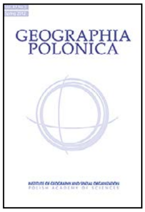

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IMPACT OF CLIMATE CHANGE ON WATER RESOURCES IN LOWLAND POLAND

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Abstract

In this study, climate change was described by area-averaged annual precipitation totals and area-averaged mean annual temperature values in each catchment area, while water resources were described by mean monthly specific discharges in these catchments. Thirty-seven catchments located entirely in lowland areas of Poland were selected for the analysis. The research was conducted based on data from hydrological years 1961-2021. In order to compare changes in annual precipitation totals and mean annual air temperature values with changes in annual mean specific discharge, linear trends of the mentioned variables were determined. The effect of precipitation totals and air temperature on specific discharge in individual catchments was determined using multiple regression. Statistically significant increase in the value of mean annual air temperature was recorded for all studied catchment areas. In none of the examined catchments were the changes in annual precipitation totals statistically significant. Analysis of the time trends of specific discharge showed statistically significant decreases in their annual mean values in almost half of examined catchments. The correlations between specific discharge, air temperature and precipitation totals are not very strong, which is mainly due to the strong impact of other, anthropogenic factors on water management. The greatest negative changes are observed in the central part of Poland. Specific discharge is more strongly dependent on precipitation totals than on temperature, with the effect of air temperature only being reflected in the volume of water resources after a certain period of time.

Keywords

Polish lowlands • specific discharge • air temperature • precipitation totals • climate change

Introduction

Global climate change, primarily rising air temperatures, is accelerating, also in Europe (Bednar-Frield et al., 2022), contributing to more frequent and prolonged periods of soil drought, limiting agricultural activities, especially in Eastern Europe and Mediterranean regions (Grillakis, 2019), and exacerbating the problem of water scarcity in areas that have long faced this problem (Bisselink et al., 2020). Climate change also affects Poland

(Degirmendžić et al., 2004; Rutgersson et al., 2014; Malinowska, 2015; Ustrnul et al., 2021), posing a serious risk of reducing water resources. The increased evaporation resulting from the increase in air temperature is not accompanied by an increase in precipitation (Wibig, 2009; Malinowska, 2015; Łupikasza & Małarzewski, 2021), and even in some regions, small (statistically insignificant) decreases are observed in this respect, especially in summer (Baran-Gurgul et al., 2022), leading to a decrease in the dominance of precipitation totals in the warm season over the cool one (Mager et al., 2009). The adverse effects of climate change on water resources intensified after 1988. Since then, an increase in the intensity of climate warming in Poland has been observed (Marsz et al., 2022; Wrzesiński et al., 2022). The problem has been further exacerbated in recent years (since 2018) due to long periods without rain and low precipitation totals (https://klimat.imgw.pl/pl/biuletyn-monitoring/). This poses both natural and economic risks, among others in Poland. In the European Union, less water per capita is recorded only for Malta and Cyprus and to some extent also in the Czech Republic (Eurostat, 2024). Due to its relatively cool climate, which allows for agricultural cultivation without additional watering, Poland is not among the countries struggling with water stress as defined by the Water Exploitation Index (WEI), which is the ratio of freshwater demand to the amount of water resources (https://www.eea.europa.eu/), but because of global warming it is approaching a dangerous level of the WEI. In most regions of Poland, water resources (both surface water and groundwater) are declining, and the water deficit is worse in summer (Szwed et al., 2010). The decrease in the number of days with snow cover and its thickness is also a problem (Falarz & Bednorz, 2021; Tomczyk et al., 2021; Wibig & Jędruszewicz, 2023), which accelerates the onset of maximum river flows (Somorowska, 2024) and limits the potential for rainwater retention from winter, when water supply to groundwater and surface reservoirs in Poland is high due to low air temperatures, to spring, when water demand is high due to the start of the vegetation season. Consequently, increased river flows in winter and decreased river flows in spring are observed in Poland (Somorowska, 2024), as in the rest of Central Europe (Rottler et al., 2020).

The study of the impact of climate change, in particular the increase in air temperature, on changes in the volume of water resources in Poland is all the more important as the country is located in the transition zone between the area of increase in water resources in the catchments of northern Europe and their decrease in the southern part of the continent (Milly et al., 2005; Malinowski & Skoczko, 2018; Caretta & Mukherji, 2022). Forecasting models, however, do not clearly identify further directions of the changes in Central Europe (Milly et al., 2005; Seager & Vecchi, 2010).

The impact of climate change on the volume of specific discharge from catchment areas (adopted as a measure of the amount of water resources also in this study) has been analysed, among others, in the Baltic States (Kriauciuniene et al., 2012), i.e. Lithuania, Latvia and Estonia, located to the north-east of Poland, and Germany (Bormann, 2010). The strongest simultaneous increases in air temperature values and decreases in precipitation totals in the summer half of the year, with negative effects on water resources, were observed in the north-eastern part of Germany adjacent to Poland (Bormann, 2009). Large increases in air temperature with simultaneous decreases in precipitation totals were also observed in Belarus (Volchak & Bulskaya, 2017). The impact of changes in precipitation totals on changes in river discharge was also noted in the catchment areas of Poland's largest rivers (Wrzesiński et al., 2023), although no statistically significant values were recorded for any of these parameters. What was also analysed in this study were the correlations between climate change and water abundance in catchment areas, e.g. of the Liwiec River (Somorowska, 2023), the Krzna River (Raczyński & Dyer, 2020) or the Ina, Rega, Parsęta and Wieprza rivers (Świątek & Walczakiewicz, 2022).

The aim of this study is to investigate the co-occurrence of changes in mean annual temperature, annual precipitation totals and specific discharge in selected catchments of lowland Poland, providing a long-term measure of the water resources of individual catchments. Precipitation totals and air temperature were included in the analysis, as these are the most important climatic factors affecting water discharge. Weak correlations between changes in river discharge and climate change would indicate a significant influence of other factors, most likely anthropogenic activities, on water resources. It is very important to determine whether resources are affected to a greater degree by natural (including climatic) or anthropogenic factors, because while humans have very limited influence on the former, they can nevertheless manage water in a sustainable way that respects existing water resources.

In addition to climate changes, changes in land cover may also have an impact on changes in the size of river runoff (Wojkowski et al., 2022), which is why the study took into account the development of the catchment landuse and its changes over time.

Characteristics of the studied area

The examined catchment areas are located on the seasides, lake districts and lowlands in the northern and central part of Poland (Fig. 1, Tab. 1). The mean annual specific discharge for the period under study averaged 6.16 $dm^3 \cdot s^{-1} \cdot km^{-2}$ and varied significantly – from 2.77 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the Wrześnica catchment in Greater Poland to 10.84 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the Słupia catchment area located in the highest elevated part of the Pomeranian Lake District and on the Koszalin Seaside (Tab. 1, Fig. 1).

The highest specific discharge was recorded for catchment areas of small rivers flowing directly to the sea (northern part of Poland) while the lowest in the Central Poland Lowlands, i.e. in the southern part of the examined area (Fig. 1). The lowest annual river discharge was recorded for the Orla catchment area in hydrological year 2020 (0.58 $dm^3 \cdot s^{-1} \cdot km^{-2}$), while the highest for the Wieprza catchment area in 1981 (15.29 $dm^3 \cdot s^{-1} \cdot km^{-2}$).

The coefficient of variation Cv of mean annual q was 0.27 on average, with the highest value in Greater Poland, i.e. in the western part of central Poland (the Orla catchment area: Cv = 0.55, catchment areas of the Wełna and Wrześnica: Cv = 0.53), indicating the highest variability of water resources in this area. In turn, the lowest value was recorded for catchment areas of small rivers flowing directly to the sea, located in the northernmost part of Poland (the Słupia catchment area Cv = 0.11, catchment areas of the Łeba and Reda: Cv = 0.12), which leads to the conclusion that the variability of q in these zones is several times lower than in Greater Poland. This is due to differences in land use of these catchment areas. In the western part of the lowland belt (mainly in Greater Poland), opencast lignite mining is taking place, which requires intensive, large-scale drainage of these areas and the discharge of water into other catchment areas. Underground water management in the areas of opencast coal mining varies over time. In addition, the lowlands (central Poland) are areas with intensive agricultural production and urban use. In the north of Poland, population density and anthropogenic impact on the natural environment are much lower. These regions are characterised by higher area sizes of forests, wetlands and drainless depressions that increase natural water retention (Fig. 2). The higher retention capacity of the catchments located in the north of Poland is indicated also by the high percentage of lakes area in the catchments. To the north of the Pomeranian phase of the last glaciation, which includes the catchments of rivers that flow directly into the sea studied in the study, the percentage of lakes area is 2.84%, with the average for Poland being 0.9% (Choiński, 2017).

