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Dynamics of water temperature in a small mountain catchment

Patrik SLEZIAK*, Martin JANČO, Michal DANKO

Water temperature has a significant effect on the river fauna and flora and changes the quality of the aquatic ecosystem. Water temperature similar to other physical and chemical indicators of water quality enters into the assessment of the ecological status of surface waters in accordance with the requirements of the framework directive on water (RSV EU). Therefore, it is important to monitor it and also to know to what extent it is influenced by other factors.
The aim of this work was to evaluate the short-term water temperature development and also to analyse its regime with respect to influencing factors, especially air temperature and altitude. The study is conducted in the foreland and mountain part of the Jalovecký Creek catchment in Slovakia and uses hourly data from the hydrological year 2022 (November 1, 2021 – October 31, 2022). We performed field water temperature measurements along the entire Jalovecký creek (six sites at altitudes from 560 to 1,110 m a.s.l.) to better evaluate the water temperature regime. Seasonality of water temperature was analyzed by statistical analysis of time series. We used scatter-plots to assess the relationship among water temperature, air temperature and altitude. The analysis of the water temperature measurements showed that the highest mean hourly/daily water temperature was recorded at Ondrašová site (22.3°C/18.3°C), and the lowest was measured at the Hlboká valley (-1.2°C/-1.5°C). This fact resulted both from the altitude of the stations (Ondrašová 560 m a.s.l., Hlboká valley 1,110 m a.s.l.). The lowest mean monthly air temperature was measured in December (-0.2°C), while the highest was observed in July (15.7°C). The highest variations of the mean monthly water temperatures among the studied sites were observed during summer (June – August), when mean monthly temperature range reached even 8.0°C. The relationship between water and air temperature did not differ significantly among the investigated sites. However, the higher correlations were found for higher altitude (i.e., Hlboká valley). The results of the work could contribute to a better understanding of temperature conditions in high mountain streams.

KEY WORDS: water temperature, air temperature, altitude, mountain stream

Introduction

Changes in the runoff regime, low water levels during the summer season, as well as atmospheric warming significantly affect the water temperature in the streams. Water temperature is an important physical characteristic of water. It has a significant impact on river fauna and flora and conditions the quality of the water ecosystem. During extreme and long-lasting heat and droughts, there is a dangerous rise in water temperature. Longer-term overheating of water in streams combined with low flows can cause undesirable processes that lead to the death of fauna and flora. Water temperature like other physico-chemical indicators of water quality is included in the assessment of the ecological status of surface waters in accordance with the requirements of the framework directive on water – RSV EU (WFD, 2000). This directive stipulates the obligation of EU member states to assess the development of water quality in streams depending on the type of water body (alpine, forested, agricultural catchments, etc.).
Hydrological research in small catchments plays an important role in improving the understanding of hydrological processes. Investigation of changes in the hydrological regime of Slovak rivers deals with the work of Poórová et al. (2023). Small experimental catchments serve the purpose of research precisely because they are mostly upper watersheds and only small landscape changes occur in them. In addition, it is easier to create a dense network of observations in them and thus obtain quality data (Schumann and Herrmann, 2010). Due to the fact that water temperature measurements do not require demanding measurement techniques, water temperature as a basic indicator of water quality is monitored for a long time in selected streams in Slovakia as well as in the world. The first continuous measurements of water temperature in Slovak streams are dated from 1924 to 1926 (Danube: Bratislava – 1926, Hron: Banská Bystrica – 1925, Starohorský potok: Motyčky – 1924, Nitra: Nitrianska Streda – 1925, Váh: Sereď – 1930). Dmitrijeva and Pacl (1952) for the first time processed the basic characteristics of water temperature on the Danube River at the Bratislava station. Horváthová and Vanetianerová (1963),

Horváthová (1964) and Horváthová and Dávid (1969) also dealt with the processing of water temperature data up to 1960 in their works. The water temperature of Czechoslovak streams until 1960 was comprehensively evaluated by Čermák (1965). Dulovič (1989) in his study dealt with the processing of long-term characteristics of water temperature up to 1980. In recent years, the authors Lešková and Škoda (2003) analyzed the development of water temperature regime in Slovak streams. They evaluated daily water temperatures from selected water measuring stations and monthly temperatures from selected climatological stations. Their results showed that the highest water temperatures in Slovak streams occur in August/July, lowest in January.

