HYDROLOGICAL DRY PERIODS VERSUS ATMOSPHERIC CIRCULATIONS IN THE LOWER VISTULA BASIN (POLAND) IN 1954-2018

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Manuscript received: January 14, 2022
Revised version: March 4, 2022

Bartczak A., Araźny A., Krzemiński M., Maszewski R., 2022. Hydrological dry periods versus atmospheric circulations in the lower Vistula Basin (Poland) in 1954–2018. *Quaestiones Geographicae* 41(1), Bogucki Wydawnictwo Naukowe, Poznań, pp. 107–125. 6 figs, 5 tables.

Abstract: The paper discusses the impact of atmospheric circulation on the occurrence of droughts. The research includes mean monthly discharges for 7 rivers in 1954-2018. Dry periods were determined with Standardised Streamflow Indices (SSI-12). Additionally, the circulation type calendar for Central Poland was used to determine the atmospheric circulation indices: western zonal (W), southern meridional (S) and cyclonicity (C). The analyses indicated a variation in the duration and intensity of droughts in the rivers. 2014-2017 was the driest period with the lowest SSI-12 for most rivers and the highest number of extremely dry months. The advection of air from the West and the South prevailed and anticyclonic synoptic situations dominated over the cyclonic types. Drought spells occurred at a dominance of anticyclonic circulation, with the inflow of air from the North and with increased western zonal circulation.

Key words: dry periods, atmospheric circulation, Box-Cox transformations, Standardised Streamflow Index (SSI), Poland

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Introduction

In its long history, our planet has seen multiple climate change events (e.g. Hoyt, Schatten 1997, Crowley 2000, Haigh 2007, 2011, Haigh, Cargill 2015, Marks 2016); however, the current one is the first that is largely related to human activity (Kundzewicz 2011, IPCC 2013). Progressive global warming has been confirmed by scientific research and reports issued by the Intergovernmental Panel on Climate Change (IPCC). In each decade following 1980, land surface temperature has been higher than not only that in the preceding 10 years but also that in any decade after 1850 (IPCC 2013). According to Twardosz et al. (2021), 1985 is considered to have been the turning point after which the rapid warming of the climate across Europe (including

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https://doi.org/10.2478/quageo-2022-0008
ISSN 2082-2103, eISSN 2081-6383

Poland) took hold. The special IPCC report *Global warming of 1.5°C* (2018) indicates that mean global air temperature in 2006–2015 and 2009–2018 exceeded that recorded in 1850–1900 (the pre-industrial period) by +0.87°C and +0.93°C, respectively. The WMO Statement on the State of the Global Climate in 2018 (2019) labels 2018 as the fourth hottest year in recorded history, and 2015–2018 the hottest period ever. This process is a threat not only to the natural environment but also to people's health and life. However, it must be said that the temperature increase is not homogenous in terms of spatial distribution and that it is demonstrated with various degrees of scale and intensity across the globe (e.g. Ji et al. 2014, Hegerl et al. 2019). Additionally, there is a certain level of risk that the elements of the atmosphere directly linked to air temperature can also be altered to the currently unknown extent.

The threat of ever more frequent and intensive extreme hydrological events may seriously disturb sustainable development in many areas, including those of agricultural character. They tend to have a social and economic dimension, as both water excess and shortage significantly deteriorate crop yield and quality (e.g. Łabędzki, Bąk 2015, Gautier et al. 2016, Ray et al. 2018, Pena-Gallardo et al. 2019). The occurrence of such events, as well as their frequency, duration, intensity and spatial scale, are difficult to predict, let alone the effects that they may have in the future. Hence, the fundamental role of research and analysis of events that occurred in the past. Their proper quantification, correct assessment and connection with a specific type of atmospheric circulation may constitute a sound basis for further modelling studies.

Disproportionate precipitation causes flooding of farmlands, excessive soil moisture, destruction of technical infrastructure and local or regional floods. The effects of excess rainfall are usually evident in the environment and tend to be dramatic (IPCC 2013).

On the other hand, shortage of precipitation results in drought, a phenomenon which is very complex, and difficult to detect and define in clear terms. What is certain, though, is the fact that its effects are severe and long-lasting. Wilhite and Glantz (1985) found it beneficial to break down the phenomenon on a 'disciplinary' basis. Based on the analysis of over 150 published drought definitions, they distinguished four main types of droughts, i.e. meteorological, agricultural, hydrological and socio-economic. The common denominator for practically all the definitions is the lack or scarcity of water and the resulting adverse situation.

It must be stressed that extreme meteorological and hydrological events should not be identified solely with the industrial period. They did occur in the past and are either well-recorded in written accounts or reconstructed based on proxy analyses (e.g. Woodhouse, Overpeck 1998, Kiss et al. 2010, Büntgen et al. 2013, Cook et al. 2015, Pritzkow et al. 2016, Słowiński et al. 2016, Brazdil et al. 2019, Przybylak et al. 2020, Bonk et al. 2021). Modern possibilities and calculation techniques enable researchers to quantify and model them fairly accurately; yet, the uncertainty of the obtained results is still very high.

According to Gutry-Korycka et al. (2014), diminishing resources of surface and underground water, combined with increased evapotranspiration, is among the most important threats resulting from the regional temperature increase projections. Consequently, we are bound to face more frequent, longer-lasting and deeper hydrological droughts. Severe water shortages will dramatically reduce water availability for plants, animals and humans alike. This is particularly alarming, as Poland is already among the countries with the smallest water resources per capita.

