PAN

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2023.147240
2023, No. 59 (X–XII): 153–163

Spatial and seasonal variability of sub–daily water temperature dynamics in the lowland agricultural catchment of the Wkra River

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RECEIVED 26.04.2023 ACCEPTED 23.09.2023 AVAILABLE ONLINE 31.12.2023

Abstract: The paper concentrates on seasonal and spatial variations of sub-daily water temperature dynamics in lowland agricultural streams. Temperature monitoring was carried out in 24 sampling sites distributed along the tributaries of the Wkra River during the hydrological year 2021. Statistical analysis of the obtained data documented the highest water temperature dynamics in the morning, from 5:00 to 9:00 CEST, while the lowest – from 14:00 to 18:00 CEST. Seasonally, greater water dynamics were noted in the winter, expressed by a coefficient of variation reaching up to 100%. Spatially, the highest dynamics occurred in sites with the lowest proportion of riparian vegetation, while the lowest dynamics was related to higher catchment area. In the winter, the minimum daily values were recorded most frequently in the morning hours, while maximum values in the afternoon. A similar pattern was observed in the summer, but with much lower dispersion of the relative frequencies. It was found that in the winter, the dominant influence on temperature dynamics was exerted in the upstream catchment area, while in the summer, a negative relationship with riparian shade was marked. The findings suggest that the presence of riparian vegetation reduces diurnal dynamics of water temperature and is simultaneously extremely important in prolonging the duration of optimum fluctuation, responsible for the proper development of poikilothermic organisms.

Keywords: river water temperature, thermal fluctuations, Mazovia, Central Poland, hourly variations, thermal conditions

INTRODUCTION

There is general agreement in the scientific literature that water temperature is one of the most important parameters of flowing water quality (Poole and Berman, 2001). This critical variable is responsible not only for dissolved oxygen saturation, but also for the rate of decomposition of organic matter, the eutrophication process, and biological activity (Zhao *et al.*, 2022). Moreover, water temperature translates directly and indirectly into the functioning of many groups of organisms, such as macroinvertebrates (Bonacina *et al.*, 2023) and fish (Mugwanya *et al.*, 2022). Different species are characterised by varied sensitivity to thermal conditions (Armstrong *et al.*, 2023), resulting in spatial variation in the habitat (Barbarossa *et al.*, 2021). Another widely discussed topic in literature is the impact of temperature on the growth, reproduction and development of species, especially valuable freshwater fish (Nobriga *et al.*, 2021; Kirk and Rahel, 2022). Existing studies concentrate on long–term changes in water temperature and their effect on water ecosystems (Walder *et al.*, 2021), however, also daytime fluctuations cause changes in the vital functions of ichthyofauna and expose species to diseases (Jobling, 1996). Studies have also shown that diurnal fluctuations in water temperature occurring below the thermal optimum of a species increased metabolism, while a decrease in the said process was recorded once the optimum was exceeded (Olginy-Hébert *et al.*, 2015). Furthermore, thermal instability manifested itself in faster consumption, faster growth, and more efficient food-to-energy conversion in species, accompanied by negative phenomena, namely an increase in mortality and the development of skin ulcers (Coulter *et al.*, 2016).

It therefore becomes extremely important to identify the environmental factors that determine water temperature values.

The modification of water temperature by environmental features has been repeatedly referred to in the literature, with a significant role attributed primarily to catchment area, channel parameters, and the presence of riparian vegetation (Broadmeadow *et al.*, 2011; Łaszewski, 2020). Catchment area can be used as a proxy of river discharge; as the catchment area increases, so too do the width and depth of the riverbed, and therefore the volume of water, which affects the rate of heating and heat loss (Caissie, 2006). A significant amount of literature is also focused on the impact of land cover. Solar radiation is recognised as the main contributor of thermal energy to watercourses. The presence of a shielding factor, that is the presence of vegetation, is therefore extremely important for reducing extreme values and influencing the presence of suitable conditions for aquatic organisms (Dugdale *et al.*, 2018; Kail *et al.*, 2021).

Due to its importance, water temperature received significant attention in hydrological literature, mainly due to growing anthropogenic pressure and climate change (Wrzesiński and Graf, 2022). This has resulted in several investigations related to the characterisation of the thermal regimes of watercourses and the detailed recognition of the environmental factors determining water temperature (Das *et al.*, 2022), as well as on the influence of anthropogenic activities on water temperature modification (Krajenbrink *et al.*, 2022) and its prediction using variable approaches (Graf and Aghelpour, 2021; Shrestha and Pesklevits, 2023). Another important research topic belongs to long–term thermal regime changes, resulting from the increase in global air temperature (Tassone *et al.*, 2023). In contrast, a small number of studies were related to diurnal temperature dynamics and its seasonal and spatial variability, especially in small lowland temperate streams, mainly due to the lack of water temperature monitoring in such scales (Łaszewski, 2020). In that way, there are only few reports regarding diurnal water temperature dynamics, based on high–resolution and spatially extensive measurements (Bae *et al.*, 2016; Łaszewski, 2018).

Thus, this paper examines the spatial and seasonal variability of water temperature in small lowland agricultural catchments, with special reference to its 24-hour dynamic. The specific objectives of the study were to: determine the frequency of occurrence of maximum and minimum water temperature (1); assess the influence of environmental factors of the catchment on the hourly dynamics of water temperature (2), and investigate the duration of optimum thermal fluctuations for ecological purposes (3).

MATERIALS AND METHODS

STUDY AREA

Monitoring of water temperature was carried out in 24 lowland catchments distributed across the southern part of the Wkra River catchment (Fig. 1), located in the Mazovian Lowland. The area in question consists mainly of boulder clays, sands and gravels, stagnant clays, and silts (Lechnio and Malinowska, 2021). The channel of the selected watercourses primarily composed of sandy deposits. The climate of the North Mazovian Lowlands can be described as temperate in the transitional zone and the hydrological regime of rivers are characterised by highest streamflow rates observed in early spring as a result of snow melting, whereas the lowest – during summer and autumn (Wrzesiński, 2017). The lowland nature of the area is also evidenced by the average channel slope of selected rivers, which accounted for 1.9%. The Wkra catchment area is characterised by good hydraulic connectivity between the first groundwater level and the surface waters. Groundwater outflow to rivers in the

