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Regional Response to Global Warming: Water Temperature Trends in Semi-Natural Mountain River Systems

Mariola Kędra

Department of Engineering and Water Management, Faculty of Environmental and Power Engineering, Cracow University of Technology, 24 Warszawska str., 31-155 Cracow, Poland; mariola.kedra@iigw.pk.edu.pl

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Abstract: River water temperature (TW) is a key environmental factor that determines the quality of the fluvial environment and its suitability for aquatic organisms. Atmospheric warming, accompanied by more frequent extreme weather phenomena, especially heat waves and prolonged drought, may pose a serious threat to the river environment and native river ecosystems. Therefore, reliable and up-to-date information on current and anticipated changes in river flow and thermal conditions is necessary for adaptive water resource management and planning. This study focuses on semi-natural mountain river systems to reliably assess the magnitude of water temperature change in the Polish Carpathians in response to climatic warming. The Mann–Kendall test was used to detect trends in water temperature series covering the last 35 years (1984–2018). Significant, rising trends in annual water temperature were found for all studied sites, with differences in intensity (0.33–0.92 °C per decade). Trends in TW were strongest in summer and autumn (0.75–1.17 and 0.51–1.08 °C per decade), strong trends were found in spring (0.82–0.95 °C per decade), and weaker in winter (0.25–0.29 °C per decade). Simultaneous air temperature trends were broadly consistent with water temperature trends. This indicates the urgent need for adaptive management strategies to counteract thermal degradation of the fluvial environment under study.

Keywords: water temperature; trend; mountain river; regional response; global warming; Polish Carpathians

1. Introduction

Water temperature (TW) in streams and rivers is a key environmental factor that determines the quality of the fluvial environment and its suitability for aquatic organisms. TW affects physical and chemical conditions, including oxygen concentration, as well as energy processes; each 10 °C increase in TW is typically associated with a doubling of chemical reaction rates [1] and metabolic rates [2]. Therefore, TW essentially affects living conditions, growth rate, development, and distribution of organisms living in rivers, which are mostly ectothermic [3–5]. TW depends on energy transport processes in the river and heat exchange between the river and its surroundings, mainly at the air–water interface [6]. Initially shaped by groundwater recharge, stream temperature tends to ambient air temperature, while the rate of change depends on insulating and buffering processes [7]. As processes and conditions in rivers are closely related to those in the catchment or riparian zone, rivers reflect climatic effects on fluxes of matter, water, and energy over large land areas [8,9]. It is therefore likely that atmospheric warming, accompanied by more frequent extreme weather events, especially heat waves and prolonged drought [10] (p. 162), combined with other factors affecting the quantity and quality of river water (e.g., urbanization, agriculture, artificial heat inputs), may pose a serious threat to the river environment and its native ecosystems.

The global average temperature has increased over the 20th century by 0.6 °C [10] (p. 124), while it has increased by 0.72 ± 0.17 °C over the period 1951–2012 [10] (pp. 161–162). The total increase between the average of the years 1850–1900 (a surrogate for the pre-industrial baseline) and the decade 2006–2015 was 0.87 ± 0.12 °C [11] (p. 4), but the last decade (2009–2018) was the warmest decade on record, with the increase of 0.91–0.96 °C above the pre-industrial baseline [12]. Due to complex interactions in the climate system and differences in response to the climate forcing [13], different regions of the world experience different warming rates. For the European land area, for the last decade (2009–2018), the average annual temperature was 1.6–1.7 °C above the pre-industrial baseline, while the year 2018 was among three warmest years on record [12]. Since 2000, extreme heat waves occurred in Europe in the years 2003, 2006, 2007, 2010, 2014, 2015, 2017, and 2018; besides, between 1960 and 2018, the number of warm days, defined as exceeding the 90th percentile threshold, doubled across the European land area [12].

In the context of river ecosystems, the key question is to what extent the observed atmospheric warming translates into warmer water in streams and rivers. In the United States (US), consistent warming trends in annual mean water temperature (0.09–0.77 °C per decade) were found for ≈50% of the river sites examined [14]. On the other hand, trends in stream temperature for minimally human-induced sites in the US do not simply parallel trends in air temperature; and for the significant trends since 1987, cooling of temperatures predominated [15]. Similarly, most sites in the eastern US did not demonstrate a consistent increase or decrease in water temperature during the summer, spring, and fall seasons, while the majority of sites in the western US demonstrated increasing water temperatures in the winter and fall seasons [16]. In Europe, the surface water temperatures of major rivers have increased by 1–3 °C over the 20th century [17]. In Switzerland, water temperature in rivers and lakes have continued to rise [18–20] after the shift observed in 1987/1988 throughout Central Europe, which corresponds to the global regime shift [21]. For fluvial waters in the Central European Plain, the annual temperature increased by 0.17–0.27 °C per decade in 1961–2010, while a decrease in water temperature was observed in 1961–1986 compared to the average value from 1961–2010 [22]. Moreover, for rivers in the foothills of the Carpathian Mountains no trends in annual temperature were detected [22].

