MAXIMUM RIVER RUNOFF IN POLAND UNDER CLIMATE WARMING CONDITIONS

Wiktoria Brzezińska, Dariusz Wrzesiński

Department of Hydrology and Water Management, Adam Mickiewicz University in Poznań, Poland

Manuscript received: September 16, 2024
Revised version: January 11, 2025

Brzezińska W., Wrzesiński D., 2025. Maximum river runoff in Poland under climate warming conditions. *Quaestiones Geographicae* 44(1), Bogucki Wydawnictwo Naukowe, Poznań, pp. 85–105. 11 figs.

Abstract: The aim of the study was to investigate the trends of changes in maximum daily river discharge in Poland from 1951 to 2020 under climate warming conditions. The study covered two sub-periods: 1951–1988 and 1988–2020, with 1988 considered the conventional year for the change in thermal conditions. Daily maximum discharge was calculated using data from 148 water gauge stations located on 97 rivers, and the Mann-Kendall test was used to analyse trends. The results showed the prevailing falling trends (more than 85%) on the rivers of central and eastern Poland, 40% of which were of statistical significance (p<0.05). The lowest discharge increased on more than 58% of the profiles, 27% of which were of statistical significance (p<0.05). The most common falling trends in maximum discharge were observed in spring (87% of the profiles) and summer (77%), with statistically significant changes accounting for 37% and 22%, respectively. Increases were recorded mainly in autumn on rivers in southern Poland and in winter – in the north-eastern part of the country. In the period after 1988, maximum discharge decreased in most seasons, especially in summer, where in August discharge decreased by as much as more than 50% in central Poland, with significant changes affecting 30% of profiles. The effect of climate warming on extreme discharge was clearly spatially differentiated, especially in spring and summer in central and eastern Poland.

Keywords: river runoff, peak discharge, climate change, change trends

Corresponding author: Wiktoria Brzezińska; wiktoria.brzezinska@amu.edu.pl

Introduction

Ongoing and projected climate change, as outlined by the Intergovernmental Panel on Climate Change (IPCC), and recent studies have shown a complex picture of increasingly frequent extreme weather conditions, rising sea levels and significant transformations in hydrological processes. Understanding these changes requires considering details of the Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathway (SSP) scenarios of the atmospheric concentrations of greenhouse gases as prepared by Pörtner et al. (2022).

Both the RCP and SSP scenarios suggest and predict that climate change will intensify extreme weather events, including heat waves, droughts, heavy rainfall and tropical cyclones. The frequency, intensity and duration of these events are expected to rise, leading to significant impacts on ecosystems, human health and the economy (Masson-Delmotte et al. 2018, Pörtner et al. 2022, Lee, Romero 2023). Hydrological changes are a key aspect of these climate change impacts. Rising temperatures and changing

https://doi.org/10.14746/quageo-2025-0006
ISSN 2082-2103, eISSN 2081-6383

precipitation patterns are likely to change the amount of water resources available and their distribution over time and space (Fortuniak et al. 2001, Kożuchowski, Żmudzka 2001, 2002, Kożuchowski 2004a). Hydrological models show that future climate change, such as rising air temperatures and torrential rains (including in winter), may lead to a higher frequency and intensity of extreme hydrological events, such as floods and droughts (Huang et al. 2020, Chiang et al. 2021). Floods generate huge economic losses on a scale, which increases with climate change. According to predictions, with a warming of 3°C, average annual flood-related losses in Europe could increase by 145% compared to the baseline period (1976–2005). Even under the most optimistic scenario, with warming limited to 1.5°C, flood-related losses are expected to increase significantly (Alfieri et al. 2018).

In the period 1965–2014, anthropogenic climate change has been shown to reduce the seasonality of river discharge in areas >50°N of the northern hemisphere (Wang et al. 2024). An analysis of the seasonal discharge of the European rivers showed an increase in winter–spring runoff and a decrease in summer–autumn discharge. These changes are most likely the result of earlier melting of the snow cover and reduced snow accumulation due to rising air temperatures (Rottler et al. 2020). Similar changes have been observed in the catchments of Arctic rivers in the European part of Russia, where an increase in winter runoff

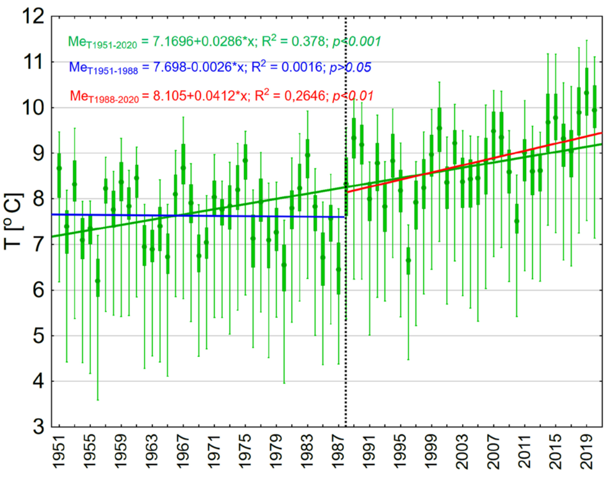

Fig. 1. The range and trend of changes in air temperatures from 1951 to 2020 and in the period before (1951–1988) and during the warming (1988–2020) according to Wrzesiński and Brzezińska (2023), modified.

has been reported, while the runoff in summer–autumn is predicted to decrease for all the rivers studied (the Northern Dvina, Pechora, Don and Kuban) (Kalugin 2023). Studies confirm that climate change is leading to a higher frequency and intensity of extreme hydrological events. Central Europe, in particular, has seen an increase in the frequency as well as the magnitude of maximum annual discharges which is associated with a higher risk of flooding (Lehmkuhl et al. 2022).

Climatic studies in Poland have shown that air temperatures have been rising as early as the late 1980s (Fortuniak et al. 2001, Kożuchowski, Żmudzka 2001, 2002, Kożuchowski 2004a, Marsz, Styszyńska 2022); however, no significant changes of the amount of precipitation in the annual cycle have been observed along with the changes in air temperatures (Żmudzka 2002, Kożuchowski 2004b). Both solar and circulatory factors, which are associated with the intensification of the zonal western atmospheric circulation and the development of the southern component of the circulation over Poland, are identified as factors that contribute to climate warming. The end of the 1980s is often pointed to as the symbolic beginning of these changes (Marsz et al. 2022, Marsz, Styszyńska 2022). Before 1988, air temperature trends were negative and statistically insignificant; however, after 1988, a clear and statistically significant upward trend was observed (Fig. 1). Data after 1988 showed an increase in the air temperature and minor changes in the amount and distribution of precipitation, which is reflected in the changes of river runoff, its structure and the duration of low discharge (Brzezińska et al. 2023, Wrzesiński, Brzezińska 2024) (Fig. 1).

The purpose of this study is to determine the trend of changes in the maximum daily discharge (annual, seasonal and monthly) of rivers in Poland from 1951 to 2020, as well as the magnitude and statistical significance of these changes under the conditions of climate warming. The study covered the years of the period 1951–2020, dividing it into two sub-periods 1951–1988 and 1988–2020. The year 1988 was considered the conventional date of the change in thermal conditions. As suggested by Marsz et al. (2022), 1988 was arbitrarily considered to be the point in time separating the two sub-periods, taking it as the last year of the first sub-period and the first year of the second sub-period.

Source materials and study area

The study uses hydrological data obtained from the collection of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB 2023). The study used daily discharge flows from 1951 to 2020 for 148 water-gauge stations located on 97 rivers in Poland (Fig. 2, Appendix 1).

Poland's river network is predominantly shaped by two major rivers: Vistula and Odra. These rivers, along with their tributaries, form a complex hydrological system that significantly influences the country's water resources, agriculture, industry and ecosystems.

Approximately 55% of the total volume of water discharged from Poland's rivers comes from the Vistula River basin, while the Oder River basin contributes about 25%. The rivers in the Pomeranian region and the Vistula Lagoon account for 9.5% and 5.9% of the country's annual runoff, respectively (Gutry-Korycka et al. 2014). Analysing the period from 1951 to 2000, the average specific runoff in the Vistula basin was found to be 5.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$, which is higher than that of 4.83 $dm^3 \cdot s^{-1} \cdot km^{-2}$ recorded in the Oder basin. The overall average specific runoff for Poland surpassed both basins, reaching 5.64 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Fal, Bogdanowicz 2002).

The Poland's river systems exhibit a diverse range of hydrological regimes due to varying

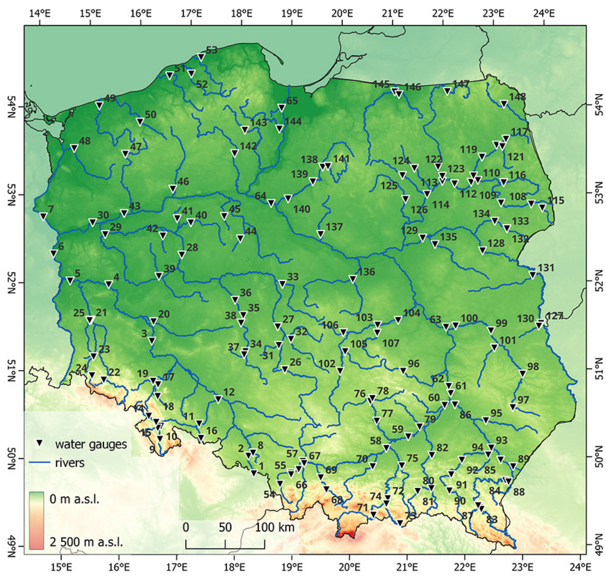

Fig. 2. The location of water gauge stations on rivers studied in Poland (based on data from IMGW-PIB; numbering in accordance with Appendix 1).

climatic conditions and geographical features across the country. These regimes are classified into five main types, namely, nival poorly developed, nival medium developed, nival clearly developed, nival-pluvial and pluvial-nival, based on the sources of water supply and the seasonal distribution of river runoff, particularly focusing on the patterns and values of the monthly discharge coefficient, which is the ratio of the mean monthly discharge to the mean annual discharge (Dynowska 1994). Details of these types of regimes can be found in Dynowska, Pociask-Karteczka (1999) and Wrzesiński (2017, 2021) (Appendix 1).

Methods

Based on the daily discharge, maximum discharge values were determined for the year, the four seasons and each of the months for the entire period of the study, as well as for the sub-periods 1951–1988 and 1988–2020.

Multiyear trends

A nonparametric Mann–Kendall test, which is used to detect a trend in a time series, was applied to assess multiyear trends in monthly, seasonal and annual discharge. The test was conducted using Microsoft Excel software with the MAKESENS overlay, which is an extended version of the Mann–Kendall test developed by researchers at the Finnish Meteorological Institute (Salmi et al. 2002).

The Mann–Kendall test is used when the given values of x_i in a time series can be described according to the following equation:

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

where is a continuous, decreasing or increasing function of time, and the residuals can be treated as coming from the same distribution with mean = 0. With this, the deviation from the distribution can be considered invariant over time. The S statistic of the Mann–Kendall test was calculated based on the following formula:

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

where x_j and x_k are sets of values of monthly, seasonal or annual water levels arranged as a time series at the corresponding time instants *j* and *k*, with *j* > *k:*

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

Declining or rising trends are determined by a negative or positive *Z* value. To calculate it, the *VAR*(*S*) should be calculated first using the following formula:

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

where *q* is the number of water level values, and t_p is the number of values in the *p*-th group. Based on the values of *S* and *VAR*(*S*), *Z* can be calculated using the following formula:

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

This procedure allows verification of the null hypothesis H_0 assuming the absence of trends. Chronologically ordered xi observations are analysed, and the alternative H1 hypothesis is the existence of a monotonically rising or falling trend. The *Z* test has a normal distribution, allowing the absolute value of *Z* to be compared with a normal distribution to assess whether there is a monotonic trend. If a trend is found, its statistical significance is determined. The study used four levels of statistical significance: $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$. For $p > 0.05$, there is no statistical significance of the changes in discharge that were observed.

