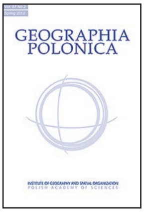

Geographia Polonica
2022, Volume 95, Issue 1, pp. 25-52
https://doi.org/10.7163/GPol.0225

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CHANGES IN SPECIFIC RUNOFF IN RIVER CATCHMENTS OF WESTERN POMERANIA VERSUS CLIMATE CHANGE

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Abstract

This paper examines specific runoffs in the catchments of the rivers Ina, Rega, Parsęta, Radew and Wieprza in the hydrological years 1981 through 2019. The magnitude of specific runoff is an indirect measure of water resources in a given region. Except for the Radew catchment, mean annual specific runoffs have diminished in all the analyzed catchments through the study period. In some or all of the catchments, runoffs from April through July have also diminished. The largest changes have been observed for June in the Ina and Parsęta catchments. These changes are basically due to the increase in air temperature.

Key words

Pomeranian Lake District • Southern Baltic coastlands • temporal trends in river runoff • climate change effects • water resource depletion

Introduction

Changes in river runoffs are highly significant for both the environment and human economy. This is because they reflect the water resources in the environment. Decreasing river runoffs may indicate water shortages in individual catchments. Also changes in water volume within a river bed have a high significance for river ecosystems and river valleys. Furthermore, they determine the potential to exploit water resources by humans.

Studies on changes in water resources due to climate change, predominantly due to global warming, have been performed in various parts of the world, both in large catchments, like the Nile or the Amazon rivers (e.g., Dai, 2011), and in small drainage basins lacking water gauging stations (e.g., Salinas et al., 2013). Such studies have identified a multitude of links, and a variety of conclusions have been drawn. It was noted, for instance, that in more dry conditions resulting from an increased temperature and reduced precipitation sums, runoff forecasting is more challenging than in more humid conditions (Haslinger et al., 2014).

Climate changes taking place in Central Europe, especially those concerning winter, influence changes in river regimes. The supply of water from snow melt is progressively diminishing (Piętka, 2009), and variations in river runoffs and river regimes are dependent not only on multiannual temperature and precipitation trends, but also on the positive or negative phase of the North Atlantic Oscillation for a given year (Danilovich et al., 2007; Wrzesiński, 2008). In addition to temporal trends, some of these works show a certain multi-year periodicity in river runoff values. Climate changes are accompanied by changes in river regimes, and mechanisms causing the formation of very low and very high flows undergo modifications (Krasovskaia & Gottschalk, 2002). Changes regarding river regimes are expressed, for instance, in river runoffs, whose winter values are increasing, while spring values are decreasing (Stahl et al., 2010). In temperate latitudes, these changes are due to winter air temperature increase, and a diminished supply from snowmelt. As a consequence, the seasonal variability in river runoffs becomes levelled due to lower early spring runoff intensity (Wilson et al., 2013, van Loon et al., 2015). This is the reason why studies aiming to determine the influence of climatic changes on water shortages and surpluses in catchments are undertaken (e.g., Hisdal et al., 2001; Bordi et al., 2009). Especially important are, for instance, the analyses of the influence that changes in winter air temperature, snow cover depth, and number of days with snow cover exert on the formation of especially low and high water flows, compiled by Blöschl et al. (2007).

The issue of climate change impact on water resources is becoming especially important in Poland, where the sustained increase in temperature is expected to result in an increasingly frequent occurrence of weather extremes, especially droughts (Somorowska, 2009; Szwed et al., 2010). In summer, over most of Poland, evapotranspiration exceeds precipitation, and the existing models predict further escalation of this unusually harmful deficit (Szwed et al., 2010). Considerable humidity shortages are indicated, e.g., by too low soil water storage (SWS) values. For instance, in the dry year 2015, SWS values for July were too low for 45% of the area of Poland. SWS values for August were too low for 72%, and for September – for 94% of the area of Poland (Somorowska, 2017). Detection of changes in water resources is therefore essential.

In the study area an increase in air temperature was observed accompanied by a simultaneous lack of increasing trends in precipitation sums (Świątek, 2011; Kirschenstein, 2013; Tylkowski, 2013; Świątek, 2017). This tendency is not restricted to this area, but also observed for the whole of Poland (Mager et al., 2009; Wibig, 2009; KLIMADA 2.0, 2017). We do know, however, that the precipitation structure is changing, as expressed by an increase in frequency of heavy, high-intensity rainfall episodes (heavy downpours; Hannessy et al., 1997; Christensen & Christensen, 2004). Such heavy precipitation is drained by rivers (and thus discharged into the sea) more rapidly than long-lasting, continuous, low-intensity precipitation. As a consequence, heavy rainfall makes little impact on replenishing water resources in a given catchment. This was documented for the study area based on an analysis of rainfall and river runoff in 2018 (Świątek & Walczakiewicz, 2019).

An analysis of monthly air temperature values and precipitation totals from the period 1955-2014 in an area approximately encompassing the catchments examined here indicated an increase in monthly air temperature from February to August, except for June (Kirschenstein, 2013; Świątek, 2017). Changes in precipitation totals displayed an increasing trend (the largest in January, March and June; Świątek, 2017), but the changes were statistically significant only for March (Kirschenstein, 2013).

The decoupling of trends in temperature and precipitation totals suggests a threat of diminishing the water resources volume through insufficient replenishing of the water that evaporates. This is further aggravated by an elevated drought probability for some months in a year, assessed for example for the period 1965 through 2004 (Kalbarczyk & Kalbarczyk, 2006). The increasing risk of water resources depletion was studied for instance by Somorowska (2009). Such shortages may result, for example, from significant changes in the river outflow in Polish rivers in spring (Piętka, 2009). A large-scale, government-commissioned study showed that catchments of small, lowland rivers are the most vulnerable to climate change, as expressed by diminishing average and low runoffs, and the resultant decrease in water resources volume. Catchments located within lake districts were found to be less susceptible to climate change (Majewski, 2012; Osuch et al., 2012). Climate change, especially in winter, is changing river regimes, which is associated with the North Atlantic Oscillation. This exerts a strong influence on seasonal variability in river supply and flood occurrence probability (Danilovich et al., 2007; Wrzesiński, 2008).

The aim of the present paper is the detection of climate change-induced variations in specific runoffs in Western Pomerania. It also aims to verify whether the relatively high retention of the Pomeranian catchments, especially in their part located within a lake district, is enough to protect the study area against water shortages. The research aims also to (1) verify whether any differences in specific runoff changes exist between catchments located within topographically varied area and those located in basically flat area, and (2) determine whether surface retention influences these changes, either via natural retention (e.g., via forests), or artificial retention (e.g., via retention basins).

Study areas and anthropogenic changes in water relations

This study covers the catchments of the rivers Ina, Rega, Parsęta, Radew and Wieprza. Catchments examined in this work are located in the Western Pomeranian Voivodeship of Poland. They comprise both topographically varied areas of the Pomeranian Lake District, and the generally flat Szczecin Coastland and Koszalin Coastland. The rivers Rega, Parsęta and Wieprza drain the Drawsko Lake District (Rega and Parsęta), and the Bytów Lake District (Wieprza), as well as the flat Szczecin Coastland (Rega) and Koszalin Coastland (Parsęta and Wieprza), following which they flow toward the northwest and empty into the Baltic Sea. Ina flows from the Ińsko Lake District, and the majority of its catchment is located within the Szczecin Coastland. It flows toward the west, and empties into the Odra River close to its mouth, i.e., between Dąbie Lake and Szczecin Lagoon. Radew is a right tributary of Parsęta, and like Parsęta it drains the Drawsko Lake District and the Koszalin Coastland while flowing toward the west. Basic information on the catchments, and the locations of water gauging stations are presented in Table 1. Characteristic features of the studied catchments with respect to relief and terrain cover, as well as their thermal and pluvial features are presented in figures 1, 2 and 3.

The studied catchments differ in absolute elevations (Fig. 1, Tab. 1). Some of the studied rivers are characterized by considerable drops, e.g., 1.44‰ drop on Wieprza (Marszelewski 2007). The highest dominance of flat and low-lying areas is characteristic of the Ina catchment (Dębowska, 2004). This catchment has the lowest average absolute elevation. Also the absolute elevation of the Rega catchment is relatively low (Tab. 1). The highest elevations occur in the catchments of Radew and Wieprza. Basically, the upper reaches of all the studied catchments include hills, and middle and lower reaches include flat areas (Fig. 1). Surface relief, especially the inclination of the catchment area, and the elevation gradient along streambed, as well as the occurrence of drainageless depressions all influence the runoff rate in the catchments, and thus also the rate of formation of swells, and the time difference between rainfall and the resultant high flow in a given river. Absolute elevation influences climatic conditions within a given catchment, especially precipitation sums and temperature, which make a direct impact on water resources volume.