Such negative projections of climate change are a determinant for continuous monitoring and analysis of climatic and hydrological elements at various spatial and temporal scales (Kazanowska et al. 2018, Hejduk et al. 2021, Karamuz et al. 2021, Tomaszewski, Kubiak-Wójcicka 2021, Ziernicka-Wojtaszek 2021).

The enormous role of atmospheric circulation in shaping the climate has long been known, and its influence on various meteorological elements has been widely studied and discussed (e.g. Bárdossy, Caspary 1990, Trenberth 1995, Corti et al. 1999). Any climate change is partly driven by natural factors, and the phenomenon of circulation epochs, or long periods of the prevalence of particular circulation types, (e.g. Sidorenkov, Orlov 2008, Degirmendžić, Kożuchowski 2018, Kononova, Lupo 2020), is among the most important of them. Depending on their type, some of these periods may have a possible tendency

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to limit the occurrence of cyclones, which promotes the emergence of droughts. The early 20th century was marked by the dominance of western zonal circulation (W) followed by meridional ones. Towards the end of the century, in its last decade, the former type started to prevail again (Sidorenkov, Orlov 2008, Degirmendžić, Kożuchowski 2018). At the same time, intensified air advection from the west was observed in Central Europe (Ustrnul 2007).

Bobiński and Meyer (1992b), Stahl and Demuth (1999), Bąk and Maszewski (2012) and Bartoszek (2014) notice that global atmospheric circulation systems that create an anticyclonic (high-pressure) circulation over a specific area are the primary cause of drought development.

The North Atlantic Oscillation (NAO) is frequently used to determine the impact of atmospheric circulations on droughts (meteorological and hydrological) in the European-Atlantic sector. The NAO has been identified as a potent factor contributing to the occurrence of hydrological droughts across Europe (e.g. Wrzesiński 2005, 2010, Pociask-Karteczka 2006, Linderholm et al. 2009, Wrzesiński, Paluszkiewicz 2011, Parry et al. 2012). Further, its bipolar influence on meteorological droughts in Northern and Southern Europe was observed (e.g. López-Moreno, Vicente-Serrano 2008, Linderholm et al. 2009, Hannaford et al. 2011). One must bear in mind, however, that atmospheric circulations can be highly changeable both in space and in time; therefore, circulation type indices or catalogues developed for vast areas (Kożuchowski 1993, Kutiel et al. 1996, Jacobeit et al. 2001, Bartoszek 2017, Lhotka et al. 2020) are not always credible in their description of an atmospheric situation on a smaller area (e.g. in mesoscale), which was proved by Niedźwiedź (1981). This is why this paper relies on atmospheric circulation indices prepared only for the research area (Araźny et al. 2021).

They were determined on the basis of the calendar of atmospheric circulation types over central Poland (i.e. the Bydgoszcz-Toruń region) developed by Maszewski (Przybylak, Maszewski 2009) according to the methodology proposed by Niedźwiedź (2000). In this study, the following monthly indices of atmospheric circulation were calculated: western zonal (W), southern meridional (S) and cyclonic (C).

The main objective of this work was the identification and assessment of the intensity of dry periods on selected tributaries of the lower Vistula (Poland) and the establishment of their possible relation with atmospheric circulation. The novelty of the paper rests in its attempt to use unique regional atmospheric circulation indices to understand and assess hydrological droughts.

Area, data and analysis methods

Area

The study area is located in the northern part of Poland (Central Europe) in the lower Vistula basin (Poland's largest river). The authors performed analyses of seven rivers: the Wierzyca, the Wda, the Brda, the Zgłowiączka, the Osa, the Drwęca and the Skrwa Prawa, whose locations are depicted in Figure 1. The entire research area fits into one physico-geographical region of the Southern Baltic Lakelands. The topographical relief and the surface geological structure of the catchments relate to the glacial sediments of the last glaciation. Such areas are characterised by significant height differences of terrain, moraine uplands built mostly of clay formations, and outwash plains of sand and gravel formations (Molewski, Weckwerth 2017). The vast areas of the uplands are cut by ice-marginal valleys (urstromtals) and valleys currently used by river-lake systems. The diverse structure of the catchment determines the processes of rainwater infiltration supplying watercourses with groundwater.

The research area is located in the zone of influence of both the Atlantic Ocean and the Eurasian continent. The lower Vistula basin lies in the temperate, warm transitional climate, separating the maritime climate from the continental one. It is often surrounded by air masses with different temperature and humidity properties, resulting in volatile weather and various types of precipitation (Woś 2010, Twardosz et al. 2011). The average annual area air temperature in Poland in 1991–2020 was +8.73°C and exceeded that in 1951–1980 by 1.54°C (Climate of Poland 2020). The multi-year mean air temperature for the study area ranged between 7.5°C and 8.5°C (Kejna, Rudzki 2021) and showed a positive,

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statistically significant upward trend amounting to +0.30°C · 10 a^{-1} (Climate of Poland 2020). It was in the summer that the most pronounced and statistically significant temperature increase was recorded, followed by winter and spring. The trends in temperature changes in autumn are insignificant. According to Okoniewska and Szumińska (2020), a statistically significant increase in air temperature, especially since the 1990s, in conjunction with the decreasing trend

