Bulletin of Geography. Physical Geography Series, No. 30 (2026): 111–128
http://doi.org/10.12775/bgeo-2026-0007

Multiannual and seasonal variability of Vistula River flows from 1953 to 2022 in the context of meteorological conditions

Katarzyna Kubiak-Wójcicka

Nicolaus Copernicus University, Department of Hydrology, Cryology and Water Management, Faculty of Earth Sciences and Spatial Management, Toruń, Poland

E-mail: kubiak@umk.pl

https://orcid.org/0000-0002-9863-3142

Abstract. The aim of this study is to analyse the variability of the average annual flows of the Vistula River in the hydrological years 1953–2022, divided into two sub-periods: 1953–1987 and 1988–2022. The analysis was conducted at eight hydrological stations located along the Vistula River. Long-term trends were calculated using the nonparametric Mann–Kendall test. Changes were noted in the distribution of mean annual and monthly flows between the periods 1953–1987 and 1988–2022, but this trend was not statistically significant. The analysis showed that the 1988–2022 period was warmer than 1953–1987, as observed at four meteorological stations. However, no trends were observed in annual precipitation totals. Mean annual flows in 1988–2022 were lower than in 1953–1987, while minimum annual flows in 1988–2022 were higher than in 1953–1987. The study highlights the changing timing of minimum average monthly flows recorded in the middle reaches of the Vistula. In the years 1953–1987, the lowest average monthly flows occurred in September, whereas, in the period 1988–2022, the lowest occurred in October.

Key words:
river flows,
hydrological regimes,
spatiotemporal variability,
change trends,
Vistula,
Poland

Introduction

River runoff variability is crucial for understanding and managing water resources, which are essential for various economic sectors. Studying runoff patterns helps predict future water availability, manage water resources, and mitigate potential threats such as droughts or floods. Precipitation and air temperature are the basic climatic factors that significantly affect changes in runoff from inland surface waters, i.e., rivers, lakes, and reservoirs (Marx et al. 2018). In addition to climate change, significant factors influencing runoff changes are anthropogenic changes, including land use changes (Levi et al. 2015; Vojtek and Vojtekova 2019; Adnan et al. 2023; Barati et al. 2023), construction of dams and reservoirs (Nguyen et al. 2023; Ho et al. 2025), and water extraction for industrial and agricultural needs (Mwirigi et al. 2024), which contribute significantly to regional characteristics of runoff variability. Therefore, changes in these factors will result in changes in river runoff, both temporally and spatially. Runoff is a key component of the water balance of terrestrial waters and a natural source of freshwater on Earth (Wang et al. 2022). Many authors have conducted studies on the regimes of European rivers (Stahl et al. 2010; Paprotny et al. 2018; Radevski et al. 2018; Blöschl et al. 2019; Rottler et al. 2020; Mentaschi et al. 2020; Šraj and Bezak 2020; Deman and Boe 2024; Leščešen et al. 2024). The analysis of long-term streamflow series can provide valuable information about trends and changes in the climate of a given area (Čanjevac and Orešić 2018). In Europe, runoff trends show a decrease in central and parts of southern Europe (Blaškovičová et al. 2022), while some regions of northern and southern Europe experience increased runoff (Gohari et al. 2022). Therefore, it is particularly important to monitor changes in runoff regimes, especially at the catchment and subcatchment levels, to determine the causes and consequences of these changes (Gnjato et al. 2024). The need for a better understanding of the impact of changing natural and anthropogenic factors on runoff changes at the local and regional scales is essential for solving water resource management tasks, especially in areas with limited water resources (Szolgay et al. 2023).

Poland exhibits high spatial and temporal variability in river runoff, which results from its location in the transitional temperate climate zone. Of European countries, Poland has among the smallest water resources, which is particularly important for water availability across individual regions of the country (Kubiak-Wójcicka 2021). The increasing pressure on water resources caused by climate change and human activity poses a serious risk (Fernando et al. 2024). This causes serious disruptions to economic activity. Identifying the problem will involve considering all water applications, including industry, agriculture, and households. The use of innovative solutions and the implementation of modern techniques require financial support not only at the national level, but also from the European Union. Counteracting the effects of drought and flood is a key task not only for Poland, but also for other EU Member States. Although the hydrological system of Polish rivers is well understood, long-term trends in runoff, both in average and extreme values, are constantly sought (Kędra 2017; Piniewski et al. 2017; Świątek 2017; Wałęga and Młyński 2017; Jokiel and Tomalski 2018; Malinowski and Skoczko 2018; Wrzesiński and Sobkowiak 2018; Mostowik et al. 2019; Kubiak-Wójcicka 2021; Raczyński and Dyer 2024; Tomaszewski and Kozek-Połomska, 2024). Studies published in recent years indicate that the negative effects of climate change on water resources in Poland have intensified since 1988. The year 1988 was a turning point because, since then, an increase in the intensity of climate warming has been observed not only in Poland (Marsz et al. 2022; Wrzesiński et al. 2022), but also in other Central European countries (Apsite 2009). The impact of precipitation changes on river flow changes in recent years has been recorded in various rivers in Poland (Szatten et al. 2025; Wrzesiński et al. 2025). In most cases, flows did not show statistically significant changes (Kubiak-Wójcicka 2021; Świątek and Walczykiewicz 2025). Research by Wrzesiński et al. (2025) showed that, after 1988, there was a statistically significant increase in mean air temperatures and a statistically significant increase in evaporation, while precipitation remained unchanged. The changes in runoff are more complex and show greater regional variation. A decrease in runoff was noted at most hydrological stations, especially in the lowlands in the central part of the Vistula River basin (Badora et al. 2023). In contrast, an increase was noted in the south of the country (Wrzesiński et al. 2025), which is associated with the disappearance of ice phenomena, demonstrating a clear trend in the Upper Vistula River basin (Szczerbińska and Siwek 2025). These divergent assessments provide a motivation to study changes in selected meteorological elements (precipitation and air temperature) in the Vistula River basin over recent decades to fill the gap in understanding the recent trends in the increase/decrease of Vistula River runoff and their implications. Such research is needed in the face of increasing and widespread signals that climate change is affecting runoff conditions, which are leading to shifts in maximum and minimum monthly average values. Analysis of average flow values is crucial for water resource managers, as water law permits are issued based on average resources for specific water use by various sectors of the national economy for periods of at least 10 years. Therefore, this study focuses on updating seasonal and annual flow variability, taking into account the latest meteorological data, with particular emphasis on the years 1988–2022.

