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Impact of North Atlantic Oscillation on water resources in South Western Poland

Impatto dell'Oscillazione Nord Atlantica sulle risorse idriche della Polonia sud-occidentale

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Riassunto

Questo lavoro descrive l'influenza dell'Oscillazione Nord Atlantica (NAO) sulle risorse idriche della Polonia sud-occidentale focalizzandosi in special modo sul deflusso di base degli acquiferi. L'impatto delle modificazioni delle condizioni climatiche sulle risorse idriche di quest'area è stato determinato analizzando le variazioni del deflusso e del deflusso di base nel periodo 1966-2015. L'analisi statistica dei dati metereologici e idrologici ha dimostrato che il deflusso dalla catena montuosa dei Sudeti e dalla regione pedecollinare antistante dipende da fattori climatici come il NAO. L'indice annuale NAO permette di descrivere la variabilità media annuale del deflusso superficiale e del deflusso sotterraneo calcolato nel periodo da febbraio a gennaio e da marzo a febbraio, mentre l'indice NAO invernale permette di descrivere la variabilità media annuale del deflusso superficiale e del deflusso sotterraneo calcolato da marzo a febbraio e da aprile a marzo. Inoltre, l'indice NAO invernale permette di descrivere la variabilità media stagionale del deflusso superficiale e del deflusso sotterraneo medio stagionale calcolato da aprile a settembre. Nei casi descritti in precedenza, il coefficiente di correlazione di Pearson è elevato raggiungendo valori di -0.65.

Abstract

The paper presents the influence of the North Atlantic Oscillation (NAO) on the water resources, especially considering groundwater discharge (baseflow) in south-western Poland. The impact of long-term changes of meteorological conditions on the water resources of this area in the 1966-2015 was determined on the basis of changes in the baseflow and total stream flow. Statistical analysis of meteorological and hydrological data showed that the runoff from the Sudeten mountain range and its foreground depends on the circulating climate factors (like the NAO). The annual NAO index best describes the variability of the average annual (12-month) total stream flow and groundwater discharge calculated from February to January and March to February, while the winter NAO index best describes the variability of the average annual (12-month) total stream flow and groundwater discharge calculated from March to February and April to March. The winter NAO index also best describes the variability of the average six-month (6-month) stream flow and groundwater discharge calculated from April to September. In the above-mentioned cases, the values of the Pearson correlation coefficient are at a high level and reach the value of -0.65.

Inroduction

Water resources play a key role in the social and economic development of a region. Analyses of long-term hydrological data point to a connection between extreme river discharge events and climate anomalies. In Europe, the North Atlantic Oscillation (NAO) is regarded as the most important factor responsible for variations in weather conditions (Hurrell and van Loon 1997).

The North Atlantic Oscillation refers to fluctuations in the pressure gradient over the North Atlantic region between the Icelandic Low and the Azores High. It is the most important manifestation of atmospheric structure in the North Atlantic region and the critical factor contributing to variations in climate conditions over the Atlantic Ocean. It has a direct effect on precipitation and temperature anomalies, especially during the winter (Hurrell 1995). Positive phases of the NAO result in wetter winters in the north of Europe and relatively dry winters in the south, whereas negative phases have the opposite effect (Visbeck et al. 2001).

The NAO's impact on precipitation corresponds directly to changes in seasonal river runoff and, by extension, water resources. These effects are visible not just in Europe (Lavers et al. 2010; Lorenzo-Lacruzet al. 2011; Massei et al. 2010; Zanchettin et al. 2008) and North Africa (Turki et al. 2016), but also in the Middle East (Cullen et al. 2002). River regimes in Poland are also affected by the NAO (Pociask-Karteczka et al. 2003; Styszyńska and Tamulewicz 2004). In Eurasia, almost a quarter of the river monitoring stations (24%) indicates significant correlations between annual discharge (in the years 1950 - 1990) and the NAO index (Hurrel 1995).

Comparisons of the NAO index with hydrological data have shown a generally positive correlation with river discharge in Northern Europe, whereas in the case of rivers in Central and Southern Europe the opposite effect was observed. Consequently, a positive NAO index results in a higher than average discharge in northern Europe (especially in winter), and a below average discharge in Central and Southern Europe (Dettinger and Diaz 2000). A significant positive correlation (r > 0.6; 1961-1990) was observed in Scandinavia during the winter (Shorthouse and Arnell 1997). Similar results were obtained in the case of drainage basins in Great Britain (Lavers et al. 2010). Rimbu et al. (2002) observed a significant negative correlation in the case of the River Danube in Central Europe (r = -0.75; 1931-1995), whereas a moderately negative correlation (r = -0.4; 1951–2000) was found in the Hron drainage basin in Slovakia (Pekarova and Pekar 2004).

Spatial variability in the impact of the North Atlantic Oscillation correlates strongly with regional river regimes in Poland (Wrzesiński 2011). Changes in the intensity of the NAO have significant effects on stream flow in the north-eastern and northern parts of the country. In winter, the flow during the positive NAO phase is twice as high as during the negative phase (Wrzesiński 2008). Carpathian rivers and the Vistula river in Poland showed much weaker correlations with the NAO (Wrzesiński 2008, 2011). Pociask-Karteczka et al. (2003) came to similar conclusions in their research, drawing attention to the weak (albeit noticeable) effect of the NAO on the discharge of the rivers Skawa and Dunajec.

Research indicates that the influence of the NAO on the discharge of rivers in Poland is at its greatest in winter and early spring, i.e. during the formation of highest river discharges, directly affecting the amount of annual water resources, especially groundwater resources (Wrzesiński 2008).