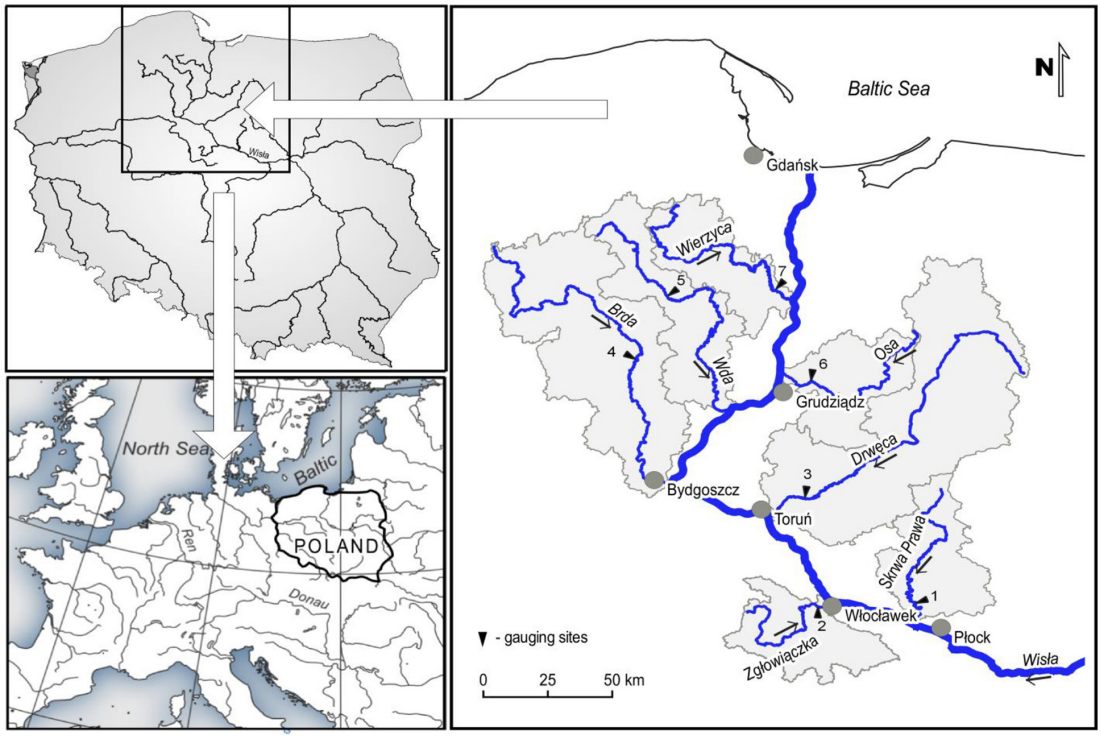

Fig. 1. Research Area. Explanations: Numbering of gauging sites according to Table 1.

Table 1. Basic statistics of the mean annual flow of the studied rivers and the *p*-value of the MK test for trend in 1954–2018.

No.	River/ gauging sites	Catchment area* (km^2)	Mean specific discharge (dm^3 · s^{-1} · km^{-2})	Mean flow (m^3 · s^{-1})	Minimum flow (m^3 · s^{-1}) (year)	Maximum flow (m^3 · s^{-1}) (year)	Standard deviation (m^3 · s^{-1})	Statistics MK test	*p*-value MK test
1	Skrwa Prawa/ Parzeń	1490.3	4.19	6.24	2.13 (2016)	11.37 (2002)	2.49	−0.057	0.9549
2	Zgłowiączka/ Włocławek Ruda	1491.8	2.40	3.59	0.64 (2016)	9.98 (1980)	1.98	−1.036	0.3002
3	Drwęca/ Elgiszewo	5019.5	5.56	27.92	13.08 (2015)	42.84 (1982)	6.51	−0.719	0.4721
4	Brda/ Tuchola	2477.2	7.87	19.50	14.22 (1992)	25.93 (2011)	2.42	−0.368	0.7129
5	Wda/ Czarna Woda	827.6	7.57	6.27	4.33 (1992)	9.08 (1962)	1.02	−1.687	0.0915
6	Osa/ Rogoźno	1135.1	3.93	4.47	1.36 (2015)	9.17 (1982)	1.78	−1.908	0.0564
7	Wierzyca/ Brody Pomorskie	1543.4	5.64	8.70	5.40 (1992)	12.87 (1982)	1.72	−1.574	0.1155

MK, Mann Kendall.
*Data based on the Hydrographic Atlas of Poland, 2005.

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of relative humidity, contributes to more intensive potential evaporation in the study area. Its particularly high values have been repeatedly recorded since the early 21st century. Precipitation is a more variable element of the climate than air temperature. The 1961–2009 mean area precipitation total for Poland was 623.7 mm and 594.2 mm for the study area (Limanówka et al. 2012) with the respective monthly maximum and minimum in July and February. Precipitation is highly diverse in terms of spatial distribution, with the lowest totals recorded in the southern part of the study area (Zgłowiączka River), where the mean long-term figures do not exceed 500 mm (Bartczak et al. 2013). In general, annual precipitation totals do not show statistically significant trends (Pińskwar et al. 2019); yet, in the long term, there are periods with higher or lower annual totals compared to the mean values. Fluctuations and short-term, statistically significant trends in precipitation are of greater importance and have a larger impact on the environment than their long-term equivalents (Bartczak et al. 2013).

All the analysed rivers share a similar feeding pattern and are characterised by various degrees of nival (snow) regime. The volume of water resources in the catchments changes both over the long term and in the annual cycle, with the highest level in spring and the lowest in summer and late autumn. The latter is often combined with low flows of varying duration and intensity. Non-existing, or insufficient, water supply in the autumn and winter may extend a low flow well into another hydrological year. Naturally, the rivers are dominantly supplied by groundwater throughout the year (Gierszewski 2000, Jokiel 2004, Bartczak 2007, Brykała 2009, Szumińska 2014). The smallest water resources are typically identified in the southern part of the study area, where the average annual specific discharges in dry years drop below 1 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (Zgłowiączka River) (Bartczak et al. 2014a, b).

