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Variation in runoff in Poland in relation to precipitation and air temperature

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Abstract: The study presents variation in river runoff in Poland in relation to precipitation and air temperature. The annual runoff value was analysed in average, warm wet, warm dry, cold dry, and cold wet years, categorized on the basis of average annual air temperature and annual precipitation totals.
In addition, a statistical mathematical model of annual runoff was developed as a function of input variables – temperature and precipitation in the warm half and cold half of the year. Statistically significant differences were demonstrated between the runoff values for warm dry years, average years, and cold wet years.

Keywords: Precipitation; Temperature; Hydrological water balance; Runoff; Poland.

1 INTRODUCTION

According to calculations made at the Institute of Meteorology and Water Management (IMGW), the total average runoff in Polish rivers in the 20th century amounted to 61.5 km^3 (Fal and Bogdanowicz, 2002). The same value is reported by Jokiel and Stanisławczyk (2012) for 1951–2010, and Gutry-Korycka et al. (2014) report a very similar value of 61.6 km^3 for the long-term average from 1946–2011. This corresponds to an average runoff layer of 197 mm and about 1612 m^3 per capita. Although other values for per capita water resources have been reported, such as 1839.3 m^3/year (average from 1946–2011) (Gutry-Korycka et al., 2014), 1566 m^3/year (average from 1999–2018) (Kubiak-Wójcicka and Machula, 2020) or 1453 m^3 in 2000 (WRI, 2000; Kowalczak, 2008), they are among the lowest in Europe, with average water resources of 4230 m^3 per capita (Kowalczak, 2008). Due to the transitional Polish climate, total annual river runoff in the country is highly variable between years (Wrzesiński et al. 2023). In a very wet year, runoff in Polish rivers may amount to even 89.9 km^3 of water (e.g. in 1981), while in an exceptionally dry year it can be less than 37.6 km^3 (in 1954). The ratio of these values is 2.4, which is one of the highest in Europe (Fal, 1993).

An important factor affecting river runoff is changes in precipitation. A study of changes in selected hydroclimatic characteristics in Poland in 1881–1980 (Jokiel and Kożuchowski, 1989) compiled the results of research on the periodicity of precipitation in Poland reported by various authors. The results confirm observations of a prevailing trend of a short-term (a few years) rhythm of changes in precipitation. Long-term fluctuations were observed as well. In the years 1881–1980, two periods of climate oceanicity can be seen in Poland – at the start of the 20th century and in the 1960s and 1970s. They are separated by a period of continentality, with a peak recognized in the 1930s on the basis of climatological indicators of continentality and one in the 1950s based on the lowest precipitation totals. Fluctuations in climate continentality, including precipitation fluctuations, suggest that they are a manifestation of cyclical – or more precisely, rhythmic – climatic fluctuations, and the changes in precipitation described here seem to correspond to the 75±2.5-year cycle established by Boryczka (1984), with maxima in 1916 and 1991 and minima in 1878 and 1953.

A similar precipitation cycle was established by Kaczorowska (1962): a 71-year cycle for Warsaw and a 73-year cycle for Wrocław. Changes in precipitation are undoubtedly the main factor influencing river runoff. Both annual runoff and runoff from the warmer and colder halves of the year are positively and statistically significantly correlated with precipitation, with correlation coefficients of 0.58, 0.54 and 0.47, respectively, while the correlation with air temperature is statistically significant only for the warm half of the year, with a coefficient of −0.32 (Jokiel and Kożuchowski, 1989). Variation in Polish river runoff, however, is greater than the variation in precipitation (Dębski, 1961), which means that changes in precipitation do not fully explain the dispersion of runoff values.

The acceleration of climate warming, which has continued for more than 40 years and is now unquestioned, specifically the rapid increase in air temperature, the increase in precipitation totals, changes in the seasonal distribution and nature of precipitation, and the increase in evapotranspiration, entails serious changes in the structure of the water balance, which determines the volume of water resources in Poland and Europe (Stagl et al., 2014; Gutry-Korycka and Jokiel, 2018; Bartczak et al., 2024). The direct cause of the increased interest in modern climate change is the second phase of global warming, observed since the mid-1970s (the first was in 1920–1940) (Przybylak, 2008). According to Migała and Getko (2003), the extreme increase in air temperature in Europe, which began in the last two decades of the 20th century, may have been induced by two simultaneous factors: the influx of warm air masses from the Atlantic (positive NAO index) and the increase in solar activity (IPCC 2021).