Agricultural land and forests prevail in the terrain cover of the studied catchments (Fig. 2). The percentage of forests

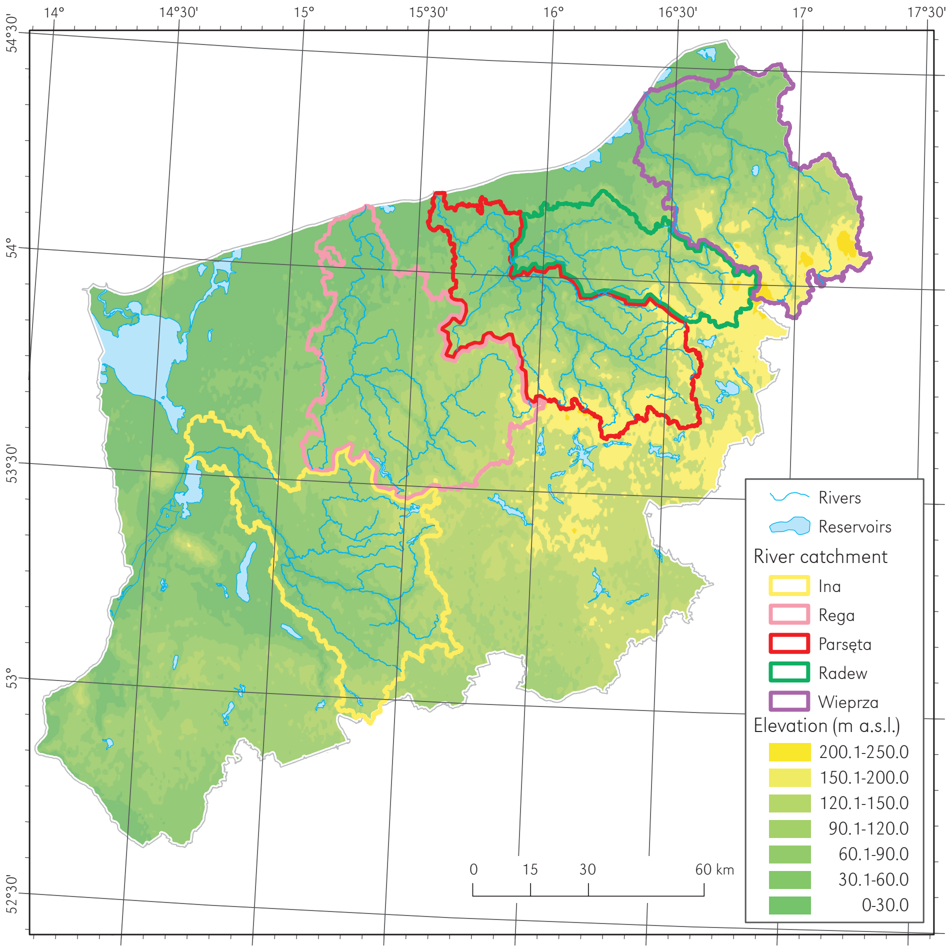

Figure 1. Absolute elevations of the Western Pomeranian Voivodeship, including the entire catchment of Wieprza.

in the total catchment area is the lowest for the Ina catchment, and the highest for the catchment of Radew. For both Wieprza and Parsęta, it is possible do distinguish the upper course of the catchment, mostly covered by forests, and the lower course, mostly occupied by farmland. Terrain cover forms significantly influence the retention potential of a catchment. Tree-covered areas are more efficient at water storage, although substrate permeability and aquifer water content are also significant (Hilsdal et al. 2001).

The differences between runoff values in these rivers are influenced by the spatial variability in atmospheric precipitation totals. In lake districts, precipitation sums are considerably higher than in coastlands. The lowest precipitation totals in the study area occur in the Szczecin Coastland, and gradually increase in an eastward direction (Koźmiński et al., 2012). In the area examined here, the lowest precipitation sums occur in the western part of the Ina catchment, where average annual rainfall sums equal about 550 mm. The highest precipitation sums (above 725 mm) occur in the northern part of the Radew catchment (Fig. 3). At the same time, the highest temperatures in Western

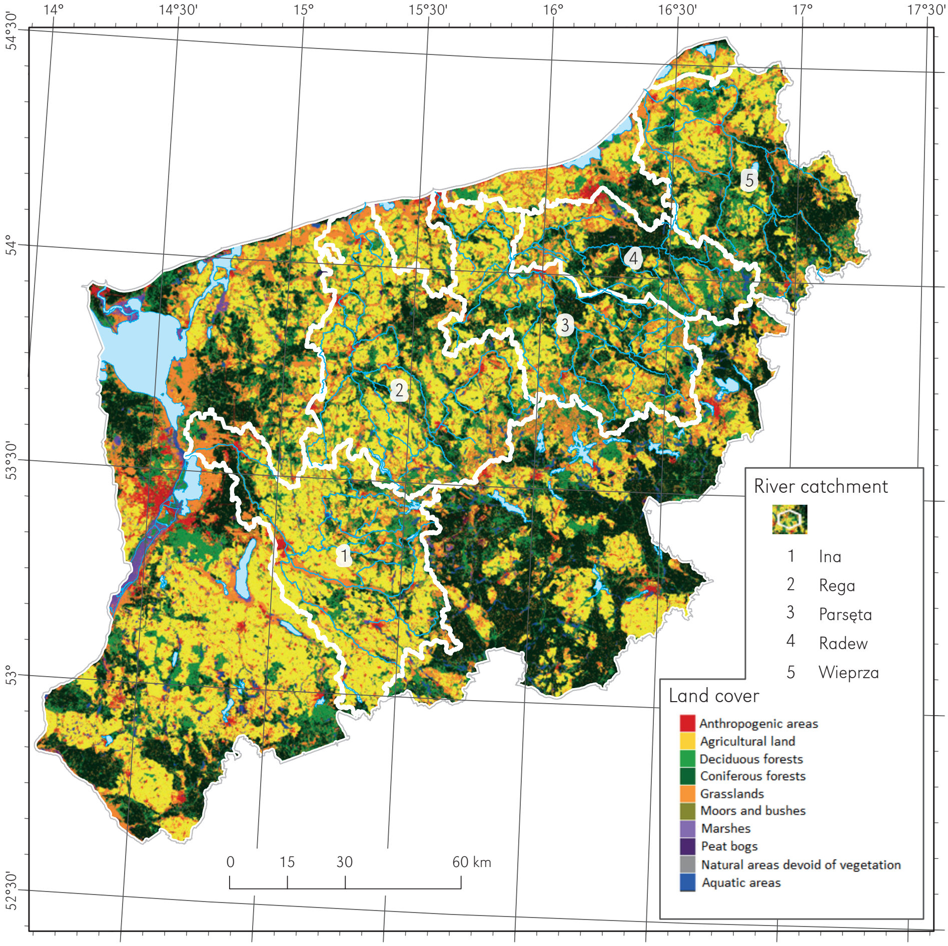

Figure 2. Terrain cover of the Western Pomeranian Voivodeship, including the entire catchment of Wieprza

Source: https://mapy.geoportal.gov.pl/ according to Polish Space Agency

Pomerania occur in the western part of the region, which includes the Ina catchment (Fig. 3). This results in elevated evaporation, and, as a consequence, leads to water shortages in this area.

Western Pomerania is characterized by a relatively low threat of both water shortages and surplus water. This is due to high surface retention, especially in the eastern and southeastern parts of the region, comprised of a lake district with numerous natural reservoirs, wetlands and drainageless depressions. Water retention is facilitated by high forest cover (fourth highest in the country, following Lubusz, Pomeranian and Subcarpathian Voivodeships according to Milewski, 2018). Surface retention and more or less even distribution of precipitation sums through the year, as well as mid-winter thaws due to the dominant above zero air temperatures, even in winter, all result in Western Pomeranian river runoff variability being lower than in the remaining part of Poland (Borówka, 2002). Periodic precipitation shortages do occur in this area, however, in particular in May, and in summer months, especially in the western

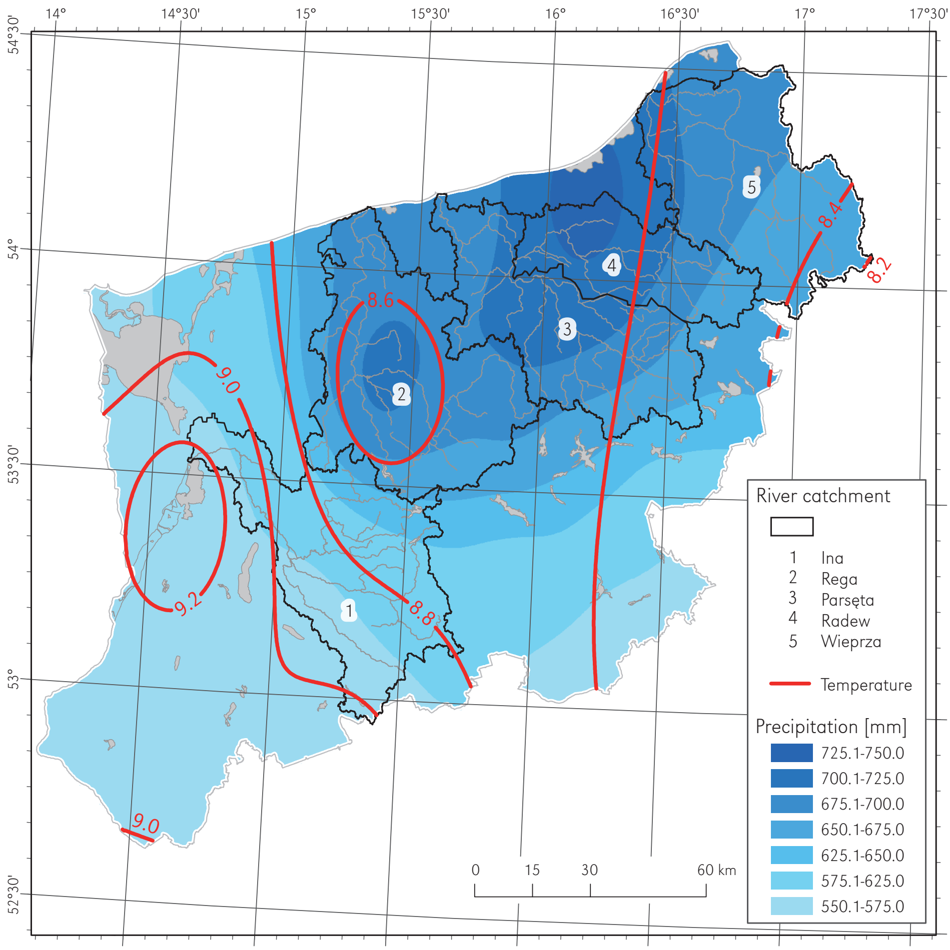

Figure 3. Average annual air temperature and average annual atmospheric precipitation totals in the Western Pomeranian Voivodeship (including the entire catchment of Wieprza), based on data from hydrological years 1981-2019