The aim of this paper is to analyse the effects of the NAO on the availability of water resources, with a focus on groundwater discharge in Poland. The impact of long-term changes of meteorological conditions, in the 1966-2015, on water resources in south-western Poland was assessed on basis the variability of total and base flows.

Study area

The study focuses on south-western Poland and the north-eastern regions of the Czech Republic (part of the Odra River catchment from springs zone to the river gauge station in Chałupki – catchment R). The area includes mountain ranges in the south (the Sudetes together with their highest peak, Mount Śnieżka at 1,603 m a.s.l.), foothills in the central region and lowlands (at 100-150 m a.s.l.) in the north, above Odra River. The region includes 17 river basins (Fig. 1) with varying surface areas and geological – hydrogeological characteristics (Tab. 1). The surface areas of the catchments range from 55.9 to 4,666.2 km^2 and their total is 21,884 km^2.

The climate of the region is diverse. The northern, lowland part of the region is one of the warmest areas in Poland (Paszyński and Niedźwiedź 1999), with long, hot summers and short, mild winters. Annual precipitation ranges from 500 to 1,100 mm (1966-2005). The highest precipitation is

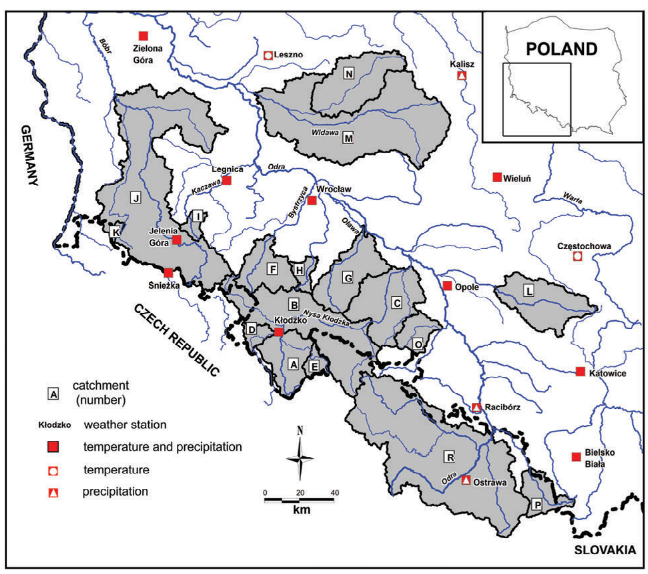

Fig. 1 - Study area. The locations of meteorological stations and river basins area have been marked.

Fig. 1 - Mappa dell'area di studio che mostra le posizioni delle stazioni metereologiche ed i bacini idrologici analizzati.

Tab. 1 - Catchments and their characteristics.

Tab. 1 - Bacini idrologici analizzati e le loro caratteristiche.

	River	Gauge station	Surface A [km^2]	Catchment type	Bedrock
A	Nysa Kłodzka	Kłodzko	1,084	mountain, foothills	crystalline rocks, compact sedimentary rocks
B		Nysa	3,276.3	mountain, foothills	crystalline rocks, compact and loose sedimentary rocks
C		Skorogoszcz	4,514.5	mountain, foothills, lowland	crystalline rocks, compact and loose sedimentary rocks
D	Bystrzyca Dusznicka	Szalejów Dln.	174.8	mountain	crystalline rocks, compact sedimentary rocks
E	Biała Lądecka	Lądek Zdrój	164.0	mountain	crystalline rocks
F	Bystrzyca	Krasków	683.4	mountain, foothills	crystalline rocks, loose sedimentary rocks
G	Oława	Oława	957.0	foothills	crystalline rocks, loose sedimentary rocks
H	Ślęza	Białobrzezie	180.9	foothills	crystalline rocks, loose sedimentary rocks
I	Kaczawa	Świerzawa	133.7	mountain, foothills	crystalline rocks, compact sedimentary rocks
J	Bóbr	Żagań	4,254.3	mountain, foothills, lowland	crystalline rocks, compact and loose sedimentary rocks
K	Czarny Potok	Mirsk	55.9	mountain	crystalline rocks
L	Mała Panew	Staniszcze Wlk.	1107.4	lowland	loose and compact sedimentary rocks
M	Barycz	Osetno	4579.3	lowland, many ponds and swamps	loose sedimentary rocks
N	Orla	Korzeńsko	1,127.2	lowland	loose sedimentary rocks
O	Biała	Dobra	353.4	foothills	compact and loose sedimentary rocks
P	Olza	Cieszyn	454.0	mountain, foothills	compact sedimentary rocks
R	Odra	Chałupki	4,666.2	mountain, foothills	crystalline rocks, compact sedimentary rocks

recorded in the summer. The southern part of the study area (mountains) has the highest precipitation, and this decreases towards the north (lowlands). The lowest average daily temperatures are recorded in the south, increasing towards the north.

In the southern, mountainous part, the climate is much harsher. Here, the average annual precipitation ranges from 750 to 1,900 mm and the snow cover lasts from 60 to 150 days a year.

The highest values of mean annual air temperature, as determined for the period 1966–2015, are recorded in lowland areas (8.9 °C in Legnica, 8.8 °C in Wrocław). With increasing altitude, the average annual temperature drops in SW Poland by an average of 0.55°C per 100 m. On the top of Mt Śnieżka it is 0.8°C.

The study area comprises several tectonic units formed as a result of Cenozoic block faulting. They include the Sudetic Block in the mountainous part of the study area, the Fore Sudetic Block (foothills) and the Fore Sudetic Monocline (lowlands). These units are divided by fault zones and decrease in altitude towards the North-East. The Sudeten are predominantly composed of crystalline igneous and metamorphic rocks, with compact sedimentary rock occurring in inner-mountain basins. In the foothills the Palaeozoic crystalline basement is covered by Cenozoic sedimentary rocks. The northernmost part of the area (the Fore Sudetic Monocline) is made up of dislocated Permian-Mesozoic rocks overlying the folded Paleozoic basement (Mizerski 2020).