The main objective of the work is to identify trends in Vistula flow changes during the hydrological years 1953–2022 on an annual, seasonal, and monthly basis. A comprehensive assessment of the spatiotemporal characteristics of flow variability was conducted for selected hydrological stations along the Vistula River.

This study aims to assess the formation of the hydrological regime of the Vistula along its entire length, taking into account variability in precipitation and air temperature at the catchment scale and their influence on the river. In particular, this study compares the flows over the period 1953–2022, divided into two sub-periods: 1953–1987 and 1988–2022. This assessment can provide valuable insights for decision-makers responsible for water resources management.

Materials and methods

Study area

The Vistula River is, at 1,022 km, the longest in Poland (Fig. 1). The source of the Vistula is located in southern Poland at the foot of the Barania Góra mountain (1,106 m a.s.l.), while its estuary reaches the Baltic Sea, forming a delta in Żuławy Wiślane (Kubiak-Wójcicka 2019). The Vistula River Basin can be divided into three parts, which are diverse in terms of area, orography, amount and structure of precipitation, land use, and other elements: the upper part (to the mouth of the San River), the middle part (to the mouths of the Narew and Bug Rivers) and the lower part of the Vistula (mouth to the Baltic Sea).

The hydrological regime of the Vistula changes with the course of the river. It ranges from a pluvial-nival regime in the upper reaches through a nival-pluvial regime downstream to Toruń and a moderately developed nival regime to the mouth of the Vistula (Bogdanowicz et al. 2021). While the nival regime is mainly represented by lowland rivers in the central and northern part of the country, rivers in the southern, upland and mountainous parts have a nival-fluvial and pluvial-nival regime. The rivers representing the weakly pluvial type are characterised by the most uniform flows and the highest proportion of groundwater flow in the total flow over the annual cycle (Wrzesiński 2021). As the catchment area increases, average and maximum unit runoff tend to decrease, and minimum unit runoff increase. Thus, the variability of the flow decreases and its inertia increases (Jokiel and Tomalski 2018) (Table 1).

The Vistula is a typical river with a complex hydrological regime, similar to other large European rivers in temperate climates. They cover different geographical regions, from mountain ranges in the river's upper reaches to large lowlands in the middle and lower reaches. A characteristic feature of large European rivers is their seasonal hydrological regime, characterised by high flow in spring and summer due to snowmelt and precipitation, followed by low flow in late summer or autumn. A study by Pfeiffer and Ionita (2017) showed that the hydrological behaviour of the Elbe and Rhine rivers has changed since the mid-20th century, likely a consequence of climate change. However, determining the exact contribution of climatic factors to hydrological changes is not straightforward, and further research is needed to quantify these effects.

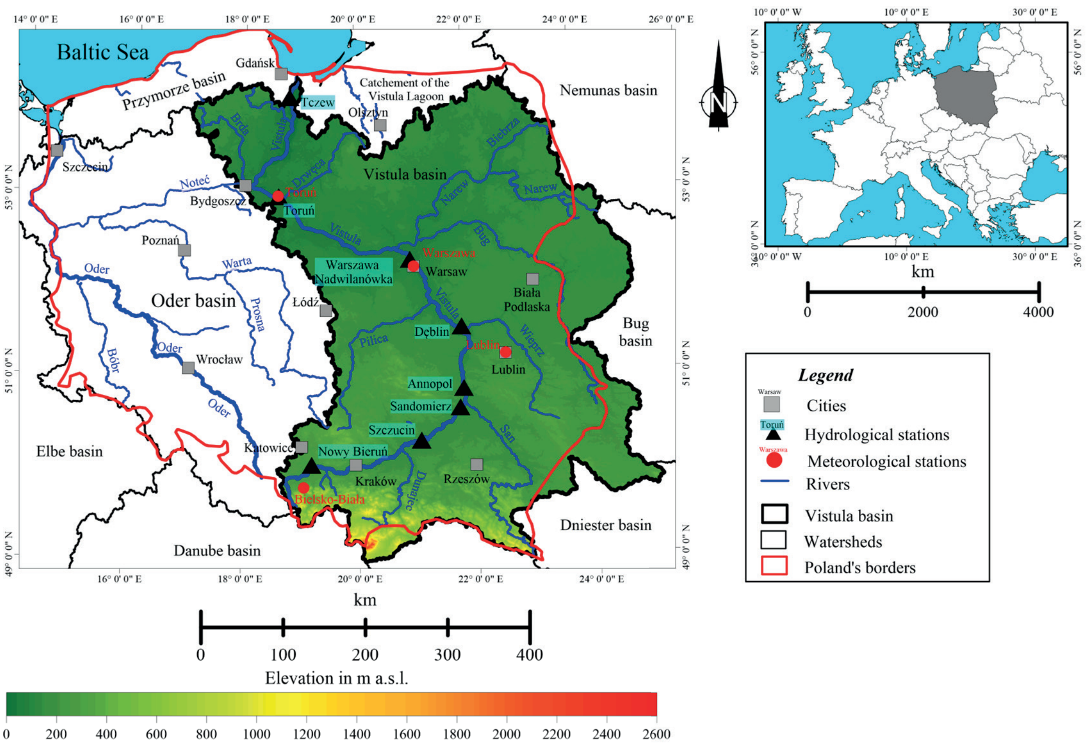

Fig. 1. Location of the study area

Table 1. Characteristics of Vistula flows at selected hydrological stations in the hydrological years 1953–2022

No	Hydrological station	Basin area [km²]	Length (from mouth) [km]	Flows in years 1953–2022 [$m^3 s^{-1}$] WWQ [$m^3 s^{-1}$]	SSQ [$m^3 s^{-1}$]	NNQ [$m^3 s^{-1}$]	Average unit runoff SSq [$l\ s^{-1} km^{-2}$]
1	Nowy Bieruń	1 774.25	921.00	763	21	1.5	11.95
2	Szczucin	23 846.92	729.60	5090	233	40.5	9.77
3	Sandomierz	31 786.02	655.07	5040	289	57.0	9.09
4	Annopol	51 472.87	624.09	6010	429	92.0	8.33
5	Dęblin	68 215.96	534.57	6000	495	114.0	7.26
6	Warszawa	84 539.86	430.83	5740	567	112.0	6.71
7	Toruń	180 266.87	207.23	6650	965	218.0	5.35
8	Tczew	193 665.62	33.78	6430	1035	264.0	5.34

*Data source: danepubliczne.imgw.pl

Explanations: WW –highest flow of the multi-year period, SSQ –average flow of the multi-year period, NNQ –lowest flow of the multi-year period, SSq – average unit runoff over a multi-year period

Data and methods

The study analysed daily flows of the Vistula River recorded at eight hydrological stations (Szczucin, Sandomierz, Annopol, Dęblin, Warsaw [Warszawa Nadwilanówka], Włocławek, Toruń and Tczew). Additionally, average monthly and annual air temperature values were used for four meteorological stations. Daily data were used to calculate maximum, minimum and average monthly and yearly values for the multi-year hydrological period 1953–2022, divided into two sub-periods: 1953–1987 and 1988–2022. Meteorological conditions were characterised using average monthly and annual precipitation and air temperature values from four meteorological stations: Bielsko-Biała, Lublin, Warsaw and Toruń. Both hydrological and meteorological data were provided by the Institute of Meteorology and Water Management - National Research Institute and encompass long-term data series, covering the hydrological years 1953–2022. In Poland, the hydrological year begins on November 1 of the year and ends on October 30 of the following year. Statistical analyses were conducted to describe the magnitudes of flows, precipitation and air temperature.