Change in runoff and its statistical significance

A rate of change was calculated to determine changes in average maximum river-specific runoff (MHq) during the warming period of 1988–2020 relative to the period of 1951–1988:

$$S_{\overline{X}_{1988-2020}} - {\overline{X}_{1951-1988}} = \frac{\overline{X}_{1988-2020} - \overline{X}_{1951-1988}}{\overline{X}_{1951-1988}} \times 100 \quad (6)$$

where are average runoff values in the sub-periods of the multi-annual period 1951–2020. The rate that was calculated shows the percentage increase or decrease in runoff in the period after the climate change (1988–2020) compared to MHq in the period before the climate change (1951–1988).

Differences in monthly, seasonal and annual MHq were calculated between the years 1988–2020 and 1951–1988. The statistical significance of these differences was tested using the *T*-test for independent samples. Each time, the hypothesis $H_0 : \mu_1 = \mu_2$ of equality of expected values was tested against the hypothesis $H_1 : \mu_1 \neq \mu_2$. Rejection of the hypothesis indicates that there are significant differences in MHq observed after and before the climate change. The *T*-statistics has the Student's distribution, with $n_1 + n_2$ and 2 degrees of freedom:

$$T = \frac{\overline{X}_1 - \overline{X}_2}{S_{\overline{X}_1 - \overline{X}_2}} \quad (7)$$

where $S_{\overline{X}_1 - \overline{X}_2}$ is

$$S_{\overline{X}_1 - \overline{X}_2} = \sqrt{\frac{(n_1 - 1) \times S_1^2 + (n_2 - 1) \times S_2^2}{n_1 + n_2 - 2}\left(\frac{1}{n_1} + \frac{1}{n_2}\right)} \quad (8)$$

where n_1, n_2 are the sample sizes, are the variances of both samples and are the averages of both samples.

Cluster analysis

In a study of the spatial regularity of changes in average maximum runoff during the warming period after 1988, water-gauge stations were clustered using the Ward's method by the values of 12-month MHq differences. The clustering results are presented in the form of a dendrogram that reflects the similarity structure of the set of water gauges studied and was used to identify separate typological classes. In this paper, the number of classes was determined by analysing the geometry of the dendrogram and the bond distance curve.

Surfer 13 (Golden Software) and additional tools from QGIS Development Team (QGIS.org) were used for graphical processing of the results, which enabled advanced visualisation of geographical and hydrological data. On the contrary, mathematical and statistical compilations of the data were done using Excel (Microsoft) and Statistica (TIBCO Software Inc.).

Results and discussion

Trends in changes of the maximum flow

The maximum daily discharge in 1951–2020 of the rivers that were studied showed a dominance of falling trends over almost the entire territory of Poland, apart from Mountain Rivers. A decrease in maximum discharge was found at >85% of the water-gauge stations, and the decrease at 45% was considered statistically significant ($p < 0.05$) (Fig. 4). Particularly, significant downward trends ($p < 0.01$) were observed in the rivers of various regions of Poland, especially in the northeastern part of the country in the Narew river basin, as well as in upland rivers (e.g. Lubaczówka, Czarna and Kamienna) and single rivers located in the Polish Lowlands (the central Warta and Bzura) and in Wda, which is in a lake district. Only the maximum discharge of most of the rivers of the mountainous areas showed rising trends, but they were usually statistically insignificant. A statistically significant positive trend ($p < 0.01$) was found only for the discharge

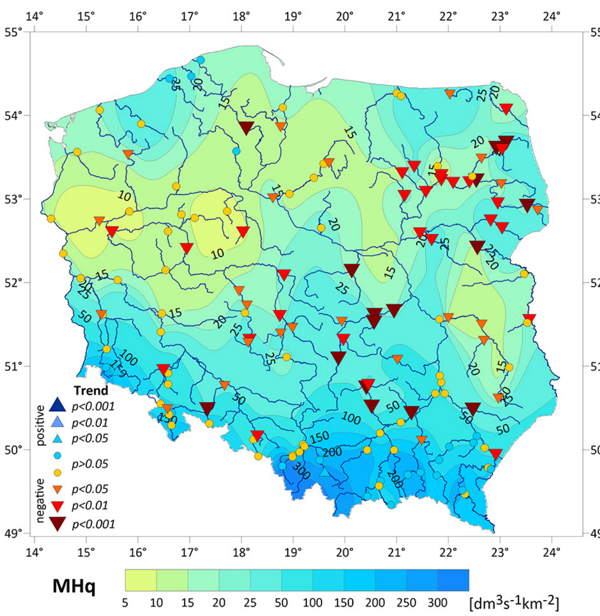

Fig. 3. Trends in changes of maximum daily discharge in a hydrological year against average maximum specific runoff from 1951 to 2020.

of the Skawa River in Sucha Beskidzka and the Kamienica River in Barcinek.

The spatial distribution of the MHq values of the rivers that were studied varies in a very characteristic way (Fig. 3). The highest values, exceeding 100 $dm^3 \cdot s^{-1} \cdot km^{-2}$, were observed in the drainage areas of the mountainous tributaries of Vistula and Oder, with maximum values reaching >300 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (in the upper Vistula drainage area up to Skoczów). High average runoff values (>200 $dm^3 \cdot s^{-1} \cdot km^{-2}$) were also found in the river basins of Soła, Skawa, Raba, the upper Dunajec up to Krościenko, Biała, Wisłoka and Ropa as well as Osława in the upper San River catchment. Towards the north, MHq values decrease, reaching 30–100 $dm^3 \cdot s^{-1} \cdot km^{-2}$ for upland river basins. Most rivers of the Polish Lowlands typically have runoff values of 10–20 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The lowest MHq values of <10 $dm^3 \cdot s^{-1} \cdot km^{-2}$ are recorded for the drainage areas of the Noteć and Wełna rivers and the Warta River basin up to Gorzów Wielkopolski. Higher runoff values (20–40 $dm^3 \cdot s^{-1} \cdot km^{-2}$) were found in the catchment areas of the coastal rivers (Rega, Parsęta, Wieprza, Słupia and Łupawa) and in the northeast catchment areas of the Guber, Gołdapa, upper Biebrza, Narew and Nurzec rivers.

Maximum daily river discharge in the winter season (December–February) showed a downward trend at >54% of the gauge stations analysed, mainly in central Poland, with only 10% of them being statistically significant ($p < 0.05$) (Fig. 4). Falling discharge values were recorded in various regions of the country, with statistically significant results ($p < 0.05$) in lake district rivers such as Drawa and Wda, as well as in Mała Noteć, Pilica, Raba, in the upper Oder drainage basin and in the catchments of Sumina, Nysa Kłodzka and Strzegomka. By contrast, a rise in the maximum winter discharge was observed in most mountain rivers and in northern and northeastern Poland, where a statistically significant increase ($p < 0.05$) was observed in the rivers in Narew, in the Biebrza basin and in single mountain rivers, such as Kwisa and Nysa Kłodzka. In spring (March–May), the majority of the rivers studied (more than 87% of the gauge stations) showed falling discharge trends, of which more than 37% were statistically significant ($p < 0.05$), mainly in northeastern Poland, in the Narew River basin, in the central part of the country and in the Pilica River basin. Increases in discharge were observed only in a small number of rivers in southern Poland (>12% of the gauge stations), with statistically significant results ($p < 0.05$) observed only in the Skawa River. Negative discharge trends dominated during the summer, which was observed at more than 77% of the gauge stations analysed, of which more than 22% reached statistical significance ($p < 0.05$). There were particularly significant decreases in daily maximum summer discharge, with significance at $p < 0.001$, recorded on rivers such as Wda, Mała Noteć and Sumina. Most of the Vistula's tributaries showed statistically insignificant trends, except for the drainage area of the Pilica, where statistically significant values were observed ($p < 0.05$). The autumn analysis showed that positive trends covering more than 45% of the water-gauge stations occurred mainly in the south and east of the country, while decreases in discharge, prevalent in central and western Poland (more than 54% of the gauges), were statistically significant in only 9% of cases. It is also worth noting that only the tributaries of Vistula in the Carpathian region showed statistically significant upward trends ($p < 0.05$).

The hydrological analysis for 1951–2020 shows significant regional variation in the average maximum winter-specific runoff in Poland. The highest values, exceeding 50 dm³ · s⁻¹ · km⁻², were found in mountainous catchments in the southern regions of the country, with MHq of 100 dm³ · s⁻¹ · km⁻² in the upper Vistula, Nysa Kłodzka and Osława in the drainage area of the San River (Fig. 5). The drainage areas of upland rivers had MHq ranging 25–50 dm³ · s⁻¹ · km⁻², and in the Koszalin Coastland and Masurian Lake District they did not exceed >30 dm³ · s⁻¹ · km⁻². The lowest runoff, below 10 dm³ · s⁻¹ · km⁻², occurred mainly in western and eastern Poland, especially in the Polish Lowlands, Polesie Lubelskie and Lublin Upland. In spring, MHq was at the highest level, and it was most important for the formation of water resources, with maximum values of >100 dm³ · s⁻¹ · km⁻² in the catchments of the Nysa Kłodzka River in the mountains and of the Carpathian rivers, and even 169 dm³ · s⁻¹ · km⁻² in the drainage area of the upper Vistula. The lowest values, below 10 dm³ · s⁻¹ · km⁻², were recorded in western Poland, especially in the catchments of Noteć and the middle and lower Warta, while in eastern and northeastern Poland spring runoff exceeded 25 dm³ · s⁻¹ · km⁻². In summer, a significantly lower runoff was observed in the north of the country, where it did not exceed 10 dm³ · s⁻¹ · km⁻², while in the south it reached >200 dm³ · s⁻¹ · km⁻² in some places. The lowest values, <5 dm³ · s⁻¹ · km⁻², occurred in the drainage areas of Warta, Noteć and the eastern regions, such as the Krzna River and part of Narew, while values exceeding 150 dm³ · s⁻¹ · km⁻² were recorded in the upper Vistula and its Carpathian tributaries. In autumn, the distribution of runoff was similar to summer, with the highest values, >50 dm³ · s⁻¹ · km⁻², in the south of the country, and locally even >100 dm³ · s⁻¹ · km⁻². In central Poland, runoff did not exceed 10 dm³ · s⁻¹ · km⁻², and in the drainage basins of Warta, Noteć,

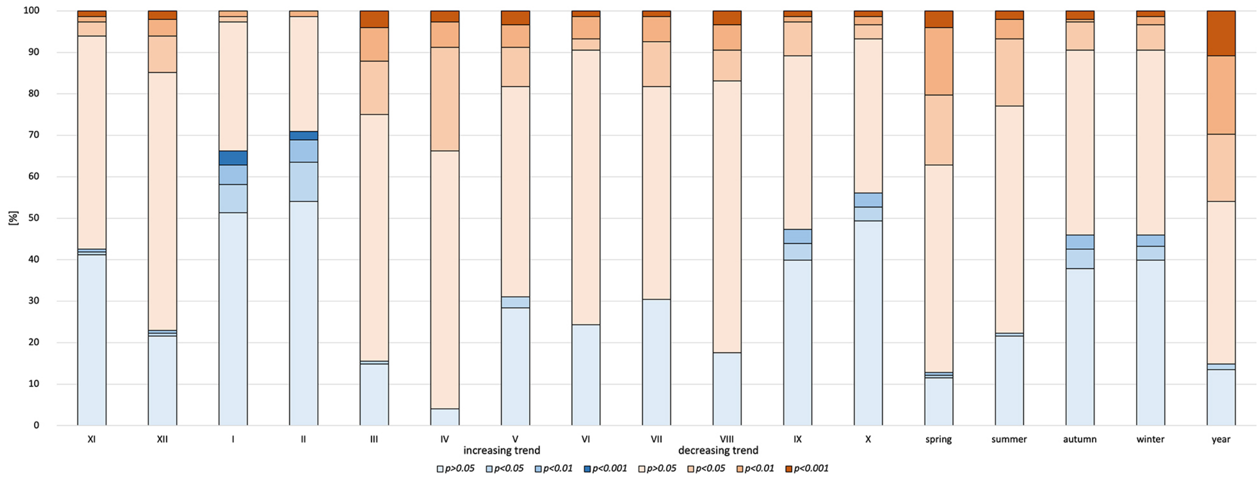

Fig. 4. Trends in changes of maximum daily seasonal discharge against the average maximum specific runoff in four seasons in 1951–2020.