The influence of the hydrological regime of streams on water temperature is evident from the work of Pekárová et al. (2008), where the thermal flow of the Danube water was evaluated in the Bratislava profile. Another work on the assessment of water temperature in the Danube (Bratislava profile) for the period 1931–2005 is the work of Škoda et al. (2007). The dependence of water temperature on air temperature is evaluated in the work of Bajtek et al. (2022a; b).

In recent decades, the question of air temperature increases due to the strengthening of the atmosphere's greenhouse effect, as well as the question of the influence of the phenomena of the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) on temperature fluctuations, has come to the fore. The influence of the Severoatlantic Oscillation on the multiple variability of water temperature in Vienna, Salzach and Traune was studied by Webb and Nobilis (2007). The authors found out that a statistically significant increase in water temperature occurred during the 20th century at all the following stations. Changes in water temperature values are closely related to the development of air temperatures. The expected increase in air temperature will also be reflected in the increase in water temperature in streams (Bonacci et al., 2008). Since water has an order of the magnitude higher thermal capacity than air, an increase in the temperature of the water in the stream could be a significant signal of the warming of the watershed (Pekárová et al., 2008).

Since water temperature is a basic physico-chemical characteristic indicating water quality, its future development is extremely important. In order to eliminate human influence on water temperature, it is necessary that monitoring is also carried out in catchments with a natural regime. In our study, the water temperature dynamics is evaluated at six sites with different altitudes in the foreland and pristine mountain part of the Jalovecký Creek catchment, located in the Jalovecká valley in northern Slovakia. The aim of this study is (a) to evaluate experimental measurements of water temperature in the studied catchment, (b) to analyze the seasonality of water temperature (hourly, daily and monthly course), (c) to assess the relationship between water temperature and influencing factors, especially air temperature and altitude.

Study area and data

This study is carried out in the the Jalovecký Creek catchment located in northern Slovakia (Fig. 1). In 1986,

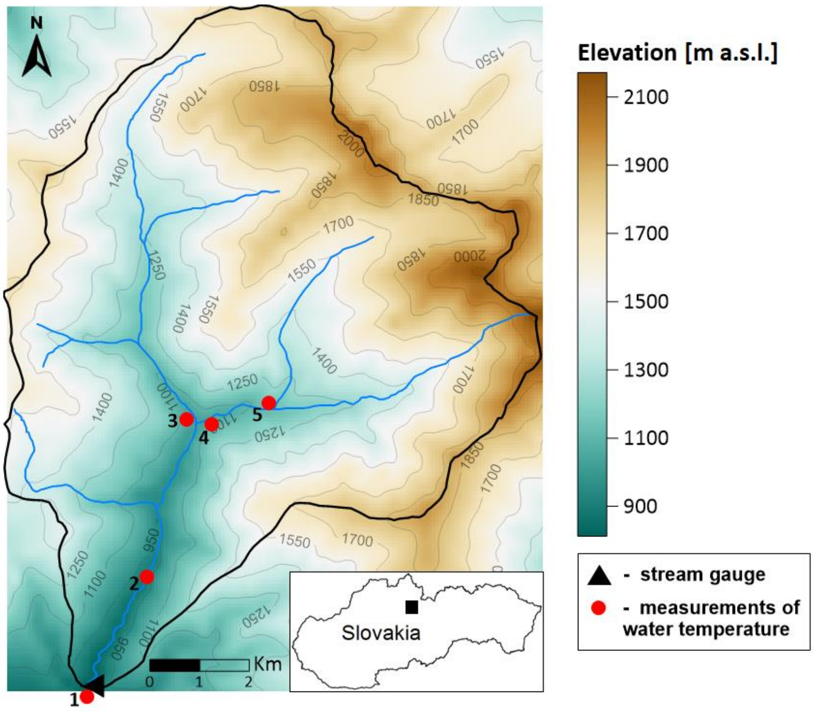

Fig. 1. Topography of the Jalovecký Creek catchment and location of selected water temperature measurement sites (numbers 1 – 5 (the red points), 1 – Catchment outlet, 2 – Jalovecká valley, 3 – Bobrovecká valley, 4 – Parichvost valley, 5 – Hlboká valley, one station called Ondrašová is located outside the catchment). The map also includes location of the stream gauge at the outlet of the catchment (the black triangle).