Source: Plotted based on data retrieved from Institute of Meteorology and Water Management – National Research Institute

part of the study area, especially in the Ina catchment (Rojek, 2004). The discussed catchments are characterized by high river resources (especially in comparison to the remaining part of Poland; Marszelewski, 2007), which display low variability through time. The highest (per unit of catchment area), and at the same time the least variable water resources occur in the Wieprza catchment. The lowest, and the most variable water resources occur in the Ina catchment (Bogdanowicz, 2009; Wrzesiński & Brychczyński, 2014). Ina is characterized also by the highest variability in extreme runoffs among all rivers of Western Pomerania (Bogdanowicz, 2009). The highest runoffs in Western Pomerania occur in the cold season from December to March (with a maximum in March), and the lowest runoffs are observed in the warm season, from June to August (Bogdanowicz, 2009).

High water resources of the western Pomeranian rivers (except for the slightly

Table 1. Total catchment area of a given river (A), area-mean catchment elevation of a given river (H), area-mean annual air temperature in catchment (T; hydrological years 1981-2019), area-mean annual precipitation sum in catchment (P; hydrological years 1981-2019), water gauging station locality, latitude (ϕ) and longitude (λ),absolute elevation (H*) of water gauging station, and its distance from river mouth/distance along river course (L), catchment area down to the given measuring profile/water gauge (A*), mean annual discharge at a given water gauging station (Q), specific runoff (q) from a catchment for selected river catchments of Western Pomerania (hydrological years 1981-2019).

River catchment	A [km²]	H [m a.s.l.]	T [°C]	P [mm]	Ggauge's location					A* [km²]	Q [m³s⁻¹]	q [dm³s⁻¹ km⁻²]
					town	ϕ	λ	H* [masl]	L [km]			
Ina	2362	62.0	8.9	597.3	Goleniów	53°33'47"N	14°49'37"E	1.7	15.8	2163	13.59	6.28
Rega	2648	72.0	8.7	673.4	Trzebiatów	54°03'48"N	15°15'39"E	0.0	12.9	2628	20.15	7.67
Parsęta	2070	90.7	8.7	671.4	Bardy	54°03'45"N	16°07'00"E	3.6	25.0	2955	27.79	9.40
Radew	1197	89.9	8.6	691.2	Białogórzyno	54°03'45"N	16°07'00"E	25.5	26.5	807	7.86	9.74
Wieprza	2245	88.0	8.5	673.0	Stary Kraków	54°26'32"N	16°36'23"E	5.2	20.6	1519	16.31	10.73

poorer Ina catchment) are due to relatively high precipitation sums and diminished evaporation from the lake districts (located at higher elevations) caused by lower air temperatures. Relatively frequent occurrence of low-intensity rainfall and snow cover instability are also significant (Wrzesiński & Brychczyński, 2014). Among non-climatic factors, it is important to note the occurrence of subglacial furrows and deeply incised river valleys draining deep groundwater levels (Bogdanowicz, 2009). The low range of runoff variability is dependent on the river supply structure, featuring mostly underground supply (Wrzesiński & Brychczyński, 2014). The percentage of underground river supply in this area ranges even up to above 70% (Dynowska, 1972). Such high significance of underground supply results from the occurrence of numerous, large endorheic permeable areas, and the occurrence of thick, highly permeable bedrock (Bogdanowicz, 2009, Wrzesiński & Brychczyński, 2014). Note that such bedrock is the least widespread in the Ina catchment (Bogdanowicz, 2004). The relatively low runoff variability is also influenced by flow-through lakes, which prevail in the studied area, both with respect to their number, and with respect to their surface area (Borowiak, 2000).

Most of the studied rivers and their tributaries are characterized by a nival, moderately well developed regime which features an average spring month runoff equal to 130 to 180% of an average annual runoff. Some of the rivers located in the western part of the study area display a nival, poorly developed regime. A nival, very well developed regime is observed for some of the rivers located in the eastern part of the studied area (Wrzesiński, 2016; Wrzesiński, 2021).

Changes in runoff values and specific runoffs are not only due to climate changes, but also due to changes in land use and water relation alteration resulting from human activity. Human impact on hydrological changes in the studied catchment basins was assessed mainly based on commentaries to 1:50 000 hydrological maps. In the vast majority of the analyzed catchments, water relations changed both during the study period, and in preceding years due to human activity (Kaniecki et al., 2004, 2006a, 2006b, 2006c, 2006d; Choiński & Łyczkowska, 2006; Graf & Puk, 2006; Graf & Ziętkowiak, 2006; Kostecki, 2006, 2007; Wrzesiński, 2006; Ziętkowiak, 2006, 2007; Kaniecki & Sobkowiak, 2007; Tański et al., 2011). Only within parts of the Radew (Graf, 2006) and the Parsęta (Ziętkowiak, 2006) catchments water relations have been altered to a low and moderate degree. Changes to water relations were associated with, for instance, deforestation of parts of catchment (as in the case of Rega; Choiński & Łyczkowska, 2006; Graf & Puk, 2006), and drainage of shallow ground waters leading to a lowering of the first aquifer. Construction of channels and ditches designed to drain wetlands, river deepening and straightening, especially in the case of smaller rivers (but also Ina, Tański et al., 2011; Keszka et al., 2013), also had a high significance for altering water relations. A large number of minor streams and channels that previously lacked drainage, were subsequently made part of drainage and hydrological system. Finally, at numerous sites, hydrotechnical constructions were erected within the river bed. These modifications have acted to diminish the natural retention of the catchment, and – by accelerating outflow – caused a more frequent occurrence of water shortages in catchments and the rivers draining them. Further, owing to the modifications, the duration of water deficiencies has been prolonged, leading even to a periodic absence of water in small rivers (e.g., Kaniecki & Sobkowiak, 2007).

Some forms of human activity have contributed to a minor increase in catchment retention. These include: erection of flood protection reservoirs, hydropower reservoirs (e.g., Rosnowskie Lake and Hajka reservoirs on Radew, or Lisowskie Lake and Rejowickie Lake on Rega), as well as fish culture and firefighting reservoirs. Notably, on the studied watercourses and their tributaries, there are a number of weirs, damming valves, slope adjustment sills, and even dams supporting small hydropower facilities. These are situated on all rivers examined here; both Ina and Rega rivers have as many as eight hydroelectricity facilities each. Within the Radew catchment, in Żydowo, there is a large pumped storage power station utilizing the waters of lakes Kwiecko and Kamienne. The increase in retention was also influenced by an increase in forested area in many parts of the study area, at the expense of agricultural land. Through the latter half of the 20th century, the loss of agricultural land in the Western Poleranian Voivodeship was the largest in Poland, amounting to > 10% (Ciołkosz & Poławski, 2006). Water relations may also be altered by transfer of clean and polluted water: intake of water from one catchment into a water supply network, and discharge as foreign water in the form of urban wastewater into a different river draining a different catchment.

Data and methods

The rivers analyzed here: Ina, Rega, Parsęta, Radew and Wieprza, have catchments located entirely within Western Pomerania. Not entire catchments of these rivers were considered due to the occurrence of backflow from the Baltic Sea – data from water gauging stations located at the mouths of the respective rivers were disregarded. Backflow acts to suppress river water outflow, and during periods of strong landward winds and storm surges, it causes marine waters to intrude the lower section of a river valley, which may cause flooding (Kreft, 2014; Kowalewska-Kalkowska, 2018), resulting in a distorted estimate of true outflow from a given catchment. This work includes runoffs measured at water gauges at the following sites: Goleniów (Ina river water gauge), Trzebiatów (Rega), Bardy (Parsęta), Białogórzyno (Radew) and Stary Kraków (Wieprza). The aforementioned localities and rivers whose catchments were studied are shown in Figure 4. Watersheds of the studied river catchments were determined using a numerical terrain model, and tools