Krzna and Wieprz the values decreased below 5 dm³ · s⁻¹ · km⁻². Besides the mountain regions, larger runoff values, exceeding 15 dm³ · s⁻¹ · km⁻², were found in Pomerania.

An analysis of monthly daily maximum discharge showed prevailing downward trends in most months (Fig. 4). Particularly significant declines were observed at more than 80% of the water-gauge stations in March and April. In March, downward trends prevailed from the south to the centre of Poland, with 25% of the water-gauge stations surveyed showing statistical significance of downward trends at $p < 0.05$. The largest falls were observed in April, mainly in the eastern and central parts of the country, where more than 95% of the gauge stations showed a decreasing trend and 33% were statistically significant ($p < 0.05$). By contrast, in January and February positive trends prevailed in 66% and 70% of the cases studied, 33% and 29% were considered statistically significant, respectively. These trends were particularly prominent in northeastern Poland in the Biebrza and Narew drainage basins, where statistical significance was recorded at $p < 0.05$. In the spring and summer months, declining trends prevailed in central and southern Poland.

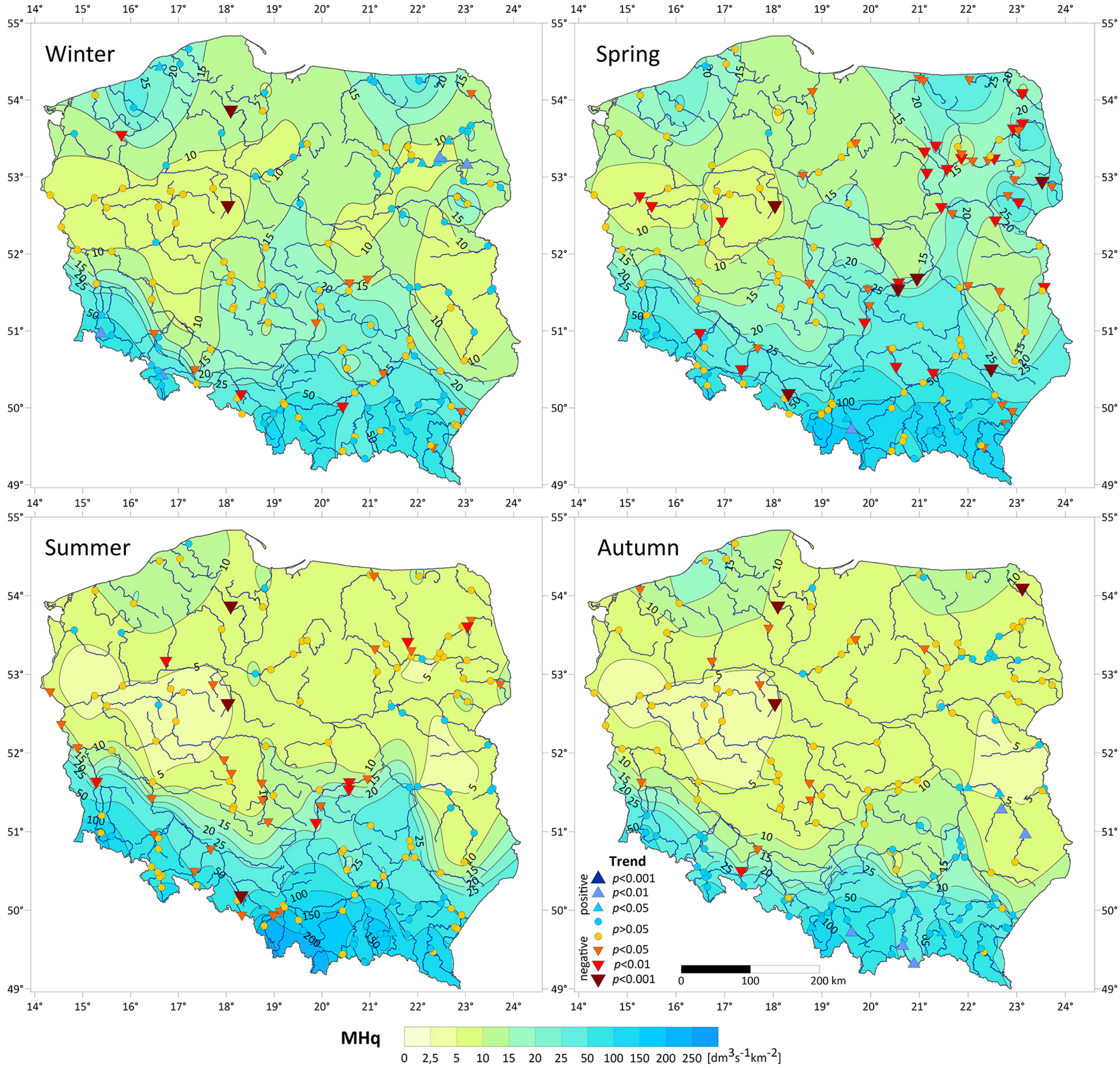

Fig. 5. Percent share of trends with a defined statistical significance (p) in analysed series of monthly, seasonal and annual maximum discharge from 1951 to 2020.

However, in May, downward trends were also recorded in Pomerania and Masuria. Starting from September, there is a clear increase in maximum discharge in mountainous regions.

Changes in maximum flow during the warming period

During the warming period of 1988–2020, the average maximum specific runoff decreased in most of the rivers studied compared to the period 1951–1988 (Fig. 6). The data show a reduction in MHq, which is particularly prominent in the northeastern and central parts of the country, where runoff has fallen by more than 30% and, in some places, by more than 40% (the Pilica, Narew and Bug catchments). In contrast to most regions, an increase in MHq was recorded in mountainous areas and the Koszalin Coastland by more than 10% and 5%, respectively. The most significant increase, exceeding 50%, was found in the Skawa River basin.

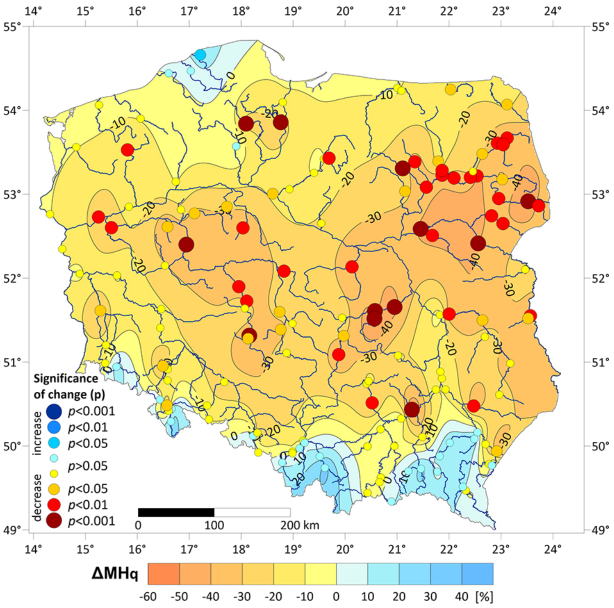

Fig. 6. Changes in average maximum runoff values [%] during the 1988–2020 warming period relative to the 1951–1988 period and their statistical significance (p).

MHq was found to have fallen for most rivers (at more than 83% of the water-gauge stations) (Fig. 7), and statistically significant ($p < 0.05$) changes occurred at more than 41% of the stations. There was a particularly high concentration of changes in MHq falls in the northeast of the country. MHq increased mainly in the Łupawa River basin, where the change was considered statistically significant ($p < 0.05$).

Seasonal changes in winter MHq during the warming period showed a decline at 78% of the water-gauge stations surveyed, with 23% of these changes being statistically significant ($p < 0.05$) (Fig. 7). The largest declines, by more than 30–40%, were recorded in central and southern Poland, especially in the drainage areas of the Mała Panew, Kłodnica, Prosna, Pilica, Czarna and Wisłoka rivers (Fig. 8), where statistical significance was recorded at $p < 0.01$. An increase in MHq was registered in the northern river basins, but only a small portion of them was statistically significant. In spring, MHq decreased at >73% of the gauge stations, of which 30% were statistically significant. The largest declines, by

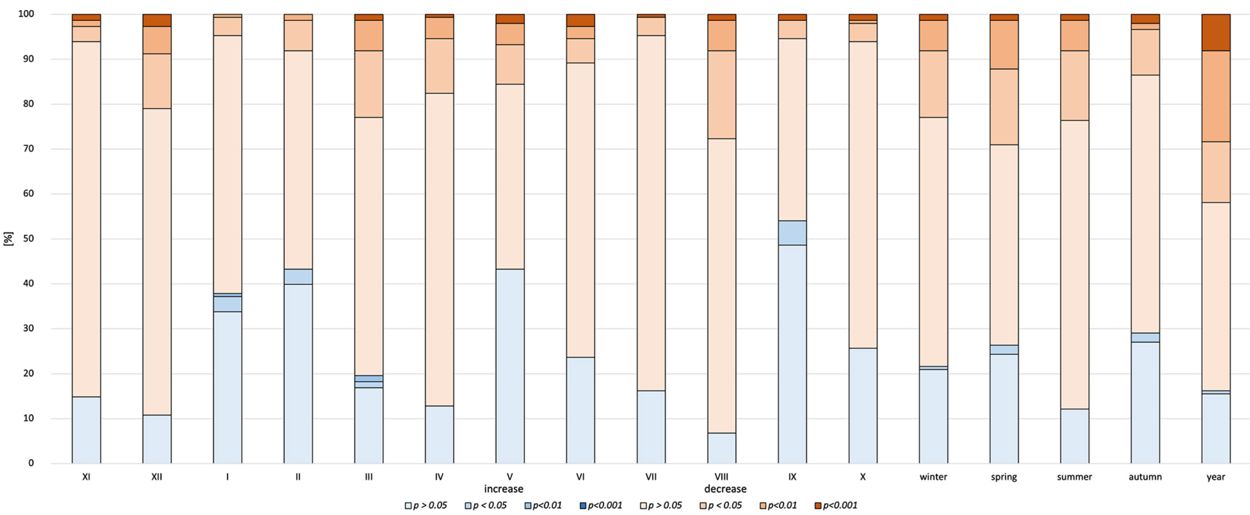

Fig. 7. Changes in seasonal average maximum runoff values [%] during the warming period of 1988–2020 relative to the 1951–1988 period and their statistical significance (p).

more than 30%, were found in the drainage areas of Warta, Wełna, Wrześnica, Narew and Bug, where declines locally exceeded 40% (Fig. 7). By contrast, increases in MHq by more than 50% were observed in the upper reaches of Vistula, particularly in the Skawa catchment, where they reached 90%. In the summer season, declines in MHq prevailed at 87% of the gauge stations, 26% of which were statistically significant (p < 0.05). The largest declines by more than 40–50% were registered in the Vistula (Narew, Biebrza, Pilica) and Noteć river basins. In autumn, 70% of the water gauges showed decreases in MHq, with 13% of the changes being statistically significant. The largest declines by more than 30% occurred in the Warta, Noteć, Narew and Biebrza river basins. In the south of the country, an increase in MHq exceeding 100% was found in the upper reaches of Vistula and its tributaries (Soła and Skawa), and there were statistically significant changes at three stations: Vistula – Skoczów, Skawa – Sucha Beskidzka and Mleczka – Gorliczyna.