Research methods

To characterise the components of the flow regime, researchers have developed and applied several hydrological indicators for specific regions (Olden and Poff 2003). The indicators commonly applied in flow regime analysis employ annual, seasonal and monthly river flow values over long observation periods (Bačová Mitková et al. 2024; Orešić et al. 2024). Long observation series of flows enable the detection of trends of change (Üneş and Kaya 2021).

In analysing trends within precipitation, air temperature and flows data time series, a simple linear regression model with the coefficient of determination (r2) was employed. The statistical formula for this regression model is:

$$Y = ax + b$$

where x represents time; a denotes the slope coefficient; and b signifies the least square estimate of the intercept.

The nonparametric Mann–Kendall test (Mann 1945; Kendall 1975), commonly used in hydrological analyses, was applied to detect trends in Vistula flows and to determine their statistical significance. The Mann–Kendall Z-statistic and the directional coefficient β, as estimated by the Theil–Sen estimator (Theil 1950; Sen 1968), were calculated for periods covering every possible combination of starting and ending years for the multi-year period under study. The period used in hydrological calculations (Kubiak-Wójcicka 2020) was taken as the length of the calculation period.

The Mann–Kendall S statistic was calculated using the formula:

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

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

where x_j and x_k represent values of the variable in individual years *j* and *k*, where *j*>*k*; *n* – sample size (number of years).

The S statistic tends to quickly approach normality, and for n>10, this statistic has an approximately normal distribution with mean 0 and variance described by the formula:

$$\mathrm{Var}(S) = [n(n-1)(2n+5)]/18$$

The normalised Z test statistic was calculated as:

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

In the Mann–Kendall test, the null hypothesis is that there is no significant trend in the data series. A trend is significant if the null hypothesis cannot be accepted. The acceptance region at a significance level of α=0.05 is defined by the interval −1.96 ≤ Z ≤ 1.96 (no significant trend), while the rejection region is defined by Z< −1.96 (significant downward trend) and Z>1.96 (significant upward trend), where Z is the standardised test statistic. The slope β, expressed by the Theil–Sen estimator (β), is calculated using the formula:

$$\beta = \mathrm{Median}\big((x_j - x_k)/(j-k)\big)$$

where a positive β value indicates an upward (increasing) trend in the time series, and a negative value indicates a downward (decreasing) trend.

The application of linear regression for a single variable, combined with the Mann–Kendall test in the analysis of river flows, allows for a comprehensive assessment of changes in water resources by combining a quantitative determination of the rate of change with an assessment of its statistical significance. This method is widely used to detect long-term and seasonal trends.

The stages of the research process are shown in the flowchart in Figure 2.

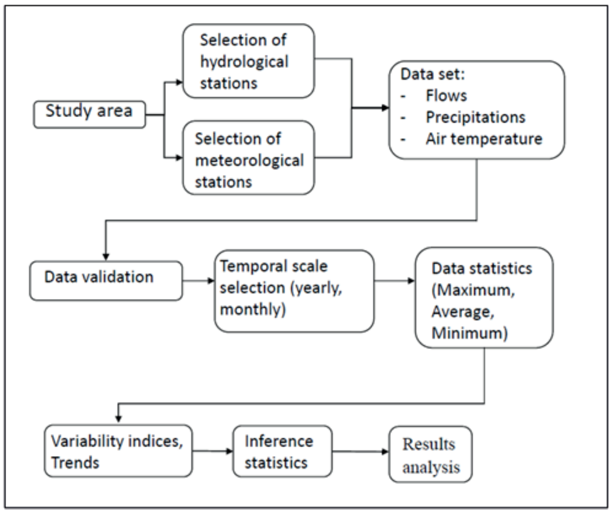

Fig. 2. Flowchart illustrating the stages of the research process

Results

Precipitation and air temperature from 1953 to 2022

Analysis of mean annual precipitation for the analysed multiyear period 1953–2022 showed that precipitation in the Vistula basin varies from 996.5 mm to 528.0 mm (Table 2). The highest precipitation totals are recorded in mountainous areas in the south of Poland, as represented by the Bielsko-Biala meteorological station. The amount of precipitation decreases northwards. For example, in the upland part, precipitation amounted to 587.6 mm at the Lublin station, whereas the precipitation is lowest in the lowland part of Poland, amounting to 537.4 mm at the Toruń station and 528 mm at the Warsaw weather station. The distribution of precipitation within the Vistula River basin shows dependence on hypsometry, and its spatial distribution corresponds to the layout of the main geographical regions, as presented in studies based on a larger number of meteorological stations (Kubiak-Wójcicka and Bąk 2018; Kubiak-Wójcicka 2021). When divided into two sub-periods, i.e., 1953–1987 and 1988–2022, small changes in mean precipitation and clear differences in mean annual air temperature are visible (Fig. 3). Statistical analysis of annual precipitation totals across the periods showed no statistically significant changes. The period 1953–1987 shows a decreasing trend in air temperature with a slight increasing trend in precipitation. On the other hand,

Table 2. Mean annual precipitation and mean annual air temperature in the hydrological years 1953–2022

Meteorological station	Precipitation (mm)			Temperature (°C)		
	1953–1987	1988–2022	1953–2022	1953–1987	1988–2022	1953–2022
Bielsko-Biała	996.5	978.6	987.6	7.8	9.0	8.4
Lublin	579.7	595.4	587.6	7.3	8.3	7.8
Warsaw	511.2	544.9	528.0	7.7	9.1	8.4
Toruń	531.3	543.5	537.4	7.6	9.0	8.3

the period 1988–2022 is warmer, with a clear upward trend in air temperature, and shows a slight upward trend in precipitation, except at the meteorological station of Bielsko-Biała. The upward trend in air temperature in the period 1988–2022 is, as in the whole period 1953–2022, statistically significant. The mean annual air temperature for 1988–2022 was more than 1.0 higher than during 1953–1987, as confirmed by data from other meteorological stations in Poland (Struzewska et al. 2024). The linear regression trends and Mann–Kendall trends of precipitation and air temperature are presented in the appendix (Table S1, S2).

