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Wind impact on the surface water temperature 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 wind impact on the surface water temperature of the Danube Delta and adjacent lakes has been determined. It is more obvious for the lakes, but some impact on the river exists as well. In general, the largest impact is observed in the warm period, when the difference in water temperature between the Black Sea and the Danube River is the largest. This influence depends on the proximity to the sea, it is greatest near the seashore. Cool breeze in summer months has an effect not only on the surface water temperature but also on the water level in the river. When the water discharge is large, the difference in water level is smaller than at low water. In general, water temperature in the Danube River is higher than in the Danube lakes and the adjacent part of the Black Sea.

Keywords: Danube Delta, Danube lakes, water temperature, wind, remote sensing

1 Introduction

Many scientific works are devoted to the thermal regime of water bodies and, in particular, to large rivers (e.g., Webb and Nobilis, 2007; Pekarova et al., 2008; Lovasz, 2012; Marszelewski and Pius, 2016; Ptak et al., 2018; Graf and Wrzesiński, 2020; Wrzesiński and Graf, 2022) and lakes (e.g., Adrian et al., 2009; Dokulil, 2014; Woolway et al., 2017; Ptak et al., 2018, 2020). All these studies refer to increasing trends of surface water temperature, linked to climate change. Some of these studies relate the increase of water temperature to the increasing air temperatures (e.g., Pekarova et al., 2008; Basarin et al., 2016; Czernecki and Ptak, 2018) or other hydrological regime shifts due to global warming, in particular to anomalies of river runoff or evaporation (e.g., Webb and Nobilis, 2007; Vyshnevskyi and Shevchuk, 2022; Wrzesiński and Graf, 2022; Vyshnevskyi, 2022) and thus often rely on modelling of *in situ* measurements. The vulnerability of lakes and rivers against global warming is discussed in view of specific lake morphometry (e.g., Ptak et al., 2018); the impact of global warming on ice-cover features or shifts of thermal regime in lakes (e.g., Ptak et al., 2020) or flood regime (Vyshnevskyi and Shevchuk, 2022). The scope of the influence of rising temperatures caused by climate change is discussed beyond physics to impact aquatic biota. The benefit of thermophilic plant and animal species (e.g., Bănăduc et al., 2016; Teubner et al., 2018) and their spread out in recent decades, which is often described as neobiota (Robinson et al., 2020; Trichkova et al., 2022), are thus of study interest in that context. Other describe cascading effects of global warming on biocenosis structures of aquatic life forms (Dokulil and Teubner, 2012; Minicheva and Marinets, 2023), which often force a degradation of the ecosystems (Nagy et al., 2023).

In the recent study the focus is on surface water temperature, to what extent it is different between water sites at the Danube Delta and the adjacent lakes along seasons and years when compared with the Black Sea and what the impact of wind is.

An increase of surface water temperature rises when moving from the south-west to the north-east of Europe (Lieberherr and Wunderle, 2018). Thus, the increase of mean water temperature in the lower reaches of the Danube River at Izmail hydrological station during 1961–2020 was 0.38 °C per decade (Vyshnevskyi and Shevchuk, 2022). A somewhat smaller increase with the rate 0.31 °C per decade was obtained for the Vistula River for the period 1971–2015 (Ptak et al., 2022).

There are studies devoted to the wind impact on the surface water temperature in lakes and the sea. Some features of such impact are described in the paper devoted to the thermal regime of the North-Western part of the Black Sea (Vyshnevskyi et al., 2023).

Meanwhile, the attention to the thermal regime of the Danube Delta is relatively small. 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 transport of sediments (Panin and Jipa, 2002; Gastescu, 2009; Vyshnevskyi and Shevchuk, 2022).

