

Article

Detecting Patterns of Changes in River Water Temperature in Poland

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Abstract: The study determined water temperature trends of rivers in Poland in the period 1971–2015, and also their spatial and temporal patterns. The analysis covered daily water temperature of 53 rivers recorded at 94 water gauge stations and air temperature at 43 meteorological stations. Average monthly, annual, seasonal and maximum annual tendencies of temperature change were calculated using the Mann–Kendall (M–K) test. Regional patterns of water temperature change were determined on the basis of Ward’s hierarchical grouping for 16 correlation coefficients of average annual water temperature in successive 30-year sub-periods of the multi-annual period of 1971–2015. Moreover, regularities in monthly temperature trends in the annual cycle were identified using 12 monthly values obtained from the M–K Z test. The majority of average annual air and water temperature series demonstrate statistically significant positive trends. In three seasons: spring, summer and autumn, upward tendencies of temperature were detected at 70%–90% of the investigated water gauges. In 82% of the analysed rivers, similarity to the tendencies of change of monthly air temperature was concluded, with the climatic factor being recognised as of decisive importance for the changes in water thermal characteristics of the majority of rivers in Poland. In the winter months, positive trends of temperature were considerably weaker and in general statistically insignificant. On a regional scale, rivers with a quasi-natural thermal regime experienced temperature increases from April to November. In the other cases, different directions of change in river water temperature (RWT) were attributed to various forms of human impact. It was also found that for the majority of rivers the average annual water temperature in the analysed 30-year sub-periods displayed upward trends, statistically significant or close to the significance threshold. Stronger trends were observed in the periods after 1980, while a different nature of water temperature change was detected only in a couple of mountainous rivers or rivers transformed by human impact. In the beginning of the analysed period (1971–2015), the average annual water temperature of these rivers displayed positive and statistically significant trends, while after 1980 the trends were negative. The detected regularities and spatial patterns of water temperature change in rivers with a quasi-natural regime revealed a strong influence of climate on the modification of their thermal regime features. Rivers characterised by a clearly different nature of temperature change, both in terms of the direction of the tendencies observed and their statistical significance, were distinguished by alterations of water thermal characteristics caused by human activity. The results obtained may be useful in optimising the management of aquatic ecosystems, for which water temperature is a significant indicator of the ongoing environmental changes.

Keywords: trends; spatial and temporal patterns; cluster analysis; thermal regime; rivers; Central Europe

1. Introduction

According to the report of the Intergovernmental Panel on Climate Change (IPCC) [1], the main factor causing the warming of river water around the world is climate change. This is confirmed by the results of research on tendencies of change of water temperature over the past few decades, conducted on a global scale in rivers in different spatial locations [2–8]. It is forecasted that river water temperature (RWT) will continue to rise along with increases in air temperature, ultimately leading to a change in processes occurring in rivers that are of decisive significance for their run-off, icing and thermal regimes [9–13]. Results of the modelling of the global river discharge and water temperature under climate change [14] show an increase in the seasonality of river discharge for about one-third of the global land surface area for 2071–2100 relative to 1971–2000. Global mean and high river water temperatures are projected to increase on average by 0.8–1.6 (1.0–2.2) °C for 2071–2100 relative to 1971–2000. The largest water temperature increases are projected for the United States, Europe, Eastern China, and parts of Southern Africa and Australia. Changes in RWT will directly impact the ecological conditions of habitats and the variability of fish populations in freshwater ecosystems [15–17]. However, the reaction of rivers differs depending on the hydrological properties and environmental conditions of catchment areas, which makes it difficult to generalize the strength and direction of their temperature trends in large spatial scales and for distinct river types [18,19].

Studies conducted in Europe confirm multidirectional trends of changes in air and RWT. The European Environment Agency report [20] underlines that the water temperature of the main European rivers (the Rhine, Meuse and Danube rivers) increased by 1–3 °C during the past century. Analysis of a number of other temporal series demonstrate a general increasing tendency in water temperature in European rivers and lakes ranging from 0.05 to 0.8 °C per decade, and in some cases exceeding 1 °C per decade [6,21,22]. Statistically significant tendencies of water temperature increase in the last three-four decades have been confirmed, among others for the Devon River in Great Britain [23], the Austrian rivers [24], the Danube River [25,26], selected rivers of Germany [18] and rivers with the alpine and lowland regime in Switzerland [27]. These studies have confirmed that in the years 1977–1990 considerable tendencies of water temperature increase were associated with changes in air temperature, and also with changes in land use, as proved by the results of research by Webb and Walling [22]. Michel et al. [27] point out that lowland rivers are becoming more vulnerable to increasing air temperature forcing, while the resilient alpine rivers will in the nearest future be progressively more susceptible to warming due to the expected reductions in snow and glacier-melt inputs.

In Poland, which is located in the transitional zone of the temperate climate, a distinct rise in air and inland water temperature in the Polish Lowlands has been confirmed [28]. During the years 1961–2010, the average annual water temperature of 14 rivers displayed a positive trend ranging from 0.17 to 0.27 °C·dec^{−1}, whereas such changes were not proved in rivers in the foothills of the Carpathian Mountains. In the majority of cases, research on the Polish rivers has shown statistically significant correlations between average annual water and air temperature ($r = 0.78$ to 0.89 , according to [28]). While analysing the thermal regime characteristics of the Warta River (Central Poland) at a few gauges in its middle reaches, Graf [29] has demonstrated that in the years 1991–2010 both the average annual water temperature of the river and air temperature had a tendency to increase. The rise in average annual water temperature of the Warta River in the period of 2001–2010 totalled 0.5–0.7 °C relative to 1991–2000. Graf et al. [30] studied tendencies of water temperature change in the Warta River in the winter half-year period (1991–2010) and concluded that over the past two decades the river's average water temperature rose by 0.4 °C, which was accompanied by an increase in average air temperature of 0.1 °C. Ptak [31] analysed changes in the water temperature of tributaries of the Warta River (Central Poland), and found that during the period of 1965–2014 it rose by 0.24 °C·dec^{−1} for the Ner River, and by 0.27 °C·dec^{−1} for the Prosna River [32]. Research conducted in the mountainous catchment of the Raba River (Polish Carpathians) showed diversified temperature change trends in the years 1960–2009 and revealed discrepancies in the direction of seasonal temperature change

in the upper and lower reaches of that river, and attributed them to the impact of human activity (water reservoir) [33].

Detection of statistically significant trends in the water temperature series is usually difficult due to their considerable year-to-year and decadal variability. Identification of changes has additionally been complicated by the variability and modification of river flows brought about by morphological changes of the river valley and its bed, groundwater consumption, and changes in land usage [1]. This study on features of the hydrological regime of rivers points out that climate change is exacerbated by human and economic activities, and also that climate change poses an additional threat to the flow and thermal regime of water ecosystems [20].

The objective of this study was to detect and quantify patterns of the RWT change in Poland. The analysis included average annual, seasonal and monthly RWT in the years 1971–2015. Research has been based on the identification of similarities in the spatial and temporal distribution of change trends of RWT through a grouping of water gauges, determination of regional patterns, and distinguishing factors that affect the transformation of features of the thermal regime, including the determination of rivers with water thermal characteristics altered by human activity. Identification of the spatial and temporal water temperature dynamics and its tendencies of change is necessary for the optimal management of river water resources in order to achieve environmental objectives and facilitate adaptation to climate change.

