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Water temperature in lowland streams: a preliminary study on its spatio-temporal variability and environmental dependence

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Abstract: The aim of the study was to evaluate the spatio-temporal dynamics of water temperature in the Wkra River catchment. Water temperature was monitored using digital recorders across 26 streams located in central Poland and representing small tributaries with variable catchment properties. On the basis of the measurement data collected during the hydrological year 2021, the spatial and seasonal variability of water temperature parameters was analyzed using statistical metrics and principal component analysis. Moreover, selected catchment and channel metrics in various spatial scales were combined with correlation analysis to assess their influence on monthly mean and maximum water temperature values. The results indicate significant spatial variability of water temperature in the Wkra River tributaries, creating a mosaic of thermal habitats. Seasonally, water temperature followed a sinusoidal pattern, while subdaily dynamics varied seasonally, with the highest values observed in spring and early summer. The mean and maximum water temperature values were related to environmental metrics mainly during the summer half-year; significant positive relationships were documented for the catchment area, whereas negative relationships were observed with channel gradient and riparian shade degree. In winter, only stream orientation demonstrated significant correlations. These findings are relevant in the context of anticipated changes in river thermal regime due to a climate warming effect, as well as setting new research issues; they also provide a unique basis in the context of fisheries management and land practices.

Introduction

The importance of stream water temperature has been widely discussed primarily in the ecological context, as this basic water quality parameter has a significant effect on a number of other abiotic and biotic variables of lotic ecosystems (Poole and Berman 2001). Specifically, the thermal regime of streams influences the life processes of aquatic species, such as their survival, growth rate, development, and distribution (Elliott and Elliott 2010). This significance is confirmed by numerous reports referring particularly to fish thermal requirements, which were based on laboratory experiments or field observations and published by environmental and fishery agencies (Solomon and Lightfoot 2008). For that reason, interest in stream water temperature has recently increased, as reflected in numerous studies and investigations (Caissie 2006). This trend has also be driven by to accelerating climate changes and their hydrological responses, as well as variable forms of human impacts (Tomczyk and Wiatkowski 2020, Bartnik and Jokiel 2021, Szarek-Gwiazda and Gwiazda 2022). Another significant factor behind this concern for stream thermal regime has been the emergence of relatively inexpensive and accurate measurement devices, such as digital temperature recorders (Jackson et al. 2016).

Across the Polish lowlands, with their transitional climate zone and streams characterized by a mixed nival-pluwial flow regime (Wrzesiński 2017), investigations into thermal dynamics have been carried out relatively sporadically (Łaszewski 2020). Moreover, access to water temperature data has determined research objectives and study areas; in consequence, investigations were carried out mainly in catchments covering hundreds, or more often thousands, of square kilometers, where monitoring stations were operated by the Institute of Meteorology and Water Management (Marszelewski and Pius 2016). In that way, several significant conclusions emerged from these studies: Graf and Wrzesiński (2020) documented that Polish rivers with a quasi-natural thermal regime experienced water temperature increases from April to November during 1971–2015, Marszelewski et al. (2022) identified changes in thermal seasons in the face of climate warming, while Yang et al. (2022) quantified the visible impact of climate variation, damming, and flow regulation on the thermal regime, using the Vistula River as an example. In the case of small lowland catchments, water temperature investigations remain unrepresentative despite considerable anthropogenic disturbances (Bartnik and Jokiel 2021). The main reason for this underestimation lies in technical limitations and difficulties, as shallow, small streams in temperate climate are difficult to measure reliably due to winter freezing and summer drying. Ice phenomena in winter can damage temperature recorders and their batteries, while summer low flows with channel overgrowth can drastically alter flow conditions and water depth.

The present study aimed to evaluate the dynamics of water temperature in the tributaries of the Wkra River. Its specific objectives were to (1) recognize spatial and seasonal water temperature patterns in lowland streams and (2) improve understanding of the environmental controls on their water temperature. Although this investigation draws on earlier worldwide studies on river thermal regime, it offers a valuable supplement contribution to knowledge of temperature dynamics in small streams within the humid continental climate zone, characterized by specific environmental conditions.

Study area

Water temperature monitoring was conducted in the southern, downstream part of the Wkra River catchment, a right tributary of the Narew River, with a length of 249.1 km and a catchment area of 5344.5 km^2. The studied tributaries are located within the Ciechanów Upland, Płońsk Upland, Raciąż Plain, and Mławskie Hills, all of which lie in the Mazovian Lowland. The morphology of the Wkra catchment was shaped during the Pleistocene glaciation, and superficial Quaternary deposits consist mainly of post-glacial sediments such as fluvial sands, clays, and loams. The whole area is characterized by relatively uniform altitudes, ranging from 77 to 209 m a.s.l. The climate of the study area is classified as warm-summer humid continental (Cfb), with dry periods in winter (December-February) and warm, wet periods from June to August. The mean annual air temperature in 1981-2020 was 8.8°C, and mean total annual precipitation was 566 mm. The highest mean temperatures and greatest monthly precipitation are typically observed in summer, and the lowest in winter. Agricultural land dominates the catchments of the studied tributaries of the Wkra River, covering almost 80% of the area. The northern part of the study area has a higher proportion of forest, while urban or rural areas occupy only a relatively small share of the land cover.