In fact, even careful processing of routine monitoring data does not make it possible to determine the spatial features of water temperature of river deltas and lakes. This is one of the reasons for the use of remote sensing (Barsi et al., 2014). There are recent papers devoted to the use of remote sensing to study the thermal regime of lakes (e.g., Reinart and Reinhold, 2008; Lieberherr and Wunderle, 2018; Vyshnevskyi and Shevchuk, 2018; Dyba et al., 2022), reservoirs (Sharaf et al., 2019; Vyshnevskyi and Shevchuk, 2021) and seas (e.g., Vyshnevskyi et al., 2022).

Nevertheless, until now the use of remote sensing to study lower course of the Danube River and its delta is rather rare. Meanwhile, it is important that the large size of the river is sufficient to study water temperature using publicly available data of Landsat satellites. It is also convenient that one satellite image covers a large area, which includes not only a large part of the delta, but also the adjacent lakes, as well as the adjacent part of the Black Sea. In this regard, the main purpose of this study is to determine the spatio-temporal features of the surface water temperature caused by the wind impact. Some attention is also paid to the seasonal features of water temperature in the Danube Delta, nearby lakes and the adjacent part of the Black Sea.

2 Material and methods

The Danube Delta is the second largest wetland in Europe after the Volga Delta. Its length/longest distance from the so called Izmail Chatal to the sea shore is about 80 km, quite similar in the length from the north to the south of the delta (Figure 1).

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. Not far from the sea is located the Sasyk Lake, which was the sea lagoon in the past but now separated from the sea as a result of dam construction. These lakes, even they cover a large area, are shallow. In only few of them, the average water depth exceeds 2 m. Details about lakes regarding lake water level, lake volume and lake area are given in Vyshnevskyi et al. (2019).

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

In addition to regular monitoring data, remote sensing data have been used. Most attention was paid to the images of Landsat 8 satellite, which were 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 series cover the entire Ukrainian part of the Danube Delta and adjacent lakes. The time of survey of the studied area is 08:50

GMT, that almost corresponds to noon of local time. The spatial resolution of B10 thermal band of Landsat 8 satellite is 100 m, the revisit time is 16 days. For the Danube River with the width of several hundred meters this is sufficient for the relevant study.

In total, about 30 satellite images were downloaded. They were processed using ArcMap 10 program. The territory, which does not belong to water area, was identified using the calculation of Normalized Difference Pond Index (NDPI). The territory, which is not the water area, was presented in grey colour for better visualization.

3 Results and discussion

The presence of meteorological stations in the cities of Izmail and Vylkove allows to characterize the climatic conditions of the Ukrainian part of the Danube Delta. The mean annual air temperature at Izmail meteorological station during 2015–2021 was 11.7 °C, at Vylkove station – 12.2 °C.

The location of the Danube Delta in the southern Europe determines a fairly high water temperature. The mean annual water temperature at Izmail station during 2015–2021 was 14.0 °C. At Vylkovo station the mean annual water temperature was with 13.6°C lower (Table 1).

The monitoring of the water regime is carried out also on some largest lakes. In this study, however, the focus is on data from two lake stations only, Yalpuh-Kosa and Sasyk-Borysivka, to show lake representatives for a coherent pattern of temperature development (Dokulil and Teubner, 2002) in this wetland lake area. Comparing annual averages, water surface temperature between the Danube River and the two

Figure 1: The location of the Danube Delta (left) and the network of available observations (right): 1 – the Danube River; 2–6 – lakes Kahul (2), Yalpuh (3), Katlabukh (4), Kytai (5) an Sasyk (6); 7 – the Black Sea, 8–9 – meteorological stations Izmail and Vylkove, 10–11 – hydrological stations on the Danube River: Izmail and Vylkove, 12–13 – hydrological stations on the lakes: Kosa and Borysivka, 14 – hydrological station Prymorske.

Table 1: The monthly (I to XII) and annual means of water temperature [°C] at five hydrological stations from 2015 to 2021. Danube River measurements from station Izmail and Vylkove, for Yalpuh Lake at station Kosa and for Sasyk Lake at station Borysivka.