To understand climate impacts on river ecosystems, it is necessary to study water temperature directly from observations; simplified approximations based on air temperature do not provide details of the thermal regime experienced by aquatic organisms [23]. This study examines changes in thermal conditions of semi-natural mountain river systems in response to global warming based on in-situ water temperature observations from the last 35 years (1984–2018). The aim of the study was to (1) determine whether regionally coherent trends in water temperature for free-flowing rivers were apparent, (2) determine whether water temperature trends were consistent with air temperature trends, and (3) describe seasonal and monthly variation in temperature trends to understand climate forcing on river ecosystems at different times of the year. To limit the impact of human interference on the thermal regime of rivers, only river sections from headwaters to gauging stations above dams were considered.

2. Materials and Methods

2.1. Study Area and Data

The research was carried out on five Carpathian rivers in the upper Vistula Basin in southern Poland, within the 49–50° N and 19–23° E coordinates (Figure 1). The Skawa and Raba Rivers originate in the Żywiec Beskids and Gorce Mountains, respectively. The upper Dunajec drains water from the Tatra Mountains, the highest mountain range in the Carpathians. The Biała River, a right-bank tributary of the Dunajec, originates in the Low Beskids. The Solinka is the left tributary of the San River; it originates in the Bieszczady Mountains. The Beskids, Gorce and Bieszczady Mountains are underlain by flysch composed by sandstone, shale, and marl, while the Tatras are underlain by poorly permeable sandstone and shale, impermeable crystalline and metamorphic rocks, and highly permeable carbonate rocks [24]. The dominant soil type is Cambisol. Climate conditions in the study area vary depending on location. The highest peaks of the Tatras (2200–2600 m above sea level (a.s.l.)) and the Beskids (1100–1700 m a.s.l.) are characterized by cold and cool climates, respectively, while in the lower-lying parts of the catchments the climate is temperate [25].

Figure 1. Study area with measurement stations used.

The physiographic characteristics of the studied catchments are outlined in Table 1. The catchments occupy an area between 210 and 835 km^2, and 536 km^2 on average. The maximal catchment length ranges from 25 to 44 km. Median elevations in the catchments are between 536 and 836 m above sea level, while the mean catchment slope is 34‰ (27–46‰) [26]. The studied catchments of the Raba, Dunajec, and Solinka Rivers are located upstream of large dams (Dobczyce on the Raba, Czorsztyn-Sromowce Wyżne on the Dunajec, and Solina-Myczkowce on the San, respectively). In July 2017, the Mucharz Reservoir on the Skawa River 12 km above Wadowice was opened, therefore data on water temperature in Wadowice ends in 2016.

The study is based on daily data obtained from the Polish Institute of Meteorology and Water Management—the National Research Institute (https://danepubliczne.imgw.pl/). Water temperature was measured at 06:00 UTC in the surface layer of flowing water at specific locations by trained staff (Table 1). For a more complete picture of regional warming, minimum and maximum air temperatures were also considered. Air temperature (minimum and maximum, TAmin and TAmax, respectively) was taken from neighboring weather stations (Table 2) with sufficiently long data records. Available data cover the period of the last 35 years (1984–2018). The average length of the water and air temperature series is 32 and 34 years, respectively. Daily temperature data were averaged to obtain monthly mean temperatures. Monthly mean temperatures were averaged over the respective 3-month periods (December to February (DJF), March to May (MAM), June to August (JJA), September to November (SON)) to obtain seasonal mean temperatures for winter, spring, summer, and autumn. In addition, monthly mean temperatures were averaged over a 12-month annual period to obtain annual mean temperatures. Then a trend analysis was performed on the monthly, seasonal, and annual mean temperatures.

In the years 1984–2018 (Table 1), the long-term mean water temperature (TW) in the studied rivers ranges from 6.4 (Solinka in Terka) to 8.8 °C (Skawa in Wadowice), while the maximum monthly TW values reach between 16.6 (Dunajec in Nowy Targ-Kowaniec) and 20.8 °C (Skawa in Wadowice). The minimum TW values drop to 0–0.1 °C in January or February. During the same time period (1984–2018), monthly air temperature ranges from −16.0 °C in January 1987 (Terka) to 28.8 °C in August 1992 (Maków Podhalański, Table 2).

Table 1. Physiographic characteristics of the studied river catchments [26], and monthly water temperature (TW) characteristics.

Catchment/Streamflow Station	Catchment Area (km^2)	Catchment Length (km)	Median Altitude (m a.s.l.)	Mean Catchment Slope (‰)	Aspect	Mean Discharge (m^3·s^{-1})	Time Period 1984–2018	TW (°C)		
								Min	Max	Mean
Skawa/Wadowice	835	44.4	536	33	NW	12.9	1984–2016 (33 yr)	0.0	20.8	8.8
Raba/Stróża	644	32.4	581	30	N	10.1	1984–2018 (35 yr)	0.1	20.4	7.9
Dunajec/Nowy Targ-Kowaniec	681	37.6	836	46	NE	14.5	1984–2018 (35 yr)	0.1	16.6	6.8
Biała/Grybów	210	25.2	549	27	NW	2.8	1989–2018 (30 yr)	0.0	19.3	7.2
Solinka/Terka	310	25.4	764	34	NW	8.3	199–2017 (27 yr)	0.0	20.6	6.4
Mean	536	33.0	653	34	NW	9.7	1986–2017 (32 yr)	0.0	19.5	7.5

Table 2. Details of weather stations used in the study (arranged from west to east) and monthly air temperature (TAmin, TAmax) characteristics.