In terms of the occurrence and development of the groundwater resources, the research area can be divided into three regions following a NW–SE course:

1. Mountain region (Sudeten mountain range): groundwater is recharged from fractured-porous, poorly isolated crystalline rocks and porous buried valleys. The highest precipitation and groundwater discharge across the region ranges from 0.007 to 0.009 $m^3/s{\cdot}km^2$ (Bocheńska et al. 1998; Olichwer 2007).
2. Foothills (Sudetic Foreland): pore waters are in sand and gravel Quaternary and Tertiary deposits, and the base, in the fractured-porous poorly isolated crystalline formations. Foothills are regions of both recharge and drainage. Groundwater discharge ranges from between 0.004 and 0.006 $m^3/s{\cdot}km^2$ (Bocheńska et al. 1998).
3. Lowland region: a groundwater feeding region in the porous Quaternary and Tertiary deposits with the Odra River as the main axis of drainage. The values of the groundwater discharge are in the range of 0.002 to 0.004 $m^3/s{\cdot}km^2$ (Bocheńska et al. 1998).

In the mountain catchments with a large forest cover (up to 77%), groundwater discharge and runoff are depended by natural conditions. In the foothills, there is an added anthropogenic factor: the forest cover is usually around 30%, whereas agricultural and urban areas comprise respectively up to 60% and 10% of the land (Chudzik et al. 2008).

Methods

Data regarding stream discharge and meteorological characteristics were taken from the Institute of Meteorology and Water Management (IMWM). River gauge stations were selected for the analysis, where:

– there is a continuous 50-year measurement period,
– the daily stream discharge data are homogeneous and undisturbed.

When developing the components of the water balance it is important to check the homogeneity of the observation series (stream disacharge). Such a study is carried out using an analysis of the summation curves (Ozga- Zielińska and Brzeziński 1997) of, for example, the stream discharge. If the observation series are considered as homogeneous, then the summation curve covers with the straight line. If the summation curve has to be covered by two or more straight lines this indicates a lack of uniformity, and in this case the balance should be defined separately for each segment. Summation curves for the river discharge values of all the rivers were made for this study and the results confirmed the homogeneity of the data used for characterization of runoff.

Data from the hydrological years 1966–2015 includes daily streamflow discharge from 17 gauging stations, mean daily temperatures from 11 meteorological stations and total monthly precipitation from 12 stations. In the case of meteorological stations and river gauge stations, points with continuous and homogeneous data from the period 1966-2015 were selected.

Hydrological and meteorological data were subjected to mathematical and statistical transformation in order to obtain the following data set:

– monthly and annual precipitation,
– monthly and annual average temperatures,
– average daily base flow and total streamflow,
– average monthly and annual base flow.

Data were processed using Excel, Grapher, Statistica and Hysep software's.

Due to the complex nature of water-bearing structures and their varying and poorly identified inflow parameters, the most suitable hydrological methods in this study area are those based on the measurement of stream discharge, which are the drainage base for the surrounding rock formations. One of the methods for calculation of the groundwater resources is determining the base flow (Fetter 1994). According to the definition of (Bocheńska et al. 2002), the base flow is a part of the total streamflow, which passes into the ground, becomes groundwater, and is discharged into a stream channel as spring or percolation water.

To determine the base flow and the surface runoff, the generic hydrograph separation method was applied. According to this method an analysis of the course of the falling curve is made, which illustrates the recession of the flood wave. Base flow was calculated using Method 1 (fixed-interval method) of the hydrograph separation and analysis HYSEP program (Sloto and Crouse 1997). According to this method, in order to determine the base flow, the lowest value of the flow on the hydrograph is estimated for a fixed time period (usually a few days) for all days, starting with the first day of the period of record. The base flow component has traditionally been associated with groundwater discharge, so both terms will be used interchangeably in the text. The sum of base flow (groundwater discharge) and surface runoff equals runoff.

The HYSEP program produces an annual hydrograph of streamflow and estimated base flow for each year of record processed. The program produces tabular output from the hydrograph separation summarizes the quantity of estimated base flow and surface runoff and the percentage of streamflow as base flow and surface runoff. Alternatively, a monthly summary can be selected that gives monthly values of mean streamflow, total streamflow, mean base flow, total base flow, mean surface runoff, total surface runoff, and percentage of streamflow as base flow. Daily values of estimated base flow or surface runoff in daily values format can be written to a file. The ASCII file that is generated can be used as input to other applications (Sloto and Crouse 1997).

Data from ASCII files generated by the HYSEP program were used to prepare the figures in the article and for statistical analyzes.

Quantitative descriptions of the North Atlantic Oscillation make use of variously defined indices. This study utilized the NAO index developed by Hurrell (1995) on the basis of normalized sea level pressure (SLP) between Lisbon (Portugal) and Stykkisholmur/Reykjavik (Iceland). Annual average indices were compiled for the period of December to March (winter NAO index) and July to September (summer NAO index). The SLP values at each station were normalized by removing the long-term mean and by dividing by the long-term standard deviation. Both the long-term means and standard deviations are based on the period 1864-1983. Normalization is used to avoid the series being dominated by the greater variability of the northern station (Climate Data Guide). Indices were provided by the websitehttps://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based.

