Geographia Polonica
2025, Volume 98, Issue 1, pp. 29-52
https://doi.org/10.7163/GPol.0291

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
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CHANGES IN THE THERMAL REGIME OF RIVERS IN POLAND WITH DIFFERENT SIZES AND LEVELS OF HUMAN IMPACT BASED ON DAILY DATA (1961-2020)

Przemysław Tomalski[1] • Bożena Pius[2] • Paweł Jokiel[1] • Włodzimierz Marszelewski[2]

[1] Faculty of Geographical Sciences
University of Łódź
Narutowicza 68, 90-139 Łódź: Poland
e-mails: przemyslaw.tomalski@geo.uni.lodz.pl (corresponding author) • pawel.jokiel@geo.uni.lodz.pl

[2] Faculty of Earth Sciences and Spatial Management
Nicolaus Copernicus University in Toruń
Lwowska 1, 87-100 Toruń: Poland
e-mails: bpius@umk.pl • marszel@umk.pl

Abstract

The article examines thermal parameters of rivers during climate warming, focusing on quasi-natural rivers and those heavily impacted by humans. It compares two periods (1961-1992 and 1993-2020) based on daily water temperatures. Results show rivers warmed by 0.7-1.0°C in the second period, except those strongly polluted, like the Przemsza River, which cooled by up to -1.2°C. In quasi-natural rivers, the largest temperature rise occurred in spring (up to 3.5°C). In contrast, heavily impacted rivers showed lower, often negative changes. The study highlights the impact of climate warming and human activity on river thermal regime.

Keywords

river thermal regime • climate change • water temperature fluctuations

Introduction

Temperature is one of the most important physical properties of substances occurring in the environment. An increase in air temperature (AT) observed in recent years is simultaneously the most characteristic and most important premise confirming climate warming. It causes an increase in the temperature of all elements of the environment, including water temperature. This in turn usually results in unfavourable physiochemical, biochemical, and ecological changes in the aquatic environment, and additionally complicates rational and sustainable management of water resources. Warmer water at different stages of the hydrological cycle (a process of continuous water exchange between the atmosphere, lithosphere, hydrosphere, and biosphere) reduces the amount of dissolved oxygen, and therefore intensifies or weakens the course of many physical, chemical, and life processes (Ji, 2008; Olden & Naiman, 2010; Deinet et al., 2020). This results in changes, usually unfavourable, in both aquatic and terrestrial ecosystems. Many organisms tolerate only a specific range of temperature; therefore its changes have a great impact on the level of their reproduction and biodiversity (Wehrly et al., 2009). Changes in water temperature beyond their natural ranges may cause death and/or migration of local and endemic species, as well as the appearance of exotic species. This may in turn lead to disturbing the ecological equilibrium of ecosystems. Higher water temperature can accelerate natural chemical reactions, release excess nutrients, and increase solubility of heavy metals harmful for aquatic ecosystems and people (i.a., Mehta, 2017; Lazăr et al., 2024). Purification of poor quality water, including that subject to thermal pollution, requires higher financial expenditure. Warmer river waters are also delivering more heat to the world ocean, causing temperatures in coastal waters to rise and transforming their ecosystems (Yang et al., 2021).

A rapid increase in river temperature (RT) observed over recent decades around the globe (Kaushal et al., 2010; van Vliet et al., 2013; Arora et al., 2016; Magritsky et al., 2023) as well as forecasts of its future changes based on climate change scenarios (Piccolroaz et al., 2016; Dugdale et al., 2017; Yang & Peterson, 2017) and predictions obtained in the scope of various physical and statistical models (Shrestha & Pesklevits, 2022; Marszelewski et al., 2022; Senlin et al., 2022) point to a potential for further acceleration of the rate of increase in RT.

The first group of models is based on water and energy balance equations. The second one is based on the determination of multivariate, usually regression dependencies between RT and AT, river flow, and other meteorological variables and/or its parameters, as well as the physico-geographic features of the catchment (Caissie, 2006; Graf, 2018; Bonacci et al., 2022; Noa-Yarasca et al., 2022). It is worth emphasising, however, that equation predictors in such models are also forecasted based on other models. As a result, they entail limitations and prediction errors along with a high degree of uncertainty.

An increase in RT has been also documented in Poland by means of various models, procedures, and methods (Łaszewski, 2015, 2018; Ptak et al., 2016; Graf & Aghelpour, 2021; Graf & Wrzesiński, 2019, 2020; Ptak et al., 2022; Marszelewski & Pius, 2016; Marszelewski et al., 2022; Senlin et al., 2022). In most cases, however, the analyses and various projections and forecasts have been based on mean monthly RT and employed regression trend models.

Results of this type of research and forecasts show varied quality, and statistical prediction errors and projection uncertainty are sometimes considerable. Some of the aforementioned authors also emphasise that the quality of RT models and forecasts is relatively low for data with an hourly and daily step, and usually decreases with a decrease in the size of the river (Caissie, 2006; van Vliet et al., 2012). It is presumably caused by the fact that a decrease in the size of the river is accompanied by an increase in the effect of geographic characteristics (e.g. relief of the catchment and its land use) and hydrological variables, e.g. water flow rate, discharge, river alimentation, forms of human pressure, type of hydrotechnical infrastructure, etc. In this context, analyses of multiannual, relatively uniform RT series measured in daily and shorter intervals are according to many authors important for the provision of material for the construction and verification of forecasting models (van Vliet et al., 2012; Isaak et al., 2012; Graf, 2018). The conveyed relations of changes in RT with variable characteristics of the catchment and river as well as frequently occurring trends and genetic heterogeneity caused by human pressure help separate the impact of the observed climate warming from equally important direct anthropogenic impact.

The objective of this paper was to determine the magnitude and direction of changes in elements of the thermal regime of rivers in an annual scale based on daily water temperature values recorded for equivalent days from a period of 60 years (1961-2020). The implementation of this objective was possible owing to the availability of this type of unique data from a long period of time. An additional, although equally important objective was the determination of differences in elements of thermal regime occurring between nine Polish rivers selected for the study, subject to different human impact. Therefore, the obtained study results fill the research gap in the scope of changes in thermal regime of rivers in the period of climate warming.

Study area

The analysed rivers, except for the Przemsza River, are located in the Middle European Lowland, and belong to the catchment of the Baltic Sea (Fig. 1). Sections of these rivers (above places of location of water gauges) run through areas located at approximate

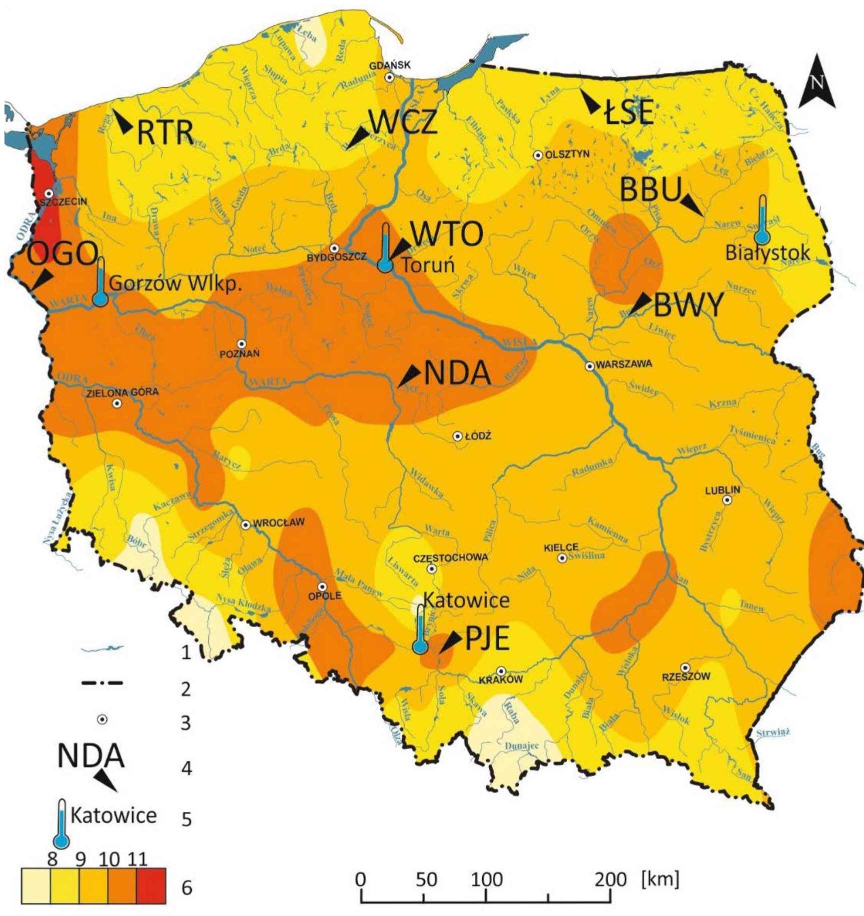

Figure 1. Location of selected gauging stations with RT measurements and meteorological station with AT measurements in Poland