2. Materials and Methods

In the study, hydro-meteorological data obtained from the resources of the Institute of Meteorology and Water Management–National Research Institute (IMGW-PIB) in Warsaw, Poland, for the period of 1971–2015 were used. They included monthly and annual water temperature of 53 rivers in Poland from 94 water gauge stations (Table S1), and average monthly and annual air temperature from 43 meteorological stations (Figure 1).

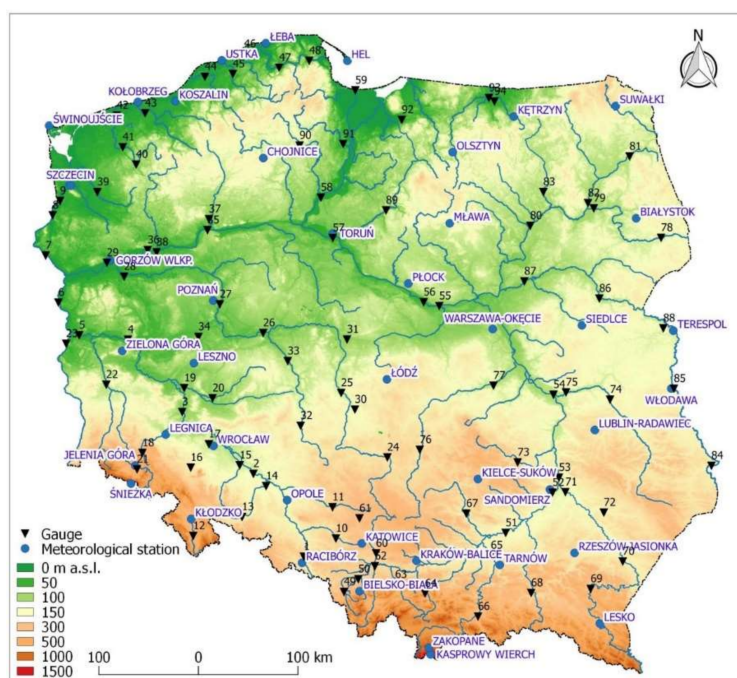


Figure 1. Location of water gauges and meteorological stations in Poland. Note: numbering of gauges in accordance with Table S1.

Measurements of water temperature in Poland are performed daily at 7 a.m. (GMT+1), simultaneously at all water gauge stations located in the rivers, using automatic station probes or,

if these were unavailable, mercury thermometers, with an accuracy of 0.1 °C. The water temperatures of inland waters differ considerably over a diurnal cycle. It is important that water temperature measurements are taken at the same time of day, as noted by Woolway et al. [34]. This is a prerequisite for comparing water temperature of different rivers and at different points. Lack of synchronization in terms of temperature measurements can bias any trend estimation.

The daily air temperature analysed in this study was the mean of a number of measurements taken during the 24 h period, by means of electrical sensors or mercury thermometers with an accuracy of 0.1 °C. Results of the measurements are given with the appropriate time step, depending on the specificity of individual parameters; measurements of current air temperature are performed every 10 min. Next, values of average monthly and annual water temperature and air temperature were calculated as the arithmetic means of the daily values.

Water and air temperature data are available on the <https://danepubliczne.imgw.pl> website and on the MONITOR IMGW-PIB platform as operational data. In this study the data have been presented with reference to the hydrological year, which in Poland lasts from 1 November until 31 October.

Poland is situated in Central Europe, which results in various air masses over its territory. Consequently, the climate of Poland is characterised by considerable variability of weather conditions and high fluctuations in the course of seasons in successive years. The following masses of air are most frequently encountered over the country: polar maritime air from the northern part of the Atlantic Ocean, polar continental air from over Eastern Europe and Asia, Arctic air from over the Arctic Sea, sub-tropical maritime air from around the Azores, and sub-tropical continental air from over Africa. The major part of the country's territory is located within the range of impact of the moderate transient climate zone, which has properties intermediate between the maritime climate and the continental climate, while an increase in continentalism is observed in the easterly direction. Only the southern part of Poland is under the influence of the mountain climate (the Carpathians and the Sudetes).

Such a diversity of climatic conditions has a direct impact on the development of a number of hydrological regimes of the Polish rivers, represented by the following types: the nival regime in the northern and central parts of the country, the nival-pluvial regime in the upland part, and the pluvial-nival regime in mountainous areas [35]. The majority of rivers are characterised by equilibrium between the groundwater and surface supply. The exceptions are post-lacustrine rivers with a considerable share of groundwater supply (>70%), and mountainous rivers with the groundwater supply share lower than 40% [36]. Transformations of the river run-off regime in Poland resulting from climate change and the variability of climatic conditions are temporally and spatially diversified [37,38].

In this study tendencies of water and air temperature change were determined for each water gauge and meteorological station for annual, monthly and seasonal (winter–December–February, spring–March–May, summer–June–August, autumn–September–November) series, and also for annual maximum series.

In order to detect and estimate trends in the time series, the Mann–Kendall (M–K) test was applied [39].

The M–K test is applicable in cases when the data values x_i of a time series can be assumed to obey the model:

$$x_i = f(t) + \varepsilon_i \quad (1)$$

where $f(t)$ is a continuous monotonic increasing or decreasing function of time and the residuals ε_i can be assumed to be from the same distribution with zero mean. Therefore, it is assumed that the variance of the distribution is constant in time.

The M–K test statistic S is calculated using the formula:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (2)$$

where x_j and x_k are the annual values in years j and k , $j > k$, respectively, and:

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (3)$$

An upward (increasing) or downward (decreasing) trend is determined by a positive or negative value of Z . First, the variance of S is computed by the following Equation (4), which takes into account that ties may be present:

$$\text{VAR}(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad (4)$$

where q is the number of tied groups and t_p is the number of data values in the p th group.

The values of S and $\text{VAR}(S)$ are used to compute the test statistic Z as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 \end{cases} \quad (5)$$

Then, the null hypothesis of no trend, H_0 , is tested in order to accept or reject it. The x_i observations are randomly ordered chronologically, contrary to the alternative hypothesis H_1 , where there is an increasing or decreasing monotonic trend. The test statistic Z (normal approximation) is computed, because all time series are longer than ten. The statistic Z has a normal distribution. The absolute value of Z can be compared to the standard normal cumulative distribution in order to identify if there is a monotone trend or not at the specified level of significance.

In the next stage of the research, trend patterns of average water temperature changes in annual and multi-annual periods were determined. For this purpose, the Ward hierarchical grouping method [40] was applied and the gauges were grouped based on:

- 12 monthly M–K test results,
- 16 correlation coefficients (R) of average annual water temperature in 30-year sub-periods of the multi-annual period of 1971–2015 with the one-year shift.

According to Ward, 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 center of the cluster to which it 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 as:

$$\text{E.S.S.} = \sum_{i=1}^n x_i^2 - \frac{1}{n} \left(\sum_{i=1}^n x_i \right)^2 \quad (6)$$

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

The grouping results were presented in the form of a dendrogram reflecting the structure of similarities between the analysed groups of gauges. The number of classes was determined based on the analysis of geometry of the dendrogram and the plot of the linkage distance curve. The aforementioned methods are commonly used in hydro-meteorological studies [41–45]. In the statistical analysis of the results obtained the Statistica (StatSoft) software was applied. The graphic design was prepared with the use of Surfer 10 (Golden Software) and CorelDraw 12 (Corel) software. In the development of the matrices of correlation coefficients, isocorrelates were drawn using the kriging procedure.