Changes in monthly MHq values after 1988 mostly showed decreases in most rivers throughout the country (Fig. 7). By contrast, a significant increase in MHq was observed in January, February, May and September. In January and February, MHq increased mainly in the northern

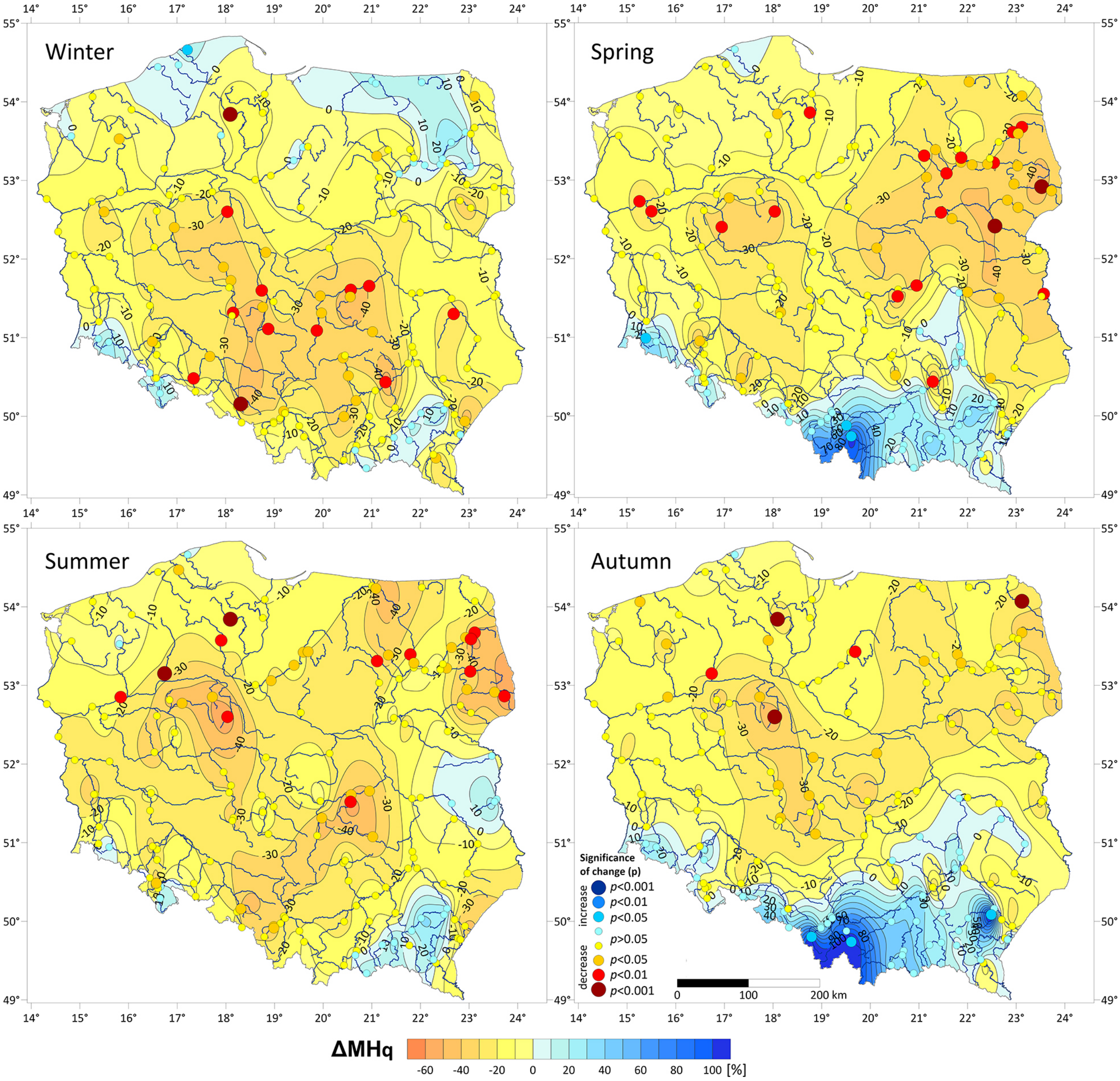

Fig. 8. Percent share of positive and negative differences in average monthly, seasonal and annual maximum discharge during the warming period of 1988–2020 relative to 1951–1988 and their statistical significance (p).

and northeastern parts of the country, where increases in MHq ranged from 20% to as much as 40%. The largest increase of >40% was observed in the Biebrza River basin and was statistically significant ($p < 0.05$). In February, an increase in runoff also appeared in southern Poland, mainly in the mountains >20% and locally >30% (Dunajec, Kwisa, Czarny Potok and Kamienica). At the same time, in January and February, there were significant decreases in MHq, mainly in the upper reaches of the Vistula and Oder rivers and their tributaries. March was characterised by significant decreases in MHq >20%, mainly in the rivers in the centre and the east of the country. The largest decreases occurred in the drainage area of Bug (MHq >30%) along with its tributaries (Liwiec, Krzna, Nurzec, Narew, Supraśl and Biebrza), and equally high decreases (>30%) in MHq occurred in the drainage area of the Warta. In both cases, the changes were statistically significant ($p < 0.05$). By contrast, rivers in the southeast stood out in terms of their increase in MHq >40% and locally >50% (Kwisa, Bóbr and Kamienica), which was statistically significant ($p < 0.05$). In May and September, rivers in the southern and southeastern parts of the country stood out in terms of a significant increase in their MHq. In May, runoff increased mainly in the upper and middle reaches of Vistula and its tributaries. The largest increases (>50%) were observed in Skawa, Raba, Soła and Vistula, but the increase was statistically insignificant. On the contrary, in the drainage areas of Oder and Warta, there were significant decreases in MHq >20%, with the largest MHq >40% in the following rivers: Bóbr, Strzegomka, Bystrzyca, Nysa Kłodzka, Flinta, Mogilnica, Sama, Mała Noteć and Gąsawka, and for most of these rivers the decreases were statistically significant ($p < 0.05$). In September, the increase in MHq was much greater than in May. In the upper reaches of Vistula, the largest increase of more than 100% was observed in the following rivers: Raba, Skawa, Dunajec, Wisłoka, Wisłok, Mleczka and Biała. An increase in MHq >50% also occurred in the coastal rivers, which was statistically insignificant. The rivers in central Poland mainly experienced decreases in MHq. The largest decrease in MHq occurred in August. The centre, south and northeast of Poland saw the highest decreases of more than 60%, even more than 80% in some places, including the following rivers: Kamienna, Czarna, Mała Noteć, Kłodnica, Mała Panew, Narew, Narewka, Supraśl and Biebrza, where statistically significant decreases occurred in most of these rivers. Other months showed significant decreases in MHq.

Clustering according to changes in extreme discharge

Based on the clustering (grouping) by changes in the monthly MHq after 1988, eight groups were distinguished (Fig. 9). The range of changes in the parameters of the analytical characteristics in the groups of rivers that were so identified is shown in Figure 11, while the spatial picture of the results of grouping rivers by differences in the parameters of MHq is shown in Figure 10.

Group 1 includes rivers and their sections in the upper part of the Warta River basin along with its tributaries (Ner, Prosna and Widawka) and the tributaries of the Vistula River (Pilica, Czarna, Nida and San) (Fig. 10). Changes in the monthly MHq mainly decreased in most of the groups that were identified (Fig. 11). During the winter and spring months, decreases in runoff were mainly observed. The summer and autumn months, on the contrary, showed a great variation but not as strong decreases as in other months. The largest decrease occurred in August (>40%), while a slight increase (>2%) was observed in May.

Group 2 represents mainly the tributaries of the following large rivers: Vistula, Oder, Warta, Narew and Bug (Fig. 10). The largest number of water gauges within this group is located on the tributaries of the lower section of Warta and on the left-bank tributaries of Oder, but overall this group shows weak spatial relationships. The characteristics of changes in the monthly MHq showed similarities to Group 1, with the difference that each month showed a decrease in MHq between 20% and 50% (Fig. 11).

Group 3 comprised the rivers of northeastern Poland, including Narew, Biebrza and their tributaries (Fig. 10). This group stood out showing an increase in MHq in January and February (>20%), but a decrease in other months (Fig. 11).

Group 4 comprises water gauges on the rivers of the Baltic coast and the left tributaries of Oder (mainly the drainage areas of Nysa Kłodzka, Bystrzyca and Bóbr) (Fig. 10). Very high monthly variability was observed on these rivers. An

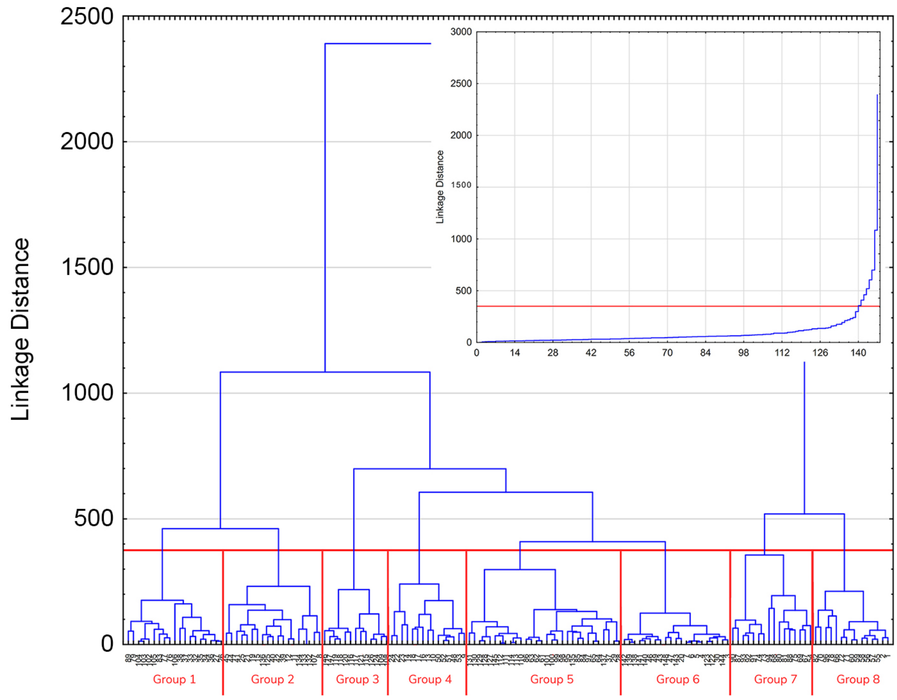

Fig. 9. Dendrogram of gauges grouping based on 12 monthly values of the changes in the average maximum specific runoff and the plot of the linkage distance. Note: gauge ID codes in accordance with Appendix 1.

increase in MHq (>2–25%) was observed from January to March (Fig. 11). Then, during the summer–autumn period, an increase in runoff (>5%) was observed only in September. Decreases in MHq were observed in the remaining months.