Explanations: 1 – rivers, 2 – country border, 3 – main cities, 4 – water gauges (expalnation in Table 1), 5 – weather stations, 6 – annual average temperatures [°C]. Spatial distribution of mean annual RT according to Graf and Wrzesiński (2020) – modified.

elevations, i.e. from approximately 1 to 110 m a.s.l. Only the catchment of the Przemsza River is located on the Silesian Upland approximately 230 m a.s.l. The surface areas of the catchments of the analysed rivers vary from 940 km^2 to approximately 181,000 km^2. While discharge in these rivers shows high variability (from 6 $m^3 \cdot s^{-1}$ to 928 $m^3 \cdot s^{-1}$).

Three rivers (Vistula, Oder, and Bug) were categorised as large due to their length (measured from source to gauging station) in comparison to other rivers in this part of Europe. It ranges from approximately 645 to 738 km. The remaining rivers (Biebrza, Wda, Łyna, Rega, Ner, and Przemsza) were classified as medium-sized. Their lengths from source to the gauging station vary from 68 to 155 km. Detailed data are included in Table 1.

Mean annual (1961-2020) water temperatures in the analysed rivers varied from 8.7°C to 11.5°C. They were approximate or somewhat higher than those obtained in previous studies (Tab. 1 and compare Fig. 1), and showed an increasing trend (Marszelewski & Pius 2016, 2021; Graf & Wrzesiński 2019, 2020). An increase in water temperature corresponds with an increase in mean air temperature that increased during the analysed period, as in other areas, from 7.6 to 9.2°C, i.e. by 0.03°C·$year^{-1}$ (Degirmendžić et al., 2004; Canales et al., 2020; Marszelewski et al., 2022). Only in the strongly polluted Przemsza River water temperature decreased due to a lowering of effluents of human origin.

The study area is located in the transitional zone of the temperate climate, between maritime and continental climates. Mean annual (1961-2020) air temperature in the western part of the area is 8.8°C (Gorzów Wielkopolski), in the southern part 8.5°C (Katowice), in the middle part 8.3°C (Toruń), and decreases eastwards to 7.2°C (Białystok). In particular months, its spatial distribution shows the highest difference in winter, i.e. in January and February. In those months, mean temperature in the western part of the area is almost 3.0°C higher than in the eastern part. In the years 1961-2020, air temperature considerably increased throughout the study area, by 0.04°C $year^{-1}$ on the average in the western and southern part, and by 0.03°C $year^{-1}$ in the eastern part.

The analysed rivers showed strong differences in terms of human pressure. The greatest human impact concerned the Przemsza and Ner Rivers. The rivers showed the highest thermal pollution in Poland (Bartnik & Jokiel, 2021a; Marszelewski & Pius, 2021). Unlike those rivers, Wda, Łyna, Biebrza, and Rega have retained their quasi-natural character (Marszelewski at al., 2022). Large rivers

Table 1. Hydrological properties of rivers and their catchments

Group of rivers	River	GS	Code	L [km]	A [$km^2 \cdot 10^3$]	MAD [$m^3 \cdot s^{-1}$]	RW [m]	STd [°C]
Large rivers	Bug	Wyszków	BWY	738.2	39.1	148.8	100	9.8
	Vistula	Toruń	WTO	734.7	181.0	928.5	425	10.4
	Oder	Gozdowice	OGO	645.3	109.7	498.9	250	10.6
Medium size rivers	Biebrza	Burzyn	BBU	146.9	6.9	36.8	40	9.3
	Wda	Czarna Woda	WCZ	68.2	0.9	6.0	14	8.7
	Łyna	Sępopol	ŁSE	89.5	3.6	24.1	30	8.9
	Rega	Trzebiatów	RTR	154.9	2.6	19.9	35	9.7
Rivers under strong human impact	Ner	Dąbie	NDA	111.5	1.7	10.2	22	10.3*
	Przemsza	Jeleń	PJE	74.2	2.0	19.0	16	11.5

Explanations: GS – gauging station; L – length of a river to a GS where water temperature measurements were conducted; A – catchment area up to GS location; MAD – mean annual discharge (1981-2019); RW – approximate riverbed width; STd – average RT (1961-2020); * – period (1961-2014). Code of gauging stations according to Figure 1.

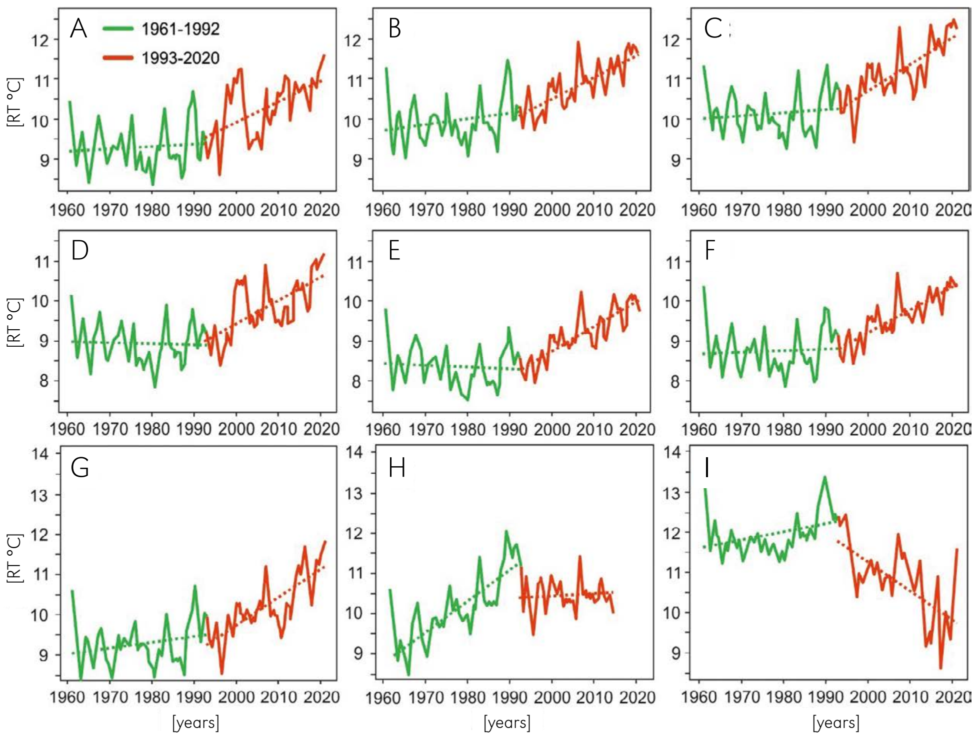

Figure 2. Long-term changes in mean annual RT and its trends (dotted lines) in the studied rivers

Explanation: RT – mean annual RT; A – Bug River; B – Vistula River; C – Oder River; D – Biebrza River; E – Wda River; F – Łyna River; G – Rega River; H – Ner River; I – Przemsza River.

(Vistula, Oder, and Bug) have also been subject to human impact, although in a considerably smaller scope. Moreover, the high flow rates of large rivers and their transit nature mitigated its impact because they have the ability to disperse heat more effectively.

An increase in mean annual RT in the studied rivers in the years 1961-2020 has primarily occurred since 1993. In the period 1993-2020, the greatest increases in mean annual RT were recorded in the Rega River (by 1.91°C) and in the Oder River (by 1.88°C). This does not concern rivers under strong human impact, namely the Ner River, and particularly the Przemsza River (Fig. 2). In the years 1961-1992, two rivers showed small decreases in RT by -0.14°C (Wda River) and -0.07°C (Biebrza River). Increases in RT were observed in the remaining four rivers, the highest in the Rega and Vistula Rivers, by 0.46°C.