Correlation analysis, on the other hand, allowed evaluation of the linear relationship between hydrological variables, meteorological data and the NAO index. The analysis was carried out using average annual values and seasonal stream flows (in the summer and winter season), as well as seasonal NAO index (December to March). The relevance of the Pearson correlation coefficients was verified at the significance level of α = 0.1, indicating that for the given time series (1966-2015, i.e. 50 years) the correlation coefficients (r) are statistically significant for values greater than 0.20 and lower than -0.20.

Characteristics of total and base flow

The river basins are characterised by an average total flow ranging from 0.53 (Ślęza) to 43.77 m^3/s (Odra). The highest values of total runoff (taking into account the catchment area) were recorded in the case of the Biała Lądecka River (676 mm) and Czarny Potok (508 mm), and the lowest in Ślęza (92 mm) and Bystrzyca (207 mm). Hydrographs from the 1966 - 2015 point towards a downtrend in the rate of total flows (Fig. 2). Correlation analysis indicates a decline in total stream flows (Q) in eight of the 17 analysed hydrological profiles, as well as a decline in base flow (Qg) in nine profiles. These trends have

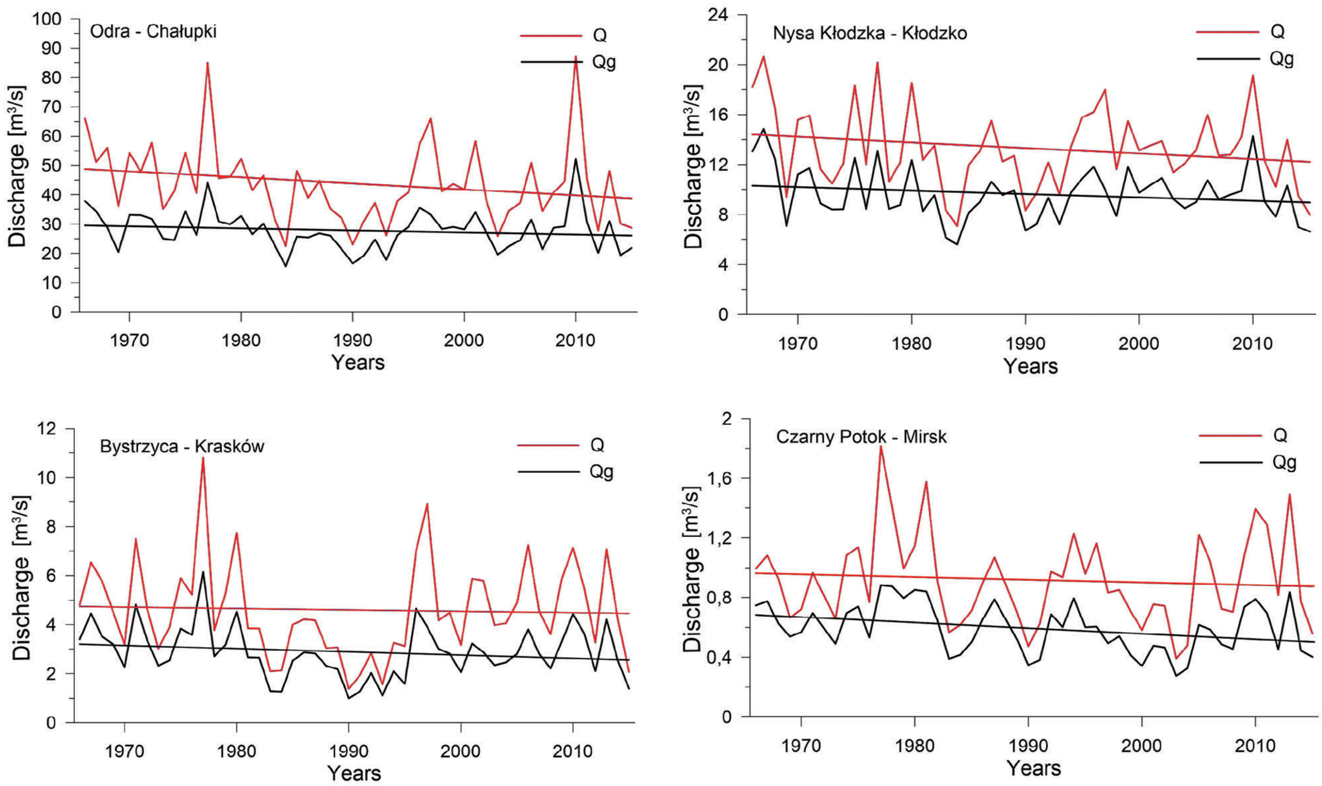

Fig. 2 - Trends of annual mean values of total stream flow and base flow in selected river gauge stations: Chałupki (Odra), Kłodzko (Nysa Kłodzka), Krasków (Bystrzyca) and Mirsk (Czarny Potok).

Fig. 2 - Andamento della portata media annuale dei fiumi e del flusso di base nelle stazioni idrometriche di Chałupki (Odra), Kłodzko (Nysa Kłodzka), Krasków (Bystrzyca) e Mirsk (Czarny Potok).

been observed in all of the rivers in Kłodzko Land, as well as Ślęza, Mała Panew and Bóbr.

Data on seasonal stream flows between 1966 and 2015 found a statistically significant runoff decline in winter in only four of the gauge stations, whereas a significant reduction of groundwater discharges was observed in just three gauge stations. Most profiles show a downtrend in total flow during the summer (Fig. 3). In the case of stream flow this trend was observed at eight sites, and in the case of groundwater discharge at ten sites. The rivers Oława, Kaczawa, Orla and Barycz did not show any significant changes in total flow and groundwater discharges in the summer months.