Group 5 represents mainly the rivers located in the east of Poland (Fig. 10). It also includes some isolated water gauges in Warta and on the tributaries of the lower Vistula. The main characteristic of this group is a decrease in MHq, averaging more than 20% (Fig. 11). The median trend at 5% was positive only for September.

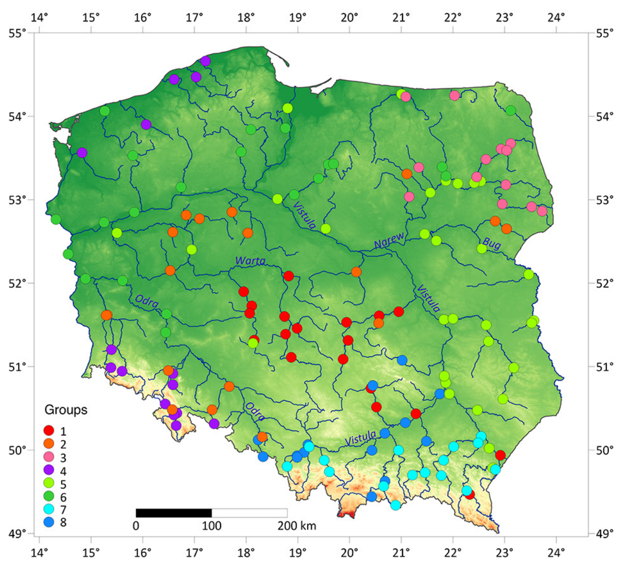

Fig. 10. Locations of water gauges grouped based on changes in the monthly average maximum specific runoff during the warming period of 1988–2020.

Group 6 includes mainly rivers in northern Poland (Fig. 10), with a few gauge stations in the middle reaches of Oder. Of all the months, none showed an increase in MHq, with decreases of about 10% in each month (Fig. 11).

Group 7 comprises Mountain Rivers in southeastern Poland, mainly the Carpathian tributaries of Vistula (Fig. 10). Changes in the monthly MHq showed a great variation. An increase in the average maximum runoff was observed in various months of the year apart from the summer season (Fig. 11). The largest increase of nearly 100% occurred in September, while the largest decrease in MHq occurred in August (>25%).

Similarly to Group 7, **Group 8** includes mountain rivers; however, compared to the previous group, its spatial scope is larger and focuses on the upper reaches of Vistula along with its tributaries (including the Soła) (Fig. 10). Changes in the MHq river runoff of this group resemble those of Group 7. However, decreases in MHq were found in most months, whereas the largest increases of 25% and >50% in runoff were found only in May and September, respectively (Fig. 11).

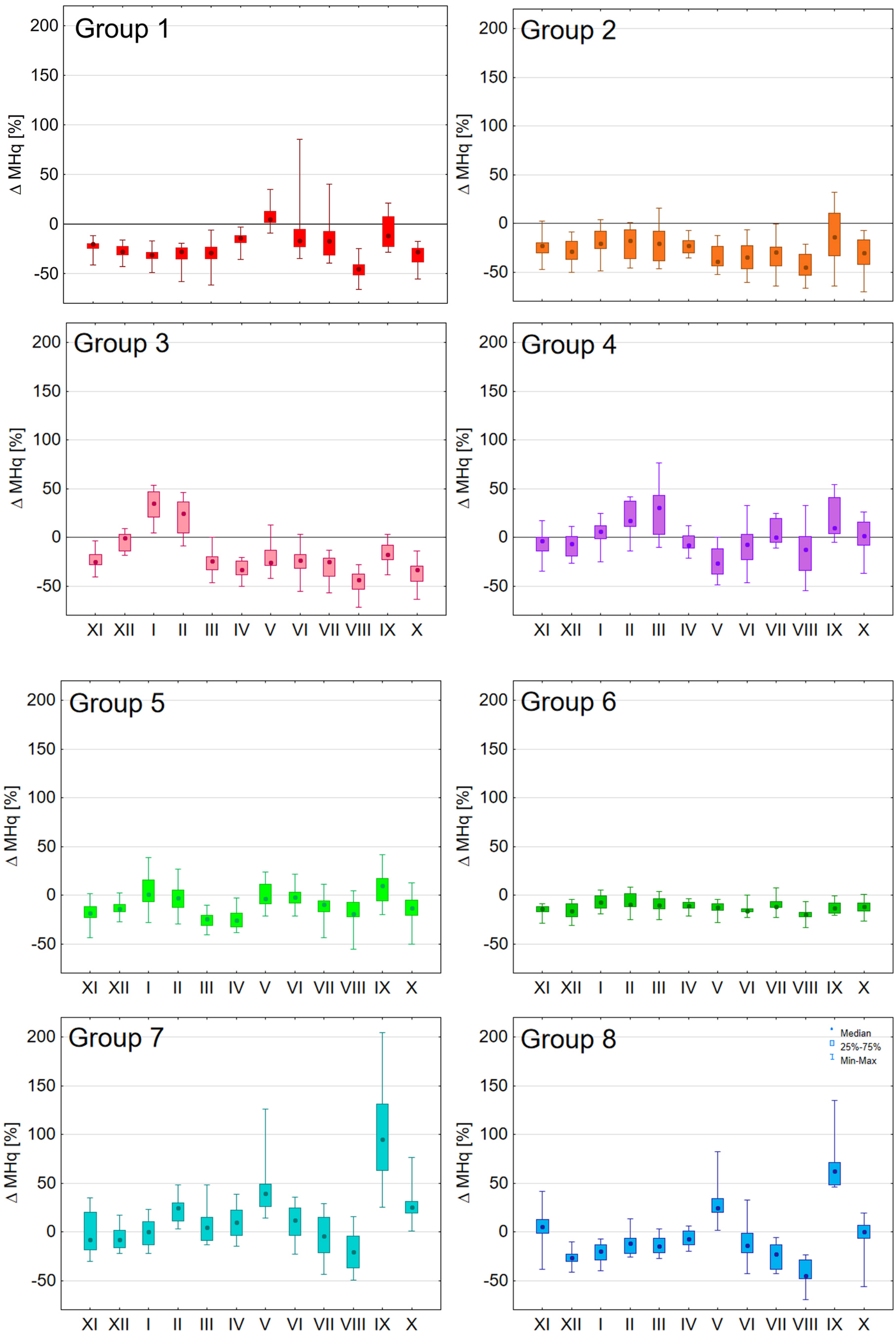

Fig. 11. The scope of changes in average maximum specific runoff (MHq) in the warming period after the 1988 in individual groups, as derived from the grouping presented in Figure 9.

Discussion

The results of the analysis of MHq in Poland for the period 1951–2020 revealed a predominance of declining trends, consistent with earlier studies on long-term changes in river runoff in Poland. As early as the study covering the years 1901–1965, Stachý (1968, 1969) reported negative trends in the runoff of rivers such as Vistula and Oder, and these patterns persisted in subsequent decades. During 1971–1980, runoff increased by 20% compared to the period 1951–1970 (Stachý 1970, 1984a, b), although this proved to be a short-term deviation in the context of the overall dominance of declining trends in later years.

Further analyses of runoff variability, including atmospheric circulation, indicate significant spatial differentiation in these trends. The Vistula's runoff exhibits a stronger response to short-term climate fluctuations than that of Oder (Jokiel, Kożuchowski 1989, Jokiel, Bartnik 2001, Fal, Bogdanowicz 2002, Wrzesiński 2009, Michalczyk 2017, Piniewski et al. 2018, Wrzesiński, Sobkowiak 2018), which is also reflected in the findings of this study, where a declining trend is particularly evident in the rivers of the Vistula basin. The results also highlight the considerable influence of the North Atlantic Oscillation (NAO) on runoff regimes (Limanówka et al. 2002, Pociask-Karteczka et al. 2002–2003, Styszyńska, Tamulewicz 2004, Wrzesiński 2011, Wrzesiński, Paluszkiewicz 2011, Wrzesiński, Sobkowiak 2018), which underscores regional differences in the response of rivers to changing climatic conditions and seasonal variability patterns in Poland. Additionally, regional differences in the timing of extreme hydrological events are evident. Venegas-Cordero et al. (2022) identified significant shifts in the timing of river floods in Poland between 1981 and 2019, with earlier flood events occurring in southern Poland and delays observed in the northeastern and northwestern parts of the country. These findings align with the results of this study, suggesting that changes in flood timing and seasonality are influenced by both climatic and regional factors, further emphasising the role of climate warming in altering hydrological extremes.

Studies on the impact of global warming on river runoff (Wrzesiński, Brzezińska 2023, 2024) indicate an increase in the proportion of winter runoff and a decline in spring and summer runoff. The findings of this analysis, showing predominantly declining trends during the spring and summer periods, align with observed changes in the seasonal structure of river runoff. In the context of the earlier occurrence of maximum winter–spring runoff observed at 85% of measurement stations (Somorowska 2024), declines in maximum daily runoff during the spring months may reflect significant seasonal shifts driven by climate change.

Additionally, studies suggest the influence of solar and circulatory factors on river runoff variability, as indicated by (Jokiel, Kożuchowski (1989), Gutry-Korycka and Boryczka 1990, Wrzesiński et al. 2023). The observed changes in runoff are consistent with broader climatic trends, including rising air temperatures and alterations in precipitation patterns. The changes in maximum river runoff since 1988, which show a reduction of more than 30% in annual maximum runoff in some regions, align with the projected impacts of climate warming, which intensify hydrological variability and the severity of extreme hydrological events.

Conclusion

The study analysed changes in the maximum daily river discharge in Poland from 1951 to 2020, considering its monthly, seasonal and annual variability. The study showed:

1. The prevalence of decreasing trends for the maximum daily discharge (>85% of the water-gauge stations), especially in central and eastern Poland, of which 40% were statistically significant ($p < 0.05$). The seasonal analysis of the daily maximum discharge showed the prevalence of decreasing trends across all seasons, especially in spring (87% of the gauges) and summer (77% of the gauges). Statistically significant changes in these periods were >37% and >22%, respectively. By contrast, increases in the maximum discharge were observed mainly on rivers in southern Poland in autumn and in northeastern Poland in winter.
2. During the warming period after 1988, a reduction in the maximum discharge was observed on most of the rivers across all seasons, except for winter. The largest reductions oc-

curred in summer (93% of the gauges), especially in August, where discharge decreased by up to more than 50%, and these changes were statistically significant for almost 30% of the water gauges.

3. The impact of climate warming on the maximum river discharge in Poland varies spatially and temporally. The maximum discharge in spring and summer decreased mainly in the central and western parts of the country, while it increased in the eastern part.
4. The clustering performed revealed varying patterns of change in the monthly average maximum specific runoff. The river groups that have been identified are characterised by specific patterns of runoff changes. Decreases in the monthly MHq prevail in most of the groups. Different patterns of change were found in group 7 (rivers in the Narew River basin in the northeast of the country) which stood out with an increase in MHq during the winter months. An increase in MHq during the winter and spring months was found in the rivers of Group 5 (the Sudeten tributaries of Oder and the coastal rivers in the north) and Group 7 (the Carpathian tributaries of Vistula). It is noteworthy that there was a strong increase in MHq in September in Groups 7 and 8 by an average of 100% and 60%, respectively.