Methods

The article is based on results of daily RT measurements from 9 gauging stations located on 9 Polish rivers of various sizes. The study employed measurement series from the period 1961-2020. Only in the case of the Ner River, the data come from a shorter period 1961-2014. Water temperature was measured daily at 06:00 UTC in the scope of the observation network of the Institute of Meteorology and Water Management – National Research Institute in Warsaw (IMWM-NRI). The measurements were conducted in accordance with the IMWM-NRI standard, in the same place in the river channel, by means of a scoop thermometer. The measurement series are complete, and their reliability has been verified twice (at IMWM-NRI and by the authors). The data were analysed in periods of the hydrological years (from 1 November to 31 October).

For the purpose of determination of changes in RT characteristics for particular rivers in the multiannual scale, each series of daily data from 60 years was divided into two subperiods (Marszelewski et al. 2022): 1961-1992 and 1993-2020 (for the Ner River 1993-2014). According to the authors, the duration of the two subperiods is sufficient to consider results of statistical analyses as credible. As a result, the obtained RT parameters permitted the determination of differences in their values in both designated subperiods. The calculations omitted RT from 29 February in leap years due to the low number of the series.

The interpretation of results of the calculations also considered average daily AT data from 4 meteorological stations located near the following gauging stations: Gorzów Wielkopolski, Toruń, Białystok, and Katowice (Fig. 1). They are representative of the entire study area. The data were also obtained from IMWM-NRI archive.

The following was calculated for individual 365 days in a year in both subperiods: average daily RT (STd), coefficient of variability of RT (CvTd) based on the standard deviation of daily temperatures, extreme RT values, including minimum (MinTd) and maximum (MaksTd), and their mean values for the subperiods (MTdmax and MTdmin).

For each day of the year of both subperiods, differences (DeltaSTd) between mean RT (STd1 and STd2) were also calculated according to the following formula:

$$DeltaSTd = STd2 - STd1 \qquad (1)$$

as well as the differences (DeltaCvTd) between corresponding variation coefficients

$$DeltaCvTd = CvTd2 - CvTd1 \qquad (2)$$

It permitted the assessment of average changes in STd and CvTd in the period 1993-2020 in comparison to the period 1961-1992, and changes in STd and CvTd that occurred in individual rivers.

The cumulative mean daily RT values (STdcum) during the hydrological year were also calculated for both subperiods. The values were used for the development of annual diagrams of cumulative RT, as well as the assessment of seasonal and annual differences in the thermal regime of rivers between the subperiods.

Differences between average temperatures of rivers from both subperiods were tested for the purpose of verifying their significance. The test verified the zero hypothesis that the averages for subperiods 1961-92 and 1993-2020 were equal. A t-Student test for independent variables was applied, and the variation uniformity was verified by means of a Levene test. All tests employed the significance level of 0.05.

Results

Changes in daily average RT

Both subperiods showed different increases in RT. The comparison of mean RT values in the second subperiod to the first subperiod (DeltaSTd) revealed the following differences: Vistula River = 0.9°C, Oder River = 1.0°C, Bug River = 1.0°C, Wda River = 0.7°C, Biebrza River = 0.9°C, Łyna River = 0.9°C, Rega River = 0.9°C. In the Przemsza River, the average daily RT in the second subperiod was lower than in the first one by 1.2°C, and in the Ner River higher by 0.4°C (Tab. 2). Examples

Table 2. Mean daily RT in the period 1961-2020 and in both analysed subperiods

River/code	1961-2020	1961-1992	1993-2020	Difference
	[°C]			
Bug/BWY	9.8	9.3	10.3	1.0*
Vistula/WTO	10.4	9.9	10.8	0.9*
Oder/OGO	10.6	10.2	11.2	1.0*
Biebrza/BBU	9.3	8.9	9.8	0.9*
Wda/WCZ	8.7	8.4	9.1	0.7*
Łyna/ŁSE	9.1	8.7	9.6	0.9*
Rega/RTR	9.7	9.3	10.2	0.9*
Ner[1]/NDA	10.3	10.1	10.5	0.4*
Przemsza/PJE	11.4	12.0	10.8	-1.2*

Explanation: [1] – period 1961-2014, * – significant at a level of 0.05

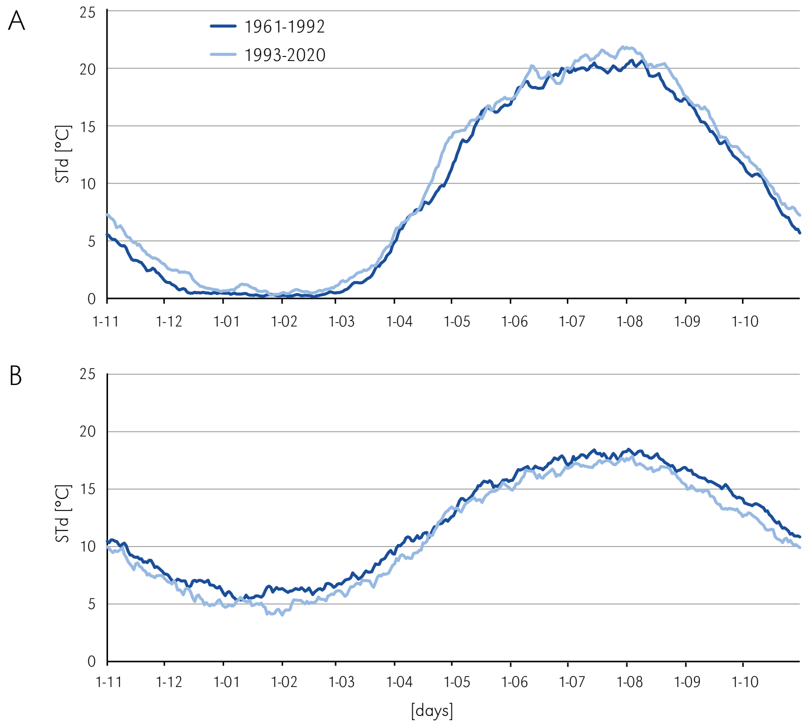

Figure 3. Mean daily RT (STd) in the Bug (A) and Przemsza (B) Rivers in both analysed subperiods

of the course of mean daily RT values in two rivers (Bug and Przemsza) are presented in Fig. 3A and B. An average increase in daily RT was higher in large rivers (average = 0.97°C) in comparison to medium-sized ones (average = 0.85°C). This does not concern rivers under strong human impact (Przemsza and Ner), where extreme increases and decreases in daily RT were recorded.

Differences in mean daily RT in both subperiods

In the second subperiod, mean daily RT in most of the analysed rivers (except for the Przemsza River) was higher on 80-100% of days in a year than in the first one (Figs. 4, 5). The increases, however, were not uniform. The highest increases occurred in large rivers, and in medium-sized rivers in the spring period (from the first decade of April to the first decade of May), reaching 2-3.5°C. A high difference in comparison to average RT also occurred in almost all rivers from the end of May to the mid-June and from the beginning of July to the end of August.

In the Bug River, the difference in mean daily RT also increased in November and December, on some days even by 1.7°C. An increase in RT in the winter half-year was mostly smaller than in the suumer half-year. The exception was the period from the second decade of December to mid-January, when mean RT in most rivers (except for the Bug River) was somewhat lower in the second subperiod than in the first one. The greatest decrease in the difference in mean RT between the subperiods was observed in the Wda River, even by 1°C on some days. Similar cases occurred in large rivers in the last decade of June, and in middle-sized rivers also at the end of January.