Materials and Methods

Temperature monitoring

Water temperature monitoring was conducted using digital recorders HOBO U22-001 and UA-001-08 (Onset Computer Corporation) with accuracies of 0.2°C and 0.47°C, respectively, and the resolution of 0.1°C. Before installation, all recorders were checked with commonly known “ice bath” method; in the case of the U22-001 devices, differences of 0.07°C around 0.0°C were recorded, while for UA-001-08 devices the differences was 0.18°C, which made possible to reliably compare results between recorders. Sensors were installed in the streams using various techniques adapted to local channel characteristics; they were anchored to the bottom, woody debris, or concrete blocks, and always placed inside perforated PCV pipes to prevent heating from solar radiation. Installation sites were located in relatively turbulent, mixed type of flow. No cross-sectional temperature gradient was detected at any site using a handheld thermometer, which confirmed the representativeness of the continuous measurements. Data were collected from 1 November 2020 to 31 October 2021 at a temporal resolution of 15 minutes.

Measurement sites were distributed across 26 streams (Fig. 1), which are tributaries of the Wkra River, with catchment areas ranging from 4.9 to 524.5 km^2, representing mesoscale monitoring (Jackson et al. 2016). Sites were selected from streams managed by the Ciechanów Region of the Polish Angling Association using a purposive sampling scheme, following approaches used in previous investigations (e.g. Broadmeadow et al. 2011, Imholt et al. 2013). Selection criteria included variation in catchment area and land cover of measurement sites, as well as the absence of major anthropogenic influences such as direct sewage inflows or reservoir releases. In most cases, sites were spatially independent; only in three cases, however, only in three cases., two loggers were installed on the same stream, with measurement points located some distance apart. Two recorders were irreversibly damaged during winter freezing (T6 and T13) and were excluded from analysis. In addition, two streams dried up periodically from June to September 2021 (T20 and T26), so only their winter-period data were analyzed.

Environmental metrics estimation

Based on the previous investigations and the specific characteristics of the study area, a set of catchment- and reach-scale environmental metrics was chosen. The upstream catchment area (UCA) of each measurement site was calculated using digital Polish hydrographic and topographic maps. Stream gradient (SG) was derived from a stream network layer in the National Database of Topographic Objects and a digital terrain model (NMT-PL-KRON86-NH, 1x1 m resolution) based on Airborne Laser Scanning. Gradient was averaged over 1, 3, and 5 km sections upstream of measurement sites, following a common procedure for determining the optimal scale for detecting significant impact (Moore et al. 2005, Hrachowitz et al. 2010). A similar approach was applied to stream orientation (SO), which was computed as the sine of the mean section orientation in degrees from the east-west direction; in consequence, values close to 1 indicate north-south channels, which are more vulnerable to heating from solar radiation (Malcolm et al. 2004).

The percentage of riparian shade (RS) was calculated using two pan-European, high-resolution and free layers from the Copernicus Land Monitoring Service: the 2018 Forest Type layer and the 2015 Small Woody Features layer. These datasets were merged to create a 10 m resolution layer including both coniferous and deciduous forest cover. According to Sweeney and Newbold (2014), a 30-meter-wide buffer zone on both stream banks was chosen for riparian shade calculations, which were conducted for the same stream section. Channel width and depth, used to compute the width-to-depth ratio (W:D), were measured during a low flow period in August 2021 directly in the measurement sites, as well as in transects located 50, 100,

