Impact of Anthropogenic Activity in the Upper Danube Basin on the Danube Water Temperature Regime at Bratislava

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Abstract

The man activity in the basin affects the water temperature in the increasingly higher levels (construction of water reservoirs, construction of thermal and nuclear power plants or drainage of waste water to streams). In this paper, we focused our attention on the evaluation of the impact of anthropogenic activity to increase the thermal load of the Danube River for the period 1926–2020 at the Bratislava (Slovakia) station. In the first part, the long-term trends of a series of monthly and annual water temperatures in the Danube (period 1931–2020) are identified. In the second part, the dependence of the range of daily water temperature values is analysed at the temperature of the atmosphere in Vienna. The impact of an increase in the temperature of the Danube water due to human activity was tried to identify for lower, average, and higher flows (for Danube discharge at Bratislava water gauge 1500 m^3s^{-1}*, 2000* m^3s^{-1}*, and 3000* m^3s^{-1}*) by comparing two periods: 1932–1961, and 1991–2020. As the effect of water heating in the river stream is most noticeable during low flow (dry) periods and high air temperatures, only daily water and air temperature data from the warm months between May and September were used in the calculations. At monthly flow rates of 1500* m^3s^{-1}*, the water temperature was, on average, 0.5°C higher during the period of 1991–2020 than it was during the period of 1932–1960. This growth could be attributed to human activities in the Danube basin above Bratislava (warming of water in the built tanks, the wastewater flow to the Danube flow, etc.)*

Keywords: Impact of Anthropogenic Activity, Upper Danube Basin, Water Temperature Regime, Bratislava

Introduction

Water temperature is an essential physical property that describes the characteristics of surface waters and directly affects the plants and animals living in aquatic systems. The temperature of a stream is influenced by the surrounding atmospheric temperature, as well as other factors such as the stream's hydrological regime and geographical features of its basin, such as elevation, catchment area, and the number of natural reservoirs present in the area. Human activities within a basin, such as the construction of water reservoirs, thermal and nuclear power plants, and discharge of sewage into surface waters, have an increasingly significant impact on the temperature of water in streams [1–2].

Over the last decade, there has been a growing focus on the impact of the greenhouse effect and phenomena like the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) on atmospheric temperatures, which in turn affect the temperature of in-stream water [3]. Several studies have been conducted to examine the long-term trends in Danube River water temperatures [4–7]. The impact of NAO on multi-year water temperature oscillations in the Danube River was studied in [8]. In addition, [9] analyzed the water temperature patterns of the Danube River and its tributaries in Croatia, with a particular focus on changes that occurred over the past twenty to sixty years, potentially due to climate change, climate variability, or both, especially during the past thirty years

Understanding the relationship between air temperature and water temperature is important for scientists to estimate how the temperature of a stream is likely to respond to future projections of the increases in surface air temperature [10–15]. Unlike air, water has a particularly high specific heat capacity, its temperature can be considered a stable indicator of long-term trends. Increased stream water temperature, as well as an increased heat flow in a river should be viewed as an expressive signal that the aquatic environment is warming.

The aim of this study is, firstly, to evaluate changes in the statistical characteristics of monthly and daily water temperature values in the Danube River at the Bratislava station during three 30-year periods: 1931-1960, 1961-1990, and 1991-2020. The second part of the study focuses on determining the impact of human activities on the temperature of the river water. Before assessing the influence of anthropogenic activities on changes in water temperature, it is necessary to separate other factors from the measured water temperature time-series, particularly:

- the impact of atmospheric temperature on the increase in water temperature, and;

- the impact of hydrological regime on water temperature during dry and wet periods.

Data

The earliest daily measurements of water temperature in Slovakian streams and rivers date back to 1925 [16], when the measurement of water temperature was investigated at the Bratislava gauging station in the Danube River for a 25-year period (1925–1950). The long-term water temperature characteristics of streams in Slovakia before 1960 were published in [17]. The temperature records prior to 1980 were processed in [18]. The recent trends of water temperature in Slovak rivers were studied in [19], while daily water temperature data for the Danube River at Bratislava for the period 1956-2000 were analysed in [20].