The pace of global warming has been increasing significantly (IPCC 2013, 2021, 2023; Rahmstorf et al., 2017; Kundzewicz et al., 2020). Comparison of average global air temperatures for each decade in the years 1931–2010, after rounding to 0.1°C, shows temperatures of approx. 13.9°C in the first five decades, but increasing values in 1981–1990, 1991–2000 and 2001–2010: 14.1, 14.3 and 14.5°C, respectively (WMO Report, 2013). In Poland, the values of temperature trends, beginning with the penultimate decade of the 20th century, are somewhat higher than the global values. Kożuchowski and Żmudzka (2001) present changes in average annual air temperatures in Poland in 1951–2000 in the form of a trend line, accenting the marked increase in temperature from approx. 7.5°C in 1951–1960 and 1961–1970 to 8.7°C at the end of the 1991–2000 decade. Żmudzka (2004) distinguishes the first three decades of the 50-year period of 1951–2000, with spatially averaged air temperatures of 7.7, 7.5 and 7.7°C, respectively, and the two subsequent warmer decades, with temperatures of 8.0 and 8.3°C.

Very similar values were reported by Wójcik and Miętus (2014) for successive decades of 1951–2010: 7.6, 7.4, 7.6, 8.0, 8.3 and 8.6°C. The spatially averaged annual air temperature for Poland for the most recent and warmest decade of 2011–2020 was as high as 9.3°C (Miętus and Marosz, 2021). The 30-year average annual air temperature values for Poland are increasing: for the periods of 1951–1980, 1961–1990, 1971–2000, 1981–2010 and 1991–2020, after rounding to 0.1°C, they are 7.2, 7.3, 7.6, 7.9 and 8.7°C, respectively (Miętus, 2021).

Despite the lack of significant trends, variability of precipitation is increasing (Szwed 2019; Rutkowska et al., 2025). The coefficient of variation of about 0.10 for annual totals in the last three decades of the 19th century and the first decade of the 20th century increased to about 0.15 in the penultimate decade of the 20th century (Kożuchowski, 1996). For 1971–2000 it was 0.17 (Ziernicka-Wojtaszek, 2006), and for 2001–2018 it increased to 0.19 (Ziernicka-Wojtaszek and Kopcińska, 2020).

The aim of the study was to determine variation in the total annual runoff in Poland depending on variable pluviothermic conditions, i.e. precipitation, the main factor determining runoff, and increasing air temperature during the pronounced phase of global warming. Particular focus was placed on the role of temperature in determining runoff volume. It was hypothesized that precipitation and air temperature values would have an equal influence on the runoff values in Poland during the period of marked global warming at the turn of the 21st century.

2 MATERIALS AND METHODS

2.1 Data collection

The analysis was conducted using data on runoff in Poland published in the Bulletin of the National Hydrological and Meteorological Service No. 13 (215) of 2019 for the years 1971–2018. Despite the availability of a longer data series, the 1954–1970 period was not used so that the analysis would cover only the second phase of modern warming, which began in the mid-1970s. In addition, a meteorological database was created based on the Institute of Meteorology and Water Management National Research Institute database for 53 stations distributed evenly around Poland. Data on monthly values were averaged for average annual periods and semi-annual periods for the winter and summer half of the year. The winter half-year was defined as November to April, and the summer half-year as May to October.

Annual runoff in Poland was studied in relation to the average annual air temperature and annual precipitation totals in warm wet, warm dry, cold dry, and cold wet years. The dividing lines were the mean values (1971–2018) of these two meteorological variables. In addition, a fifth category of years was distinguished for average values. The runoff values in individual categories of pluviothermic conditions were compared using a significance test for differences.