Other changes in mean daily RT between the subperiods were determined in rivers

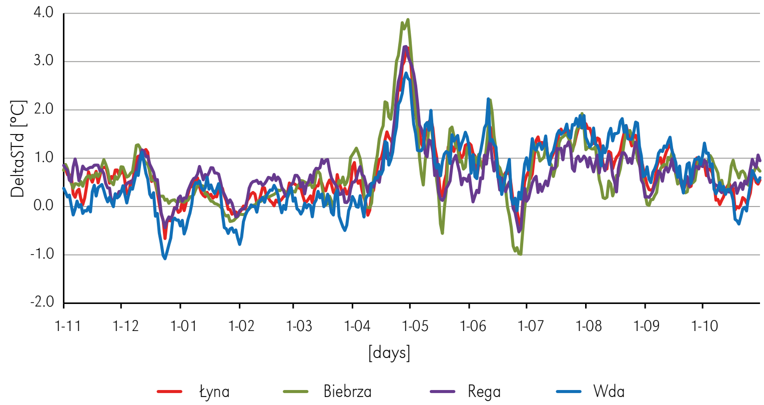

Figure 4. Differences in average daily RT from both subperiods (DeltaSTd) in medium-sized rivers

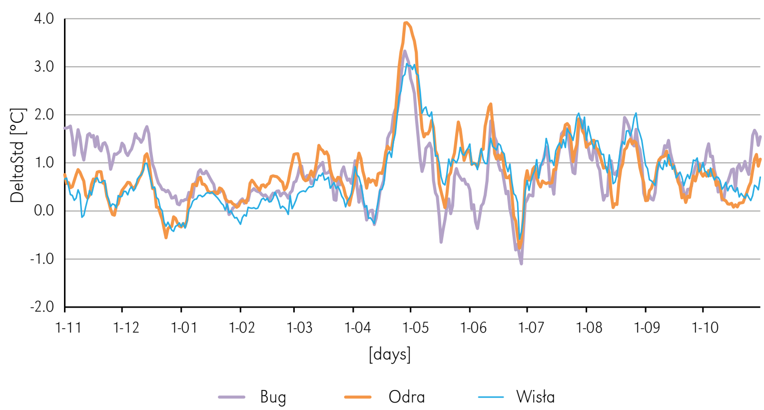

Figure 5. Differences in mean daily RT from both subperiods (DeltaSTd) in large rivers

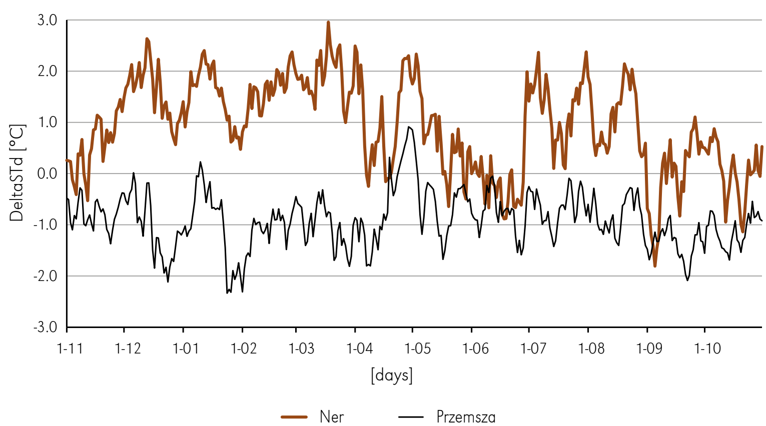

Figure 6. Differences in mean daily RT in both subperiods (DeltaSTd) in the Ner and Przemsza Rivers

under strong human impact (Fig. 6). In the Ner River, the highest increases in DeltaSTd in both subperiods (more than 1°C) were recorded in the winter half-year and from July to August. Smaller differences in average daily RT were recorded in early summer and in autumn. In the Przemsza River, on more than 95% days of the year, the difference in mean daily RT between both subperiods was negative. It was usually approximate to -1°C. It only exceeded -2°C in January and June.

Changes in multiannual daily RT variability (CvTd)

Throughout the multiannual period 1961-2020, mean CvTd coefficient in all the analysed rivers varied from 0.2 (20%, Przemsza River) to 0.7 (70%, Bug and Biebrza Rivers). In six rivers, they decreased in the second subperiod. In most cases, the change was small, reaching approximately 0.1 (10%). Only in the case of Bug, CvTd values decreased from 0.8 (80% in the first subperiod) to 0.5 (50% in the second subperiod). In the case of three rivers: Wda, Łyna, and Przemsza, similar multiannual variability of daily RT was observed in both subperiods (Tab. 3). The phenomenon occurred in rivers under low human impact (Wda and Łyna), as well as in the Przemsza River – under strong human impact, particularly in the first subperiod.

Average multiannual variability of daily RT expressed with CvTd was considerably higher in both subperiods and in all rivers in the winter and summer half-year, and varied in a broad range (Fig. 7). In the summer half-year, changes in CvTd were very small. During winter months, on individual days, CvTd values reached incomparably higher values than averages in the subperiods. The highest CvTd variability in the analysed period of 60 years was recorded on 9 February in the Bug River. The multiannual variance coefficient reached 3.15 (315%). In both subperiods, except for one case, all days with the highest CvTd variability were observed in January or February. It also appears important that maximum CvTd values in the second subperiod were lower than in the first one with the exception of those calculated for the Przemsza River (Tab. 3, Fig. 7).

Differences in multiannual daily RT variation coefficients (DeltaCvTd)

Both subperiods showed significant differences in multiannual daily RT variation expressed with CvTd coefficients. Average differences between the CvTd coefficients

Table 3. Average and maximum coefficients of variation of RT over the period 1961-2020 and in both subperiods

River/code	1961-2020	1961-1992	1993-2020	1961-1992	Day	1993-2020	Day
	CvTd	CvTd	CvTd	CvTdmax		CvTdmax	
Bug/BWY	0.7	0.8	0.5	3.15	9 Feb	2.10	30 Jan
Vistula/WTO	0.4	0.5	0.4	1.55	19 Feb	1.29	21 Jan
Oder/OGO	0.4	0.5	0.4	1.52	23 Jan	1.22	29 Jan
Biebrza/BBU	0.7	0.7	0.6	2.60	26 Feb	2.25	2 Feb
Wda/WCZ	0.3	0.3	0.3	0.84	12 Jan	0.84	6 Jan
Łyna/ŁSE	0.5	0.5	0.5	1.79	27 Feb	1.65	1 Feb
Rega/RTR	0.3	0.4	0.3	1.21	17 Feb	0.81	3 Feb
Ner*/NDA	0.4	0.4	0.3	1.19	11 Jan	0.97	29 Dec
Przemsza/PJE	0.2	0.2	0.2	0.41	11 Jan	0.59	21 Jan

Explanations: CvTd – average coefficient of variation of daily RT; CvTdmax – maximum coefficient of daily variation of RT; * – period 1961-2014.

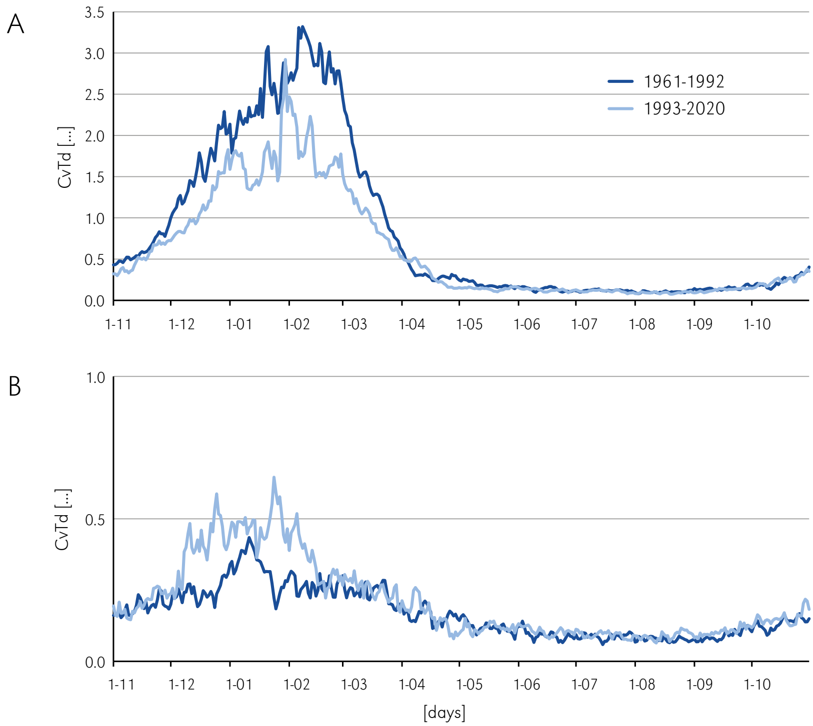

Figure 7. Coefficients of variation of multiannual daily RT (CvTd) in the Bug (A) and Przemsza (B) Rivers in both subperiods

in both subperiods (DeltaCvTd) were usually negative, and reached, respectively: Vistula = -0.07 (7%), Oder = -0.09 (9%), Bug = -0.26 (26%), Wda = -0.02 (2%), Biebrza = -0.14 (14%), Łyna = -0.07 (7%), and Rega = -0.08 (8%) (Fig. 8). The Ner River also showed a decrease in daily RT variation – DeltaCvTd = -0.05 (-5%), and Przemsza showed an increase of a similar magnitude – DeltaCvTd = 0.05 (5%). This suggests that the multiannual variation of daily RT in the analysed rivers in the second subperiod was lower by 2% to 26%. The greatest decreases were recorded in the Bug and Biebrza Rivers. In the case of two rivers under strong human impact, the changes were multidirectional. In the Ner River, a decrease in variation averaged 5%, and in Przemsza it increased by 5%. Despite small differences in mean CvTd values in both subperiods, in some seasons their changes were considerable, and usually unidirectional.

