Temporal and spatial patterns of the river flow and water temperature relations in Poland

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Abstract: Main aim of the study was to determine the temporal and spatial patterns of relations between monthly and annual average river flow (RF) and water temperature (WT) for 53 rivers in Poland. The research made use of monthly and annual WT and RF for 88 water gauges for the period 1971–2015. Correlations were established using the Spearman's rank correlation coefficient and the similarity of RF–WT relations was determined using the Ward's hierarchical grouping. It was demonstrated that correlations between average annual RF and WT were negative (for >85% of water gauges) and statistically significant ($p < 0.05$) only for 30% of water gauges. It was confirmed that the studied RF–WT relations underwent seasonal changes. Positive correlations were clearly predominant in the winter months, while from April to September these relations were negative and statistically significant. The RF–WT relations were also characterized by spatial differences and this had been confirmed by separation of seven groups of water gauge profiles distinguished with the help of the Ward's hierarchical grouping method. The strongest RF–WT relations were apparent in the case of mountainous rivers, for which snow melt supply and summer rainfall supply were predominant, and lakeland rivers, which had a considerable share of groundwater supply. These were classified as cold rivers, as opposed to the cool rivers in the lowland belt, for which the RF–WT relations were the weakest. The results obtained may contribute to the elaboration of an appropriate management strategy for river ecosystems, which are assigned important economic and environmental functions.

Keywords: River flow; Water temperature; Hydrological regime; Correlation coefficient; Hierarchical clustering; Central Europe.

INTRODUCTION

Water temperature (WT) is a good indicator of both changes in air temperature (AT) and ways of river supply (Bates et al., 2008; Ficklin et al., 2013; Goulden et al., 2009; Graf et al., 2019; Isaak et al., 2012; Koutsoyiannis and Montanari, 2007; Ul Islam et al., 2019; Zhu et al., 2018). Hydrological regime (river regime) is a characteristic, rhythmic course of hydrological phenomena in the river in the yearly cycle, established on the basis of many years of observation. The river regime consists of the following courses: river supply, water levels, discharges, icing (ice regime), including water temperature (thermal regime). Water temperature is considered one of the elements of the river thermal regime. As a significant element of the hydrological regime, it undergoes cyclical change on different time scales (Huntington, 2010). Studies on the river thermal regimes confirm its strong relation with climatic factors (Caissie, 2006; Graf, 2018, 2019; Graf and Wrzesiński, 2019, 2020; Łaszewski, 2014; Łukaszewicz and Graf, 2020; Marszelewski and Pius, 2018; Mohseni and Stefan, 1999; Rice and Jastram, 2015; Van Vliet et al., 2013; Webb et al., 2003; Wiejaczka, 2007). The observed seasonal changes in WT are first and foremost the consequence of surface heat exchange with the atmosphere and the turbulent mixing of waters of varying temperatures (Hannah et al., 2004; Webb and Nobilis, 2007). The spatial variability of WT is caused, among others, by such factors as the river autochthonicity or allochthonicity, the water temperature of its tributaries, the inflow of wastewater, and the hydro-morphological changes occurring within the river channel and river valley (Caissie et al., 2004;

Gallice et al., 2015; Graf, 2015, 2018, 2019; Hester and Doyle, 2011; Kreft, 2013; Westhoff and Paukert, 2014).

Air temperature (AT) and river flow (RF) determine the thermal characteristics of river waters mainly through the regulation of river-heat runoff. Usually, the relationship between WT and RF is seasonally and spatially diversified, as a consequence of the type of hydrological regime and periodic changes in the structure of total river runoff. Under conditions of the temperate climate, with only low RFs and low water levels, a higher WT than that occurring under average conditions is observed (Sinokrot and Gulliver, 2000). The strongest correlations between RF and WT are most often identified in case of small rivers, in which heating and cooling of water occurs decidedly more quickly. While studying WT in rivers in Lithuania, Jurgelėnaitė and Jakimavičius (2014) determined its strongest correlations with AT (0.98–0.99), considerably weaker positive correlations with precipitation (0.01–0.43), and a very weak inverse relation with RF (0–(–0.35)), whereas Webb et al. (2003), while analysing catchment areas with a different relief in the Exe River basin (Devon, UK), found that WT was inversely proportional to RF in all catchment areas and in all temporal scales (hourly, daily and weekly), however, with RF having a greater impact when taking into consideration changes in WT over shorter temporal scales and in larger catchment areas.

Numerous studies have indicated that two of the factors modifying the RF–WT relations may be the degree of riverbed development, which conditions free flow or flow regulated by hydrotechnical structures, and the shading of riverbanks (Bogan et al., 2003; Caissie et al., 2004; Langan et al., 2001; Mohseni

and Stefan, 1999; Ozaki et al., 2003; Webb et al., 2003; Wiejaczka, 2007). Mountainous rivers and rivers impacted by longstanding human activities are usually characterized by different features of the hydrological regime compared to the average conditions in the region (Graf and Wrzesiński, 2020; Marszelewski and Pius, 2016, 2018; Pekarova et al., 2008; Younus et al., 2000; Żelazny et al., 2018). While analysing the natural variability of temperature in surface waters in the mountainous region of the Tatras, Żelazny et al. (2018) revealed an extremely high heterogeneity of temporal WT fluctuation patterns between streams in comparison with lake waters and springs. Łaszewski (2020), when documenting the spatial variability of WT in Polish lowland rivers, studied the impact of environmental factors on their thermal heterogeneity. He concluded that in terms of the magnitude and variability of thermal parameters, measurement stations at main river tributaries displayed clear thermal heterogeneity, which was the effect of anthropogenic factors such as reservoir water releases and the inflow of wastewater. While analysing the summer thermal heterogeneity patterns for the second–seventh-order rivers throughout the Pacific Northwest and northern California (USA), Fullerton et al. (2018) demonstrated that thermal heterogeneity varied among rivers, some of which had long uninterrupted stretches of warm water $\geq 20^{\circ}\text{C}$, while others had many smaller cool patches. According to these authors, this was an effect of climate change and the adopted scale of research, which was confirmed by indicating the non-linear relationships between thermal heterogeneity and spatial resolution of water temperature data.

The multitude of environmental factors impacting and modifying the course and scope of the WT variability in rivers may increase thermal heterogeneity along the flow of a single river, but also between rivers with different thermal regimes and manner of supply. Research conducted by Yang and Peterson (2017) in the Mackenzie and Yukon river basins confirmed that the warming of rivers in northern Canada resulted from strong relationships between WT and local AT, but lakes may be a factor modifying these relationships. Delays between the water temperature of the studied rivers and the air temperature vary from 1 to 40 days, and the largest, identified in the Great Bear River (tributary of the Mackenzie River), were caused by the strong influence of the heat accumulated in the Great Bear Lake on the temperature of the river water. Yang et al. (2021), analysed the thermal regime of waters in relation with the air temperature in the Yukon, Mackenzie and Lena river basins indicated that these rivers were characterized by a clear dynamics of water temperature. Comparison of monthly mean water temperatures at different locations (between upstream and downstream areas) showed significant spatial variability and some inconsistency between locations, mainly due to differences in the data collection patterns. The study of the thermal regimes of rivers and their spatial and temporal changes in the northern regions was a great challenge due to the data limitations, which was emphasized, among others, by Yang et al. (2021).