the Institute of Hydrology of Slovak Academy of Sciences (IH SAS) established an extended workplace in Liptovský Mikuláš – the Experimental Hydrological Base. The Jalovecký Creek catchment in the West Tatras was chosen as a representative research catchment. The main content of the workplace is the research of the water balance components in the mountains and as well as the experimental research of hydrological processes that determine the formation of water sources and runoff.

Jalovecký creek is a typical mountain stream. It is formed by the confluence of two streams of Parichvost and Bobrovecký creek at an altitude of 1,000 m a.s.l., Jalovecký creek flows into the river Váh. The mouth of the stream is located at an altitude of 560 m a.s.l. in the town district of Liptovský Mikuláš (part Liptovská Ondrášová). The catchment is led on both sides by the ridge of the Western Tatras. Catchment area is 45 km^2 and it is composed of two parts: the upper part (called mountain part) and the lower part (called foothill part).

The mountain part of the catchment is located in the Tatra National Park (TANAP), which implies that human activities here are limited to tourism and the occasional removal of wood after calamities. Its area is 22.2 km^2, the elevation ranges between 820 and 2,178 m a.s.l. (mean 1,500 m a.s.l.) and mean slope 30°. The bedrock is dominantly formed by granodiorite and gneiss that are covered by fluvioglacial sediments and slope debries. About 7% of the catchment is formed by Mesozoic rocks dominated by limestone and dolomite. Soil cover is represented by cambisols, podsols, rankers and lithosols. Forests dominated by spruce cover 44% of catchment area, dwarf pine covers 31% and alpine meadows and bare rocks cover the rest 25%.

The foothill part of the catchment is located in the Liptov Basin. Geology is represented by the low permeability claystones and sandstones (at some places Carphatian flysch dominated by claystone) that are covered in the valley by the alluvium of Jalovecký creek. The soil is represented by fluvisols.

The water temperature in the Jalovecký creek was evaluated from hourly measurements at six locations (Fig. 1, 2. and Table 1) during the hydrological year 2021/22 (November 1, 2021 – October 31, 2022). The air temperature at three locations was evaluated from hourly measurements too. From the measured water temperatures, hourly, daily, and monthly mean water temperature values were calculated for each location. These measurements were also used in evaluating the dependence of water temperature on altitude and air temperature. The list of sites and their location in the catchment and their associated altitude for water temperature and air temperature is shown in Table 1.

Fig. 2. The water temperature measurement sites in the Jalovecký Creek catchment.

Methods

From November 2021, we started measuring the water temperature along the creek (stream) at six locations at different altitudes (560–1,110 m a.s.l.) in the mountain catchment of the Jalovecký creek. We named the measurement sites according to the positions where the water temperature sensors were located, namely: Ondášová, Catchment outlet of the Jalovecká valley, Jalovecká valley, Bobrovecká valley, Parichvost valley and Hlboká valley (Fig. 1, 2). The water temperature sensors in the upper part of the catchment were placed in such a way as to cover the area of the Bobrovecká valley, through which the Poliansky creek flows and the Hlboká valley, through which the Hlboký creek flows. The Poliansky and Hlboký creek subsequently flow into the Jalovecký creek, which flows through the Parichvost valley. The water temperature sensors were placed on the left sides of the creek, so that access to them was possible. During the installation, the following criteria were observed: the water temperature sensors were placed in flowing water so that they were always below the water surface and were placed in shaded areas to avoid increased influence of solar radiation. Shading was provided by riparian vegetation.