In large and medium-sized rivers, the greatest changes in variability (CvTd) occurred from February through May. They only sometimes entailed a small increase in variability (positive DeltaCvTd), mainly at the end of winter. Variability mostly evidently decreased, particularly in winter and spring (negative DeltaCvTd). The greatest decreases in multiannual variability of CvTd were recorded in Bug and Biebrza, i.e. rivers draining the north-eastern and eastern part of Poland (compare Fig. 8 and Fig. 1). Multiannual RT variability calculated for most days of the winter half-year of the second subperiod was from 20% to 50% lower than on the equivalent days of the first subperiod. In the Biebrza and Bug Rivers, the decreases reached as much as 100% and 150%.

In rivers under strong human impact (Ner and Przemsza), the greatest changes in CvTd were also observed in the winter half-year. The values of the changes, however, were

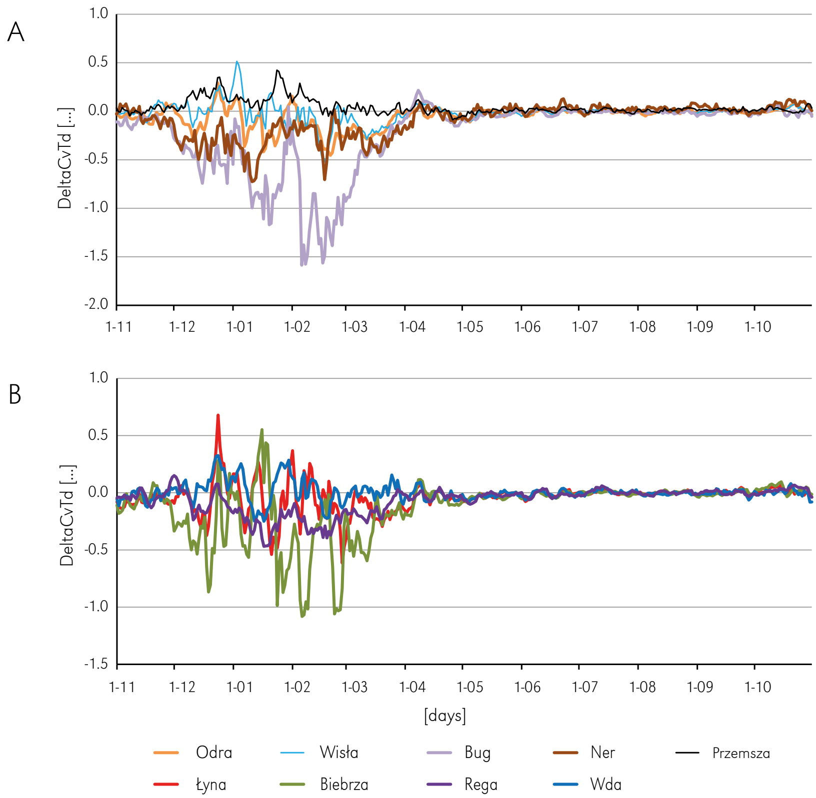

Figure 8. Differences in daily variation coefficients of RT between subperiods in large rivers and rivers under strong human pressure (A) and in medium-sized rivers (B)

different: the Ner River sowed a decrease in the variability of daily RT, and the Przemsza River an increase (compare Fig. 8). Differences in both subperiods on some days reached +45% (Przemsza) and -40% (Ner).

In the remaining rivers (large and medium-sized), differences in the coefficients of variation of daily RT (DeltaCvTd) were rarely higher than 0.5 (50%) or smaller than -0.5 (-50%). Among medium-sized rivers, the variation of daily RT in late winter and early spring in the second subperiod increased the most in the Wda River, and its greatest decrease occurred in the Biebrza and Rega Rivers. The Łyna River also showed dominance of decreases in the variation in the second subperiod. In the Vistula and Oder Rivers, small variation increases occurred in the second subperiod, highest from January to February. Evident decreases were characteristic of spring days (from March through May). Almost identical and relatively low variation of DeltaCvTd (approximately 0) was determined from June to December in all rivers.

Daily RT extremes

Maximum temperatures in the analysed rivers in the period 1961-1992 varied from 20.4°C (Wda) to 26.0°C (Bug) in rivers under low human impact, and up to 28.8°C (Ner) in rivers under strong human impact. In the second subperiod (1993-2020), almost all rivers showed an evident increase in maximum RT from 1.4°C to 3°C (Tab. 4). A considerable decrease in maximum RT was recorded only in the Przemsza River (-3.7°C). The analysis of average multiannual maximum RT also revealed its increase in the second subperiod from 0.1°C in the Ner River to 1.1°C in the

Table 4. Extreme daily RT in the designated subperiods

River/code	Mtdmax 1961-1992	Mtdmax 1993-2020	Mtdmin 1961-1992	Mtdmin 1993-2020	Tdmax 1961-2092	Day	Tdmax 1993-2020	Day
	[°C]						[°C]	
Bug/BWY	13.6	14.5	6.0	6.6	26.0	12Jul	27.4	23Jul
Vistula/WTO	13.8	14.5	7.0	7.6	25.5	27Jul	27.0	2Aug
Oder/OGO	14.0	15.1	6.9	7.7	25.4	21Jul	27.2	2Aug
Biebrza/BBU	12.9	13.9	5.8	6.5	25.1	22Jul	27.8	3Aug
Wda/WCZ	11.5	12.2	5.5	6.1	20.4	5Aug	22.9	16Jul
Łyna/ŁSE	12.1	13.1	6.0	6.6	22.7	20Jun	25.7	18Jul
Rega/RTR	12.7	13.5	6.2	7.1	24.0	17Jun	23.8	13Jul
Ner*/NDA	14.8	14.9*	6.2	6.4*	28.8	9Jul	28.6*	31Jul
Przemsza/PJE	15.3	14.1	8.4	6.6	24.9	31Jul	21.2	2Aug

Explanations: Tdmax – maximum daily RT; MTdmax – average maximum daily RT; MTdmin – average minimum daily RT; * – period 1961-2014.

Oder River. Its decrease was only observed in the Przemsza River (-1.2°C).

Somewhat smaller differences occurred in the case of multiannual average minimum RT. Its increase in the second subperiod varied from 0.2°C in the Ner River to 0.9°C in the Rega River. Like in the case of maximums, a decrease in average minimum RT by 1.8°C was only recorded in the Przemsza River (Tab. 4).

Mean cumulative annual RT

Cumulative daily RT provided the basis for the calculation of mean cumulative annual RT in both subperiods (STdcum1 and STdcum2). Significant differences were determined in their course as well as the rate and magnitude of increases in particular seasons of the year. The highest cumulative annual temperature in the first subperiod was recorded for the Przemsza River (4361°C), and in the second subperiod for the Oder River (4083°C), and the lowest for the Wda River in both subperiods (3049°C and 3336°C). The comparison of both subperiods evidently shows high variability of cumulative annual temperatures. In most rivers, their values were higher in the second subperiod, varying from 43°C (Bug, by 1.2%) to 453°C (Oder, by 12.5%). Only in the Przemsza River a high decrease in the value was recorded by -434°C, equivalent to 9.9%. Data for all rivers are presented in Table 5.