Table 1. The area, mean annual specific discharge (q) and coefficient of variation (Cv) of q at studied catchments

River	Water gauge	A [km^2]	q [dm^3·s^{-1}·km^{-2}]	Cv
Reda	Wejherowo	406	10.96	0.12
Słupia	Słupsk	1450	10.84	0.11
Łyna	Sępopol	3647	10.84	0.22
Wieprza	Stary Kraków	1519	10.57	0.15
Łeba	Cecenowo	1120	10.44	0.12
Łupawa	Smołdzino	805	10.40	0.13
Parsęta	Bardy	2869	9.30	0.18
Gołdapa	Banie Mazurskie	548	8.26	0.27
Czarna Hańcza	Czerwony Folwark	481	8.03	0.19
Brda	Tuchola	2462	7.95	0.12
Rega	Trzebiatów	2628	7.69	0.20
Ełk	Przechody	1456	6.92	0.31
Wda	Czarna Woda	845	6.64	0.16
Wel	Kuligi	787	6.59	0.18
Mała Panew	Turawa	1424	6.09	0.34
Ina	Goleniów	2163	6.04	0.28
Ner	Dąbie	1712	6.02	0.31
Pisa	Dobrylas	4061	5.64	0.23
Piława	Zabrodzie	1375	5.54	0.18
Wierzyca	Brody Pomorskie	1544	5.54	0.20
Omulew	Krukowo	1265	5.35	0.24
Guber	Prosna	1568	5.30	0.34
Okrzejka	Mika	300	4.94	0.35
Sokołda	Sokołda	464	4.89	0.24
Rozoga	Myszyniec	231	4.84	0.29
Mroga	Bielawy	467	4.82	0.22
Orzyc	Krasnosielc	1268	4.46	0.28
Liwiec	Łochów	2466	4.30	0.31
Rawka	Kęszyce	1191	4.11	0.22
Skrwa	Parzeń	1534	4.07	0.41
Orla	Korzeńsko	1217	3.81	0.55
Prosna	Bogusław	4304	3.72	0.35
Krzna	Malowa Góra	3128	3.55	0.31
Szprotawa	Szprotawa	863	3.55	0.38
Obra	Bledzew	2618	3.44	0.35
Mała Noteć	Gębice	176	3.18	0.52
Wełna	Pruśce	1130	3.09	0.53
Myśla	Dolsk	729	2.92	0.41
Wrześnica	Samarzewo	360	2.76	0.53

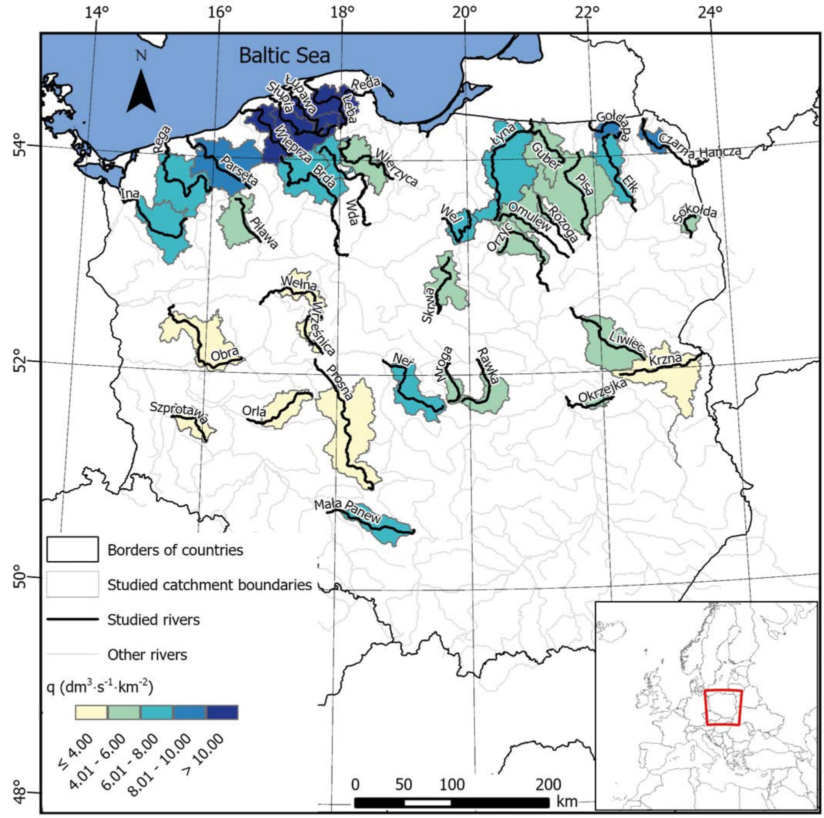

Figure 1. Location of studied catchments with value of specific discharge (q), hydrological years 1961--2021

Data and methods

In this study, climate change was described by area-averaged annual precipitation totals and area-averaged mean annual temperature values in each catchment area, while water resources were described by mean annual specific discharges in these catchment areas. Thirty-seven catchments located entirely in lowland areas of Poland were selected for the analysis (Fig. 1). The specific discharge in rivers not fed from upland or mountainous areas was investigated. Only catchment areas with complete set of hydrological data (river discharge) from the hydrological years 1961 to 2021 were examined. The only missing data was discharge from April, May and June 2021 for the Rawka and from July and August 2021 for the Mroga. Unfortunately, river gauging stations with complete data sets are not uniformly distributed across lowland Poland.

As a rule, in controlled catchments the area closed by the hydrological posts is smaller than whole catchment. These hydrological gauging stations are listed in Table 1. In the case of rivers flowing directly into the sea, the gauging stations are located relatively far from the river mouth. The reason for this location is that they need to be out of reach of high water of storm retreat during periods of sea level rise in the coastal zone. All catchment areas are separated from each other.

Specific discharge was determined on the basis of monthly mean values of river flows for the hydrological years 1961-2021

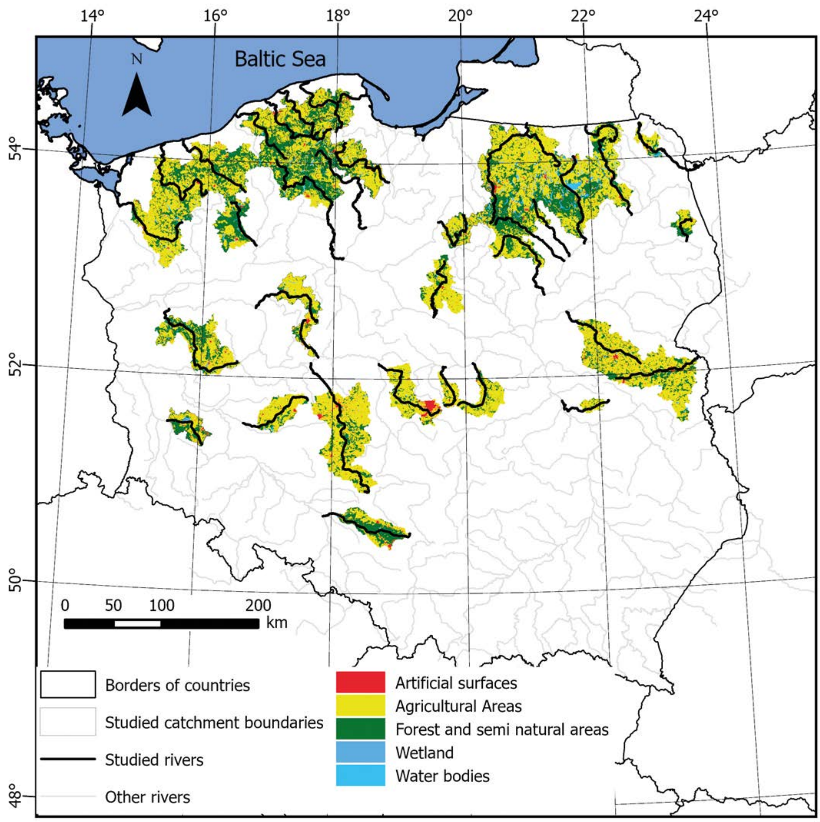

Figure 2. Land cover of the examined catchment areas

Source: Compiled on the basis of Corine Land Cover 2018 (clc.gios.gov.pl).

(from November 1960 to October 2021) published by Institute of Meteorology and Water Management – National Research Institute (Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy, IMGW-PIB). Average annual values of specific discharge were calculated taking into account the whole area of the examined catchments. The analysis of specific discharge enabled a temporal and spatial analysis of water resources in individual catchments of different areas.