Our calculations have shown no temporal changes in runoff at the 0.1 significance level in ten of the drainage basins. Data from the remaining seven locations indicate a downtrend in stream flow rates, with correlation coefficients ranging from r = -0.28 (Oława) to r = -0.48 (Mała Panew) (Tab. 2). Similar observations have been made in the case of temporal changes in the annual 7-day minimum river discharge. Eleven drainage basins showed no correlation, whereas in the remaining six the correlation coefficient ranged from r = -0.28 (Biała) to r = -0.59 (Bóbr) (Tab. 2). Different observations have been made in the case of groundwater discharge, with six drainage basins showing no temporal decline and the remaining 11 experiencing a reduction in base flow in the 1966-2015; the correlation coefficients ranged from r = -0.29 (Biała Lądecka) to r = -0.51 (Mała Panew) (Tab. 2).

Long-term trends and the effects of the NAO

Precipitation and air temperature are crucial climate components affecting directly and indirectly groundwater resources. Data from the period between 1966 and 2015 point towards a decline in precipitation at most of the measurement stations taken into account in this study (Fig. 4). Air temperature on the other hand shows an upward trend at all 11 measurement stations. Estimated decrease for precipitation is 5 % and increase for temperature is about 10 %.

Figure 4 shows general trends in the average annual values of precipitation and air temperature at the selected weather stations, representing mountain areas (Śnieżka), foothills (Kłodzko) and lowlands (Wrocław).

Most of the drainage basins show a good correlation between total and base flows and meteorological conditions, specifically temperature and precipitation (Tab. 3). The dominant values of the correlation coefficient are in the range of 0.3 - 0.5. The weakest correlation in the study area is between flows (total and base) and precipitation in winter period. Most of the calculated correlation coefficients are in the statistically significant range (Tab. 3). In light of the fact that local meteorological conditions are created by large-scale phenomena, the remainder of this paper will attempt to draw a connection between runoff and the NAO index.

Figures 5 and 6 show correlation coefficients between the NAO index and annual total and base flows calculated year-

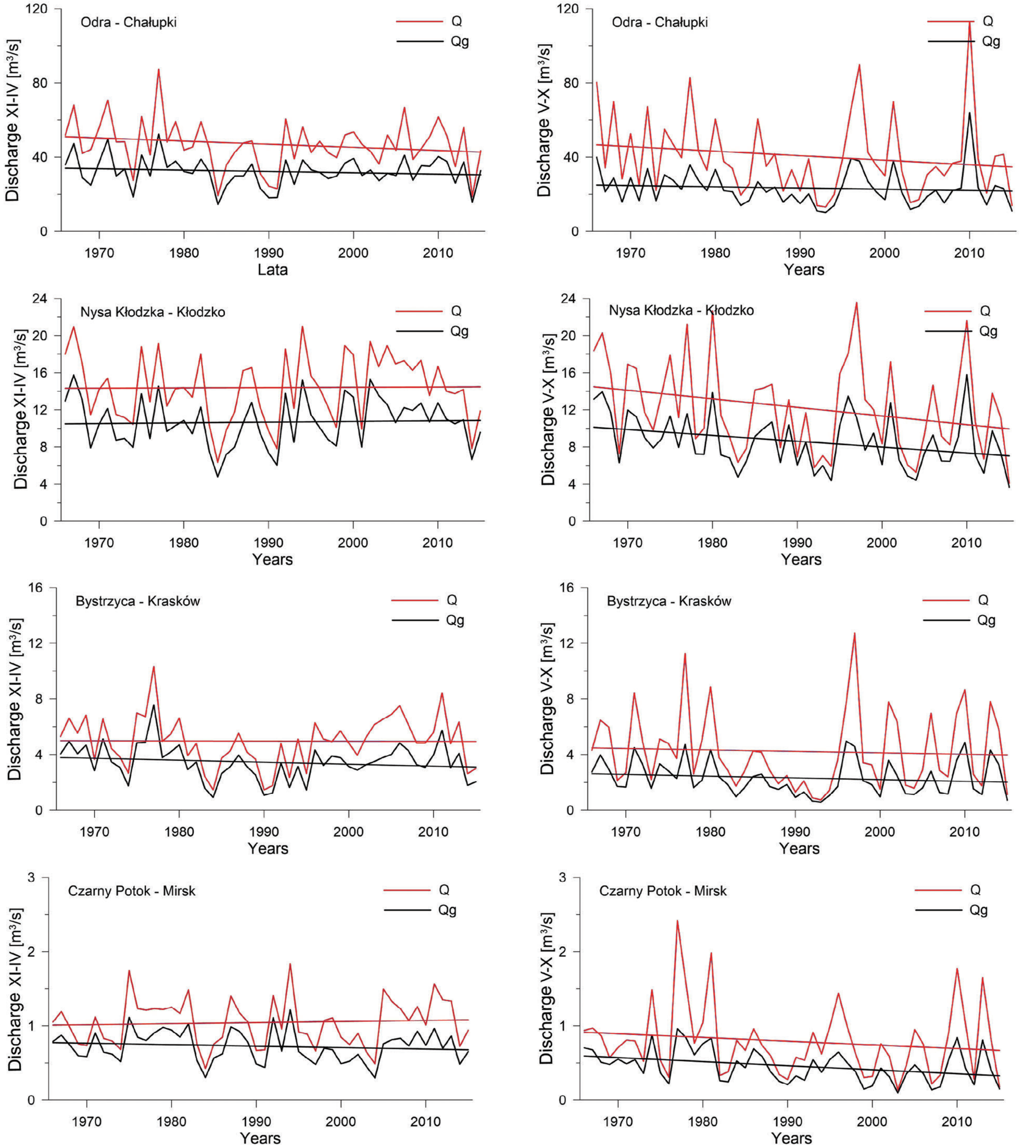

Fig. 3 - Variations of seasonal (semi-annual winter (November-April) and semi-annual summer (May-October)) values of stream discharge and base flow in selected river gauge stations: Chałupki (Odra), Kłodzko (Nysa Kłodzka), Krasków (Bystrzyca) and Mirsk (Czarny Potok). Roman letters used in the legend refer to the months (XI-IV winter period, V-X summer period).

