establish and preserve self-sustaining fish populations, which includes the restoration of the longitudinal connectivity of the river necessary for fish.

The location and site-specific design of the entrance(s) to any fishway are crucial features of their functionality. Therefore, information on the movement and (horizontal and vertical) distribution of fish trying to pass the dams is a prerequisite to ensure that the fishway entrance(s) will be located in an area where it/they can be detected by as many up- or downstream moving fish as possible. Sturgeon conservation activities including passage facilitation to Iron Gate dams and further upstream, are prominently addressed in the Danube River Basin Management Plan Update 2021 of the ICPDR, endorsed by Danube Ministers in February 2022.

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Climate change in the Danube Delta and its consequences

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Abstract

Climate change in the Danube Delta, as well as changes in water temperature, evaporation from the water surface and the ecological state of wetlands have been identified on the basis of available observational data and satellite images. It was determined that during the last six decades, the air temperature in the Danube Delta has increased significantly, by more than 2 °C. Simultaneously, the precipitation slightly decreased. As a result, the climate in the studied region became drier than it was at the beginning of the observation in the 1960s. According to the air temperature increase is observing the water temperature increase and the increase of the evaporation from the water surface. It is important, that dependence between evaporation and water temperature is nonlinear. This means that even a small increase of the water temperature causes an essential increase in evaporation. In turn, such changes concern the Danube wetland. During the last years, several fires were observed, which comprised a large area. At the same time, some shallow lakes fell dry and were transformed into salt marshes.

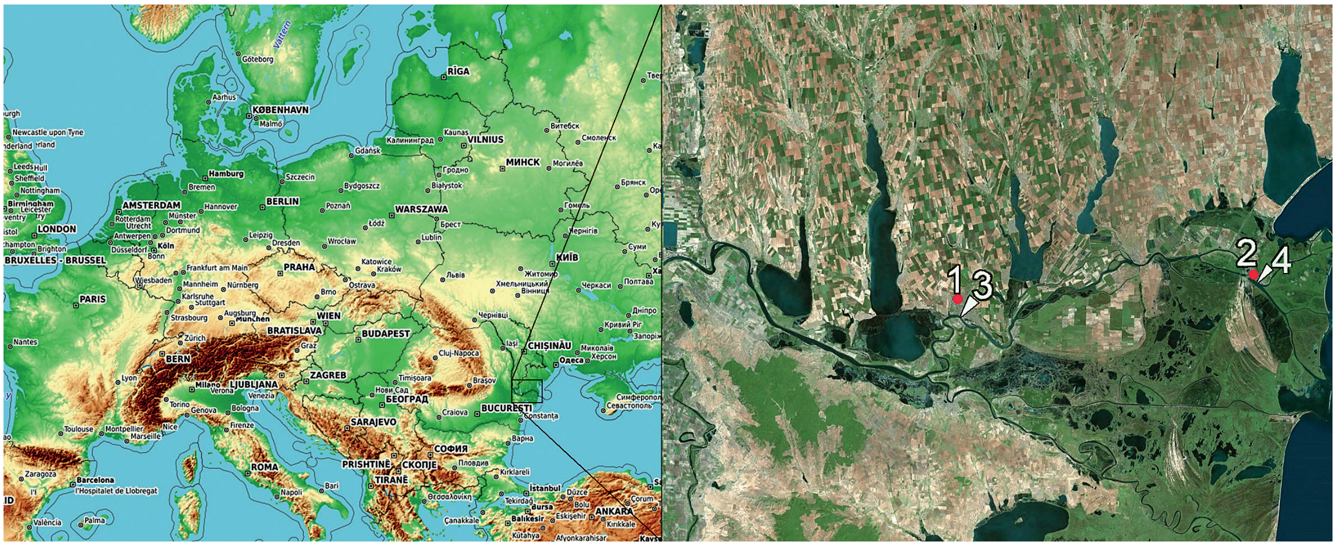

Figure 1. The location of the studied area: 1 – Izmail meteorological station, 2 – Vylkove meteorological station, 3 – Izmail hydrological station, 4 – Vylkove hydrological station

Introduction

The Danube Delta is the second largest in Europe after the Volga Delta. The length from its top to the sea edge in a straight line is 80 km. Approximately the same is the length from the north to the south. According to book edited by Mykhajlov (2004) this area is estimated at 4200 km^2, including the Ukrainian part – 830 km^2, the Romanian one – 3370 km^2. Other sources report an area of 4152 km^2 (Romanian part = 3446 km^2; Olson & Krug 2020). If we consider the Razim-Sinoe Lagoon as part of the Danube Delta, the total area reaches 5,165 km^2 (Olson & Krug 2020). In general, the boundaries of the delta and, accordingly, its area are somewhat debatable.