The results of studies on the variability of maximum river discharge in Poland are spatially variable and show an increase in winter and a decrease in summer–autumn runoff. Long-term trends reveal significant decreases in the maximum daily discharge river in Poland.

Acknowledgements

The authors would like to thank two anonymous reviewers for their valuable suggestions on the article.

Authors' Contributions

WB: conceptualisation, investigation, software, data curation, writing original draft, writing – review & editing, visualisation, project administration; DW: conceptualisation, methodology, investigation, data curation, writing – original draft, writing – review & editing, project administration, supervision. The authors declare no conflict of interests in this study. All authors have read and agreed to the published version of the manuscript.

References

Alfieri L., Dottori F., Betts R., Salamon P., Feyen L., 2018. Multi-model projections of river flood risk in Europe under global warming. *Climate* 6: 16. DOI 10.3390/cli6010016.

Brzezińska W., Świątek S., Wrzesiński D., 2023. Wpływ ocieplenia klimatu na odpływ rzek w Polsce w latach 1951–2020. Geoprzestrzeń 7: 59–74.

Chiang F., Mazdiyasni O., Kouchak A., 2021. Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nature Communications, Vol. 12, Issue 1, p. 2754. DOI 10.1038/s41467-021-22314-w.

Dynowska I., 1994. Reżim odpływu rzecznego. Mapa 1:2 500 000. [plansza 32.3-1 w:] *Atlas Rzeczypospolitej Polskiej.* Główny Geodeta Kraju, IGiPZ PAN, Warszawa, Polska: 1–157.

Dynowska I., Pociask-Karteczka J., 1999. Obieg wody. In: Starkel L. (ed.), Geografia Polski. Środowisko przyrodnicze. Wydawnictwo Naukowe PWN, Warszawa, Polska: 43–373.

Fal B., Bogdanowicz E., 2002. Zasoby wód powierzchniowych Polski. In: Wiadomości Instytutu Meteorologii i Gospodarki Wodnej. Warszawa, Vol. 2. s. 3–38.

Fortuniak K., Kożuchowski K., Żmudzka E., 2001. Trendy i okresowość zmian temperatury powietrza w Polsce w drugiej połowie XX wieku. Przegląd Geofizyczny 46(4): 283–303.

Gutry-Korycka M., Boryczka J., 1990. Long-term changes in water balance elements in Poland and the Baltic Sea basin. Przegląd Geofizyczny 35: 19–32.

Huang X., Stevenson S., Hall A.D., 2020. Future warming and intensification of precipitation extremes: A "double whammy" leading to increasing flood risk in California. Geophysical Research Letters 47(16): e2020GL088679. DOI 10.1029/2020GL088679.

IMGW- PIB [Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy], 2023. Dane publiczne IMGW. Online: https://danepubliczne.imgw.pl (accessed 30 June 2023).

Jokiel P., Bartnik A., 2001. Zmiany w sezonowym rozkładzie odpływu w Polsce środkowej w wieloleciu 1951–1998. Wiadomości Instytutu Meteorologii i Gospodarki Wodnej 2: 3–16.

Jokiel P., Kożuchowski K., 1989. Zmiany wybranych charakterystyk hydroklimatycznych Polski w bieżącym stuleciu. In: Dokumentacja Geograficzna. Vol. 6. IGiPAZ PAN, Zakład Narodowy im. Ossolińskich – Wydawnictwo PAN, Warszawa.

Kalugin A., 2023. Climate change effects on river flow in Eastern Europe: Arctic rivers vs. southern rivers. Climate 11(5): 103. DOI 10.3390/cli11050103.

Kożuchowski K., 2004a. Skala i tendencje współczesnych zmian temperatury powietrza w Polsce. In: Kożuchowski K. (ed.), Skala, uwarunkowania i perspektywy współczesnych zmian klimatycznych w Polsce. Wydawnictwo Biblioteka, Łódź: 25–46.

Kożuchowski K., 2004b. Zmienność opadów atmosferycznych w Polsce w XX i XXI wieku, [w:]. In: Kożuchowski K. (ed.), Skala, uwarunkowania i perspektywy współcze-

snych zmian klimatycznych w Polsce. Wyd. Biblioteka, Łódź: s. 47–58.
Kożuchowski K., Żmudzka E., 2001. Ocieplenie w Polsce: skala i rozkład sezonowy zmian temperatury powietrza w drugiej połowie XX wieku. Przegląd Geofizyczny 46(1–2): 81–90.
Kożuchowski K., Żmudzka E., 2002. Cyrkulacja atmosferyczna i jej wpływ na zmienność temperatury powietrza w Polsce. Przegląd Geograficzny 74(4): 591–604.
Lee H., Romero J. (eds), 2023. Climate change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland: 35–115. DOI 10.59327/IPCC/AR6-9789291691647.
Lehmkuhl F., Schüttrumpf H., Schwarzbauer J., Brüll C., Dietze M., Letmathe P., Völker C., Hollert H., 2022. Assessment of the 2021 summer flood in central Europe. Environmental Sciences Europe 34: 107. DOI 10.1186/s12302-022-00685-1.
Limanówka D., Nieckarz Z., Pociask-Karteczka J., 2002. The North Atlantic Oscillation impact on hydrological regime in Polish Carpathians. Interdisciplinary Approaches in Small Catchment Hydrology: Monitoring and Research, FRIEND International Conference, 25–28 September 2002, Demanovska Dolina: 132–135.
Marsz A.A., Sobkowiak L., Styszyńska A., Wrzesiński D., 2022. Causes and course of climate change and its hydrological consequences in the Greater Poland region in1951–2020. Quaestiones Geographicae 41(3): 183–206. DOI 10.14746/quageo-2022-0033.
Marsz A.A., Styszyńska A., 2022. Proces ocieplenia w Polsce – przebieg i przyczyny (1951–2018). Przejaw wewnętrznej dynamiki systemu klimatycznego czy proces antropogeniczny? Prace i Studia Geograficzne 67: 51–82. DOI 10.48128/pisg/2022-67.2-04.
Masson-Delmotte V., Zhai P., Pörtner H.O., Roberts D., Skea J., Shukla P.R., Pirani A., Moufouma-Okia W., Péan C., Pidcock R., Connors S., Matthews J.B.R., Chen Y., Zhou X., Gomis M.I., Lonnoy E., Maycock T., Tignor M., Waterfield T. (eds), 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva. DOI 10.1017/9781009157940.
Michalczyk Z., 2017. Odpływ średni, zmienność w czasie i zróżnicowanie przestrzenne. In: Jokiel P., Marszalewski W., Pociask-Karteczka J. (eds), Hydrologia Polski. Polskie Wydawnictwo Naukowe PWN, Warszawa: s. 153–160.
Piniewski M., Marcinkowski P., Kundzewicz Z.W., 2018. Trend detection in river flow indices in Poland. Acta Geophysica 66: 347–360. DOI 10.1007/s11600-018-0116-3.
Pociask-Karteczka J., Limanówka D., Nieckarz Z., 2002–2003. Wpływ oscylacji północno-atlantyckiej na przepływy rzek karpackich (1951–2000). Folia Geographica, Geographica-Physica 33–34: 89–104.
Pörtner H.-O., Roberts D.C., Tignor M., Poloczanska E.S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., Rama B. (eds), 2022. Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA: 3056. DOI 10.1017/9781009325844.
Rottler E., Francke T., Bürger G., Bronstert A., 2020. Long-term changes in central European river discharge for 1869–2016: Impact of changing snow covers, reservoir constructions and an intensified hydrological cycle. Hydrology and Earth System Sciences 24: 1721–1740. DOI 10.5194/hess-24-1721-2020.
Salmi T., Maatta A., Anttila P., Ruoho-Airola T., Amnell T., 2002. Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall Test and Sen's Slope estimates—The excel template application MAKESENS. Finnish Meteorological Institute, Publications on Air Quality, Helsinki: 31.
Somorowska U., 2024. Earlier emergence of winter-spring maximum streamflow across Poland, 1981–2020. Acta Geographica Lodziensia 115: 109–124. DOI 10.26485/AGL/2024/115/6.
Stachý J., 1968. Zmniejszanie się odpływu rzek polskich w bieżącym stuleciu. In: Prace Państwowego Instytutu Hydrologiczno-Meteorologicznego. Warszawa, Vol. 95. s. 3–13.
Stachý J., 1969. Wieloletnia prognoza odpływu rzek polskich. In: Wiadomości Służby Hydrologiczno-Meteorologicznej. Vol. 5. s. 5–64.
Stachý J., 1970. Wieloletnia zmienność odpływu rzek polskich. In: Prace Państwowego Instytutu Hydrologiczno-Meteorologicznego. Warszawa, Vol. 97. s. 1–42.
Stachý J., 1984a. Odpływ rzek polskich w latach 1971–1980 na tle danych wieloletnich. In: Gospodarka Wodna. Warszawa, Vol. 5. s. 138–141.
Stachý J., 1984b. Odpływ rzek polskich w latach 1971–1980 na tle danych wieloletnich. In: Gospodarka Wodna. Warszawa, Vol. 6. s. 163–167.
Styszyńska A., Tamulewicz J., 2004. Warta River discharges in Poznań and atmospheric circulation in the North Atlantic region. Quaestiones Geographicae 23: 63–81.
Venegas-Cordero N., Kundzewicz Z.W., Jamro S., Piniewski M., 2022. Detection of trends in observed river floods in Poland. Journal of Hydrology: Regional Studies 41: 101098. DOI 10.1016/j.ejrh.2022.101098.
Wang H., Liu J., Klaar M., Chen A., Gudmundsson L., Holden J., 2024. Anthropogenic climate change has influenced global river flow seasonality. Science 383: 1009–1014. DOI 10.1126/science.adi9501.
Wrzesiński D., 2009. Tendencje zmian przepływu rzek Polski w drugiej połowie XX wieku. Badania Fizjograficzne nad Polską Zachodnią 60: 147–160.
Wrzesiński D., 2011. Regional differences in the influence of the North Atlantic Oscillation on seasonal river runoff in Poland. Quaestiones Geographicae 30(3): 127–136. DOI 10.2478/v10117-011-0032-y.
Wrzesiński D., 2017. Reżimy rzeczne. In: Jokiel P., Marszelewski W., Pociask-Karteczka J. (eds), Hydrologia Polski. Wyd. Nauk. PWN, Warszawa: 215–221.
Wrzesiński D., 2021. Flow regime patterns and their changes. In: Zeleňáková M., Kubiak-Wójcicka K., Negm A.M. (eds), Management of water resources in Poland. Springer Nature, Cham, Switzerland: 163–180.
Wrzesiński D., 2024. Zmiany wybranych cech reżimu rzek w Polsce w warunkach ocieplenia klimatu. Acta Geographica Lodziensia 115: 175–195. DOI 10.26485/AGL/2024/115/10.

Wrzesiński D., Brzezińska W., 2023. Sezonowa struktura odpływu rzek w Polsce w warunkach ocieplenia klimatu. In: Wrzesiński D., Graf R., Brzezińska W. (eds), Naturalne i antropogeniczne zmiany obiegu wody. Badania interdyscyplinarne. Studia i Prace z Geografii. Vol. 98. Bogucki Wydawnictwo Naukowe, Poznań: 101–115.

Wrzesiński D., Brzezińska W., 2024. Niepewność reżimu odpływu rzek w Polsce w warunkach ocieplenia klimatu. Czasopismo Geograficzne 95(2): 183–208. DOI 10.12657/czageo-95-08.