Area-averaged annual precipitation totals and area-averaged annual mean values of air temperature in individual catchment areas were determined on the basis of monthly precipitation totals and monthly mean values of air temperature for the hydrological years 1961-2021, also published by IMGW-PIB. For this purpose, stations with full data sets were selected (46 in total). The only exceptions were the stations at Mława and Sulejów, where data, both thermal and pluvial, were available from January 1961 and May 1961 respectively. The database thus collected then allowed a multivariate interpolation of the meteorological data for the entire area of Poland using the inverse distance weighted (IDW) method for each month in the study period. In the next step, area-averaged annual precipitation and area-averaged annual mean air temperature values were calculated for each analysed hydrological year for the 37 examined catchment areas. The analysis was carried out using ESRI's ArcGIS Pro software.

In order to compare changes in area-averaged precipitation and area-averaged air temperature values with changes in annual mean specific discharge, linear trends of the mentioned variables were determined. Their statistical significance was determined using the Fisher-Snedecor test at $p \leq 0.05$.

The next stage of the study was to determine the effect of precipitation totals and air temperature on the water resources in individual catchments, as measured by specific discharge, using multiple regression. The dependent variable was the specific discharge determined, while independent variables (descriptors) were area-averaged values of annual precipitation totals and annual mean air temperature from a given year and the year preceding the year for which the specific discharge was determined. The statistical significance of the regression parameters was determined using the F-Snedecor test at $p \leq 0.05$. The regression was described by regression coefficients and the coefficient of determination of the entire regression relationship. Due to the different magnitudes of the independent variables (total precipitation and temperature), regression coefficients based on standardised data (β) and the corrected (adjusted) coefficient of determination ($R^2_{cor.}$) were used for the analyses.

The land cover map of the examined catchment areas analysed in this paper was created based on the Corine Land Cover 2018 database. The Corine Land Cover 2018 project was carried out in Poland by the Institute of Geodesy and Cartography and funded by the European Union. The results of the project were obtained from the website of the Chief Inspectorate for Environmental Protection (https://clc.gios.gov.pl/). https://clc.gios.gov.plThe spatial data derived from the database were processed and limited to the area of the 37 catchment areas in question. The maps of the general distribution of land cover/land use show Level I, which includes the following classes: artificial surfaces, agricultural areas, forests and semi natural areas, wetlands and water bodies.

The impact of climate change on changes in river runoff is disrupted by anthropogenic pressure. In this work, an attempt was made to determine it using the analysis of JCWP (homogeneous parts of the surface water bodies) Data Sheets published by Państwowe Gospodarstwo Wodne Wody Polskie – National Water Management Polish Waters (http://karty.apgw.gov.pl:4200/jcw-powierzchniowe) and the land cover map from 2018 taken from Corine Land Cover 2018 (clc.gios.gov.pl). The waters of the rivers studied in the paper were classified into several JCWP. Their data sheets noted the status of the JCWP, ecological state (in the case of a heavily modified water body – ecological potential) and the main sources of hydromorphological pressure. The status of the JCWP is determined mainly on the basis of the Hydromorphological River Index (HIR) value characterizing hydrotechnical transformations and morphological and biological naturalness of the riverbed and the area within 100 m from the river bank (Assessment Manual..., 2016). The ecological status (potential) of the JCWP in terms of watercourses is determined on the basis of biological, physicochemical and hydromorphological parameters, which include the hydrological regime and morphological conditions of the riverbed and riparian zones (Regulation of the Minister of the Environment of 9 November 2011).

The impact of the land development on changes in the specific discharge in individual catchments was determined based on the simple Pearson correlation coefficients between the percentage shares of specific land cover forms in 2018 in the total areas of the studied catchments and the slope coefficients of the linear time trend of the average annual specific runoff values in individual catchments in the hydrological years 1961-2021.

Additionally, in order to show the changes that occurred in the areas of the studied catchments, differences in land cover were calculated between the individual years: 2000 and 2006, 2006 and 2012 and 2012 and 2018. Initially, the areas of all studied catchments were extracted from the Corine land Cover spatial data for the years 2000, 2006, 2012 and 2018. Then, the percentage share of individual land use classes (level I) for each catchment in relation to its area was calculated. The results were presented in cumulative bar charts (Fig. 7). The Corine Land Cover data for the specified years also came from the website https://clc.gios.gov.pl.

Results

Trends in mean annual air temperature, annual precipitation totals and mean annual specific discharge

During the period under study (hydrological years 1961-2021), there was very little spatial variation in the change in the value of mean annual air temperature in all the examined catchment areas (coefficient of variation Cv equal to 0.043). It increased on average by 0.35°C per 10 years, from 0.31°C/10 years in the Guber River catchment in the north-eastern part of Poland to 0.38°C/10 years in some catchment areas of small rivers flowing directly into the sea (the Łupawa, the Słupia and the Parsęta) and the Orla River in the Greater Poland Lowlands (in western central Poland). The increase in values in all analysed catchments was statistically significant (Tab. 2).

In none of the examined catchment areas were the changes in annual precipitation totals statistically significant. Slight upward trends were recorded for most catchments. The highest values of increase were 9.51 mm over 10 years in the Liwiec catchment area and 9.36 mm over 10 years in the Czarna Hańcza catchment area. In 10 catchments,

Table 2. Changes in area-averaged mean annual values of air temperature (T), area-averaged annual precipitation totals (P) and mean annual specific discharge (q) over 10-year periods; hydrological years 1961-2021

Catchment	Change T [°C·10 yr^{-1}]	Change P [mm·10yr^{-1}]	Change q [$dm^3 \cdot s^{-1} \cdot km^{-2}$·10 yr^{-1}]
Liwiec	0.33*	9.51	-0.13
Czarna Hańcza	0.36*	9.36	0.06
Gołdapa	0.35*	8.55	-0.02
Ełk	0.35*	8.25	0.04
Sokołda	0.34*	8.01	-0.10
Krzna	0.34*	7.47	0.04
Pisa	0.34*	7.30	-0.13
Brda	0.36*	7.29	-0.16*
Guber	0.31*	6.96	-0.03
Wierzyca	0.34*	6.60	-0.19*
Wda	0.35*	6.09	-0.24*
Rozoga	0.35*	5.97	-0.11
Łyna	0.34*	5.51	-0.13
Okrzejka	0.33*	5.17	-0.36*
Wel	0.35*	4.97	-0.33*
Omulew	0.35*	4.72	-0.30*
Reda	0.34*	4.41	-0.06
Rega	0.36*	4.09	-0.26*
Skrwa	0.35*	3.79	-0.18
Orzyc	0.36*	3.25	-0.21*
Parsęta	0.38*	2.71	-0.19
Łeba	0.34*	2.10	0.08
Rawka	0.36*	2.10	-0.21*
Ina	0.36*	1.92	-0.10
Piława	0.37*	1.56	-0.20*
Mroga	0.36*	0.67	-0.22*
Łupawa	0.38*	0.24	0.06
Myśla	0.36*	0.16	-0.24*
Wełna	0.35*	-0.21	-0.29*
Słupia	0.38*	-0.54	-0.13
Ner	0.36*	-1.07	-0.38*
Wrześnica	0.34*	-2.42	-0.21
Obra	0.37*	-2.98	-0.26*
Wieprza	0.36*	-4.45	-0.04
Orla	0.38*	-7.11	-0.24
Prosna	0.36*	-8.48	-0.24*
Szprotawa	0.34*	-8.61	-0.24*
Mała Panew	0.35*	-9.72	-0.41*
Mean	0.35	2.45	-0.16

The catchment areas were ranked in descending order of the values of changes in precipitation totals
* – statistically significant coefficients at $p \leq 0.05$

located mainly within the Central Polish Lowlands, slight downward trends were observed, the greatest in the Mała Panew catchment (to the south of the examined area), where there was a statistically insignificant decrease in annual precipitation of 9.72 mm over 10 years (Tab. 2, Fig. 3).

Analysis of the time trends of specific discharge from the examined catchment areas showed statistically significant decreases in their annual mean values in 18 catchment areas (out of 37 examined), i.e. in almost half (47.4%) of them (Fig. 4, Tab. 2). The largest (in terms absolute terms) negative values of trend directional coefficients were observed for the mean annual specific discharge from the catchments of the Mała Panew, Ner and Okrzejka located within the Central Polish Lowlands. In the Mała Panew catchment area, this decrease co-occurred with a statistically insignificant (but at the same time the largest among the examined catchments) decrease in area-averaged annual precipitation (9.72 mm·10 yr^{-1}).

In five catchment areas there was a statistically insignificant increase in mean annual specific discharge (Fig. 4, Tab. 2). It should be added that in the catchments of Czarna Hańcza, Krzna and Ełk, statistically insignificant increases in discharge were accompanied by statistically insignificant increases in precipitation totals (9.36 mm·10 yr^{-1}, 7.47 mm·10 yr^{-1} and 8.25 mm·10 yr^{-1} respectively). The spatial variability of the magnitude of change in specific discharge is shown in Figure 5.