A factor that may contribute to an increase in WT and at the same time to changes in the runoff regime is an increase in AT. The progressive increase in AT has been confirmed in climate change projections taking into account the forecasts of changes until the end of the 21st century. (Caldwell et al., 2015; Kaushal et al., 2010; Luo et al., 2013; Olsson et al., 2015; Taniwaki et al., 2017; van Vliet et al., 2013). The results of global modelling point to an increase in the seasonality of RF (both an increase in high flow and a fall in low flow), and also an increase in the global average and high WT in rivers, on

average by $0.8\text{--}1.6^{\circ}\text{C}$ ($1.0\text{--}2.2^{\circ}\text{C}$) on around one third of the global land area in the years 2071–2100 in comparison with the period 1971–2000 (van Vliet et al., 2013). The greatest changes in the hydrological regime (the largest water temperature increases and decreases in low river flows), are forecasted for the United States, Europe, eastern China, and parts of southern Africa and Australia. According to the IPCC (2018), river flows in Europe have been increasing in winter and decreasing in summer since the 1960s, however, considerable regional and seasonal differentiation is apparent. It is assumed that climate change may have a small impact on rivers, which are characterized by low WT due to considerable groundwater supply. The influx of cold groundwater into a watercourse has a cooling effect on WT in the warm season (Jurgelėnaitė and Jakimavičius, 2014).

Disturbances in water thermal conditions were also confirmed on rivers located in higher latitudes, in the Arctic region. It was proved that the temperature of river waters underwent significant changes due to the very strong climate change, which was mainly manifested by an increase in air temperature. As a consequence, the inflow of warmer river waters to the seas of the Arctic zone (e.g. the Laptev Sea, the Beaufort Sea), and then to the Arctic Ocean, may lead to an increase in sea water temperature and a change in their ice regime (Liu et al. 2005; Nghiem et al. 2014). According to Park et al. (2020), runoff from Arctic rivers has increased over the past few decades, and by carrying warmer and fresh water to the Arctic Ocean, it has impacted the sea ice extent and the ocean's heat budget. Studies conducted by these authors for the period 1980–2015 showed that the increase in river water temperature contributed to a 10% reduction in the regional extent of sea ice over the Arctic shelves, which occurred in late spring and early summer. The warming effect of rivers on the sea water temperature and ice phenomena in the Arctic zone was also confirmed by studies conducted by Nghiem et al. (2014). These authors showed that the Mackenzie River (Canada) transported large amounts of heat to the Beaufort Sea, which affected the sea ice regime, leading, for example, in 2012 to a significant reduction in the extent of sea ice. The Mackenzie and other large rivers in the Arctic can transport huge amounts of heat indirectly into the Arctic Ocean, in sharp contrast to Antarctica, which lacks rivers that could affect the extent and structure of sea ice.

According to Caissie (2006), climate change modifies the temporal variability of RFs and their thermal characteristics to a steadily increasing extent, and this may, in turn, have adverse impact on the ecological condition of surface waters: rivers, lakes, transitional and coastal waters, marine and oceanic waters. In order to preserve the ecological function of watercourses (that is appropriate conditions necessary for the existence and development of aquatic organisms) it is necessary to maintain optimal water flow conditions and its thermal characteristics (Allan and Castillo, 2007; Eby et al., 2014; Elliott and Elliott, 2010; Jackson et al., 2016; Letcher et al., 2016; Padilla et al., 2015).

The primary objective of this research was to determine the temporal and spatial patterns of the RF–WT relations in Poland. Specific objectives of the study included: (1) describing the RF–WT relations in the yearly and monthly time series, (2) identifying the RF–WT relations on a spatial scale, and (3) defining similarities and differences in the significance of the correlation coefficients between RF and WT. This is the first study on this subject conducted for rivers in Poland on a regional scale, and its results could be helpful in developing management strategy to larger river ecosystems, which are assigned important economic and environmental functions.

STUDY AREA

Poland is situated in Central Europe (Fig. 1) within the moderate transient climate zone, which is intermediate between the maritime and continental climates. An increase in continentalism is observed in the easterly direction (Woś, 2010). Due to the country's physico-geographical location, various masses of air clash above its territory and have impact on the development of weather conditions, and therefore the climate, which is characterized by considerable weather variability and changes in the course of seasons in successive years. The following masses of air are most frequently encountered over the territory of Poland: the polar maritime air from the northern part of the Atlantic Ocean, the polar continental air from Eastern Europe and Asia, the Arctic air from the Arctic Sea, the subtropical maritime air from around the Azores, and the subtropical continental air from Africa.

Poland, with an area of 312,823 km², is characterized by considerable differences in its environmental conditions, both climatic and hydrological, that are reflected in different river feeding conditions and in distinctive seasonal fluctuations of river flow. Woś (2010) distinguished 28 climatic regions in Poland, while Wrzesiński (2016, 2021), in accordance with the criteria proposed by Dynowska (1994), identified five major types of hydrological regimes of Polish rivers, namely: nival poorly formed, nival moderately formed, nival well-formed,

nival-pluvial, and pluvial-nival (Fig. 2). In addition, in Poland there is a regionally differentiated influence of macro-scale climatic phenomena on the country's hydrological and meteorological elements.

In accordance with the classification of thermal regimes of Polish rivers (PHP IMGW-PIB, 1986) rivers in the north of the country, in the lake district zone, similarly to the mountainous tributaries of the Odra and Wisła (Vistula) rivers (in southern Poland), are classified as so-called cold rivers, with a range of variability of average annual temperatures of 6.5–10.4 °C and an amplitude of fluctuation from 7.0 to 10.2 °C. In the case of these rivers, the phase shift coefficient for the commencement of cyclic changes in temperature may attain approximately 23 days. This is the period of time from the beginning of the hydrological year, after which river water temperature exceeds the average value. In the lowland belt, rivers with an average annual temperature of 8.6–10.0 °C, an amplitude of fluctuation of 10.3–11.4 °C, and a phase shift coefficient for the commencement of cyclic changes in temperature of up to 14 days have been classified as cool.

Research on the thermal regime of Polish rivers has confirmed the existence of significant relationships between variability of air temperature and river water temperature (Choiński et al., 2021; Graf, 2019; Graf and Wrzesiński, 2020; Łaszewski, 2014; Marszelewski and Pius, 2016, 2018; Żelazny et al., 2018).

Fig. 1. Study area and the location of water gauges of the IMGW-PIB. Numbering of water gauges and retention reservoirs in accordance with Table A1.

Fig. 2. Average annual WT (A) and river runoff (B), and types of flow regimes of rivers in Poland (after Wrzesiński, 2021). Types of regimes: 1 – nival poorly formed; 2 – nival moderately formed; 3 – nival well-formed; 4 – nival-pluvial; 5 – pluvial-nival.