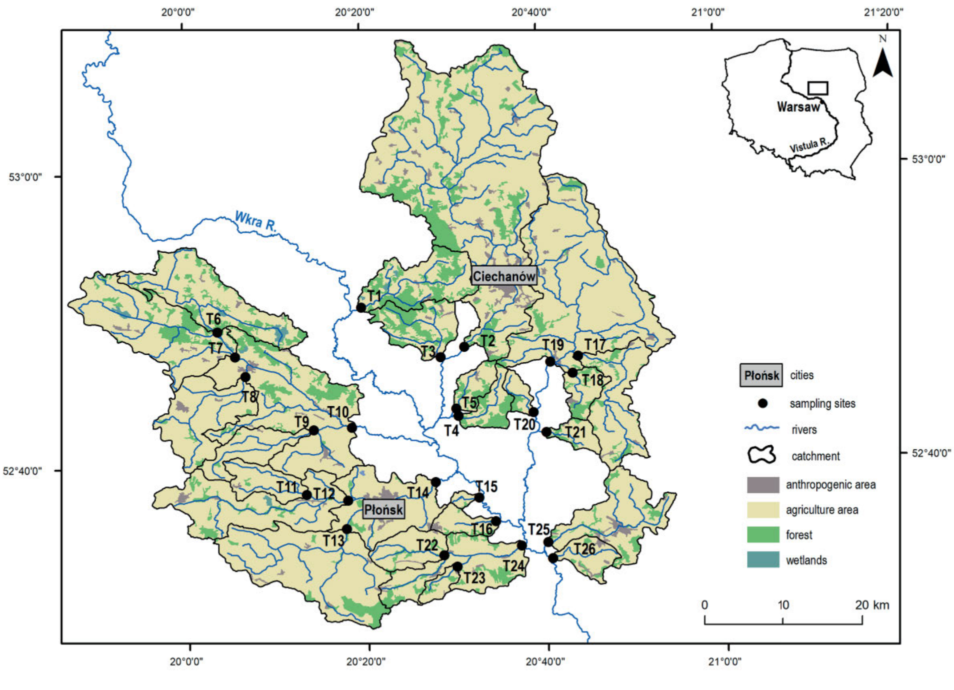

Fig. 1. Sampling sites against the background of land cover of the analysed catchments; explanations of measurement sites and names of watercourses are presented in Tab. 1; source: own elaboration based on Sentinel-2 Global Land Cover and Wody Polskie (2010)

Table 1. Selected environmental characteristics of the catchment areas defined by the sampling sites

River	Site	Catch-ment area (km^2)	Mean-channel width (m)	Mean-channel depth (m)	*W*:*D*	Slope (%)	Riparian shade 30 m, 5 km (%)	Forest area (%)	Agri culture area (%)	Anthro-pogenic area (%)
Rosica River	T1	76.8	2.0	35.0	5.7	2.4	25.5	41.4	34.3	0.3
Łydynia River	T2	524.5	6.5	57.5	11.3	2.0	19.5	17.3	58.2	1.9
Stawnica River	T3	54.0	1.5	66.7	2.3	2.2	10.8	42.9	34.6	0.5
Żochy Stream	T4	26.4	1.0	16.7	6.0	2.3	54.3	49.4	35.2	0.1
Ojrzeń Stream	T5	22.0	2.0	50.0	4.0	2.0	19.7	35.8	42.9	0.7
Upper Raciążnica River	T7	247.5	5.0	75.0	6.7	1.7	5.4	19.4	44.8	0.4
Karsówka River	T8	86.5	3.0	30.0	10.0	1.4	3.3	4.9	80.3	0.7
Dobrzyca River	T9	42.3	1.6	60.0	2.7	1.4	19.1	3.7	82.7	0.3
Downstraem Raciążnica River	T10	568.3	5.0	86.7	5.8	1.7	2.1	14.7	59.4	0.7
Dzierzążnica River	T11	35.2	2.5	46.7	5.4	1.5	3.1	3.9	83.5	0.6
Upstream Płonka River	T12	153.8	3.5	32.5	10.8	1.6	24.5	9.1	78.3	0.7
Downstream Płonka River	T14	416.5	4.0	95.0	4.2	1.6	11.7	9.4	76.2	1.6
Niewikla Stream	T15	4.9	0.8	8.3	9.6	1.9	34.8	16.5	62.7	0.1
Lisewo Stream	T16	20.8	1.8	33.3	5.4	2.1	48.9	20.1	54.8	1.0
Kolnica River	T17	80.2	3.0	23.3	12.9	2.0	26.3	16.5	55.7	0.3
Gąsocin Stream	T18	24.4	1.8	20.0	9.0	2.4	30.2	34.0	40.2	0.5
Sona River	T19	386.7	4.5	53.3	8.4	1.6	9.2	10.1	71.1	0.7
Brodzęcin Stream	T20	13.0	0.5	8.3	6.0	1.9	8.6	20.8	56.1	0.3
Tatarka River	T21	17.0	1.2	18.3	6.5	2.3	59.1	25.1	50.9	0.5
Upper Naruszewka River	T22	38.7	2.0	38.3	5.2	1.7	78.1	12.8	65.5	1.0
Olszyny Nowe Stream	T23	12.5	1.5	11.0	13.6	2.2	81.7	23.0	59.0	1.0
Downstream Naruszewka River	T24	135.3	2.5	60.0	4.2	2.0	65.8	20.4	63.0	0.9
Nasielna River	T25	87.5	3.6	31.7	11.4	2.1	28.9	23.7	45.4	2.0
Mogów Stream	T26	27.3	1.0	13.0	7.7	1.8	52.9	17.2	63.1	1.7

Explanations: W = channel width (m), D = channel depth (m).
Source: own elaboration based on Map of Hydrographic Division of Poland (Wody Polskie, 2010), Sentinel-2 Global Land Cover (S2GLC, 2017) and Digital Elevation Model SRTM with 30 m resolutions.

Wkra catchment by the Cieksyn gauge in the 1951–1980 period was 67 mm·y^{-1}. In extremely dry years (e.g., 1952, 1954, 1984, 1993), there was a natural disappearance of flow in the upper sections of the Wkra's tributaries: Raciążnica, Płonka, Naruszewka and Sona (Herbich *et al.*, 2013). Selected catchments have a typically agricultural character, with the crops of wheat, maize, potatoes, and sugar beet, while forested areas consist mainly of *Pinus sylvestris* L., *Betula pendula* Roth, *Quercus robur* L., and *Populus tremula* L. The analysed area characterised by a low participation of urbanisation, with small villages and towns predominating throughout the area.

