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The influence of reservoirs on water temperature in the downstream of Ipeľ

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The temperature regime of river systems is influenced by seasonal temperature stratification in reservoirs and climate change. The release of cold water from reservoirs can affect river temperature, with a decrease in river temperature during warm periods and an increase in river temperature during winter. However, warmer air temperatures and increased solar radiation may reduce the influence of reservoirs on downstream temperatures in the future. The cooling potential of reservoirs remains strong for river reaches downstream of reservoirs with strong temperature stratification. The study analyzed air temperature trends at two climate stations, Boľkovce and Málinec, over different time periods. Data on the temperature of the water were collected from a number of stations located above the reservoirs: Smolná I and Smolná II and Málinec, and several stations below the reservoir, namely Málinec, Kalinovo, Holiša and Slovenské Ďarmoty downstream of the Ipeľ River. The Málinec Reservoir, which regulates the upper part of the Ipeľ River and serves as a drinking water reservoir, was built in 1986–1993 and put into operation in 1994. The analysis was divided into two parts. The first part analyzed data from stations with time series before the construction of Málinec reservoir, while the second part analyzed data from stations with time series after the construction of the reservoir. Increasing water temperatures were observed throughout the year, while increasing air temperatures were significant in warm months. The influence of the reservoir can be seen in the slight change of the mean monthly temperatures. The mean temperature decreases in the summer months and increases in the winter months in the period after the construction of the reservoir.

KEY WORDS: temperature stratification, reservoirs, trends, Ipeľ

Introduction

Climate change, characterized by rising air temperatures, is having a negative impact on the environment and social systems. One of the consequences of these changes is an increase in water temperature in rivers, which represent a unique ecosystem. The main factors influencing water temperature variations are groundwater inflow, evaporation, return flow, atmospheric and solar radiation, and vegetation-topographic radiation. Human activities, such as the construction of dams, the regulation of river flow and changes in land use, can also have an impact on these characteristics. Changes in water temperature have a significant effect on the physical, chemical and biochemical properties of rivers, affecting water quality and biological processes. Aquatic organisms depend on water temperature for their development, distribution and ecology, and their life cycles are regulated by temperature and hydrological and hydraulic conditions. Considering the potential negative consequences of increasing water temperature, it is necessary to study the influence of these factors, which is supported by advanced machine learning techniques that can facilitate the analysis of the evolution of water temperature in open waterways.

The study of water temperature in rivers and water reservoirs has received much attention in recent decades (Sleziak et al., 2023; Soomro et al., 2023; Varga et al., 2023; Varga and Velísková, 2021). This is mainly because of concerns about the effects of climate change and human intervention. Poorly controlled anthropogenic activities and the inability to maintain minimum biological flows and water levels disrupt the ecological functioning of ecosystems. Rising water temperatures affect water quality, habitats and the availability of water for human use. Reduced water flow exacerbates the heating effect of dilution, which increases the concentration of pollutants. Warmer water temperatures also reduce dissolved oxygen, making the flow toxic to freshwater organisms, including fish.

Guo et al. (2023) presents a novel approach to determining the evolutionary patterns and driving mechanisms of water temperature and offers fresh insights into quantifying the extent of water temperature changes influenced by dam construction and climate change as well as its intrinsic connection with various meteorological factors. Based on the analysis results, water temperature shows both warming and cooling trends during different periods.

(Bonacci et al., 2022) deals with the analysis of water temperature changes in the Drava River in different time intervals and its relation to air temperature. The aim of the study by Long et al. (2019), was to analyze the thermal regime and flow variation in two newly constructed reservoirs in the lower reaches of the Jinsha River (Xiluodu (started operation in 2013) and Xiangjiaba (started operation in 2012)). They used water temperatures in both reservoirs and combined them with longer-term observations of flow and temperature in the Jinsha River prior to filling. They used a set of indices to evaluate the accumulation effect of water temperature after the filling of the two reservoirs and to analyze the change in flow from 1980 to 2015. They used the data to calibrate a two-dimensional hydrodynamic model (CE-QUAL-W2), which they applied to analyze the spatial and temporal distribution of water temperature and the formation of thermal stratification in the two reservoirs.