We used Minikin Tie temperature sensors from the EMS Brno company to record the water temperature at five locations. These are durable and waterproof devices that measure and record water temperatures in intervals from 30 seconds to 4 hours. The datalogger case is manufactured from high-density polyethylene terephthalate. The data was downloaded via a portable field computer, Mini32 software and an IrDA cable (Fig. 3). At the catchment outlet of the Jalovecká valley, we took the water temperature data from the MicroStep-MIS automatic station. Data from this station is available to us online. We took air temperature data from three locations, namely Ondrašová (560 m a.s.l.), Priemstav (750 m a.s.l.) and Hlboká valley (1,400 m a.s.l.). At the Ondrašová location, the air temperature is recorded by means of the MicroStep-MIS automatic station. At the Priemstav and Hlboká valley sites, air temperatures are recorded using Minikin THi or Minikin RTHi devices with radiation shield (EMS Brno), which, like Minikin Tie temperature sensor, record air temperature in intervals from 30 seconds to 4 hours.

Table 1. The water/air temperature measurement sites and their corresponding altitude in the Jalovecký Creek catchment

Water temperature [°C] Locality	Altitude [m a.s.l.]	Air temperature 2 m [°C] Locality	Altitude [m a.s.l.]
Ondrašová	560	Ondrašová	560
Catchment outlet	850	Priemstav	750
Jalovecká valley	960	Hlboká valley	1,400
Bobrovecká valley	1,009	-	-
Parichvost valley	1,015	-	-
Hlboká valley	1,110	-	-

Fig. 3. Equipment for downloading water temperature data (portable field computer, Minikin Tie temperature sensor and IrDA cable).

Results and discussion

Hourly, daily and monthly dynamics of water temperature

The hourly course of water temperature during the day was analyzed on the basis of data from hydrological year 2022 (Fig. 4, Table 2). The highest variation in hourly water temperature (from -1.0°C to 22.3°C) was recorded at site Ondrašová, and the lowest differences (from -0.4°C to 10.5°C) were recorded at the Bobrovecká valley. As altitude increases, the variation in hourly water temperature decreases (up to altitude 1009 m a.s.l.).
Minima occur in the morning at sunrise and maxima in the afternoon. The highest averages of the mean water temperature were recorded at site Ondrašová (6.7°C), and the lowest were recorded at the Bobrovecká valley (4.1°C). Similar mean hourly water temperature values were also recorded at Jalovecká valley (4.2°C) and Parichvost valley (4.2°C). In the winter months, the water temperature during the day has a lower amplitude (not shown here). The winter averages of the mean water temperature at lowest altitude (560 m a.s.l.) ranged from -1.0°C to 12.6°C and the summer temperatures were between 4.1°C and 22.3°C. The winter temperature at highest altitude (1,110 m a.s.l.) varied from -1.2°C to 7.9°C and the summer temperatures ranged from 2.1°C to 15.1°C.
Fig. 5 shows the daily course and dynamics of fluctuations in the measured water temperature during the hydrological year 2022. Basic statistics of the mean daily water temperatures is given in Table 3. We can see that the course of water temperature represents a long-known sinusoid. Generally, the water temperature should range from 0°C to 25°C during the year in a temperate climate zone.
The averages of the mean daily temperatures range from 4.1°C (Bobrovecká valley) to 6.7°C (Ondrašová). The highest mean daily water temperature was recorded at Ondrašová (18.3°C), and the lowest was measured at the Hlboká valley (-1.5°C). This fact resulted both from the altitude of the stations (Ondrašová 560 m a.s.l., Hlboká valley 1,009 m a.s.l.). The minimum daily water temperature dropped to or below 0°C at all sites (except