During the analysis of the temperature regime of the Danube River, we used a series of daily temperatures measured at the Bratislava station at 7:00 am. The Danube River flows through Vienna, and the long-term annual average temperature of the atmosphere Ta at the Vienna Hohe Warte station for the period 1931–2020 is almost identical to the long-term average temperature of the Danube River at Bratislava (Figure 1).

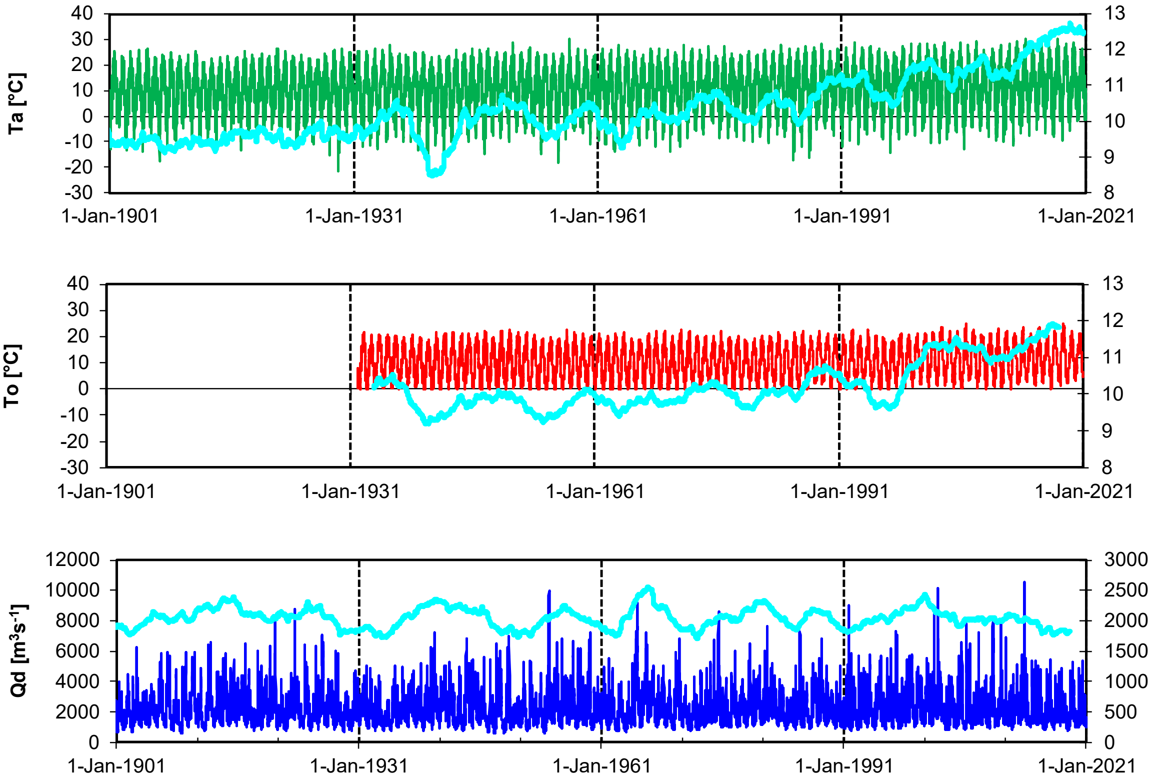


Fig. 1. The course of daily air temperature values Ta at the Vienna-Hohe Warte station, water temperatures To at the Bratislava station, and the discharges Qd of the Danube at the Bratislava station. The light blue colour shows the 4-year moving averages

The water temperature in the river is in equilibrium with the temperature of the environment through which it flows. A detailed analysis of the dependence of the temperature of the Danube River and the temperature of the atmosphere from Germany to the mouth of the Danube can be found in [21].