Wiejaczka et al., (2018) present the spatial and temporal dynamics of water temperature in two reservoirs on the upper reaches of the Dunajec River in the Polish Carpathian Mountains, with the aim of presenting how spatial patterns and temporal evolution of water temperature in the reservoirs influence water temperature in the river. Based on measurements, he showed that the reservoir complex influences the river water temperature over the year and that the existence of a smaller lower reservoir can dampen the cooling or warming effect of the main reservoir on the river. Study by Gough, (2008) investigated temperature variability in three different climatic conditions. The researchers found that the standard deviation accurately measures variability in random climates, but is not effective for ordered and oscillating climates. Instead, a direct calculation of diurnal variability provides a more accurate representation. The study focused on two Canadian cities, Toronto and Calgary. Toronto's climate was found to be orderly, characterized by humidity, cyclones, and winds from Lake Ontario, resulting in lower temperature variability. In contrast, Calgary's climate, influenced by aridity and Chinook winds, showed greater temperature variability, particularly in winter. The study also noted a significant decrease in *Tmin* exceedance of 5 degrees Celsius in Toronto. Overall, both cities showed a reduction in diurnal temperature variability, but only Toronto's decrease was deemed statistically significant.

In our paper we build on the work of Gough, who used a method to analyze the temperature of the water in the river and combine it with the influence of the reservoir. The assessment itself is divided into two parts according to the data available: in the first part, stations with data for the period prior to the construction of the reservoir are used. In the second phase, stations with shorter measurement periods are included in the assessment and compared with the first.

This comparison showed that the reservoir influences the river water temperature over the year and has a cooling effect on river in summer and warming effect on the river over the winter months of the year.

Material and methods

In this paper we focused on the Málinec Reservoir and how it influences the temperature regime of the upper Ipeľ River (Fig. 1). It was built between 1986 and 1993 and serves as a drinking water reservoir for surrounding districts and as a regulator of upper Ipeľ River. It has a volume of 26.7 million m^3 and a surface area of 1.38 km^2. The length of the dam is 620 m and its height is 48 m. It has been in operation since 21 January 1994. (Fig. 1).

We had data from seven water gauging stations and one climate station (Fig. 2). The stations Málinec Smolná 1 and 2 and Málinec – Ipeľ above the water reservoir, Málinec – Ipeľ below the water reservoir, Kalinovo, Holiša and Slovenské Ďarmoty and as a climatic station we have selected the station Boľkovce which is located between the water gauging stations Kalinovo – Holiša. Among these stations, the last three have measurements which pre-date the construction of the water reservoir

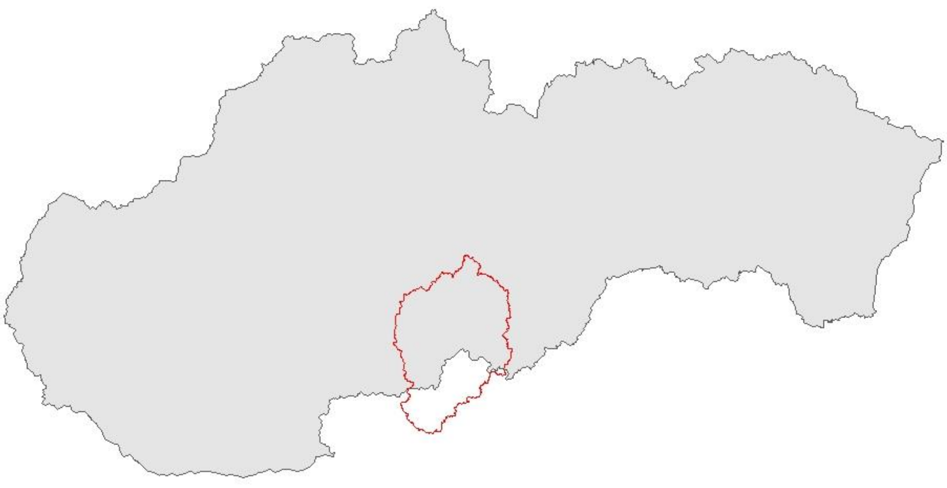

Fig. 1. Location of the area of interest within the Slovak Republic.