2.2 Statistical analysis

An attempt was made to characterize the complex relationships linking runoff values in Poland with precipitation and air temperature, which influences evapotranspiration, using optimization methods. Computer programs automatically search for the best fit of measured values and values calculated by the model. The modelling results can provide the basis for important decisions for the environment and economy, including measures aimed at adapting to climate change.

With regard to annual runoff values in relation to average air temperatures for the summer half-year and winter half-year, the stepwise multiple regression method was used to search for the form of a regression function (mathematical model) which would best approximate the annual runoff value (R) in Poland as a function of winter and summer air temperature values and of winter and summer precipitation totals, varying in individual years. The significance of the fit of the function was determined for $\alpha = 0.05$. The most complex regression function has four independent variables: temperature in the winter half-year (tw), temperature in the summer half-year (ts), precipitation in the winter half-year (pw), and precipitation in the summer half-year (ps). The function takes the following form:

$$R = a_0 + a_1 \cdot tw + a_2 \cdot pw + a_3 \cdot ts + a_4 \cdot ps + a_5 + tw^2 + a_6 \cdot pw^2 + a_7 \cdot ts^2 + a_8 \cdot ps^2 + a_9 \cdot tw \cdot pw + a_{10} \cdot tw \cdot ts + a_{11} \cdot tw \cdot ps + a_{12} \cdot pw \cdot ts + a_{13} \cdot pw \cdot ps + a_{14} \cdot ts \cdot ps \quad (1)$$

The first four terms contain individual variables, the second four terms contain the same meteorological variables in the second power, and the final six contain their interactions in the first power. The value a_0 is a constant, and the quantities a_i, i = (a_1, a_2, a_3, …, a_{14}) are the sought-for stepwise multiple regression coefficients of the independent (input) variables. These quantities are unknowns in the assumed form of the regression function.

There are three methods for searching for a significant regression function: elimination, addition, and elimination–addition (Draper and Smith, 1973; Kunwoo, 1999). The addition method, which was used here, involves successively introducing single terms (the most significant) to the function, i.e. building the simplest regression function and gradually increasing it (Draper and Smith, 1973; Kunwoo, 1999). After the assumed form of the regression function is entered into the stepwise multiple regression program, together with experimental data gathered during the time string of N = 48 years, consisting of temperatures and precipitation in the summer half-year (May to October) and winter half-year (November to April), the program calculates a matrix of correlation coefficients of all variables $r(y_i, x_j)$, where i, j = 1, 2, 3, …, 14. The program calculates the following values for each step: the step number, R – multiple correlation coefficient, se – standard deviation of the residual (standard error), the numbers of the variables introduced for their identification, the value of Fisher's F-test for the degrees of freedom (N-k-1) in a given step (where: N – number of observations, k – number of independent variables), a_i – values of regression coefficients corresponding to the independent variables j, a_0 – value of the constant in the regression equation, and t_j – value of Student's t test for each multiple regression coefficient for given degrees of freedom. Based on the set of calculated data, the best form of the function should be chosen according to statistical principles and the natural phenomena represented by the variable data. The most important criteria for choosing the best regression equation to adequately describe the phenomenon are as follows:

- The multiple regression coefficient r should be as large as possible, close to 1. The value of Fisher's F-function, i.e. the numerator of the expression F/F_{kr} in the inequality $F/F_{kr(\alpha, N-k-1)} \geq 1$, representing the hypothesis that the model is adequate to the subject of the analysis ($F \geq F_{kr}$), should be as large as possible, so that the adopted condition is fulfilled (at least equal to 1). This requires the adoption of a level of significance, e.g. $\alpha = 0.05$, and the determination of the number of degrees of freedom of the critical value of $F_{kr(\alpha, N-k-1)}$, where: N – number of observations, k – number of variables in the regression equation. Values of F_{kr} are given in statistical tables (Mańczak, 1976; Zieliński, 1972).
- All regression equation coefficients a_i should be significant at the adopted level of significance. The significance of individual regression coefficients is tested by Student's t-test with similar use of tabulated values of t_{kr} from Student's t-distribution at defined levels of significance α, and the value of $t/t_{kr(\alpha, N)}$ should be ≥ 1. This condition, also written as $t \geq t_{kr}$, means that the hypothesis that the tested quantity is significant is true.
- The correlation coefficients of the dependent variable and independent variables in the regression equation should be as large as possible.
- The cross-correlation coefficients between the independent variables in the regression equation should be as small as possible.