Fig. 3 - Variazioni stagionali nei periodi da novembre a aprile e da maggio a ottobre della portata dei fiumi e del flusso di base nelle stazioni idrometriche di Chałupki (Odra), Kłodzko (Nysa Kłodzka), Krasków (Bystrzyca) e Mirsk (Czarny Potok). I numeri romani utilizzati nei grafici si riferiscono ai mesi del periodo analizzato (XI-IV periodo invernale, V-X periodo estivo).

Tab. 2 (see next page) - Correlations between annual total stream flow, base flow and climate characteristics (1966-2015). Q – stream discharge (total flow), Qg – base flow, 7-days – seven day annual minimum flow, bold – at the significance level of 0.1.

Tab. 2 (vedi pagina a fianco) - Correlazione fra il deflusso, il flusso di base e le caratteristiche climatologiche nei bacini analizzati nel periodo 1966-2015. Q rappresenta il deflusso, Qq rappresenta il flusso di base, 7 days rappresenta il flusso minimo annuale per un periodo di 7 giorni. Le correlazioni statisticamente significative con livello di significatività $\alpha = 0.1$ sono riportate in grassetto.

Table 2 - Tavola 2

River	Characteristic	Years	Temperature	Precipitation
Bystrzyca Dusznicka	Q	0.05	**-0.28**	**0.38**
	Qg	0	**-0.21**	**0.38**
	7 days	0.06	-0.03	0.11
Biała Lądecka	Q	**-0.25**	**-0.28**	**0.28**
	Qg	**-0.29**	-0.16	**0.23**
	7 days	0.17	-0.04	-0.18
Oława	Q	**-0.28**	**-0.44**	**0.26**
	Qg	**-0.2**	**-0.36**	0.19
	7 days	-0.10	-0.11	**-0.05**
Ślęza	Q	**-0.42**	**-0.43**	**0.40**
	Qg	**-0.47**	**-0.42**	**0.42**
	7 days	**-0.56**	**-0.45**	**0.30**
Bystrzyca	Q	-0.17	**-0.35**	**0.39**
	Qg	**-0.34**	**-0.39**	**0.51**
	7 days	**-0.25**	**-0.30**	**0.41**
Kaczawa	Q	-0.12	**-0.38**	**0.21**
	Qg	-0.19	**-0.38**	**0.26**
	7 days	0.14	-0.16	**0.35**
Czarny Potok	Q	**-0.26**	**-0.34**	0.13
	Qg	**-0.50**	**-0.50**	0.14
	7 days	**-0.20**	**-0.29**	0.15
Odra	Q	**-0.35**	**-0.41**	0.09
	Qg	**-0.35**	**-0.39**	**0.22**
	7 days	-0.02	-0.19	**0.27**
Olza	Q	0.12	-0.17	**-0.22**
	Qg	0.09	-0.13	-0.19
	7 days	0.11	-0.04	-0.04
Biała	Q	**-0.43**	**-0.51**	**0.39**
	Qg	**-0.37**	**-0.39**	**0.48**
	7 days	**-0.28**	-0.11	**0.41**
Mała Panew	Q	**-0.48**	**-0.48**	**0.52**
	Qg	**-0.51**	**-0.46**	**0.56**
	7 days	**-0.56**	**-0.30**	**0.42**
Nysa Kłodzka - Kłodzko	Q	**-0.21**	**-0.30**	**0.42**
	Qg	**-0.23**	-0.13	**0.50**
	7 days	**-0.36**	0	**0.50**
Nysa Kłodzka - Nysa	Q	**-0.40**	**-0.42**	**0.49**
	Qg	**-0.38**	**-0.31**	**0.47**
	7 days	-0.09	0.01	**0.24**
Nysa Kłodzka - Skorogoszcz	Q	**-0.38**	**-0.49**	**0.35**
	Qg	**-0.40**	**-0.47**	**0.36**
	7 days	**-0.31**	-0.11	**0.37**
Bóbr	Q	**-0.24**	**-0.38**	**0.65**
	Qg	**-0.30**	**-0.35**	**0.71**
	7 days	**-0.59**	**-0.32**	**0.47**
Orla	Q	-0.16	**-0.38**	**0.40**
	Qg	-0.14	**-0.37**	**0.40**
	7 days	**-0.24**	**-0.36**	**0.24**
Barycz	Q	**-0.26**	**-0.48**	**0.52**
	Qg	**-0.27**	**-0.46**	**0.53**
	7 days	0.05	-0.05	0.19