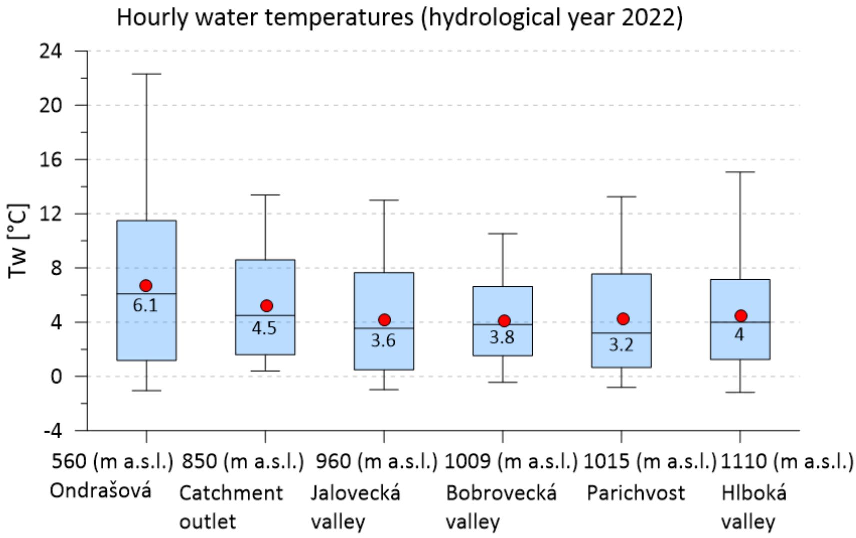

Fig. 4. Hourly water temperatures (Tw) measured at different sites and altitudes. The whiskers represent minima and maxima; the boxes show 25% and 75% percentiles; the line shows the median of the water temperature; the red point indicates the mean water temperature value.

Table 2. Basic statistics of hourly water temperatures measured at different sites and altitudes in the foreland and mountainous part of the Jalovecký Creek catchment in the hydrological year 2022 (November 1, 2021 – October 31, 2022)

Locality	Altitude [m a.s.l.]	Minimum [°C]	Maximum [°C]	Median [°C]	Mean [°C]
Ondrašová	560	-1.0	22.3	6.1	6.7
Catchment outlet	850	0.4	13.4	4.5	5.2
Jalovecká valley	960	-1.0	13.0	3.6	4.2
Bobrovecká valley	1,009	-0.4	10.5	3.8	4.1
Parichvost valley	1,015	-0.8	13.3	3.2	4.2
Hlboká valley	1,110	-1.2	15.1	4.0	4.5

for the Catchment outlet). Interestingly, the water temperature course varies more between Bobrovecká valley and Parichvost valley in the summer. This can be caused by a different subsoil (dolomites vs granite). Daily fluctuations are, in general, higher in deforested areas, where the bank vegetation does not prevent water against overheating during the day.

Mean monthly water temperatures can be described as one of the important sources that is provided to various sectors of the water management. This is because they very clearly show changes in water temperature during the year and represent a balanced value, without substantial distortion by random influences, as is the case with daily water temperatures. Changes in water temperature distribution on the Jalovecký Creek at 6 selected locations were analyzed for the hydrological year 2022 (Fig. 6). Mean monthly values were calculated from measurements in hourly time step for the evaluated period and they are summarized in Table 4. The water temperature rose especially markedly in July and August, which corresponds to an increase of the air temperature. The highest mean monthly water temperature was measured in July (15.7°C) at Ondrašová site, while the lowest was observed in December (-0.2°C) at the same site and also at Jalovecká valley. The monthly water temperature dynamics had a clear seasonal pattern; the highest variations of water temperature among the studied sites were observed during summer (June – August), when mean monthly temperature range reached even 8.0°C, while the lowest were observed in January, February, March and April with the mean monthly range approximately of 1°C. The largest difference between the lowest (560 m a.s.l.) and highest (1,110 m a.s.l.) altitudes is observed in July, when mean monthly temperature range reached even 6.7°C.