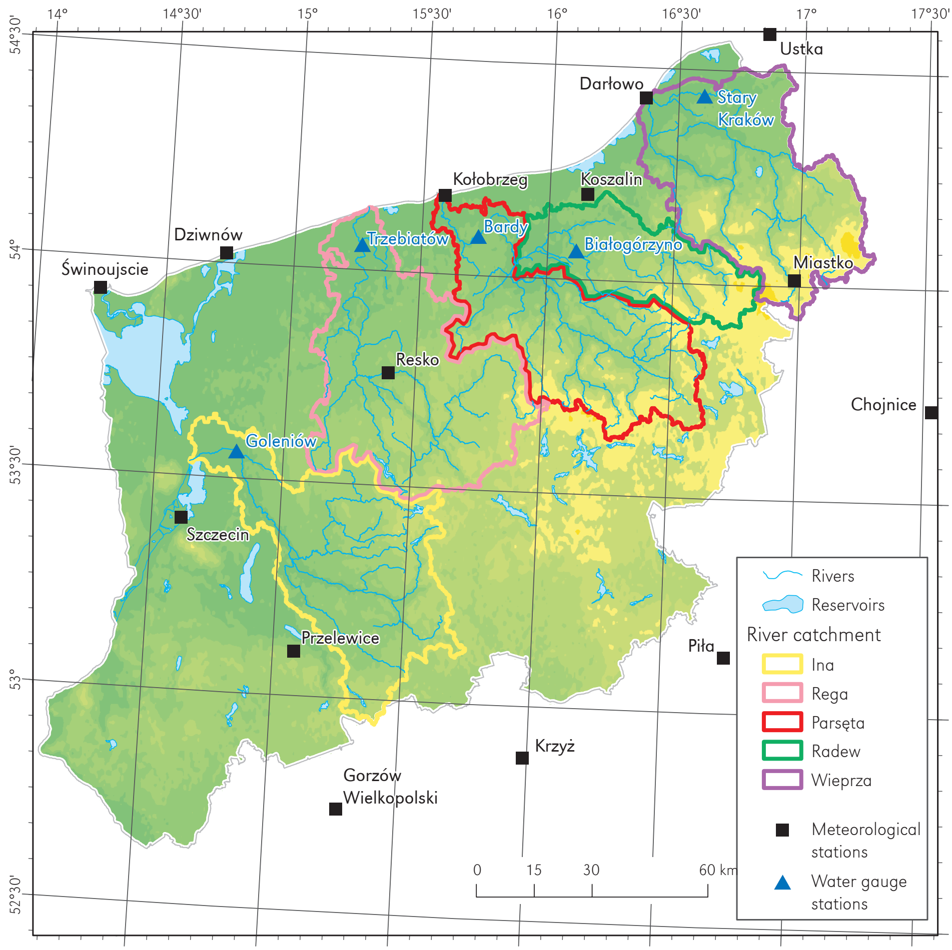

Figure 4. Outline map of the Western Pomeranian Voivodeship, with locations of the rivers whose catchments were examined here, including water gauging stations and weather stations that served as data sources

included in ArcGIS Pro package, enabling a determination of flow direction. Terrain cover was imaged using a map of Poland available in WMS service via Geoportal (https://mapy.geoportal.gov.pl). The map was commissioned by Polish Space Agency (POLSA), and prepared by Space Research Center, Polish Academy of Sciences. The maps presented in this paper basically cover the area of the Western Pomeranian Voivoideship. Since a small part of the catchment of Wieprza (included in this study) is located within the adjacent Pomeranian Voivodeship, the respective part of the Pomeranian Voivodeship is included in the relevant map figures as well.

This paper utilizes mean monthly values of river runoff at the water gauging stations mentioned above, from hydrological years 1981 through 2019, i.e., starting from November 1980 and ending with October 2019. These data were divided by the catchment area of a given river locked on a given water gauging station, yielding a specific runoff expressed in cubic decimeter per 1 second per 1 square kilometer of catchment area

($dm^3s^{-1}km^{-2}$). In the present paper, specific runoff was used as a measure of water resources. Calculating specific runoffs based on river runoffs at individual water gauging stations enabled a comparison between individual rivers and catchments, regardless of their size.

This study also utilizes mean monthly air temperature values from hydrological years 1981-2019 from Świnoujście, Koszalin, Kołobrzeg, Ustka, Resko, Chojnice, Szczecin, Piła and Gorzów Wielkopolski – a total of 9 weather stations. Mean monthly precipitation totals were used not only from these weather stations, but – due to a higher number of stations with continuous data series available – also from Miastko, Przelewice and Krzyż (a total of 12 weather stations, Fig. 4). Although the majority of these sites are located outside of the study area, the meteorological data retrieved from these stations enabled an interpolation, and, ultimately, determining area-mean values.

Monthly and annual area-mean air temperature values, and monthly and annual area-mean atmospheric precipitation sum values for the catchments of the five studied rivers were computed using the tools available as part of the ArcGIS Pro package based on inverse distance weighted interpolation. This enabled the generation of maps showing spatial distribution of air temperature and atmospheric precipitation for part of northwestern Poland in monthly increments from November 1981 to October 2019. Following this, each studied catchment was extracted from the generated maps, and spatial statistics were computed, including area-mean air temperature, and area-mean atmospheric precipitation sum.

Characterized in this paper are changes in annual and monthly specific runoff, as well as specific runoff changes for the vegetation season and for the period of active plant growth. The temporal span of these latter periods was estimated using maps included in the "Atlas of climatic resources and hazards in Pomerania" by Koźmiński & Michalska (2004) as follows: April through end of October (vegetation season) and May through September (active plant growth period). Absolute (expressed as volume of water drained from a unit of a given catchment area per unit of time) and relative (expressed as percentage of total mean specific runoff from a given catchment) values of estimated specific runoff decrease in the whole study period were also estimated.

The analysis of trends in mean yearly, monthly and seasonal (vegetation season and active plant growth period) specific runoffs and area-mean temperature and precipitation sum values was described by the non-parametric Kendall's correlation coefficient τ for the analyzed values versus time (consecutive years). Additionally, figures were plotted in order to visualize the obtained results. Figures show linear trends in: area-mean air temperature from the combined area of the studied catchments, area-mean annual atmospheric precipitation sums from the combined area of the studied catchments, and average annual specific runoffs from individual catchments – both in a year, and in those months for which the largest changes were observed in a multi-year perspective. The magnitudes of changes (decreases) and values of specific runoffs from the studied catchments were determined based on the regression line equations. These were subsequently divided by average multi-year specific runoffs in a given catchment, which yielded a relative measure of change (expressed as %).

Results

The river catchments examined in the present study vary with respect to relief, absolute elevation, and terrain cover, which is reflected in the specific runoff values. Also the magnitudes of specific runoffs vary in association with the precipitation totals occurring in the given region. Data on water gauging stations and catchments are presented in Table 1. Seasonal variability in specific runoffs in individual catchments is mainly dependent on air temperature changes through the year, which determine the intensity of evaporation. These parameters are therefore significantly higher in winter and early spring than in summer (Fig. 5).

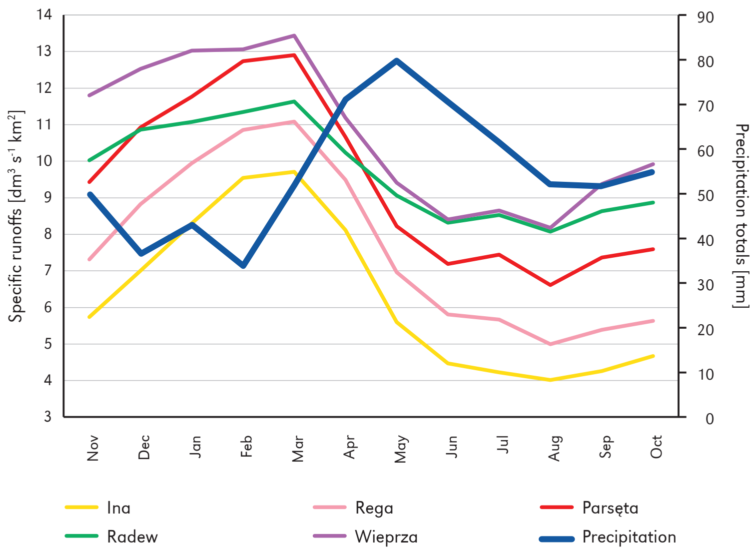

Figure 5. Seasonal variability in mean monthly specific runoff for selected river catchments of Western Pomerania and in mean monthly precipitation totals (hydrological years 1981-2019)

Table 1 and Figure 5 show that the runoff magnitude in the analyzed rivers increases in an eastward direction: the lowest specific runoffs, both annual and monthly means, are recorded for the Ina catchment, and the highest ones – at the boundary with Pomeranian Voivodeship, in the Wieprza catchment. Seasonal discharge variability, and consequently also specific runoff variability, is similar, and dependent mostly on air temperature impacting the amount of evaporation, and – to a considerably lesser extent – on the relatively low supply of water from snowmelt. Thus, the highest runoffs occur in March, and the lowest ones in August. The relatively high runoff magnitude in March is influenced by the accumulation of water in catchments through the low evaporation period in winter. Water released in late winter/early spring from snow cover is also significant, although the volume and durability of snow cover in western Pomerania are minor (including frequent mid-winter thaws; Koźmiński et al., 2012). Furthermore, an ongoing reduction in the number of days with snowfall is observed in this region (Szwed et al., 2017).