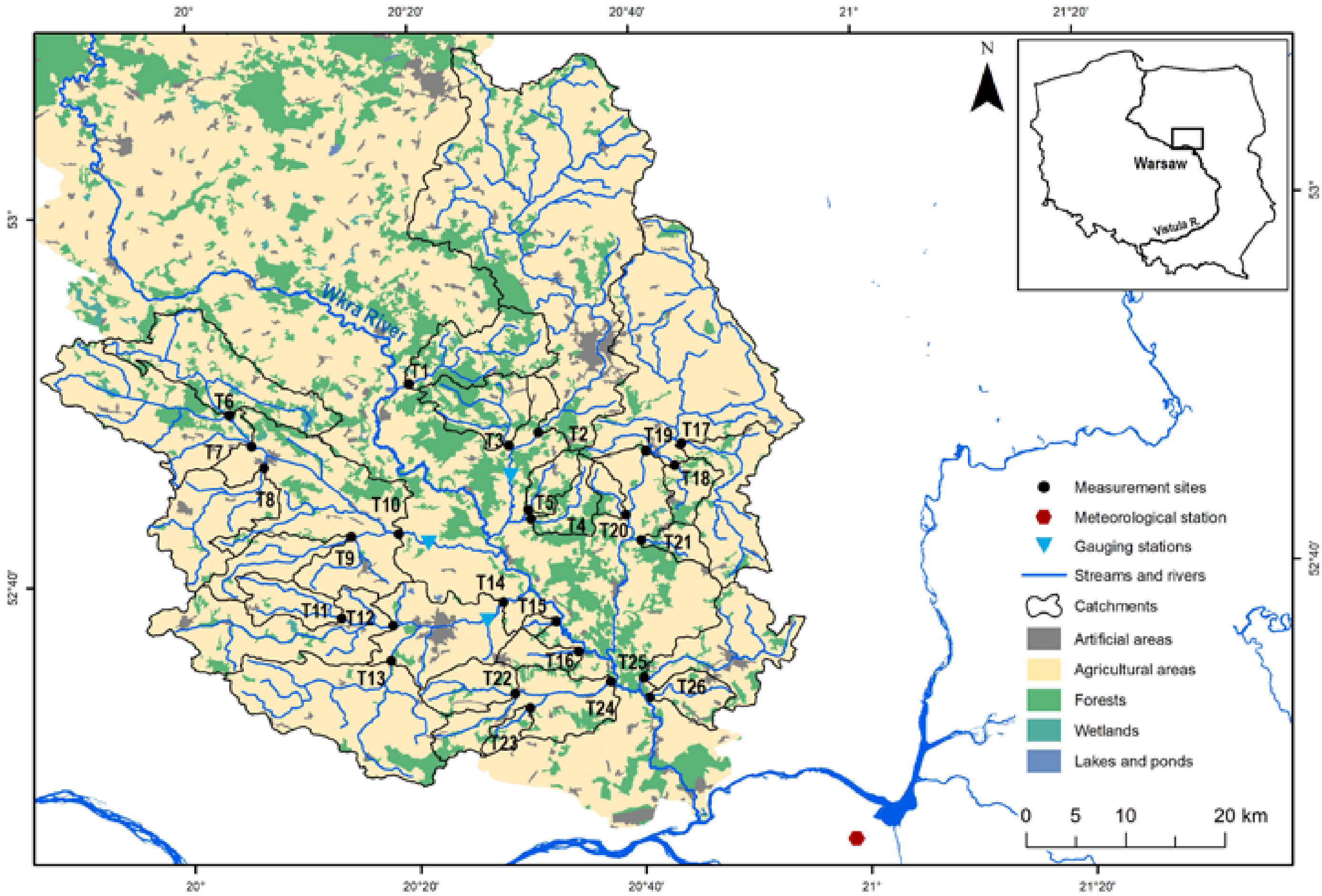

Figure 1. Measurement sites distributed across the Wkra River catchment on the background of land cover, based on CLC 2018 dataset. Author's own elaboration

300, and 500 m upstream; values were then averaged. National-scale metrics such as distance from coast and elevation were omitted, as they are not relevant for mesoscale studies or in a relatively flat terrain (Jackson et al. 2016).

Statistical analysis

Before statistical analysis, the raw 15-minute water temperature data were inspected to remove incorrect values, such as those caused by temporary logger exposure to air during data downloading, as well as potential errors. Such single values were interpolated using neighboring measurements. The verified 15-minute water temperature data were presented in box-and-whiskers plots for each measurement site and for certain months, enabling preliminary inspection of the spatial and seasonal variability of thermal dynamics.

In order to present and visualize overall relationships between water temperature metrics for individual months, and to assess the relative similarity of the investigated sites, principal component analysis (PCA) was applied. PCA is commonly used in environmental studies, including those related to stream water temperature (Imholt et al. 2013). The thermal regime metrics adopted for the monthly-scale analysis were mean (Mean) and mean daily range (Mdrange) of water temperature values, as well as seven-day average of daily maximum (7damax) and daily minimum (7damin) stream temperature (Grabowski et al. 2014). PCA was performed with a correlation matrix for component loading (Cload) calculations, while the number of significant components (PCs) was selected using an empirical Kaiser criterion. Due to the valuable contribution of the second component, results were visualized in a two-component space. Component loadings equal to or greater than 0.50 were considered significant correlations, following Żelazny et al. (2018). The suitability of PCA was confirmed by Bartlett's test of sphericity ($p<0.001$) and Kaiser–Meyer–Olkin (0.652) tests, which indicated that selected variables are statistically significantly interrelated and that the sampling adequacy was at an intermediate level.

Correlation analysis was conducted to identify the optimal spatial scale of adopted environmental variables explaining selected temperature metrics. Spearman correlation analysis was used, mainly due to the small sample size and the non-normal distribution of data, as confirmed by the Shapiro-Wilk test. The correlation analysis was conducted for every month for two temperature parameters: monthly mean water temperature (Mean) and seven-day average daily maximum temperature (7damax). Environmental metrics included catchment area, W:D ratio, as well as riparian shade, channel gradient, and stream orientation at 1 km, 3 km, and 5 km upstream scales; riparian shade was calculated within a 30-meter-wide buffer zone. A probability value of correlation of less than 0.05 was considered as statistically significant.

Hydrometeorological data for the study period were obtained from the Institute of Meteorology and Water Management. Daily mean air temperature and daily precipitation sums were collected from the Legionowo meteorological station, which is the closest one to most measurement sites. Mean daily streamflow data were sourced from gauging stations located in the downstream sections of the largest investigated rivers – Łydynia, Raciążnica, and Płonka –at Luberadz, Sarbiewo, and Strachowo, respectively. To evaluate thermal and precipitation conditions during the study year, quantile thermal classification by Miętus et al. (2002) and Kaczorowska's precipitation classification (Kaczorowska 1962) were used, with the reference period set as 1991-2020.

Results

Hydrometeorological background

The hydrological year 2021 was quite typical in terms of seasonal air temperature and precipitation patterns (Fig. 2a). The mean air temperature at the Legionowo meteorological station was 9.1°C; July turned out to be the warmest month (22.2°C), while February was the coldest (-2.4°C). According to the Miętus classification, the investigated year can be considered normal in relation to the 1991-2020 multiyear period. Precipitation occurred mainly in the summer half-year (76%), with a total of 589 mm; thus, the studied year can also be considered normal on the basis of the Kaczorowska precipitation classification and the 1991-2020 reference period.