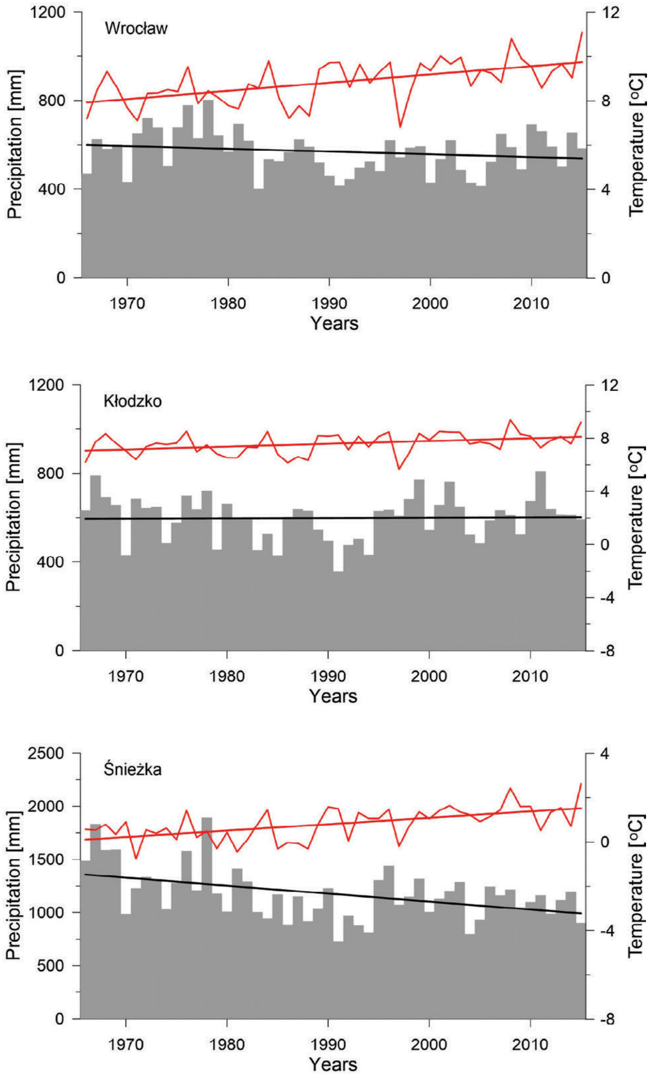

Fig. 4 - Trends in the average annual values of precipitation and air temperature at the selected weather stations (Śnieżka, Kłodzko, Wrocław). The red line is the air temperature, bar graph is the precipitation.

Fig. 4 - Andamento della precipitazione annuale e della temperatura media annuale dell'aria alle stazioni metereologiche di Śnieżka, Kłodzko e Wrocław. La linea rossa rappresenta la temperatura dell'aria, mentre l'istogramma rappresenta la precipitazione.

Tab. 3 - Correlation coefficients between the annual and seasonal values of total flow (Q) and base flow (Qg) and air temperature and precipitation in catchments of study area. The statistically significant correlations at the level of α = 0.1 are bolded.

Tab. 3 - Coefficienti di correlazione fra il deflusso (Q) e il flusso di base (Qq) annuale e stagionale e la temperatura dell'aria e la precipitazione nei bacini idrografici analizzati. Le correlazioni statisticamente significative con livello di significatività α = 0.1 sono riportate in grassetto.

No	River	Gauge station	Q annual	annual NAO index		winter NAO index		
				Qg annual	Q annual	Qg annual	Q winter	Qg winter
1	Bystrzyca Dusznicka	Szalejów Dolny	-0.45	-0.44	-0.26	-0.22	-0.16	-0.11
2	Biała Lądecka	Lądek Zdrój	-0.41	-0.37	-0.32	-0.26	-0.16	-0.08
3	Nysa Kłodzka	Kłodzko	-0.55	-0.54	0.42	-0.42	-0.29	-0.27
4	Nysa Kłodzka	Nysa	-0.35	-0.33	-0.21	-0.18	-0.15	-0.14
5	Nysa Kłodzka	Skorogoszcz	-0.58	-0.59	-0.57	-0.59	-0.57	-0.55
6	Bystrzyca	Krasków	-0.51	-0.53	-0.62	-0.65	-0.60	-0.65
7	Oława	Oława	-0.52	-0.37	-0.53	-0.35	-0.57	-0.41
8	Ślęza	Białobrzezie	-0.58	-0.57	-0.64	-0.63	-0.70	-0.67
9	Kaczawa	Świerzawa	-0.46	-0.45	-0.47	-0.51	-0.38	-0.42
10	Czarny Potok	Mirsk	-0.35	-0.37	-0.34	-0.37	-0.17	-0.20
11	Bóbr	Żagań	-0.48	-0.45	-0.40	-0.35	-0.26	-0.20
12	Mała Panew	Staniszcze Wielkie	-0.55	-0.50	-0.48	-0.46	-0.41	-0.36
13	Orla	Korzeńsko	-0.49	-0.46	-0.46	-0.44	-0.36	-0.35
14	Barycz	Osetno	-0.44	-0.44	-0.49	-0.49	-0.32	-0.30
15	Biała	Dobra	-0.54	-0.44	-0.57	-0.50	-0.59	-0.50
16	Olza	Cieszyn	-0.52	-0.41	-0.39	-0.26	-0.17	-0.06
17	Odra	Chałupki	-0.69	-0.65	-0.65	-0.61	-0.57	-0.47

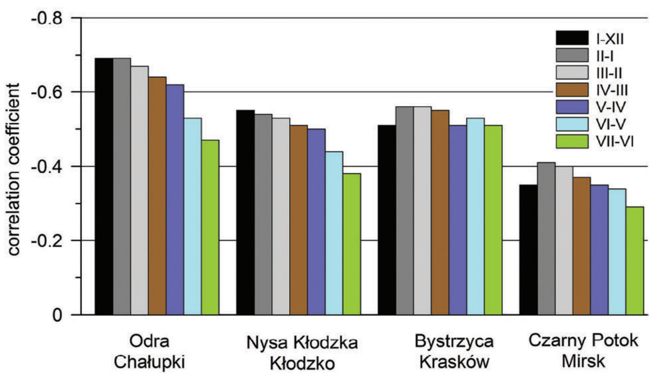

Fig. 5 - Correlation of the annual NAO index and the annual total flow. Roman letters used in the legend refer to the months.