Seasonal variability of precipitation and air temperature

The percentage share of precipitation in the summer half-year (V–X) ranged from 63.1% to 67.1%, whereas in the cold half-year (XI–IV) it ranged from 32.9% to 36.9% in the multiannual period 1953–2022. At most of the meteorological stations analysed, a slight increase in the share of precipitation in the summer half-year (except for Lublin) was recorded in the period 1988–2022 in relation to the same half-year in the multiannual period 1953–1987. In the summer half-year, the share of precipitation in the multiannual period 1953–1987 ranged from 62.7% to 67.3%, whereas in the multiannual period 1988–2022 it ranged from 63.85 to 67.7%.

The distributions of average monthly precipitation and air temperature in the respective periods are shown in Figure 5. Irrespective of the period considered, the average air temperature was highest in July and August and lowest in January and February. It can be clearly seen that the air temperature of individual months was higher in 1988–2022 than in 1953–1987. The distribution of monthly precipitation totals indicates that precipitation was highest in June, July and August and lowest in January and February. The greatest variations in the distribution of precipitation in individual years are at the Bielsko-Biała and Lublin stations in the summer months, mostly from June to September. At the Warsaw and Toruń stations, the differences in distribution of precipitation in individual months between sub-periods are small.

Variability of annual flows in 1953–2022

Flow variability was analysed in three periods: 1953–2022, 1953–1987 and 1988–2022. As indicated by the data on characteristic flows in the analysed periods (Table 3), the average annual flows (SSQ) in 1988–2022 were lower than in 1953–1987. The highest flows (WWQ) at most hydrological stations were recorded in the period 1953–1987, with the exception of the stations in Sandomierz, Dęblin and Warsaw, where the highest flows were recorded in the period 1988–1922. In turn, the lowest annual flows (NNQ) were higher in the period 1988–2022 than in the period 1953–1987, but the differences in magnitude of lowest flows decreased along the course of the river.

During the full study period 1953–2022, there was a decreasing trend in mean annual flows at all analysed hydrological stations except Nowy Bieruń (Fig. 4). Linear regression trends for mean annual flows are presented in the appendix (Table S3). The results of the Mann–Kendall test showed that the decrease in mean annual flows was not statistically significant. A larger variation was observed in the sub-period 1988–2022, where an increasing trend of mean annual flows was recorded at hydrological stations located in the upper reaches of the Vistula River (Nowy Bieruń, Szczucin, Sandomierz, Annopol), while a decreasing trend of flows was recorded at stations in the middle and lower Vistula (Dęblin, Warsaw, Toruń, Tczew). This trend was statistically insignificant. It should be emphasised that, irrespective of the observation period, no trends (other than trends with a very slight slope in mean annual flows) were recorded (Appendix Table S4). It should be noted here that, from a hydrological perspective, the observed upward trend in average

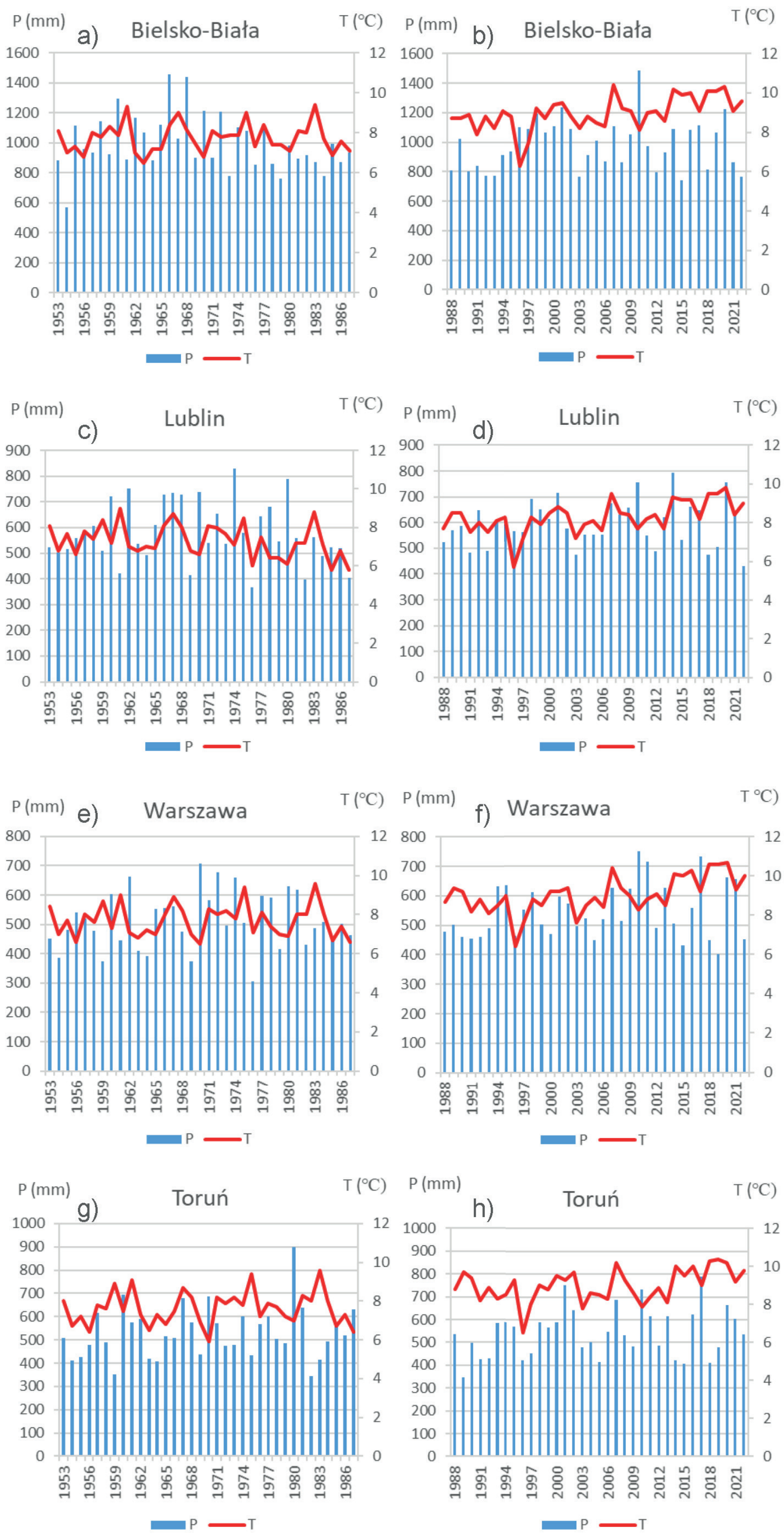

Fig. 3. Annual precipitation (P) and mean annual air temperature (T) at each meteorological station in the hydrological years: 1953–1987 (a) and 1988–2022 (b)