Increases in the cumulative RT value showed seasonal variability in particular rivers (Fig. 9). A rapid increase in RT occurred in the summer half-year, and considerably slower in the winter half-year. Only in the case of the Przemsza River, the rate of increase in cumulative values showed low variability in both half-years. Irrespective of the subperiod, in the winter half-year cumulative temperatures increased the fastest in the Przemsza and Ner Rivers, and the slowest in the Biebrza and Bug Rivers. It is confirmed by the dates of reaching the conventional value of STdcum = 1000°C that can be considered characteristic of the transition period between the winter and summer half-year (Tab. 6).

The comparison of dates in which cumulative temperatures reach STdcum = 1000°C in both subperiods shows that in the second subperiod in all rivers (except for Przemsza), STdcum = 1000°C occurred earlier by 8 (Vistula River) to 13 days (Rega River). Only RT in the Przemsza River in the second subperiod reached STdcum = 1000°C later, by as many as 20 days in comparison to the first subperiod.

Similar dependencies were determined in the case of STdcum = 3000°C. The value can be considered characteristic of the transition

Table 5. Mean annual cumulative daily RT in the analysed drivers in both subperiods

River/code	STdcum 1961-1992	STdcum 1993-2020	Increase in the second period
	[°C]		
Bug/BWY	3707	3750	43
Vistula/WTO	3630	3960	330
Oder/OGO	3630	4083	453
Biebrza/BBU	3254	3569	315
Wda/WCZ	3049	3336	287
Łyna/ŁSE	3184	3492	308
Rega/RTR	3380	3721	341
Ner*/NDA	3701	3825*	124
Przemsza/PJE	4363	3929	-434

Explanations: * – 1961-2014.

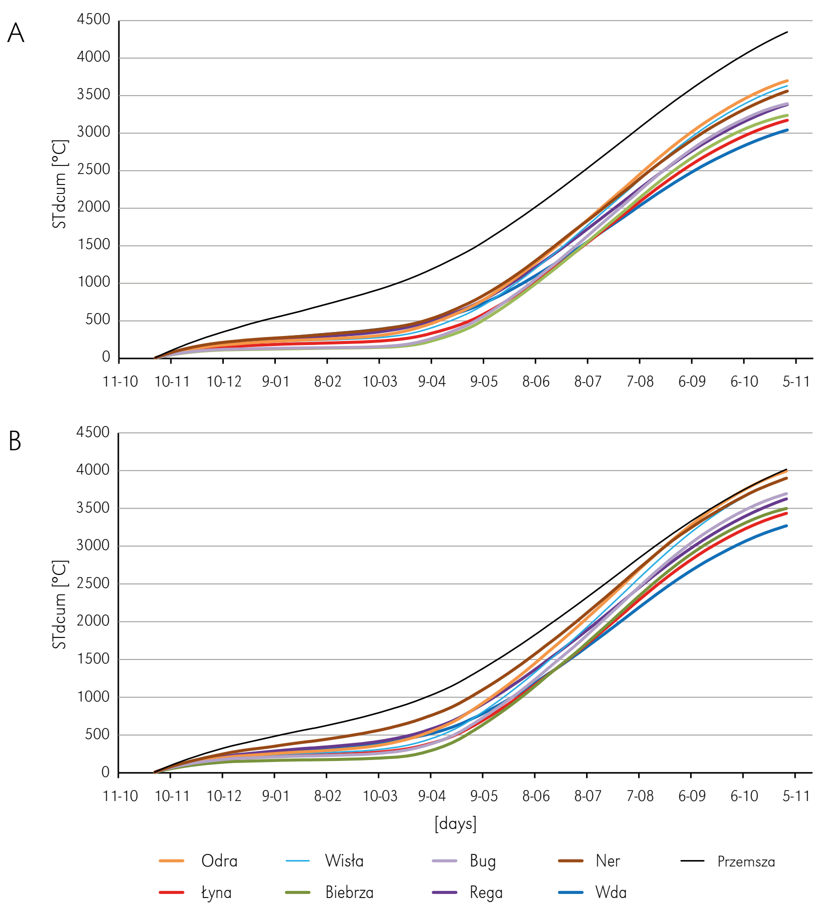

Figure 9. Annual cumulative curves of mean daily RT in the subperiod 1961-1992 (A) and in the subperiod 1993-2020 (Ner 1993-2014; B)

Table 6. Dates of achievement of characteristic mean daily cumulative RT (STdcum) in the subperiods

River/code	1961-1992		1993-2020	
	Day 1000 °C	Day 3000 °C	Day 1000 °C	Day 3000 °C
Bug/BWY	5 Jun	21 Sep	25 May	1 Sep
Vistula/WTO	28 May	10 Oct	20 May	25 Aug
Oder/OGO	23 May	5 Sep	12 May	19 Aug
Biebrza/BBU	8 Jun	1 Oct	30 May	9 Sep
Wda/WCZ	1 Jun	25 Oct	24 May	27 Sep
Łyna/ŁSE	7 Jun	9 Oct	28 May	15 Sep
Rega/RTR	26 May	21 Sep	13 May	3 Sep
Ner*/NDA	15 May	5 Sep	6 May *	26 Aug *
Przemsza/PJE	21 Mar	3 Aug	10 Apr	22 Aug

Explanations: * – 1961-2014.

period between summer and autumn. In the first subperiod, it was reached the fastest by the Przemsza River, and the slowest by the Wda River (Tab. 6). In the second subperiod, it was the fastest in the Oder River, and the slowest, like in the first subperiod – in the Wda River. According to the analyses, STdcum = 3000°C in the second subperiod in all rivers (except for Przemsza) occurred from 10 (Ner River) to 28 days (Wda River) earlier. Only in the Przemsza River, the value was recorded 19 days later. It is worth emphasising that in the second subperiod in comparison to the first one, the course of the cumulative RT curve for the Przemsza River has a shape approximate to the course of curves designated for the remaining analysed rivers (Fig. 9).

Discussion

Results presented in this paper concern a period characterised by an evident increase in RT. The phenomenon has been well documented in different parts of the world, particularly on the Northern Hemisphere (Kaushal et al., 2010; van Vliet et al., 2013; Magritsky et al., 2023). The rate of increase in RT, however, was variable depending on the location (climate features) and size of the river. Different results were also obtained depending on the duration of the period covered by research. The rate of increase in RT was usually (Webb et al., 2007; Orr et al., 2015; Magritsky et al., 2023) evidenced that differences in mean multiannual RT calculated for subperiods 1960-1987 and 1988-2019 for 231 water gauges on rivers northeast of the Asian part of Russia are almost always positive, spatially variable, and range from 0.8°C to 2.2°C, whereas the highest ones were observed in autumn – from 1.5°C to 3.5°C. A similar rate of increase in RT was documented in the rivers of the European Lowland (Webb & Nobilis, 1995; Hari et al., 2006; Hardenbicker et al., 2017) and in Poland (Marszelewski & Pius, 2016; Graf & Wrzesiński, 2019; Ptak et al., 2022).

It is commonly assumed that seasonal and multiannual changes in RT correspond with changes in air temperature (Caissie, 2006; Basarin et al. 2016; Graf, 2019). The statement is completely justified, although many studies have also pointed to human impact as the primary or additional factor modifying the dynamics of changes in RT (Caissie, 2006; Ji, 2008; Olden & Naiman, 2010; Deinet et al., 2020; Bartnik & Jokiel, 2021a; Yang et al., 2021; Marszelewski & Pius, 2021). For example, for the Yangtze River, it was proven that the construction of the Three Gorges Dam (TGD) caused an average annual increase in water temperature by 4% (Guo et al., 2023). It has, however, rarely been attempted to explain the issue in a quantifiable way through the comparison of RT in rivers under various degrees of intensity of human impact (Bonacci at al., 2022). This results from the complex effect of a high number of anthropogenic factors on the thermal regime of rivers. They are related not only to the global factor of climate warming, but also to other types of human impact on the water environment (Lorenzo-Gonzalez et al., 2023).