Runoff conditions in the studied streams in 2021 were assessed based on streamflow analysis and directly reflected the prevailing meteorological conditions. The mean streamflow rates during the hydrological year 2021 reached 2.62, 2.04, and 2.06 $m^3 \cdot s^{-1}$ for the Łydynia, Raciążnica, and Płonka rivers, respectively. These values were higher by 8.0, 19.9, and 53%, respectively, compared with the 2011-2020 multiyear means, largely due to numerous dry years in the reference decade (2015, 2016, 2019, and 2020), which lowered the long-term average. Peak flows were observed mainly in winter and spring, being a result of snowmelt and spring rainfalls, and ranged from 7 to 12 $m^3 \cdot s^{-1}$. Following a convective rainfall event in July 2021, streamflow rate at the Strachowo gauging station on the Płonka River peaked at 18.8 $m^3 \cdot s^{-1}$. In consequence, both the dynamics and magnitude of runoff conditions differed between catchments, especially during summer half year. For the Płonka River, mean streamflow was higher in summer than in winter, whereas for the Łydynia and Raciążnica rivers, higher average streamflow values were recorded in winter (Fig. 2b). Nevertheless, simultaneous low-flow periods occurred in June, September, and October, across the investigated streams, with discharge falling below 1 $m^3 \cdot s^{-1}$.

Spatial and seasonal water temperature variability

Thermal contrasts during the hydrological year 2021 were evident both spatially and seasonally, as indicated by the

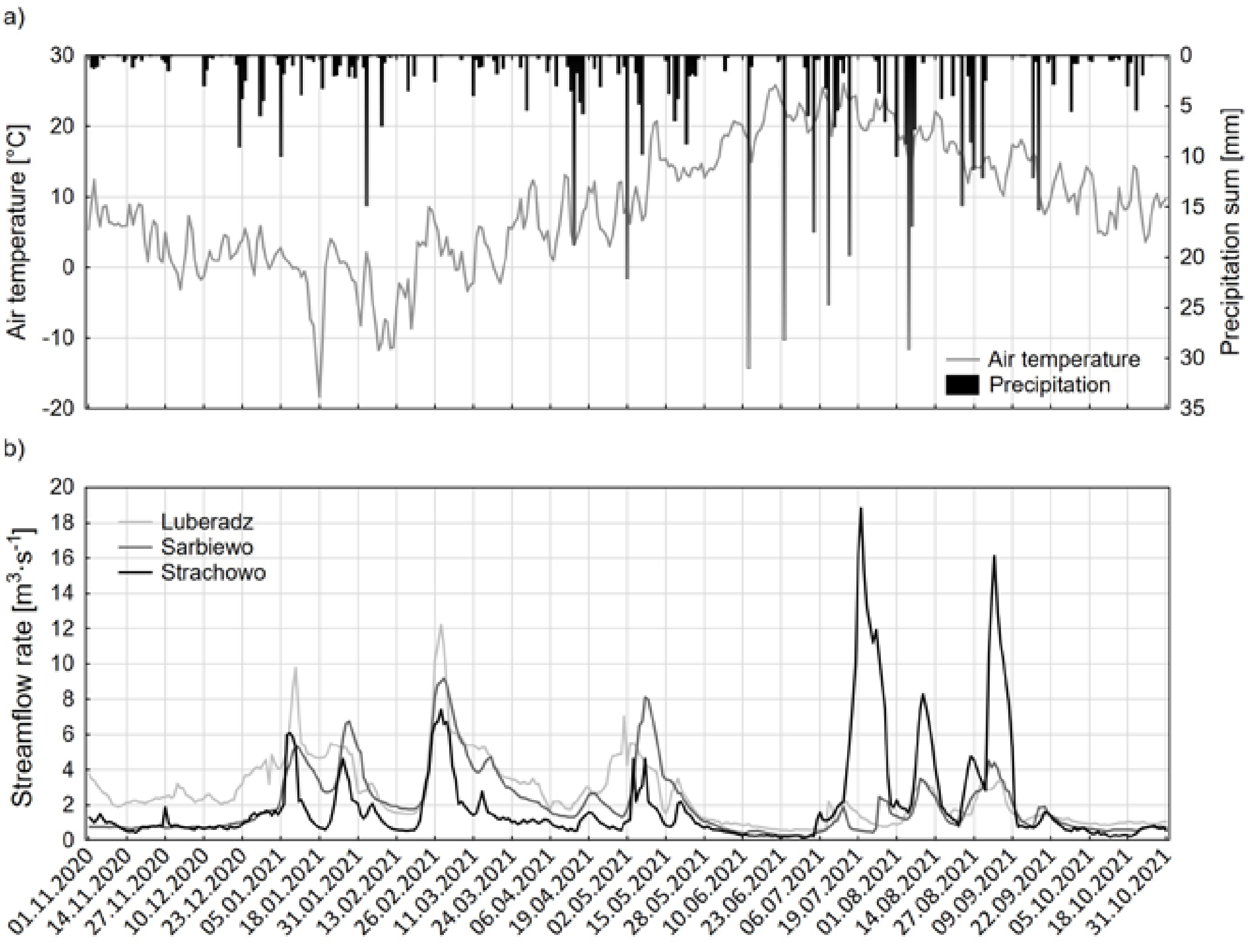

Figure 2. Mean daily air temperature and precipitation pattern at the Legionowo meteorological station (a) and mean daily streamflow rate in Luberadz (Łydynia River), Sarbiewo (Raciążnica River), and Strachowo (Płonka River) (b) during the hydrological year 2021. Author's own elaboration based on data from Institute of Meteorology and Water Management

distribution of 15-minute values on the boxplots (Fig. 3). Spatially, mean water temperature values at most sites ranged from 9.0 to 10.0°C, which was generally equal to or higher than the local annual mean air temperature. The highest mean value was noted for site T2, representing the second largest catchment (11.0°C), while the lowest was at site T15, representing the smallest catchment (8.7°C). Absolute instantaneous maximum water temperatures varied by up to 7.0°C, ranging from 22.1°C in site T15 to 29.1°C in site T18 (Fig. 3a). At most sites, however, these maxima did not exceed 25-26°C. During winter, freezing water temperature values of around 0.0-0.1°C were noted at nearly all investigated sites, except at site T11, where the temperature during winter did not drop below 0.4°C. Such low water temperature values occurred in January and, particularly, in February, as indicated by right-skewed asymmetry of measured values (Fig. 3).