Data

The analysis of dry periods was based on mean monthly discharges of seven main tributaries of the lower Vistula in 1954–2018 (Table 1). The data, obtained courtesy of the Institute of Meteorology and Water Management – National Research Institute [in Polish: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy (IMGW-PIB)], mostly came from the water gauges located at the lower end of the studied catchments. However, as the selection of the stations was dictated by the need to maintain the temporal homogeneity of the analysis, some of them do not close the examined catchments (Fig. 1).

Analysis methods

The analysis of air circulation over central Poland used Maszewski's catalogue of air circulation types (Przybylak, Maszewski 2009) based on the classification proposed by Niedźwiedź (1981, 2013). It distinguishes 21 kinds depending on the direction or lack of air advection, and the pressure system. The situations with advection were marked with capital letters indicating the direction of the air inflow (N, NE, E, SE, S, SW, W and NW). The type of the pressure system is marked with the index 'a' for anticyclonic or 'c' for cyclonic situations. Additionally, the authors distinguished two non-advective situations: Ca (centre of high pressure) and Ka (high-pressure wedge or ridge), and two situations with varied advection: Cc (centre of low pressure) and Bc (cyclonic trough over central Poland). Cols and indifferent situations that are difficult to define are given an 'x' mark. The types of air circulation were determined using the calendar of daily surface weather maps by Deutscher Wetterdienst. Similar calendars based on 21 types of circulation have already been successfully applied to assess the impact of atmospheric circulation on climate change in Poland (e.g. Twardosz, Niedźwiedź 2001, Niedźwiedź et al. 2009, Twardosz et al. 2011) and the Arctic (e.g. Isaksen et al. 2016, Araźny et al. 2018, Araźny 2019, Łupikasza, Niedźwiedź 2019).

The overall atmospheric circulation over the research area was presented with circulation indices which enable the determination of the degree of dominance of the western zonal (W), the southern meridional (S) or the cyclonic circulation (C) (Niedźwiedź 2000, 2001). The W index determines the intensity of the western zonal (positive values) or eastern (negative values) circulation. To calculate its value, the following scoring was used for particular directions of air advection: +2 for the W direction, +1 for NW and

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SW, −2 for E and −1 for NE and SE. The remaining types of circulation were assigned 0 points. The S index (southern circulation) is a measure of the intensity of the meridional circulation, with its positive values attesting to the dominance of air inflow from the southern sector, and negative – from the northern one.

The considered circulation types displayed the following distribution of points: +2 for S types, +1 for SW and SE directions, −2 for N and −1 for NW and NE. The cyclonicity index C indicates intensified low- (positive values) or high-pressure (negative values) activity. The points corresponding to particular situations are ascribed as follows: +2 for Cc and Bc, +1 for the other cyclonic types, −2 for Ca and Ka and −1 for the remaining anticyclonic types (Niedźwiedź 2000, 2001, Przybylak, Maszewski 2009). The calculated values of the W, S and C indices were then grouped into 12-month periods using the so-called moving sum windows. Hereafter, they are referred to as W-12, S-12 and C-12.

The study of the direction of changes in mean annual discharges and atmospheric circulation indices (estimation and significance) was carried out using the non-parametric Mann Kendall (MK) test (Hirsch et al. 1982). The null hypothesis of the H0 test assumes that the data come from a population of independent data and are evenly distributed. On the other hand, the HA hypothesis of the test assumes that the data follow a monotonic trend. The significance of the MK test was assessed at the level of 0.05.

Dry periods were determined with the Standardised Streamflow Index (SSI), whose advantage is the possibility to calculate values for different time periods. In this study, we opted for the 12-month SSI-12. The considered series were normalised using the general Box–Cox transformation (Box, Cox 1964, 1982), which allowed the authors to obtain a vector of normalised values. The Box–Cox transformation of the variable, indexed by the parameter λ, is given by the formula:

$$u^{(\lambda)} = \begin{cases} \dfrac{x^{\lambda} - 1}{\lambda} & (\lambda \neq 0) \\ \ln x & (\lambda = 0) \end{cases} ; \text{for } x > 0$$

The number of values that λ can take in the formula is virtually infinite, which maximises the effect of the transformation.

As the normalised series had different mean values of u and different values of the standard deviation σ, their standardisation was necessary, with the aim being to obtain series with the mean value $(u) = 0$ and the standard deviation $(\sigma) = 1$. Hence, the series with the normal distribution were subjected to the linear transformation according to the procedure:

$$z = \frac{u - \overline{u}}{\sigma_u} \sim N(0,1)$$

The normalisation and standardisation processes made it possible to compare numerous series with a different scale of input data. This procedure positively influenced the homogeneity of the series, which was verified and presented in Bartczak et al. (2014b).

Finally, dry periods were identified following a suggestion put forward by McKee et al. (1993) and WMO (2012), where a drought starts when the SSI value is equal to or below −1.0 and ends when the value becomes positive. Next, the indices were classified so that the degree of their intensity could be assessed. In the original classification presented in McKee et al. (1993) and later Guttman (1999), the index thresholds indicating shortages are −1.0 (moderate drought), −1.5 (severe drought) and −2.0 (extreme drought). Standard deviation values between −1.0 and +1.0 inform about average conditions.

The relationship between the SSI-12 during dry periods and the corresponding indices of a specific atmospheric circulation was expressed using Spearman's rank correlation coefficient. The statistical significance of the coefficient was verified with the null hypothesis H0: $\rho = 0$ and the alternative hypothesis HA: $\rho \neq 0$. The significance was assessed at the level of 0.05.