The location in the south-east of Europe and the abundance of water determines the richness of the delta biodiversity. In turn, the state of this richness depends on many factors. One of them is the climate and its change. There are many studies devoted to climate change in the Danube Delta and its consequences (Covaliov et al. 2022; Gastescu 2009; Mikhajlov et al. 2004; Stagl & Hattermann 2015; Stan et al. 2016; Vyshnevskyi & Shevchuk 2022). According to these studies, the air temperature in the delta is rising. The last years in the delta occurred not only warmer than usual, but very dry. In this regard, the main purpose of this study is to identify the features of climate change in the delta and its impact on other natural components of the delta ecosystem.

Materials and methods

There are two meteorological stations near the Ukrainian part of the Danube Delta: Izmail and Vylkove. Meteorological station Izmail is located on the northern outskirts of Izmail City, 4.7 km from the Danube River, meteorological station Vylkove is located almost on the river bank. Hydrological stations are located in the same cities. This gives the opportunity to study not only changes in air and water temperature but the correlation between these parameters (*fig. 1*).

Air temperature at meteorological stations is measured every 3 hours, and water temperature at hydrological stations at 8:00 and 20:00 local time.

Evaporation from the water surface in the Danube Delta was estimated on the basis of data from meteorological station Vylkove, where the observations are carried out using a GGI-3000 evaporator, the water surface of which is 3000 cm^2.

In addition to regular monitoring data, remote sensing data have been used. Most attention was paid to the images of Landsat 8 and Landsat 9 satellites, and Sentinel 2 satellite (available at https://scihub.copernicus.eu and https://earthexplorer.usgs.gov). The downloaded images were processed using ArcMap 10 program. Data from the Fire Information for Resource Management System (https://firms.modaps.eosdis.nasa.gov) was also used to analyze fires in the Danube Delta.

Results and discussion

The available data about mean annual air temperature offer the possibility to determine not only characteristic features

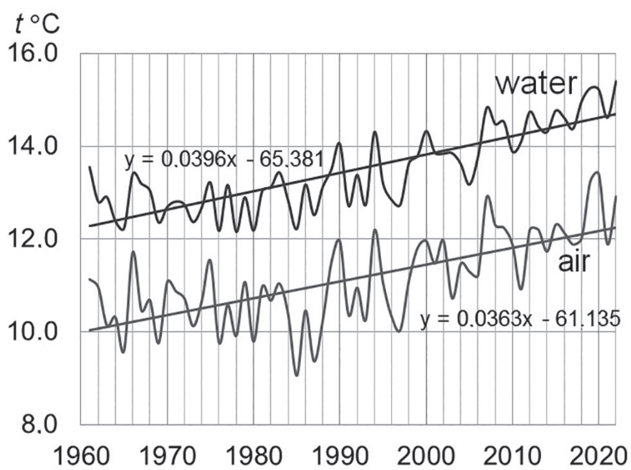

Figure 2. Changes of mean annual air and water temperature at Izmail meteorological and hydrological stations in 1961–2022

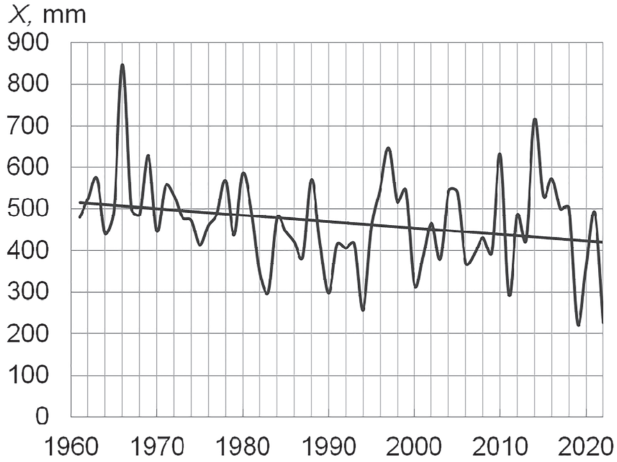

Figure 3. Changes of averaged annual precipitation at Izmail and Vylkove meteorological stations in 1961–2022