Seasonally, the mean monthly water temperature across all investigated sites followed the sinusoidal air temperature pattern – on average, June was the warmest month in all measurement sites (20.1°C) while February – the coldest (0.7°C). Absolute maximum values occurred in most streams in July, during extended periods of high air temperature; however, in some measurement sites, such as those located in the Płonka River catchment, maximum values were recorded in June. The greatest variability in water temperature, indicated by both the interquartile and absolute ranges, was documented in spring and early summer, whereas winter months generally showed minimal thermal dynamics (Fig. 3b). On the sub-daily time scale, fluctuations were most pronounced in June and April, whereas January and February exhibited the lowest dynamics.

A more detailed insight into thermal dynamics was revealed by principal component analysis (PCA) (Fig. 4). Spatial and seasonal variability of water temperature parameters across streams in the Wkra River catchment was represented by two independent components (factors), with a cumulative explained variance of 99.3%. Although the eigenvalue of the second principal component was below 1, and thus not meeting the Kaiser criterion, it was retained in the analysis and graphical presentation due to its informative value for the daily range parameter. The first principal component (PC1) explained 80.5% of the total variance. Loadings indicated strong positive correlations with mean monthly temperature (Cload=0.99), 7damax (C load=0.99), 7damin (C load=0.93), and a moderate positive correlation with mean daily range of water temperature (C load=0.64). The second principal component (PC2) explained 18.8% of the variance and was associated with the thermal regime dynamics, showing a single strong positive correlation with mean daily range parameter (C load=0.86).

As presented in Figure 4b, the first PC adequately describes all four thermal regime parameters and shows

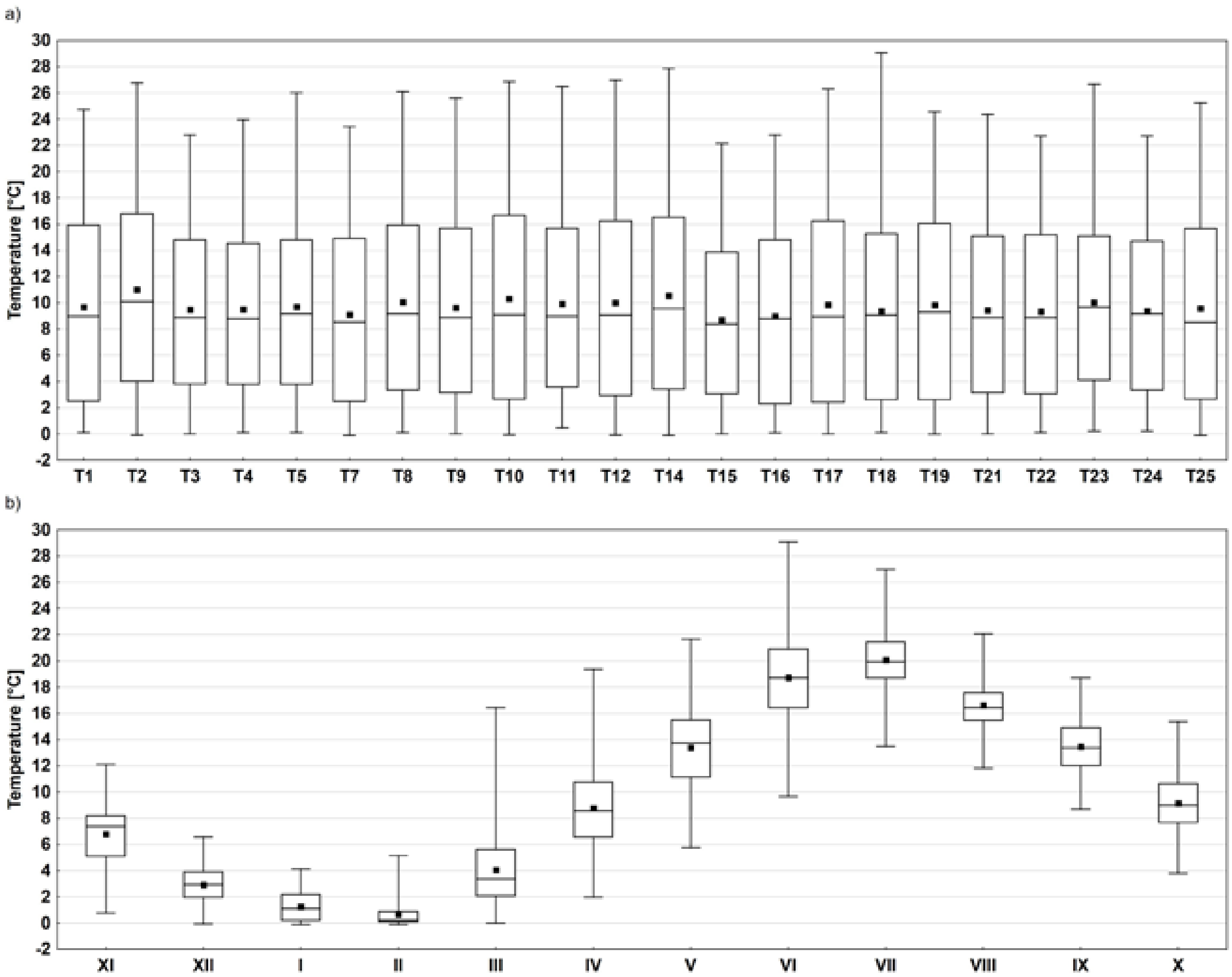

Figure 3. Spatial (a) and seasonal (b) variability of 15-minutes water temperature values across investigated sites (excluding sites T20 and T26) from November 2020 to October 2021. Author's own elaboration