3 RESULTS

3.1 Weather – general characterization of pluviothermic conditions and runoff during the study period

The study period can be considered representative of the 1981–2010 climate normal. The average annual air temperature calculated for 1971–2018 is 8.3°C, which is the same as the 1981–2010 normal (Wójcik and Miętus, 2014). The average precipitation total from 1971–2018 was 610 mm, which was nearly equal to the normal of 609 mm (Miętus, 2021) or 607 mm (Grzywna et al., 2020). The runoff of 61.5 km^3 was the same as for the entire 20th century (Fal and Bogdanowicz, 2002).

The lowest average annual air temperature of 6.2°C was recorded in 1996, and the highest temperature of 10.0°C in 2007. During the 48-year study period, substantial temperature fluctuations occurred, which are typical of Poland's transitional climate, with an overall upward trend of 0.36°C/10 years, significant at a level of 0.001. The correlation coefficient between temperature and time was 0.55 (Fig. 1). This was more rapid than in 1951–2020, when the increase was 0.29°C/10 years (Ustrnul et al., 2021).

Precipitation fluctuated widely during the study period, from 460 mm in 2015 to 771 mm in 2010. Higher precipitation was recorded at the start of the study period in the years 1971–1981 and at the end of the study period, from 2001. The years 1982–1996 were a period of decreased precipitation. Precipitation showed a weak and statistically non-significant increase of 7.56 mm/10 years. The linear correlation coefficient for annual precipitation totals and time is 0.14 (Fig. 1).

Runoff in Poland ranged from 40.8 km^3 in 2015 and 41.4 in 2016 to 87.4 km^3 in 1975. It was slightly lower in 1981, at 87.1 km^3. Runoff showed a statistically significant (significance level of 0.05) decreasing trend of 2.65 km^3/10 years (8.49 mm/10 years). The correlation coefficient between runoff value and time was 0.30 (Fig. 1).

Comparison of the two 30-year periods (1971–2000 and 1989–2018) reveals a 0.7°C increase in the average annual air temperature and a slight increase in the precipitation total, amounting to 14.7 mm. Despite this, the total runoff decreased, both in volume (−5.8 km^3) and per unit area (−18.4 mm), which may be indicative of the intensification of evaporation processes in the warmer climate (Table 1).

To sum up, the marked increase in air temperature and less pronounced increase in precipitation during the period analysed were accompanied by a statistically significant downward trend in annual runoff from Poland. Temperature can be assumed to have played a very important role in determining runoff values during the study period.

3.2 Modelling and estimating changes in the water balance

The average water balance in Poland in the periods 1971–2000 and 1989–2018 for the values measured was as follows:

1971–2000 precipitation 600.4 = runoff 203.6 + evaporation 396.8 (mm)

1989–2018 precipitation 615.1 = runoff 185.2 + evaporation 429.9 (mm)

Analysis of the water balance equations for the two periods reveals changes in the relationships between the main components of the water balance. In the years 1971–2000, the average annual precipitation total was 600.4 mm, for which runoff accounted for 203.6 mm and evaporation for 396.8 mm. In 1989–2018, the average precipitation total increased to 615.1 mm, while runoff decreased to 185.2 mm and evaporation increased to 429.9 mm.

These changes indicate that despite the slight increase in precipitation, the share of evaporation in the water balance increases at the expense of runoff in the conditions of a warming climate. This may suggest intensification of evapotranspiration processes associated with higher air temperatures. In consequence, water retention in catchments may be less effective, which in the long term may affect the availability of water resources and the runoff regime.

This difference suggests the possibility, and even necessity, of using a somewhat shorter period for runoff modelling, ideally beginning in 1985, when the temperature began to increase at a faster rate. Comparison of these two periods reveals a slight overestimation of runoff values.

Table 1. Average annual air temperature, annual precipitation totals, and annual runoff in two 30-year periods.