Trough the study period (hydrological years 1981-2019) the climate of Western Pomerania has undergone significant changes. These concerned mostly an increase in air temperature (Fig. 6A). Changes to mean annual precipitation sums were relatively minor, displaying a statistically insignificant ($p < 0.05$) increasing trend (Fig. 6B). At the same time, a very high year-to-year variability was observed in precipitation totals. A statistically significant ($p < 0.05$) increase in air temperature has occurred in all catchments in April, June, August, September and November. Average temperature has increased also for the whole year, the vegetation season, and active plant growth period. The largest changes, expressed as the value of Kendall's τ correlation coefficient between temperature and time, were observed for the vegetation season (Tab. 2A) in the catchments located in the central and eastern parts of Western Pomerania. Temperature increase occurred also in December and July. At the same time, no statistically significant changes have been observed for precipitation sums (Tab. 2B), except for small increases in monthly precipitation sum for July and annual precipitation

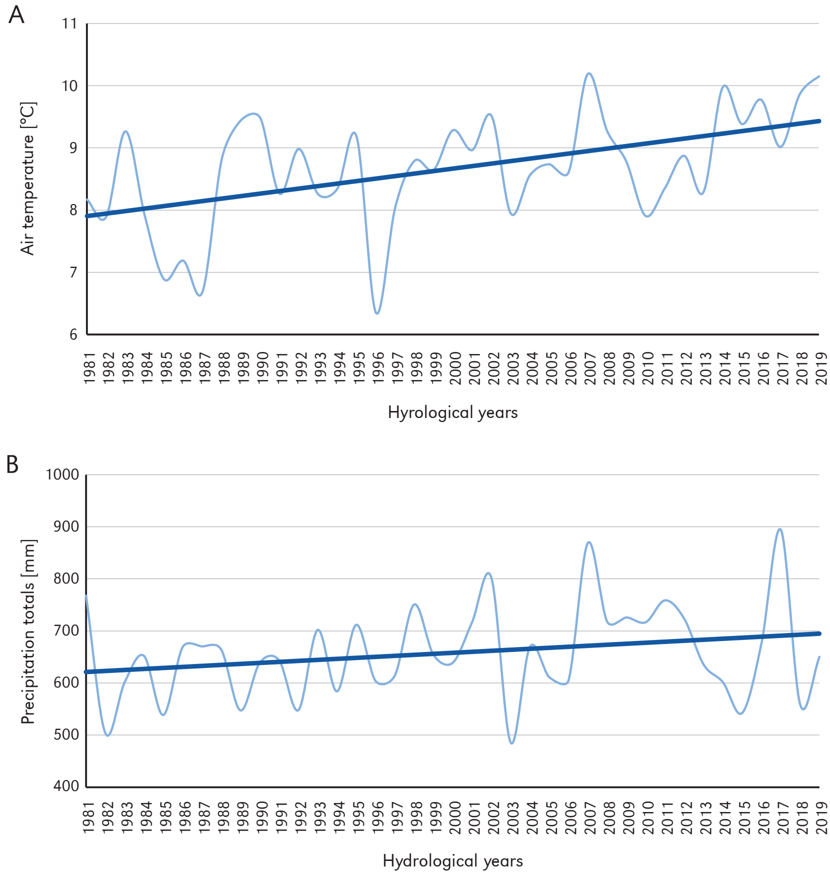

Figure 6. Multiannual changes in areal-mean annual air temperature values (A) and area-mean annual precipitation totals (B) from the combined area of the studied catchments (hydrological years 1981 to 2019), along with a regression line, its equation, and determination coefficient

sum for the Wieprza catchment, both statistically significant at 0.05 level.

As shown in Fig. 6, the seasonal variability in precipitation sums in individual months does not directly influence specific runoff values. Variability in air temperature is a more significant factor influencing the water resources depletion in the catchments in summer and early spring, due to elevated evaporation during the summer season. This is because temperature varies seasonally in the study area to a higher degree than precipitation sums. The variation coefficient for mean monthly air temperature values from hydrological years 1981-2019 (area-mean from the combined area of all the studied catchments), calculated as the standard deviation to arithmetic mean ratio equals 0.65. An analogous variability coefficient for precipitation is considerably lower and equals 0.24.

To a high degree, climate changes are manifested in river discharge and specific runoff changes. Mean annual runoffs in consecutive hydrological years, beginning with water year 1981, are basically decreasing, as expressed by the decreasing specific runoff values (Tab. 3A). In catchments of Ina, Rega and Parsęta, the drops are statistically significant at $p < 0.05$ level. Except for the Radew catchment, also the decreases in specific

Table 2. Kendall's τ correlation coefficients for area-mean air temperature values (A) and area-mean precipitation sums in catchments (B) versus time

	River catchment	Nov-Oct	Apr-Oct	May-Sep	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
A	Ina	0.32	0.45	0.40	0.25	0.21	-0.03	0.10	0.06	0.34	0.100	0.35	0.18	0.25	0.23	0.05
	Rega	0.31	0.47	0.41	0.26	0.21	-0.03	0.09	0.05	0.34	0.090	0.34	0.20	0.29	0.24	0.05
	Parsęta	0.35	0.50	0.46	0.29	0.23	-0.05	0.09	0.09	0.33	0.104	0.37	0.23	0.30	0.28	0.05
	Radew	0.35	0.51	0.45	0.29	0.23	-0.05	0.09	0.09	0.31	0.090	0.34	0.22	0.30	0.29	0.07
	Wieprza	0.36	0.53	0.48	0.31	0.23	-0.04	0.08	0.08	0.34	0.090	0.38	0.23	0.31	0.32	0.07
B	River catchment	Nov-Oct	Apr-Oct	May-Sep	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	Ina	0.13	0.14	0.10	0.09	0.00	0.06	0.06	0.02	-0.13	0.06	-0.12	0.17	0.07	0.10	0.19
	Rega	0.02	0.02	0.06	0.05	0.01	-0.04	0.04	-0.04	-0.14	0.03	-0.09	0.13	0.02	-0.06	0.13
	Parsęta	0.12	0.05	0.10	0.07	0.01	-0.05	0.11	0.02	-0.06	0.00	-0.10	0.18	0.11	-0.07	0.12
	Radew	0.19	0.10	0.10	0.05	0.14	0.00	0.12	0.08	-0.02	-0.05	-0.07	0.22	0.13	-0.03	0.10
	Wieprza	0.31	0.19	0.17	0.07	0.21	0.06	0.16	0.13	0.04	0.06	-0.04	0.29	0.16	-0.04	0.12

Grey shading indicates values that are statistically significant at $p < 0.05$ level

Table 3. Kendall's τ correlation coefficients for specific runoff versus time – hydrological years 1981-2019 (A) and hydrological years 1998-2019 (B)

	River (gauge)	Nov-Oct	Apr-Oct	May-Sep	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
A	Ina (Goleniów)	-0.23	-0.26	-0.29	-0.17	-0.18	-0.08	-0.11	-0.14	-0.23	-0.27	-0.40	-0.27	-0.19	-0.18	-0.15
	Rega (Trzebiatów)	-0.24	-0.28	-0.30	-0.12	-0.14	-0.11	-0.18	-0.2	-0.21	-0.32	-0.30	-0.24	-0.11	-0.19	-0.09
	Parsęta (Bardy)	-0.26	-0.32	-0.34	-0.08	-0.12	-0.06	-0.15	-0.2	-0.28	-0.36	-0.39	-0.21	-0.19	-0.23	-0.03
	Radew (Białogórzyno)	-0.09	-0.16	-0.19	0.02	-0.04	-0.05	-0.01	-0.12	-0.13	-0.19	-0.25	-0.04	-0.09	-0.16	-0.04
	Wieprza (Stary Kraków)	-0.19	-0.30	-0.31	-0.12	-0.09	-0.06	-0.00	-0.13	-0.28	-0.27	-0.33	-0.22	-0.18	-0.21	-0.16
B	River (gauge)	Nov-Oct	Apr-Oct	May-Sep	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	Ina (Goleniów)	-0.46	-0.47	-0.43	-0.37	-0.33	-0.26	-0.38	-0.5	-0.55	-0.49	-0.49	-0.38	-0.28	-0.30	-0.32
	Rega (Trzebiatów)	-0.25	-0.32	-0.33	-0.19	-0.10	-0.04	-0.19	-0.34	-0.25	-0.12	-0.22	-0.22	-0.27	-0.32	-0.19
	Parsęta (Bardy)	-0.25	-0.3	-0.32	-0.19	0.05	-0.06	-0.19	-0.35	-0.25	-0.24	-0.45	-0.17	-0.2	-0.22	-0.08
	Radew (Białogórzyno)	-0.08	-0.23	-0.26	0.01	0.16	0.00	-0.19	-0.26	-0.16	-0.28	-0.42	0.00	-0.24	-0.24	0.01
	Wieprza (Stary Kraków)	-0.21	-0.31	-0.25	-0.17	0.15	0.02	-0.10	-0.16	-0.32	-0.3	-0.41	-0.23	-0.22	-0.07	-0.09

Grey shading indicates values that are statistically significant at $p < 0.05$ level runoff during vegetation season and active plant growth period are statistically significant. Kendall's correlation coefficient τ for the annual specific runoff values versus time (consecutive years) vary from -0.09 in Radew to -0.26 in Parsęta (Tab. 3A). The decreases in specific runoffs through the vegetation season (April through October) were higher than annual average (τ value up to -0.32 for Parsęta), and still higher for the active plant growth period (May through September): for all studied catchments (except for Radew), τ equalled about 0.3 (Tab. 3A). The average annual specific runoff for the Wieprza catchment did not change through the study period. For the vegetation season, however, the changes were statistically significant.

The correlation coefficient values τ for specific runoff versus time (corresponding months in consecutive years) for June in all catchments (except Radew), and for May in Parsęta and Rega catchments equal from -0.3 to -0.4 (Tab. 3A). These are the highest correlation coefficients regarding monthly specific runoff values. The remaining statistically significant relationships (at $p < 0.5$ significance level), indicated with grey shading in Table 3A, are weaker negative correlations – τ values range in these cases from -0.2 to -0.3 (Tab. 3A). These relationships are not statistically significant for the period from August to March (except September in catchment of Parsęta), although decreasing trends in specific runoffs occur in nearly all catchments and all months (except November in catchment of Radew).

An intensification of the decreasing trend in specific runoffs took place approximately at the beginning of the 21st century. The analyses performed for the period 1998-2009 (Tab. 3B) indicated a very strong drop in specific runoff values for the Ina catchment (including all months except for January, August and September). In the remaining catchments, the drops were lower, and – due to the small sample size (only 11 hydrological years), usually statistically insignificant at $p < 0.05$ level.