When evaluating the hydrological regime of the Danube, we used average daily flows evaluated at the Bratislava station for the period from 1931 to 2020. Water level measurements on the Danube at the Bratislava station have been carried out since 1825. Average daily flows of the Danube at the Bratislava station have been evaluated since 1876. A detailed analysis of long-term trends of the Danube at stations along its length is presented in [22].

Results

Statistical analysis of Ta, To, and Q during 1931–2020

Changes in water temperature, air temperature and Danube discharge at the Bratislava station were evaluated on a series of average monthly data for the period 1931–2020.

Summer-autumn air temperatures at Vienna station: Hohe Warte were decreasing in the period 1861–1910, increasing in the period 1910–2020. Figure 2 plots the 21-year moving averages of air temperature for the summer-autumn and winter-spring seasons. In the winter-spring season, air temperature growth has been pronounced since the 1960s. A comparison of the period 1931–1960 with the period 1991–2020 shows that temperatures rose more significantly in the months January to March.

An analysis of long-term trends in the water temperature of the Danube River reveals that the water temperature increased insignificantly until 1990, after which a significant increase was recorded. Figure 2 plots the 21-year moving averages of the

Danube water temperature for the summer-autumn and winter-spring seasons. The increase in water temperature is mainly observed in the months of August, October, November, and December (as shown in Table 1).