Fig. 3. Scope of change of monthly and annual WT (A) and runoff (B) for the studied rivers in the years 1971–2015.

In contrast to AT, the spatial distribution of average annual WT in rivers is close to the latitudinal distribution (Fig. 2). The highest values of average annual WT occur in rivers of central and north-western Poland ($>10\text{ }^{\circ}\text{C}$), while the lowest, below $8.0\text{ }^{\circ}\text{C}$, in southern Poland, in the mountain tributaries of the Wisła and Odra rivers. Average monthly WT in January ranges from 1.0 to $3.0\text{ }^{\circ}\text{C}$ (Graf and Wrzesiński, 2019). In January, rivers in the eastern part of the country are colder, while these in the coastal strip and of the Odra and Warta (in their upper reaches) are warmer. The highest WT values ($>3.0\text{ }^{\circ}\text{C}$) are detected in the rivers of Upper Silesia transformed by human activity.

Rivers of the Upper Silesian Industrial District (including the Przemsza and Brynica rivers) for many years have been a receiver of polluted mine water for many years (Matysik, 2018). Changes in the thermal regime of rivers in Poland caused by human activity were confirmed by Marszałewski and Pius (2016), among others, in the upper Odra and Vistula rivers. Main reason of these changes was the discharge of mine and post-cooling waters into rivers, which modified their hydrological and thermal regimes. Pollution and wastewater discharged into the waters of rivers flowing through industrial areas (for example, discharge of heated waters) cause, especially in the winter season, an increase in the temperature of their waters, often by several degrees (Graf, 2015). Modifications of the thermal regime of rivers in Poland, related to the increase in

water temperature, are also observed in rivers in urbanized areas (Ciupa, 2006, Graf, 2018).

In July, which is the warmest month of the year (Fig. 3), water isotherms have a latitudinal course, while their values decrease to the north and south of the zone with the highest temperature in central Poland. In July, average monthly WT is the highest ($>20.0\text{ }^{\circ}\text{C}$) in the river valleys of the Central Polish Lowland (Fig. 2). In turn, the coolest, with a temperature under $14.0\text{ }^{\circ}\text{C}$, are the rivers in the Przymorze region (Rega, Łeba), of the Sudeten tributaries of the Odra River, and the Carpathian tributaries of the Wisła River. Lower WT values are also registered in the rivers of Upper Silesia (Przemsza). Graf and Wrzesiński (2019) analysed the impact of NAO, AO, EA, EAWR, SCAND and AMO atmospheric macroscale circulations on changes in water temperature in Polish rivers in 1971–2015, and found that these relationships were not strong, but noticeable, and also varied in time and space. The impact of the atmospheric circulation on the temperature of river waters in Poland increases in the winter. The strongest effect was observed for the positive and negative NAO and AO phases, during which the water temperature deviations from the mean values are $(+/-) 1.0\text{--}1.5\text{ }^{\circ}\text{C}$, and the SCAND circulation phases (water temperature deviations ranging from 0.8 to $1.2\text{ }^{\circ}\text{C}$).

The differentiated circulation of humidity, which is conditioned by atmospheric circulation and environmental factors,

mainly the morphology and geology, results in considerable spatial differentiation of river runoff throughout the country. That differentiation refers to the characteristic, latitudinal course of isohyets (Wrzesiński, 2016; Wrzesiński and Sobkowiak, 2018). High runoff occurs in the mountains, with the highest values (>1500 mm) in the river catchments of the Tatras – Fig. 2. High runoff (>500 mm) is also observed in the catchment areas of the upper sections of the Carpathian tributaries of the Wisła River and the Sudeten tributaries of the Odra River. Rivers of the Carpathian foreland and the Przymorze region are characterized by runoff totalling 200–500 mm. Lower runoff values (200–300 mm) are observed for lakeland rivers, while upland rivers are characterized by average runoffs ranging from 150 to 200 mm. However, the river valleys of the Central Polish Lowland are characterized by low runoff values (< 150 mm), with the lowest – under 100 mm – observed in the Kuyavia and Greater Poland region. The groundwater contribution to the total runoff is an important element of the runoff regime of rivers, as it also describes the retention capacity of the catchment. On average, it totals 55% for the entire Poland, which means that groundwater runoff plays a greater role in the runoff structure than surface runoff. Rivers in the Przymorze region, lakeland rivers, and rivers in carbonate rock uplands have the largest share of groundwater supply (>65%), while the Carpathian rivers and the upper sections of Sudeten rivers have the smallest share (<35%). In all other areas the share of both runoff components is similar and ranges from 45 to 55% (Wrzesiński, 2013). In Poland, the most abundant water resources, following the snow melt, appear during the winter-spring period. In these seasons, and especially in spring, that the runoff of the majority of rivers is greatest – Fig. 3. During the summer half-year period (V–X), higher runoff caused by intense rainfall supply is observed only in the mountains.

MATERIALS

Average annual and monthly RF and WT time series for 53 rivers in Poland for 88 water gauges for the period 1971–2015 were used in this study (Fig. 1). Data were provided by the Institute of Meteorology and Water Management – National Research Institute (IMGW - PIB, Warsaw, Poland) and are available at <https://danepubliczne.imgw.pl>. In Poland measurements of water temperature are performed daily at 7:00 (GMT+1). Average monthly and annual WT and RF values were calculated on the basis of daily values using the arithmetic mean. Data were presented in relation to the hydrological year, which in Poland lasts from 1 November until 31 October.

METHODS

First, the Spearman's rank-order correlation between average monthly and annual RF and WT time series were calculated for the 53 selected rivers. The Spearman's rank-order correlation is a non-parametric test, which is based on the ranks of the variables. The analysis made it possible to correlate variables that had a non-normal distribution at the order and quantitative level, and at the same time remained largely insensitive to outliers. The Spearman's rank-order correlation constitutes a measure of the monotonic statistical dependence between random variables. The results of the correlational analysis made it possible to determine the percentage shares of positive and negative correlation coefficients at various levels of statistical significance. An analysis was also performed of the spatial differentiation of correlation coefficients RF–WT and of their statistical significance.

In the next step, the similarity of RF and WT correlations was determined for the 88 analyzed water gauges, on the annual time scale. For this purpose, the Ward's hierarchical grouping method (Ward, 1963) was applied, and the water gauges were grouped based on 12 monthly Spearman correlation coefficients.

According to Ward (1963), at each step of the analysis the loss of information associated with merging objects can be calculated as the sum of squares of distances of each object from the centre of the cluster to which a given object belongs. At each step of the grouping, an association of every possible cluster pair is considered, and two clusters whose function results in the lowest increase in information loss are combined. The information loss in this method is referred to as the error sum of squares (E.S.S.), defined:

$$E.S.S. = \sum_{i=1}^n x_i^2 - \frac{1}{n} \left(\sum_{i=1}^n x_i \right)^2 \quad (1)$$

where: x_i is the score of the i -th object.