Linear regression analysis also indicated the largest decreases were observed in the Parsęta catchment (Fig. 7), where the mean annual specific runoff decreased on a year-to-year basis during the study period by 0.062 $dm^3s^{-1}km^{-2}$, which, given the multiannual specific runoff value of 9.5 $dm^3ls^{-1}km^{-2}$ (Tab. 1), is a relatively high value. In this case the determination coefficient equals $R^2 = 0.156$, which means that time explains the multiannual variability in specific runoff in 15.6%. Periods of diminished water

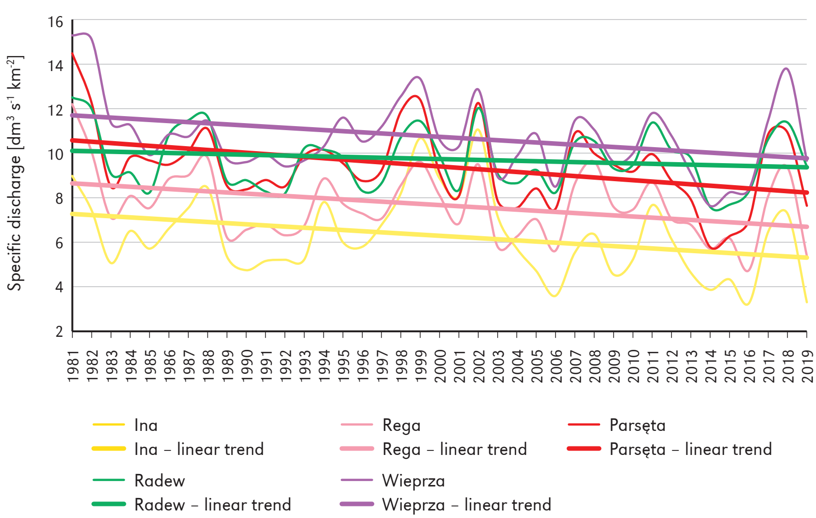

Figure 7. Multiannual variability in mean annual specific runoff (hydrological years 1981-2019)

resources in the catchments, measured using runoff values, are interrupted by more humid periods, e.g., at the turn of the 20th century.

The analysis of changes in specific runoffs in individual months indicated the occurrence of statistically significant cases in spring and summer months, i.e., from April through August (Tab. 3A). Changes in these months are plotted in Figure 8. The largest changes concerned the discharge values for June (Fig. 8C), ranging from 0.051 $dm^3ls^{-1}km^{-2}$ on a year-to-year basis in the Radew catchment (down to the water gauging station in Białogórzyno) to 0.09 $dm^3s^{-1}km^2$ in the Ina catchment (down to the water gauging station in Goleniów). Notably, the mean multiannual specific runoff for June for the Ina catchment in Goleniów is only 4.3 $dm^3s^{-1}km^{-2}$, and the annual value is 6.3 $dm^3s^{-1}km^{-2}$ (Tab. 1). Large drops in specific runoff values occur also in May (Fig. 8B). The largest drop was observed in the Parsęta catchment, 0.086 dm^3s^{-1} km^2 on a year-to-year basis.

The slope of the regression line (regression coefficient values, and other statistics describing the trends) describing specific runoffs values for individual months is largely influenced by single cases of very high runoffs. For instance, April 2008 (Fig. 8A), July 2007 (Fig. 8D), or winter months of the hydrological year 2017 (close to the end of the study period) caused a decrease in the trend statistics. For May and June, there were no such cases of single months with runoff values significantly exceeding multiannual means.

Figure 9 shows the specific runoff decrease through the study period (39 hydrological years). These range as high as nearly 4 $dm^3s^{-1}km^{-2}$ (exact -3.978 $dm^3s^{-1}km^{-2}$) in the Parsęta catchment in April (R^2 = 0.039).

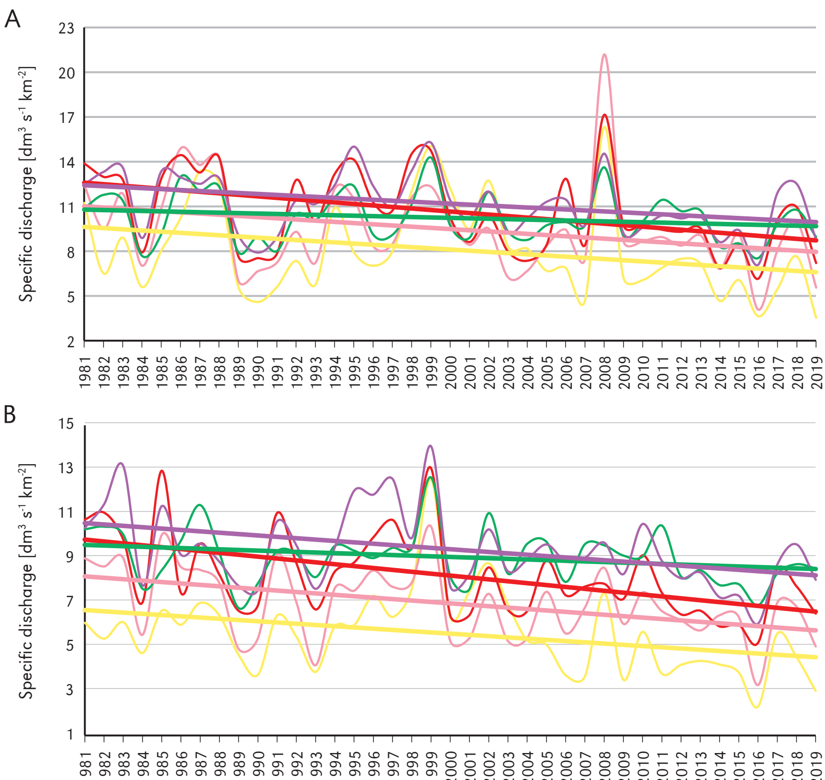

Figure 8. Multiannual variability in mean monthly specific runoff values (hydrological years 1981-2019) for April (A), May (B)

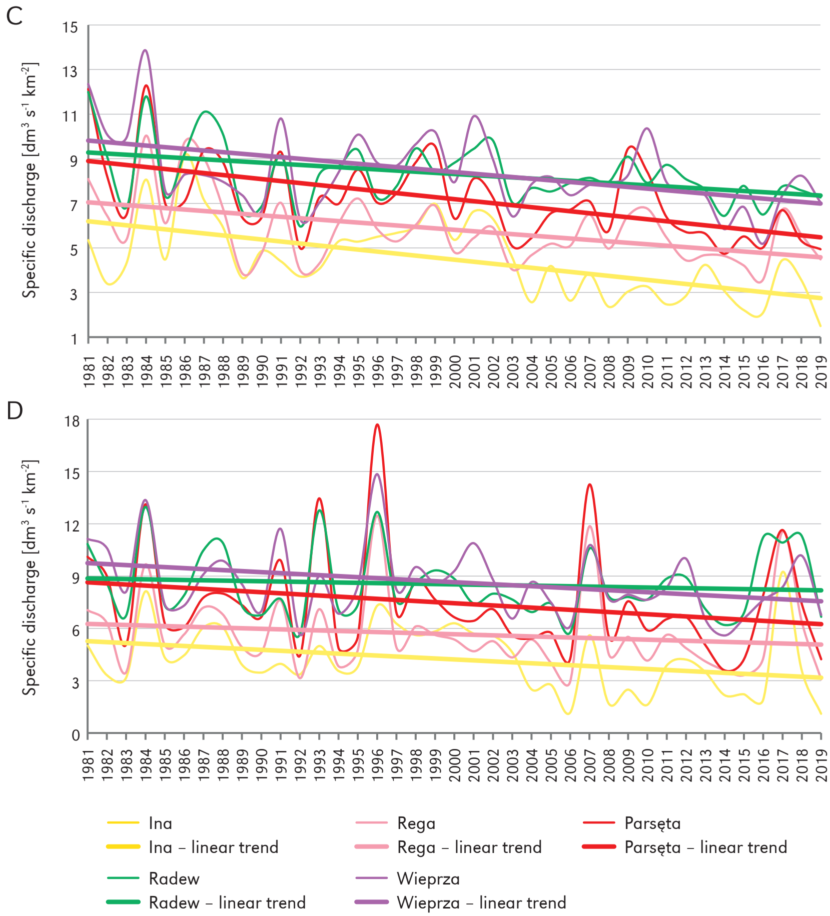

Figure 8. Multiannual variability in mean monthly specific runoff values (hydrological years 1981-2019) for June (C) and July (D)

The lowest drops occur in the catchment of Radew, a tributary to Parsęta.

The absolute magnitude of water resource depletion, but even more importantly, the relative decrease in water resources relative to the average runoff magnitude, has a large significance for the environment and economy (mostly agriculture). Such relative values, i.e., the contribution of specific runoff change in the study period to the average multiannual specific runoff from a given catchment within this same time interval, are presented in Figure 10.