Weather Station	Latitude (N)	Longitude (E)	Altitude (m a.s.l.)	Catchment	Time Period 1984–2018	TAmin (°C)			TAmax (°C)		
						Min	Max	Mean	Min	Max	Mean
Zawoja	49°36′42″	19°31′07″	697	Skawa	1984–2018 (35 yr)	−15.1	12.7	2.2	−5.8	27.0	11.6
Maków Podhalański	49°43′33″	19°41′17″	360	Skawa	1984–2014 (31 yr)	−15.9	13.2	2.5	−5.6	28.8	13.3
Zakopane	49°17′38″	19°57′37″	855	Dunajec	1984–2018 (35 yr)	−14.9	12.8	1.6	−5.3	25.3	10.9
Ptaszkowa	49°36′02″	20°53′07″	520	Dunajec	1986–2018 (33 yr)	−14.2	15.8	3.9	−6.9	27.3	12.0
Terka	49°17′48″	22°25′40″	445	Solinka	1984–2018 (35 yr)	−16.0	13.5	2.7	−6.2	27.5	12.3
Mean			575		1984–2017 (34 yr)	−15.2	13.6	2.6	−6.0	27.2	12.0

2.2. Methods

Each time series was carefully examined to ensure there were no processing errors or spurious values. To detect potential monotonic trends in water and air temperature series, the non-parametric Mann–Kendall (MK) test was used as it does not require the normality assumption [27,28]. To fulfill the serial-independence requirement, the trend-free pre-whitening procedure [29,30] was also applied. The two-sided MK test was used at the significance level α: 0.001 (strong evidence) and 0.05 (medium evidence). The magnitude of trends was quantified using Theil–Sen's slope [31,32] as a very robust slope estimate.

3. Results

3.1. Trends in Water Temperature

Table 3 shows the intensity of trends in the annual, seasonal, and monthly series of water temperatures for the years 1984–2018. Significant ($p < 0.05$) upward trends in annual water temperature were found for all studied rivers (Figure 2), from 0.33 °C per decade (Dunajec in Nowy Targ-Kowaniec) to 0.92 °C per decade (Solinka at Terka), and an average of 0.60 ± 0.28 °C. This means that the annual water temperature in the studied rivers increased by an average of 2.1 °C over the last 35 years (1984–2018), with the smallest increase (by 1.2 °C) related to the high-mountain river (Dunajec).

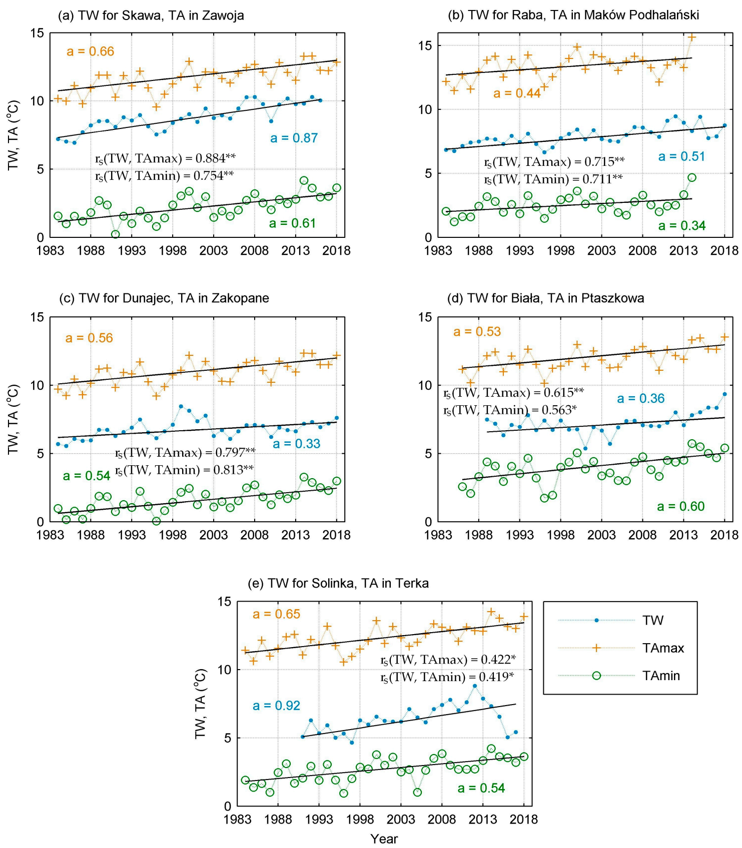

Figure 2. The course of annual water and air temperatures, and significant ($p < 0.05$) trend intensity *a* (°C per decade) for the studied rivers in comparison to air temperatures (TAmin, TAmax) at neighboring stations. The comparisons were made for: (**a**) TW for the Skawa in Wadowice and TA in Zawoja; (**b**) TW for the Raba in Stróża and TA in Maków Podhalański; (**c**) TW for the Dunajec in Nowy Targ-Kowaniec and TA in Zakopane; (**d**) TW for the Biała in Grybów and TA in Ptaszkowa; (**e**) TW for the Solinka in Terka and TA in Terka. Spearman's rank correlation coefficient (r_s) shows a significant correlation between the annual water temperature series and the annual air temperature series (TAmin, TAmax); r_s significant at $p < 0.001$ and $p < 0.05$ was marked ** and *, respectively.