3. Results

3.1. Tendencies of River Water Temperature (RWT) Change

The analysis of tendencies of the RWT change in Poland was strengthened by the determination of air temperature trends. The results were presented graphically—Figure 2. First and foremost, temperature trends were positive during the whole research period. The weakest and, usually, statistically insignificant temperature trends are observed from December to March. The strongest increase in air temperature is noted throughout Poland in April. In consequence, the water temperature of the majority of rivers is characterised by the same trend. Whereas at the majority of meteorological stations air temperature in May does not show statistically significant positive trends, such a trend is observed for water temperature at 70% of water gauge stations, due to the memory of the hydrological system. The series of air and water temperatures in the summer months display strong positive tendencies, with a stronger tendency for air temperature. From September, the share of statistically significant air trends decreases visibly, while that of water temperature is maintained, and this occurs at approximately 70% of water gauges. Also, the majority of series of average annual air and water temperature demonstrate statistically significant positive trends.

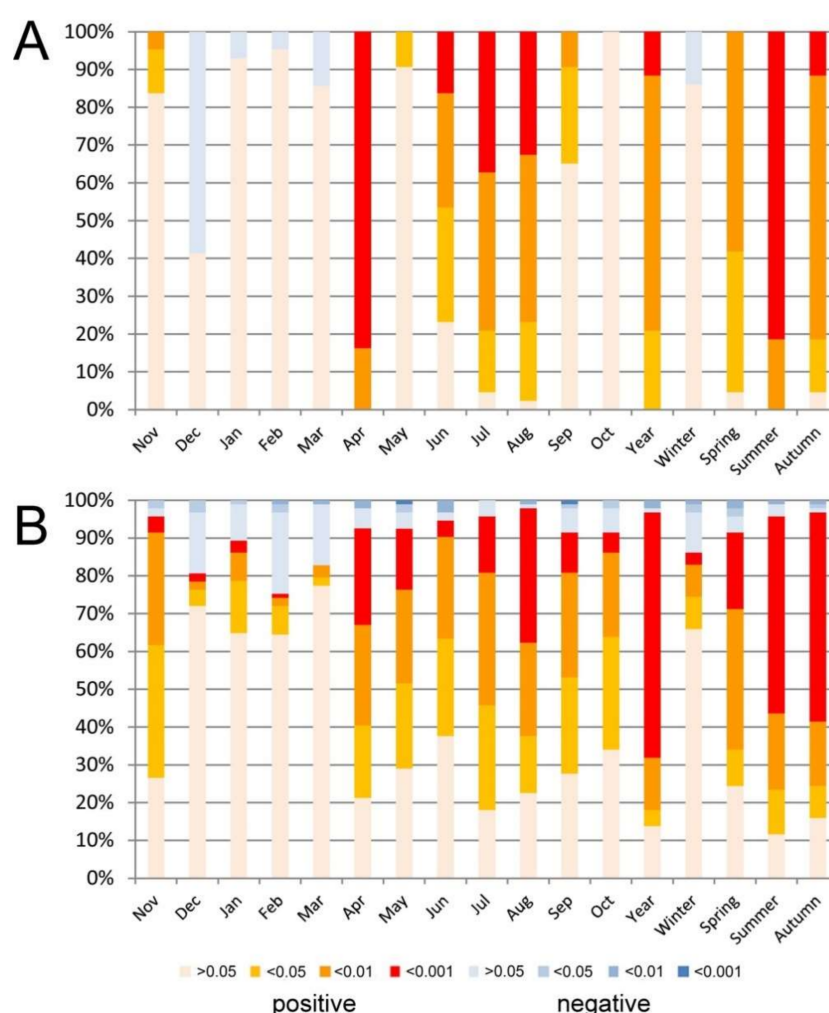


Figure 2. Percent share of trends with a defined statistical significance in analysed series of air (A) and river water (B) temperature in the years 1971–2015.

In the case of the Polish rivers, temperature and its tendencies of change are temporally and spatially diversified (Figure 3). The water temperature in the majority of the analysed rivers in the

months of the winter half-year period, with the exception of November and April, ranged from 0 °C to approximately 5 °C. In the turning-point months, water temperature had clearly higher values, while its characteristic spatial distribution became marked. In November, warmer waters could be found in the rivers of western Poland ($T > 5$ °C), while the water temperature of rivers in the eastern part of the country was distinctly lower ($T < 5$ °C). Meanwhile, towards the end of the winter half-year period, in April, the temperature of water in the Polish rivers stabilised at 7–8 °C, with the exception of the central and lower sections of the Odra (the Oder) and Warta rivers, where water temperature exceeded 8–9 °C. In the months of the winter half-year period (December–March), water temperature at the majority of gauges did not demonstrate statistically significant positive trends. An increased share of positive, statistically significant trends was observed in November at approximately 70% of gauges. The most statistically significant water temperature trend ($p < 0.001$) was detected first in the upper reaches of the Wisła River and in its tributaries, but also in the upper reaches of the Warta River, in the middle reaches of the Odra River, in the rivers of the Przymorze region, and in the Bug and Narew rivers. In the remaining months of the analysed half-year period, positive and statistically significant ($p < 0.05$) water temperature trends were identified only at 10%–20% of gauges.

In April, positive and statistically significant ($p < 0.01$) air temperature trends were recorded at all analysed gauges, which was reflected in a positive and statistically significant RWT trend at approximately 70% of gauges. During this month statistically insignificant water temperature trends were recorded mainly in the mountainous tributaries of the Wisła and Odra rivers (in the southern part of Poland), and at a few gauges along the Warta River.

In the months of the winter half-year period, the analysed water temperature series displayed decreasing trends only a few times (in November and April) and a dozen gauges (December–March). For the majority of these gauges located in the upper and middle reaches of the Odra and Wisła rivers (and partially along the lower reaches of the Wisła—in January), along the Warta River, and along the rivers of the Przymorze region (in the north of the country), the trends were statistically insignificant (Figure 3). The exceptions were the negative water temperature trends detected in February–April in the Kłodnica River (a tributary of the Odra River near Katowice) and in the Wisła River at Kraków and Sandomierz gauges, with the statistical significance determined at $p < 0.001$.

In the months of the summer half-year period (May–October), warmer waters ran first in the rivers of Central Poland, including the lower Odra, the middle and lower reaches of the Warta River, the middle and lower Wisła River, and the Bug and Narew rivers. High temperatures were also detected in the waters of the upper Odra. In July–August, river waters in this zone had temperatures higher than 20 °C, whereas in the other regions of Poland RWT did not exceed 16–18 °C (in the north and south of the country) (Figure 4). Towards the end of the hydrological year a cooling of river waters occurred. During this period, water temperature in Central Poland equalled 15–16 °C (September) and 10–11 °C (October), while in the other areas it was noticeably lower, and did not exceed 11 °C in September and 9 °C in October, respectively.

In July and August, air temperature at approximately 95% of meteorological stations displayed positive and statistically significant trends ($p < 0.01$). However, no statistically significant tendencies were observed for air temperature series in May and October. Meanwhile, a positive and statistically significant trend was detected for water temperature series from May to October at approximately 75% of stations. As opposed to air temperature, water temperature in the majority of rivers increased in each month of the hydrological half-year period. In May, the most statistically significant ($p < 0.001$) positive trend of water temperature became apparent first in the Odra River, partially in the Warta River, and also in a number of rivers in the Przymorze region: the Rega, Ślupia, Łeba and Łyna. In July–August, a positive and statistically significant ($p < 0.001$) water temperature trend was recorded in the upper reaches of the Odra River, along nearly the entire Wisła River mainstream and its selected tributaries (the San, Wieprz and Bug rivers), along the Warta River mainstream (middle reaches), and in the rivers of the Przymorze region. In September, the statistically most significant ($p < 0.001$) positive water temperature trend was observed in the rivers of the Przymorze region and at a few gauges on the

Warta River, while in October only along the Warta mainstream. In the summer months the analysed water temperature series displayed negative trends only at a few gauges (Figure 4).