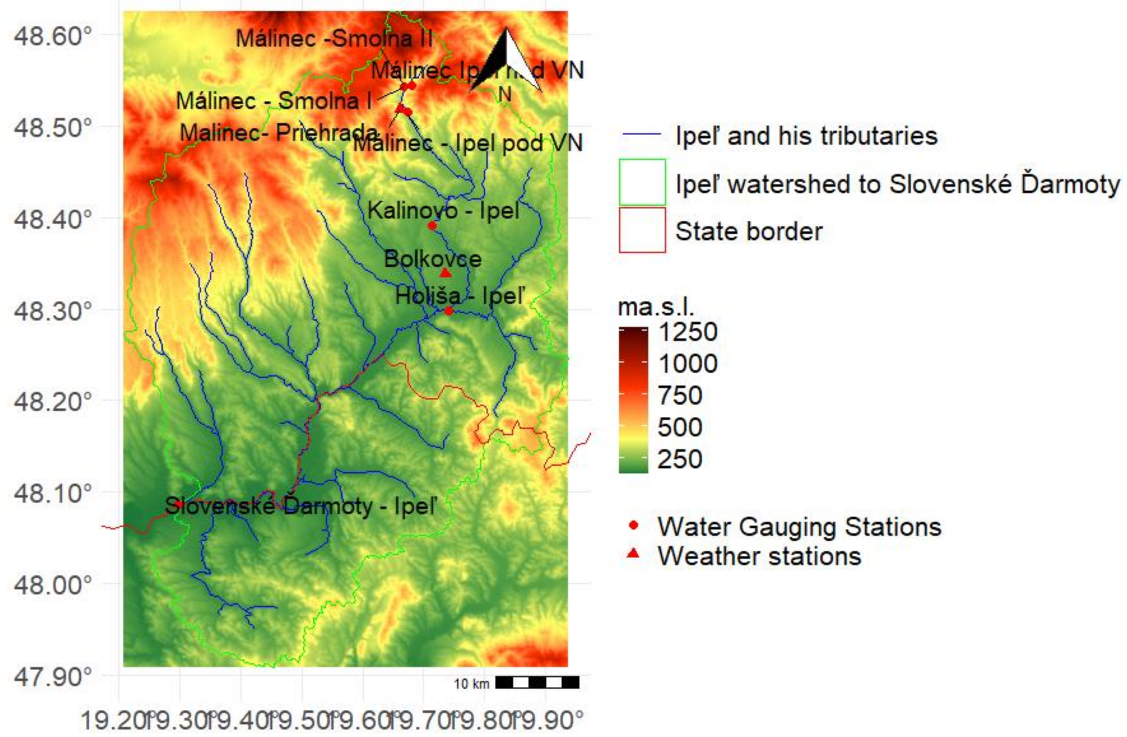

Fig. 2. Ipeľ to Slovenské Ďarmoty water catchment area and water and climate stations.

itself, and after reviewing them, we have chosen the years from 1 January 1969 – 31 December 2020. These data were used in the first phase of our analysis. In the second phase, we used data from all stations, choosing the period from 1 January 2009 – 31 December 2020.

Statistical analysis

This section introduces the statistical analysis and is based on an approach introduced by Gough, (2008). This introduced a formalism for standard deviation and an alternative measure of daily variability. The standard deviation is defined as follows:

$$SD = \left[\sum_{i=1}^{N-1} (T - Tavg)^2/(N-1)\right]^{1/2} \quad (1)$$

where

N – is the number of data elements (e.g., 30 days per month),

Tavg – is the monthly average of *T*.

The alternative measure, DTD, calculates the departure of a given day, not from the monthly mean, but from the value of the previous day. Since it is not important for this work whether the change is positive or negative, all differences were taken as positive. This, following Karl et al. (1995), is represented as:

$$\text{DTD} = \sum_{i=1}^{N-1} |T_i - T_{i-1}|/(N-1) \quad (2)$$

where

N – is number of days in the month,

i – is a counter that marches through the days of the month.

The so-called Day-to-Day (DTD) method quantifies the climatic variations in temperature between two adjacent days over the course of a year. The DTD method is a very useful tool for the analysis of climate variability. It has been shown that changes in DTD values over time can have a significant impact on a range of environmental and social processes. As the process of global warming intensifies, the DTD method has a particular quantitative definition and explanation of the causes and possible consequences of climate processes. To compare the two measures, a ratio, G can be taken of the two measures:

$$G = DTD/SD \quad (3)$$

Temporal trends using the periods 1969–2020 and 2009–2020 climate records are tested for statistical significance using linear regression.

Results and discussion

As already mentioned in the first phase, we focused on the stations from which data were also available for the period prior to the construction of the Málinec Reservoir. The analysis itself was carried out in three time frames: Annual, Monthly and Daily, in which we applied the described statistical analysis. Fig. 3 shows a series of mean annual water temperatures for the Ipeľ River, measured at the stations Kalinovo (red color) and Holiša (green color), and air temperatures measured at

Boľkovce climatic station (blue color), from 1969–2020. The regression lines are plotted with their numerical values and the squared values of the linear correlation coefficients, R^2. The direction of increasing air temperature is observed to be greater than the trend of rising water temperature.