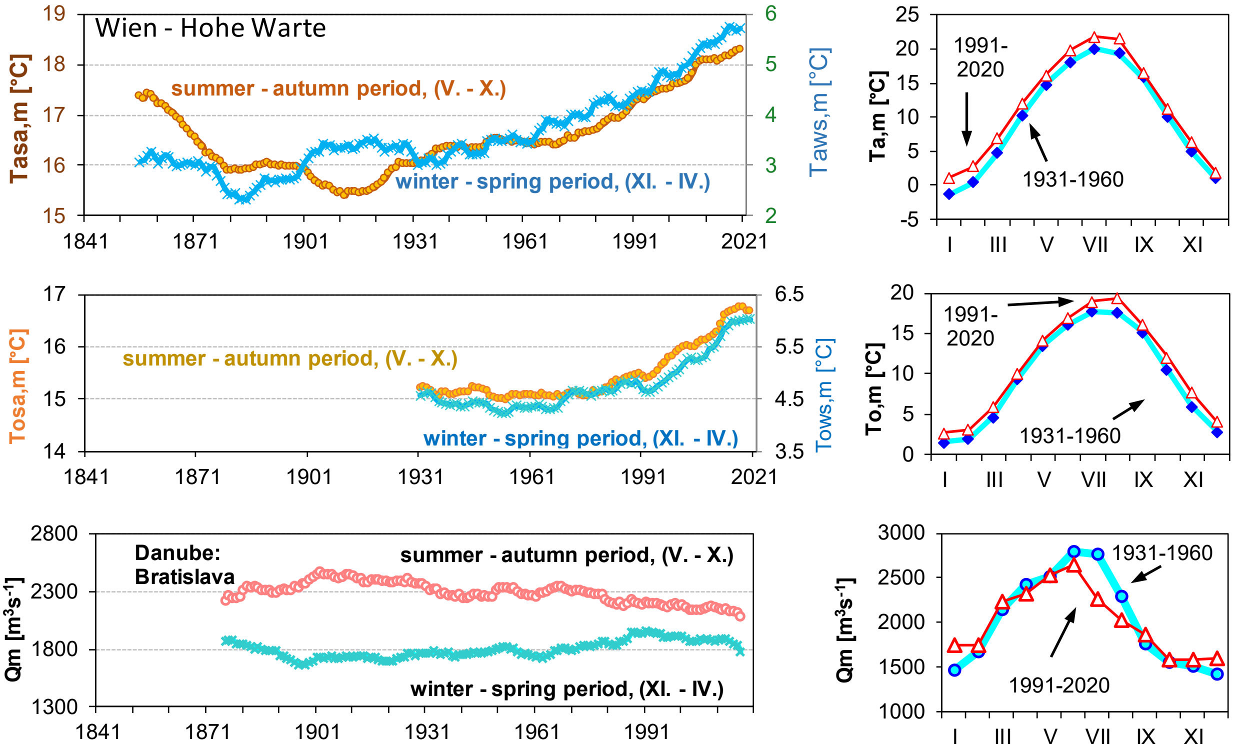


Fig. 2. The course of moving averages of seasonal air temperatures *Ta*, water temperatures *To* and monthly discharge Qm (left figures). Comparison of monthly air temperature *Ta*, water temperature *To* and monthly discharge Qm during two periods 1931–1960, and 1990–2020. (right figures)

Tab. 1. Basic monthly water temperature *To* characteristics in the Danube River at Bratislava, period 1931–2020

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	XI-IV	V-X
To,mavg	1.90	2.44	5.14	9.60	13.59	16.40	18.12	18.24	15.56	11.29	6.82	3.23	**10.23**	4.85	15.53
To,mmin	0.02	0.00	1.83	6.50	7.40	13.34	14.90	15.70	11.39	7.47	3.49	0.27	**8.53**	3.06	13.89
To,mmax	4.91	5.76	8.02	12.83	16.39	20.46	22.31	23.30	18.25	14.01	9.35	6.38	**12.62**	7.14	18.48
P10	0.38	0.74	2.81	8.00	12.17	14.79	16.21	16.73	14.10	9.55	5.38	1.88	**9.23**	3.78	14.51
P50	1.64	2.27	5.29	9.55	13.57	16.31	18.26	18.01	15.47	11.43	6.75	3.10	**10.10**	4.78	15.54
P90	3.68	4.19	6.92	11.52	15.14	17.90	19.87	20.00	17.42	12.72	8.56	4.83	**11.40**	6.05	16.64
tr	0.019	0.019	0.020	0.014	0.017	0.013	0.019	0.028	0.014	0.026	0.023	0.021	**0.019**	0.019	0.019
cs	0.41	0.23	-0.35	0.11	-0.76	0.64	0.05	1.03	-0.12	-0.52	-0.01	0.28	**0.51**	0.41	0.60
cv	0.649	0.554	0.299	0.135	0.101	0.080	0.079	0.076	0.083	0.116	0.179	0.377	**0.079**	0.185	0.058

To,mavg – long-term monthly average water temperature, *To,mmin* – monthly minimum water temperature, *To,mmax* – monthly maximum water temperature, P10, P50, P90 – percentiles, *tr* – long-term monthly linear trend slope, *cs* – coefficient of assymetry, *cv* – cofficient of variability

Tab. 2. Average monthly, yearly and seasonal water temperature *To* in the Danube River at Bratislava during three periods: 1931–1960, 1961–1990, and 1991–2020

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	XI-IV	V-X
1931-1960	1.49	1.90	4.66	9.39	13.52	16.14	17.78	17.63	15.19	10.50	6.01	2.85	**9.79**	4.38	15.13
1961-1990	1.59	2.42	4.95	9.39	13.34	16.11	17.66	17.89	15.42	11.44	6.63	2.88	**10.01**	4.64	15.31
1991-2020	2.67	3.10	5.90	10.12	14.20	16.97	18.98	19.38	16.08	12.09	7.73	4.03	**10.98**	5.59	16.28

Analysis of the water temperature must also take into account the amount of water in the stream. The evolution of the monthly Danube discharge at Bratislava station for the observation period 1876–2020 is shown in the lower Figure 2. A comparison of the two thirty-year periods shows that in the period 1991–2020 the flows in the summer months of July and August were significantly lower. In contrast, flows were higher in the winter months.