FIELD WATER TEMPERATURE DATA COLLECTION

On selected tributaries, draining catchment areas ranging from 4.9 to 568.3 km^2, 24 sampling sites were located. They were selected to ensure diversity and no significant anthropogenic impact in the catchment area (Tab. 1). Monitoring of water temperature was conducted from the 1st November 2020 to 31st of October 2021 with the use of digital recorders HOBO U22-001 (accuracy of 0.2°C and the resolution of 0.1°C) and UA-001-08 (0.47 and 0.1°C, respectively), while their measurement interval was set to 15 min. The 15-minute interval was chosen to reliably capture the maximum and minimum values, according to the results from previous studies, realised in mountainous, foothill, and lowland catchments (Broadmeadow *et al.*, 2011; Żelazny *et al.*, 2018). All sensors were installed in perforated PVC pipes attached to concrete weights placed at the bottom of the streambed, which stabilised the equipment during floods and protected it from direct solar radiation and sediments. Before the deployment, the loggers were checked with the use of the common "ice bath" procedure (Dunham *et al.*, 2005).

STATISTIC METHODS

With the use of 15-min measurement data downloaded from the loggers, several statistical methods were applied to characterise and evaluate spatial and seasonal variability of diurnal water temperature dynamics. In order to determine the time of the occurrence of water temperature extremes during the day, the relative frequency of minimum and maximum water temperature values at particular hours was calculated, expressed as a percentage for all days in the winter and summer halves of the hydrological year (November–April, May–October) (Bae *et al.*, 2016). To evaluate the potential influence of basic environmental characteristics on water temperature in certain hours, correlation analysis was performed, which allowed to establish the relationship between such characteristics (catchment area, contribution of riparian forest in 30 m wide buffer zone 5 km upstream from sampling sites, and width:depth (W:D) ratio of the channel) and mean, maximum, and minimum water temperature calculated for all studied hours. Spearman rank correlation coefficient ($p < 0.05$) was used for these purposes, as the Shapiro–Wilk goodness of fit test indicated previously that variables do not meet the assumption of normal distribution ($p < 0.05$). Catchment area was computed from the Digital Hydrographic Map of Poland from 2010 (Wody Polskie, 2010) and the contribution of forests in buffer zone was selected from coniferous and deciduous forest classes found in the Sentinel-2 Global Land Cover map with 10 m spatial resolution. Data on stream channel parameters (mean width and depth, of the bankfull necessary for the width:depth ratio calculation) were measured directly in the measurement site, as well as in transects of 50, 100, 150, and 200 m upstream and were then averaged. The relationships between environmental characteristics were checked using Spearman rank correlation. It was noted that there was a statistically significant correlation of –0.58 between catchment area and riparian shade in buffer zone of 30 m wide and 5 km length; for the remainder the correlations were statistically insignificant.

The relationship between the mean value of the water temperature per hour and the coefficient of variation in the winter and summer half-years was determined, analogous to method proposed by Bartnik and Tomalski (2018). The coefficient of variation was obtained as a ratio of the standard deviation to the mean value, and presented as a percentage and its higher values indicates high variability of the characteristic and indicates heterogeneity of the population. Such calculations were conducted for the selected sites; those with the highest and lowest percentage of riparian forest in buffer zones (71.8 and 2.3%, respectively), as well as with the largest and smallest catchment area (524.5 and 4.9 km^2, respectively). The duration of the thermal fluctuation optimum for the existence of ichthyofaunal species was in turn determined for all sites. The value of 2°C was chosen due to the occurrence of changes in the functioning of aquatic organisms at selected water temperature fluctuations above or below the thermal optimum (Beauregard *et al.*, 2013; Oligny-Hébert *et al.*, 2015) and was based on Jensen's inequality (Morash *et al.*, 2018). This method is used in biology and ecology to show the system's average response to variable conditions, which differs from the response of a system to average conditions.

RESULTS

HYDROMETEOROLOGICAL BACKGROUND

The investigated period can be characterised as quite typical, mainly due to the lack of large deviations in air temperature (+0.3°C) and the precipitation sum (+23 mm) in comparison to values from the reference period (1981–2020). The mean temperature at the Legionowo meteorological station during the investigated period reached 9.1°C, with the highest mean daily value noted in July (26.0°C) and the lowest – in January (–18.3°C). The analysed period can be considered as slightly wet, with the total precipitation sum of 589 mm. More than half of the precipitation sum was measured from May to August, while the lowest sums occurred in October, November, and March. As a result, clear seasonal streamflow variability was observed in the catchment (Fig. 2). The mean streamflow of the Wkra River at the Borkowo hydrological station reached 18.4 m^3·s^{-1}, with the highest values observed during the spring in April (60.1 m^3·s^{-1}), while the minimum – during autumn in September (4.5 m^3·s^{-1}).

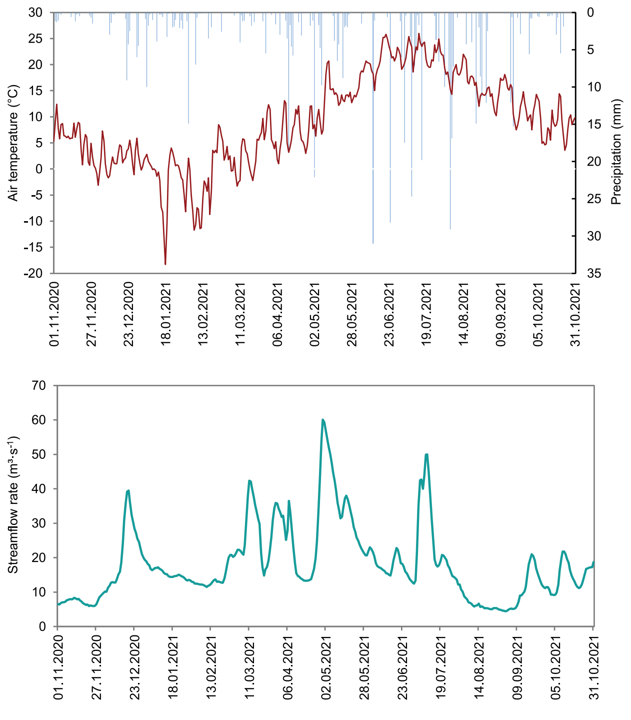

Fig. 2. Hydrometeorological background of the investigated hydrological year 2021: a) mean daily air temperature and daily precipitation at Legionowo, b) streamflow rate of the Wkra River at Borkowo; source: own elaboration based on data from Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)

MONTHLY AVARAGE RANGE OF WATER TEMPERATURE

The average daily range water temperature calculated in the monthly time scale varied from 0.1 to 6.6°C. The lowest values occurred in February, while the highest in June (Fig. 3). The lowest daily range at all measuring points showed greater homogeneity at all measuring points, in contrast to the highest recorded values. The months from July to February were characterised by significantly lower values of the daily range, while the highest daily fluctuations occurred in the spring months from March to June.