Fig. 5 - Correlazione fra l'indice NAO annuale e i valori annuali del deflusso. I numeri romani nella legenda si riferiscono ai mesi del periodo analizzato.

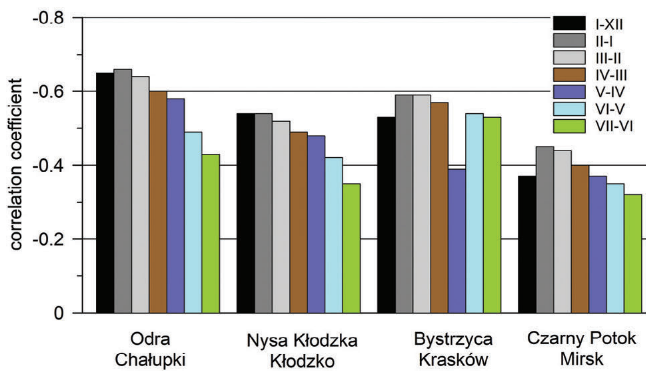

Fig. 6 - Correlation of the annual NAO index and the annual base flow. Roman letters used in the legend refer to the months.

Fig. 6 - Correlazione fra l'indice NAO annuale e il flusso di base. I numeri romani nella legenda si riferiscono ai mesi del periodo analizzato.

over-year (I-XII), as well as annual total flow values delayed by one month against NAO index (from February to January of the following year, from March to February of the year after that, and so on). Analysis of these figures indicates that the strongest correlations occur when comparing annual NAO indices:

- with the annual total flow for the period between January and December (I-XII) in large drainage basins (Chałupki, Kłodzko);
- with the annual total flow for the period between February and January (II-I) and between March and February (III-II) in small drainage basins (Krasków, Mirsk);
- with the base flow assessed following the algorithm based on the delayed values, i.e. from February to January of the following year (II-I) and from March to February of the following year (III-II).

The situation is different when comparing the winter NAO index with the total and base flows values from each 6-month period (Fig. 7 and 8). The strongest correlations occur when comparing the winter NAO index with total and base flows for the period between March and August (III-VIII) and April and September (IV-IX). This suggests a significant impact of the winter NAO index on the formation of runoffs during the warmer months.

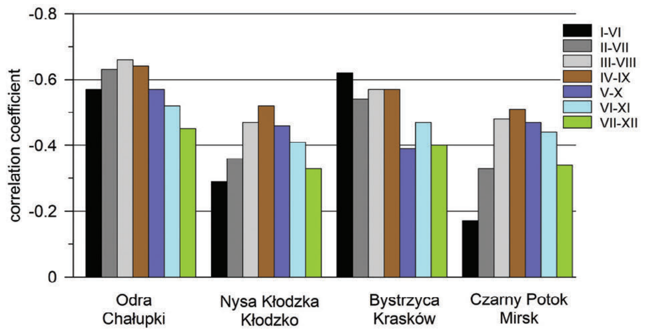

Fig. 7 - Correlation of the winter NAO index and semi-annual mean values of total flow. Roman letters used in the legend refer to the months.

Fig. 7 - Correlazione fra l'indice NAO invernale e i valori medi del deflusso per diversi periodi dell'anno. I numeri romani nella legenda si riferiscono ai mesi del periodo analizzato.

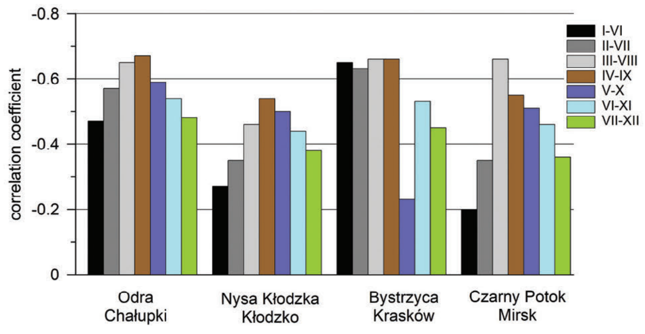

Fig. 8 - Correlation of the winter NAO index and the semi-annual mean values of base flow. Roman letters used in the legend refer to the months.

Fig. 8 - Correlazione fra l'indice NAO invernale e i valori medi del flusso di base per diversi periodi dell'anno. I numeri romani nella legenda si riferiscono ai mesi del periodo analizzato.

Conclusions

The following conclusions can be drawn on the statistical analysis of meteorological and hydrological data from the period 1966-2015 in south-western Poland:

- Total flow (stream discharge) from the Sudeten area (including the Sudeten Foreland) depends on atmospheric circulation (NAO).
- The NAO index describes in more detail the variability of total and base flows in south-western Poland in relation to changes in temperature and precipitation
- The significance of the relationship between average annual total and base flows and the NAO index remains similar to the annual and winter NAO index,
- The annual NAO index is most useful in describing the variability of average annual (12-month) total and base flows from February to January and from March to February.
- The winter NAO index is most effective in describing the variability of average annual (12-month) total and base flows from March to February and from April to March.
- The winter NAO index is most effective in describing the variability of average half-yearly total and base flows from April to September.
- The cases described above are indicative of high Pearson correlation coefficients, equalling -0.65.
- The influence of the summer NAO index on the total and base flows is statistically insignificant

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Competing interest

The authors declare no competing interest.

Author contributions

Collection of data, Tarka R; data processing, Tarka R; interpretation of results, Olichwer T, Tarka R; writing-original draft preparation, Olichwer T, Tarka R, Buczyński S; writing-review and editing, Olichwer T; visualization, Tarka R; supervision, Buczyński S; project administration, Olichwer T. All authors have read and agreed to the published version of the manuscript.

Additional information

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