Table 3. Trend intensity (°C per decade) in water temperature (TW) for each month, each season (1984–2018), and for the annual means (the last column).

Catchment/Streamflow Station	January	February	March	April	May	June	July	August	September	October	November	December	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Year
Skawa/Wadowice	0.16	0.22	0.77 *	1.15 **	1.11 **	1.25 **	1.20 **	1.20 **	1.13 **	0.59 *	1.04 **	0.52 *	0.29 *	0.95 **	1.17 **	0.95 **	0.87 **
Raba/Stróża	−0.05	−0.02	0.09	0.24	0.67*	1.10 **	1.05 **	0.91 **	0.83 **	0.71 **	0.90 **	0.01	−0.02	0.28	0.94 **	0.78 **	0.51 **
Dunajec/Nowy Targ-Kowaniec	0.20 *	0.16	0.24	0.19	0.11	0.33	0.22	0.38	0.64 *	0.31	0.62 *	0.35 *	0.28 *	0.18	0.30	0.51 **	0.33 **
Biała/Grybów	0.13	0.11	0.05	0.73 *	0.42	1.03 *	0.71	0.62	0.24	0.14	0.68 *	0.35 *	0.25 *	0.42	0.75 *	0.25	0.36 *
Solinka/Terka	0.12	0.12	0.24	0.91 *	1.19	1.54 *	0.79	0.64	1.29 *	0.72	0.76	0.27	0.21	0.82 *	1.15 *	1.08 *	0.92 **

** Data significant at $p < 0.001$ (strong evidence). * Data significant at $p < 0.05$ (medium evidence).

For individual seasons and months of the year, all statistically significant trends in water temperature were also rising. For most rivers (four out of five, Figure 3), TW trends were strongest in summer (0.75–1.17 °C per decade) and autumn (0.51–1.08 °C per decade). Weaker TW trends were found for two rivers in spring (0.82–0.95 °C per decade) and three rivers in winter (0.25–0.29 °C per decade). For individual months, the strongest trends in water temperature were in June (1.03–1.54 °C per decade), September (0.64–1.29 °C per decade), and November (0.62–1.04 °C per decade) for most of the rivers studied (four out of five, Table 3, Figure 4a). Other significant TW trends mainly concerned April (0.73–1.15 °C per decade) and December (0.35–0.52 °C per decade), but were less frequent (three out of five rivers). For two neighboring Beskid rivers (Skawa and Raba), strong trends were identified for 10 and 7 consecutive months (March–December and May–November), respectively.

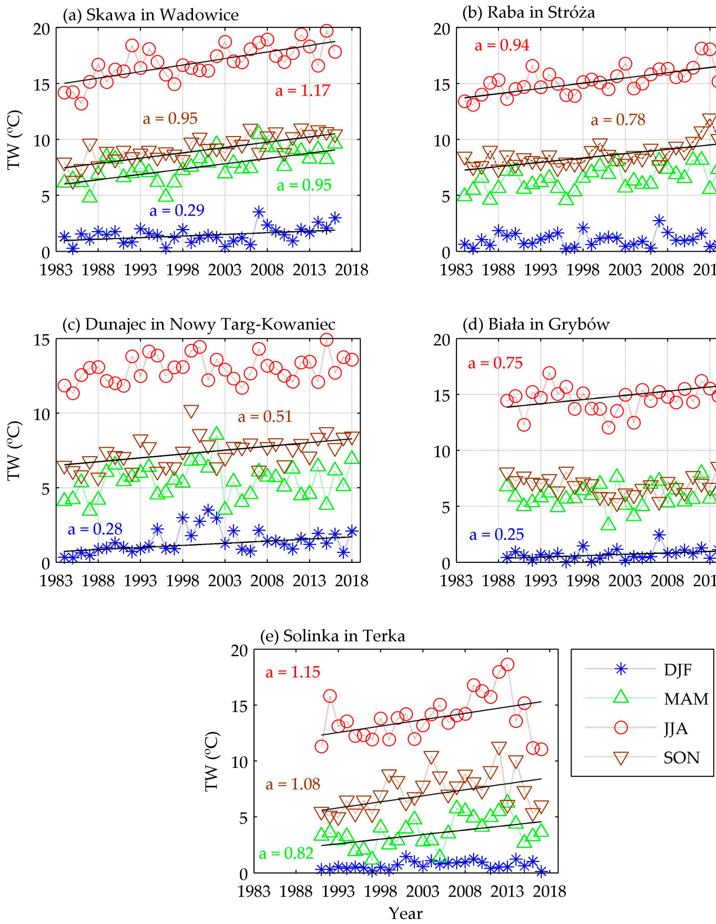

Figure 3. The course of seasonal water temperature and significant ($p < 0.05$) trend intensity a (°C per decade) for the studied rivers: (**a**) the Skawa in Wadowice; (**b**) the Raba in Stróża; (**c**) the Dunajec in Nowy Targ-Kowaniec; (**d**) the Biała in Grybów; (**e**) the Solinka in Terka.