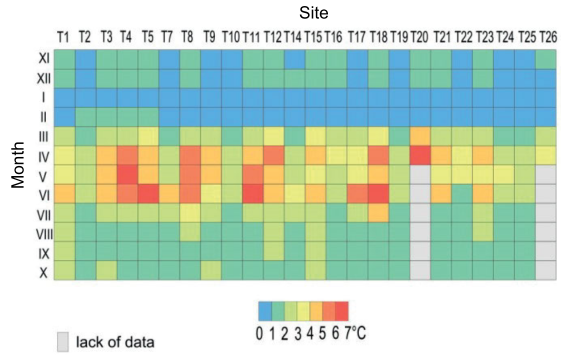

Fig. 3. Variation in the average daily range of water temperature at all measurement points; source: own study

MAXIMUM AND MINIMUM WATER TEMPERATURE TIMING

The occurrence of maximum and minimum water temperatures was dependent on the spatial characteristics of sampling sites and the season (Fig. 4). In the winter half-year, a much greater dispersion of the relative frequencies of maximum and minimum temperatures over the 24-hour cycle was observed. The minimum temperature in the winter months occurred from 22:00 to 10:00, while the maximum temperature was noted from 12:00 to 00:00 (Fig. 4a). In the summer, minimum water temperature occurred mainly from 6:00 to 10:00 and from 23:00 to 00:00, while maximum from 14:00 to 19:00, with a similar distribution at all sites. Spatially,

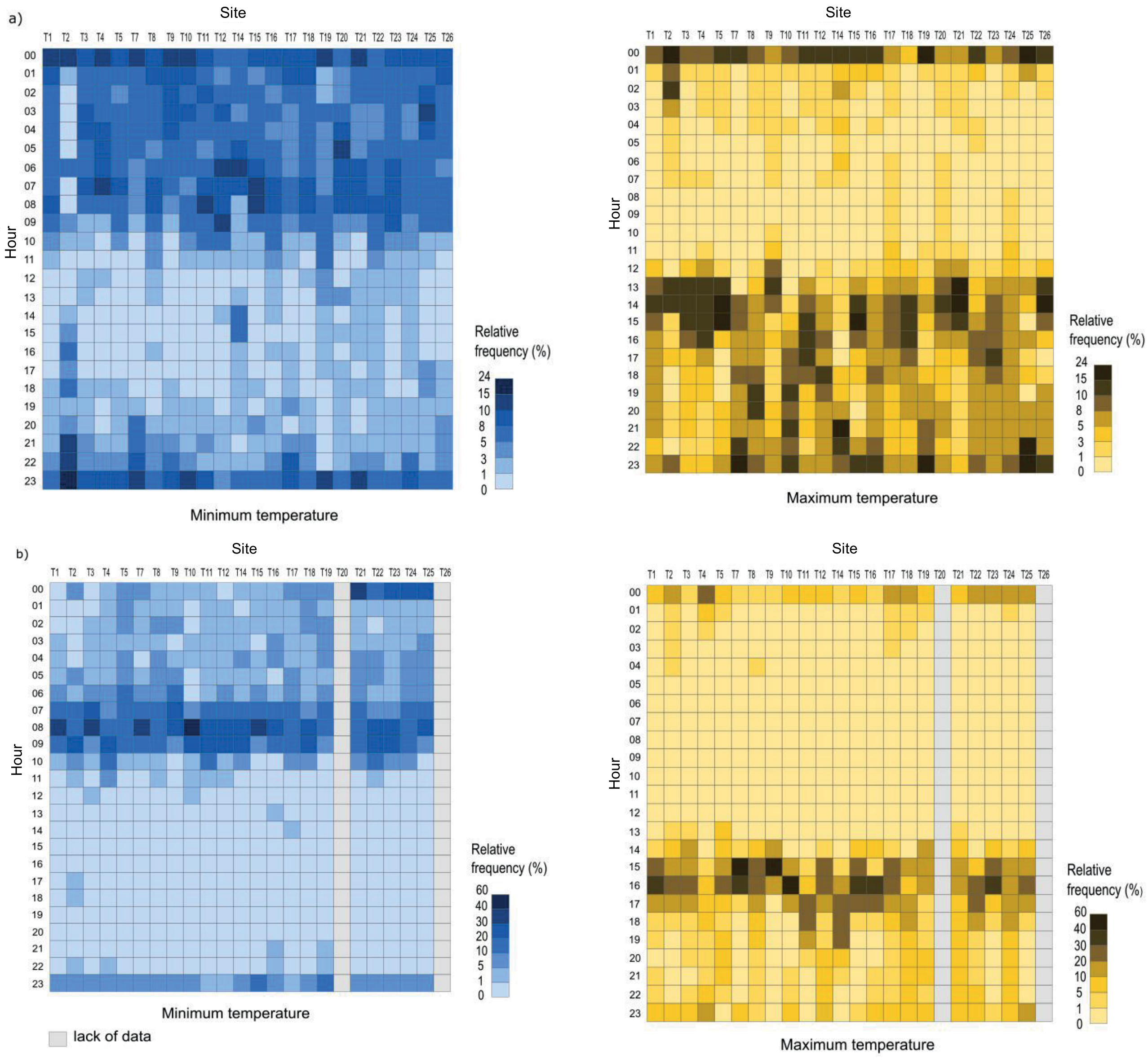

Fig. 4. Relative frequency of minimum and maximum values of water temperature timing at particular hours in: a) winter, b) summer; source: own study

in the winter extreme values at sites T2 and T14 were mostly recorded later in the day, while in the summer at site T4 highest frequency of maximum values was recorded at 23:00 and 00:00.