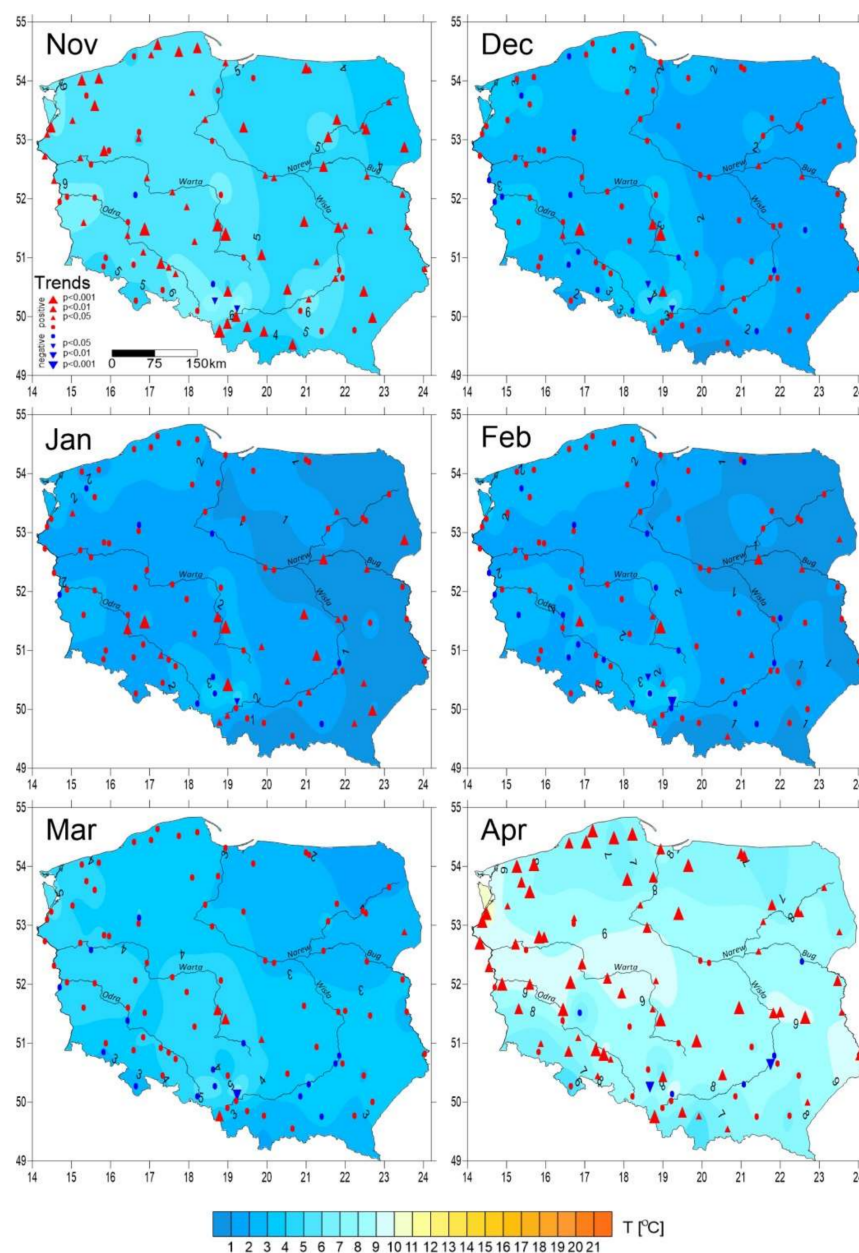


Figure 3. Spatial distribution and tendencies of change of average monthly river water temperature (RWT) in the winter half-year period.

Tendencies of changes of water temperature detected in the Polish rivers in individual months were reflected in changes in successive seasons of the hydrological year (Figure 5). In three seasons—spring, summer and autumn—these tendencies referred to the demonstrated air temperature trends at 70%–90% of stations, as presented in Figure 2. The most significant air and RWT trends were concluded in the summer season (June–August). During this period air temperature at all analysed meteorological stations in Poland demonstrated a positive and statistically significant trend, which at 80% of stations equalled $p < 0.001$. Regarding water gauges, the most statistically significant ($p < 0.001$) positive water temperature trend was observed in summer at 50% of gauges. At a few gauges located along the upper and middle reaches of the Wisła River and at a small number of its tributaries, and also at one

of the gauges in the middle reaches of the Odra and the Warta, a negative water temperature trend was concluded. Regarding the distribution of water temperature in rivers in Poland, exceptionally in the winter season (December–February) at 20% of water gauges a positive and statistically significant change tendency of water temperature was detected. However, it was not accompanied by any significant tendencies of change of air temperature (Figure 2). During that season, statistically significant positive water temperature trends were observed along the middle reaches of the Odra and Warta rivers, partially along the upper reaches of the Wisła River (at a few stations), and along the Bug and Narew rivers (North-Eastern Poland)—Figure 5.