The results of the grouping have been presented in the form of a dendrogram reflecting the structure of similarities between the studied groups of water gauges. There are various methods of estimating the correct number of clusters (Rousseeuw and Silhouettes, 1987; Sugar and James, 2003). One of them is the assessment of the stopping criterion, which indicates at what step further clustering should be halted. In the present study the use has been made of the stopping criterion known as the “Mojena rule” (Mojena, 1977). Although this is just one of many available stopping criteria, it is distinguished by calculational simplicity and is reasonably well accepted by researchers (Milligan and Cooper, 1985). It is calculated using the formula:

$$Rm = d_h + \delta \cdot b \quad (2)$$

where Rm is the Mojena rule; d_h is the average distance between connecting clusters; δ is the standard deviation of distances between connecting clusters; and b is the equation constant (2.75–3.50) (Mojena, 1977; Tomalski et al., 2021).

The number of classes was verified based on an analysis of the geometry of the dendrogram and the plot of the linkage distance curve. The methods presented above are commonly used in hydro-meteorological research (Berhanu et al., 2015; Graf and Wrzesiński, 2020; Isik and Singh, 2008; Wrzesiński et al., 2018; Zhang et al., 2012).

RESULTS

The Spearman's correlation between annual RF and average annual WT in rivers in Poland are not strong, however, they are visible and display a clear spatial differentiation (Figs. 4 and 5). Negative correlations were obtained for the majority of water gauges (>85%), however, statistically significant ($p < 0.05$) correlations were determined for 30% of gauges with different locations throughout the country.

Considerably stronger and more statistically significant correlations were observed in the case of monthly values – Fig. 4. In the annual cycle, and particularly in the winter months of January and February, positive correlations are clearly predominant, with statistically significant correlations demonstrated at 17% and 36% of the analysed water gauges, respectively. These are located primarily in the mountains, on the Carpathian tributaries of the Wisła River (southern Poland), but additionally on its tributaries along its middle course, on the lowland, and on rivers of the Masurian Lake District, and in January also on the

Fig. 4. Percent share of correlation coefficients (positive and negative) with a specific statistical significance (p) for RF and river WT in the years 1971–2015.

Fig. 5. Spatial distribution of the correlation coefficient significance (p) of annual RF and WT in the years 1971–2015.

ivers of the Przymorze region and the Pomeranian Lake District (in northern Poland) – Fig. 6. March, similarly to October and November, is a month with the weakest correlations between RF and WT. For the majority of the analysed rivers, correlational relations between the analysed variables are negative, however, statistically insignificant. A different type of dependence is observed on rivers in the Przymorze region and

the Pomeranian Lake District in the north-western part of the country. RF and WT are correlated positively and, again, are statistically insignificant. Correlations between RF and WT from April to September are different than in the winter season, and statistically most significant. Negative correlations were determined at more than 90% of analysed water gauges, of which 50% were statistically significant.

Fig. 6. Spatial distribution of the correlation coefficient significance (p) of monthly (November–April) RF and WT in the years 1971–2015.

In these months the arrangement of isocorrelates is very similar, with four regions being distinguished by the strongest relations – Figs. 6 and 7. The strongest negative correlations ($p < 0.001$) were determined for the Carpathian tributaries of the Wisła River, while significant negative correlations were also

observed along the upper sections of the Sudeten tributaries of the Odra River (in southern Poland), on rivers of the Masurian Lake District (with the exception of the River Pisa), and on rivers of the Pomeranian Lake District and in the western part of the Przymorze region.

Fig. 7. Spatial distribution of the correlation coefficient significance (p) of monthly (May–October) RF and WT in the years 1971–2015.

The grouping of water gauge profiles on the basis of the values of 12 correlation coefficients of monthly RF and WT made it possible to distinguish seven groups, in which relations between the analysed variables for the years 1971–2015 are different – Fig. 8. The course of correlation coefficients in the

annual cycle for all groups is similar, with the highest values in winter, in January and February, and the lowest in the summer period. The results of the analysis have demonstrated that distinguishing of groups was determined primarily by the values of correlation coefficients and their statistical significance (Fig. 9).

Fig. 8. Dendrogram of the gauge grouping based on 12 monthly values of RF and WT correlation coefficients and the plot of linkage distance (note: gauge ID codes in accordance with Table A1).

The spatial differentiation of water gauges representing individual groups is on the whole varied, conditioned mainly by features of the river runoff regime, and modified by anthropogenic changes in the thermal regime. The weakest correlations are apparent in rivers from group 1 (20 profiles) and group 2 (12 profiles), which comprise water gauge profiles located mainly on rivers in central Poland. As a rule, their RFs do not display statistically significant relations with WT in the annual cycle. Group 3 stands out from among the established groups. It comprises 10 water gauge profiles located on the Carpathian tributaries of the River Wisła, from the upper course of the Wisła River to the San River, and on the Bóbr River in the Sudeten Mountains (in the south of the country). The RF of these rivers is most strongly correlated with their WT, positively in February and negatively from April to September, being statistically significant at a level of $p < 0.001$. The RF of rivers categorized in group 4 (11 profiles) was negatively and at once statistically significantly correlated with temperature in April and May ($p < 0.05$). Furthermore, this is a compact group of profiles located on the middle Odra River and on the lower sections of its tributaries. Group 5 is represented by 16 water gauge profiles situated mainly on rivers of the Przymorze region (in the north of the country). In January and February, their RFs display positive correlations with WT, and negative, statistically significant relations from July to September ($p < 0.05$). Similar relations have been determined for rivers of group 6 (15 profiles) and group 7 (4 profiles), which are located in different regions of the country. As regards the rivers of groups 6 and 7, negative and statistically significant RF and WT correlations are observed from April to September, at a level of $p < 0.05$ and $p < 0.001$, respectively.

DISCUSSION

The results obtained for the relationship between RF and WT in rivers in Poland are coincident with findings of numerous studies, which analysed changes in the features of the thermal regime of rivers (Bartholow, 1989; Graf and Wrzesiński, 2020; Kaushal et al., 2010; Magnuson et al., 2000; Marszelewski and Pius, 2018; Webb and Nobilis, 2007). In most studies, also related to the analysed in this research Polish rivers, correlations between average annual RF and WT are weak and spatially differentiated, and subject to seasonal change, which result from changes in AT and WT, and changes in the dynamics and structure of runoff.