ENVIRONMENTAL DRIVERS OF 24-HOURS WATER TEMPERATURE DYNAMIC

A clear relationship was observed between environmental drivers and water temperature in particular hours, which varied seasonally (Tab. 2). In the winter months, minimum water temperature showed a negative correlation with catchment area throughout the day, while a positive correlation with maximum values was observed from 22:00 to 6:00. In the summer months, a positive correlation occurred between mean water temperature, with the lowest correlation in the afternoon and highest in the early morning. A positive correlation also occurred with maximum values from 17:00 to 12:00, with the highest correlation at 8:00 (+0.72); and with the minimum from 04:00 to 13:00, with the highest values at 11:00 (+0.53). The presence of vegetation cover had the effect of reducing mean water temperature mainly at noon and in the afternoon. Moreover, a negative correlation between maximum water temperature and vegetation cover appeared in the afternoon and at night; in contrast to minimum temperature, which was noted mainly during the day. In the case of the *W*:*D* ratio, no statistically significant correlation was noted, although a negative trend was observed for mean and minimum values in the winter months, while a positive trend was noted for all statistical parameters in the summer months and for maximum values in the winter months.

In the winter and summer months, in the case of sites T15, T2 and T10 (Fig. 5a, 5b, 5d, 6a, 6b, 6c), the occurrence of the lowest mean water temperature and the highest values of the coefficient of variation was recorded in the morning (5:00–9:00); the highest mean temperatures were recorded along with the lowest coefficient of variation in the afternoon (14:00–18:00). However, the opposite tendency was found in site T23 (Fig. 5d, 6d). In the winter, a significantly higher dynamics of diurnal water temperature was observed. The highest values of the coefficient of variation were recorded in site T10 throughout the year (100% and 30%), while the lowest values were noted in site T2 (67% and 26%). Similarly, the lowest mean water temperatures throughout the year were recorded in site T15, while the highest – in site T2.

It is worth noting that the relationship between the coefficient of variation and mean water temperature is not linear. Typically, the night (00:00–6:00) and morning hours (7:00–11:00), as well as the evening (17:00–23:00) and afternoon hours (12:00–16:00) were characterised by similar values of mean water temperature, while differences became apparent in the case of the coefficient of variation. For example, for the winter half-year, in site T23 (Fig. 5c), mean temperature at 12:00 and 19:00 reached 5.35 and 5.37°C, respectively, while the coefficient of variation at 12:00 reached 72 and 78% at 19:00.

ECOLOGICAL SIGNIFICANCE OF THERMAL FLUCTUATIONS

The duration of the optimum of thermal fluctuations varied within the sampling sites (Fig. 7). For 24-hour thermal fluctuations below 2°C, the duration of the optimum ranged from 80% of days per year in site T19 to 47% of days per year in site T15. The longest duration of the thermal fluctuation optimum occurred in sites T2, T7, T10, T14, T19, T22, T24, T25, ranging from 67 to 80%, while a significantly shorter duration was observed at sites T1, T8, T12 and T15 (52–47%). The Spearman rank correlation showed a positive, statistically significant relationship between catchment area and the 2°C daily range (+0.49).

DISCUSSION

Water temperature dynamics of selected lowland rivers in the hydrological year 2021 followed a pattern noted in previous studies. As documented, the thermal regime of watercourses is mainly driven by short- and long-wave radiation and variability, heating/cooling rates – dependent on hydrological conditions and the environmental characteristics of the catchment (Caissie, 2006). The pattern of water temperature dynamics observed in the hydrological year 2021 was consistent with other studies – with highest water temperature dynamics in the spring and lowest during the winter. In winter, direct radiation is much lower, with high cloud cover and the presence of ice cover further isolating the watercourses from the weather. The highest fluctuations in spring, however, are caused by still undeveloped vegetation, with the increasing influence of the atmospheric heat fluxes (Dugdale *et al.*, 2018).

The important role of solar radiation in heating the watercourses was also marked by the timing of maximum and minimum temperatures. The results obtained in the study were consistent with other studies (Broadmeadow *et al.*, 2011; Łaszewski, 2018). During the midday and afternoon hours, maximum water temperature occurs most frequently due to the solar radiation flux. However, during the winter, the maximum and minimum temperatures lasted much longer and were spread over a larger part of the day, mainly as a consequence of lower atmospheric heat fluxes and simultaneously more cloudy days. Moreover, the obtained results clearly documented that a non-sinusoidal water temperature pattern was definitely more common during the winter half-year, as indicated by the higher frequency of minimum and maximum temperatures at midnight in comparison to the summer period. This suggested that water warming or cooling was driven mainly by changes of air masses due to advection not being conditioned by the time of day, which in such a period is typical for the temperate transition climate (Graf and Wrzesiński, 2019). In contrast, during the summer, the dominant sinusoidal water temperature cycle was observed as a result of radiative heat fluxes on the water-air surface (Yang *et al.*, 2021).

As indicated in previous research, the presence of riparian vegetation stabilises and reduces the maximum water temperature due to scattering direct solar radiation (Fuller *et al.*, 2022; Davies-Colley and Payne, 2023). Dugdale *et al.* (2018) observed greater variation of water temperature (standard deviation 5.7) and a higher daily mean during the winter in grassland areas than in deciduous forests. Also, Kail *et al.* (2021) suggested that in small lowland rivers in Germany, the maximum water temperature could be reduced by 4.6°C downstream of a change from unshaded to fully shaded conditions. Results of the correlation analysis conducted in the current study confirmed the important role of riparian vegetation; negative, significant relationships between water temperature parameters and the riparian shade contribution in 30 m buffer zone were noted primarily in the summer. However, such values were calculated for the afternoon,

Table 2. Spearman's rank correlation coefficients ($p < 0.05$) linking environmental factors of the catchment with thermal parameters at particular hours in the winter and summer semesters