Smoothing of the calculated SSIs and circulation indices was presented with a moving trend (Hellwig 1967). This method is commonly applied for the analysis of long series with irregular and frequent variations in the direction of trends. In order to perform the smoothing process, a smoothing constant k ($k<n$) is arbitrarily set. In the next step, the structural parameters of the trend linear function are estimated on the basis of successive fragments of the series with a fixed length k. Then, the structural parameters of the functions in each segment are estimated with the

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least squares method. The number of segments in a series equals $n-k+1$. Finally, arithmetic means of the theoretical values are calculated. The analysis was performed for the constant k = 10 years.

All the analyses were carried out within the space of a hydrological year, i.e. 1st November–31st October.

Results

Mean annual flows and their trends

The analysis of mean annual flows concerned seven main tributaries of the lower Vistula basin. The findings as to the characteristics of the mean annual flows and mean annual specific discharges are presented in Table 1, and Figure 2 depicts the basic parameters of the distribution of mean annual specific discharges. The analysed rivers differ both in terms of their catchment area and the mean annual flow (Table 1). For the entire period of 1954–2018, the trends of the mean annual flow are statistically insignificant for all of the rivers (Table 1).

The annual SSI for the rivers with the highest, average and lowest values of the mean annual flow in 1954–2018 are shown in Figure 3. Although the trends of the mean annual flows are insignificant for the period as a whole, some characteristic sub-periods can still be identified. The first one commenced in 1954 and continued until the early 1980s. At that time, it gave way to the other one, which lasted until the end of the study period. It may be emphasised that the differences in trends and the intensity of the years classified as dry or wet can be observed in both of these sub-periods.

Annual circulation indices and their trends

One of the research objectives was to investigate the possible dominance of the western zonal (W), southern meridional (S) or cyclonic (C) atmospheric circulation over the study area. In the analysed period, the advection from the west decidedly prevailed over the one from the east (index W = 114.6 per year), with a statistically significant growing trend for the index (p-value of 0.0062 for the MK test). The annual index W took a negative value only twice during the studied time (1969 and 1996) (Fig. 4), and the 21st century has only seen the dominance of the western circulation. Additionally, air inflow from the south was slightly more common than that from the north. Interestingly, however, the mean multi-year value of the index S stands at 0, indicating proportional (approx. 50% frequency each) inflow of air masses from the south and the north in the research period. That said, since the second decade of the 21st century, the intensity of the meridional circulation started to increase, with the maximum in 2014 (Fig. 4). Further, the frequency of anticyclonic synoptic situations was higher than that of cyclonic types (index C = −24.7 per year). However, the C index is also characterised by considerable volatility. Its trend is not significant (Table 2), with two characteristic sub-periods identifiable:

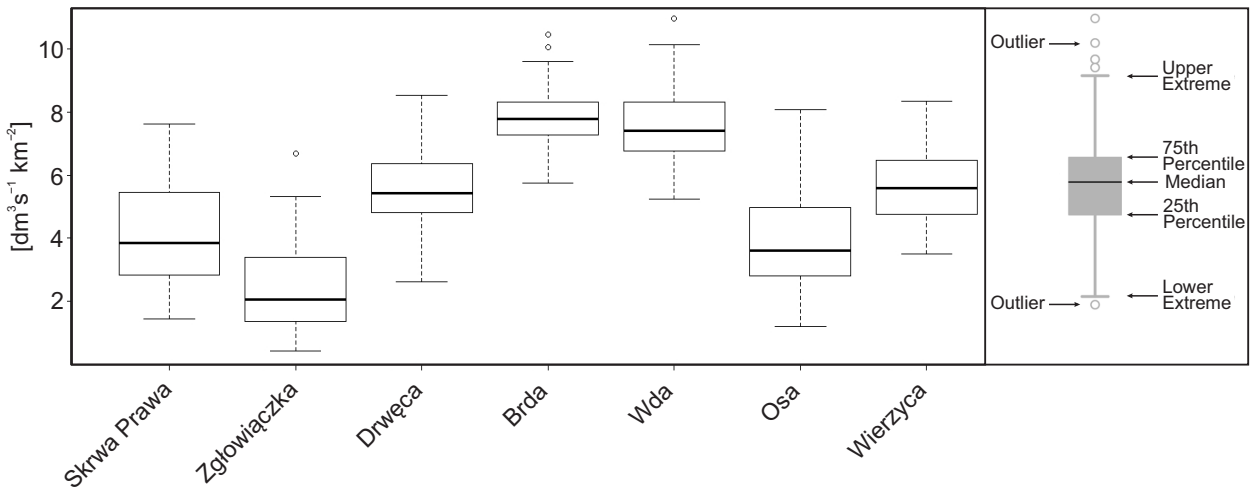

Fig. 2. Basic parameters of the distribution of mean annual specific discharges of the studied rivers in 1954–2018.