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Danube-Izmail	2.8	4.1	7.3	12.5	18.5	23.2	26.3	26.7	23.2	16.5	11.1	5.7	14.8
Danube-Vylkove	2.8	3.9	7.2	12.3	18.3	23.0	26.0	26.4	23.0	16.3	11.1	5.7	14.7
Yalpuh-Kosa	1.4	2.8	7.4	13.2	19.0	24.4	25.8	25.3	20.5	14.4	8.6	3.3	13.8
Sasyk-Borysivka	1.0	2.8	7.1	12.5	18.6	23.4	24.7	23.8	19.2	12.9	7.4	3.1	13.0
Black Sea- Prymorske	2.8	3.5	6.3	10.8	16.7	22.2	24.0	24.7	20.7	15.3	10.1	5.6	13.6

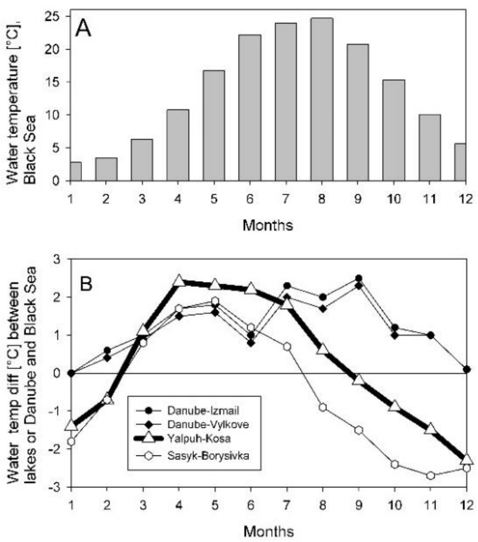

Figure 2: Long-term monthly averages (2015 to 2021) for the water temperature of Black Sea at station Prymorske (bar chart, A) and the difference between water temperature at the Black Sea and measuring stations of the Danube River and the Yalpuh Lake and Sasyk Lake (line graph, B).

lakes, values for the Danube River were higher while in the both Delta Lakes it was the same or a lower water temperature than in the adjacent part of the Black Sea (Table 1).

When looking at monthly averages surface water temperature (Table 1), a more specific seasonal dynamic is obviously. At no month the average surface water temperature at the both Danube River stations was lower than in the adjacent part pf the Black Sea (Figure 2). The most pronounced elevation of surface water temperate (plus 2.4°C more than in the Black Sea) was in here early autumn (September) and thus after peak of growing season. Different from the Danube River, water temperature in autumn and winter is lower in Yalpuh Lake, but shows a steep increase of water temperature in spring from March to May, and also highest relative water temperature in early summer. Such spring warming is most important for hatching of animals and exponential growth of microbial plants, as algae and blue-green forming phytoplankton.

It could be shown in other studies, that rapid warming early in the year triggers many aspects of lake phenology, from the lake physics (earlier ice-off, earlier off-set of thermal stratification, e.g. Adrian et al., 2009; Czernecki and Ptak, 2018) to the lake biology (earlier on-set of hatching and earlier phytoplankton spring bloom, earlier clear-water phase, e.g., Dokulil and Teubner, 2012; Teubner et al., 2018) and are linked to the climate signal. The early period in year, i.e., spring to early summer is thus in general seen as the most sensitive time span in a year responding to global warming.

One of the factors, which determines the high temperature of surface water in the Danube Delta, is the river flow direction at the Romanian section from the south to the north. In this section the water temperature has time to rise. Simultaneously the rather cool water temperature at Prymorske station is caused by the dominant direction of sea current from the north to the south.

It is worth notifying that in spite higher air temperature at Vylkovo meteorological station than at Izmail station the water temperature at Vylkovo hydrological station is lower, especially during the period from April till October. This phenomenon can be explained by the vicinity of the Black Sea and the direction of breezing wind in warm period: in the daytime – from the sea towards land, in the night – from the land to the sea.