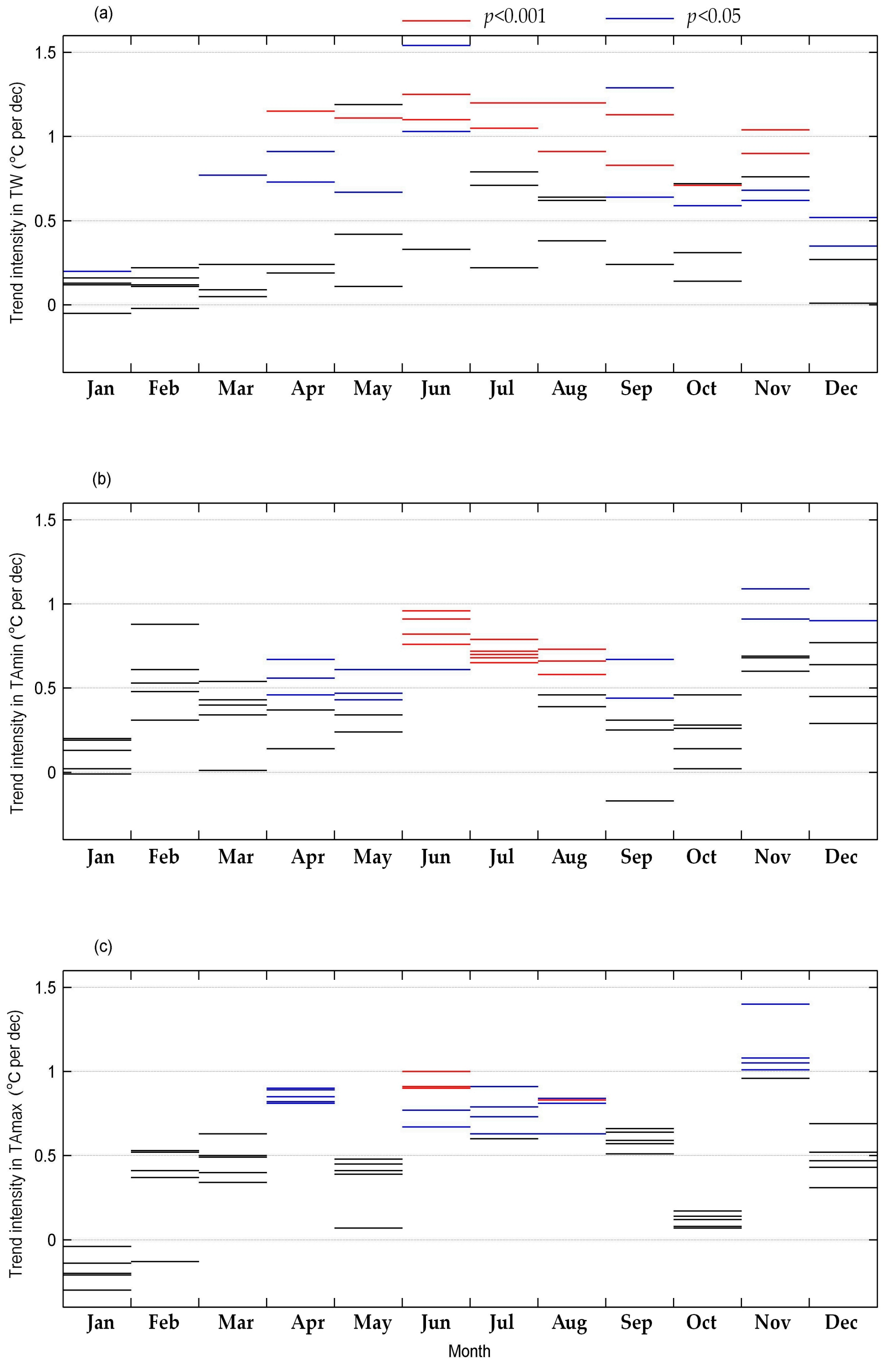

Figure 4. Trend intensity *a* (°C per decade) for each month for the studied rivers (**a**) in comparison to air temperature trends for TAmin (**b**) and TAmax (**c**) at neighboring stations.

3.2. Trends in Air Temperature

The intensity of trends in the annual, seasonal, and monthly series of air temperature is shown in Table 4 (for TAmin) and Table 5 (for TAmax). In 1984–2018, all statistically significant ($p < 0.05$) temperature trends were increasing. Significant trends in annual temperature series were found for all analyzed stations (Figure 2), and the intensity of the trends for TAmax (0.44–0.66 °C per decade and on average 0.57 ± 0.09 °C) was slightly higher than for TAmin (0.34–0.61 °C per decade and on average 0.53 ± 0.11 °C). This means an average annual temperature increase of 2.0 °C for TAmax and of 1.8 °C for TAmin over the last 35 years for the analyzed stations.