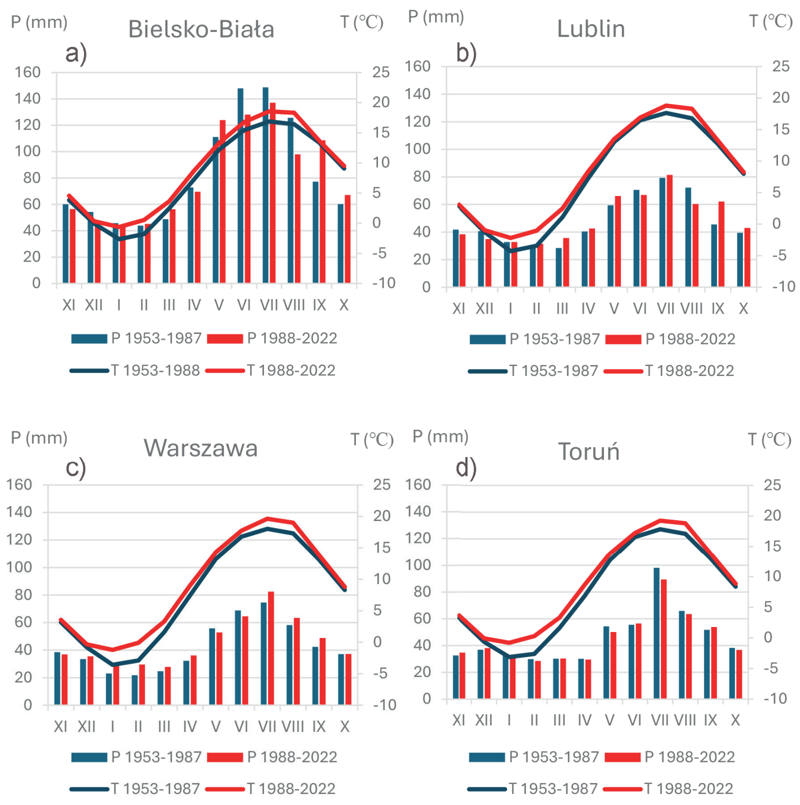

Fig. 4. Distribution of mean precipitation totals (P) and mean air temperature (T) for 1953–1987 and 1988–2022 at the meteorological stations in Bielsko-Biała (a), Lublin (b), Warsaw (c) and Toruń (d)

Table 3. Characteristics of characteristic flows of the Vistula River

Hydrological station	Period	WWQ ($m^3 s^{-1}$)/ WWq ($l s^{-1} km^{-2}$)	SSQ ($m^3 s^{-1}$)/ SSq ($l s^{-1} km^{-2}$)	NNQ ($m^3 s^{-1}$)/ NNq ($l s^{-1} km^{-2}$)
	1953–1987	524 / 295.34	21 / 11.95	1.5 / 0.85
Nowy Bieruń	1988–2022	763 / 430.04	21 / 11.89	2.5 / 1.41
	1953–2022	763 / 430.04	21 / 11.95	1.5 / 0.85
	1953–1987	4440 / 186.19	238 / 9.98	40.5 / 1.70
Szczucin	1988–2022	5010 / 210.10	229 / 9.60	60.9 / 2.55
	1953–2022	5010 / 210.10	233 / 9.77	40.5 / 1.70
	1953–1987	5040 / 158.56	293 / 9.22	57.0 / 1.79
Sandomierz	1988–2022	4470 / 140.63	283 / 8.90	72.0 / 2.27
	1953–2022	5040 / 158.56	288 / 9.06	57.0 / 1.79
	1953–1987	6010 / 116.76	443 / 8.61	92.0 / 1.79
Annopol	1988–2022	5350 / 103.94	414 / 8.04	97.4 / 1.89
	1953–2022	6010 / 116.76	429 / 8.33	92.0 / 1.79
	1953–1987	6000 / 87.96	517 / 7.58	114 / 1.67
Dęblin	1988–2022	5440 / 79.75	479 / 7.02	134 / 1.96
	1951–2022	6000 / 87.96	498 / 7.30	114 /1.67
	1953–1987	5570 / 65.89	583 / 6.90	112 / 1.32
Warsaw	1988–2015	5740 / 67.90	550 / 6.51	157 / 1.86
	1953–2022	5740 / 67.90	567 / 6.71	112 / 1.32
	1953–1987	6650 / 36.89	1016 / 5.64	234 / 1.30
Toruń	1988–2022	6190 / 34.34	912 / 5.06	218 / 1.21
	1953–2022	6650 / 36.89	964 / 5.35	218 / 1.21
	1953–1987	6430 / 33.20	1069 / 5.52	264 / 1.36
Tczew	1988–2022	6360 / 32.84	984 / 5.08	266 / 1.37
	1953–2022	6430 / 33.20	1028 / 5.31	264 / 1.36

Explanations: WWQ – highest flow of the multi-year period, SSQ – average flow of the multi-year period, NNQ – lowest flow of the multi-year period, WWq – highest unit runoff in a multi-year period, SSq – average unit runoff in a multi-year period, NNq – lowest unit runoff in a multi-year period annual flows – despite the lack of statistical significance – indicates an increase in flooding events. Conversely, a decreasing trend in average annual flows indicates, despite the lack of statistical significance, a decline in water resources available in the watershed, which is important from the perspective of water resource utilisation across various economic sectors.

Seasonal variability of flows

The Vistula is characterised by a predominance of flow in the winter half-year (Nov–Apr) over the summer half-year (May–Oct). In the years 1953–2022, depending on the station, the percentage share of the Vistula flow in the winter half-year ranged from 50.0% to 57.1% of total flow. The percentage share of flow in the winter half-year increases downstream along the Vistula. Winter flow was recorded to have predominated in between 38 and 56 years (depending on station) (Table 4). Little change is apparent in the breakdown by sub-period. In the period 1953–1987, the winter half-year exhibited the predominant percentage flow, except at the Szczucin station, where the summer half-year flow predominated. The percentage share of flow ranged from 49.6% to 56.4%. Between 1988 and 2022, the number of years (20–30) in which cold half-year flow dominated increased relative to the previous period 1953–1987 (18–26).