Additional data as to the spatial distribution of surface water temperature are retrieved from remote sensing, in particular, from the images obtained by Landsat 8 and Landsat 9 satellites.

Even not strong wind can cause visible changes of water temperature not only in the lakes, but also in the river. That was the case on June 01, 2018 in the eastern wind (Figure 3).

The mean water temperature on June 01, 2018 on hydrological stations was as follows: Danube River–Izmail – 23.2, Danube River–Vylkove – 22.8, Yalpuh lake–Kosa – 22.3, Sasyk–Borysivka – 22.5, Black Sea–Prymorske – 21.3 °C. As can be seen on Figure 3, the measured and calculated water temperature are quite close. In general, the water temperature near the banks, where it is measured, is slightly higher than in the middle of the lakes and the river. It is important that both measured and calculated data show that water temperature at Vylkove station was lower than at Izmail station.

Figure 3 shows that among the lakes the lowest temperature is observed in Sasyk Lake, which is located near the sea shore. It is obvious that wind impact from the cool sea on this lake is here overwhelming, if compared with temperature from other areas.

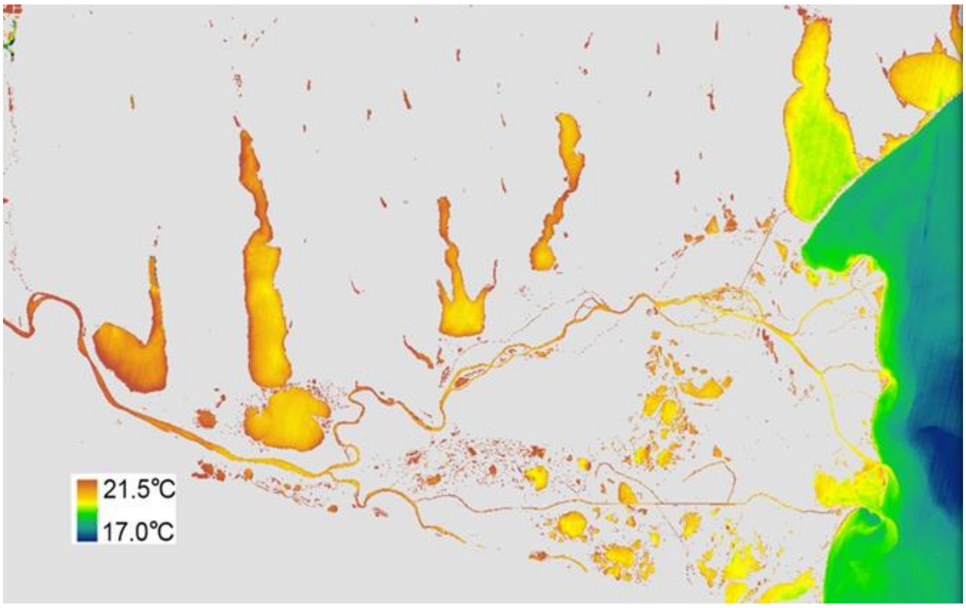

Figure 3: Spatial features of surface water temperature in the Danube Delta and the adjacent reservoirs on June 01, 2018, under impact of the eastern wind, according to Landsat 8 satellite data.