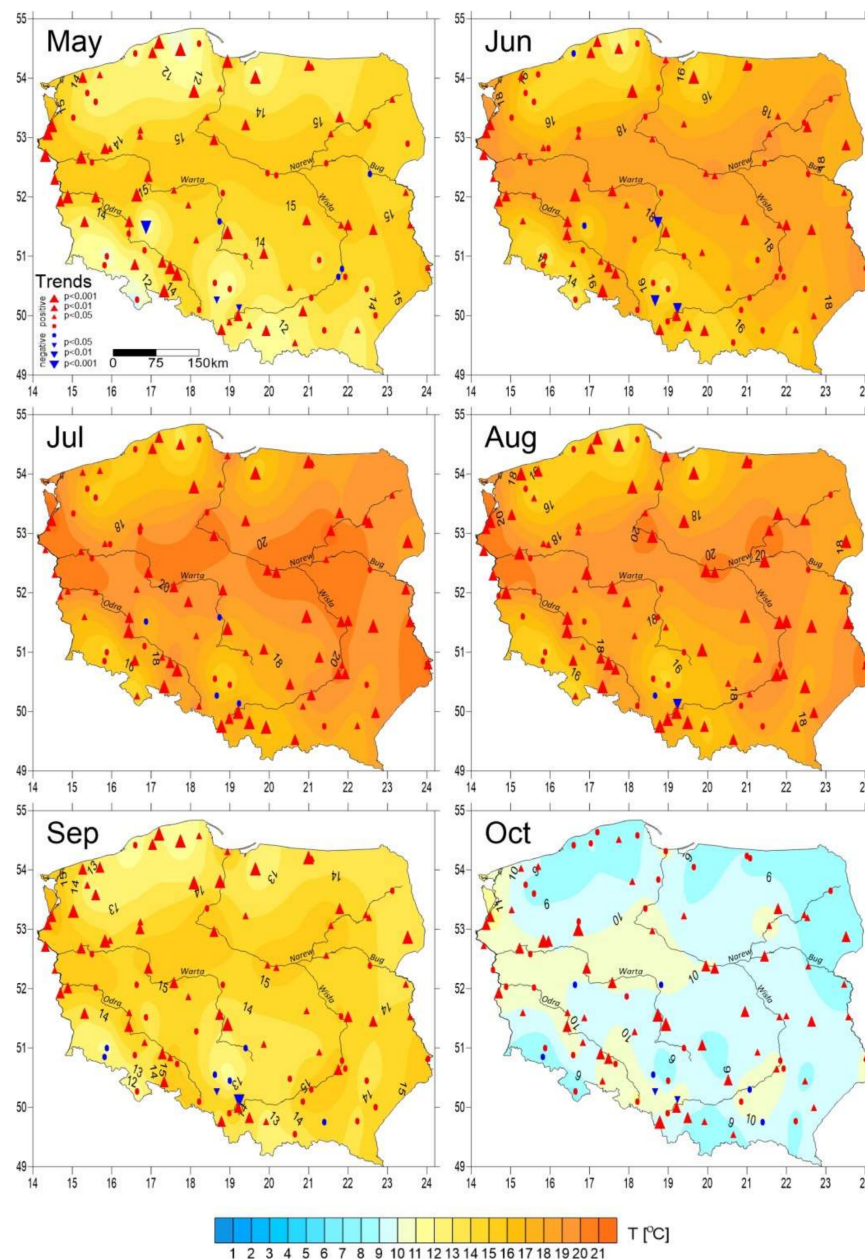


Figure 4. Spatial distribution and change tendencies of average monthly RWT in the summer half-year period.

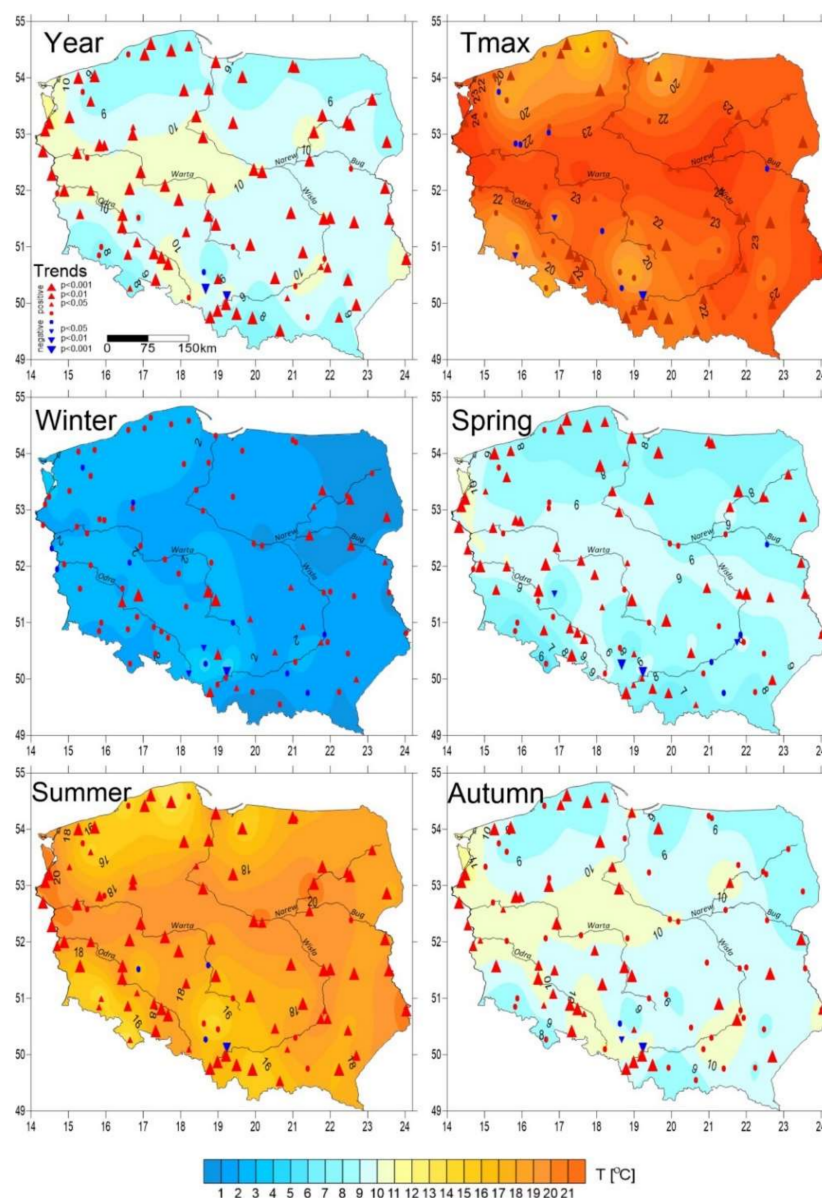


Figure 5. Spatial distribution and tendencies of change of average annual, maximum and seasonal RWT.

The distribution of change tendencies of maximum water temperature was similar to that observed in the summer season (Figure 5). In the analysed period, the highest average maximum temperatures exceeded 23 °C, and they were recorded mainly in the rivers of Central, North-Western and North-Eastern Poland. Only at a few gauges on the Wisła River, on tributaries of the Odra River, and on the Noteć River did the series of maximum water temperatures display a negative trend. At the remaining stations, primarily along the upper and middle reaches of the Wisła and Odra rivers, and on the rivers of the Przymorze region in the north the trend was positive and statistically significant

A positive and statistically significant trend ($p < 0.001$) was determined for series of average annual air temperature at all stations, while regarding average annual water temperature values, a positive and statistically significant trend ($p < 0.001$) was identified at approximately 85% of measurement stations. Only at three water gauges (on tributaries of the Wisła and Odra rivers) a negative water temperature trend was determined, and only at two stations was it statistically significant ($p < 0.001$)—Figure 5.

3.2. Spatial Patterns in Monthly Water Temperature Trends

The grouping of water gauges based on the M–K test results obtained for 12 monthly water temperature series allowed us to distinguish five groups of rivers, whose monthly temperature trends for the years 1971–2015 displayed distinct regularities (Figures 6 and 7).

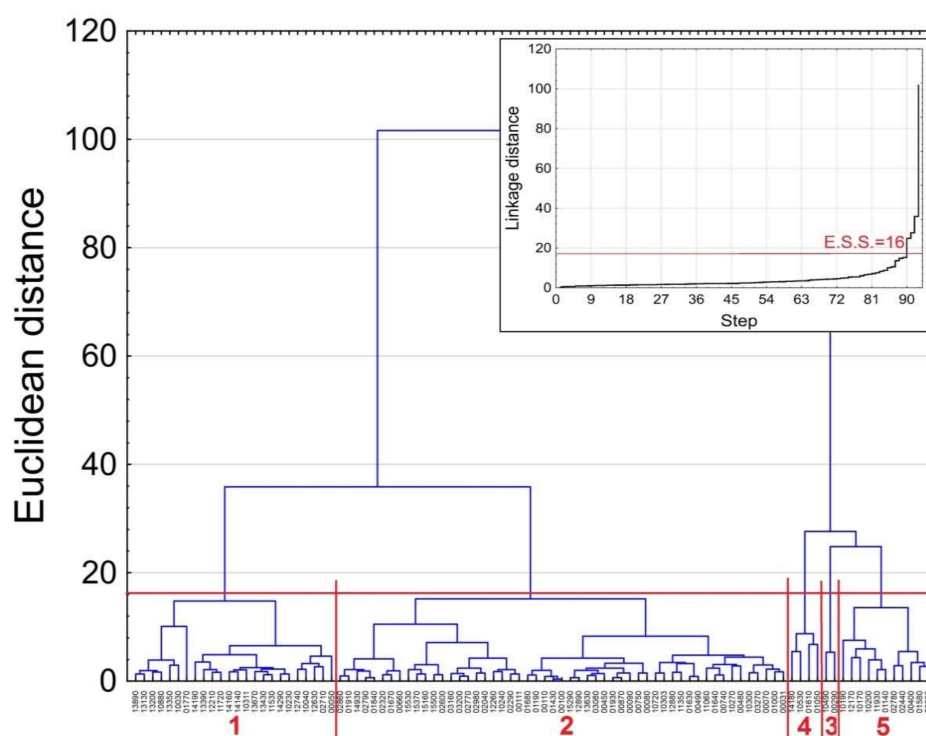


Figure 6. Dendrogram of gauges grouping based on 12 monthly values of the Mann–Kendall (M–K) Z test and the plot of the linkage distance. Note: gauge ID codes in accordance with Table S1.