In order to at least partially explain the issue, this paper presents the analysis of rivers with quasi-natural thermal regime (e.g., the Wda and Bug Rivers) as well as rivers under various degrees of human impact, including strong human impact (the Przemsza and Ner Rivers). It should be emphasised that the intensification of various forms of human impact showed certain variability in the multiannual period. It appears that the selection of rivers was accurate. It is confirmed among others by different courses of mean daily RT values in both subperiods. In rivers with quasi-natural regime (e.g. the Bug River), almost on each day in a year during the second subperiod (1993-2020), higher mean RT was recorded in comparison to the first subperiod (compare Fig. 3A and compare Tab. 2). RT in rivers under strong human impact changed in a completely different way, namely in the Przemsza (compare Fig. 3B) and Ner River. In the Przemsza River, high decreases in mean RT were recorded in almost 95% of all days in a year. In the case of the Ner River, most decreases in RT occurred in early summer and autumn, whereas in winter and summer an increase in RT was recorded (compare Fig. 6). The determined dependencies confirm the different course of changes in water temperature in rivers subject to anthropogenic transformations in comparison to quasi-natural rivers.

One of the primary causes of a decrease in temperature in the Przemsza River was limiting the amount of waters discharged from lignite mines, zinc and lead ore mines, and municipal wastewater (Marszelewski & Pius, 2021). The amount of water from coal mines in the Przemsza River decreased from approximately $130 \cdot 10^6$ m^3 in 1990 to $83\text{-}92 \cdot 10^6$ m^3 in the period 1999-2010. Their share in mean flow rate of the lower section of the Przemsza River in the years 1967-2013 was approximately 35%, corresponding to 6.66 m$^3 \cdot$s^{-1} (Matysik, 2018). Waters discharged from mines showed high and relatively constant temperature. Depending on the mine it varied from 10°C to 15°C (Janson et al., 2009), or from 13°C to 24°C (Solik-Heliasz, 2002). It therefore raises no doubts that the temperature of those waters transformed the thermal regime of the Przemsza River to the greatest degree. Reducing the supply of mining waters to the river since the end of the 20th century contributed to the commencement of the process of a decrease in its temperature despite climate warming. The phenomenon co-occurred with positive changes in municipal wastewater management. In the Przemsza River catchment, water use by the population decreased from $440 \cdot 10^3$ m$^3 \cdot$day^{-1} in the 1980's to approximately $130 \cdot 10^3$ m$^3 \cdot$day^{-1} in the second decade of the 21st century (Pistelok, 2016). This resulted in a decrease in the amount of wastewater discharged to the Przemsza River, and consequently limiting the amount of heat supplied to the river.

In the Ner River, also characterised by strong human impact, differences in mean daily RT (DeltaSTd) on some days were approximate to the values for the Przemsza River, and on others similar to those for rivers with quasi-natural thermal regime. The number of days in a year with negative values of differences in daily temperature between the second and first subperiod was considerably lower in comparison to the Przemsza River, reaching 32% (compare Fig. 6). In the case of quasi-natural rivers, negative differences were sporadic, and occurred more frequently in medium-sized than large rivers (compare Fig. 4).

In the first subperiod in the Ner River, a rapid and statistically significant increase in mean annual RT was recorded, by an average of 0.8°C per decade (compare Figs. 2 and 10). In the second subperiod, the rate of increase in RT was only 0.2°C per decade, whereas the trend was also statistically significant (Jokiel & Bartnik, 2020). At the end of the first subperiod and at the beginning of the second one, an evident decline of the rate of increase in mean RT was recorded. This resulted in a change in the trend strength at the beginning of the second subperiod (compare Fig. 10). It was primarily caused by a decrease in the amount of untreated industrial and municipal wastewater with higher than average temperature discharged to the Ner River. The wastewater mainly came from clothing industry plants and from the Łódź agglomeration inhabited by approximately a million people. The amount of wastewater was limited as a result of the collapse of the industry that commenced at the end of the 1980's. The amount of discharged industrial and municipal wastewater decreased in the first half of the 1990's by more than 50%, and after 1995 as a result of construction of a collective treatment plant its thermal and chemical pollution also decreased. The amount of wastewater also decreased due to rationalisation of water use caused by a high increase in its price (Bartnik & Jokiel, 2021a; Jokiel & Bartnik, 2020). Currently, approximately 20% of mean water discharge in the Ner River in water gauge Dąbie is constituted by waters discharged from a waste water treatment plants. In periods of hydrological droughts and intensified irrigation of agricultural areas, treated wastewater from the waste water treatment plants accounts for almost 100% of the discharge rate at the mouth of the Ner River (Bartnik & Jokiel, 2021b).

Interesting conclusions can be drawn regarding the variability of daily RT in the winter half-year of the second subperiod in comparison to the first subperiod. In almost all the analysed rivers, after a period of specific "thermal distress" with substantial RT changes in the multiannual scale (high CvTd) and variable rate of RT increases, a period of relative stabilisation evidently occurred. In that period, daily RT values rapidly increased, but in a relatively uniform way. The situation was different in the Przemsza River. The variability of daily RT, particularly in the winter half-year, considerably increased, and the dynamics of changes in CvTd in a year showed similarity to mean values calculated for quasi-natural rivers (compare Figs. 8 and 9). This was caused by the weakening of human impact and a decrease in the amount of thermally stable mine waters introduced to the river, as mentioned above.

The anthropogenic character of the thermal regime of the Przemsza River is also confirmed by coefficients of variability of temperature (CvTd). In both subperiods, they were the lowest and equalled 0.2. Somewhat higher variability (CvTd = 0.3), although identical in both subperiods, was observed in the Wda River. The determined similarity of the

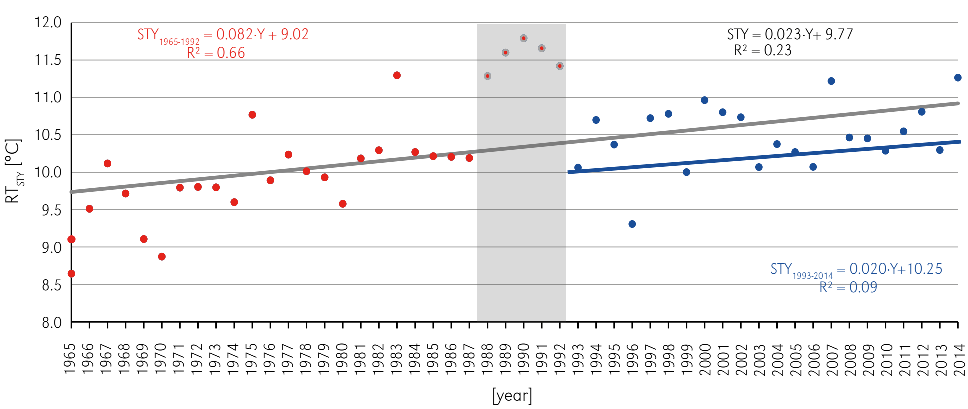

Figure 10. Annual RT changes in the Ner River from 1965 to 2014 (after Jokiel & Bartnik, 2020). Explanation: RT_{STY} – mean annual RT; Y – year; R^2 – coefficient of determination

level of variability of RT in rivers with extremely different human impact results from the type of alimentation of the Wda River. The share of groundwater supply in the outflow of the river is approximately 80% (Jokiel, 1994), and is 20-30% higher than that in most rivers in other regions of Poland. This results in evidently lower RT of the river (compare Tabs. 1 and 4) and its low variability (compare Tab. 3) caused by high thermal inertia of groundwaters supplying the river. Shading of its channel can also play a considerable role. The Wda River runs through extensive coniferous forests, contributing to equalising water temperature in time and its decrease, particularly in the summer season. Study results show that deforestation of banks of small and medium-sized rivers can cause an increase in RT even by 5°C (Caissie, 2006).

The aforementioned differences and similarities between rivers with different human impact are highly significant during modelling of the course of RT in the past, as well as in predicting RT in the future decades, including by the end of the 21st century. The number of papers regarding RT where RT modelling is conducted based on air temperature has rapidly increased over the recent years (Caissie, 2001; Toffolon et al., 2015). This particularly concerns catchments with no results of in situ RT measurements or catchments with results of RT measurements only from short periods of time. The results presented in the paper evidence that modelling and prediction of RT must be preceded by thorough environmental research. This is the only way to determine the role of human impact and/or natural elements (e.g. groundwaters) on the thermal regime of rivers. It can make the analysis of results from RT modelling more accurate.