RF-TW relations on different time scales

Regarding rivers characterised by a strong seasonality, with the highest WT values recorded during periods of low RF, these can be attributed mostly to the direct influence of AT, and up to 26% of the increase in high (95 percentile) WT can be attributed to indirect changes in RF (van Vliet et al., 2013). The exchange of thermal energy in a river takes place mainly at the air-water level and is less distinct at the riverbed-water level (Caissie, 2006; Jackson et al., 2016). It is stressed that changes in river water temperature are mostly a consequence of changes in AT and heat instability in a riverbed, with the latter factor being, among others, a function of heat transfer from groundwater and its exchange in the hyporheic zone. In the case of a complex hydrological regime (nival-pluvial, pluvial-nival), which is typical of rivers in southern Poland, the RF-TW relations are determined by the share and predominance of a

Fig. 9. Results of water gauge grouping based on monthly correlation coefficients of RF–WT in the years 1971–2015 (A), and the scope of change in correlation coefficients in individual groups (B).

specific type of water supply, i.e. from snow melt, rainfall, or the increased share of groundwater supply in the total runoff. The relatively considerable differentiation of environmental conditions in Poland – both climatic and hydrological – results in various forms of water supply observed on rivers, thereby leading to a varied seasonality of river runoff (Jokić and Tomalski, 2018; Pociask-Karteczka, 2011; Wrzesiński, 2016),

which determines the thermal characteristics of waters. In the annual cycle, this concerns the most characteristic and distinctive periods, that is those of freshets and low waters, when the structure of total river runoff undergoes change. For the majority of the analysed water gauges located on Polish rivers, correlations between RF and WT in the annual period are weak and negative, and this means that a decrease in RF for a given river

results in an increase in WT, mainly in the summer season, while a rise in RF may result in a drop in WT. Small lowland rivers are characterized by a relatively small RF, which corresponds to their shallow depth, and thus small thermal inertia, whereas according to Toffolon and Piccolroaz (2015) larger lowland rivers may behave differently. According to these authors, the influence of RF on WT in a river becomes more pronounced for rivers supplied from snow melt (mountainous rivers) and ones impacted by the hydropower production. In the case of mountain rivers, which are located at considerable heights and characterized by a noticeable share of snow melt supply in total runoff, WT is usually low throughout the year (Lisi et al., 2015). Similar effects may be brought about by the considerable share of the inflow of cool groundwater to a river (Tague et al., 2007).

The operation of hydropower plants may cause changes in the flow volume and water status as well as water temperature (Adynkiewicz-Piragas, 2008; Jarosiewicz and Obolewski, 2013). Mountain rivers (in Sudetes and Carpathians) and rivers in Masuria and Pomerania (northern part of Poland) have the most favourable conditions for the development of hydropower in Poland. Hydropower plants are located in areas with usually large slope gradients of the river bed and favourable water flow conditions, which is influenced by the river features, the amount of rainfall and soil permeability, as well as in areas where reservoir retention is possible, where artificial damming of water is possible (dam regulations) (Fig. 1, Appendix 1). The effects of hydropower plants on the thermal behaviour of rivers are observed at different time scales and at different distances from the dam, as for example, changes in the average daily water temperature in the Słupia River (Fig. 1, Appendix), the most utilized in terms of hydropower production river in Central Pomerania, is approximately 0.5 °C, while the highest daily temperature increase was around 2.4 °C (May 22, 2006), and the highest decrease was around 3.0 °C (May 30, 2007). In the summer season on rivers used for energy purposes, the increase in water temperature is usually inhibited, which is related to the release of cold water during the production of hydropower. In the case of larger hydrotechnical investments, changes in the natural hydrological regime become more visible (Jarosiewicz and Obolewski, 2013), e.g. significant changes in the flow rate and daily changes in water levels (amplitude 2–3.0 m) of the Vistula River below the Włocławek barrage in the period 1970–2002 (Habel, 2010), daily maximum water fluctuations (up to 3.5 m) in the Myczkowice Reservoir in Solina as a result of the operation of the hydropower plant (Wojtuszevska, 2007), changes in daily flows in Niedzica from May to October (from 9.0 m³ s⁻¹ at night to 25–45 m³ s⁻¹ during the day) and changes in the water level by several dozen centimeters in a few minutes, as a result of the operation of the hydropower plant in Czorsztyn (Augustyn, 2010). The dynamics of changes in the levels, flow and temperature of surface waters caused by the influence of hydropower plants is very diverse and characteristic of individual rivers; however, there are no regional studies that would identify modifications to the RF–TW relationship in the case of rivers used for energy purposes.

Seasonal changes in the structure of runoff of Polish rivers are visible in the varying relations between average monthly RF and WT values. Positive correlations in winter months indicate that the thermal nature of winters exerts a sizeable influence on the thermal regime of rivers in this season (January, February). In warmer winters, mid-winter snow melt are frequently observed, causing an increase in RF and river WT. During more severe winters, the lack of surface supply leads to a fall in RF

and the occurrence of winter low waters, which is accompanied by a decrease in river WT. This concerns in particular mountainous rivers (the mountainous tributaries of the Wisła River).

In the spring season, and especially in March and April (the weakest relations between RF and WT), the snow melt results in the attainment of the maximum RF values, which results in the water circulation system in catchment areas being supplied with cooler water. This is confirmed, among others, by research conducted by Krasovskaia and Gottschalk (2002), Wenger et al. (2011), Zolezzi et al. (2011), and Hilderbrand et al. (2014). In consequence, correlations between the analysed variables are negative and yet statistically insignificant for the majority of rivers. A different type of dependence is observed on rivers in the Przymorze region and the Pomeranian Lake District in the north-western part of the country. RF and WT correlate positively and, again, are statistically insignificant. These rivers are distinguished by a different supply regime, with earlier winter flow maxima. As a result, in March the thermal characteristics of river waters are more strongly impacted by the increase in AT than by the rise in RF.

In the summer period, when RF is low, WT attains higher values. The strong negative correlations between RF and WT in mountain rivers (southern Poland) in the summer season are impacted by an increasing rainfall supply, which causes RF to rise and WT to fall. These different relations between RF and WT in mountain rivers may be explained by the specificity of these regions, including a longer duration of the winter season and the intense rainfall supply of rivers in the summer season (Graf and Wrzesiński, 2019, 2020; Marszelewski and Pius, 2018; Żelazny et al., 2018).

In turn, in lakeland rivers (in northern Poland) runoff in the summer season is very low, totalling less than 20% of annual runoff; it originates mainly from groundwater supply. Its share in the total runoff of these rivers is the greatest when viewed on the whole country scale, as it exceeds 70%. During the summer low water periods, the rise in RF brought about by the increase in groundwater supply may reduce river WT. The modifying impact of groundwater on the thermal river regime has been confirmed, among others, by Kanno et al. (2014) and Westhoff and Paukert (2014).

When analysing changes in the thermal characteristics of waters in a lowland river (Noteć River in Poland), Graf (2018, 2019) demonstrated that the share of the periodic component associated with seasonality in the structure of the WT measurement series can be very high (even up to 90% of variability), accompanied by a low share of the trend component and random fluctuations. Regarding rivers characterised by a strong seasonality, with the highest WT values recorded during periods of low RF, these can be attributed mostly to the direct influence of AT, and up to 26% of the increase in high (95 percentile) WT can be attributed to indirect changes in RF (van Vliet et al., 2013).

Spatial differentiation of the RF–WT relations

For the studied Polish rivers the RF–WT correlations are spatially differentiated. This is due to the classification of thermal regimes of Polish rivers (PHP IMGW-PIB, 1986). Cold rivers in Poland include rivers in the Lakeland zone (the northern part of Poland) and mountainous tributaries of the Wisła and Odra rivers (southern Poland), while in the lowlands rivers are classified as cool. In the case of mountainous rivers, for which snow melt supply and summer rainfall supply are predominant, and lakeland rivers, which have a considerable share

of groundwater supply, are apparent the strongest RF–WT relations.