The basic features of tendencies of change of monthly water temperature are demonstrated by rivers representing the 1st and 2nd groups. Rivers of group 1 include 24 profiles, located mainly on rivers in South-Eastern Poland. For majority of them, monthly temperature series display positive trends; from April to November, they are statistically significant ($p < 0.05$), while in the winter and spring months, from December to March, they are at the significance threshold. Similar tendencies have been determined for temperature series obtained from 53 water gauges of group 2, while from December to March positive temperature trends are statistically insignificant. These rivers are situated mainly in Northern and Western Poland. For the remaining groups, monthly river temperatures are characterised by a clearly different direction of change. Only two rivers—the Kłodnica and the Przemsza near Katowice—have been classified into group 3 (Figure 1). The monthly temperatures of these two rivers display downward trends, frequently statistically significant throughout the year. The tendencies of change of monthly temperature values of rivers of groups 4 and 5 are also different. In group 4, into which four rivers have been classified (the Brynica and Orla rivers, the Warta River at the Sieradz gauge and the Bug River at the Frankopol gauge, respectively), monthly water temperature displays an upward and statistically significant trend from October to February. In the remaining months, temperature trends are considerably weaker, while in May and June they are even negative, however, statistically insignificant. In the winter months from December to March, water temperature of the 11 rivers belonging to group 5 show weak negative trends. In the remaining months, temperature trends are upward, however, only in July they are statistically significant ($p < 0.05$).

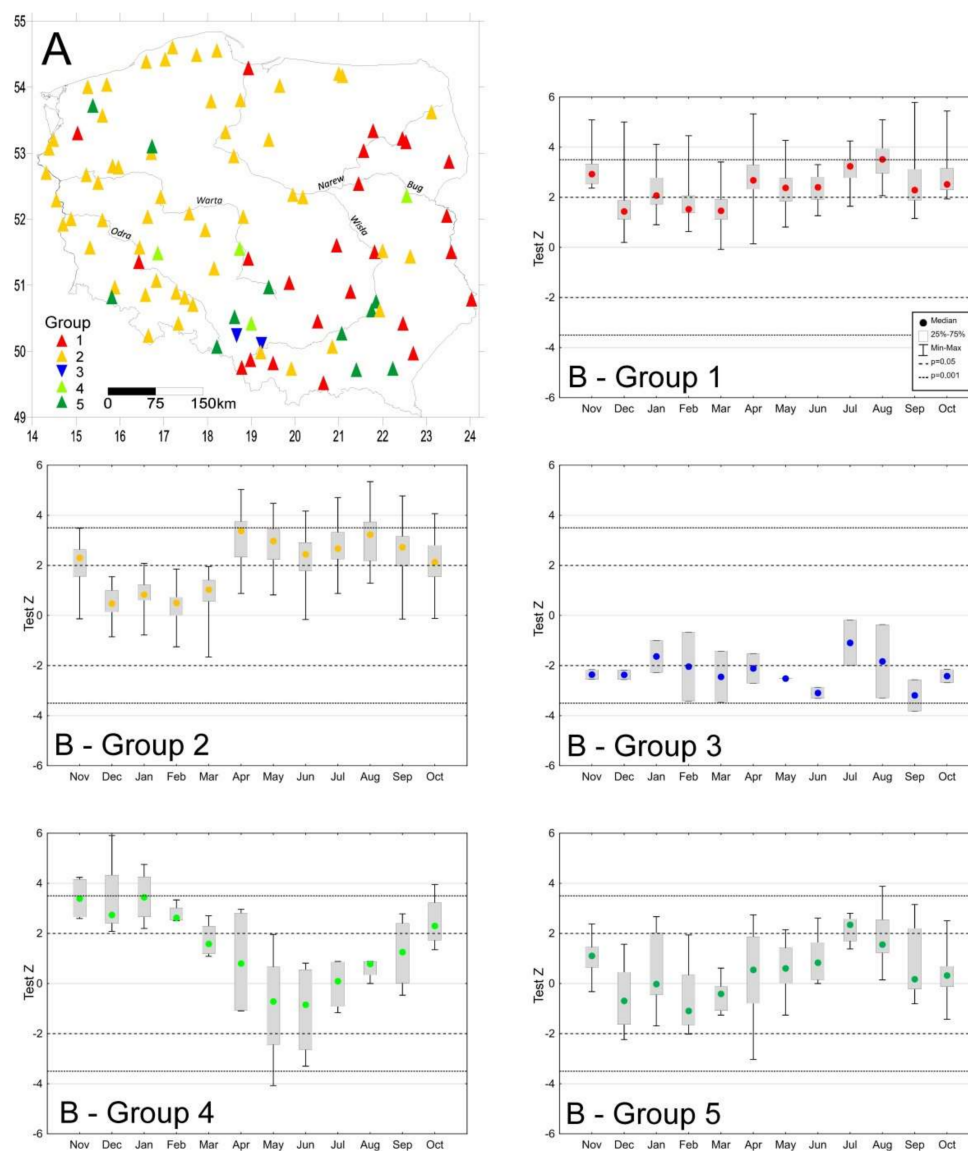


Figure 7. Result of the water gauges grouping based on values of the Mann–Kendall Z test for monthly temperatures in the years 1971–2015 (A), and the scope of change in the Z test in individual groups (B).

3.3. Tendencies of Change of Average Annual River Water Temperature

The grouping of water gauges based on 16 correlation coefficients of average annual water temperature in the 30-year sub-periods of the multi-annual period of 1971–2015 allowed us to distinguish five groups of rivers—Figure 8. For the analysed rivers, tendencies of change of average annual RWT are spatially diversified (Figure 9).