Mean monthly flows and their variability

The mean monthly flows of the Vistula throughout the year in the full study period 1953–2022 are presented in the Appendix (Fig. S1). The highest values of mean monthly flows were recorded in April, and the lowest in September and October. However, there were single years in which particular mean monthly flows were exceptionally high. These included May, which was associated with the 2010 floods that occurred in the Vistula basin. In May 2010, due to intense precipitation in southern Poland, there was a sudden surge of water in the upper and middle sections of the Vistula (Maciejewski et al. 2011). The intensity the flood's peak at the Toruń and Tczew stations was attenuated due to dikes below Warsaw having been breached.

The mean monthly flow values of the individual sub-periods indicate smaller flow amplitudes in the period 1988–2022 compared to 1953–1987 (Fig. 6). In general, peak mean flows were recorded in April. At the hydrological station at Nowy Bieruń, the maximum mean flows were shifted to April (1988–2022). The minimum values of monthly mean flows show greater variation. At the Nowy Bieruń station, the minimum values shifted from September (1953–1987) to August (1988–2022), whereas at the other hydrological stations they shifted from September (1953–1987) to October (1988–2022). In the lower reaches of the Vistula (Toruń and Tczew), the annual patterns of the two periods were similar to one another.

The variability of mean monthly flows (Cv), which systematically decreased along the river, was highest in the upper reaches of the Vistula and reached its lowest values at Tczew (Appendix – Fig. S2). In 1953–1987, the variability was highest in the summer months (i.e., June, July, August) and in March in the upper and middle reaches of the river. In the lower section of the Vistula, the variability of mean monthly flows held steady for most months of the year (except March). Noteworthy are the September and October increases in flow variability during 1988–2022.

Discussion

The article analyses the mean annual and monthly flows of the Vistula River at eight hydrological stations along its course for the hydrological years 1953–2022. There is a notable lack of trends in mean annual flows (or trends are only very slight). Thus, no significant changes in the annual flows were observed in the study period. The information obtained for the 70-year period is consistent with studies by other authors who analysed the variability of the Vistula River flows in the years 1951–2010 (Jokiel and Tomalski 2017; Wrzesiński and Sobkowiak 2020). The novelty of the research lies in its use of current data for analysis, especially for the period 1988–2022, during which, a significant decline in flows of great economic importance occurred. When determining the direction and trend of flow changes, the choice of the study period is extremely important (Bogdanowicz et al. 2021). The variability of water abundance in Polish rivers shows regional variability. Regardless of the month, rivers were less

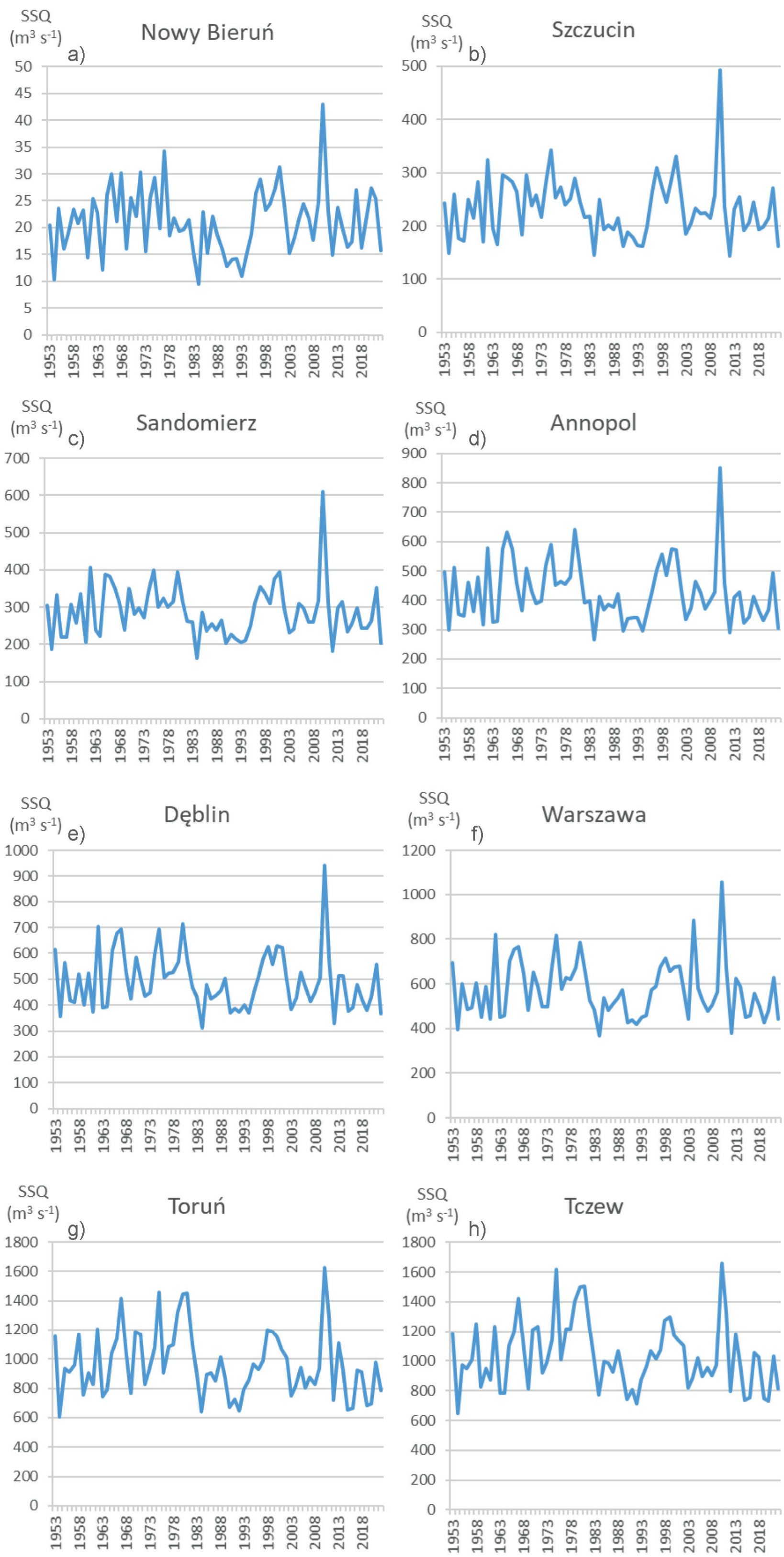

Fig. 5. Average annual flows (SSQ) of the Vistula River in the hydrological years 1953–2022 at hydrological stations at Nowy Bieruń (a), Szczucin (b), Sandomierz (c), Annopol (d), Dęblin (e), Warsaw (f), Toruń (g) and Tczew (h)