When analysing the impact of environmental factors on the spatial variability of WT in Polish lowland rivers in summer, Łaszewski (2020) demonstrated that in small, quasi-natural watercourses (the tributaries of main rivers) WT is typified by decidedly greater variability than in the first-order rivers (greater thermal contrasts). These results reference research conducted at other geographical locations (Dick et al., 2015; Imholt et al., 2013; Kanno et al., 2014). The susceptibility of WT in small watercourses to the influence of climatic factors varies considerably and is determined by a group of factors associated with land development, morphology, and the magnitude of groundwater supply (Grabowski et al., 2016; Hrachowitz et al., 2010; Żelazny et al., 2018). In turn, in the case of larger rivers a greater similarity of the thermal regime is observed, which is generally connected with the homogeneity of the studied area in terms of climatic, hydrological and hydrogeological factors, which are recognised as superordinate from the perspective of thermal regime regulation (Hannah and Garner, 2015; Łaszewski, 2020).

According to Żelazny et al. (2018), mountain rivers are amongst the most diverse in terms of the WT patterns, due to weather conditions, catchment area characteristics and flow rate. Research conducted by these authors has shown that WT of rivers in the Tatra Mountains to a significant degree is controlled by the topographical factor and hypsometry, which in 48% contribute to changes in the structure of the TW measurement series. Whereas relations between RF and WT are disturbed in the case of transit rivers (the Odra and Wisła), which, according to Jokiel and Tomalski (2018) at individual sections can display changes in the RF seasonality index. The seasonality index ranges from 0% to 100%, and along with its increase, the level of seasonality of the examined feature increases. The regularity of RF variability in the annual cycle of a transitory river is impacted by the regime of its tributaries and the delay in its supply caused by river length and drainage basin size. While conducting an identification of RF seasonality for the Wisła River at 14 water gauge cross-sections located along its course, Jokiel and Tomalski (2018) determined a considerable differentiation of RF seasonality indices, which is the resultant of a steadily increasing number of physico-geographical factors occurring over an ever greater and more diverse area. In this case, changes in the river regime, particularly in the dynamics of catchment area runoff, translate into changes in features of the thermal regime of waters. Relations between transitory river supply components vary depending on the magnitude of impact of both external conditions (weather factors: air temperature and atmospheric precipitation) and internal conditions (orography, lithological conditions, drainage system) in the catchment area. Wrzesiński and Sobkowiak (2020) have determined that the transformation of the hydrological regime observed in the Wisła River in multi-annual and annual patterns occurred along its entire course, however, the most frequent changes were found in its upper (mountainous) course, influenced by the RF characteristics of its tributaries.

Temporal changes in the RF- WT relations

It is assumed that rivers located in a single hydroclimatic region maintains more homogenous runoff regime (Poff et al., 2006), which can in some ways stabilize the thermal characteristics of waters. However, the forecast changes in WT and RF, and this may disturb river-heat runoff conditions cannot be excluded. Spatially coherent and at the same time a

significant increase in the maximum ten-year temperature of rivers was confirmed for the period 1929–2003 in the European part of the Russian pan-Arctic, while for the three largest catchments (Ob, Yenisei and Lena) a decrease in the trend in area averaged energy flux was reported (Lammers et al., 2007). These studies emphasized that the difference in time between the temperature peaks in the river and the flow resulted in a lack of consistency between the trends in temperature and energy flow. It was also indicated that in the case of large catchments, due to high spatial variability, it is difficult to identify consistent trends in water temperature changes and water flow in rivers, and human impact was an important factor masking the impact of climate change on the increase in the maximum temperature of rivers.

Numerous forecasts assume the temporal shift of fundamental phases of the hydrological regime and changes in the runoff structure. For the Danube River in the years 1901–1990 there has been observed an increase in runoff from December to April (the heightened runoff of so-called “cold” water) and a decrease in river runoff in the summer months from June to August (the lessened runoff of so-called “warm” water) (Pekarova et al., 2008). Due to the growth in recent years of river runoff in the winter season and the reduction of the magnitude of runoff in the summer months, high increases and decreases in WT are ever more frequent.

Liu et al. (2005), who analyzed the long-term open water season stream temperature variations and changes in the Lena River basin in Siberia in 1950–1992, found strong positive correlations between the average monthly air and water temperature in the warm season (early and mid-June). It was observed that due to the increase in water temperature at the peak of the flow, the heat flux of the Lena River increased by 23% in June, which in turn may affect the thermal conditions in the Laptev Sea at the beginning of the summer season.

In Poland, located in the transitional zone of the temperate climate, a significant increase in air and inland water temperature was found for the Polish Lowlands. Marszelewski and Pius (2016), when examining changes in water temperature in 14 rivers in Poland in the period 1961–2010, found a clear increase in water temperature in lowland rivers ($0.17\text{--}0.27\text{ }^{\circ}\text{C dec}^{-1}$), while such changes were not registered in the rivers in the foothills of the Carpathians Mountains (in the rivers of Przedgórze Karpackie area). The research carried out in the mountain catchment of the Raba (Polish Carpathians) showed differentiation of the trends in changes in the temperature of the river waters in the years 1960–2009 (Kędra, 2020). Graf and Wrzesiński (2020, 2020a) revealed different spatio-temporal trends in changes in water temperature in Polish rivers (53 and 44 rivers, respectively) in the years 1971–2015. In most of the measurement series (70–90% of the tested water gauges), positive trends in water temperature from April to November were found, while the smallest changes in water temperature were observed in the winter half-year. Ptak et al. (2016) showed an increase in water temperature in the period 1971–2015 (from $0.26\text{ }^{\circ}\text{C dec}^{-1}$ to $0.31\text{ }^{\circ}\text{C dec}^{-1}$) in selected rivers in the Przymorze zone, and Łukaszewicz and Graf (2020) confirmed these trends also for the period 1951–2010. The changes in water temperature observed at that time were related to positive trends in air temperature, hence the climatic factor was considered to be decisive for changes in the temperature of water in most rivers in Poland.

It is often the case that analyses of WT time series display no significant annual value trend but identify an increase in spring and summer temperature maxima, associated with the decreased share of snow melt in river runoff supply in spring.