Table 4. Trend intensity *a* (°C per decade) in minimum air temperature (TAmin) for each month, each season (1984–2018) and for the annual means (the last column).

Weather Station	January	February	March	April	May	June	July	August	September	October	November	December	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Year
Zawoja	0.20	0.53	0.54	0.56 *	0.47 *	0.91 **	0.70 **	0.58 **	0.31	0.28	1.09 *	0.64	0.55	0.65 *	0.71 **	0.68 *	0.61 **
Maków Podhalański	0.19	0.31	0.01	0.14	0.24	0.61 *	0.68 **	0.39	−0.17	0.02	0.69	0.29	0.24	0.15	0.50 **	0.17	0.34 *
Zakopane	0.02	0.61	0.34	0.46 *	0.43 *	0.96 **	0.72 **	0.66 **	0.44 *	0.14	0.68	0.45	0.43	0.47 *	0.80 **	0.58 *	0.54 **
Ptaszkowa	−0.01	0.48	0.40	0.67 *	0.61 *	0.82 **	0.65 **	0.73 **	0.67 *	0.46	0.91 *	0.77	0.14	0.64 *	0.76 **	0.69 **	0.60 **
Terka	0.13	0.88	0.43	0.37	0.34	0.76 **	0.79 **	0.46	0.25	0.26	0.60	0.90 *	0.64	0.38 *	0.63 **	0.42 *	0.54 **

** Data significant at $p < 0.001$ (strong evidence). * Data significant at $p < 0.05$ (medium evidence).

Table 5. Trend intensity (°C per decade) in maximum air temperature (TAmax) for each month, each season (1984–2018) and for the annual means (the last column).

Weather Station	January	February	March	April	May	June	July	August	September	October	November	December	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Year
Zawoja	−0.14	0.53	0.63	0.90 *	0.45	1.00 **	0.73 *	0.83 **	0.59	0.08	1.08 *	0.52	0.27	0.68 *	0.87 **	0.60 *	0.66 **
Maków Podhalański	−0.30	0.41	0.40	0.85 *	0.07	0.77 *	0.91 *	0.63 *	0.57	0.12	1.40 *	0.31	0.13	0.34	0.72 *	0.63 *	0.44 *
Zakopane	−0.20	0.37	0.34	0.89 *	0.41	0.91 **	0.63 *	0.84 **	0.51	0.07	1.05 *	0.43	0.14	0.59 *	0.75 **	0.53 *	0.56 **
Ptaszkowa	−0.21	−0.13	0.49	0.81 *	0.39	0.67 *	0.60	0.81 *	0.64	0.14	0.96	0.69	0.10	0.56 *	0.74 **	0.62 *	0.53 **
Terka	−0.04	0.52	0.50	0.82 **	0.48	0.90 **	0.79 *	0.84 *	0.66	0.17	1.01 *	0.47	0.34	0.65 *	0.92 *	0.71 *	0.65 **

** Data significant at $p < 0.001$ (strong evidence). * Data significant at $p < 0.05$ (medium evidence).

In individual seasons of 1984–2018, the strongest air temperature trends occurred in summer, with often higher intensity in TAmax than TAmin (0.72–0.92 °C and 0.50–0.80 °C per decade, respectively). Strong trends occurred in autumn; they were in the range of 0.53–0.71 °C per decade for TAmax and of 0.42–0.69 °C per decade for TAmin. For most stations (four out of five), significant trends were also found in spring, from 0.56 to 0.69 °C per decade for TAmax and from 0.38 to 0.65 °C per decade for TAmin. In winter, no air temperature trends were significant.

In individual months of 1984–2018 (Figure 4b,c), significant air temperature trends occurred in April, June, July, August, and November for all or most of the analyzed stations (four out of five). They ranged from 0.67 to 1.40 °C per decade for TAmax and from 0.46 to 1.09 °C per decade for TAmin. Significant trends in TAmin were also found in May (0.43–0.61 °C per decade), but were less frequent (three out of five stations).

4. Discussion

The results presented in this study indicate regionally coherent warming trends in water temperature (0.33–0.92 °C per decade) observed in 1984–2018 for semi-natural mountain river systems in the Polish Carpathians. These results are consistent with predictions that atmospheric warming will translate into warmer water in streams and rivers, and with a number of studies e.g., [18,22,33–38] indicating growing trends in river water temperature over the last 3–4 decades, but in contrast to [15] for minimally human-induced sites in the US, where water cooling has been dominant since 1987. Similarly, the abrupt increase in regional air temperature observed in 1987/1988 throughout Central Europe [18] is accompanied by an increase in water temperature in most Swiss rivers, with the exception of alpine catchments or catchments strongly influenced by hydropower plants [19].

The obtained results demonstrate that over the last 35 years (1984–2018), the annual water temperature in the studied rivers increased by an average of 2.1 °C, with the smallest increase (by 1.2 °C) related to the high-mountain river (Dunajec) in its upper course. The observed smaller temperature rise in the Dunajec River in Nowy Targ-Kowaniec may imply that high-mountain rivers are less responsive to climatic forcing than the Beskid rivers studied. Similarly, a moderate increase in temperature in Alpine rivers is linked to the fact that melting snow and ice are the main source of their waters, and external drivers (solar radiation, air temperature, hyporheic exchange, etc.) have a relatively weak effect on the river water temperature [39] (p. 17).