Table 4. Average % of flow in cold (XI–IV) and warm (V–X) half-years for 1953–2022 and for the years 1953–1987 and 1988–2022 (number of years in brackets)

No	Hydrological station	1953–2022		1953–87		1988–2022	
		XI-IV	V-X	XI-IV	V-X	XI-IV	V-X
1	Nowy Bieruń	52.0 (38)	48.0 (32)	50.9 (18)	49.1 (16)	53.0 (20)	47.0 (15)
2	Szczucin	50.0 (40)	50.0 (30)	49.6 (19)	50.4 (16)	50.5 (21)	49.5 (14)
3	Sandomierz	51.4 (47)	49.6 (23)	51.0 (23)	49.0 (12)	51.8 (24)	48.2 (11)
4	Annopol	53.1 (48)	46.9 (22)	52.8 (22)	47.2 (13)	53.3 (26)	46.7 (9)
5	Dęblin	53.6 (49)	46.4 (21)	53.4 (23)	48.6 (12)	53.8 (26)	46.2 (9)
6	Warszawa Nadwilanówka	54.3 (50)	45.7 (20)	53.6 (24)	46.4 (11)	54.7 (26)	45.3 (9)
7	Toruń	57.1 (56)	42.9 (14)	56.4 (26)	43.6 (9)	57.7 (30)	42.3 (5)
8	Tczew	56.5 (55)	43.5 (15)	55.9 (26)	44.1 (9)	57.1 (29)	42.9 (6)

abundant in water in the central part of Poland (in the lowlands) than in other regions of the country (Kubiak-Wójcicka et al. 2021), while mountain rivers were characterised by the highest abundance (Baran-Gurgul et al. 2023).

The results of this study indicate significant variability in trends over time, depending on the length of the time series analysed. The lengthening or shortening of the time-series dataset results in a strengthening or weakening of the trend, a change in the trend's directionality, or both (Górnik 2020). The division into two sub-periods adopted in this study (1953–1987 and 1988–2022) reveals that flows were more variable in each of the two sub-periods than in the full study period taken as a whole, although the differences were not statistically significant. The analyses confirmed significant changes in the mean annual air temperature over the long term, especially during 1988–2022, compared with the reference period 1953–1987. The latter years 1988–2022 were clearly warmer than the years 1953–1987, whereas no distinct increase in precipitation was recorded at the analysed meteorological stations. In Poland, over the full study period, annual precipitation totals changed significantly only in some areas of the country. In south-eastern, central-eastern and north-western Poland, precipitation increased significantly, whereas the total precipitation decreased only locally in south-western Poland (Kalbarczyk and Kalbarczyk 2021).

Many researchers emphasise that, although the mean annual flow remains unchanged or decreases slightly over longer study periods, there is considerable variability in flows throughout the year. Brzezińska and Wrzesiński (2025) showed that the effect of climate warming on extreme flows was clearly spatially differentiated, especially in spring and summer in central and eastern Poland. Seasonal changes in lows were particularly evident in small river catchments (Świątek and Walczakiewicz 2025) and mountainous regions (Mostowik et al. 2019; Baran-Gurgul 2022; Cupak and Kaczor 2023). A detailed study by Somorowska (2024) on 102 rivers in Poland revealed a clear shift in the timing of maximum spring water flow towards earlier in the season in many rivers across the country. An increase in maximum water flows was observed in 87 of the 102 rivers analysed over the period 1981–2020. In contrast, Raczyński and Dyer (2022) showed that the frequency of low flows in south-eastern Poland peaked in early August. This is consistent with the results for the Szczucin station, where the occurrence of lowest monthly mean flows shifted from August to September in the 1988–2022 sub-period. At Szczucin, the appearance of mean flow minima was delayed from September in the earlier sub-period to October in 1988–2022; this change occurred at all other hydrological stations except Toruń and Tczew. This may be due to the large increase in catchment area (below Warsaw, the Narew River joins the Vistula with the Bug River (catchment area is 74,522 km^2 according to Statistical Yearbook of the Republic of Poland, 2024) and the physiographic characteristics of the catchment, which may account for its high hydrological inertia. Research conducted by Mačiulytė et al. (2022) showed that annual precipitation in the eastern part of the Baltic Sea region increased significantly between 1950 and 2019, with positive changes observed throughout the year, except for April and September.

Studies conducted on central European rivers indicate that, with increasing air temperature, monthly flow will increase during winter seasons and decrease during summer seasons (Oblak et al. 2021; Sleziak et al. 2021; Orešić et al. 2024). In particular, the peak of