The Fig. 4 shows a graph representing the range of differences in annual mean water and air temperatures from 1969 to 2020. There are six lines on the graph, each representing different time periods (1969–1994, 1994–2008, 2008–2020) and types of temperature differences (*ΔTHo* and *ΔTKa*). The temperature differences are defined as *ΔTHo* = ToHomean – TaBolmean and *ΔTKa* = ToKamean – TaBolmean, where *Ta* is the air temperature (Boľkovce, TaBol station) and *To* is the discharge temperature (ToKa for Kalinovo station and ToHo for Hoľiša station). These differences show how the mean annual water and air temperatures have varied over different time periods. The first period preceded the construction of the reservoir and its commissioning. The second period begins with the commissioning of the reservoir and ends with a change in the method of measuring water temperature in the river. And the last period is after the change in the method of measuring the water when, instead of measuring at 7 a.m. as it was in the second period, the stations switched to automatic mode and the daily water temperature is the average of the hourly data. By comparing these lines on a graph, you can see how the temperature differences have changed over time.

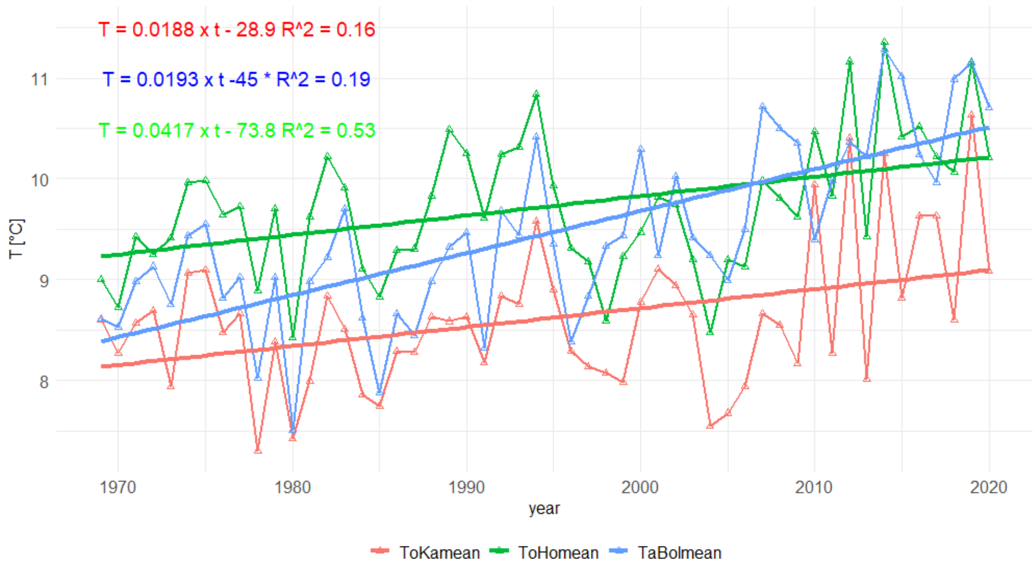

Fig. 3. Series of mean annual water temperatures of the Ipeľ at the stations Kalinovo (ToKamean, red color) and Hoľiša (ToHomean, green color), and air temperatures at the Boľkovce (TaBolmean, blue color), TV, from 1969–2020.

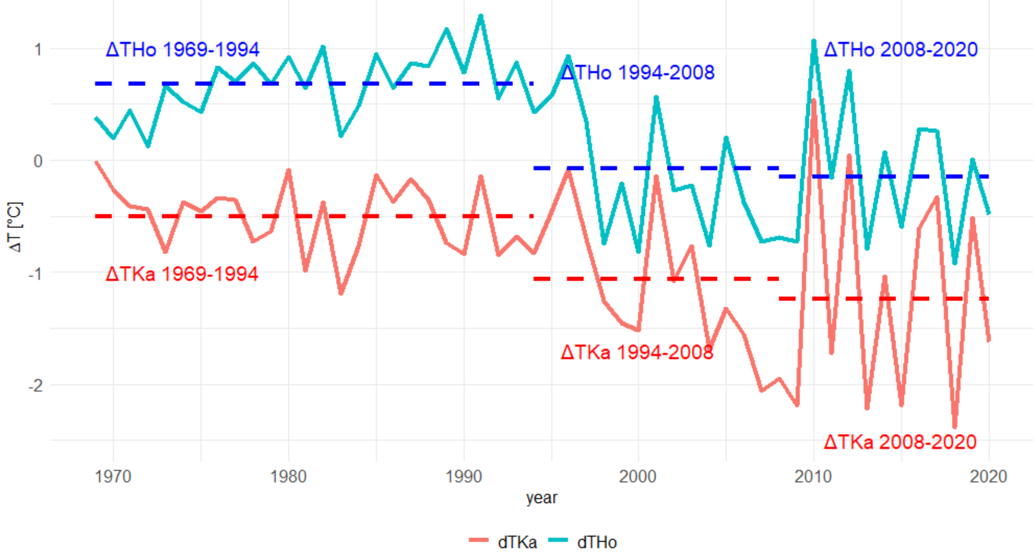

Fig. 4. Series of differences in mean annual water and air temperatures, ΔTHo = ToHomean – TaBolmean and ΔTKa = ToKamean – TaBolmean , from 1969–2020.