In this study, minimum and maximum air temperatures were also considered to provide a more complete picture of regional warming. Minimum and maximum temperatures are typically associated with nighttime and daytime, respectively [40]. Nighttime temperatures are highly influenced by local conditions [41] and are sensitive to the heat capacity of the land surface [42], while maximum temperatures are in principle a more robust measure of the heat content of the atmosphere than minimum temperatures [41]. It turned out that the annual air temperature trends were significant for all analyzed weather stations, and for most stations (four out of five) the intensity of trends for TAmax was only slightly higher than for TAmin (on average 0.57 ± 0.09 °C and 0.53 ± 0.11 °C per decade, respectively). This means that in the last 35 years (1984–2018) the annual air temperature for the analyzed stations increased by an average of 2.0 °C for TAmax and of 1.8 °C for TAmin, i.e., comparable to the annual water temperature studied. A slightly higher increase in the annual water temperature (by an average of 2.1 °C) compared to the annual air temperature (by an average of 1.8–2.0 °C) may be related to the fact that air temperature affects more than one physical process in river heat budgets and warms rivers directly through sensible heat fluxes, indirectly by increasing groundwater temperatures and advective heat transfer, and by radiating more long-wave radiation into rivers [6,34,43,44].

The extent of the statistical dependence between the annual water and air temperatures, quantified using the Spearman's correlation coefficient (r_s), is shown in Figure 2. The significant correlation between TW and TA is stronger for the Skawa, Raba, and Dunajec rivers (0.7–0.9) and weaker for the Biała and Solinka rivers (0.4–0.6). Moreover, for most rivers (except Dunajec), the correlation between TW and TAmax is slightly higher than between TW and TAmin. The correlation between the annual water temperature and the corresponding river flow (Q) is not statistically significant (not shown), while the r_s values are negative for the Skawa, Raba, and Biała (−0.10, −0.11, −0.25, respectively and positive for the Dunajec (0.17). The identified correlations imply that TW for the Skawa and Raba rivers is highly dependent on TAmax, while TW for the Biała is less dependent on TAmax probably due to the negative dependence between TW and Q. On the other hand, TW for the Dunajec is highly dependent on TAmin and weakly positively dependent on Q. A significant but relatively weak dependence between water and air temperature for the Solinka (r_s = 0.4) and no dependence between TW and Q may suggest that other factors play a role, including land cover with dense forest on over 80% of the catchment area [45].

As heat waves and periods of abnormal warm weather can have significant consequences for river thermal regimes and ecology [46], the 90th percentile for the monthly time series of water and air temperatures was calculated in a moving window of ≈10 years, with a 5-year shift (Figure 5). Upward trends (per decade) in the 90th percentile values are significant for the Skawa, Raba, and Solinka rivers (0.50–0.73 °C), and not significant for the Dunajec and Biała rivers (0.17–0.25 °C), while for TAmin and TAmax are all significant (0.27–0.40 and 0.36–0.50 °C, respectively). This shows that the air temperature in persistent periods of abnormal warm weather, defined in terms of the 90th percentile, is likely to increase, and river thermal regimes will not necessarily be resistant to this increase.

The results of this study also show that regional response to global warming may vary at different times of the year, in line with other studies, e.g., [11,16,22,33,47–51]. Consistent, growing trends were the strongest in summer for both the studied air and water temperatures (0.50–0.92 and 0.75–1.17 °C per decade, respectively). For most stations, strong trends in air and water temperatures were also found in autumn (0.42–0.71 and 0.51–1.08 °C per decade, respectively), while in spring, significant trends in TW were strong (0.82–0.95 °C per decade), but less frequent (two out of five rivers), despite apparent air temperature trends (0.38–0.69 °C per decade). In general, seasonal water temperature trends were in line with air temperature trends in the same season, except in winter when no significant air temperature trends were detected.

Climate change is one of the most influential current and future environmental drivers, so understanding its impact on aquatic ecosystems and their function is therefore of high importance [39] (p.1). In this study, a trend analysis was conducted for both seasons and months to better understand the impact of climate warming on river ecosystems at different times of the year. The obtained results show that all significant trends in air and water temperatures were rising for both seasons and months of the year. In individual months, strong trends in water temperature were found in April, June, September, November, and December for most of the rivers studied (three–four out of five, Table 3), while the neighboring Beskid Skawa and Raba Rivers experienced warming at least seven consecutive months (May–November).

Identified water warming in semi-natural mountain river systems can have significant biological implications for both the quality and quantity of habitats available to species of regional importance [34], such as coldwater and coolwater fish, mainly salmonids and cyprinids [52,53]. Salmonids typically show divergence into different spawning populations, e.g., spring and autumn spawning [54]. Due to differences in spawning times and locations, populations experience different temperature regimes during early life [55]. Patterns of plasticity for larval growth and survival suggest that population responses to climate change will differ substantially, while populations that experience relatively cold temperatures during early life might be more sensitive to changes in temperature [55]. For instance, in response to significant increases in river temperatures linked to regional warming, a 3–4-week shift of spawning to earlier dates (early spring) occurred in a population of European graylings in Switzerland [56]. The change in the timing of spawning has reduced the temperatures at which embryos, larvae, and fry developed, and these temperature changes correlated with a decrease in the number of egg-bearing females [56]. As a result, this wild population suffered from male-biased population sex ratios [57].