Hour	Winter months									Summer months								
	T_{mean}			T_{max}			T_{min}			T_{mean}			T_{max}			T_{min}		
	catch-ment area	riparian shade 30 m, 5 km	W:D	catch-ment area	riparian shade 30 m, 5 km	W:D	catch-ment area	riparian shade 30 m, 5 km	W:D	catch-ment area	riparian shade 30 m, 5 km	W:D	catch-ment area	riparian shade 30 m, 5 km	W:D	catch-ment area	riparian shade 30 m, 5 km	W:D
00	+0.12	–0.10	–0.26	+0.44	–0.18	+0.21	–0.57	+0.32	–0.24	+0.69	–0.44	+0.35	+0.66	–0.55	+0.25	+0.35	–0.21	–0.11
01	+0.16	–0.10	–0.26	+0.42	–0.17	+0.15	–0.57	+0.32	–0.25	+0.69	–0.44	+0.32	+0.68	–0.41	+0.23	+0.33	–0.16	+0.18
02	+0.17	–0.11	–0.27	+0.43	–0.14	+0.11	–0.57	+0.33	–0.26	+0.70	–0.44	+0.30	+0.68	–0.40	+0.23	+0.36	–0.17	+0.17
03	+0.17	–0.11	–0.27	+0.43	–0.13	+0.14	–0.57	+0.30	–0.27	+0.71	–0.44	+0.29	+0.68	–0.33	+0.24	+0.39	–0.21	+0.13
04	+0.17	–0.11	–0.29	+0.44	–0.11	+0.18	–0.59	+0.33	–0.28	+0.71	–0.40	+0.28	+0.59	–0.24	+0.28	+0.42	–0.23	+0.10
05	+0.17	–0.12	–0.27	+0.45	–0.11	+0.22	–0.58	+0.32	–0.27	+0.72	–0.40	+0.29	+0.59	–0.24	+0.27	+0.52	–0.26	+0.19
06	+0.14	–0.09	–0.25	+0.41	–0.10	+0.24	–0.59	+0.33	–0.22	+0.72	–0.41	+0.28	+0.63	–0.24	+0.23	+0.50	–0.27	+0.21
07	+0.12	–0.08	–0.22	+0.32	–0.03	+0.31	–0.60	+0.34	–0.17	+0.71	–0.42	+0.28	+0.69	–0.26	+0,21	+0.49	–0.25	+0.22
08	+0.04	–0.01	–0.20	+0.24	+0.04	+0.35	–0.56	+0.28	–0.17	+0.68	–0.43	+0.30	+0.72	–0.27	+0.18	+0.51	–0.30	+0.24
09	–0.06	+0.01	–0.17	+0.04	+0.06	+0.27	–0.56	+0.30	–0.17	+0.67	–0.49	+0.34	+0.78	–0.35	+0.14	+0.51	–0.30	+0.24
10	–0.21	+0.08	–0.13	–0.17	+0.15	+0.24	–0.56	+0.28	–0.19	+0.64	–0.50	+0.35	+0.60	–0.35	+0.29	+0.52	–0.35	+0.17
11	–0.34	+0.09	–0.11	–0.25	+0.10	+0.20	–0.56	+0.28	–0.19	+0.63	–0.58	+0.32	+0.53	–0.39	+0.30	+0.53	–0.40	–0.12
12	–0.38	+0.07	–0.12	–0.33	+0.16	+0.05	–0.56	+0.32	–0.21	+0.62	–0.57	+0.32	+0.45	–0.35	+0.34	+0.47	–0.40	–0.03
13	–0.39	+0.03	–0.12	–0.42	+0.10	+0.12	–0.56	+0.23	–0.21	+0.60	–0.58	+0.28	+0.42	–0.37	+0.33	+0.41	–0.44	–0.02
14	–0.41	+0.04	–0.15	–0.39	+0.07	+0.11	–0.56	+0.23	–0.21	+0.60	–0.60	+0.26	+0.40	–0.36	+0.35	+0.36	–0.40	+0.01
15	–0.42	+0.04	–0.10	–0.33	+0.04	+0.05	–0.54	+0.22	–0.23	+0.60	–0.60	+0.27	+0.40	–0.38	+0.32	+0.31	–0.41	–0.05
16	–0.30	+0.02	–0.07	–0.20	–0.02	+0.03	–0.55	+0.23	–0.27	+0.60	–0.58	+0.27	+0.43	–0.43	+0.28	+0.24	–0.30	–0.09
17	–0.22	–0.05	–0.08	–0.08	–0.05	+0.05	–0.60	+0.35	–0.25	+0.60	–0.58	+0.27	+0.46	–0.45	+0.28	+0.28	–0.46	–0.09
18	–0.20	–0.05	–0.10	+0.07	–0.09	+0.05	–0.71	+0.37	–0.20	+0.62	–0.58	+0.31	+0.52	–0.56	+0.26	+0.39	–0.42	–0.03
19	–0.12	–0.02	–0.14	+0.19	–0.12	+0.14	–0.61	+0.38	–0.20	+0.61	–0.56	+0.32	+0.56	–0.56	+0.25	+0.31	–0.30	+0.00
20	–0.07	–0.02	–0.19	+0.28	–0.19	+0.20	–0.62	+0.38	–0.18	+0.60	–0.53	+0.31	+0.60	–0.54	+0.30	+0.33	–0.31	+0.00
21	–0.05	–0.03	–0.22	+0.40	–0.17	+0.15	–0.59	+0.34	–0.25	+0.60	–0.53	+0.31	+0.64	–0.58	+0.26	+0.33	–0.22	+0.07
22	+0.06	–0.08	–0.23	+0.44	–0.16	+0.17	–0.59	+0.34	–0.25	+0.64	–0.50	+0.33	+0.66	–0.55	+0.25	+0.36	–0.22	+0.07
23	+0.10	–0.07	–0.25	+0.45	–0.16	+0.21	–0.57	+0.32	–0.24	+0.64	–0.49	+0.33	+0.67	–0.48	+0.21	+0.33	–0.19	+0.10

Explanations: blue cells = correlation statistically significant, W = width, D = depth.
Source: own study.