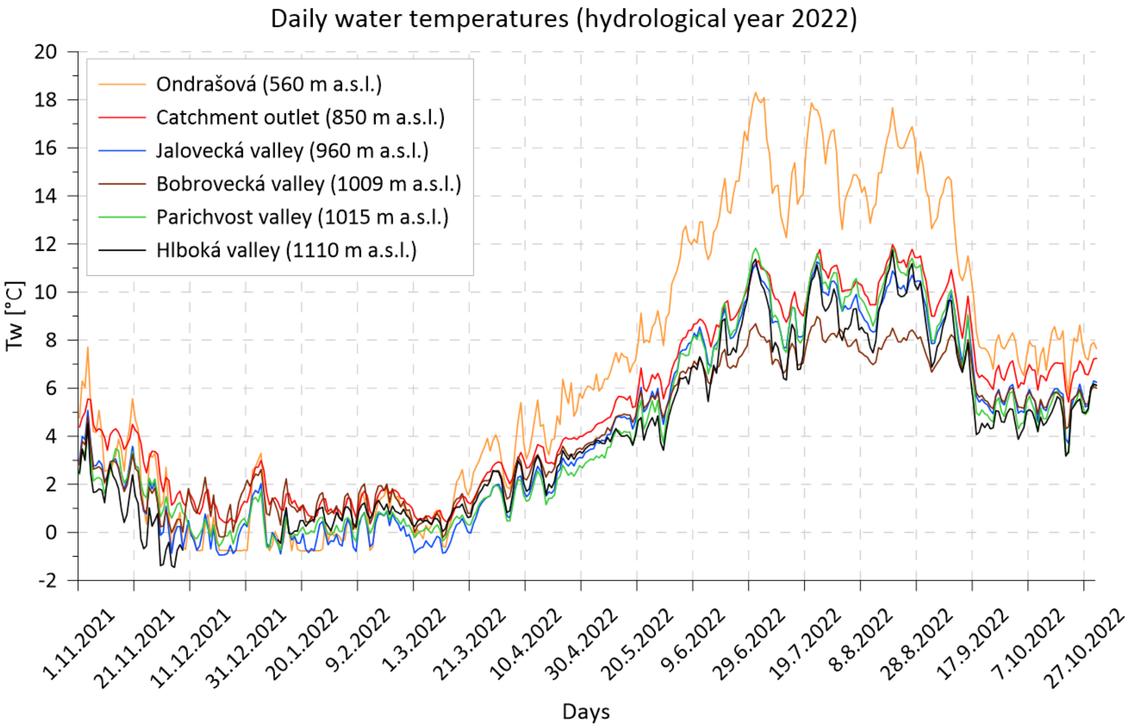

Fig. 5. Mean daily water temperatures (Tw) measured at different sites and altitudes.

Table 3. Basic statistics of the mean daily water temperatures measured at different sites and altitudes in the foreland and mountainous part of the Jalovecký Creek catchment in the hydrological year 2022 (November 1, 2021 – October 31, 2022)

Locality	Altitude [m a.s.l.]	Minimum [°C]	Maximum [°C]	Median [°C]	Mean [°C]
Ondrašová	560	-0.8	18.3	6.0	6.7
Catchment outlet	850	0.4	12.0	4.5	5.2
Jalovecká valley	960	-0.9	11.3	3.7	4.2
Bobrovecká valley	1,009	-0.2	9.0	3.8	4.1
Parichvost valley	1,015	-0.8	11.8	3.2	4.2
Hlboká valley	1,110	-1.5	11.7	4.0	4.3

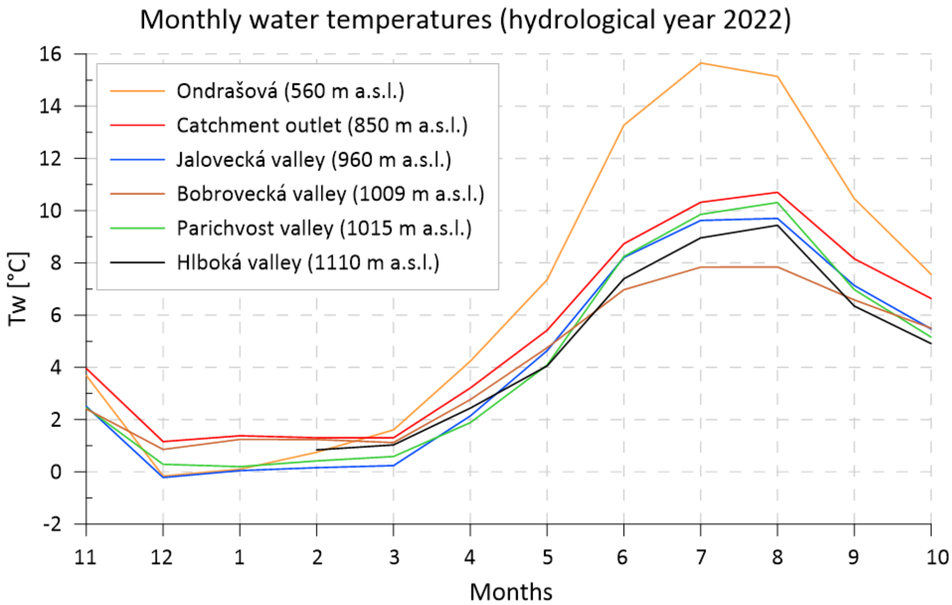

Fig. 6. Mean monthly water temperatures (Tw) measured at different sites and altitudes.