In Fig. 5 we can see the histograms for the stations Kalinovo, Holiša and Boľkovce, where the lighter color represents the period before the construction and commissioning of the Málinec reservoir and the dark color represents the period after commissioning. While the air temperature shows an increase in all months of the year, the water temperature at both stations shows an increase in the winter months and a decrease in the summer months, due to the influence of the reservoir. Graphical representations of a series of annual values of DTD for water temperatures measured at Kalinovo (red color) DTD_ToKa and Holiša (green colour) DTD_Ho, annual values of DTD for air temperatures measured at Boľkovce (blue color), DTD_TaBol from 1 January 1969–31 December 2020 are shown in Fig. 6. The lines of linear regression are drawn for each series and their analytical expressions, the squares of the correlation coefficients (R^2), are also shown. The DTD values for the air are significantly higher than the DTD values for the water, which is understandable given the fact that they are different media. However, it is important to note that the trend of the air temperature DTD series show an insignificant increase, while the trend of the water temperatures shows a significant decrease, especially for the DTD_ToHo. From this it can be concluded that the water of the Ipeľ River downstream of the reservoirs is heating up more slowly than the surrounding air, which could have a positive effect on the part of the Ipeľ River downstream of the Málinec Reservoir.

For 1969–1993 and 1993–2020 daily water and air temperature data, G is calculated for each month of the year and then values for each month are averaged over the given time period. As seen in Fig. 7, G is less than 1 throughout the year, ranging from 0.5 to 0.65 for air temperature and 0.3–0.5 for water temperature. This suggests these temperature does not have a random climate and there is some degree of order in all months of the year. Seasonality of this ratio is not strong, although there is more randomness (higher G value) in summer for both air and water. It can also be seen that the G-values for water temperature obtained from the data for the years 1994 to 2020 are more similar to each other compared to the previous period. In the second part we have included data from other stations, namely Málinec Smolná 1, 2 and Málinec – Ipeľ, which are located at the inflow to the reservoir, and Málinec – Ipeľ below the reservoir (Málinec – Ipeľ below WR) and Slovenské Ďarmoty. Daily water and air temperatures at the stations for the period 2009–2020 are shown in Fig. 8. The shades of grey represent the stations located above the reservoir. The blue station is located directly below the reservoir (Málinec – Ipeľ below WR) and the green stations are Kalinovo, Holiša and Slovenské Ďarmoty. The air temperature from the Boľkovce station is shown in orange. As can be seen from these data, the water temperature is significantly affected at Málinec – Ipeľ under WR and partly in some years also at Kalinovo station. The graph in Fig. 9 shows a histogram of the stations' mean monthly temperatures for the period 2009–2020. The graph shows in particular the influence on the station Málinec – Ipeľ under WR, where the average water temperature in the winter months is significantly higher than the values of the other stations and, on the contrary, in the summer months the temperature is significantly lower than the other stations. For the other sites below the dam, the effect is not as strong as for this site, but as the results of the first part show, there is an effect on the water temperature