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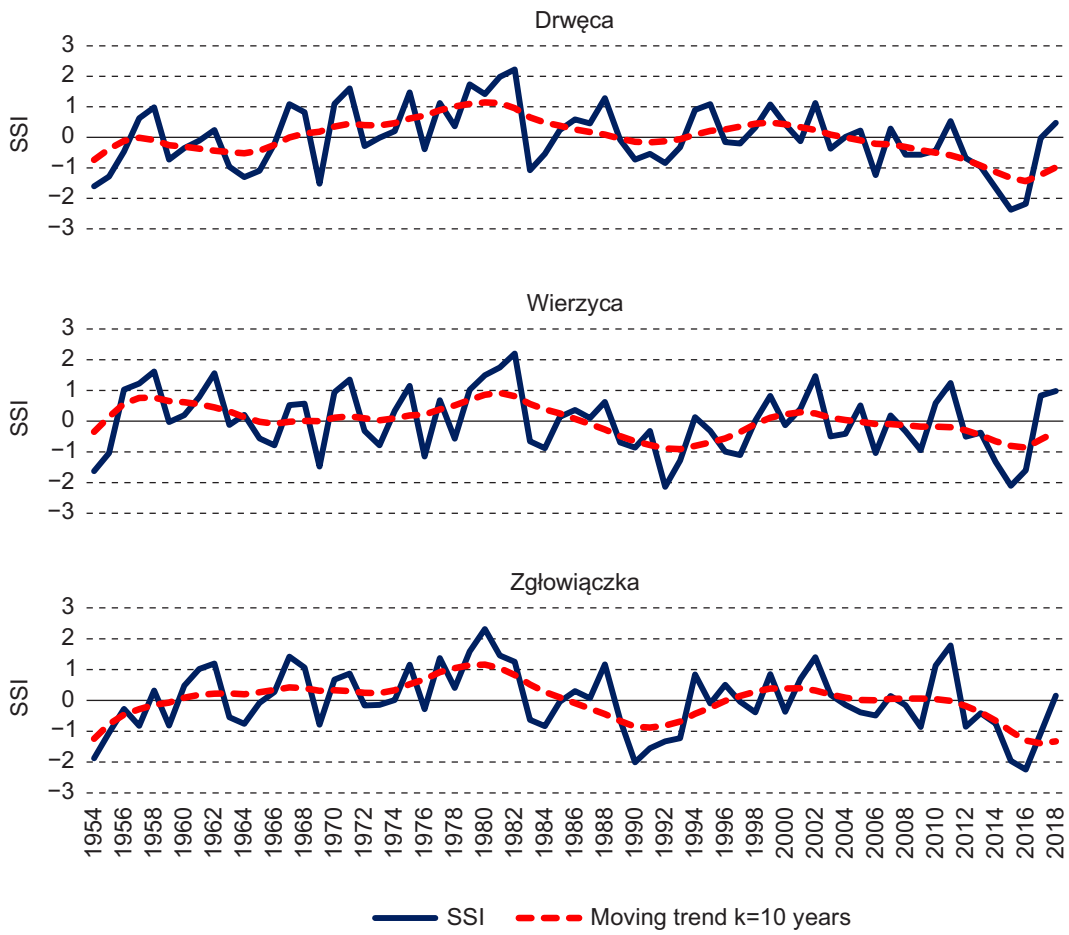

Fig. 3. The course of annual SSI on selected rivers: Drwęca (the highest mean multi-year flow), Wierzyca (average mean multi-year flow) and Zgłowiączka (the lowest mean multi-year flow) in 1954–2018. SSI, Standardised Streamflow Index.

Table 2. Characteristics of annual atmospheric circulation indices: western zonal (W), southern meridional (S) and cyclonicity (C) in the analysed area and *p*-value of the MK test for the trend in 1954–2018 (hydrological year from November to October).

No.	Circulation index	Mean	Maximum (year)	Minimum (year)	Standard deviation	Statistics MK test	*p*-value MK test
1	W	114.6	226 (1983)	−48 (1960)	54.4	2.735	**0.0062**
2	S	0.7	88 (1960)	−57 (1997)	31.7	−0.170	0.8651
3	C	− 24.7	110 (2001)	−178 (1959)	54.6	0.532	0.5945

MK, Mann Kendall.
Bold value denotes statistical significance at the $p < 0.05$ level.

1. Since the mid-1950s to the early 1990s (increase in the frequency of low-pressure systems), and
2. Since the late-20th century to 2018 (evident dominance of anticyclonic systems) (Fig. 4).

Dry periods

The course of the SSI-12 on all the studied rivers in the analysed period is shown in Figure 5.

The total number of the identified dry periods ranged from 6 (Zgłowiączka River) to 10 (Wierzyca River) (Table 3). Interestingly, the total duration of dry periods in individual catchments differed substantially. The total share (months) of dry periods ranged from 163 (Drwęca River) to 217 (Osa River).

In all but two analysed rivers (Drwęca and Zgłowiączka), the longest dry period occurred between 1990 and 1994 (Table 4), with drought