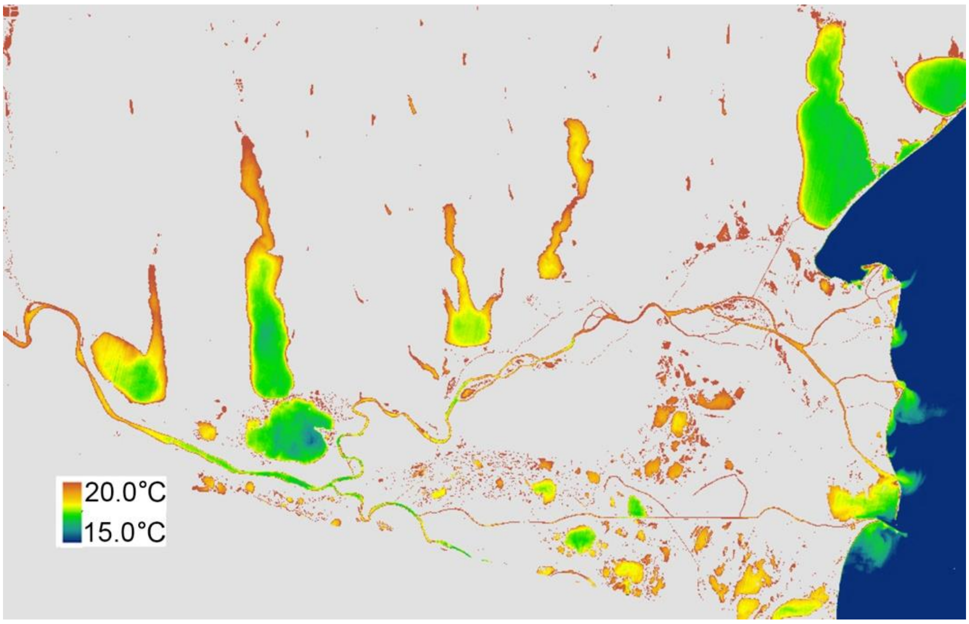

Figure 4: As in figure 3, but for June 06, 2020, under the impact of wind from the south-south-east.

It can be added, that water temperature in the Danube River depends not only on air temperature, but also on water discharge. With the decrease of water discharge, 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, its heating during the warm period decreases as a result of a simultaneous increases in the water mixing and the depth of the river. In some cases, it is possible to monitor the changes of surface water temperature along the river. On June 01, 2018 and a few days before, the water discharge was decreasing in the delta. As a result, the water temperature at the upper part of the delta was higher than near the sea shore. Meanwhile, this factor did not impact on the surface water temperature in the lakes.

Another case with an impact of wind on the surface water temperature occurred on June 6, 2020. At that time, wind of 7 m s^{-1} from the south-south-east caused warm water moved to the northern shores of the lakes. Moreover, relatively warm water was observed in the northern sections of the Danube River and slightly colder in the southern ones (Figure 4). In general, the water temperature at this time was quite cool, cooler than on the previous occasion. This is due to the cool weather in the weeks leading up to the satellite survey. When warming began, the Black Sea turned out to be much colder than other water bodies. It is further worth mentioning 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 of this phenomenon is the slow warming up of the large volume of sea water.

Another characteristic case of wind impact on lake and river temperature was observed on July 06, 2022

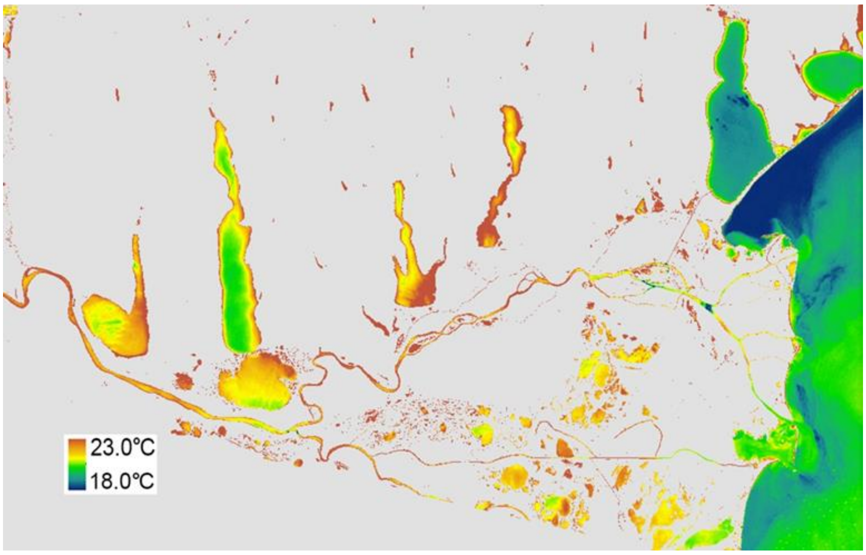

Figure 5: As in figure 3, but for July 06, 2022, at north-west wind.

