satellite imagery on July 29, 2016 (*b*).

Intraday water level fluctuations at Vylkovo station also confirm the effect of breeze wind on the water surface. In the summertime, the highest level is observed at 6–7 p.m., the lowest at 2–3 a.m.

Careful analysis of satellite images, especially in a warm period, makes it possible to find places on the river with relatively warm and cool areas. In particular, such areas, where the water temperature is usually lower than nearby, are in front of the Izmail Chatal. The main reason for this feature is the presence of a shallow water area. This shallow section (it is not the only one) is indicated on the navigation map of the lower Danube River. The characteristic depth at this site is 5–7 m, which is two to three times less than at adjacent sites. The presence of this shallow water leads to increased flow velocity, and greater mixing, which is reflected in surface water temperature (Fig. 11).

Another shallow and simultaneously straight section is located 10–18 kilometres downstream of Kiliya town. The characteristic depth at this section is about 6 m. As a result of the increased mixing, the water temperature in the summer period in this section is usually lower than in the surrounding area (Fig. 12).

One more shallow section is located near Kiliya town itself, where some river branches coincide. The water temperature in this section in warm periods is also cooler than nearby.

DISCUSSION

The obtained results concern both water temperature in the Danube Delta and some impacting factors: air temperature, water discharge, and the wind.

Overall, the observed temperature changes in the Danube Delta are close to those reported in other studies (Pekarova et al., 2008; Ptak et al, 2022; Vyshnevskyi, 2020; Vyshnevskyi and Shevchuk, 2021; Webb and Nobilis, 2007; Woolway et al., 2017). For example, mean annual air temperature increase at meteorological stations near the Vistula River in Poland during 1971–2017 had the range 0.30–0.39 °C (Ptak et al., 2022). Almost the same increase (0.33 °C per decade) was obtained for the whole territory of Poland for period 1961–2018 (Kejna and Rudzki, 2021). The increase of air temperature for the period 1961–2010 at 122 meteorological stations, located in Central Europe, showed an average warming rate of 0.31 ± 0.06 °C per decade (Woolway et al., 2017). In our study the increase of air temperature for the period 1961–2021 was somewhat higher: Izmail – 0.35 °C, Vylkove – 0.37 °C per decade. The small differences between the results found here and in the literature can be explained by higher air temperature in 2019 and 2020.

There are some local features of the water temperature in the Danube River and nearby water bodies. The water temperature in the studied section of the river is higher than in many

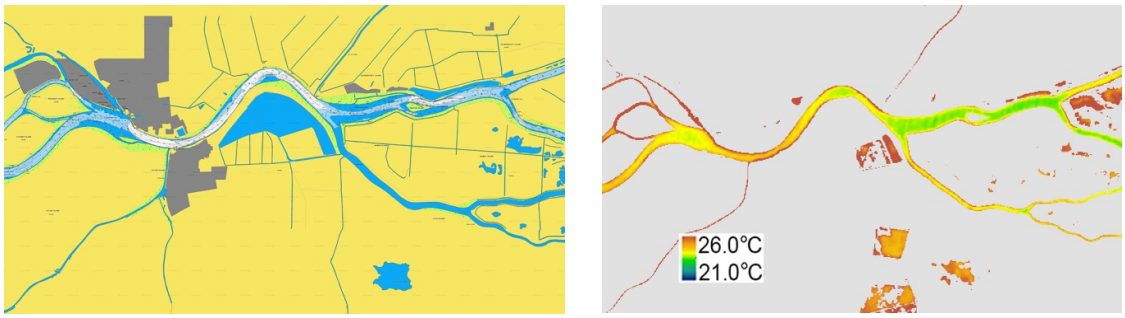


Fig. 12. The fragment of navigation map of the Danube River near Kiliya town (*a*) and the water temperature at this section, according to Landsat 8 satellite imagery on July 29, 2016 (*b*).

European rivers. In recent years the water temperature in the Danube River in July and August reached 26.0 °C.

The temperature of the lower Danube River has risen significantly in recent decades. This increase near Izmail (about 0.38 °C per decade for the period 1961–2021) is larger than on the southern border of the Hungarian section of the river, where for the period 1951–2010 it was 0.243 °C per decade. At the same time, the increase in water temperature in the studied section is slightly larger than the increase in air temperature. This result is somewhat unusual. As a rule, the increase in air temperature is larger than an increase in water temperature in rivers. For example, according to Ptak et al. (2022), the increase in air temperature near the Vistula River during 1971–2017 was equal to 0.30–0.39 °C per decade and water temperature increased – 0.31 °C per decade. A similar result was achieved with a higher temperature increase compared to the water temperature for the Dnipro Reservoirs (Vyshnevskyi and Shevchuk, 2021). Such specifics of the thermal regime are likely caused by the decrease of the river discharge. But during the last six decades, the water discharge of the Danube River at Reni station practically did not change. At the same time, there was a noticeable decrease in the share of the flow of the Kiliyskyi branch. Whereas in the early 1960's its share was about 60% of the total, nowadays it is about 50 %. It means that the water discharge of the Kiliyskyi branch decreased significantly, contributing to the increase in water temperature.