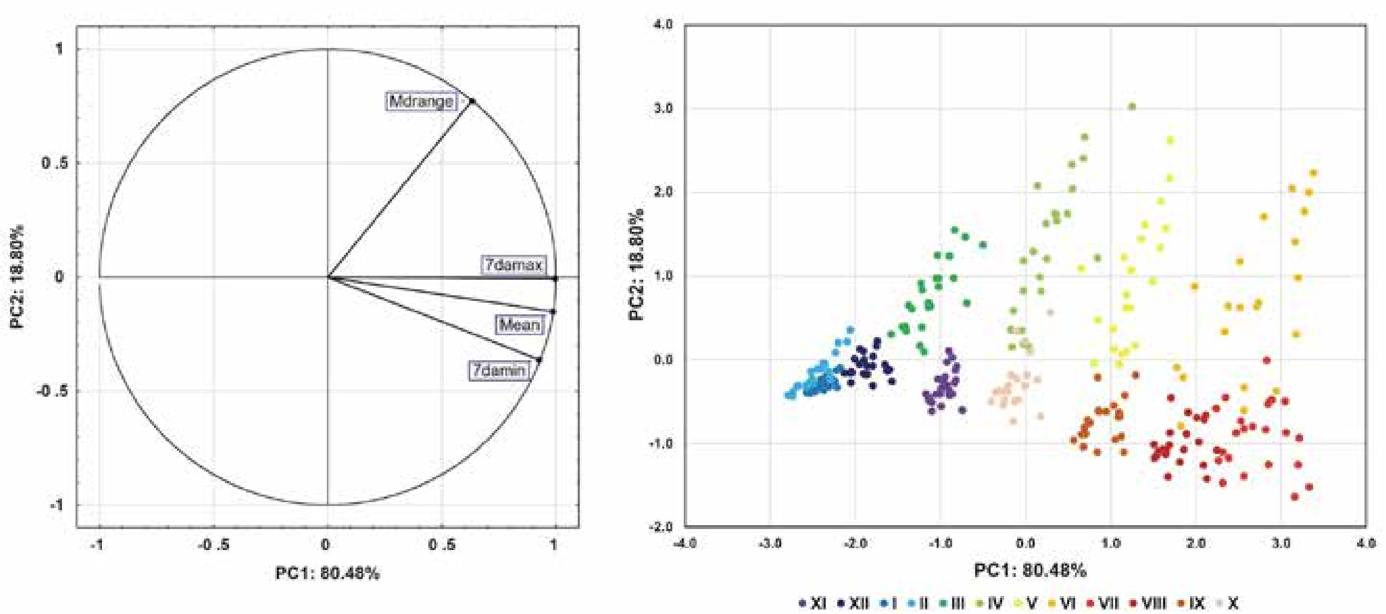

Figure 4. Component loadings associated with all thermal parameters (left) and bi-plot presenting projection of certain cases (right) on the factor plane in the PCA analysis. The colors represent different months. Author's own elaboration

their increases from winter to summer months. The biplot indicates that during the winter (December-February), the investigated tributaries were the most homogenous in terms of the temperature regime, while in June and July, the sites were the most diverse on the factor plane. A second tendency was demonstrated by the second principal component (PC2), which pointed to an increase in water temperature dynamics; analysis revealed that the highest daily fluctuations, indicated by Mean_rg, occurred from March to July, particularly in April, May, and June. During these five months, the sites were also relatively more variable in terms of dynamics, as indicated by case projection. Overall, this interesting tendency is notable: autumn and spring months were similar in mean values but were represented by different case paths, indicating different daily dynamics (Fig. 4b).

Environmental dependence of water temperature

Correlation analysis, conducted using a Spearman rank coefficient, indicated substantial seasonal variability in both the direction and performance of relationships between thermal parameters – mean monthly water temperature values (Mean) and 7damax – and environmental metrics calculated for different spatial configurations (Tables 1 and 2). Generally, similar patterns were observed for mean and maximum values; however, significantly more correlations ($p<0.05$) were found for the summer half-year, mainly from May to October, for both water temperature parameters. During the winter half-year, only stream orientation (SO) displayed negative, statistically significant relationships for both mean and maximum values. In contrast, during the summer months, a positive relationship was found with upstream catchment area (UCA) and a negative one with stream gradient (SG). Significant negative relationships were also documented for riparian shade metrics (RS). The best spatial configuration for stream gradient was 1 km, the same as for stream orientation, whereas 3-kilometer-long buffer zone had the highest predictive power for riparian shade. For W:D, significant relationships were observed only in May and mean temperature. Despite the lack of significant correlations, it is noteworthy that the direction of correlation coefficients changed across months, for example, during winter, mean and maximum water temperature were negatively related to upstream catchment area, while in April/May, the relationship changed.

Discussion

Comprehensive monitoring of stream water temperature across small lowland streams provided unique insights into spatial and temporal heterogeneity and their main environmental drivers. The present study contributes to numerous studies on the variability of river thermal regimes on a small spatial scale (e.g., Malcolm et al. 2004, Broadmeadow et al. 2011), while specifically focusing on lowland streams, which, despite their ecological importance, have received relatively little research attention.