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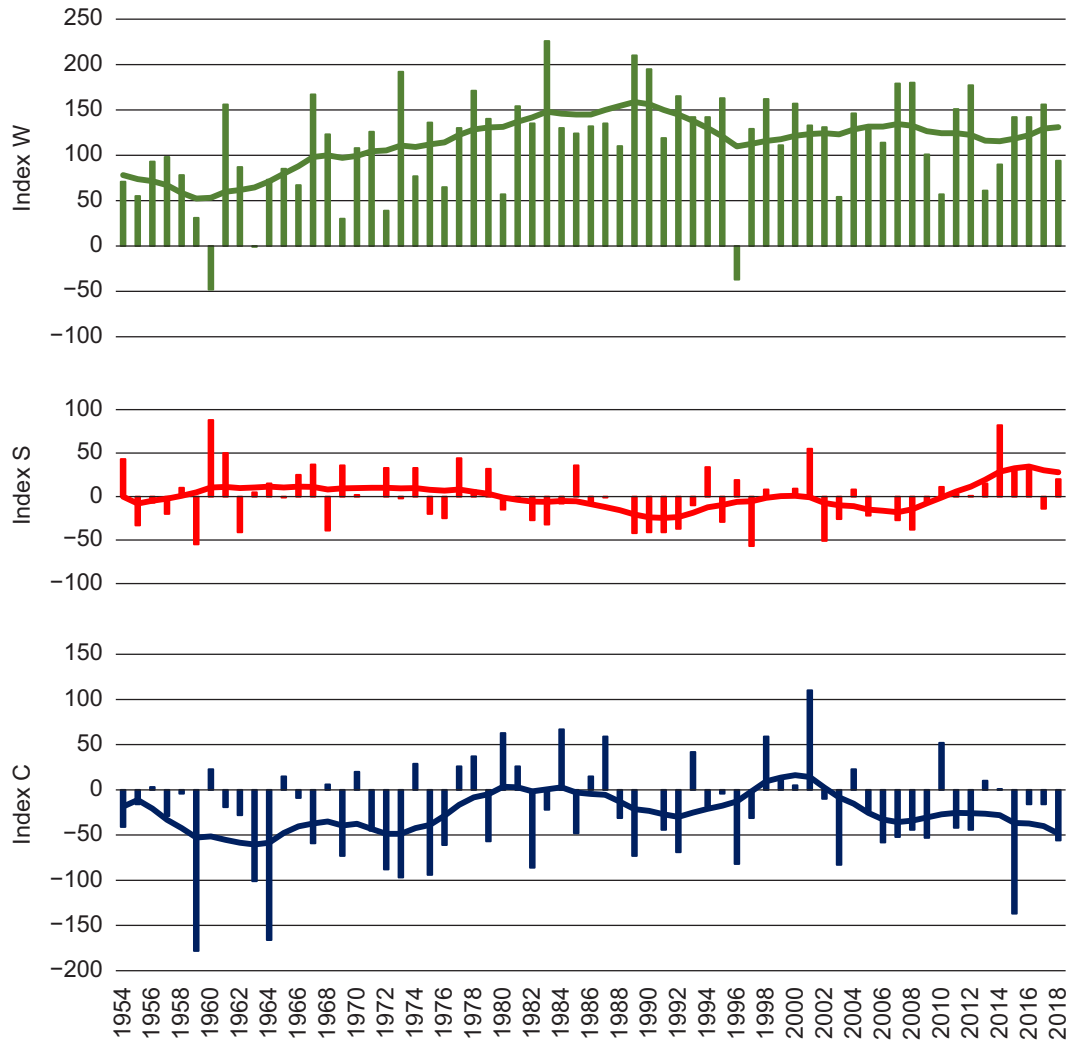

Fig. 4. The course of annual values of circulation indices (W, S and C) in the research area in 1954–2018 (hydrological year from November to October).

Table 3. Characteristics of dry periods on the analysed rivers in 1954–2018.

No.	River	Total number of dry periods	Total number of months	Max. number of months during one dry period	Min. number of months during one dry period
1	Skrwa Prawa	9	196	49	3
2	Zgłowiączka	6	170	61	8
3	Drwęca	7	163	43	11
4	Brda	8	203	69	6
5	Wda	6	180	49	13
6	Osa	9	217	50	4
7	Wierzyca	10	194	51	3

spells lasting from 49 months to 69 months. The Brda River is a particularly telling example, where a dry period, according to the adopted methodology, lasted 69 months, i.e. from February 1990 to October 1995, which makes it the longest one in the entire study period. At the other end of the spectrum is the Drwęca River with no dry periods observed. Although the SSI-12 for this river did happen to be in the negative area, on no occasion did they reach the value of −1.0. It should be noted, however, that although 1990–1995 was quantified as the longest dry period, its intensity on most rivers was not the highest.

The second characteristic dry period occurred in the 21st century between 2014 and 2017 (except the Zgłowiączka – drought starting in

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January 2013 and the Skrwa Prawa in January 2015) (Table 4). The duration of dry spells in that period ranged from 33 months to 61 months. The analysis of the number of months classified as moderately, severely or extremely dry (Table 4) indicates that the intensity of this drought was higher than that of 1990–1995 (Table 4). In no other dry spell throughout the entire research period were there so many months in which SSI-12 was lower than two standard deviations, which stands for extreme drought. The number of months marked as extremely dry ranged from 12 (30% of the total duration) on the Wda River to 22 (51% of the total duration) on the Drwęca River. The mean value of the SSI-12 also indicates a much greater overall intensity of those dry periods.