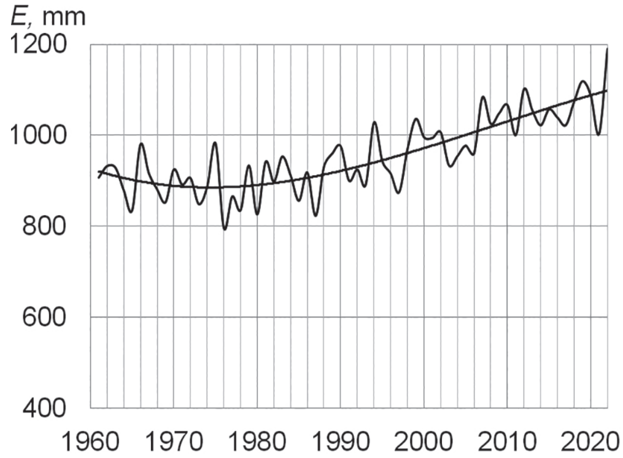

Figure 5. The changes of the calculated evaporation from water surface at Vylkove meteorological station in 1961–2022

of the climate in the studied region but also its changes during the last decades. The mean annual air temperature at Izmail meteorological station during the standard observation period of 1991–2020 was 11.7 °C, and at Vylkove station 12.2 °C. Over the past 60 years, namely 1961–2022, the mean annual air temperature in the studied area has increased significantly. The changes during this period was about 0.36 °C per decade. The highest air temperature for the entire observation period was in recent years, namely in 2019, 2020, and 2022 (*fig. 2*).

It is important that the water temperature in the Danube Delta is essentially higher than the air temperature with a difference of more than 2 °C. This excess is not stable during the year. The largest difference is observed in October when the mean air temperature at Izmail station is 11.9 °C and the mean water temperature is 16.1 °C. Even in March and April, when a rapid increase of the air temperature is observed, the water temperature is higher than the air temperature. The largest increase in water temperature is observed in July and August, the lowest in April. In recent years, the mean water temperature at Izmail station in July and August exceeded 26 °C.

As can be seen in figure 2, there is a good correlation between mean annual air and water temperature. The strongest correlation (r = 0.916) is observed between the annual values. A slightly lower correlation is observed in the warm period 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.

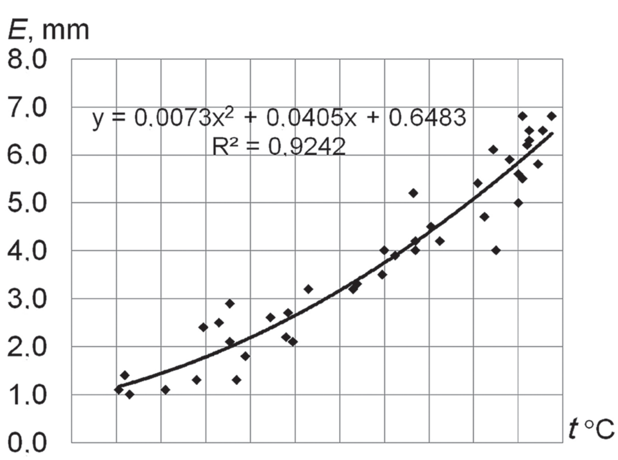

Figure 4. The dependence between air temperature and evaporation from water surface at Vylkove meteorological station

Another important factor influencing the Danube Delta state is the amount of precipitation. The mean annual precipitation at Izmail meteorological station during 1991–2020 was 449 mm, at Vylkove station 463 mm. In the previous 30 years (1961–1990) the precipitation was slightly higher, i. e. 490 and 481 mm, respectively.

As the precipitation is characterized by considerable spatial and temporal variability, averaging was carried out at the two mentioned meteorological stations to assess the changes. It turned out that the smallest precipitation was in 2019 and in 2022 (*fig. 3*).

According to the available observations at Vylkovo meteorological station, the daily evaporation layer on summer days can reach 6.0–7.0 mm and the monthly evaporation can exceed 200 mm. It was identified that evaporation from the water surface is highly dependent on air temperature. It is important, that this dependence is nonlinear. The same results were obtained for many meteorological stations and for different conditions (Vyshnevskyi, 2022) (*fig. 4*).

Based on the obtained dependence shown in Fig. 4 it is possible to determine the changes in evaporation from the water surface over a long period (*fig. 5*).

These data show that in recent decades, evaporation from the water surface has increased significantly from about 900 mm to 1100 mm. The obtained result is similar to that given for the adjacent territory of Romania (Neculau & Stan 2016), where an evaporation of more than 1000 mm was determined as well.