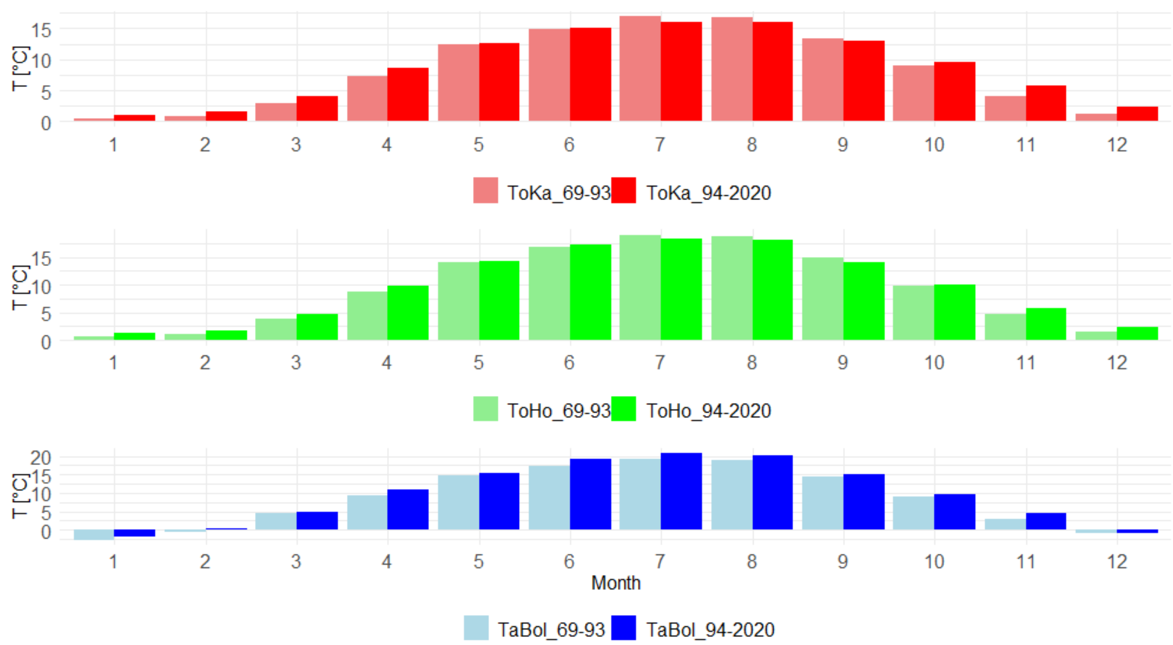

Fig. 5. Histograms of the mean monthly water temperatures of the Ipeľ river at the Kalinovo (red color) and Holiša (green color), and the air temperatures at Boľkovce (blue color), for periods 1969–1993 and 1994–2020.

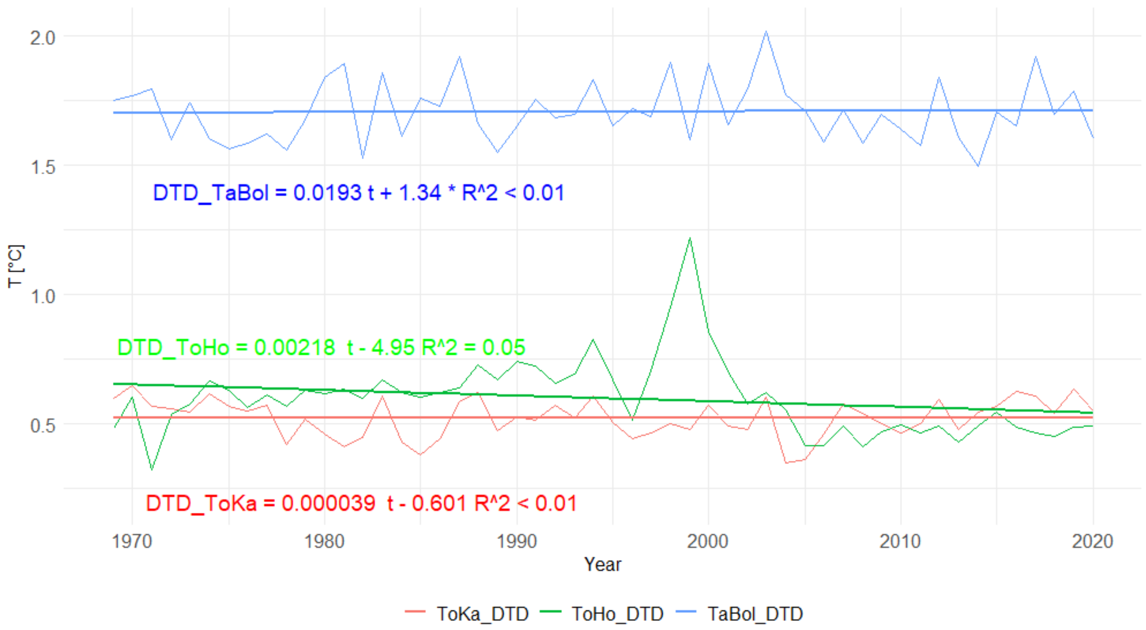

Fig. 6. Series of annual values of water temperatures day-to-day for Kalinovo (DTD_ToKa, red color), Holiša (DTD_ToHo, green colour) and air temperature for Boľkovce (DTD_TaBol, blue color) from 1969–2020.