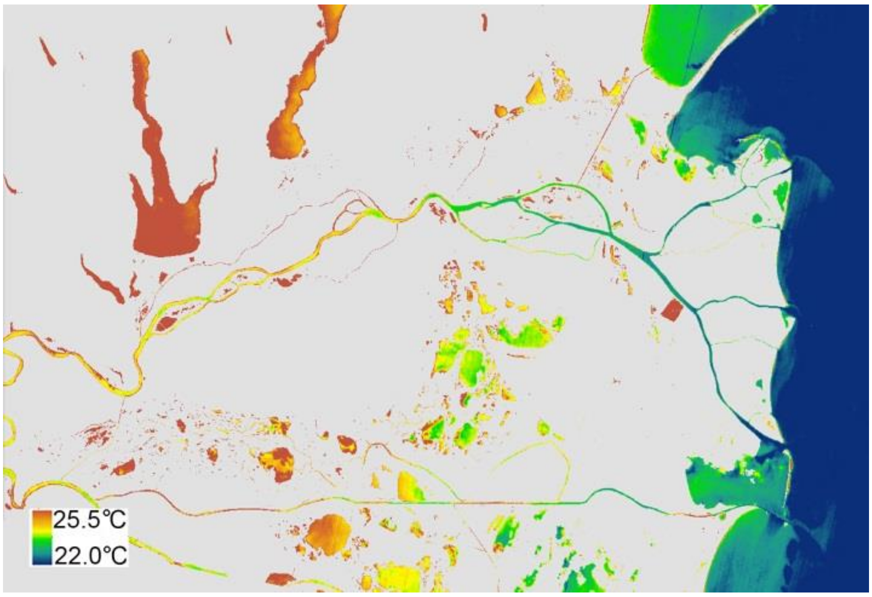

Figure 6: As in figure 3, but on July 29, 2016, at eastern wind.