Figure 3 presents the dependence of the daily values of the Danube water temperature at the Bratislava station on the average daily air temperatures at the Vienna station for the two periods analysed: 1932–1961 (in 1961 daily values are only available from November) and 1991–2020. Also plotted in the figures are the values estimated by an empirical 3-parameter exponential model [10–11] to indirectly estimate the daily Danube water temperature at Bratislava station from the air temperature at Vienna station. Equations of the model are as follows:

$$To = 20.9324/(1+\mathrm{Exp}(-0.185613*(Ta-11.162))), \quad \text{for } 1932–1961 \qquad (1)$$

$$To = 23.8008/(1+\mathrm{Exp}(-0.147026*(Ta-13.0399))), \quad \text{for } 1991–2020. \qquad (2)$$

In the summer months of July-August (at air temperatures above 22°C), the empirical curves differ significantly (Fig. 4). One reason for this is that the July-August flows were significantly lower in the 1991–2020 period.

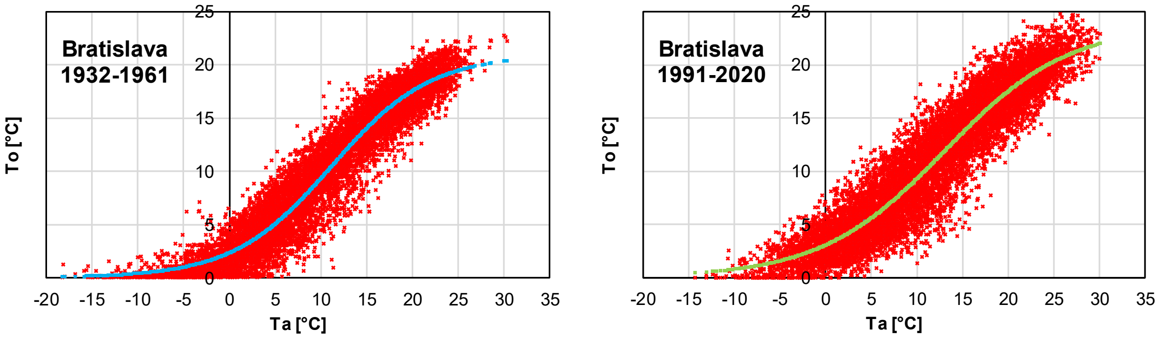


Fig. 3. The relation between air temperature *Ta* and water temperature *To* at Bratislava during two periods 1932–1961 (left), and 1991–2020. (right)

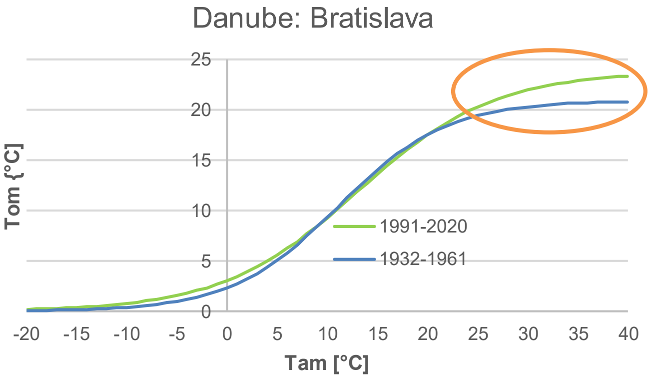


Fig. 4. The difference between empirical relations between air and water temperatures during two periods 1932–1961, and 1991–2020

Identification of the anthropogenic activities impact on water temperature

We have attempted to identify the impact of human activities on the increase in Danube water temperature for lower, average, and higher flows (1500, 2000, and 3000 m^3s^{-1}). The effect of water heating in the stream is expected to be most pronounced during low flows and high air temperatures, making it easier to identify.

In Figure 5a, we have segregated the water temperatures in the Danube based on the flow rates (Q< 1400 m^3s^{-1} and Q>2100 m^3s^{-1}). At discharges below 1400 m^3s^{-1} the water temperature of the Danube during summer-autumn months is significantly higher. We have also segregated the rise and fall of air temperatures for months I-VI and VII-XII (Figure 5b). The hysteresis curve shows the lag of water temperature behind the air temperature.