	1971–2000	1989–2018	Difference
Temperature (°)	8.0	8.7	0.7
Precipitation (mm)	600.4	615.1	14.7
Runoff (km^3)	63.7	57.9	–5.8
Runoff (mm)	203.6	185.2	–18.4

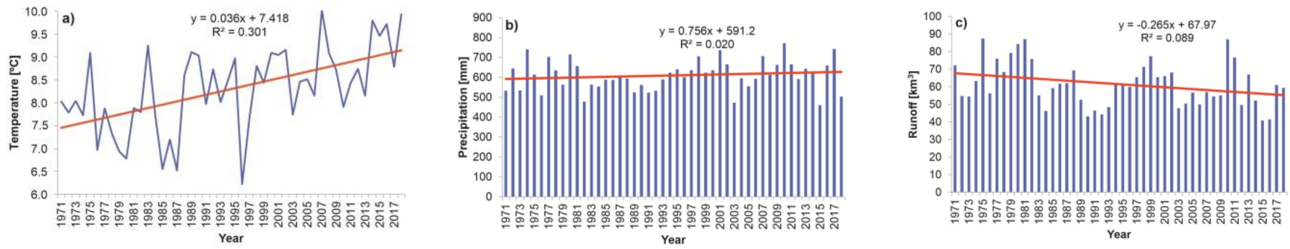

Fig. 1. Course of average annual air temperature (a), annual precipitation totals (b) and annual runoff (c) in Poland.

3.3 Effect of air temperature and precipitation on the runoff value in light of various configurations of annual values for pluviothermic conditions

After distinguishing five groups of years with markedly different pluviothermic conditions, i.e. warm and wet, warm and dry, cold and dry, cold and wet, and average years, a clear differentiation of values for annual runoff can be observed between categories of years. In average years, the annual runoff value was 59.2 km^3, and similar values of 60.1 km^3 and 62.8 km^3 were detected in cold dry and warm wet years. There was marked variation between warm dry years, with low runoff averaging only 50.3 km^3, and cold wet years, when runoff was the highest, averaging 73.3 km^3 (Fig. 2). The differences in runoff between cold dry, average, and warm wet years, with values of about 60 km^3, are not statistically significant. Low temperatures compensate for low precipitation, and high precipitation at high temperatures, due to increased evaporation, does not cause a significant increase in runoff. In contrast, the differences between runoff in warm dry and cold wet years are statistically significant at a significance level of 0.001.

3.4 Analysis of the effect of air temperatures and precipitation in half-year periods on runoff using stepwise multiple regression calculations

The calculations indicate that the relationship between the meteorological parameters taken into account and the runoff value in the hydrological year is best described by the following mathematical model:

$$R = -52.94379 + 13.5673 \cdot ts - 0.70506 \cdot tw^2 + 20.54759 \cdot pw^2 - 6.43022 \cdot pw \cdot ts + 2.89025 \cdot pw \cdot ps \quad (2)$$

where R is expressed in (km^3), tw and ts in (°C), and pw and ps in (dcm). Table 2 shows runoff values (km^3) calculated using t equation 2, in relation to increasing temperatures in the winter and summer half-years, as well as increasing precipitation in the winter and summer hydrological half-years.

The model makes it possible to evaluate and predict the annual runoff volume in Poland in conditions of high and increasing variation in precipitation and increasing air temperature in the global warming process. Assessing the 'efficiency' of the increase in air temperature, i.e., the decrease in runoff per unit of temperature increase, based on the equation obtained and values presented in Table 2, we can estimate that an increase in temperature of 1°C and low precipitation levels of about 190 mm in winter and 360 mm in summer will cause a decrease in runoff of 1 km^3. At a temperature 1°C higher than average, the decrease will be about 3.2 km^3, and at temperatures 2°C higher than average, the decrease will be about 5.6 km^3. At higher precipitation totals of about 246.7 mm for the winter half-year and 462.3 mm for the summer half-year, an increase in temperature to the average value causes a decline in annual runoff of 4.4 km^3. At a temperature °C higher than normal in the summer and winter half-years, annual runoff decreases by 6 km^3. If the temperature increases by 2°C, the decrease in annual runoff is 9.0 km^3. For the highest precipitation values, i.e., 302 mm in winter and 563 mm in summer, the values will be approximately 7.0, 9.0 and 12.6 km^3, respectively (Table 2).