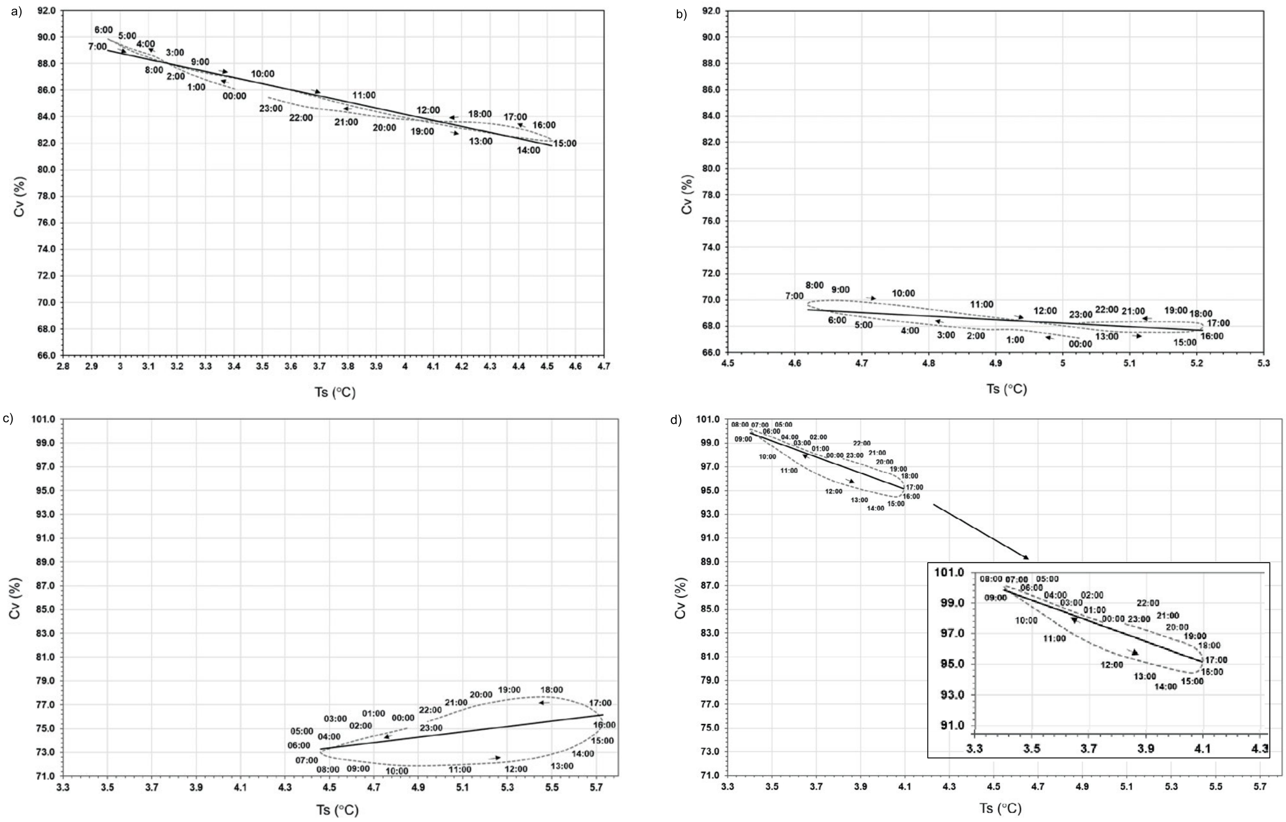

Fig. 5. Relationship between mean water temperature in individual hours (*Ts*) and coefficient of variation (*Cv*) values in the winter half-year for catchments with: a) the smallest area (T15), b) the largest area (T2), c) the highest percentage share of riparian vegetation (T23), d) the lowest percentage share of riparian vegetation (T10); source: own study

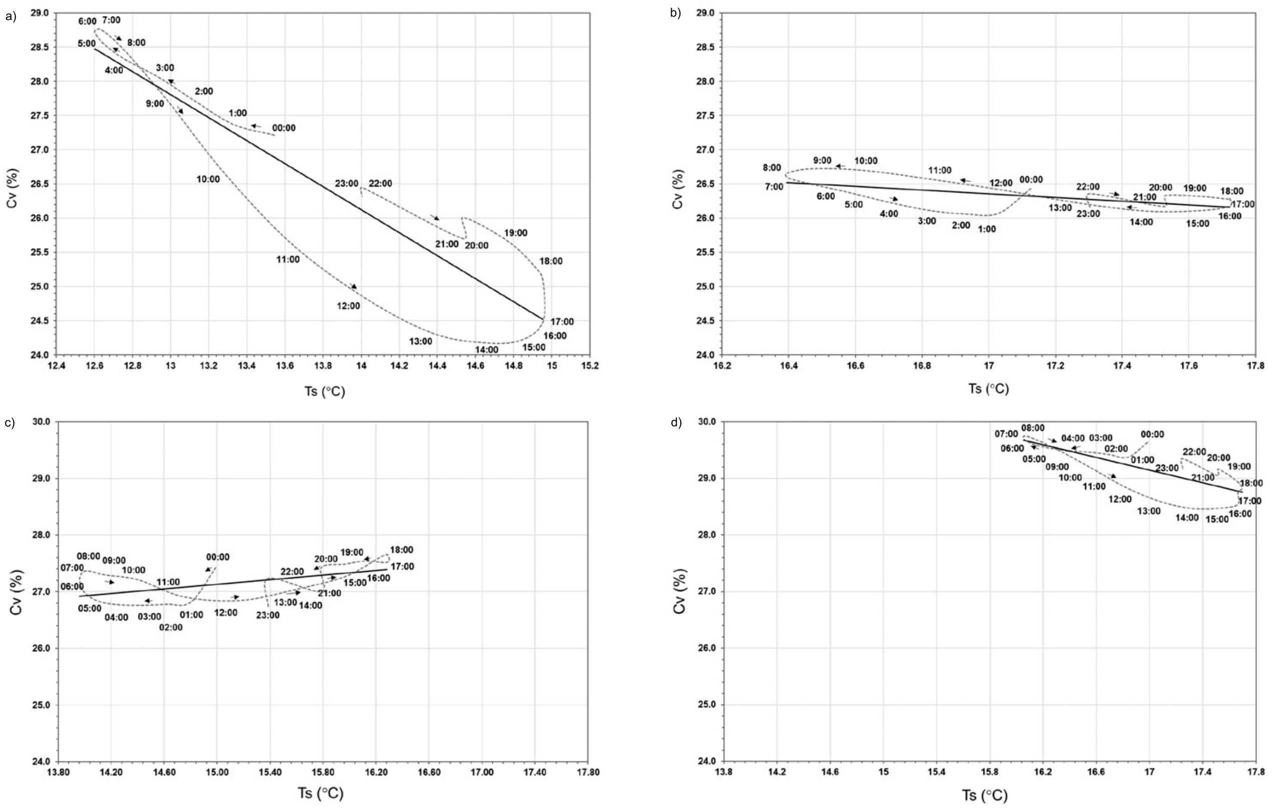

Fig. 6. Relationship between mean water temperature in individual hours (*Ts*) and coefficient of variation (*Cv*) values in the summer half-year for catchments with: a) the smallest area (T15), b) the largest area (T2), c) the highest percentage share of riparian vegetation (T23), d) the lowest percentage share of riparian vegetation (T10); source: own study