The study revealed significant spatial heterogeneity in water temperature across the investigated sites, with mean and maximum annual values differing by 2.0°C and 7.0°C, respectively. These differences were similar to, or even greater than, those reported for the mountainous Dee River catchment, where water temperature varied by 7.6°C in maximum values despite considerable environmental gradients (Imholt et al. 2013), and for the dynamic forest-urbanized Silnica River catchment, which showed a 5.6°C difference in summer maximum values (Ciupa and Suligowski 2024).

From a temporal perspective, significant dynamics in stream water temperature were noted both on annual and diurnal basis. In addition to the typical sinusoidal pattern, reflecting atmospheric variability, including solar radiation intensity and air temperature (Dugdale et al. 2018), distinct winter conditions occurred when water temperature reached 0.0°C and ice phenomena persisted from December to March. During periods of ice cover, diurnal temperature variation was absent due to isolation from atmospheric heat fluxes. In

Table 1. Spearman rank correlation coefficients linking mean monthly water temperature and environmental metrics across the investigated lowland streams. Abbreviations: UCA – upstream catchment area, WD – width:depth ratio, SD – stream gradient, RS – riparian shade, SO – stream orientation; 1km, 3km, and 5km – buffer zone length. The * indicates statistically significant correlation at p = 0.05

	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X
UCA	0.04	-0.1	-0.17	-0.32	-0.02	0.3	0.65*	0.61*	0.63*	0.64*	0.62*	0.49*
WD	-.23	-0.3	-0.27	-0.2	-0.14	0.22	0.43*	0.34	0.36	0.27	0.17	-0.07
SG_1km	0.13	0.23	0.21	0.22	0.01	-0.29	-0.58*	-0.38	-0.49*	-0.52*	-0.51*	-0.35
SG_3km	0.07	0.25	0.22	0.22	0.01	-0.25	-0.53*	-0.42	-0.53*	-0.54*	-0.47*	-0.36
SG_5km	-0.01	0.19	0.22	0.24	0.01	-0.29	-0.61*	-0.51*	-0.62*	-0.58*	-0.51*	-0.46*
RS_1km	0.13	0.29	0.08	0.13	0	-0.12	-0.35	-0.38	-0.37	-0.39	-0.36	-0.34
RS_3km	0.06	0.22	0.07	0.07	-0.1	-0.17	-0.4	-0.47*	-0.48*	-0.52*	-0.50*	-0.51*
RS_5km	0	0.17	0.03	0.06	-0.09	-0.14	-0.33	-0.46*	-0.48*	-0.49*	-0.44*	-0.50*
SO_1km	0.49*	0.43*	0.45*	0.50*	0.58*	0.3	-0.09	0.08	0.18	0.04	-0.01	0.11
SO_3km	0.29	0.15	0.18	0.19	0.41*	0.46*	0.18	0.11	0.25	0.18	0.14	0.11
SO_5km	0.27	0.17	0.15	0.27	0.36	0.43*	0.16	0.2	0.32	0.17	0.08	0.11

Table 2. Spearman rank correlation coefficients linking monthly maximum of 7DAMAX water temperature and environmental metrics across the investigated lowland streams. Abbreviations: UCA – upstream catchment area, WD – width:depth ratio, SD – stream gradient, RS – riparian shade, SO – stream orientation; 1km, 3km, and 5km – buffer zone length. The * indicates statistically significant correlation at p = 0.05

	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X
UCA	-0.23	-0.28	-0.22	-0.24	-0.47*	-0.2	0.05	0.38	0.51*	0.59*	0.43*	0.42
WD	-0.01	-0.16	-0.17	-0.26	0.05	0.16	0.18	0.35	0.32	0.36	0.29	-0.05
SG_1km	0.17	0.26	0.34	0.16	0.32	-0.04	-0.33	-0.38	-0.67*	-0.42	-0.51*	-0.45*
SG_3km	0.27	0.28	0.34	0.19	0.25	0.03	-0.27	-0.37	-0.60*	-0.48*	-0.37	-0.38
SG_5km	0.19	0.24	0.31	0.16	0.29	0.13	-0.17	-0.42	-0.57*	-0.55*	-0.39	-0.35
RS_1km	-0.19	0.11	0.18	0.05	0.11	-0.12	-0.26	-0.41	-0.52*	-0.32	-0.4	-0.27
RS_3km	-0.13	0.09	0.18	0.03	0.18	-0.09	-0.21	-0.43*	-0.58*	-0.47*	-0.51*	-0.47*
RS_5km	-0.11	0.07	0.15	0.01	0.23	-0.03	-0.18	-0.42*	-0.54*	-0.47*	-0.45*	-0.45*
SO_1km	0.36	0.57*	0.44*	0.50*	0.50*	0.25	0.13	0.3	0.24	0.23	0.02	0.13
SO_3km	0.23	0.3	0.19	0.17	0.26	0.09	-0.1	0.27	0.32	0.2	0.07	0.13
SO_5km	0.16	0.35	0.14	0.23	0.24	0.1	-0.06	0.32	0.34	0.26	0.06	0.07

contrast, during spring and early summer months (April-June), sub-daily water temperature contrasts were most pronounced. This was due to the gradual increase of riparian shading (with leaf and herbaceous growth peaking in July and August) as well as the gradual warming of streambed and groundwater; during spring nights, these contributed to cooling water temperature and enhancing diurnal variability (Kail et al. 2021). In addition, frequent northern oscillation circulation blockages during this period caused alternating inflows of air masses from northern and southern Europe, resulting in large fluctuations in air temperature (Graf and Wrzesiński 2019).