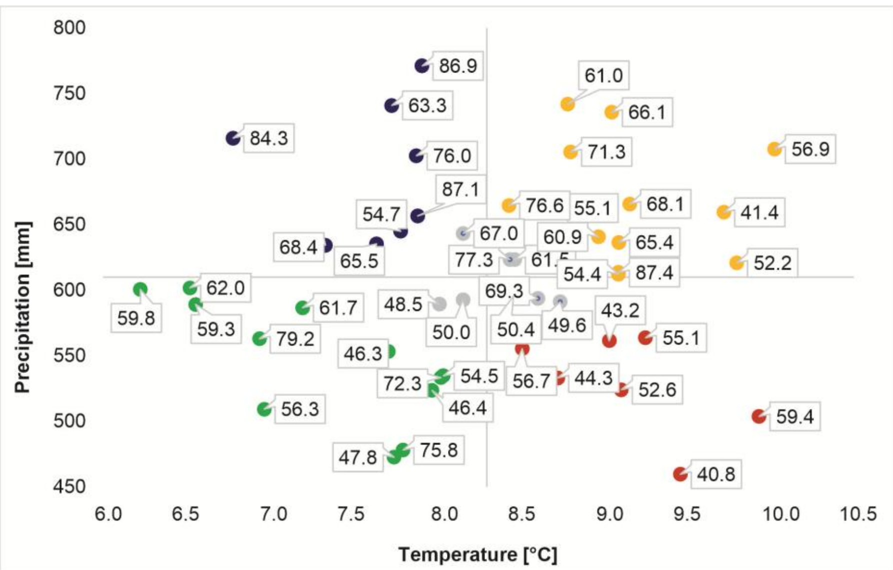

Fig. 2. Annual runoff values (km^3) for years: warm and wet (yellow), warm and dry (dark red), cold and dry (green), cold and wet (navy blue), and average years (grey).

Table 2. Runoff values in relation to increasing air temperature values in both the winter and summer half-years and increasing precipitation values in the winter and summer hydrological half-years.

Temperature in the winter half-year (°C) / Precipitation in the winter half-year (mm)	Temperature in the winter half-year (°C) / Precipitation in the summer half-year (mm)	1.2	1.6	2.1	2.5	3.0	3.4	3.9	4.3
Temperature in the summer half-year (°C) / Precipitation in the winter half-year (mm)	**Temperature in the summer half-year (°C) / Precipitation in the summer half-year (mm)**	14.4	14.7	15.1	15.4	15.8	16.1	16.5	16.8
191.3	361.7	59.5	59.0	58.3	57.3	56.0	54.4	52.6	50.5
246.7	462.3	71.1	69.4	67.4	65.2	62.7	59.9	56.8	53.5
302.0	563.0	98.5	95.5	92.4	88.9	85.2	81.1	76.8	72.2

The most important parameters calculated in the statistical analysis and their values and explanations are as follows:

R = 0.581 – the multiple regression coefficient provides information about the strength of the relationship between the dependent variable y and the entire set of independent (explanatory) variables $x_i, \ldots, x_k$. In this case, the critical value of the multiple regression coefficient for the multiple regression equation is $R_{kr(\alpha, K, N)} = R_{kr(0.05, 5, 48)} = 0.438$ (Zieliński, 1972).

S_e = 10.736 – standard deviation of the residual. The S_e value expresses the average deviation of the experimental values of the target variable from the theoretical values calculated from the estimated regression function.

F = 4.269 – value of Fisher's F-function in the regression equation. This value is essential for analysing the significance (adequacy) of the regression function at the adopted significance level of α = 0.05 by Fisher's F-test. The Fisher test involves testing the relation $F/F_{kr(\alpha,N-K-1)} \geq 1$. If for the adopted significance level α the value of the function $F \geq F_{kr(\alpha,N-K-1)}$, where F_{kr} is read from tables, then the function is significant at this level of significance or a higher level. The function with the best fit has the highest value for $F/F_{kr} \geq 1$. The calculated value of F is 4.269. The critical value, read from the tables, is $F_{kr}(\alpha,N-K-1) = F_{kr(0.05, 42)} = 2.418$ (IBM, 1970; Mańczak, 1976).