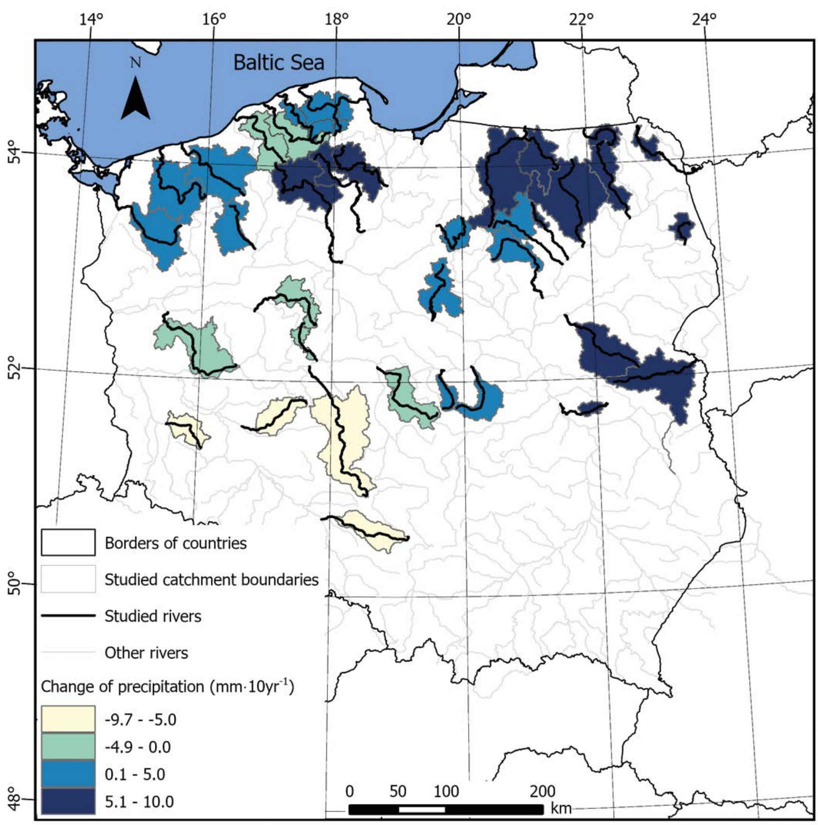

Figure 3. Spatial variability of changes in area-averaged annual mean precipitation totals in the examined catchment areas per 10 years; hydrological years 1961-2021

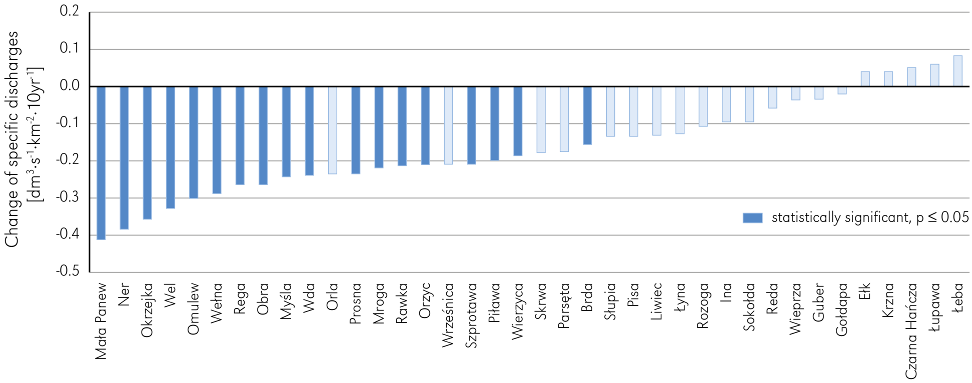

Figure 4. Changes in mean annual specific discharge in the examined catchment areas per 10 years; hydrological years 1961-2021

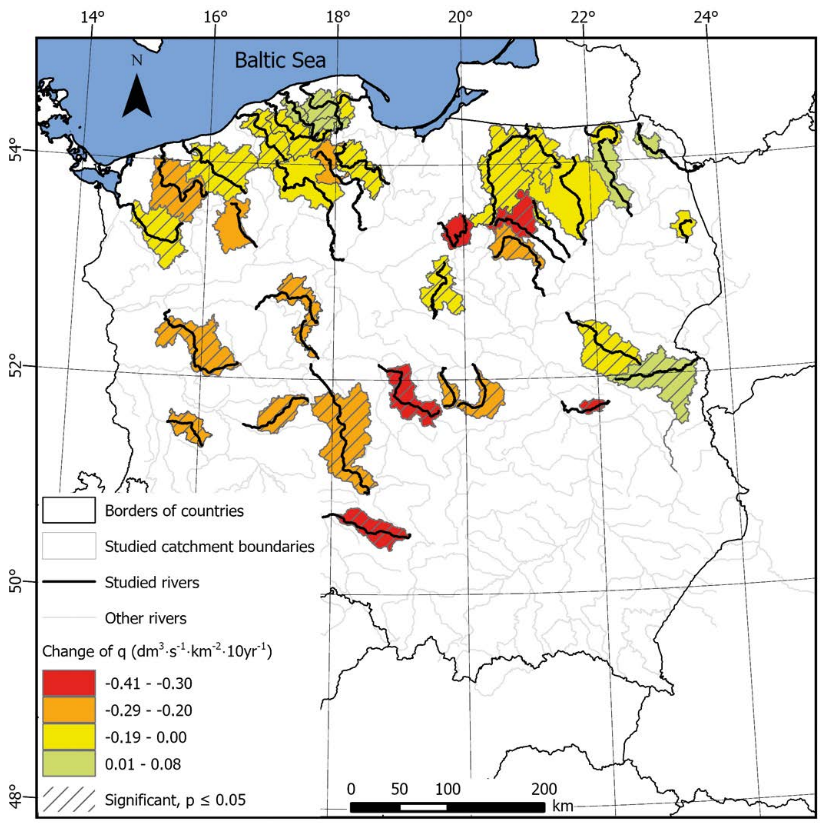

Figure 5. Spatial variability of changes in mean annual specific discharge in the examined catchment areas per 10 years; hydrological years 1961-2021

Correlations between mean annual specific discharge and mean annual air temperature and annual precipitation totals

An analysis of the correlation between area-averaged mean annual precipitation totals and mean annual air temperature values for individual catchments and mean annual specific discharge in these areas using multiple regression showed a stronger correlation between precipitation and discharge than temperature and discharge (Tab. 3). For 30 catchments (81.1% of those examined), the effect of precipitation totals on specific discharge was statistically significant. An increase in precipitation totals resulted in an increase in specific discharge values. The effect of temperature on mean annual specific discharge was significant only in the case of 9 catchments (24.3% of those examined), which included catchment areas of the rivers: Neru, Mroga, Orzyc, Rawka, Rega, Wełna, Obra, Omulew and Wel, i.e. mainly in the lowlands of central Poland (Tab. 3). The increase in air temperature there has resulted in a decrease in the specific discharge in a given catchment. Consequently, annual precipitation totals and mean annual air temperature had a significant effect on specific discharge in a given catchment in 28 (75.7%) of the examined areas.

The mean value of the coefficient of determination, calculated from the adjusted R^2 for each catchment, averaged 0.177, indicating that the variability in annual precipitation and mean annual air temperature in a given catchment explained only 17.7% of the variability in mean annual specific discharge. To the greatest extent (in more than 30%), the sum of precipitation totals and temperature

Table 3. Multiple regression coefficients determined from standardized values of annual mean specific discharge and area-averaged annual precipitation totals (β_P) and area-averaged annual mean air temperature (β_T), with adjusted multiple regression coefficients of determination ($R^2_{cor.}$); hydrological years 1961-2021

Catchment	β_P	β_T	$R^2_{cor.}$
Piława	0.598*	-0.143	0.384*
Obra	0.585*	-0.170	0.376*
Wełna	0.582*	-0.195	0.360*
Szprotawa	0.496*	-0.250*	0.296*
Omulew	0.491*	-0.278*	0.293*
Brda	0.509*	-0.162	0.283*
Wel	0.515*	-0.240*	0.281*
Wrześnica	0.546*	-0.141	0.278*
Pisa	0.466*	-0.315*	0.277*
Łyna	0.509*	-0.258*	0.272*
Prosna	0.485*	-0.196	0.254*
Rega	0.402*	-0.300*	0.233*
Czarna Hańcza	0.418*	-0.259*	0.221*
Wierzyca	0.469*	-0.215	0.211*
Orla	0.455*	0.169	0.210*
Mroga	0.459*	-0.177	0.209*
Skrwa	0.485*	-0.017	0.205*
Mała Panew	0.455*	-0.056	0.184*
Wda	0.451*	-0.070	0.173*
Guber	0.428*	-0.190	0.170*
Ner	0.379*	-0.251*	0.160*
Ełk	0.365*	-0.227	0.154*
Orzyc	0.425*	-0.080	0.151*
Ina	0.407*	-0.109	0.141*
Słupia	0.405*	0.036	0.135*
Parsęta	0.402*	0.010	0.133*
Gołdapa	0.363*	-0.057	0.099*
Krzna	0.299*	0.160	0.083*
Rozoga	0.230	-0.211	0.061
Reda	0.270*	-0.147	0.059
Wieprza	0.173	-0.256*	0.057
Liwiec	0.210	-0.195	0.045
Rawka	0.261*	0.042	0.041
Sokołda	0.255	0.047	0.039
Okrzejka	0.218	-0.062	0.018
Łupawa	0.177	-0.012	-0.002
Łeba	0.150	-0.091	-0.006
Mean	0.400	-0.132	0.177