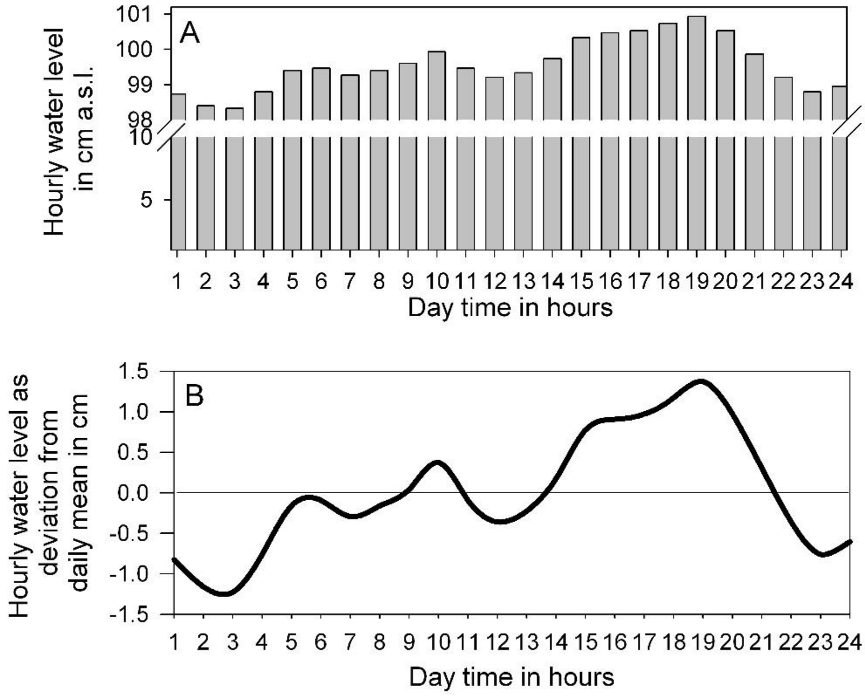

Figure 7: Water level fluctuations at Vylkovo hydrological station. A: Hourly water level covering 24 hours, calculated as hourly long-term averages for summer period (June–August) from 2017 to 2021. B: The same data, but the hourly water level is calculated as deviation from daily mean. Negative values indicate water levels lower, positive values higher than daily water level average.

(Figure 5). At that time the wind direction was north-west, which essentially impacted the surface water temperature. As in many other cases the lowest temperature, except the Black Sea, was observed in the Sasyk Lake.

Wind impact on the surface water temperature of the Danube River becomes more obvious when considering the territory on a larger scale than shown in Figures 3-5. The characteristic case occurred on July 29, 2016, when in the studied area was observed the wind from the east and north-east. As a result of this wind, blowing from the cool Black Sea, the water temperature in the Danube River near the sea shore occurred much cooler than on some distance. At the same time, the water discharge in the delta was almost constant. At Izmail station on July 28, 2016 it was 3200 m^3s^{-1}, on July 29, 2016 it was 3250 m^3s^{-1} (Figure 6).

The effect of the wind on the water surface is also confirmed by fluctuations of the water level at Vylkovo station. In the summer-time, the highest water level is observed at 6–7 p.m., the lowest one at 2–3 a.m. (Figure 7). Usually the difference between the highest and the lowest water level is small – about 2–3 cm. This difference depends on the water discharge. When the water discharge is large, the difference in water level is smaller than with low water (Figure 7). The impact of water discharge and water temperature (e.g., Webb and Nobilis, 2007; Wrzesiński and Graf, 2022) and also further to biotic changes is reported from other studies (e.g., Minicheva and Marinets, 2023).

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 on the distance from it. It is further worth emphasizing that water temperature in the Black Sea during warm period is much colder than in the river and the lakes (see also time-lag between seasonal air and water temperature for the Black Sea in Vyshnevskyi et al.2022). This means that the wind from the sea causes a cooling effect on Danube Delta lakes. As shown by satellite imagery, the water temperature of Lake Sasyk, which is close to the sea, is thus much lower than that of the other Delta lakes that are much far distant from the Black Sea. To some extent, this concerns also the water temperature in the Danube River section near the sea. This further agrees with Figure 3, showing that water temperature at Vylkove station in summer period is slightly less, than at Izmail station.

4 Conclusions

The location of the Danube Delta in the southern part of Europe refers to high air and water temperature. The annual averages of water temperature for water bodies in the Danube Delta are higher than in the adjacent part of the Black Sea. Wind at the seashore, which is faster than at a distance from the shore, is interpreted to force water mixing and to have a cooling effect on surface water during the warm period in the Danube Delta and the lakes located nearby. The water surface temperatures of the Danube River and adjacent Delta lakes compared to those of the Black Sea, however, can vary among seasons. While the seasonal surface water temperature at both Danube station is never lower than at the Black Sea, it is a different seasonal scenario in the Sasyk Lake. In winter the surface water temperature of this lake is much lower than in the Black Sea. In particular, a steep water temperate increase relative to Black Sea is measured over months in spring, from March to May. Further in summer to autumn at all studied Danube Delta water bodies water temperature was much higher than in the Black Sea. The relative higher water surface temperature, might have not only affect many hydro-physiological conditions, but also biota as hatching in spring and biomass development during peak time of growing season. Thus, complementing regular in situ temperature data from measuring stations by data retrieved from remote sensing assessing the impact of warming for all water bodies in the whole area of Danube Delta, is strongly recommended.

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