The impact of climate change on individual species will depend on their physiological and ecological traits, their evolutionary potential, and potentially on the resources that people commit to prevent their extinction [58]. Regionally consistent warming trends in water temperature identified for the Carpathian catchments point to the urgent need for adaptive management strategies to counteract thermal degradation of the fluvial environment under study.

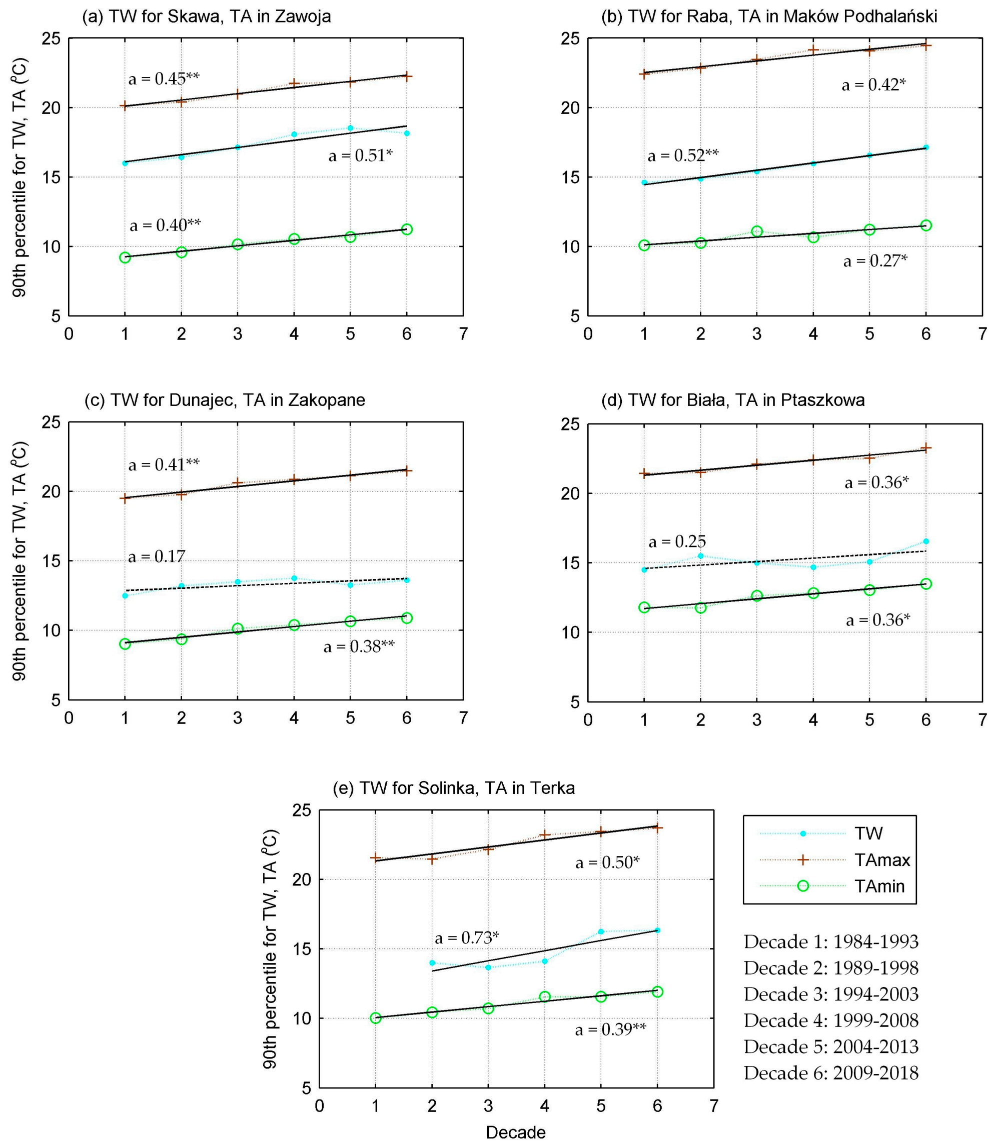

Figure 5. The 90th percentile for the monthly time series of water and air temperatures calculated in a moving window of 10 years with a 5-year shift. The comparisons were made for: (**a**) TW for the Skawa in Wadowice and TA in Zawoja; (**b**) TW for the Raba in Stróża and TA in Maków Podhalański; (**c**) TW for the Dunajec in Nowy Targ-Kowaniec and TA in Zakopane; (**d**) TW for the Biała in Grybów and TA in Ptaszkowa; (**e**) TW for the Solinka in Terka and TA in Terka. The intensity of the linear trend *a* (°C) is shown with its significance at $p < 0.001$ and $p < 0.05$ marked ** and *, respectively.

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