The catchment areas were ranked in descending order of the value of the adjusted R^2

* – statistically significant coefficients at $p \leq 0.05$

Table 4. Multiple regression coefficients determined from standardised values of annual mean specific discharge and area-averaged annual precipitation totals from the preceding year (β_P) and area-averaged annual mean air temperature values from the preceding year (β_T), with adjusted multiple regression coefficients of determination ($R^2_{cor.}$); hydrological years 1961-2021

Catchment	β_P	β_T	$R^2_{cor.}$
Piława	0.540*	-0.533*	0.516*
Obra	0.595*	-0.398*	0.502*
Wełna	0.501*	-0.497*	0.490*
Szprotawa	0.528*	-0.374*	0.447*
Omulew	0.427*	-0.545*	0.416*
Brda	0.539*	-0.394*	0.400*
Wel	0.370*	-0.554*	0.393*
Wrześnica	0.468*	-0.428*	0.388*
Pisa	0.508*	-0.452*	0.382*
Łyna	0.469*	-0.460*	0.362*
Prosna	0.443*	-0.370*	0.359*
Rega	0.506*	-0.417*	0.351*
Czarna Hańcza	0.562*	-0.321*	0.343*
Wierzyca	0.460*	-0.397*	0.338*
Orla	0.432*	-0.357*	0.329*
Mroga	0.417*	-0.421*	0.327*
Skrwa	0.459*	-0.389*	0.325*
Mała Panew	0.434*	-0.341*	0.317*
Wda	0.547*	-0.219*	0.313*
Guber	0.498*	-0.355*	0.301*
Ner	0.351*	-0.431*	0.298*
Ełk	0.509*	-0.295*	0.291*
Orzyc	0.284*	-0.495*	0.283*
Ina	0.505*	-0.274*	0.278*
Słupia	0.442*	-0.298*	0.263*
Parsęta	0.476*	-0.303*	0.257*
Gołdapa	0.477*	-0.289*	0.246*
Krzna	0.480*	-0.269*	0.227*
Rozoga	0.348*	-0.395*	0.222*
Reda	0.454*	-0.191	0.214*
Wieprza	0.432*	-0.189	0.203*
Liwiec	0.362*	-0.347*	0.192*
Rawka	0.335*	-0.340*	0.189*
Sokołda	0.306*	-0.348*	0.176*
Okrzejka	0.328*	-0.300*	0.142*
Łupawa	0.405*	-0.056	0.138*
Łeba	0.386*	-0.119	0.132*
Mean	0.448	-0.356	0.307

The catchment areas were ranked in descending order of the value of the adjusted R^2

* – statistically significant coefficients at $p \leq 0.05$

explains the variability of specific discharge in the Prosna, Mała Panew and Szprotawa catchment (Tab. 3, Fig. 6A), i.e. in the Silesian and Greater Poland Lowlands, located in the south west and west of the lowland part of Poland.

Stronger correlations were identified between mean annual specific discharge, area-averaged annual precipitation and area-averaged annual air temperature in the preceding year (Fig. 6B). A significant effect of the preceding year's precipitation totals on specific discharge was observed for all the examined catchment areas, while for the preceding year's temperature it was observed in 33 catchment areas (89.2% of those examined; Tab. 4). This represents a much stronger correlation than those between the specific discharge, precipitation totals and temperature from the same year. In particular, the preceding year's temperature is much more important for specific discharge volumes than the temperature of a given year. An increase in total precipitation resulted in an increase in the volume of specific discharge both in the same and in the following year, while an increase in air temperature resulted in a decrease in the volume of specific discharge basically in the following year.

The mean value of the coefficient of determination in the correlations, where the dependent variable was the specific discharge from the catchment area and the independent variables were the annual precipitation totals and the mean annual air temperature in the preceding year, was 0.307 and thus the variation in both variables explained 30.7% of the variation in mean annual specific discharge. The highest similarity between the variability of specific discharge and of precipitation totals and temperature (explaining the varia-

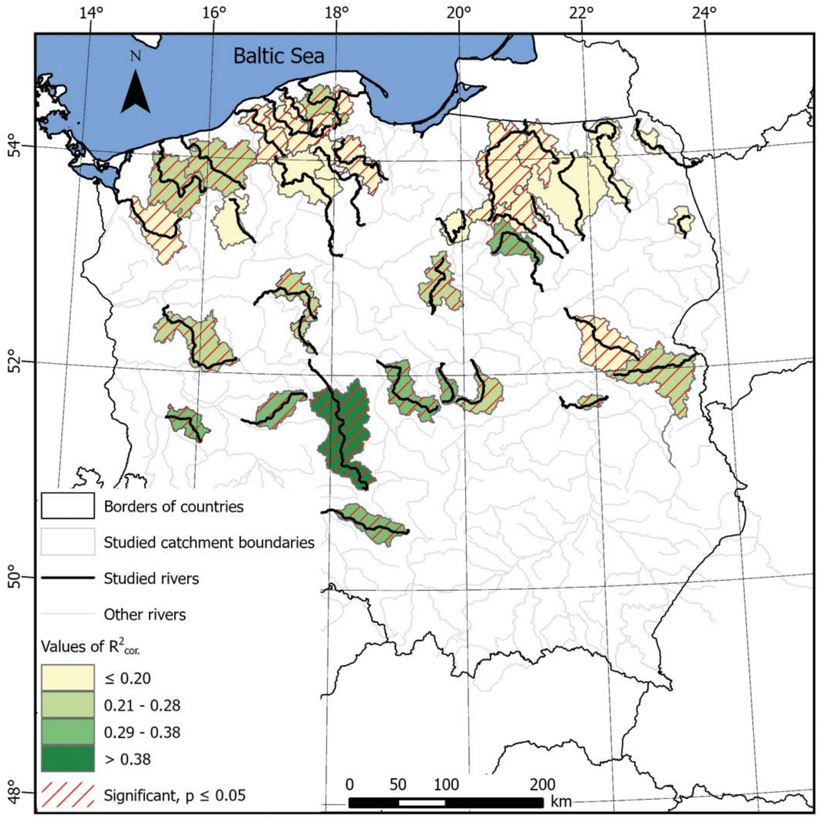

Figure 6A. Values of the corrected coefficient of determination of the multiple regression ($R^2_{cor.}$) of specific discharge with area-averaged annual values of precipitation totals and temperature from a given year (A) and the preceding year (B) for individual catchment areas; hydrological years 1961-2021

bility in more than 40%; Tab. 4) was observed in the catchment areas of the Piława, Obra, Wełna, Szprotawa, Omulew and Brda rivers, in the central part of Poland. No statistically significant correlations between specific discharge and mean annual air temperature from the preceding year were observed for the catchment areas of the Reda, Wieprza, Łupawa and Łeba. These are rivers located in the northern part of Poland, flowing directly into the Baltic Sea (Fig. 6B).

The spatial variability of the variation in specific discharge explained by the variation in annual precipitation totals and mean annual temperature for a given year and the preceding year is relatively high. The strongest correlations were identified within the lowlands, especially in western Poland, while the weakest ones in the catchment areas of small rivers flowing directly to the sea, located on the border of lake districts and coastal zones, and in the north-eastern part of the Mazurian Lake District, in the north-eastern part of Poland, which results from relatively big natural storage in these areas (Fig. 6).