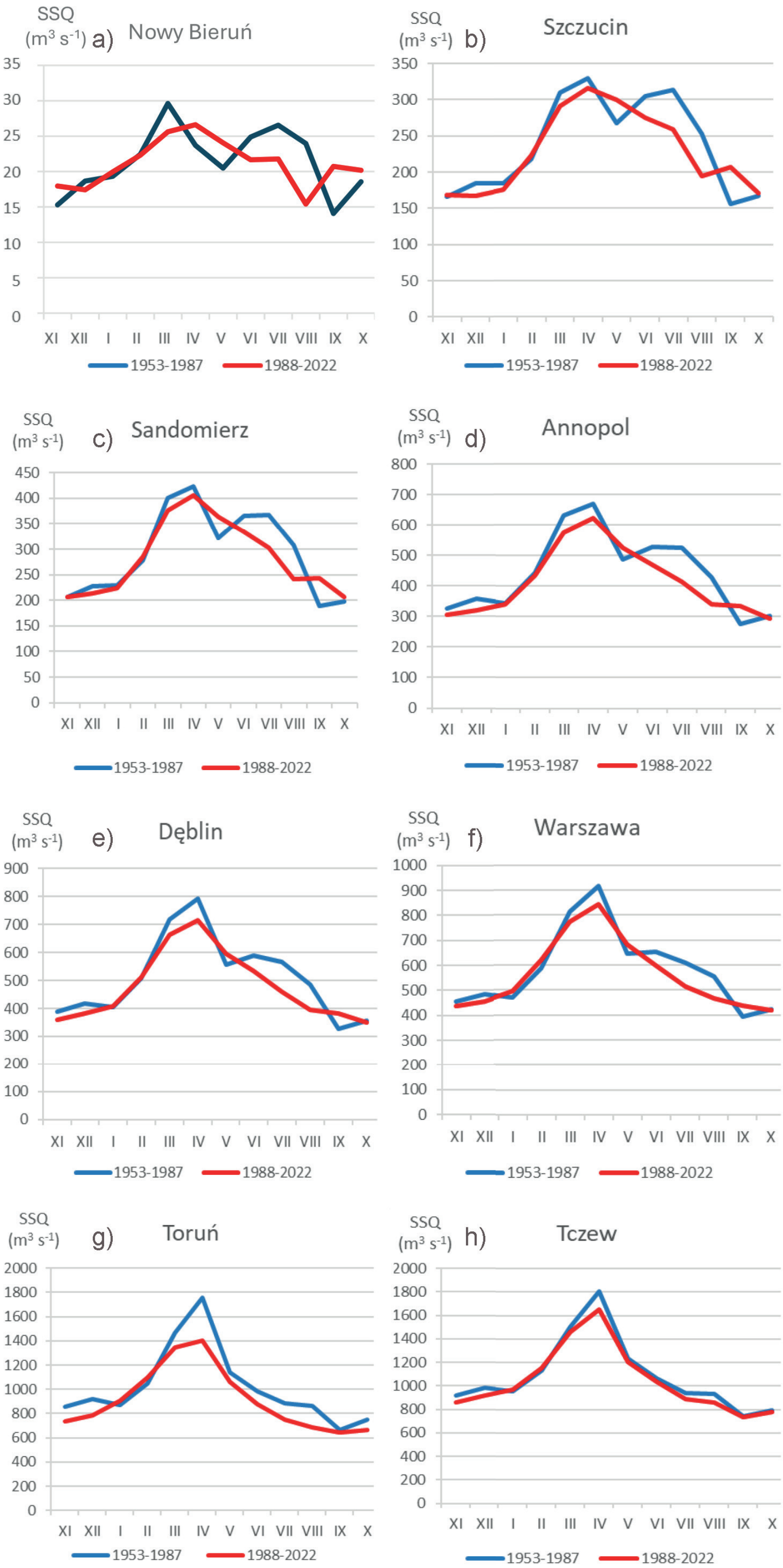

Fig. 6. Mean monthly flows (SSQ) of the Vistula River in the years 1953–87 and 1988–2022 at hydrological stations: Nowy Bieruń (a), Szczucin (b), Annopol (c), Dęblin (d), Sandomierz (e), Warsaw (f), Toruń (g) and Tczew (h). Explanations: XI – November, XII – December, I – January etc.

spring river flow is predicted to shift to earlier months for the Pripyat, Southern Bug and Dniester (Didovets et al. 2020). Additionally, a change in the month of occurrence of the average flow maxima and minima is noticeable. This phenomenon is noticeable in the flow of mountain rivers in Slovakia, Austria and Slovenia (Čanjevac and Orešić 2018). Studies by Pfeiffer and Ionita (2017) for the Elbe and Rhine rivers have shown that river flows vary significantly with rainfall and snowmelt in the upper part of the river basin. One reason why the water regime at downstream hydrological stations is less affected by climate change is that the reception of major tributaries reduces the effects found in the upper river basin. The results of the analyses of the Vistula River indicate changes in mean monthly flows especially during 1988–2022, but it will be necessary to study other hydrological elements to assess changes in the hydrological regime. According to Woś et al. (2022), reservoir storage plays a decisive role in shaping river flows in response to observed climate change, enabling a reduction in flows during periods of heavy precipitation and an increase in flows during periods of drought. This is particularly evident in the upper reaches of the Vistula and its upper tributaries, where reservoirs play an important role in water management. In the lower and middle reaches of the Vistula and on its tributaries, reservoirs have a smaller capacity, which limits their role in regulating flows over the long term. Another issue requiring detailed analysis involves the problem of water abstraction for economic purposes from both surface and groundwater sources (Kubiak-Wójcicka and Machula 2020). As emphasised by many authors, the study of the hydrological regime can be important for the management of water resources, including ecosystems and various branches of the national economy (Ďurigová et al. 2019; Oblak et al. 2021; Gnajto et al. 2024; Rattayová et al. 2024).

Conclusions

On the basis of the analysis carried out, it was concluded that:

- The mean annual air temperature in the multiannual period 1953–2022 showed a clear increasing trend (statistically significant) at all four analysed meteorological stations, which is particularly evident in the period 1988–2022. Annual precipitation totals exhibit no changes in precipitation in the analysed periods, or only small changes.
- The mean annual flows of the Vistula River in the 1953–2022 study period showed a downward trend except at the hydrological station Nowy Bieruń. The changes are not statistically significant.
- Mean annual flow values were higher in the 1953–1987 sub-period than in 1988–2022 and the whole full 1953–2022 period.
- In, no significant changes in river runoff were observed between the winter and summer half-years. The winter half-year flow was slightly higher in the 1953–1987 sub-period.
- Vistula flows exhibited seasonal variability during the hydrological year. The highest mean monthly flows of the 1953–2022 study period occurred in March and April at all hydrological stations, and the lowest in September and October.
- The distribution of mean monthly flow values of individual sub-periods indicates smaller flow amplitudes in the 1988–2022 sub-period compared to the earlier 1953–1987 sub-period.
- There was a shift in the maximum and minimum values of mean monthly flows in 1988–2022 compared to 1953–1987. In the upper reaches of the Vistula, maximum mean flows shifted from March to April (Nowy Bieruń). Conversely, minimum mean monthly flows shifted from September (1953–1987) (Nowy Bieruń) to August (1988–2022) at the Nowy Bieruń station, while at the other hydrological stations, the shift was from September (1953–1987) to October (1988–2022). In the lower reaches of the Vistula (Toruń and Tczew), the highest and lowest values of mean monthly flows occurred in the same months, and the courses of their annual cycles were similar.
- The variability of mean monthly flows (Cv) was highest in the upper reaches of the Vistula and decreased systematically along the river, reaching its lowest values at the station in Tczew. In 1953–1987, the variability of flows was highest in the summer months (June, July, August) and in March in the upper and middle reaches of the river. In the lower section of the

Vistula, the variability of mean monthly flows was more stable for every month of the year except March. Noteworthy is the increase in flow variability during the period 1988–2022 in September and October.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: MB; data collection: MB; statistical analysis: MB, NB, MR-K; manuscript preparation: MB, MR, AB, MR-K; literature review: NB, MR, AB.

Supplement

Additional materials related to the article are available at the link: https://apcz.umk.pl/BOGPGS/article/view/67900/46777

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Received 1 January 2026
Accepted 30 April 2026