Clear seasonality was also observed in terms of spatial variability. As indicated by PCA, the highest thermal contrast occurred in summer, when radiative heat fluxes reached their maximum values (Dugdale et al. 2018) and streamflow was impacted by convective rainfall episodes (such as in the Płonka

River catchment). The opposite situation was documented in winter: higher streamflow rates in all streams, resulting from a different character of precipitation, made water temperature less vulnerable to atmospheric heat fluxes due to greater thermal capacity and the lack of riparian shade (Poole and Berman 2001). Overall, it is worth noting that the monitored period was generally average in terms of air temperature, precipitation totals, and runoff conditions with periods of both peak and low flows, which made the results of spatio-temporal water temperature variability relatively representative.

Recent studies on water temperature have adopted various landscape (environmental) metrics as proxies for physical parameters influencing heat exchange processes in streams (Hrachowitz et al. 2010). This approach is considered reasonable and practical, because GIS-based landscape data are relatively easy to derive and cost-effective compared with field measurements (Jackson et al. 2016). Consequently, it can be efficiently applied to environmental and fisheries management, as well as to temperature prediction at non-monitored sites (Isaak and Hubert 2001).

The current study brings some new findings. Overall, relationships between environmental metrics and temperature parameters across the lowland landscape were weak or moderate, which indicates that meteorological parameters have a dominant impact on stream water temperature at the mesoscale (Żelazny et al. 2018). This low correlation was due to flat terrain is flat terrain, which together with channel macrophytes cause a low flow velocities, and, in consequence, long overland flow. Such extended residence time makes water more vulnerable to radiative heating and cooling (Garner et al. 2017). Moreover, the investigated post-glacial lowland area is relatively uniform in other geographical properties, such as sediment lithology, vegetation, and land cover, so some metrics used in earlier research, including slope (Grabowski et al. 2016) and elevation (Isaak and Hubert 2001) were not informative and were therefore excluded from analysis. Nevertheless, some predictors exhibited statistically significant relationships with thermal parameters, although their effects varied seasonally. In summer, when solar and long-wave radiation dominate the energy budget, metrics displayed the strongest relationships, partly due to the relatively high spatial variability. Catchment area was positively related to temperature metrics; in larger catchments, mean and maximum temperatures tended to be higher due to longer heating periods (Garner et al. 2017). In contrast, riparian forest cover was negatively correlated with mean and maximum monthly values, which confirm previous findings (Broadmeadow et al. 2011, Kail et al. 2021). A similar negative effect was observed for stream gradient, in the particularly in the hottest months (May, July, August). As stream gradient influences flow velocity, and thus heating rate, it may also serve as a proxy for channel erosion, which increases bank cover over the water surface. Notably, in the study area, stream gradient was generally negatively correlated with catchment area; larger catchments had lower stream gradients. In the winter half-year, only the orientation metric was significantly related to mean and maximum water temperatures, with a positive relationship: north-south oriented channels were more exposed to solar radiation (Malcolm et al. 2004, Jackson et al. 2021). This influence was weaker in summer months, when riparian shade exerts stronger control over radiative heat fluxes at the air-water interface.

The obtained results could be significant in the context of the future changes in the thermal regime of rivers as an effect of climate warming. They could also raise new research questions, such as quantifying the effect of aquatic macrophytes on stream temperature, which are commonly present in lowland streams. Moreover, the results provide a unique basis for fisheries management and land management practices. Due to the high thermal heterogeneity, some streams in the Wkra River catchment could act as refugia for coldwater fish species; on the other hand, in larger catchments such as the Łydynia, Raciążnica, and Płonka, maximum water temperature values exceeding 25°C could be unsuitable for these species (Elliott and Elliott 2010), particularly when combined with low oxygen concentrations and slow current velocities. In this context, the possibility for fish and invertebrate migration should be maintained (Kanno et al. 2014).This could be achieved through removing artificial obstacles, such as small weirs, which are widespread across the Wkra River and its tributaries, as well as in other lowland catchments in Poland. Maintaining migration pathways could be particularly important in warmer years, which are expected to create a more pronounced thermal contrast and higher maximum values during summer months. Finally, analysis of the environmental dependence of thermal parameters exhibited that restoring riparian buffer zones covered with trees and woodland vegetation would have a clear impact on reducing mean and maximum water temperature in lowland streams, particularly in north-south oriented river reaches. Such measures could also effectively protect the overall ecological integrity of small streams (Sweeney and Newbold 2014) and, together with removing obstacles, could be considered part of the naturalization of stream channels.

Conclusions

The current study revealed several important conclusions about the spatio-temporal variability of the thermal regime of lowland streams.

1. Despite similar meteorological and geological settings, clear heterogeneity in maximum, mean, and daily range water temperature values was documented across streams.
2. Seasonally, the thermal regime of streams exhibited substantial variation in sub-daily temperature dynamics, with the highest daily water temperature fluctuations occurring in spring and early summer. During winter, water temperature often remained close to 0.0°C for extended periods, and sub-daily dynamics was minimal or absent.
3. Environmental metrics calculated using GIS software showed a generally moderate but statistically significant and physically-justified impact on thermal regime parameters, mainly during the summer half-year when spatial contrasts were most pronounced. Mean and maximum water temperature values positively correlated with catchment area, whereas channel gradient and riparian shade degree were negatively correlated. In winter, only stream orientation demonstrated significant correlations. Such results could be readily applied to estimate spatial variation in lowland stream temperatures for fisheries and land management purposes.

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