Relative declines in runoffs, expressed as percentages, vary spatially. The largest relative drop in annual specific runoff, and consequently also in water resources, occurred in the Ina catchment (down to Goleniów) – by 32% (Fig. 10). In the Parsęta (down to Bardy) and Rega (down to Trzebiatów) catchments, the drop equalled 26%, in the Wieprza catchment (down to Stary Kraków) – 19%, and in the Radew catchment (to Białogórzyno) as little as 8%. Figure 7 shows that in the Ina catchment, down to the water gauging station in Goleniów (15 km from its mouth), the loss of specific runoff in June was nearly 80% (precisely 79%), which is a catastrophic result, given the large requirement for water in late spring. Notably, the determination

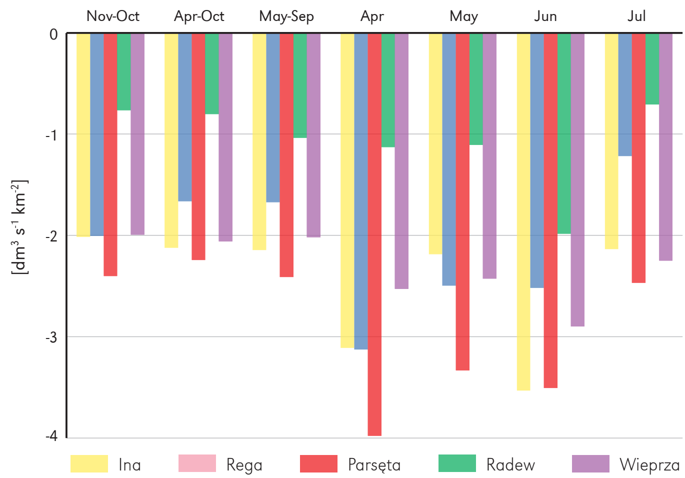

Figure 9. Specific runoff decrease through the study period (hydrological years 1981-2019)

coefficient R^2 is 0.358, which is a measure of fit of the regression line to the empirical data. In this particular case, it indicates that the passage of time explains the variability in specific runoff in 35.8%. The relative specific runoff decreases during the vegetation season in the Wieprza catchment (55%, with a determination coefficient $R^2 = 0.199$) and in the Ina catchment in July (51%, $R^2 = 0.109$) are also alarmingly high.

Discussion

In the Western Pomeranian river catchments, there is a disturbing decrease in specific runoffs in spring and early summer. The largest changes were observed for June. Unfortunately, the largest decreases in water resources occur in the period of the highest plant demand for water.

The highest values of specific runoff decrease are observed for June in the Ina catchment (down to Goleniów water gauging station). It is alarming and poses a threat to agriculture, as the Ina river catchment is among those areas of the Western Pomerania that are the poorest in water. With respect to precipitation sums, such areas are similar to the lowland belt of Poland (Lorenc, 2005; Fig. 3).

Changes in specific runoff values from April to July are mostly due to an increase in air temperatures in this period causing enhanced evaporation from the terrain surface, water bodies, plants and other surfaces. Increase in evaporation diminishes surface runoff, and even more importantly, prevents water from infiltrating into the substrate, thus inhibiting groundwater supply to rivers. Runoff values are influenced, moreover, by the retention potential of the catchment, river network density, catchment size and surface morphology (including the angles of valleys of a given river and its tributaries) that together determine the outflow rate.

The decrease in early spring water resources is certainly influenced by the increase in winter temperatures in Western Pomerania (Marosz & Ustrnul, 2010; Lehmann et al., 2011; Świątek, 2014), which prevents the formation of a permanent snow cover. The thawing of such snow cover at the end of winter would supply rivers and groundwaters in water. A decreasing trend in snow cover depth is observed essentially in most of the area of Poland (especially in lowlands) and in northern Germany (Falarz et al., 2018). Also the number of days with snow cover is diminishing (Szwed et al., 2017). The retention of the river catchment, enabling storage of water

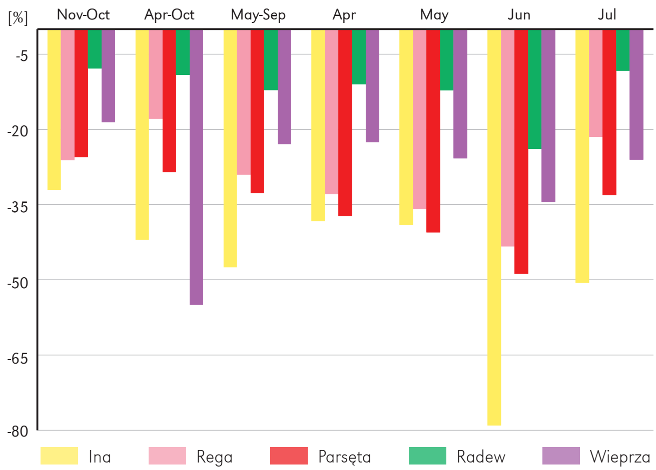

Figure 10. Contribution of change through the study period to the mean multiannual specific runoff (hydrological years 1981-2019)

from a colder period with lower evaporation for a warmer period characterized by an elevated demand for water due to active vegetation, is also diminished due to human impact, mostly manifested by draining wetlands, inclusion of drainageless areas into the overall hydrological system, sometimes excessive exploitation of groundwaters, and regulation of rivers, which accelerates runoff, and by diminishing retention in river valleys. The study area is, unfortunately, affected by such human activity (Kaniecki et al., 2004, 2006a, b, c, d; Graf & Puk, 2006; Choiński & Łyczkowska, 2006; Wrzesiński, 2006; Ziętkowiak, 2006, 2007; Kaniecki & Sobkowiak, 2007; Kostecki, 2007; Tański et al., 2011). Yet, given the decreasing nival retention (in the form of snow cover), other forms of temporary water storage are becoming increasingly important. Retention is also highly influenced by forest cover. Natural, multilayered forests (e.g., riparian forest in wetlands, mostly in river valleys) are the best form of leveling river runoff through the year, and at the same time for water purification. Afforestation basically facilitates an increase in river catchment retention, albeit not in all soil types: it is most valuable on heavy soils and on slopes (Chang, 2012). The 5th IPCC Report (2019) also points out that afforestation favours an increase in humidity and precipitation sums in a given region. Whereas in the whole Western Pomeranian Voivodeship between 1930 and 2000 forest cover increased by as much as 14.25% (the largest increase in the Poland), some parts of the Ina (Tański et al., 2011) and Rega (Choiński & Łyczkowska, 2006; Graf & Puk, 2006) catchments underwent deforestation, including sites immediately adjacent to these rivers. In 1995, the National Program for Expanding of Forest Cover was approved for implementation. In accordance with the Program, the forest cover in Poland increased to ~30%, and is projected to rise to 33% by 2050. Unfortunately, since 2009 the extent of afforestation in Poland drastically decreased due to a change in criteria for qualification of privately owned agricultural land for afforestation, and exclusion of permanent pasture and land located within Natura 2000 sites from afforestation funding. Further, direct payments to farmers dissuade private land owners from afforestation (Milewski, 2018).

Urbanization and industrialization also influence the magnitude of runoff (Gutry-Korycka & Jokiel, 2017). There has been no increase in these factors in the study area, however. The Ina (Tański, 2011) and Rega (Kaniecki et al., 2004; Ziętkowiak,

2007) valleys, however, have undergone river engineering, including the erection of flood embankments and cutting out meanders. These modifications induced faster runoff of water in the rivers, by decreasing the width of floodplains retaining water, and elimination of water storage in ox-bow lakes. Yet, it is essential for water to be retained for as long as possible within the catchment and in the form of shallow groundwater. For this reason, the protection of wetlands located mostly within river valleys and in the surrounding of natural water bodies is so important. Increasing retention is very important, so that water from the winter period characterized by low temperatures and low evaporation can be stored for as long as possible until the vegetation season, especially late spring. The water resources of northwestern Poland are considerably larger in the cold period than in the warm period. This is because their quantity is mostly determined by temperature variability. Precipitation is rather uniform through the year (Koźmiński et al., 2012), and supply of water from snowmelt is negligible. At the same time, the highest requirement for water to sustain vegetation occurs from May to September, i.e., when water resources in river catchments are smaller, which is even further compounded by the decrease of specific runoff, as shown in the present work. Precipitation totals in the study area are the highest in July, followed by August and September (Koźmiński et al., 2012), but in summer, evaporation is also the highest in a year. For this reason, it is advisable to grow winter crops. Firstly, they utilize soil moisture in the cold season characterized by low evaporation. Further, in spring, winter crops protect the substrate from evaporation and surface runoff in a more efficient manner than spring crops, which are only sprouting at that time of the year. This way, winter crops enhance the catchment retention. Conservation of catchment retention is all the more important, because climate projections performed as part of project named KLIMADA 2.0 (2017) indicate that in the 21st century, the air temperature increase in northern Poland is going to be especially high, while the increase in precipitation sums is going to be practically negligible. Further, the number of days with rainfall in western Poland is going to be decreasing, suggesting an elevated contribution of heavy rainfall to the overall precipitation sums, which is unfavourable from both economic and environmental points of view. Unfortunately, these changes will increase the threat of drought in the studied catchments, especially in the Ina catchment basin.

Previous studies performed in other European countries indicated that changes in water resources in river catchments are influenced most of all by changes in precipitation sums, but artificial inflows in catchments are also significant. An important factor is also the natural storage capacity, associated, for instance, with the aquifer resources, and the changes taking place in groundwater level volumes (Hisdal et al., 2001). In the 21st century, so-called "snowmelt droughts" have gained special significance in temperate latitude zones. Such droughts are associated with changes in winter temperature and precipitation, resulting in a diminished nival supply to rivers (van Loon et al., 2015).