The significance of individual coefficients of independent variables of the stepwise multiple regression was tested by Student's t-test. The critical value of F_{kr} for the defined number of degrees of freedom is $t_{kr(\alpha, N-K-1)} = t_{kr(0.05, 48-5-1)} = 2.0181$. The values of Student's t function for individual independent variables in the selected regression equation are $t_3 = 2.263$, $t_5 = -2.197$, $t_6 = 2.318$, $t_{12} = 2.412$, and $t_{13} = 2.681$. All results are greater than the critical values, so the coefficients of the regression equation are significant at the adopted level of α = 0.05.

4 DISCUSSION

The analysis of the results for the 48-year observation sequence from 1971 to 2018 includes the initial decade, when there was not yet a pronounced, abrupt increase in air temperature either globally or in Poland. It also includes the period beginning with the penultimate decade of the 20th century and including nearly two decades of the 21st century, in which the air temperature increase is pronounced – each decade is about 0.3°C warmer than the preceding one in terms of average annual temperature (Żmudzka, 2004; Wójcik and Miętus, 2014). The main goal of the study was to determine the effect of this temperature rise on the value of the annual runoff in Poland. Only analysis at the input stage – precipitation taking into account thermic conditions – and output stage – runoff of water from the catchment – was performed.

Kostić et al. (2016) created a similar model, not for the annual flow rate but for the monthly flow rate of the Great Morava, the largest river in Serbia, based on research from 1950–1990, as a non-linear function of air temperature and precipitation. According to the authors, although the model was aimed at identifying the relationship between the input factors and the response (output data) without analysing the internal structure of the physical process, it can be used to predict monthly flow on the basis of weather forecasts. This means that this is an important element of decision-making processes in water management. It is extremely convenient for engineering practice, as precipitation and air temperature are commonly measured climate parameters. Secondly, the proposed method, which uses only precipitation and air temperature to predict discharge, may be useful when other parameters describing catchment properties are unavailable due to an inadequate network of measurement stations (Kostić, 2016). But there are also examples of individual analyses of changes in air temperature, precipitation and runoff over time (Kubiak-Wójcicka, 2020). The main aim of the study was to determine how changes in air temperature and precipitation in the Vistula basin translated to the hydrology of the river. Trends in temperature, precipitation and runoff during a 65-year observation period (1951–2015) were analysed, and two sub-periods, 1951–1980 and 1981–2015, were compared. While the years 1951–1980 were characterized by a statistically significant increase in average annual runoff, the perceptible downward trend in the volume of runoff in the years 1981–2015 was not statistically significant in comparison to 1951–1980 (Kubiak-Wójcicka, 2020).

The problem can be simplified or generalized by including the whole of Poland in the analysis, without taking into account regional variation in the runoff–precipitation relationship. Individual catchments are highly varied in terms of elements of the natural environment, such as geological structure, relief, hydro-climatic conditions, soil cover, vegetation, and land use, which determine the runoff regime. This regime determines the state of the river system and its reaction to the climate system and the physical and geographic features of the river basin (Fal, 1997; Gutry-Korycka, 2001; Jokiel and Stanisławczyk, 2012). The typology of the regimes of Polish rivers has been presented in works by Dębski (1961), Dynowska (1971) and Wrzesiński (2017).

Older studies from the early 20th century – the equations of Opokow from 1904 and Keller from 1906 (qtd. in Kossowska-Cezak and Bajkiewicz-Grabowska, 2008) – made the runoff value practically dependent on precipitation, as the runoff was equal to precipitation minus the empirically established value multiplied by a certain coefficient. According to Opokow's formula $H = 0.85 (P - 395)$, the runoff for the study period was 57.2 km^3, and thus somewhat lower than the average runoff from the years 1971–2018, amounting to 61.5 km^3. According to a study covering the 100-year period from 1881 to 1980, both annual runoff and runoff from the summer and winter half-years had positive, statistically significant correlation coefficients with precipitation, with values of 0.58, 0.54 and 0.47, respectively, while the correlation with air temperature was statistically significant only for the summer half-year, with a coefficient of −0.32 (Jokiel and Kożuchowski, 1989). According to that study, the effect of precipitation was dominant, but the effect of temperature began to be evident as well. The results of the present study, on the other hand, show a significant effect of temperature and precipitation in both the summer and winter half-years.