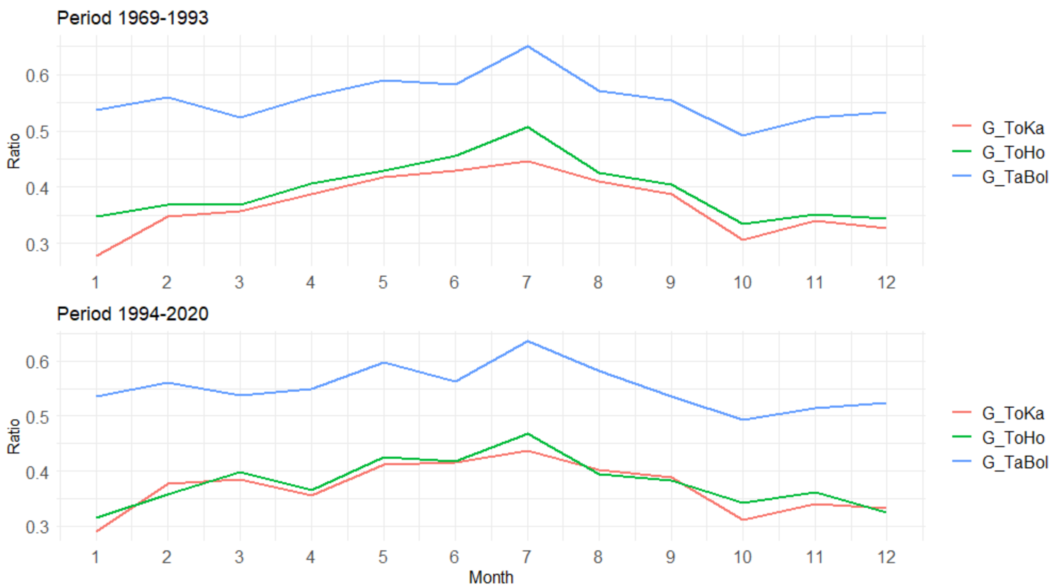

Fig. 7. DTD/SD ratio (G) for Kalinovo, Holiša and Boľkovce using temperature data split in to two periods 1969 to 1993 and 1994 to 2020 for each month of the year.

by reducing the average water temperature also for these sites.

As in the first section, for all the stations we calculate the G ratio for the 2009–2020 data for each month of the year, and then we average the values for each month over the period. As can be seen in Fig. 10, the *G* value is less than 1 throughout the year, indicating that these temperatures do not have a random climate and that there is some order in all months of the year. Similar to the first section, the G-value for air temperature ranges from 0.5 to 0.65. In the case of water temperature, we see a significant variation in *G* ratio only for the stations above Málinec reservoir and Málinec below WR, where it ranges from 0.26 to 0.6 for the water temperature at Málinec below WR. The highest values are observed in the months of January and August, while the lowest values are observed at this station in the months of April–June and September–October. It is also seen that the *G*-values for water temperature at other stations below WR follow a similar pattern during the year.

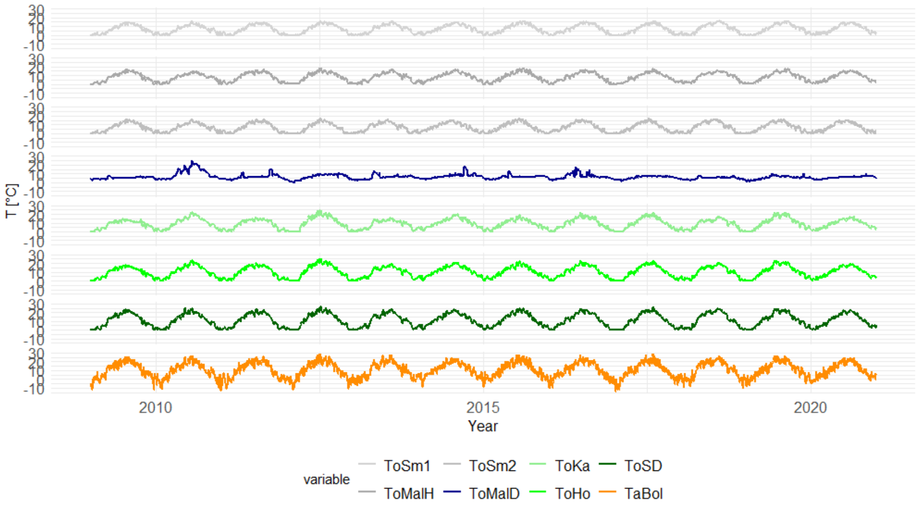

Fig. 8. The daily water and air temperatures at the stations for the period 2009–2020.