A positive exception among the studied catchments is the Radew catchment, where a statistically significant case of specific runoff decrease was observed only for June. It is remarkable, as in the adjacent catchment of the river Parsęta, which is fed by Radew, the surface runoff depletion is among the highest in the region. The lack of changes in spring and summer months (excluding June) is probably due to a higher retention of the Radew catchment compared to other areas included in the present study. The Radew catchment is characterized by a higher proportion of rolling hills interspersed with drainageless depressions that retain water. There are also relatively large reservoirs – lakes Hajka and Rosnowskie. Also the forest cover is more extensive than in other catchments analyzed here (Fig. 2). The lack of significant water resource decline in the Radew catchment may therefore evidence the high significance of forests in the protection against negative hydrological effects of climate changes. The river regime of Radew is strongly influenced by the pumped-storage facility in Żydowo, which utilizes the 83 m difference in elevation between the surfaces of Lake Kwiecko and Lake Kamienne, which are located 1.7 km away from one another. Radew River originates from Lake Kamienne, which represents the upper basin of the facility.

The largest relative changes in specific runoff values (relative to the total specific runoff value) were observed for the Ina catchment. Apart from climatic factors, this was most likely influenced by the regulation of Ina River, which eliminated meanders, but also diminished the forest cover and enabled the development of agriculture (Tański et al., 2011; Keszka et al., 2013). This resulted in a diminished retention in the Ina catchment, especially within the river valley. Ina catchment is susceptible to water resources depletion also because of the lowest relative elevations, and the lowest density of drainageless depressions capable of storing water (Dębowska, 2004), compared to other studied catchments. Finally, the percentage of forests – which make a positive impact on water retention – is low in the Ina catchment surface area (Fig. 2).

The changes taking place from 1981 to 2019, presented here, are the opposite to previously recorded multiannual changes. In the period 1951-1980 the trends in runoff changes were positive in the whole of Poland. Runoffs were systematically increasing then. According to the regression equation, the runoff increase for the whole of Poland through this period equalled 0.733 billion m^3/year (Stachy, 1984). This likely resulted from a modest increase in precipitation sums through this period, and mainly from human impact. The latter was manifested by a shift in land use, and draining of river valleys, which consequently accelerated the cycling of water in catchments (Soja, 1988). The anthropogenic factor was thought to be the key cause for the runoff increase, especially in strongly urbanized and industrialized areas (Jankowski, 1988). There were also views suggesting that drainage works and river engineering do not increase the total sum of river runoff, and instead only result in shifts to the runoff distribution through the year (Bajkiewicz-Grabowska, 1975; Dębski, 1978). In the subsequent period (i.e., the study period of the present work), changes concerning land use and wetland reclamation for farming were considerably smaller, for instance due to an increase in agricultural productivity, allowing for a more efficient use of the existing farmland acreage (Gorzelak, 2010). Studies covering the entire second half of the 20th century indicated that a marked change in runoff trends, from increasing to decreasing, took place in Poland in the 1970s (Wrzesiński, 2009). Changes regarding land use in Poland were taking place mostly from the 1950s to 1980s, and were largely based on reclaiming wetlands for agricultural use. More recent works corroborate the mechanisms presented here: a diminishing spring runoff, especially in lowland and lake district rivers in Poland, which points to the decreasing significance of river feeding from snowmelt (Piętka, 2009). A decline in water resources was also identified, manifested for instance by an increased threat of drought in the summer months (Somorowska, 2009). Analyses focused on the period approximately equal to the one examined in the present work (years 1981-2016) indicate decreasing runoffs in northern Poland, increasing runoffs in southern Poland, and no changes in central Poland (Piniewski et al., 2018).

Within the Baltic Sea basin, the impact of climate change on river runoffs varies. Changes such as those occurring in the rivers of Western Pomerania are not observed everywhere. In fact, trends of changes can be quite the opposite. Whereas air temperature increase is observed in the whole Baltic Sea basin, trends in precipitation sum changes vary spatially. Precipitation sums are declining over some areas, while in other regions they are rising, sometimes strongly enough to increase runoffs, especially in winter. In spring however, precipitation sums are usually decreasing, due to milder winters with less snow and less durable snow cover, and therefore – a weaker supply from snowmelt in spring (Stahl et al., 2010). A general conclusion can be drawn that slight decreases in river runoff values are occurring in the southern part of the Baltic Sea basin (including Poland), while runoff values in the northern part of the Baltic Sea basin are increasing (Graham, 2004). For instance, a 5% increase in average river runoff has been recorded through the 20th century in Sweden, although the trend is not statistically significant. Flooding probability is increasing there at a faster rate (Lindström & Bergström, 2004). In Denmark evapotranspiration is increasing, but an increase in precipitation sums is considerably stronger, and consequently an increase in average annual runoffs is anticipated. However, due to the decline in summer precipitation totals, September and October runoffs are projected to diminish (Thodsen, 2007; Andersen et al., 2006). Forecasts for Lithuania indicate slight increases in average annual river runoff values (Kilkus et al., 2006). As winters are getting warmer, and the snow cover less durable, winter runoffs in Lithuania are significantly increasing, especially in January and February, while spring runoffs are decreasing, especially in April. Spring swells also occur earlier (Kilkus et al., 2006; Stonevičius et al., 2014). Average annual runoffs and winter runoffs are increasing also in Latvia and Estonia (Reihan et al., 2007; Kriauciuniene et al., 2012). On most water gauging stations in Germany, an increase in low flows is noted, which can be attributed mainly to reservoir management. On Havel River, whose catchment is located in close proximity to Poland, however, a progressively decline in average annual runoffs is observed (Bormann & Pinter, 2016). Runoff value drops are observed also in catchments supplied from snowmelt (Bormann, 2010). Modelling studies for Rhine, however, predict an increase in winter runoffs, and a decrease in summer runoffs (Middelkoop, 2001). In general, negative trends in annual runoff values occur in the southern and eastern regions of Europe, while positive trends are observed in the remaining regions. The largest rises in runoffs concern the winter season (Stahl et al., 2010). Despite an increase in air temperature in Europe, no increase in drought frequency and intensity is observed, except for regions characterized by diminishing precipitation sums, such as Slovakia or Spain (Bordi et al., 2009). Also changes in terrain cover, mostly anthropogenic, make a significant impact on the formation of dangerously high and low flows (Blöshl et al., 2007).

An important part in multiannual variability in runoffs and river discharges is played by the North Atlantic Oscillation (NAO) index. Depending on the occurrence of several year to > 10 year-long periods of positive or negative NAO indices, an increase or a decrease in runoffs occurred in rivers of northern Poland (Wrzesiński & Sobkowiak, 2018). During a positive NAO phase, characterized by an increased inflow of air masses from the west, the runoff in Pomeranian Lake District rivers increases on average by 20% per year. This increase is the highest in summer months – by 30% (Wrzesiński, 2011). Remarkably, NAO makes the largest impact on precipitation conditions in winter (Hurrell & Deser, 2010). This relationship further emphasizes the role of retaining surplus winter precipitation in lake district areas for the summer season. An increase in frequency of air mass inflow from western directions in the late 20th Century caused an increase in water resources in catchments of the western part of Pomerania (Marszelewski, 2007). A decrease in intensity of western air mass inflow approximately from the beginning of the 21st Century (Luo et al., 2012) caused an intensification of water depletion, especially in the westernmost catchment of Ina, as a result of precipitation sum decline, especially in winter and early spring, when NAO, which controls the advection from the west, makes the strongest impact on weather conditions (Li & Wang, 2003). The end of the positive NAO phase, made an influence on river runoff decreases in March in the central part of the study area (i.e., the catchments of Rega and Parsęta), but the Ina catchment responded to NAO-related changes the strongest. The North Atlantic Oscillation determines the occurrence of alternating periods of increasing and decreasing river discharge and specific runoff values. This is because an inflow of air masses from the west (mostly in winter) results in higher precipitation sums, and > 0°C air temperatures, which together inhibit nival retention, thus influencing changes in river regimes.

Conclusions

- An increase in air temperature with no concomitant changes in precipitation sums caused a significant reduction in water resources in Western Pomerania, manifested by diminishing specific runoffs in selected river catchments.
- Changes in specific runoffs vary both spatially and temporally.
- Especially significant changes have occurred for spring and summer months.
- Runoff magnitude for a given month is influenced by the amount of evaporation, directly impacted by air temperature. These changes are essentially associated with the air temperature rise determining the changes of magnitude of evaporation. Changes of water retention conditions in the catchments are also important.
- To some extent, changes in river runoff volume and specific runoffs in spring and summer periods are also influenced by human impact on river catchments, for instance by deforestation, regulation of rivers, and drainage works, which together influence the potential for retention of water from colder periods.
- The largest relative decrease in runoff values was observed for the catchment characterized by the lowest retention, located within the flat Szczecin Coastland. The decreases in runoff values were lower for those regions that have a denser forest cover, and more diverse topography. This implies that unfavorable changes may be reduced by the retention potential (conditions) of individual regions.
- A sustained decrease in water resources is observed also in catchments located in lake districts, despite their relatively high retention. In this case, however, the magnitude of the decrease was lower, especially in the most densely forested catchment.
- Water retention in catchment is essential due to higher supply of water to soils in cold months, and the increased requirement for water in the vegetation season. Conservation of natural retention and a reasonable water management in a catchment are essential, especially with regard to drainage works and river engineering. Forest cover and terrain relief are highly significant for water retention in a catchment, as these factors facilitate the leveling of river runoffs and a reduction in specific runoff depletion – as exemplified by the Radew catchment.

Acknowledgments

The authors would like to thank anonymous reviewers for their help in improving the quality of the manuscript and cartographic editor for involvement in the reliable preparation of maps.

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

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Article first received • March 2021
Article accepted • November 2021