Disturbances in the relationship between climate change and specific discharges resulting from anthropogenic pressure

The influence of anthropogenic pressure is synthetically presented in Table 5. The catchment area cover was developed based on the

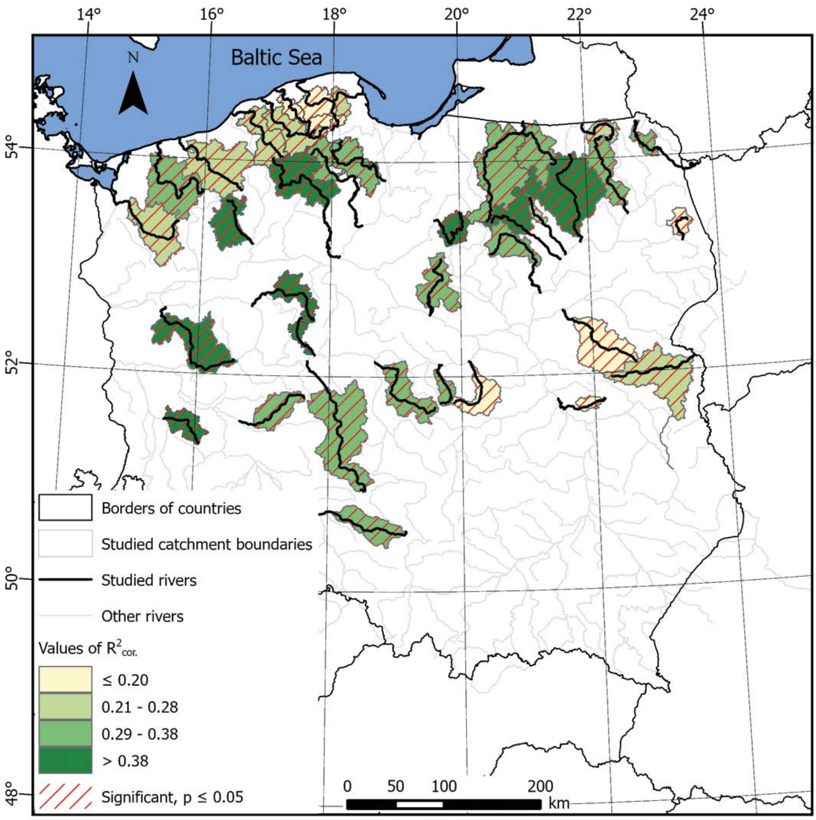

Figure 6B. Values of the corrected coefficient of determination of the multiple regression ($R^2_{cor.}$) of specific discharge with area-averaged annual values of precipitation totals and temperature from a given year (A) and the preceding year (B) for individual catchment areas; hydrological years 1961-2021

Corine Land Cover 2018, and the remaining elements based on the JCWP Data Sheets. In all studied catchments, anthropogenic pressure is exerted on the morphology of the river bed and river valley, most often consisting in straightening the bed (78% of the studied rivers) and building water damming devices (weir structures) in the stream (86% of the studied rivers). The moderate ecological status of the JCWP dominates. Almost all JCWP included in the studied rivers have the status of natural water bodies. Only the Ner, Okrzejka, Orla, Prosna and Szprotawa rivers contain heavily modified water bodies (SZCW). Parts of the Okrzejka, Orla, Prosna and Szprotawa waters were recognized as SZCW due to low values of the Hydromorphological River Index. In the case of the Ner River, the indication for recognizing a water body as SZCW was the disturbed hydrological regime associated with the strong sealing of the catchment area, which, according to the data sheets of JCWP, covered as much as 33.9% of its area in the section to the mouth of the Dobrzynka River.

The studied catchments cover an average of 4% of artificial surfaces (Tab. 5), with the largest percentage (14%) in the Ner catchment and the smallest in the Gołdapy and Rozoga catchments (approx. 1% each). Agricultural areas usually occupy the largest area of the studied catchments, an average of 58%, from 32% in the Mała Panew catchment and 33% in the Brda catchment to 77% in the Skrwa catchment. Forests and semi natural

Table 5. The magnitude of anthropogenic pressure on water conditions in the examined catchments

Catchment	Status JCWP	Ecological status / potential	Catchment area cover [%]					Main source of hydromorphological pressures					
			Anthropogenic areas	Agricultural areas	Forests and seminat. ecos.	Wetlands	Water areas	Straightening of riverbed	Weir structures	Mining	Flood embankments*	Regulatory struc.	Water management facil.**
Brda	NAT	GS, MS	2	33	61	0	4	X					
Czarna Hańcza	NAT	GS, MS, PS	6	63	24	0	7	X	X				
Ełk	NAT	MS	3	61	31	1	5	X	X				
Gołdapa	NAT	MS, PS	1	65	30	0	1	X	X				
Guber	NAT	MS	3	75	18	1	2		X				
Ina	NAT	MS	4	68	27	0	2	X		X	X		
Krzna	NAT	MS, PS	5	66	28	0	1	X	X				
Liwiec	NAT	MS	6	71	23	0	0	X	X				
Łeba	NAT	MS, PS	4	52	44	0	1	X	X		X		
Łupawa	NAT	MS, PS, BS	3	52	43	0	2		X		X	X	
Łyna	NAT	MS	4	57	35	0	4		X	X			
Mała Panew	NAT	MS, PS, BS	6	32	60	0	2	X	X			X	X
Mroga	NAT	MS	7	73	19	0	1	X	X				
Ner	NAT, SZCW	MP, BP, PS	14	70	15	0	0	X	X		X		
Obra	NAT	PS, BS	4	51	43	0	2	X				X	X
Okrzejka	NAT, SZCW	MP, MS	4	75	21	0	1	X	X				
Omulew	NAT	GS	3	34	59	1	3	X					
Orla	NAT, SZCW	MS, PS	5	74	19	0	1	X	X		X	X	
Orzyc	NAT	MS	2	57	41	0	0	X	X				
Parsęta	NAT	MS	3	50	46	0	0	X	X		X		X
Piława	NAT	GS, MS	2	32	62	0	4		X				X
Pisa	NAT	MS, PS	2	45	43	1	9	X	X			X	
Prosna	NAT, SZCW	MS, PS, PP	6	72	21	0	0	X	X	X		X	
Rawka	NAT	MS	4	73	23	0	0		X				
Reda	NAT	GS, MS	6	50	43	0	1	X	X				
Rega	NAT	MS	4	60	35	0	1	X	X	X	X	X	X
Rozoga	NAT	MS	1	55	42	0	1	X	X				
Skrwa	NAT	GS, PS	2	77	21	0	0	X	X				
Słupia	NAT	GS, MS, PS	4	48	46	0	2	X					
Sokołda	NAT	MS	4	50	46	0	0		X			X	
Szprotawa	NAT, SZCW	BS, MP	6	46	45	2	1	X	X	X	X		
Wda	NAT	GS, MS	2	34	59	0	4	X	X				
Wel	NAT	MS, PS	3	65	28	1	3	X	X				
Wełna	NAT	MS, PS	5	76	16	0	2	X	X				
Wieprza	NAT	GS, MS	2	44	53	0	1		X				
Wierzyca	NAT	MS, PS, BS	4	66	28	0	2	X	X				
Wrześnica	NAT	MS	7	68	26	0	0		X				

* – bank borders, spurs, longitudinal training dams; ** – artifical reservoirs, fishponds; NAT – the natural water body; SZCW – heavily modified water body; GS – good status; MS – moderate status; PS – poor status; BS – bed status; MP – moderate potential; PP – poor potential; BP – bed potential

Source: compiled on the basis of Corine Land Cover 2018 (clc.gios.gov.pl) and JCWP Data Sheets (http://karty.apgw.gov.pl:4200/jcw-powierzchniowe).

areas occupy an average of 36%, although there are catchments such as the Brda, Mala Panew, Piława and Szprotawa, where they constitute approx. 60%. Wetlands are most numerous in the Szprotawa catchment (approx. 2%) and Water bodies in the Pisa catchment (9%), Czarna Hańcza (7%) and Brda, Łupawa, Piława and Wda (4% each).

The influence of land cover on changes in the average annual specific discharge in individual catchments is insignificant (Tab. 6). Although the correlation between the percentage share of artificial surfaces in the total catchment areas and the values of the directional trend coefficient of average annual unit runoff values in catchments is statically significant at the level of $p = 0.039$ (Tab. 6), it is influenced by very high values of both compared values in the Ner catchment. After eliminating this catchment from the analysis, the correlation coefficient takes the value of: -0.190, significant at the level of $p = 0.262$. The lack of significance of this coefficient is influenced by the small sample size.