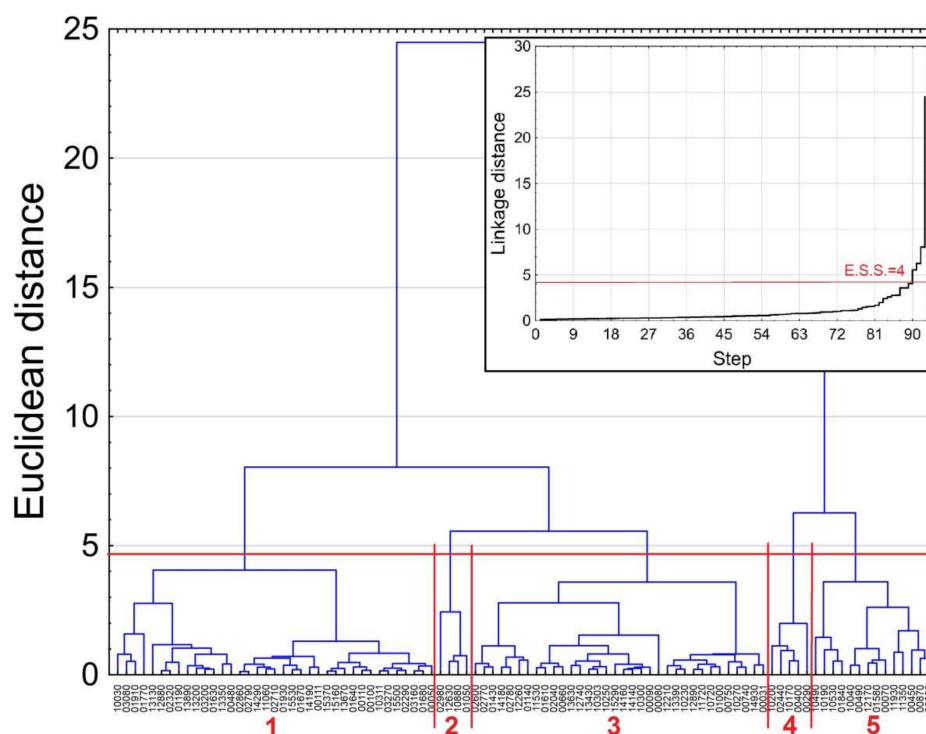


Figure 8. Dendrogram of gauges grouping based on 16 correlation coefficients of average annual water temperature values in successive 30-year periods and the plot of the linkage distance. Note: gauge ID codes in accordance with Table S1.

The separated groups include rivers, whose temperature changes demonstrate a distinct specificity, both in terms of the direction of tendencies observed and their statistical significance. Rivers classified into groups 1 and 3 are characterised by a thermal regime closest to the natural, and are represented by 37 and 34 water gauges, respectively. In all of the studied 30-year periods water temperature values observed for the majority display a positive trend. However, the temperature trends of rivers from group 1 are in general stronger and statistically significant ($p < 0.05$), with the exception of the first two 30-year periods. The strongest and statistically most significant ($p < 0.001$) increase in temperature is observed in the multi-annual period of 1976–2005. RWT values in profiles classified into the remaining groups are characterised by clearly different trends of change. Group 2 comprises only four rivers (the Wieprza, Orla, Skawa and Tanew), and their temperature change trends in the successive sub-periods are increasingly stronger and more significant. They change from negative trends in the years 1971–2000 to strongly positive and very statistically significant ones ($p < 0.001$) after the year 1984. Group 4, which consists of five water gauges at the Gwda, Mała Panew, Kłodnica and Wisła (in gauges Szczucin and Zawichost) rivers, is also small. The temperatures observed in these rivers in the analysed sub-periods usually display negative and statistically insignificant trends. Only four 30-year temperature series, starting from 1980, are characterised by negative statistically significant ($p < 0.05$) trends. A different direction of temperature change is demonstrated by rivers, whose 14 water gauges have been classified into group 5. At the beginning of the analysed multi-annual period, the 30-year temperature series of the majority of rivers from this group demonstrate positive and statistically significant trends ($p < 0.05$). After 1980, the direction of temperature change becomes different, with prevailing negative tendencies, however, usually statistically insignificant.

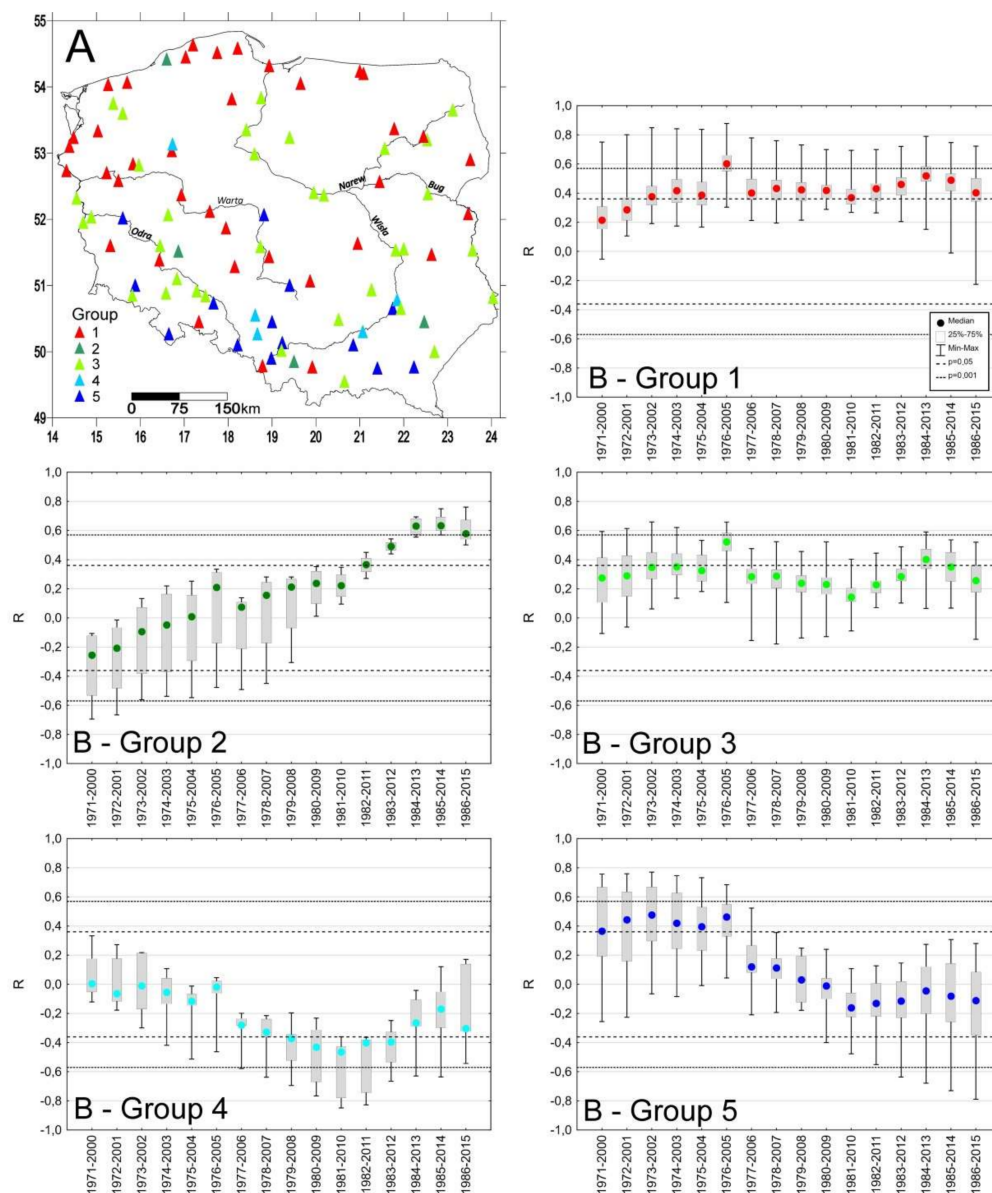


Figure 9. Result of the water gauges based on tendencies of average annual water temperature in successive 30-year periods (A) and the scope of change of correlation coefficients R in individual groups (B).

4. Discussion

Results obtained in this research are consistent with findings of numerous studies on changes in the features of the thermal regime of rivers [3,9,28,46–50]. On the basis of the measurement data sets collected for the Polish rivers, it can be concluded that during the period analysed a visible increase in water temperature took place. In some series of water temperature also negative tendencies or statistically insignificant tendencies in the water thermal conditions of the Polish rivers were revealed. It is often the case that analyses of temporal water temperature series display insignificant trend of annual values, with only an increase in spring and summer temperature maxima. The research on the features of the thermal regime of rivers in the United Kingdom [51] indicates that this may be related to the spring decrease in the share of snowmelt in river run-off supply.