Wrzesiński D., Paluszkiewicz R., 2011. Spatial differences in the impact of the North Atlantic Oscillation on the flow of rivers in Europe. Hydrology Research 42(1): 30–39. DOI 10.2166/nh.2010.077.

Wrzesiński D., Sobkowiak L., 2018. Detection of changes in flow regime of rivers in Poland. Journal of Hydrology and Hydromechanics 66(1): 55–64. DOI 10.1515/johh-2017-0045.

Wrzesiński D., Sobkowiak L., Mares I., Dobrica V., Mares C., 2023. Variability of river runoff in Poland and its connection to solar variability. Atmosphere 14: 1184. DOI 10.3390/atmos14071184.

Żmudzka E., 2002. O zmienności opadów atmosferycznych na obszarze Polski nizinnej w drugiej połowie XX wieku. Wiad. IMGW, XXV(XLVI), 4, 23–38.

Appendix 1.

Inventory of rivers and water gauge cross sections and basic hydrological data from 1951 to 2020 after Wrzesiński 2016, 2021, modified (Note: Mq – mean specific runoff; MLq – mean low specific runoff; *Types of river regime: 1 — nival poorly developed, 2 — nival moderately developed, 3 — nival strongly developed, 4 — nival-pluvial, 5 — pluvial-nival. Statistically significant change at: * p<0.05, ** p<0.01, *** p<0.001).

ID	River	Water gauge	Latitude	Longitude	Catchment area	Mean specific runoff $Mq_{1951–2020}$	Mean high specific runoff $MHq_{1951–2020}$	Mean low specific runoff $MLq_{1951–2020}$	River Regime*	Mean high specific runoff MHq		Test of change $MHq_{1988–2020}$ – $MHq_{1951–1988}$
										1951–1988	1988–2020	
			[°]		[km²]	[dm³ s⁻¹ km⁻²]			[–]	[dm³ s⁻¹ km⁻²]		
1	Odra	Chałupki	18.33	49.92	4666	8.95	82.12	2.02	4	82.13	80.52	0.11
2	Odra	Racibórz-Miedonia	18.23	50.12	6744	9.54	80.60	2.36	4	77.76	82.53	0.34
3	Odra	Ścinawa	16.44	51.41	29584	5.99	24.02	2.17	4	25.11	22.48	0.76
4	Odra	Cigacice	15.61	52.03	40106	5.41	18.94	2.13	2	19.64	18.07	0.64
5	Odra	Połęcko	14.89	52.05	47370	5.30	16.88	2.21	2	17.48	16.13	0.63
6	Odra	Słubice	14.56	52.35	53600	5.52	16.29	2.35	2	17.28	15.12	1.21
7	Odra	Gozdowice	14.32	52.76	109729	4.66	10.76	2.22	2	11.3	10.2	1.08
8	Sumina	Nędza	18.31	50.16	94.4	6.12	67.18	1.93	4	75.45	56.67	1.64
9	Nysa Kłodzka	Bystrzyca Kłodzka	16.65	50.29	260	14.80	189.86	2.46	4	174.09	208.3	1.02
10	Nysa Kłodzka	Kłodzko	16.66	50.44	1084	11.57	113.74	3.17	4	104.53	123.71	0.85
11	Nysa Kłodzka	Nysa	17.34	50.48	3276	8.83	48.10	1.99	4	51.37	43.79	0.55
12	Nysa Kłodzka	Skorogoszcz	17.67	50.76	4514	7.92	43.73	2.17	4	49.61	36.39	1.4
13	Bystrzyca Dusznicka	Szalejów Dolny	16.6	50.42	175	11.99	118.41	4.33	2	123.67	112.24	0.61
14	Ścinawka	Tłumaczów	16.44	50.55	256	8.87	111.80	2.19	2	110.97	112.45	0.06
15	Ścinawka	Gorzuchów	16.57	50.49	511	8.71	122.88	2.40	4	151.28	88.52	**2.51***
16	Biała Głucho-łaska	Głuchołazy	17.38	50.32	283	17.19	162.11	5.60	4	168.72	150.77	0.33
17	Bystrzyca	Krasków	16.58	50.92	683	6.53	90.31	1.11	4	94	84.04	0.4
18	Piława	Mościsko	16.58	50.78	291	5.47	73.34	1.03	4	79.47	64.66	1
19	Strzegomka	Łażany	16.49	50.95	356	6.28	68.49	2.26	4	81.99	51.49	**2.06***
20	Barycz	Osetno	16.46	51.63	4579	3.22	14.68	0.35	3	16.08	13.17	1.48
21	Bóbr	Żagań	15.32	51.62	4254	8.74	46.54	2.97	4	53.16	38.8	1.66
22	Kamienica	Barcinek	15.6	50.94	97.2	12.36	165.20	1.72	2	153.57	176.19	0.51
23	Kwisa	Nowogrodziec	15.4	51.2	736	9.73	93.96	2.60	4	100.97	85.37	0.85
24	Czarny Potok	Mirsk	15.38	50.99	55.9	15.68	225.55	2.91	4	233.86	213.7	0.44
25	Czerna Wielka	Żagań	15.29	51.61	896	4.72	22.59	1.58	2	26.45	18.02	**2.06***
26	Warta	Działoszyn	18.87	51.11	4088	5.89	22.22	2.77	2	24.27	19.6	1.67
27	Warta	Sieradz	18.74	51.6	8140	5.43	18.81	2.60	2	21.15	15.97	**2.43***

ID	River	Water gauge	Latitude	Longitude	Catchment area	Mean specific runoff $Mq_{1951-2020}$	Mean high specific runoff $MHq_{1951-2020}$	Mean low specific runoff $MLq_{1951-2020}$	River Regime*	Mean high specific runoff MHq		Test of change $MHq_{1988-2020}$ – $MHq_{1951-1988}$
										1951–1988	1988–2020	
			[°]		[km²]	[dm³ s⁻¹ km⁻²]			[–]	[dm³ s⁻¹ km⁻²]		
28	Warta	Poznań-Most Rocha	16.95	52.4	25126	3.95	11.39	1.59	2	13.68	8.75	**3.64*****
29	Warta	Skwierzyna	15.5	52.6	31268	3.91	10.33	1.66	2	12.27	8.18	**3.44****
30	Warta	Gorzów Wielkopolski	15.25	52.73	52186	3.94	8.64	1.92	2	9.81	7.38	**2.92****
31	Oleśnica	Niechmirów	18.76	51.39	592	4.02	29.98	0.95	3	36.11	23	**2.48***
32	Grabia	Grabno	18.98	51.46	811	5.08	34.39	1.35	3	38.19	29.58	1.86
33	Ner	Dąbie	18.82	52.08	1712	5.76	22.38	1.44	2	25.76	18.54	**3.21****
34	Prosna	Mirków	18.16	51.32	1255	3.99	26.71	0.94	2	32.94	19.56	**3.75*****
35	Prosna	Piwonice	18.11	51.73	2938	3.78	19.83	1.03	2	23.44	15.65	**3.03****
36	Prosna	Bogusław	17.95	51.9	4304	3.62	18.59	0.90	2	22.23	14.38	**3.16****
37	Niesób	Kuźnica Skakawska	18.13	51.28	246	3.93	30.25	0.95	3	36.15	23.28	**2.5***
38	Ołobok	Ołobok	18.07	51.64	447	3.51	25.12	0.56	3	27.46	22.44	1.5
39	Mogilnica	Konojad	16.53	52.15	663	2.45	13.05	0.25	3	15.44	10.92	1.99
40	Wełna	Pruśce	17.1	52.77	1130	2.93	9.28	0.68	3	11.17	7.48	**2.37***
41	Flinta	Ryczywół	16.84	52.82	276	2.35	11.33	0.36	3	12.74	10.02	1.83
42	Sama	Szamotuły	16.58	52.61	395	2.64	13.59	0.42	3	17.39	10.39	**2.33***
43	Noteć	Nowe Drezdenko	15.84	52.85	15970	4.54	8.03	2.47	2	8.53	7.57	1.89
44	Mała Noteć	Gębice	18.03	52.6	182	3.23	8.71	0.81	2	10.73	6.67	**2.99****
45	Gąsawka	Żnin	17.72	52.85	148	3.45	8.88	0.80	3	10.3	7.34	**2.15***
46	Gwda	Piła	16.74	53.15	4704	5.71	11.30	3.08	1	11.86	10.73	1.53
47	Drawa	Drawsko Pomorskie	15.81	53.53	609	6.63	17.11	2.61	2	18.82	15.26	**2.75****
48	Ina	Goleniów	14.83	53.56	2163	5.88	15.76	2.54	2	16.55	14.94	1.06
49	Rega	Trzebiatów	15.26	54.06	2628	7.59	19.99	3.48	2	20.29	19.75	0.41
50	Parsęta	Tychówko	16.07	53.9	896	9.17	37.00	4.42	2	38.69	35	1.2
51	Wieprza	Stary Kraków	16.61	54.44	1519	10.37	26.89	6.09	1	26.88	26.88	0
52	Słupia	Słupsk	17.03	54.47	1450	10.73	21.47	6.03	1	21.14	21.75	0.56
53	Łupawa	Smołdzino	17.21	54.66	805	10.33	19.89	6.67	1	18.33	21.62	**2.24***
54	Wisła	Skoczów	18.79	49.8	297	20.33	329.98	2.18	4	315.92	341.59	0.47
55	Wisła	Goczałkowice	18.99	49.93	738	12.08	142.09	1.40	5	145.39	135.27	0.36
56	Wisła	Jawiszowice	19.12	49.97	971	13.51	143.98	2.43	5	142.19	143.08	0.03
57	Wisła	Bieruń Nowy	19.19	50.06	1748	12.11	105.48	3.06	4	110.2	98.19	0.65
58	Wisła	Jagodniki	20.68	50.2	12058	10.60	85.32	3.87	4	84.91	84.4	0.04
59	Wisła	Szczucin	21.08	50.33	23901	9.75	72.43	3.37	4	72.54	71.15	0.13