This effect of temperature on the runoff value, in addition to the fundamental effect of precipitation, is also observed in neighbouring countries. According to Pekárová et al. (2023), assuming a temperature increase of +1°C, runoff is projected to decrease across almost all sub-basins of the Danube River. A study in five large German catchments shows that a large portion of the changes in the discharge regime can be explained by climate change, which has been clearly evident since the acceleration of global warming from the mid-20th century. Other changes have been caused by the construction of dams and regulation of rivers, changes in land use, and mining activity (Bormann, 2010). Changes in the runoff regime in Lithuanian rivers can also be linked to climate change. Rapid increases in runoff in January and February in the years 1960–2009 were the greatest changes in the entire observation period of 1812–2009. A decrease in the runoff rate in April was another of the most significant changes. Spring flooding and minimum discharge in winter are observed earlier than previously (Stonevičius et al., 2014). In Estonia in 1951–2015, warming in the winter and spring associated with the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) indices, as well as less pronounced changes in precipitation, with the greatest increases in the cold half of the year – from November to March – and in June, led to a considerable increase in winter runoff, especially in March. The maximum runoff caused by snowmelt moved up from April to March, and the runoff in April decreased. There were few changes in runoff in the warm half of the year (Jaagus et al., 2017). Further south in Macedonia, significant downward trends were noted in each of 13 stream gauges during the last four decades of the 20th century. The cause of the decrease in discharge was not decreasing precipitation, but a marked upward trend in the average annual temperature, causing an increase in evaporation. The most important asset of that research is the rare set of values of discharge in natural conditions, as only stream gauges in the upper reaches of the rivers were used in order to rule out any significant impact of human activity. The results can be extrapolated to other Balkan countries for a better understanding of modern discharge trends (Radevski et al., 2018). According to Sleziak et al. (2023), the evaluation of the spatially distributed hydrological model MIKE SHE, applied to simulate hourly catchment runoff in the Jalovecký Creek for the years 2014, 2015, 2017, and 2018, highlighted the need to focus on runoff events induced by short, high-intensity rainfall. These events were often not adequately captured by the model. Areas of potential saturation, initially confined to zones adjacent to the stream network during smaller events, were observed to expand into the flatter sections of the mountain valleys during larger events. To verify this expansion, field-based measurements are recommended. Furthermore, the quantification of the spatial extent and duration of hydrologically connected areas within the catchment during such events has yielded new insights that are valuable for advancing the understanding of runoff generation processes in similar mountainous environments.

5 CONCLUSIONS

The natural variation of the transitional climate of Poland between the oceanic climate of Western Europe and the continental climate of Eastern Europe causes substantial fluctuations in river runoff in Poland, ranging from 62% to 142% of the long-term average runoff.

Average runoff is generally recorded in years with near-average pluviothermic conditions, as well as in years deviating from them, i.e., cold dry years and warm wet years. The lowest runoff, amounting to about 50 km^3, is recorded in warm dry years, and the highest, about 73 km^3, in cold wet years. This indicates the simultaneous effect of both precipitation and temperature on the annual runoff value.

Analysis of annual runoff in varied pluviothermic conditions in the cold and warm halves of the year revealed that both temperature and precipitation significantly influence the runoff value in both parts of the year. The reduction in the runoff value is not proportional to the increase in temperature, but it takes on increasingly high values and is represented by an increasing function.

The very pronounced and significant increase in air temperature during the study period, amounting to 0.36°C/10 years, and the less distinct non-significant increase in precipitation, amounting to 7.56 mm/10 years, was accompanied by a statistically significant downward trend in annual runoff in Poland, amounting to 2.65 km^3/10 years (8.49 mm/10 years).

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