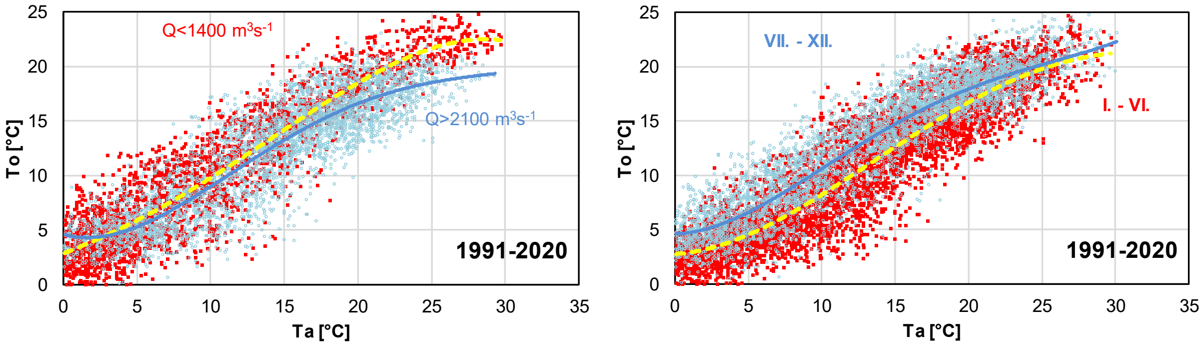
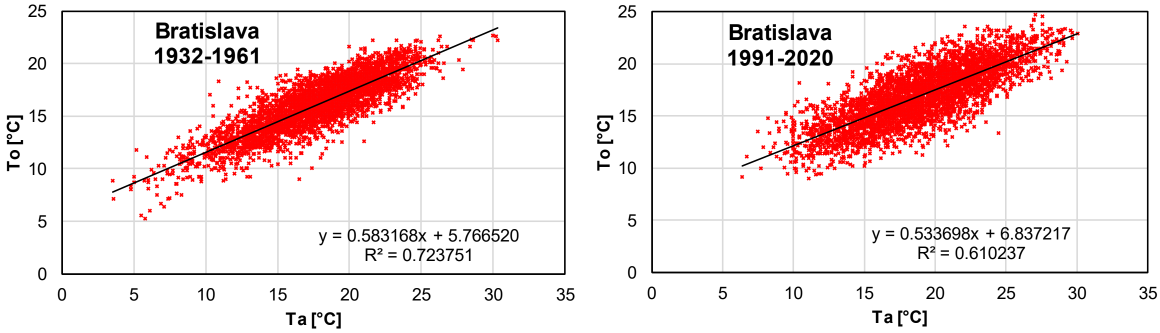


Fig. 5. a) The difference of the dependence between air and water temperatures at discharges Q< 1400 m^3s^{-1} (red points) and Q>2100 m^3s^{-1} (blue points); b) The difference of the dependence between air and water temperatures at January-June and July-December during 1991–2020.

To analyse the increase in water temperature in the Danube due to anthropogenic activity (in the two periods 1932–1961, and 1991–2020) we only use the daily water and air temperature data warm months between May and September (Figure **6**). For both periods, we obtained regression equations to estimate water temperature using multivariate regression analysis based on air temperature Ta and Danube discharges Q:

$$To = 0.573*Ta - 0.00034*Q + 6.762, \qquad \text{for } 1932\text{–}1961 \qquad (3)$$

$$To = 0.497*Ta - 0.0007*Q + 9.147, \qquad \text{for } 1991\text{–}2020. \qquad (4)$$



(a) (b)

Fig. 6. The dependence between air and water temperatures of May-September 1932-1961 (a) and May-September 1991–2020 (b), the Danube River at Bratislava station