Table 4. The mean monthly water temperatures measured at different sites and altitudes in the foreland and mountainous part of the Jalovecký Creek catchment in the hydrological year 2022 (November 1, 2021 – October 31, 2022)

Months	Ondrašová (560 m a.s.l.)	Catchment outlet (850 m a.s.l.)	Jalovecká valley (960 m a.s.l.)	Bobrovecká valley (1,009 m a.s.l.)	Parichvost valley (1,015 m a.s.l.)	Hlboká valley (1,110 m a.s.l.)
November	3.7	4.0	2.5	2.4	2.5	1.6
December	-0.2	1.2	-0.2	0.9	0.3	-
January	0.1	1.4	0.0	1.2	0.2	-
February	0.7	1.3	0.2	1.2	0.4	0.8
March	1.6	1.3	0.2	1.1	0.6	1.0
April	4.2	3.2	2.1	2.8	1.9	2.4
May	7.4	5.4	4.6	4.8	4.1	4.1
June	13.3	8.7	8.2	7.0	8.2	7.4
July	15.7	10.3	9.6	7.8	9.9	9.0
August	15.1	10.7	9.7	7.8	10.3	9.4
September	10.5	8.2	7.1	6.6	7.0	6.3
October	7.6	6.6	5.5	5.5	5.2	4.9

Dependence of water temperature on influencing factors – altitude and air temperature

The relationship among air temperature, water temperature and altitude was assessed by scatterplots and correlation coefficients. The correlations were evaluated for three sites with different altitudes (560 m a.s.l., 750 m a.s.l., 1,400 m a.s.l.) as shown in Fig 7. A value of the correlation coefficient (r) close to 1 indicates a strong dependence between the variables. It is evident, that there is a high dependence between air and water temperatures (r for summer and winter seasons above 0.9).

The results indicate that the correlations between air and water temperatures do not differ significantly between the seasons. Higher correlations were found at higher elevations, particularly at the Hlboká valley site. For instance, the summer correlation between water temperature (*Tw*) and air temperature (*Ta*) at the Ondrašová site (560 m a.s.l.) was about 0.82, while it was around 0.87 at the Hlboká valley site. This could be attributed to the fact that the water temperature increases gradually along the entire length of the stream, resulting in lower correlations at lower altitudes (such as the Ondrašová site) and higher correlations at higher altitudes (such as the Hlboká valley site).

In winter season, the correlations are as follows: 0.80 (Ondrašová), 0.85 (Catchment outlet – Priemstav), 0.86 (Hlboká valley). In general, the air temperature is higher than the water temperature, particularly at higher altitudes.