ID	River	Water gauge	Latitude	Longitude	Catchment area	Mean specific runoff $Mq_{1951-2020}$	Mean high specific runoff $MHq_{1951-2020}$	Mean low specific runoff $MLq_{1951-2020}$	River Regime*	Mean high specific runoff MHq 1951–1988	Mean high specific runoff MHq 1988–2020	Test of change $MHq_{1988-2020} - MHq_{1951-1988}$
			[°]		[km²]	[dm³ s⁻¹ km⁻²]			[–]	[dm³ s⁻¹ km⁻²]		
60	Wisła	Sandomierz	21.75	50.67	31846	9.03	64.86	3.02	4	67.4	60.88	0.74
61	Wisła	Zawichost	21.86	50.81	50732	8.30	53.20	2.65	4	56.42	48.81	1.25
62	Wisła	Annopol	21.83	50.89	51518	8.30	51.89	2.68	4	54.17	48.6	0.92
63	Wisła	Dęblin	21.83	51.56	68234	7.23	37.81	2.59	4	38.44	36.65	0.43
64	Wisła	Toruń	18.61	53.01	181033	5.31	18.96	2.02	2	20.64	16.92	**2.26***
65	Wisła	Tczew	18.8	54.1	194376	5.30	16.83	2.16	2	17.8	15.6	1.48
66	Iłownica	Czechowice-Dziedzice	18.99	49.91	194	15.53	280.63	2.66	5	280.49	276.73	0.07
67	Soła	Oświęcim	19.22	50.04	1386	15.00	217.87	2.19	4	211.85	220.41	0.25
68	Skawa	Sucha Beskidzka	19.61	49.74	468	16.11	278.35	2.68	4	239.3	318.73	1.46
69	Skawa	Wadowice	19.51	49.88	836	14.74	211.23	2.62	4	195.77	225.01	0.94
70	Raba	Proszówki	20.43	50	1470	11.31	216.76	2.24	4	221.95	206.76	0.41
71	Dunajec	Krościenko	20.43	49.44	1580	20.13	216.22	4.94	5	219.8	208.3	0.37
72	Dunajec	Nowy Sącz	20.69	49.63	4341	14.99	176.01	3.57	4	176.37	171.93	0.15
73	Poprad	Muszyna	20.89	49.34	1514	11.60	120.53	2.84	4	114.92	124.57	0.55
74	Poprad	Stary Sącz	20.66	49.57	2071	12.07	130.75	3.02	4	132.36	126.38	0.29
75	Biała	Koszyce Wielkie	20.95	50	957	9.21	207.34	1.35	4	217.84	191.74	0.66
76	Nida	Brzegi	20.41	50.74	2259	5.62	42.04	2.05	2	46.51	36.23	1.67
77	Nida	Pińczów	20.52	50.51	3352	5.33	33.55	1.96	2	39.7	25.99	**2.96****
78	Czarna Nida	Tokarnia	20.45	50.77	1216	5.43	54.19	1.94	2	57.88	49.02	0.96
79	Czarna	Połaniec	21.28	50.43	1354	4.73	58.81	1.52	3	77.41	36.18	**4.34*****
80	Wisłoka	Żółków	21.46	49.73	581	12.20	235.40	1.05	4	211.26	260.34	1.41
81	Ropa	Klęczany	21.22	49.7	483	12.90	249.96	2.66	4	234.54	263.99	0.72
82	Brzeźnica	Brzeźnica	21.49	50.11	484	6.74	132.28	1.53	4	145.56	113.93	1.38
83	San	Lesko	22.32	49.47	1614	17.60	148.82	3.64	4	149.42	147.91	0.07
84	San	Przemyśl	22.77	49.78	3686	14.11	131.75	2.88	4	140.58	120.18	1.14
85	San	Jarosław	22.7	50.02	7041	9.91	79.45	2.53	4	87.39	69.57	1.67
86	San	Radomyśl	21.93	50.67	16824	7.66	46.92	2.32	4	49.07	43.89	1.06
87	Osława	Zagórz	22.27	49.51	505	16.14	254.87	1.56	4	234.36	277.31	1.21
88	Wiar	Krówniki	22.82	49.77	789	8.01	167.62	1.03	4	158.96	174.8	0.46
89	Wisznia	Nienowice	22.92	49.94	1185	5.66	83.74	0.95	4	98.66	66.04	**2.13***
90	Wisłok	Krosno	21.77	49.69	596	10.39	132.14	1.44	4	128.34	135.73	0.46
91	Wisłok	Żarnowa	21.82	49.88	1427	9.11	107.57	1.52	4	100.65	115.05	1.14
92	Wisłok	Rzeszów	22.02	50.04	2086	8.34	91.88	1.30	4	83.99	100.03	1.39

ID	River	Water gauge	Latitude	Longitude	Catchment area	Mean specific runoff $Mq_{1951-2020}$	Mean high specific runoff $MHq_{1951-2020}$	Mean low specific runoff $MLq_{1951-2020}$	River Regime*	Mean high specific runoff MHq		Test of change $MHq_{1988-2020} - MHq_{1951-1988}$
										1951–1988	1988–2020	
			[°]		[km²]	[$dm^3 s^{-1} km^{-2}$]			[–]	[$dm^3 s^{-1} km^{-2}$]		
93	Wisłok	Tryńcza	22.55	50.16	3516	7.22	62.19	1.66	4	60.3	63.81	0.5
94	Mleczka	Gorliczyna	22.49	50.08	529	5.49	92.89	0.79	4	85.06	100.17	0.86
95	Tanew	Harasiuki	22.47	50.48	2034	6.01	37.01	2.42	2	44.17	28.17	**3.22****
96	Kamienna	Wąchock	21.02	51.08	476	6.11	62.81	1.55	2	68.27	55.43	1.62
97	Wieprz	Zwierzyniec	22.97	50.61	405	5.08	17.45	2.77	1	19.58	14.89	1.69
98	Wieprz	Krasnystaw	23.18	50.99	3001	4.12	16.46	2.06	2	19.72	12.54	1.97
99	Wieprz	Lubartów	22.64	51.5	6364	3.54	11.69	1.67	2	14.23	8.61	**2.27***
100	Wieprz	Kośmin	22	51.57	10231	3.59	11.98	1.57	2	14.4	9.05	**2.72****
101	Bystrzyca	Sobianowice	22.69	51.3	1265	3.98	16.48	2.06	2	18.26	14.22	1.15
102	Pilica	Przedbórz	19.88	51.09	2536	5.90	27.00	2.23	2	32.24	20.53	**2.8****
103	Pilica	Nowe Miasto	20.57	51.61	6717	5.29	21.96	2.33	2	26.41	16.49	**3.45*****
104	Pilica	Białobrzegi	20.95	51.66	8664	5.09	19.91	2.24	2	24.68	14.08	**4.36*****
105	Czarna	Dąbrowa	19.97	51.31	941	6.25	48.05	1.79	2	55.24	38.94	**2.53***
106	Wolbórka	Zawada	19.94	51.53	616	4.36	38.87	1.19	2	43.39	33.32	1.66
107	Drzewiczka	Odrzywół	20.56	51.52	1004	5.29	36.78	1.76	2	49.48	21.49	**4.43*****
108	Narew	Narew	23.52	52.92	1978	4.63	21.96	1.28	3	29.82	13.59	**5.03*****
109	Narew	Suraż	22.96	52.95	3376	4.42	21.18	1.21	3	25.71	16.45	**3.02****
110	Narew	Strękowa Góra	22.54	53.22	7181	4.48	17.15	1.38	3	21.37	12.49	**3.43****
111	Narew	Wizna	22.41	53.2	14308	4.71	16.71	1.58	3	20.1	13.06	**2.87****
112	Narew	Piątnica-Łomża	22.09	53.19	15296	4.79	16.51	1.66	3	19.86	12.86	**2.93****
113	Narew	Nowogród	21.86	53.23	20106	4.83	14.99	1.92	3	18.14	11.55	**2.97****
114	Narew	Ostrołęka	21.56	53.08	21862	4.94	15.00	1.96	3	18.14	11.52	**3.1****
115	Narewka	Narewka	23.73	52.86	590	4.97	32.10	1.10	3	38.67	25.21	**3.02****
116	Supraśl	Fasty	23.03	53.18	1817	4.86	18.36	1.98	2	21.2	15.52	**2.4***
117	Biebrza	Sztabin	23.12	53.67	846	5.44	31.24	1.44	3	38.72	23.18	**3.14****
118	Biebrza	Dębowo	22.93	53.61	2322	5.30	21.80	1.50	3	26.31	16.88	**3.13****
119	Biebrza	Osowiec	22.64	53.48	4365	5.07	17.74	1.55	3	20.63	14.46	**2.21***
120	Biebrza	Burzyn	22.46	53.27	6900	5.01	18.35	1.67	3	20.82	15.88	1.62
121	Brzozówka	Karpowicze	23.04	53.59	650	4.89	43.14	0.98	3	52.74	32.59	**3.29****
122	Pisa	Ptaki	21.79	53.39	3562	5.76	10.62	3.13	1	11.56	9.61	**2.32***
123	Pisa	Dobrylas	21.87	53.28	4061	5.78	11.59	3.11	2	12.94	10.15	**3.24****
124	Rozoga	Myszyniec	21.34	53.39	231	4.92	27.05	0.85	2	32.93	21.5	**2.79****
125	Omulew	Krukowo	21.11	53.31	1265	5.39	12.49	2.07	2	14.18	10.63	**3.86*****

ID	River	Water gauge	Latitude	Longitude	Catchment area	Mean specific runoff $Mq_{1951–2020}$	Mean high specific runoff $MHq_{1951–2020}$	Mean low specific runoff $MLq_{1951–2020}$	River Regime*	Mean high specific runoff MHq		Test of change $MHq_{1988–2020}$ – $MHq_{1951–1988}$
										1951–1988	1988–2020	
			[°]		[km²]	[dm³ s⁻¹ km⁻²]			[–]	[dm³ s⁻¹ km⁻²]		
126	Orzyc	Krasnosielc	21.15	53.04	1268	4.51	21.86	0.90	2	25.02	18.41	**2.18***
127	Bug	Włodawa	23.57	51.55	14410	3.82	15.57	1.28	3	19.32	11.07	**3.32****
128	Bug	Frankopol	22.56	52.41	31336	3.74	12.90	1.30	3	15.84	9.48	**3.88*****
129	Bug	Wyszków	21.45	52.59	39119	3.89	14.31	1.34	3	17.75	10.44	**3.57*****
130	Włodawka	Okuninka	23.52	51.52	576	3.70	21.70	0.73	3	25.34	17.51	**2.18***
131	Krzna	Malowa Góra	23.47	52.1	3128	3.43	18.11	0.83	3	19.83	16.28	1.51
132	Nurzec	Boćki	23.04	52.65	556	4.25	40.95	0.77	3	50	30.72	**2.81****
133	Nurzec	Boćki	23.04	52.65	556	4.25	40.95	0.77	3	50	30.72	**2.81****
134	Nurzec	Brańsk	22.82	52.74	1227	4.02	46.77	0.67	3	57.67	35.28	**3.44****
135	Liwiec	Łochów	21.68	52.51	2466	4.25	32.71	0.92	3	40.65	23.66	**3.28****
136	Rawka	Kęszyce	20.13	52.14	1191	4.02	17.32	1.71	2	20.88	13	**2.86****
137	Skrwa	Parzeń	19.54	52.65	1534	3.96	25.48	0.90	3	28.35	22.21	1.3
138	Drwęca	Nowe Miasto Lubawskie	19.59	53.42	2725	5.99	12.22	2.87	2	12.79	11.69	1.01
139	Drwęca	Brodnica	19.4	53.26	3526	6.10	11.70	3.17	2	12.29	11.13	1.17
140	Drwęca	Elgiszewo	18.93	53.06	4959	5.51	10.95	2.82	2	11.65	10.19	1.36
141	Wel	Kuligi	19.69	53.43	764	6.54	12.44	3.61	1	13.44	11.28	**2.71****
142	Brda	Tuchola	17.9	53.57	2462	7.88	12.29	4.60	1	12.21	12.41	0.3
143	Wda	Czarna Woda	18.09	53.84	940	6.68	11.00	4.07	1	12.31	9.49	**5.09*****
144	Wierzyca	Brody Pomorskie	18.76	53.86	1544	5.55	13.72	2.79	2	15.54	11.61	**3.67*****
145	Łyna	Sępopol	21.01	54.27	3647	6.71	25.12	2.57	2	26.19	24.04	0.89
146	Guber	Prosna	21.09	54.23	1568	5.44	33.22	0.85	2	35.09	31.16	1.02
147	Gołdapa	Banie Mazurskie	22.03	54.25	548	8.46	44.39	2.20	3	48.87	39.48	**2.26***
148	Czarna Hańcza	Czerwony Folwark	23.12	54.07	454	8.33	13.75	4.68	2	14.92	12.34	**2.45***

Note: *Types of river regime (Wrzesiński 2016, 2021, modified): 1 – nival poorly developed, 2 – nival moderately developed, 3 – nival strongly developed, 4 – nival-pluvial, 5 – pluvial-nival. Statistically significant change at: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.