Table 6. Pearson correlation coefficients between the percentage shares of the areas of specific land cover forms in 2018 in the total areas of the studied catchments and the slope coefficients of the linear time trend of the average annual specific discharge in individual catchments in hydrological years 2061-2021

Land cover	Correlation coefficient with change of q
Artificial surfaces	-0.342*
Artificial surfaces without the Ner catchment	-0.190
Agricultural areas	-0.003
Artificial surfaces and agricultural areas	-0.055
Forests and semi natural areas	0.033
Forest, semi natural areas, wetlands and water bodies	0.052

* – statisticaly significant at $p \leq 0.05$

The analysis of land cover changes in the areas of the studied catchments did not show any major differences. In the case of artificial surface (Fig. 7A), the largest changes are visible for all catchments between 2006-2012, where they average about 1.2%. In the Liwiec river catchment, these changes were the largest in the same years and exceeded 3.2%. The situation was similar in the Mroga river catchment between 2000 and 2006. The highest increase in artificial surface was recorded in the catchments of the Ner (4.4%), Mroga (4.3%), Reda (3.7%), Liwiec (3.6%). Wrześnica (3.45%), Prosna (3.4%) rivers. Agricultural areas in the studied catchments decreased, only in the Gołdapa river catchment, where a small increase of 0.17% was recorded between 2012 and 2018 (Fig. 7B). The largest decrease was recorded between 2006 and 2012, on average by about -2.4%, while the smallest between 2000 and 2006 (on average by about -0.8%). In the case of catchments, the highest decreases in agricultural areas were observed in the catchments of the Wel (-7.1%), Łyna (-6.7%), Liwiec and Łeba (on average by -6.5%), Rozoga (-6.4%) and Ner (-6.2%) rivers. Forest and semi natural areas generally increased, except for individual periods when some catchments recorded a slight decrease in these areas (Czarna Hańcza, Gołdapa, Mała Panew, Okrzejka, Orla, Rawka, Wełna) (Fig. 7C). The largest increases were also recorded between 2006 and 2012, on average by about 1.2%. The largest changes were recorded in the catchments of the Wel (5%), Rozoga (4.9%), Łyna (4.5%) and Łeba (4.2%) rivers. The smallest changes but the greatest diversity were recorded in Wetlands and Water bodies (Figs 7D and 7E). Most catchments recorded increases in both of these areas, but there were some where a decrease occurred. In the case of Wetlands, the highest increase was recorded in the Guber river catchment (0.5%), and the highest decrease in the Szprotawa river catchment (-0.81%) (Fig. 7D). In turn, Water bodies increased the most in the Gołdapa river catchment (0.33%), and the most decreased in the Wel river catchment (-0.32%) (Fig. 7E). An interesting case was recorded in the Wrześnica

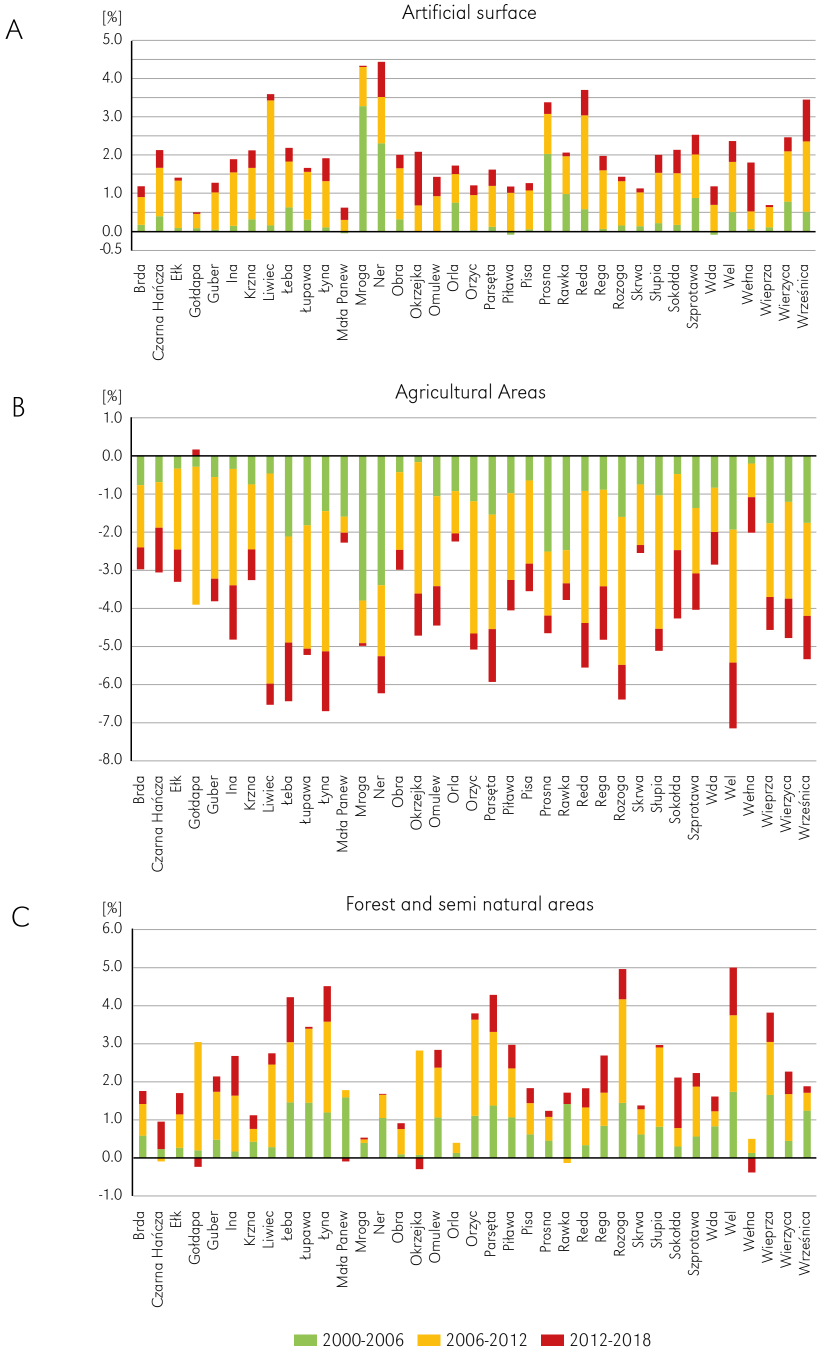

Figure 7A-C. Changes in land cover in the studied catchments for artificial surfaces (A), agricultural areas (B), forests and semi natural areas (C)

Source: compiled on the basis of Corine Land Cover data (clc.gios.gov.pl).

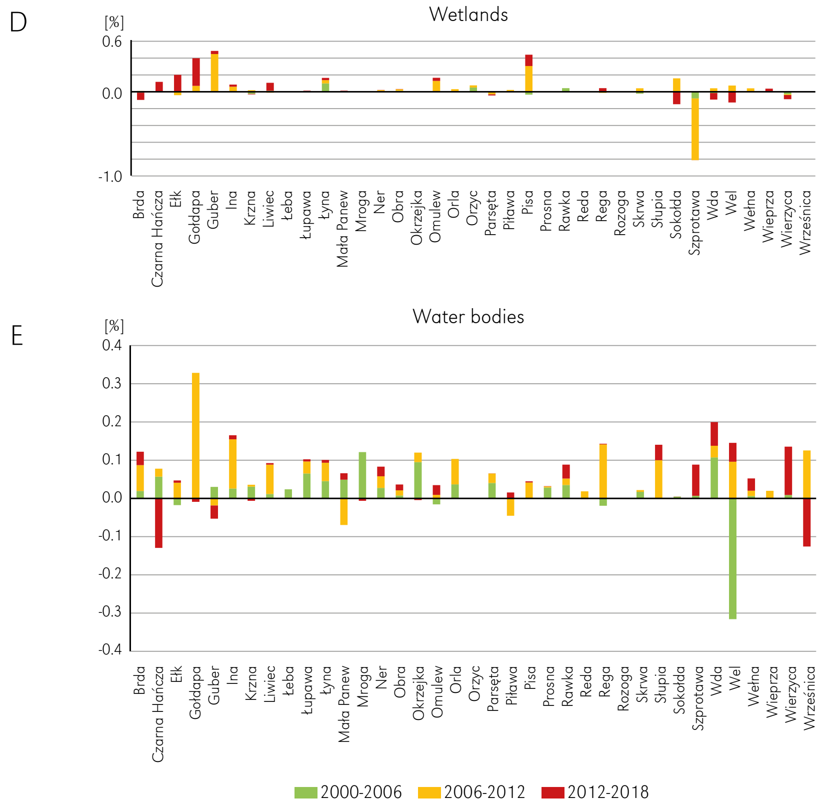

Figure 7D-E. Changes in land cover in the studied catchments for wetlands (D) and water bodies (E)

Source: compiled on the basis of Corine Land Cover data (clc.gios.gov.pl).

river catchment, where in the years 2006-2012 an increase in water bodies by approx. 0.13% was recorded, while in the subsequent period 2012-2018 there was a decrease by the same amount.

Discussion

Similar to the results of the research presented in this paper, correlations between increasing temperature and changes in river discharge have also been described in studies on the Liwiec River (Somorowska, 2023), the Krzna River (Raczyński & Dyer, 2020) and the Seaside rivers (Świątek & Walczakiewicz, 2022). Similarly, stronger correlations between changes in precipitation totals and air temperature have been observed in catchment areas located at a greater distance from the sea, while weaker ones in rivers of the coastal zone in Lithuania (Kļaviņš et al., 2008), Poland's north-eastern neighbour.