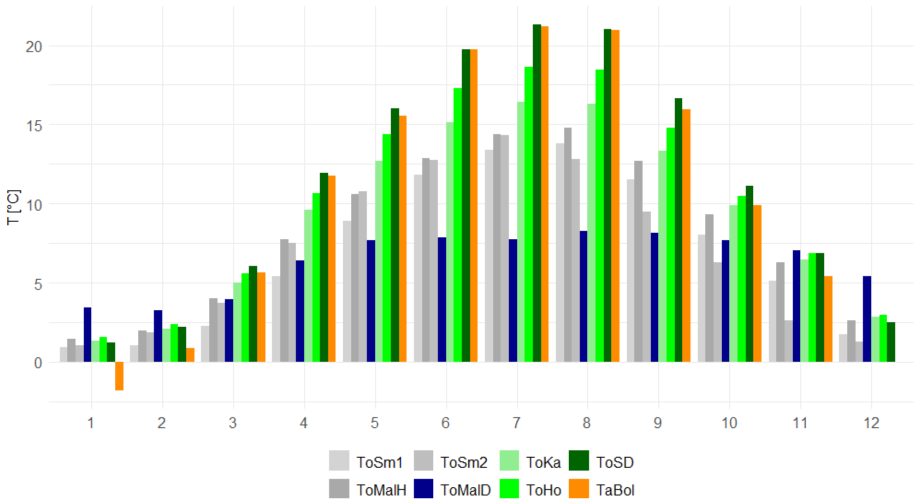

Fig. 9. Histogram of average monthly temperatures in these stations for the period 2009–2020.

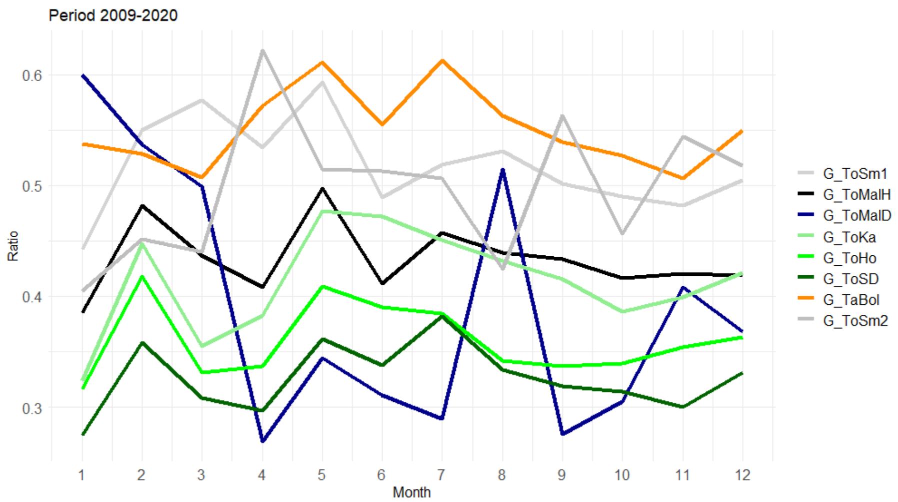

Fig. 10. DTD/SD ratio (G) for water temperatures at stations Málinec Smolná 1 and 2 and Málinec – Ipeľ above the WR, Málinec – Ipeľ below the WR, Kalinovo, Holiša and Slovenské Ďarmoty and climatic station Boľkovce using temperature data for years 2009 to 2020 for each month of the year.

Conclusion

The relationship between river water temperature and air temperature depends on the size of the water body, variable hydrological conditions (flow, velocity, etc.) and different river shapes and channel dimensions changing over time with anthropogenic interventions. At the annual timescale, a significant trend towards increasing mean annual air temperature was observed, while the increase in water temperature was less pronounced. On a monthly scale, air temperature shows an increase in all months of the year, while water temperature at the Kalinovo and Holiša stations shows an increase in winter months and a decrease in summer months due to the influence of the reservoir. The results of the daily time series (DTD) show that the trend of increasing annual air temperature variations is not significant. The DTD values for air are significantly higher than those for water, which is to be expected given that they are different media. However, it is important to note that the air temperature DTD series trend shows an insignificant increase, whereas the water temperature trend shows a significant decrease, especially for the DTD at Holiša. The G values for water temperature for the years 1994 to 2020 are more consistent with each other compared to the previous period (1969–1993), indicating possible changes in water temperature patterns over time. This analysis provides valuable insights into the temperature patterns and their changes over time, which could be crucial for climate studies and environmental planning.

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