According to Web and Nobilis [3,24], diverse tendencies of water temperature are observed in rivers impacted by human activity. The results obtained in the present study indicate that the tendencies of change of RWT observed in Poland can also result from the joint impact of natural factors

and human activity. Numerous studies conducted in Europe—similarly to those performed for rivers in Poland—failed to arrive at a uniform pattern of tendencies of RWT change. Marszelewski and Pius [28], who analysed the scope and course of changes in the thermal regime of 14 rivers in Poland (mainly rivers of the Central European Plain) in the years 1961–2010, have demonstrated a negative water temperature trend in the majority of rivers in relation to the mean value in the first part of the analysed period, i.e., the years 1961–1986. A positive trend of water temperature has been concluded starting from 1987, with the strongest positive trend detected in Western Poland, and the weakest in the eastern part of the country. Changes of that kind have not been observed in the southern part of the study area (i.e., the foothills of the Carpathians). This has also been confirmed partly by the results of this study. From the 1980s, a positive trend of water temperature has been observed in the majority of gauges (rivers of groups 1–4). A different nature of water temperature change has been determined only for some mountainous rivers located in the eastern part of the Carpathian Plateau and the Carpathians proper (group 5)—Figure 9. In the beginning of the period analysed (1971–2015) these rivers displayed positive and statistically significant average annual water temperature trends, while starting from 1980 they trends proved to be negative.

Woolway et al. [52] investigated long-term increase in annual average surface water temperatures of 20 Central European lakes (situated in Austria, Switzerland and Poland, respectively) with data spanning between 50 and ~100 years. They revealed significant warming during the past few decades and substantial increase in annual average water temperatures during the late 1980s, in response to an abrupt shift in climate, associated with so-called climate regime shifts (CRS), often distinguished by abrupt temporal changes in temperature. The late 1980s regime shift is a well-documented example of CRS. The conclusion that rise of water temperature has accelerated over the past 30 years (1971–2015) in Poland has been confirmed in this research. The CRS impact has been also well documented and exemplified by the rise in regional and global lake and river temperatures [7,34,53–55].

Frequently, water temperature trends are disclosed in partial data series, for example, after a given year or in a given decade, as in the case of the Serbian section of the Danube River [26]. Research conducted on this topic allowed it to be determined that the trend commenced in the 1980s and was associated with climatic patterns over the Northern and Eastern Atlantic. According to Arora et al. [18], the impact of the North Atlantic Oscillation (NAO) index is particularly visible in the variability of the winter temperature of rivers, and to lesser extent in its general variability. Also regarding the Polish rivers, in recent papers [49] the authors have demonstrated a significant impact of NAO on RWT in the winter season. However, during the analysed multi-annual period of 1971–2015 this did not contribute to significant temperature trends in the winter period.

The considerable increases and decreases of RWT very often refer to situations where greater differences are observed between the seasonal distribution and the magnitude of recorded temperature maxima and minima. This may be the result of the conclusions that in recent years there have been increases of river run-off in the winter season, accompanied by the reduction of the magnitude of run-off in the summer months (Figure 5). Arora et al. [18] analysed long-term river temperature tendencies in selected drainage basins in Germany, and pointed on changes in air temperature, average flow and basic flow, and the North Atlantic Oscillation index as the main causative factors of changes in water temperature. According to the IPCC report [1], river flows in Europe have increased in winter and decreased in summer starting from the 1960s, however, with considerable regional and seasonal differences. Wrzesiński and Sobkowiak [37] analysed changes in the flow regime of rivers in Poland in the period 1951–2010 and concluded that the stability of the regime was varied both spatially and temporarily, and rivers impacted by human activity were characterised by the greatest change in flow conditions.

Research on rivers in the Northern Hemisphere proved that changes in the thermal characteristics of river waters were recorded in individual seasons, usually in winter or in summer, and the observed exceptions may result from weather anomalies or the impact of human activity [3,49,50,56–61]. Regarding the Polish rivers, positive tendencies of water temperature have been identified in winter

data series only at a small number of gauges. The present analysis indicates that the general regularities of change tendencies of monthly water temperature are characteristic for rivers from groups 1 and 2 (Figure 7). During the analysed multi-annual period, monthly temperatures rose, and statistically significant positive trends of water temperature were recorded from April to November. In the winter months, positive trends were considerably weaker. These regularities of temperature change have been determined for the majority (82%) of the analysed rivers. Similarity to tendencies of change of air temperature allows the climatic factor to be recognized as of key importance for changes in water thermal characteristics in the majority of rivers in Poland. In the remaining cases different directions of change in RWT are probably the result of various forms of human impact on the water circulation. Similar conclusions have been formulated in research conducted for the area of Poland by, among others [28,29,48–50]. As previous studies have shown, the detected increase in human activity in the Warta River valley may lead to the disruption of features of the river's thermal regime [30,62–64].

Research conducted by the authors of this paper has resulted in the identification of water gauges, among others on the Warta River, where water temperature has shown a tendency of change reverse to that observed in other parts of the country (Figures 3 and 4). In the majority of cases they are located along river sections exposed to human activity, such as the storage reservoirs, the mining and municipal waste disposals, and changes in the method of land usage. Human impact on the thermal regime of rivers in Poland has already been confirmed in previous studies [61,65], conducted among others in the upper Odra and Wisła basins [28,66], where discharges of mine waters and spent cooling water into rivers—which modify their hydrological and thermal regime—have been indicated as the main cause of the tendencies detected.

5. Conclusions

The analysis carried out in order to detect water temperature patterns in rivers in Poland revealed diversified positive and negative trends in the temperature series for the period 1971–2015. A positive and statistically significant trend for average annual water temperature was observed at approximately 85% of measurement stations. No statistically significant tendencies of change of RWT were proved in Poland during the winter half-year months (November–April). The most significant RWT trends were confirmed in the summer season (June–August).

Detection of patterns (regularities) of spatial changes in water temperature in the annual and multi-annual periods was an important methodical result of this study, obtained with the help of cluster analysis. The distinguished groups of rivers may indicate different factors (natural factors and human activity) determining changes in water temperature both in the hydrological year (monthly changes) and in the multi-annual period.

Rivers with water thermal conditions changed by human activity were identified following the analysis of a group of rivers, whose temperatures displayed a clearly distinct type of change, both in terms of the direction of tendencies observed, and their statistical significance. As regards the remaining groups of rivers, the division obtained is more uniform regionally, which would indicate that these are mainly rivers with a basically quasi-natural thermal regime. Spatial diversification is the result of the variability of river supply conditions and the environmental features of the catchment area. The regularities observed may also point to the importance of changes in the intensity of macroscale types of air circulation, which have an impact on water circulation conditions not only in Europe, but also in Poland. However, determining the nature of transformations of the thermal regime brought about by changes and the variability of the climate requires further analyses based on materials referencing only objects with quasi-natural conditions of the hydrological and thermal regime. The results of the present analysis broaden knowledge on features of the thermal regime, specifically in terms of seasonal and multi-annual patterns of their change. Furthermore, they may be used to enrich databases concerning the state of quality of water ecosystems, for which water temperature is a significant indicator of change. It is forecasted that the observed climate change will

enhance the impact of this parameter on the temperature of inland waters. This, in fact, will contribute to further increase of the importance of research on multi-annual tendencies of the RWT change.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/12/5/1327/s1>, Table S1: Basic data on the studied rivers.

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