The important feature of the thermal regime of the Danube River is also a close correlation between air and water temperature, which is closer than in many other rivers. In particular, this correlation for Izmail and annual values (r = 0.916) is tighter than for the Austrian and Slovak sections of the river (Pekarova et al., 2008; Webb and Nobilis, 2007). In our view, this correlation depends on the size of the river and flow velocity. The water regime of the Danube River in the delta is much less changeable than in the upper reaches. The large volume of water in the river's lower reaches also has some influence. Besides, the share of groundwater on the delta is very small. As a result, the closeness of the correlation between air and water temperature for the Danube Delta exceeds the same indicator for the Vistula River (Ptak et al., 2022).

The increase in air and water temperature causes the growth of evaporation from the water's surface. It means the essential increase of evaporation from the Danube Delta and the decrease of water discharge downstream Reni station. It can be added that the Danube Delta's main territory is the shallow water occupied with air-water vegetation, which is dominated by reeds. According to the studies (Stan et al., 2016), carried out in Romania, evaporation from such reservoirs is about twice as much as evaporation from the water surface. The increase in air and water temperature in the Danube Delta has affected and will continue to affect the ecosystem of the Danube Delta. The results published in the study (Strat, 2014) show a noticeable increase in growing season length, mainly due to the earlier start of this season.

The paper (Živković et al., 2019) describes the appearance of the thermophilic Pistia stratiotes in the Danube River, also known as water lettuce. The increase in water temperature can have a negative effect on the concentration of dissolved oxygen in the water. As a result of the water temperature increase, favourable conditions for the spawning of silver carp were created (Jawdhari et al., 2022).

The carried out research based on regular monitoring and remote sensing data, showed some impact of water discharge and flow velocity on the surface water temperature. Even small changes of water discharge in the river during warm period are accompanied by the changes of the surface water temperature. Moreover, remote sensing makes it possible to determine the phase of the water regime: an increase or decrease in water discharge. At the same time, remote sensing allows us to find shallow sections of the river.

The effects of wind on surface water temperature can also be studied from remote sensing data. In general, this impact on seas and lakes is well known. In our case, we observe a similar effect of wind on the surface water temperature of the Danube lakes and the large river. The result of wind blowing against the current (especially with a lower temperature than water temperature) has a more significant effect on the river flow than the wind blowing in the same direction as the river flow.

CONCLUSIONS

The location of the Danube Delta in the southern Europe causes high air and water temperature. Generally, the water temperature in the Danube River is higher than the air temperature. During 1991–2021 the mean annual air temperature near Izmail was 11.7 °C, and the mean water temperature 14.0 °C. In spring this excess is about 1 °C, in autumn it reaches 4 °C.

During 1961–2021 the mean annual air temperature in the studied region increased by about 0.35–0.37 °C per decade or about 2.2 °C overall. As a result of this increase, an increase in water temperature was also observed. Over the past three decades, more significant increases in air and water temperatures have been observed.

The increase in water temperature in the Ukrainian part of the Danube Delta is slightly larger than the increase in air temperature. The main reason for this is the noticeable decrease in share discharge of the Kiliyskyi branch during the observed period.

The distribution of water temperature in the individual components of the Danube River–Danube lakes–Black Sea system is diverse during the year. In spring and June the warmest water is observed in the lakes, the coldest – in the sea. From July to autumn's end, the warmest water is observed in the Danube River. With the onset of autumn, the water temperature in the lakes decreases markedly – it becomes lower than in the Danube River and the adjacent part of the Black Sea.

On the whole, the water temperature in the Danube Delta is higher than in the Danube lakes and in the adjacent part of the Black Sea.

In addition to the air temperature, the water temperature in the Danube Delta is affected by water discharge. With a large water discharge the mixing of water is intensified and it causes the decrease of surface water temperature during the main part of the year with the exception of the coldest months. The largest impact of water discharge on the water temperature is in June.

The use of remote sensing gives the opportunity to discover the changes of water temperature along the river caused by the changes of water discharge. In addition, it allows finding places with different temperatures, due to shallow depth and significant mixing. In a warm period, the water temperature in the shallow sections is colder than in nearby ones.

Another factor influencing the surface water temperature is the wind. Wind at the seashore, which is faster than at a distance from the shore, leads to more water mixing and at the same time to the cooling effect of surface water temperature during the warm period in the Danube Delta and the lakes located nearby.

On the whole, the use of regular monitoring data and remote sensing data allows us to discover many features of the thermal regime of different water bodies. For the study of temporal changes in water temperature it is better to use the long-term data of regular monitoring, for the study of the spatial features – the remote sensing data.

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