Similar conclusions were obtained from studies on the features of the thermal regime of rivers in the United Kingdom (Hannah and Garner, 2015), which determined that rivers for which the share of groundwater in runoff was the smallest and the time of exposure of water to atmospheric influences was the longest are characterized by the greatest susceptibility to changes in thermal water conditions. Research conducted by Michel et al. (2020) in Swiss rivers indicates that lowland rivers are becoming steadily more vulnerable to increasing air temperature (AT) forcing, while the resilient alpine rivers will in the immediate future be more susceptible to warming due to the expected reductions in snow and glacier-melt inputs. Forecasts elaborated for Lithuanian rivers have shown that the increase in river-heat runoff will be determined by two main factors: the relatively slight rise in RF (on average by 1.7%) and the rise in WT (by 2.9 °C) (Jurgelėnaitė and Jakimavičius, 2014). On the other hand, forecasts for other European rivers, which assume the continued growth of WT, stress that the thermal sensitivity of rivers is augmented by anticipated decreases in low RFs, leading to reduced thermal capacity (van Vliet et al., 2013). Significant and permanent changes in the reference characteristics of RF and WT are also caused by various forms of anthropogenic activity in catchment areas (Graf, 2018; Graf and Wrzesiński, 2020; Kanno et al., 2014; Younus et al., 2000). In the case of rivers with a disturbed regime, associated with the functioning of, for example, a storage reservoir, the thermal regime of waters downstream of the reservoir is determined by the inflow of waters from the reservoir with parameters independent of the course of weather (Graf et al., 2019; Graf and Wrzesiński, 2019). However, the scale of the transformation of the natural thermal system of rivers caused by the operation of a water reservoir depends on its depth and surface, as well as the time of water retention and the method of its discharge (Olden and Naiman, 2010; Webb and Walling, 1996; Wiejaczka, 2011; Łaszewski, 2015). In temperate climates, deep reservoirs (with a bottom discharge type) increase the river water temperature in winter and lower it in summer. In the case of larger rivers in Poland, where retention reservoirs are located (Fig. 1, Appendix 1), especially those with thermal stratification developed during the year, modification of the water temperature and changes in the RF–WT relations should be expected. The effect of the retention reservoirs on increasing water temperature in the winter season is visible, among others, on the upper and middle section of the Odra and on the upper section of the Warta (Graf and Wrzesiński, 2020; Marszelewski and Pius, 2018). In the case of the Warta river, this increase is caused by the influence of the Jeziorsko reservoir, which flows through the river, and may be additionally reinforced by the inflow of water with increased temperature from the Geotermia Uniejów area (Graf et al., 2018). On the other hand, shallow reservoirs, characterized by a lack of thermal stratification, in the summer half of the year rather increase the water temperature of rivers below the dams. Łaszewski (2015) showed that shallow reservoirs without thermal stratification significantly modified the thermal structure of lowland rivers in Poland (an average monthly temperature increase of about 0.6–1.2 °C), breaking their natural thermal continuum.

Changing climatic conditions may lead to a destabilisation of characteristics of the runoff regime and of the thermal conditions of river waters, causing them to transform into a different type of regime, with clearly different regularities concerning the seasonality of high and low waters and their temperatures (Graf, 2018; Huntington, 2010; Krasovskaia and Gottschalk, 2002). Global forecasts anticipate that the joint impact of a high increase in WT and fall in low RFs will be unfavourable for

river ecosystems, potentially leading to the deterioration of water quality and freshwater habitats (van Vliet et al., 2013).

CONCLUSIONS

1. The analysis carried out for 53 rivers in Poland (1971–2015) demonstrated that correlations between annual river flow (RF) and average annual water temperature (WT) values were weak and spatially differentiated, and that they underwent seasonal change, which was associated with the dynamics of changes in both air temperature and the structure of river runoff.

2. On a monthly scale, these relations were negative for the majority of water gauges, while positive correlations had been determined for the winter months, which pointed to the considerable impact of the thermal character of winters on the development of river water thermal characteristics during this season. The weakest correlational relations were observed in the transitory months between winter and spring (March) and autumn (October and November).

3. The study made it possible to distinguish seven groups of water gauge profiles with a similar course of the RF–WT correlation coefficients in the annual cycle, which were differentiated by the intensity and significance of correlation.

4. For Polish rivers, a factor which significantly influences the relations what is their spatial location and the character and climatic features of the drained region (mountainous rivers, lowland rivers, lakeland rivers, and rivers in the Baltic coastal area), which condition the features of the hydrological regime. The strongest RF–WT relations are obvious in the case of mountainous rivers, for which snow melt supply and summer rainfall supply are predominant, and lakeland rivers, which have a considerable share of groundwater supply. These are classified as cold rivers, as opposed to the cool rivers in the lowland belt, for which RF–WT relations are the weakest.

5. Relations between RF and WT are subject to disturbances caused by, among others, the instability of characteristics of the river and thermal regime of Polish rivers, which is the result of the joint impact of natural factors and human activity. Examples of rivers with disturbed RF–WT relations are transitory rivers (e.g. the Wisła River), which are distinguished by strong seasonal changes in water flow and thermal characteristics brought about by their complex supply regimes.

6. The detected RF–WT relations for rivers in Poland – the first of its kind on this scale – are important for the further monitoring of changes taking place in these relations. The results of this analysis may contribute to a verification of river ecosystem management strategies, particularly in periods threatened with a shortage of water resources and the occurrence of high temperatures. Thanks to the maintenance of minimal requirements for RF in rivers, i.e. the appropriate management of infrangible (environmental) flow in the summer period, it will be possible to reduce the adverse impact of high WT on the functioning of aquatic ecosystems.

In further research, it is expected to investigate the directions of transformation of the RF–WT relationship in Poland at various spatial scales with a probabilistic forecast for the nearest and further future and based on multi-aspect forecasting modeling. It is also assumed to establish correlation relationships between the extreme RF and WT, which are likely to increase in the near future, which will bring important findings for assessing the stability of the functioning of aquatic ecosystems in a changing climate.

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APPENDIX A.

Table A1. Basic data on the studied rivers.