The results presented in (Vyshnevskyi 2022), show that the evaporation from the evaporation basins used at some meteorological stations (water surface is 20 m^2), is slightly smaller than from the evaporator GGI-3000 due to less water heating. It is about 0.9 from the data of evaporator GGI-3000. With this in mind, we obtained the mean annual evaporation from the water surface for different periods: 1991–2000 – 853 mm, 2001–2010 – 905 mm, 2011–2022 – 958 mm.

These data suggest that a part of the river flow in the Danube Delta is lost as a result of evaporation, as it is twice larger than precipitation. In the summer period the mean evaporation layer exceeds precipitation by about four times.

It should be kept in mind that most of the delta is not a water space. The main territory is covered by shallow water areas with air-water plants, which is dominated by reeds (Covaliov et al., 2022). According to the studies carried out in Romania (Stan et al., 2016), evaporation from such aquatic areas is about twice as much as evaporation from the water surface. It means that evaporation from such water bodies can reach 1900 mm and the excess of evaporation over precipitation is equal to 1450 mm. According to these data, it is possible to estimate the loss of water in the Danube Delta due to evaporation. Taking into account the delta area of 4200 km^2, the additional evaporation from natural landscapes can be estimated as 4–5 km^3. This is quite a noticeable value even for such a large river as the Danube (Vyshnevskyi & Shevchuk, 2022).

The increase of evaporation mostly impacts those parts of wetlands which are remote from the branches of the Danube River. In the Ukrainian part of the delta, such a problematic area is the Stentsivsko-Zhebrijanivsk wetland which is the most northern part of the delta. The lack of water has repeatedly affected the ecological state of this territory, but the most dramatic situation was in the fall of 2022. As a result of extreme arid conditions and the human factor, a large part of this wetland was burned (*fig. 6*).

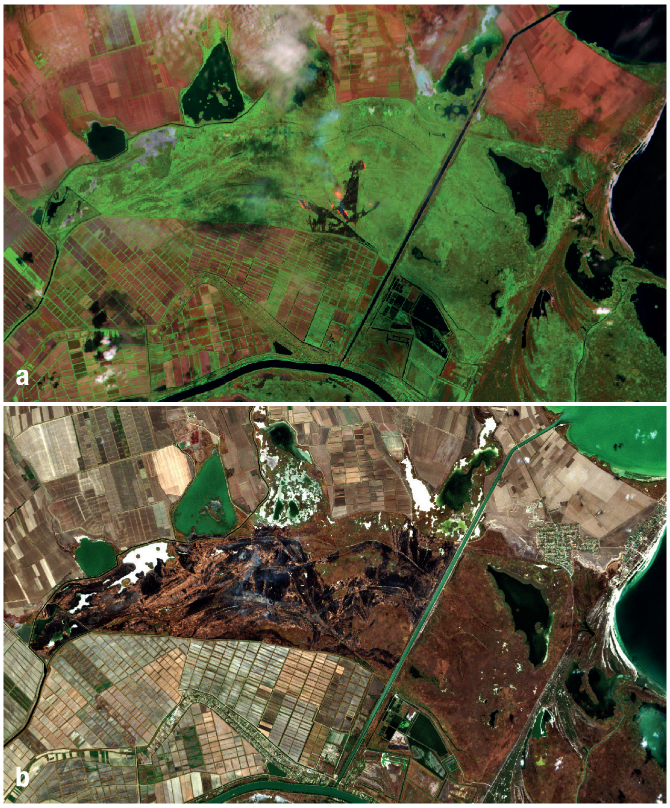

Figure 6. The burning reed and the burned Stentsivko-Zhebrijanivsk wetland on Sentinel 2 satellite images: a – on 29.09.2022, b – on 20.10.2022

Figure 7. The burning reed on the satellite images of MODIS Aqua and MODIS Terra satellites: a – on October 14, 2022, b – on October 28, 2022