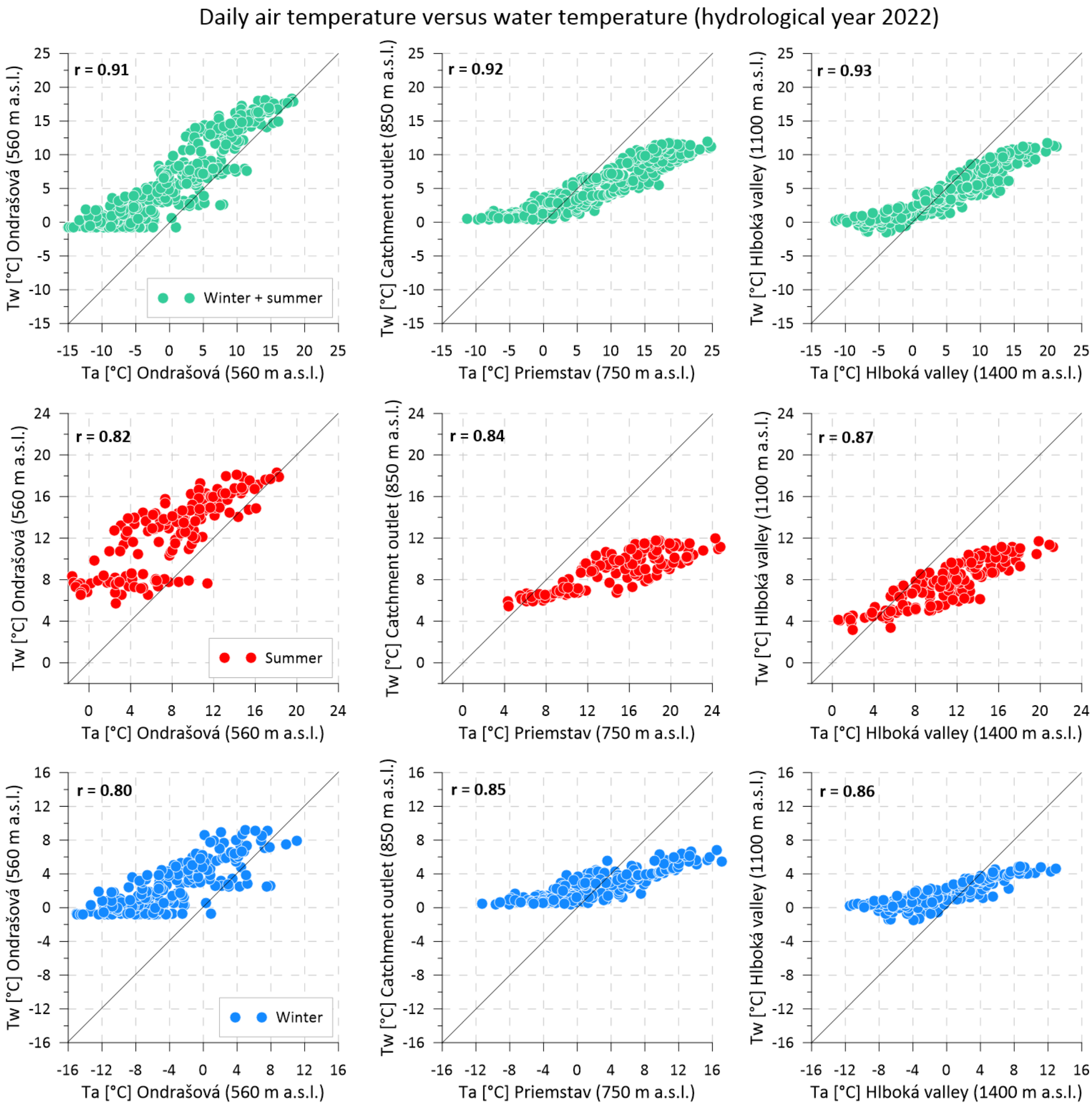

Fig. 7. Measured daily air temperature (Ta) versus water temperature (Tw) at different elevations in the hydrological year 2022 (November 1, 2021 – October 31, 2022) and its warm (June–October) and winter season (November–May); the diagonal represents the 1:1 line.

Conclusion

Data on water temperature and air temperature measured at different altitudes in the Jalovecký Creek catchment confirm the differences between the mountain and foothill parts of the studied catchment.

The highest mean hourly/daily water temperatures were recorded at lower altitudes (560 m a.s.l.), while the lowest were measured at higher altitudes (1,110 m a.s.l.). The lowest monthly water temperature variations were observed in the winter, they increased in the spring to reach maximum values early summer, and then decreased again in the autumn. Water temperature at the studied sites followed the air temperature pattern. The higher dependence between the water and air temperatures were found for higher altitudes.

The measurements may serve to determine the limit values of the water temperature for a good ecological condition for altitudes between 560 and 1,100 m above sea level in small mountain catchments.

The monthly values could be used when classifying the water of high mountain streams into individual water quality classes with regard to water temperature. Although it would be necessary to evaluate a longer series of measurements to determine the boundaries, these values provide us with at least indicative values for flows little affected by human activity in high mountain environments.

Acknowledgement

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Ing. et Ing. Patrik Sleziak, PhD. (*corresponding author, e-mail: sleziak@uh.savba.sk)
Ing. Martin Jančo, PhD.
Ing. Michal Danko, PhD.
Institute of Hydrology SAS
Dúbravská cesta 9
841 04 Bratislava
Slovak Republic