No.	River	Gauge station	Latitude (°N)	Longitude (°E)	Area (km ²)	T_{Year} (°C)	R_{Total} (mm)	Type regime	Retention Reservoir
1	Odra	Racibórz	50.12	18.22	6,744	10.6	307	4	
2	Odra	Ścinawa	51.40	16.43	29,584	10.6	195	4	
3	Odra	Cigacice	52.03	15.60	40,106	10.9	177	2	
4	Odra	Połęcko	52.05	14.88	47,370	10.8	171	2	
5	Odra	Słubice	52.33	14.55	53,600	10.6	182	2	
6	Odra	Gozdowice	52.75	14.32	109,729	10.5	153	2	
7	Kłodnica	Gliwice	50.28	18.67	444	10.2	431	4	
8	Mała Panew	Krupski Młyn	50.57	18.62	655	8.7	198	2	Turawski (1)
9	Nysa Kłodzka	Bystrzyca Kłodzka	50.28	16.65	260	7.0	481	4	
10	Nysa Kłodzka	Nysa	50.47	17.33	3,276	9.9	277	5	Otmuchów (2), Nysa (3)
11	Nysa Kłodzka	Skorogoszcz	50.75	17.67	4,514	10.3	243	5	
12	Oława	Oława	50.93	17.28	957	9.5	129	4	
13	Bystrzyca	Krasków	50.90	16.58	683	9.1	210	4	
14	Bystrzyca	Jarnołtów	51.12	16.83	1,71	9.5	169	5	Mietków (4)
15	Kaczawa	Świerzawa	51.02	15.88	134	7.5	285	4	Kaczorów (5)
16	Barycz	Osetno	51.62	16.45	4,579	10.0	107	3	
17	Orla	Korzeńsko	51.53	16.87	1,127	8.6	127	3	
18	Bóbr	Wojanów	50.87	15.82	535	8.1	354	4	Pilchowice (6)
19	Bóbr	Żagań	51.62	15.32	4,254	9.3	279	4	
20	Nysa Łużycka	Gubin	51.97	14.70	3,974	10.3	230	2	
21	Warta	Bobry	51.02	19.40	1,8	9.7	186	2	Poraj (7)
22	Warta	Sieradz	51.60	18.73	8,14	9.6	182	2	Jeziorsko (8)
23	Warta	Nowa Wieś Podgórna	52.13	17.58	20,763	10.4	144	2	
24	Warta	Poznań	52.38	16.93	25,126	10.4	134	2	
25	Warta	Skwierzyna	52.60	15.50	31,268	10.4	132	2	
26	Warta	Gorzów Wielkopolski	52.72	15.23	52,186	10.4	130	2	
27	Widawka	Podgórze	51.45	18.93	2,354	9.4	191	2	
28	Ner	Dąbie	52.08	18.82	1,712	10.5	198	2	
29	Prosna	Mirków	51.30	18.15	1,255	9.7	132	2	
30	Prosna	Bogusław	51.88	17.95	4,304	10.0	122	2	
31	Kanał Kościański	Kościąn	52.08	16.63	1,247	10.2	95	3	
32	Noteć	Ujście 1	53.05	16.72	6,308	9.9	93	2	
33	Noteć	Nowe Drezdenko	52.85	15.83	15,97	9.9	148	2	
34	Gwda	Piła	53.15	16.73	4,704	9.6	185	2	
35	Drawa	Drawiny	52.83	15.97	3,298	9.6	204	1	

Temporal and spatial patterns of the river flow and water temperature relations in Poland

No.	River	Gauge station	Latitude (°N)	Longitude (°E)	Area (km ²)	T_{Year} (°C)	R_{Total} (mm)	Type regime	Retention Reservoir
36	Ina	Stargard Szczeciński	53.35	15.03	1,833	9.5	165	2	
37	Rega	Łobez	53.62	15.60	609	8.5	236	2	
38	Rega	Resko	53.77	15.38	1,122	8.8	247	2	Rejowice (9)
39	Rega	Trzebiatów	54.05	15.27	2,628	9.6	247	2	
40	Paręta	Bardy	54.08	15.70	2,955	8.9	299	2	
41	Wieprza	Stary Kraków	54.43	16.60	1,519	8.0	341	1	
42	Słupia	Słupsk	54.47	17.03	1,45	8.9	345	1	Krzynia (10)
43	Łupawa	Smóldzino	54.65	17.20	805	8.2	335	1	
44	Łeba	Łębork 2	54.53	17.75	552	7.9	346	1	
45	Reda	Wejherowo	54.60	18.22	395	8.3	345	1	
46	Wisła	Skoczów	49.80	18.78	297	8.6	657	4	
47	Wisła	Goczałkowice	49.92	18.98	738	9.8	356	4	Goczałkowice (11)
48	Wisła	Szczucin	50.32	21.07	23,901	10.3	312	4	
49	Wisła	Sandomierz	50.67	21.75	31,846	10.5	288	4	
50	Wisła	Zawichost	50.80	21.85	50,732	10.0	265	4	
51	Wisła	Dęblin	51.55	21.82	68,234	10.1	230	4	
52	Wisła	Kępa Polska	52.42	19.95	168,956	10.0	174	2	Włocławek (12)
53	Wisła	Toruń	53.00	18.60	181,033	10.3	172	2	
54	Przemsza	Jeleń	50.15	19.23	1,996	11.4	300	4	
55	Brynica	Brynica	50.47	19.00	98.2	7.7	164	2	
56	Soła	Oświęcim	50.03	19.22	1,386	9.1	445	4	Żywiecki (13), Międzybrodzki (14)
57	Skawa	Wadowice	49.87	19.50	836	8.6	481	4	
58	Raba	Stróża	49.78	19.92	644	7.7	497	4	Dobczyce (15)
59	Dunajec	Żabno	50.12	20.85	6,735	9.6	415	5	Czorsztyn (16), Rożnów (17)
60	Poprad	Stary Sącz	49.57	20.65	2,071	8.1	388	5	
61	Nida	Pińczów	50.50	20.52	3,352	9.3	166	2	
62	Wisłoka	Krajowice	49.77	21.40	2,092	9.5	368	4	
63	San	Dynów	49.78	22.23	2,944	8.4	501	4	Solina (18)
64	San	Jarosław	50.02	22.70	7,041	9.7	320	4	
65	San	Radomyśl	50.67	21.93	16,824	10.1	251	4	
66	Tanew	Harasiuki	50.47	22.47	2,034	8.7	187	2	
67	Kamienna	Kunów	50.95	21.27	1,106	9.1	160	2	
68	Wieprz	Lubartów	51.48	22.63	6,364	9.7	116	2	Nielisz (19)
69	Wieprz	Kośmin	51.57	22.00	10,231	9.9	118	2	
70	Pilica	Przedbórz	51.08	19.87	2,536	9.1	183	2	Sulejowski (20)
71	Pilica	Białobrzegi	51.65	20.95	8,664	9.7	161	2	
72	Narew	Narew	52.92	23.52	1,978	8.8	156	3	Siemianówka (21)
73	Narew	Strękowa Góra	53.22	22.53	7,181	9.4	149	3	
74	Narew	Ostrołęka	53.08	21.57	21,862	10.9	163	2	Zegrzyński (22)
75	Biebrza	Sztabin	53.67	23.12	846	9.0	182	3	
76	Biebrza	Burzyn	53.27	22.45	6.9	9.2	175	3	
77	Pisa	Ptaki	53.38	21.78	3,562	9.1	185	1	
78	Bug	Strzyżów	50.83	24.03	8,945	10.4	149	4	
79	Bug	Włodawa	51.55	23.57	14,41	9.6	130	2	
80	Bug	Frankopol	52.40	22.55	31,336	9.3	125	2	
81	Bug	Wyszków	52.58	21.45	39,119	9.7	130	2	
82	Krzna	Małowa Góra	52.10	23.47	3,128	9.3	115	2	
83	Drwęca	Brodnica	53.25	19.40	3,526	9.3	204	2	
84	Wda	Czarna Woda	53.83	18.08	940	8.6	205	1	
85	Wierzyca	Brody Pomorskie	53.85	18.75	1,544	8.7	175	2	
86	Wąska	Pasłęk	54.07	19.65	224	7.9	262	2	
87	Łyna	Sępól	54.25	21.00	3,647	9.0	213	2	
88	Guber	Prosna	54.22	21.08	1,568	8.7	170	3	

Note: T_{Year} refers to annual average temperature and R_{Total} annual runoff during 1971–2015.