Further analysis of the variability of temperature (CvTd) cannot ignore the fact that the greatest decrease in RT variability in the second subperiod occurred in rivers in the eastern part of the analysed area, i.e. in the Bug and Biebrza Rivers. The variability of CvTd in these rivers in the second subperiod decreased by 14% and 26%. In the case of those rivers, the primary factor causing lower variability of water temperature were climate conditions, particularly in the winter half-year. An increase in RT stability during winter seasons is caused by a decrease in the number of days with water temperature approximate to 0°C. It is related to increasingly shorter periods of occurrence of ice phenomena and snow cover (Łupikasza & Małarzewski, 2022; Burrell et al., 2023; Wibig & Jędruszkiewicz, 2023). The effect of a decrease in RT variability in the second subperiod in the Biebrza and Bug Rivers are the observed (particularly in the winter half-year) negative differences in coefficients of variability of DeltaCvTd (compare Fig. 3). In the case of the Bug River, the difference exceeded 1.5 (150%), and in the Biebrza River 1.0 (100%).

Another parameter pointing to differences in the thermal regime of rivers under strong human impact are maximum RT values (compare Tab. 4). In both subperiods, unnaturally high Tdmax occurred in the Ner River, and reached 28.8°C and 28.6°C, respectively in both subperiods. It was related to the discharge of industrial and municipal wastewater, as mentioned above. In the winter half-year, they always showed temperature higher than that of natural waters, and an additional warming impulse (in winter and summer) was their unnatural colour and high amount of suspension facilitating absorption of solar radiation. It should be emphasised, however, that maximum RT also increased in almost all the remaining large and small rivers. Increases in mean maximum RT (MTmax) usually exceeded 1°C, and maximum daily RT varied from 1.4°C (Bug) to 3.0°C (Wda). Only in the Reda and Przemsza Rivers, maximum daily RT decreased (compare Tab. 4).

Total cumulative RT can be considered a marker of daily/seasonal heat resources transported by rivers (Fig. 9). After the determination of threshold values (e.g. physiological zeros for specific living organisms or degree-days markers), they can be useful for the determination of indices of effective temperatures for various species, ecosystems, or river aquacultures (Venturelli et al., 2010). Tracing their changes resulting from an increase in RT can be helpful in the analysis of directions and rate of changes observed in river ecosystems (Chezik et al., 2014; Radtke & Dobosz, 2015). After considering the discharge volume and specific heat values of water, it is also possible to calculate a cumulative heat stream transported by each of the rivers (Yang et al., 2014).

The greatest increase in cumulative RT occurred in the Oder River, and the smallest in the Bug River. Data included in Table 5 suggest that large and anthropogenically transformed rivers were the warmest in both subperiods. An increase in annual cumulative temperatures in the Ner River, however, was lower. It was a consequence of both climatic factors, like in other catchments caused by an increase in the temperature amplitude, and local human impact. Among the analysed rivers, only Przemsza was cooler in the second subperiod than in the first one, and the cause was the already mentioned decrease in its pollution and renaturisation and pro-ecological measures intensively conducted in the catchment. Finally, it is worth emphasising that the recorded changes in terms of reaching cumulative temperatures (1000°C and 3000°C; compare Tab. 6) are confirmed by previously documented transformations of the durations and terms of start and end of thermal seasons in Polish rivers (Marszelewski et al., 2022).

It is also worth recalling the existence of close links between RT and AT. The dependence of RT on AT and the influence of local and environmental conditions on the perceived spatial differences in water temperature have been documented for a very long time (Humphreys & Abbot, 1867). The air temperature is the main factor influencing changes in RT (among others Webb & Nobilis 1995; Webb et al., 2003; Garner et al., 2013). The increase in RT due to increased AT during climate warming has been widely documented in the literature in almost all parts of the world (e.g., Mohseni & Stefan, 1999; Swansburg et al., 2004; Yang et al., 2005; Hari et al., 2006; Moatar & Gailhard, 2006; Webb & Nobilis, 2007; Pekarova et al., 2008; van Vliet et al., 2013; Garner et al., 2013; Hannah & Garner, 2015; Marszelewski & Pius, 2016; Dokulil 2018; Kędra & Wiejaczka, 2018; Docherty et al., 2019; Du et al., 2019; Pohle et al., 2019; Graf & Wrzesiński, 2020; Michel et al., 2020; Ouellet et al., 2020; Johnson et al. 2024). Previous studies also show that the impact of AT clearly exceeds the impact of other factors, including human impact (Isaak et al., 2018; Zhu et al., 2018). The relationship between AT and RT was examined for the rivers analysed and the nearest meteorological stations in an earlier paper (Marszelewski & Pius, 2016). Apparently, the correlations between AT and RT values are highest in spring, ranging from $r = 0.83$ to $r = 0.93$, and on average over the year from $r = 0.80$ to $r = 0.87$.

Conclusion

The calculations and analysis of several indices of the thermal regime of rivers were conducted based on unique data, i.e. more than 194 thousand results of daily measurements of RT from a period of 60 years. It is a new approach to the assessment of changes in the regime in the period of climate warming. Moreover, the considered group of rivers covered those with varied human impact, allowing for more detailed study results and assessment of the strength and directions of human impact on the thermal regime of rivers. In the case of the analysed rivers, human pressure is related to water management, including municipal and industrial wastewater, among others water from drainage of lignite mines and metal ore mines. It should be emphasised that the political and economic transformation commenced in the 1990's resulted in radical reorganisation of wastewater management, including substantial limitation of the volume of discharged mine waters. These processes co-occurred with the period of acceleration of climate warming, permitting slow recovery of biotic conditions of rivers in respect of their thermal regimes.

Effects of the aforementioned phenomena and processes are confirmed by the obtained study results. They showed that the thermal regimes of all the analysed rivers differed in both subperiods (1961-1992 and 1993-2020). The rivers were considerably warmer in the second subperiod, with the exception of rivers with strong human impact. The average increase in RT was higher in large rivers (Vistula +0.9°C, Oder and Bug +1.0°C) in comparison to medium-sized rivers (Wda +0.7°C, Biebrza, Łyna and Rega +0.9°C). The changes were lateral in almost all the rivers. They particularly resulted from large-scale climatic factors (global warming), and not local factors, including human impact. The exception was the Przemsza River, strongly thermally polluted in the first subperiod. As a result of renaturalisation, its water temperature in the second subperiod decreased (-1.2°C). In the thermally polluted Ner River, a small increase in RT (+0.4°C) was the effect of the aforementioned multidirectional changes in water and wastewater management. Differences in mean daily RT between the designated subperiods in large and medium-sized rivers were the highest in spring, reaching +3.5°C. In rivers under strong human impact, they were considerably smaller: even negative in the Przemsza River (up to -2.2°C). High differences were also recorded in the case of maximum daily RT, in the second subperiod including high increases reaching even 3°C. The exception was also the Przemsza River where high decreases in daily RT were observed, reaching -3.7°C. In the thermally polluted Ner River, maximum RT in both subperiods was almost identical.

RT showed high variability in the winter half-year and low in the summer half-year. In rivers under strong human impact (e.g. Przemsza and Ner) and in rivers with a high share of groundwater supply, RT variability was considerably lower (e.g. the Wda River). The study also evidences that in the second subperiod, in most rivers, RT considerably decreased. Its greatest decreases were also recorded in the winter half-year. Multiannual RT variability on many winter days decreased from 50% to 150%. The greatest decreases in variability were recorded in the Bug, Biebrza, and Reda Rivers, and the smallest in Vistula and Wda. In the case of Przemsza, an evident increase in daily variabilities of RT was documented in the second subperiod, whereas the highest increases in CvTd were recorded in the winter half-year also in that river.

The variability and changes in the thermal regime of rivers depending on human impact are well reflected by courses of cumulative daily RT. An increase in heat resources of rivers caused a change in the start, end date, and duration of thermal seasons in the rivers, and consequently changes in thermal regimes. It should be emphasised that in the case of the Przemsza and Ner Rivers, thermal pollution considerably decreased. The thermal regimes of these rivers are slowly becoming increasingly similar to those typical of rivers with a quasi-natural character.

According to the authors, the multiparametric analysis of the thermal regime of rivers based on daily measurement data proved a useful and innovative method of identification of its changes as a result of climate warming and human impact. This permitted evidencing several new patterns and dependencies currently occurring in the water environment. Moreover, it was possible to identify and separate the effect of climate warming from human impact caused by improper water management.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

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Article first received • 22 October 2024
Article accepted • 21 February 2025