A decrease in water resources in the catchment areas of lowland rivers in central Poland has been observed based on studies of the small Zagożdżonka River, located in the southern part of Mazovia (Banasik & Hejduk, 2012; Krajewski et al., 2019). These declines intensified significantly after 1981 due to the accelerated increase in air temperature. While in the Warta catchment area Ilnicki et al. (2014) observed no significant impact of climate warming on the volume of water resources determined from river flows, the study by Marsz et al. (2022) showed significant losses of water resources in that area after 1988. These resulted from an increase in evaporation rate, amounting to 6.4 mm·yr^{-1} in the period 1988-2020 (a statistically significant trend), which was influenced not only by an increase in air temperature but also by an increase in the amount of sunshine duration and a decrease in relative humidity. According to Marsz et al. (2022), the increase in the intensity of northward heat transport since 1987-1989 was largely due to a change in the North Atlantic thermohaline circulation.

In the Narew catchment area (Malinowski & Skoczko, 2018) in the eastern part of central Poland, only small, insignificant changes in hydrological parameter values have been reported, despite significant climatic changes. In Belarus a decrease in runoff of the Western Dvina and the Viliya basins are observed, although some catchments of the Dnieper and Pripyat river basins record its increases (Volchak & Bulskaya, 2017). In Lithuania annual precipitation totals rise statistically. In connection with the increase in air temperature (influencing among others on significantly decreasing of snowfall duration) this affects not so much the average annual runoff volume but winter-spring runoff distribution (Stonevičius et al., 2014). An increase in average annual runoff is expected in many Lithuanian catchments (Plunge et al., 2022), although forecasts indicate decreases in river runoff in the south-eastern and central parts of the country (Jakimavičius at al., 2020).

A significant decrease in river flows in the upper Noteć River catchment area in Greater Poland (western part of central Poland) has been explained by the impact of lowering groundwater levels due to lignite mining in the Konin area (Nowak et al., 2018). Also in the upper Warta catchment area (also in the region of Greater Poland), drainage associated with opencast coal mining in Bełchatów has caused severe water shortages and reduced river flows (Kozek, 2018). In the Greater Poland region, which is the least water-rich region (due to the lowest precipitation totals in Poland), large-scale land drainage to enable opencast mining is common. They cause a cone of depression of the groundwater table, which reduces the volume of water resources to such an extent that some lakes and rivers dry up periodically or permanently. An example of this is the Little Noteć River, which has almost disappeared, with only a small section surviving (Nowak et al., 2018). According to measurements and documentation kept by the Regional Water Management Board, the overlapping cones of depression of the groundwater table enabling the operation of opencast mines located to the west of Konin and several others located, for example, on the drainage divide between the Vistula and Oder rivers basins (Poland's largest rivers) deprive an area of about 2000 km^2 of drainage (Detailed note..., 2024), exacerbating the already large water deficits in this area. On the border of the cone of depression area are the catchment areas of the Wełna and Wrześnica rivers analysed in this study. These rivers periodically shorten their course and the volume of water flowing through them depends on the intensity of mining operations.

The correlations between specific discharge, air temperature and precipitation totals presented in the paper are not very strong (in the case of correlations of average values of these parameters in the same year, they are not even statistically significant in all cases), which is mainly due to the strong impact of other, anthropogenic factors on water management.

Even though the analysis of the JCWP Data Sheets did not reveal any general relationships between the intensity of anthropogenic pressure and the change in the average annual specific discharges, some influence of anthropogenic pressure on the relationship between climate change and river runoff can be observed.

For example, the volume of specific discharge in the Ner River catchment area, where large decreases in the values of this parameter and their strong correlation with climate change have been observed, is influenced by the volume of inflows of used water from outside the catchment area within the Łódź agglomeration (inhabited by about

1 million people). The decrease in discharge is largely influenced by the smaller allochthonous water discharges into the Ner catchment area. Water abstractions for irrigation in the middle river valley and to replenish ponds and improve wetlands downstream in Natura 2000 areas also have a significant impact (Jokiel & Bartnik, 2020). Similar correlations, albeit less strong, have also been observed in the other examined catchment areas. The high level of urbanization in the Ner catchment has an important impact on the changes in the volume of the specific discharges. This level is manifested by the coverage of the studied catchment by artificial surfaces as much as 14% (Tab. 5). The very large transformation of the Ner river catchment area occurs especially in the initial section of the river (up to the mouth of the Dobrzynka), where urbanized areas occupy 50% of the catchment area and approx. 1/3 of its area are permanently hardened areas, impermeable to water (JCWP Ner to Dobrzynka Data Sheet – http://karty.apgw.gov.pl:4200/jcw-powierzchniowe).

Changes in specific discharges in some catchments are influenced by the water management conducted in them. This applies, among others, to the Turawa catchment. The hydrological gauge, from which the data were analyzed in the work, is located a short distance behind the dam limiting the artificial Turawa reservoir (JCWP Mała Panew from the Turawa reservoir to the Odra Data Sheet -http://karty.apgw.gov.pl:4200/jcw-powierzchniowe).

The changes in the size of the area of a given land cover form were so small (within a few percent of the catchment area) that they could not have influenced the changes in the specific discharge, especially since no significant correlations were found between the land cover form and the change in the specific discharge in the catchment area

The lack of strong causal relationships between the variability of climatic parameters and river flow volumes was also observed in the upland, south-eastern part of Poland (Raczyński & Dyer, 2020). In catchment areas located in Germany (Bormann, 2010), the influence of changes in precipitation totals on changes in discharge has been noted, but other factors have also been identified, including land cover changes, river engineering, artificial reservoir operations and mining activities. All these factors are also observed in Poland. Wrzesiński and Sobkowiak (2018) noted that the greatest changes in river flows occur primarily in rivers flowing through the most anthropogenically transformed areas of Poland, with the highest rates of urbanisation and industrialisation.

The delayed response of the specific discharge to the air temperature is due to the time required for the underground discharge formation process depending on the amount of evaporation. Increased land evaporation reduces rainwater infiltration, which reduces the volume of groundwater resources in the shallow aquifers that feed the rivers.

A very worrying phenomenon is the reduction in water resources over the last 60 years, where serious water shortages for agricultural purposes were observed as early as the 1950s (Urbański, 1956; Narkiewicz-Jodko, 1959), i.e. before the beginning of the period under study in this paper. Studies conducted by Kubiak-Wójcicka and Machula (2020) showed severe water shortages in many catchment areas located in central Poland due to an increase in air temperature, a slight decrease in precipitation totals and an increase in water abstraction for agricultural purposes.

Conclusions

Correlations between climatic factors (air temperature and precipitation totals) and unit discharge are not very strong due to the interference of natural processes by water management measures (e.g. river engineering or water reclamation) and water abstraction for industrial and municipal purposes, and in the case of Greater Poland also by the mining industry. Nevertheless, climate change undoubtedly affects the volume of water resources in the lowland part of Poland. A strong, statistically significant, increase in air temperature in all the examined catchment areas is manifested in a spatially differentiated decrease in mean annual specific discharge in about half of the examined catchment areas. Spatial variability is due to different trends in changes in precipitation totals (statistically insignificant), different intensities of human impact on the environment and the degree of transformation of the natural water cycle in the environment. The greatest negative changes are observed in the central part of Poland. The impact of land cover form on changes in specific discharge is small.

Specific discharge is more strongly dependent on precipitation totals than on temperature, with the effect of air temperature only being reflected in the volume of water resources after a certain period of time. The general analyses carried out for the study show that this happens more often in the following year, after a year with high air temperature values. Thus, if a given year is exceptionally warm, the decrease in water resources as measured by the average annual specific discharge from a given catchment area will not be observed until the following year.

Changes in air temperature are not a factor in the spatial variation in the magnitude of the change in discharge, as the area-averaged mean air temperature increases almost uniformly in all the catchment areas examined.

Analyses of the magnitude of changes in specific discharge and mean annual precipitation totals show that decreases in specific discharge are partly linked to changes in precipitation totals. Although these values do not change statistically significantly in any catchment area, they do show slight upward or downward trends in some regions of Poland, which is reflected in the magnitude of change in discharges in some of the catchment areas examined in this paper.

Even relatively large regression coefficients and coefficients of determination in the correlations between climatic factors and discharges in some catchment areas do not necessarily prove a cause-and-effect relationship between the variables under study. They may result from co-occurrence of changes of equal or opposite directions caused by other factors. In all likelihood, in many catchment areas the significant reduction in water resources was due to inadequate water management and only coincidentally coincided with the increase in air temperature. This is particularly true for catchment areas located in the lowlands, subject to strong human influence.

The relatively weak correlations between climate change and the volume of water resources indicate the importance of anthropogenic factors, which is an optimistic observation because we can control our water management to a greater extent than climate change.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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