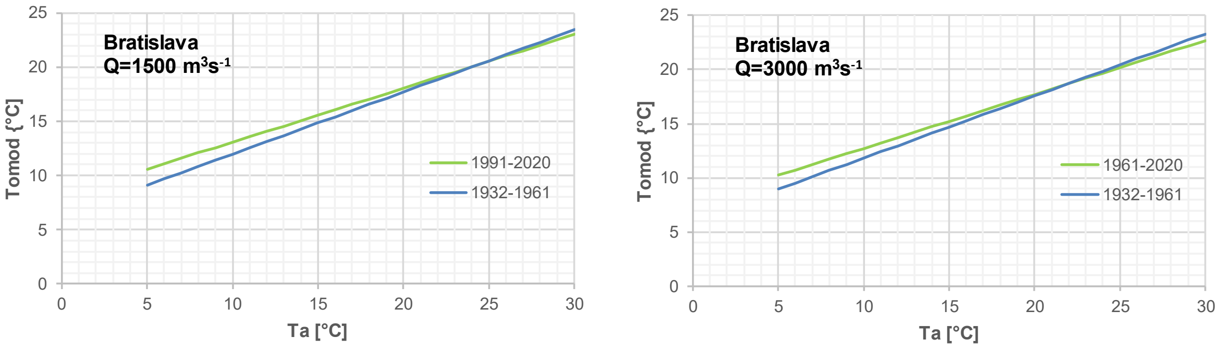


Fig. 7. The modelled values of water temperature related to discharge 1500 m^{3}s^{-1} (a), and 3000 m^{3}s^{-1} (b), Danube, Bratislava for the two compared periods according to equations (3) and (4)

At monthly flow rates of 1500 m^{3}s^{-1}, the water temperature was, on average, 0.5°C higher during the period of 1991–2020 than it was during the period of 1932–1960 (Figure 7a). Currently, at a flow rate of 3000 m^{3}s^{-1}, the water temperature was, on average, 0.3°C higher than it was 60 years ago (Figure 7b).

Conclusion

- The long-term average (arithmetic mean) annual water temperature of the Danube at Bratislava (1926–2020) is 10.23°C. The highest average annual water temperature for the whole period of observations was in 2018 (12.62°C), the lowest ones in 1996 and 1940 (8.56°C; 8.79°C, respectively).
- The average annual water temperature is highly related to average annual air temperature. The water temperature of the stream equilibrates with the temperature of the environment through which it flows.
- The average annual water temperatures of the Danube and of the air in Vienna (arithmetic mean) have had a significant upward trend over the last 30 years. The water temperature was 9.79°C in 1931–1960; 10.01°C in 1961–1990, and 10.98°C in 1990–2020. The coefficient of increase was 0.019 during the 90-years period.
- In the first half of the year, water temperatures are about 1.6°C lower than when temperatures drop in the second half of the year.
- With air temperatures at 20°C and high monthly discharges, daily water temperatures can be up to 4.5°C lower than at low flows.
- We identified the effect of temperature increase due to human activities for low, average and high flows only for the warm months of May-September. At monthly flow rates of 1500 m^{3}s^{-1}, water temperature is currently on average 0.5°C higher than 60 years ago. At a flow rate of 3000 m^{3}s^{-1} the water temperature is currently on average 0.3°C higher than 60 years ago

Determining the impact of anthropogenic activity on water temperature rise is not a simple matter. Measured water temperature values are influenced by a number of different factors that have a much greater influence on the change in water temperature in the stream than the reservoirs and wastewater discharged into the Danube. In order for the influence of wastewater on thermal pollution to be identifiable at all, we had to treat only days with low flows. If at a flow rate of 1000 m^{3}s^{-1} the water temperature rise is about

0.8 °C, then at 2000 m^3s^{-1} it will be only 0.4 °C. Identification of such small deviations borders on the accuracy of the in-stream water temperature measurements, therefore the warming of the water due to human activities in the catchment cannot be considered demonstrable.

However, the long-term trend of the weighted annual water temperatures of the Danube at the Bratislava station is very remarkable. This series has a zero trend, which means that the heat load on the Danube is constant. If there were an increase in the water temperature of the Danube flow due to climate change, an increase should also be observed in the series of weighted average annual water temperatures. This result should also be verified on other streams, whether within Slovakia, Europe or even the whole world.

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