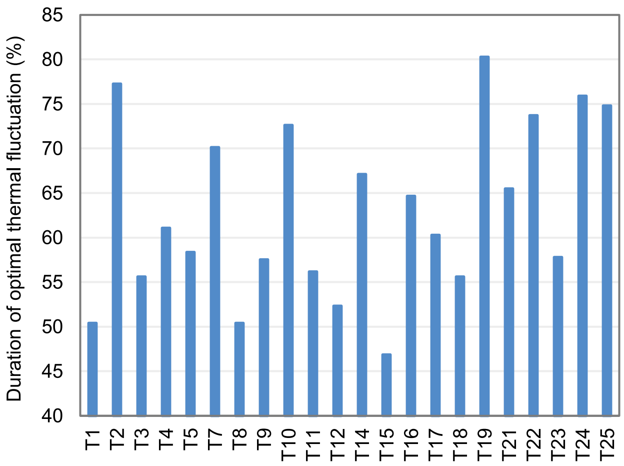

Fig. 7. Spatial variation in the duration of optimum thermal fluctuations: for a diurnal range below 2°C in the hydrological year 2021; source: own study

evening and night hours (16:00–01:00); this tendency could be explained by the fact that maximum temperatures occur naturally in the afternoon due to the previous, midday heating of the water surface and lasts much longer in summer due to the longer day. Furthermore, the presence of vegetation reduces wind speed and air temperature, and simultaneously retains air near the stream surface, which slows down heat advection and can decrease maximum water temperatures at night (Johnson, Wilby and Toone, 2014).

It was also documented that riparian vegetation reduces hourly fluctuations in water temperature, indicated in this study by the coefficient of variation computed for certain hours. Sites with a higher percentage of riparian vegetation had lower fluctuations in water temperature in winter and summer, up to almost 30%. Interestingly, only the site with the highest contribution of riparian shade showed the lowest fluctuation in the morning and the highest in the afternoon; the presence of vegetation also contributes to less heat loss through the emission of its own long–wave radiation (Turunen *et al*., 2021). Moreover, it is worth noting that during the whole summer period, vegetation could cause higher fluctuations in water temperature, which is determined by the vegetation cycle. Riparian vegetation in temperate climate across the Mazovian Lowland develops mainly from April to June, reaching its apex from late July to August and slowly dying back in autumn. This led to an increase in water temperature variation in the afternoon; in July the riparian shade reduced the water temperature extremes, and in May and June the water surface was exposed to direct solar radiation.

Another investigated environmental characteristic was the catchment area, typically considered as a proxy of streamflow rate (Jackson *et al*., 2017). In the present study, at sites representing smaller catchment area higher fluctuation was much more frequent, even up to 20% in the winter months. Also, the increase in the catchment area led to a decrease in water temperature parameters, while in the summer the relationship was opposite. The highest correlations with mean, maximum, and minimum values occurred during hours without direct solar radiation, which indicates the importance of heat capacity in the cooling rate of water. It must be emphasised that larger catchment area is generally combined with a greater depth of the streams; this was evidenced by the relationships with the *W*:*D* ratio, which even statistically insignificant, were positive and the highest in the evening and morning hours. Thus, it can be stated that all adopted environmental characteristics had greater impact on water temperature values during the non–solar radiation exposure time.

Ultimately, the obtained results also have a practical aspect in terms of ecology, angling and the fisheries management. It was documented that sampling sites with larger catchment areas were distinguished by a smaller range of thermal fluctuations, which translated into a longer duration of optimum thermal fluctuations for aquatic biota (<2°). However, these watercourses were also characterised by higher maximum water temperatures, which are crucial in terms of the survival of fish and macroinvertebrates (Krajenbrink *et al*., 2022; Bonacina *et al*., 2023). This, therefore, prevents the occurrence of cold–water species, which are the most sensitive to changes in water temperature. Simultaneously, sites with a higher proportion of riparian vegetation were characterised by longer duration of optimum thermal fluctuations; similar conclusions were presented by Broadmeadow *et al*. (2011), who reported differences between the diurnal range of water temperature for catchments with different proportions of vegetation. Nevertheless, thermophilic species respond negatively to significant fluctuations in water temperature; Takeuchi *et al*. (2021) presented that ayu (*Plecoglossus altivelis*) exhibited higher mortality when exposed to 4–6°C diurnal water temperature ranges. Presented conclusions suggest that fishery management in small catchments in terms of stocking with fry and fingerling, as well as the construction of spawning areas, requires special caution and previous recognition of thermal characteristics, which as was documented, are seasonally and spatially complex.

The response of different aquatic species not only to variation in water temperature over longer time scales, but also to fluctuations in a 24-hour cycle, should be an important research issue in the future, especially when combined with climate-change-induced thermal regime transformation. Thus, the evidence on environmental dependence of diurnal water temperature dynamics is crucial for the effective conservation of biodiversity and reliable prediction of changes in aquatic ecosystems.

CONCLUSIONS

Typical hydrometeorological conditions observed during the investigated period, although with some extremes in terms of air temperature values, nonetheless make the results related to the sub-daily water temperature dynamics quite representative also for numbers of streams located across the lowland agricultural landscape.

1. Maximum water temperature values were recorded in the afternoon, while minimum values were recorded in the morning. A similar time frame was found for water temperature dynamics; the highest occurred in the morning hours from 5:00 to 9:00 CEST, while the lowest – from 14:00 to 18:00 CEST.
2. Environmental factors exhibited seasonal variation in their impact on water temperature values. Catchment area influenced water temperature values in the winter half-year, while riparian vegetation became important in the summer half-

year. In the summer half-year, riparian shade caused greater variation in water temperature values from hour to hour due to the variability of tree and shrubs cover associated with the vegetation cycle.
3. Seasonally, greater water temperature dynamics were noted in the winter half-year. Spatially, on the other hand, the highest sub-daily dynamics occurred for the sites with the lowest proportion of riparian vegetation, while the smallest dynamics occurred for sites representing higher catchment area.
4. The presence of riparian shade and a larger catchment area influenced less diurnal temperature dynamics, which translated into a longer duration of the optimum of thermal fluctuations.

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