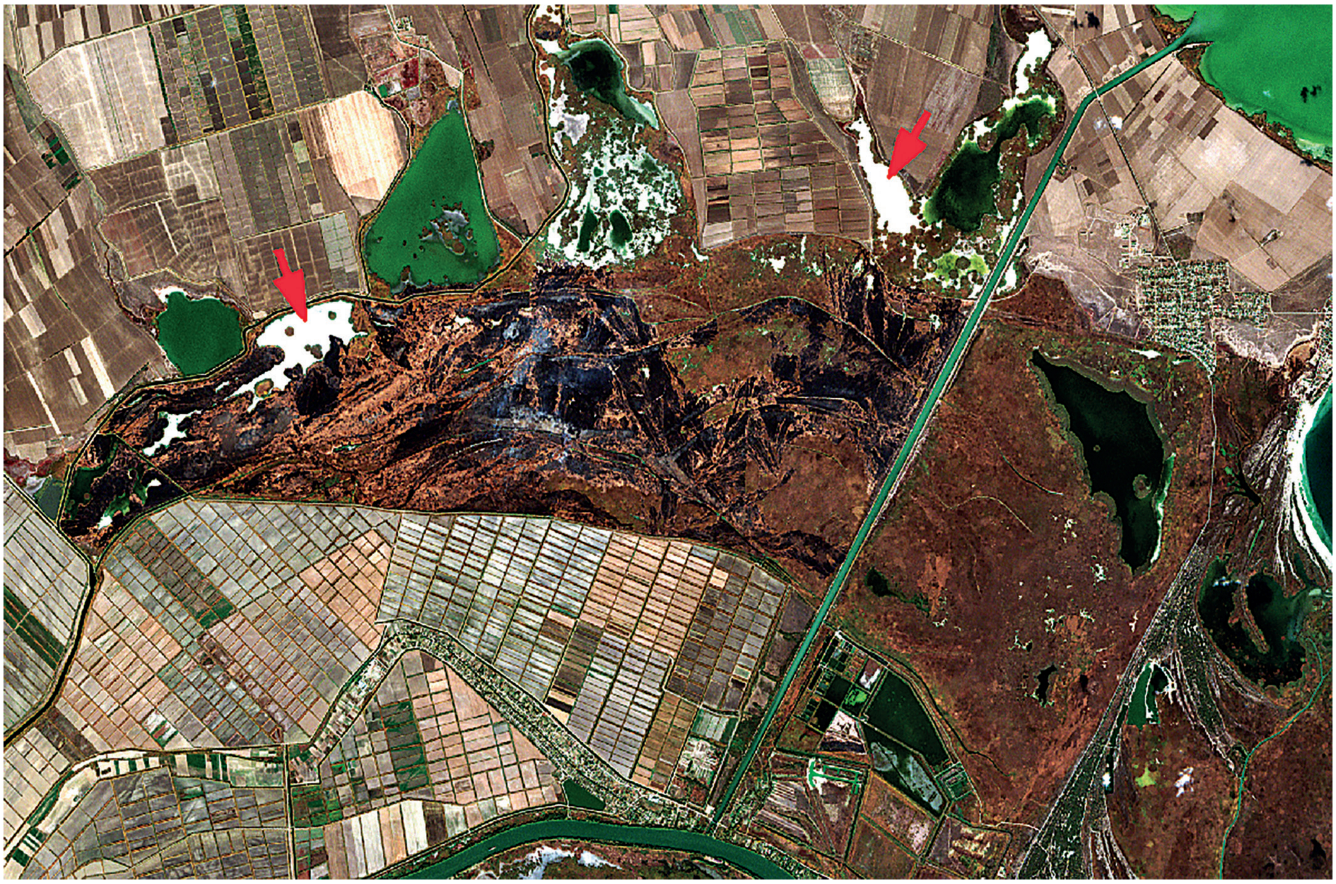

Figure 8. The salt marshes in the northern part of the Danube Delta wetland on Sentinel 2 satellite image on 29.10.2022

The satellite images obtained from the Fire Information for Resource Management System show that burning in the Ukrainian part of the delta started on September 28, 2022 and lasted until October 21, 2022. Two weeks later (October 14. 2022) the fires started in the Romanian part of the delta. They lasted till November 10, 2022 (*fig. 7 a and b*).

In the dry autumn of 2022, many shallow lakes in the Danube lakes dried up and turned into salt marshes. It can be assumed that the increase in the salinity of water became common features of many lakes (*fig. 8*).

Analysis of the satellite image in fig. 8 indicates that in the fall of 2022, the algal bloom also became significant.

Conclusions

During last six decades the air and water temperatures in the Danube Delta increased by more than 2 °C. Simultaneously, a small decrease of precipitation was observed. The smallest precipitation was observed in 2019 and 2022. In general, the climate in the studied region became drier than it was at the beginning of the observation in the 1960s. According to the air temperature increase an increase of evaporation from the water surface was identified. Such changes concern all Danube wetlands. During last years, many fires occurred, which comprised large areas. The most wide spread fires happened in autumn 2022. At this time, some shallow lakes fell dry and transformed into salt marshes.

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