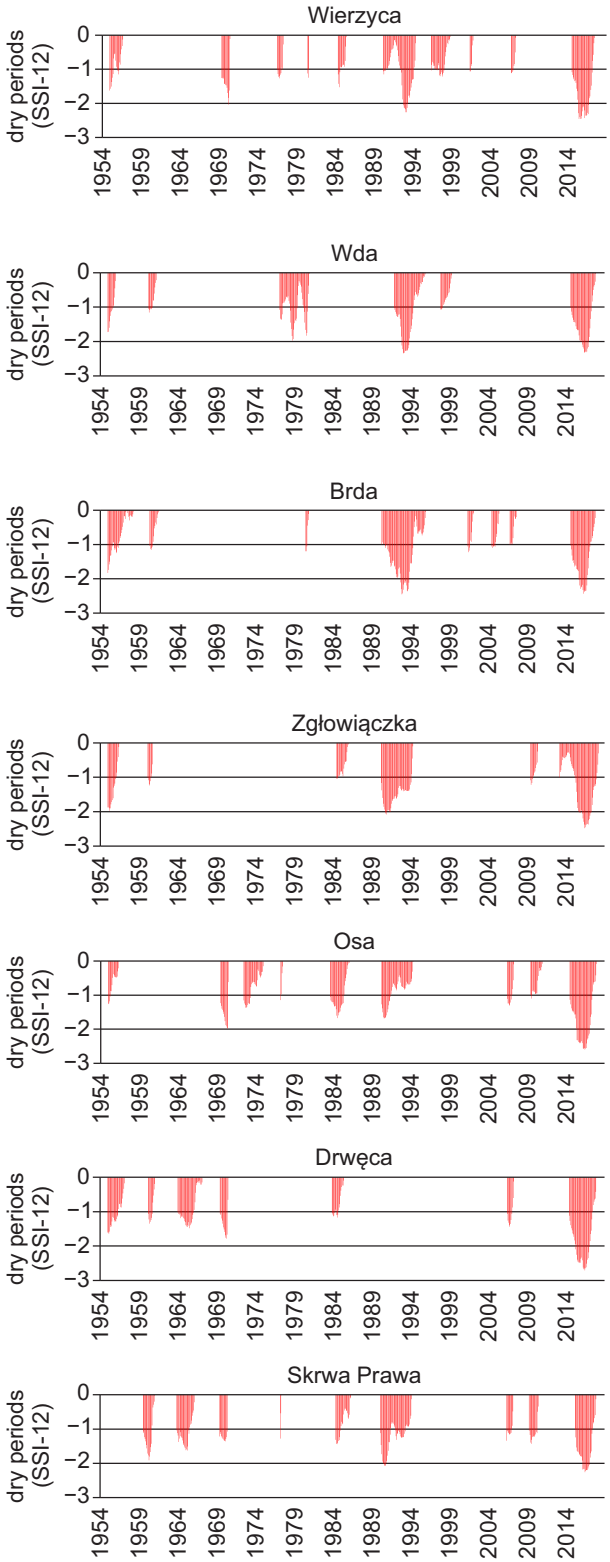

Fig. 5. The course of dry periods (SSI-12) on analysed rivers in 1954–2018. SSI, Standardised Streamflow Index.

Relationship between dry periods and the indices of atmospheric circulation

During dry periods, the SSI-12 and the C-12 circulation index expressed with the correlation coefficient are convergent as to their course. At the onset of a dry period, when the SSI-12 decrease, the value of the C-12 index tends to go down, as well. And conversely, at the end of a dry period, when the SSI-12 increase, so does the C-12 index. This relationship is exemplified by the Brda River (Fig. 6). Ergo, the occurrence and duration of dry periods are heavily influenced by the presence of anticyclonic systems (Table 5). That said, however, one cannot claim that the incidence of a dry period is up to any specific values of the C-12 index.

In turn, the relationship between SSI-12 and S-12 and between SSI-12 and W-12 is not so unambiguous. We note that the values of the correlation coefficient tend to be negative, which suggests the opposite directions of the SSI-12 and the circulation indices S-12 and W-12. However, not all of the results are statistically significant, and they do not unequivocally determine the existence of such a relationship (Table 5). This may mean that the occurrence of dry periods over such a long time is heavily influenced by the masses of air flowing in from the north or south. Similarly, the development of droughts may be determined by weakened advection of air masses from the west and intensified inflow from the east. This means that the influence of air circulation should be considered individually and independently for each drought that occurred in the studied multi-year period.

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Table 4. Characteristics of a dry period on the analysed rivers and the values of atmospheric circulation indices in 1990-1994* and 2014-2017*.

River	Period	SSI-12 0.0 ÷ −1.0	SSI-12 −1.0 ÷ −1.5	SSI-12 −1.5 ÷ −2.0	SSI-12 <−2.0	Min. value of SSI-12	Mean value of SSI-12	Total duration [months]	C-12 (mean)	S-12 (mean)	W-12 (mean)
1990-1994*											
Skrwa Prawa	Dec 1990–Dec 1994	17	21	5	6	−2.07	−1.23	49	−30.59	−33.78	159.57
Zgłowiączka	Jan 1990–Feb 1994	3	23	18	6	−2.08	−1.51	50	−25.76	−31.56	156.88
Drwęca	–	–	–	–	–	–	–	–	–	–	–
Brda	Feb 1990–Oct 1995	24	13	18	14	−2.45	−1.33	69	−14.14	−20.75	158.29
Wda	Sep 1991–Sep 1995	19	12	6	12	−2.35	−1.23	49	−15.16	−13.39	151.06
Osa	Jan 1990–Feb 1994	35	7	8	0	−1.68	−0.90	50	−25.76	−31.56	156.88
Wierzyca	Jan 1990–Mar 1994	26	11	6	8	−2.26	−1.11	51	−23.41	−30.18	156.10
2014-2017*											
Skrwa Prawa	Jan 2015–Sep 2017	5	4	13	11	−2.26	−1.63	33	−64.85	28.15	138.51
Zgłowiączka	Jan 2013–Jan 2018	26	10	7	18	−2.48	−1.30	61	−36.98	29.93	122.92
Drwęca	Apr 2014–Oct 2017	6	6	9	22	−2.71	−1.86	43	−51.04	34.02	129.74
Brda	Jun 2014– Aug 2017	8	8	10	13	−2.43	−1.58	39	−55.28	35.74	130.46
Wda	Jun 2014–Sep 2017	7	10	11	12	−2.33	−1.54	40	−54.38	35.00	130.25
Osa	May 2014–Oct 2017	7	7	8	20	−2.59	−1.78	42	−52.38	33.79	130.35
Wierzyca	May 2014–Apr 2017	4	9	6	17	−2.46	−1.74	36	−52.16	40.41	128.47

*Dry periods on most of the study area (the lower Vistula basin).

The ambiguous results of the relationship between the direction of the SSI-12 and S-12 and SSI-12 and W-12 indices suggest that the development of all dry periods may be affected by air masses flowing in from various directions. Located in the transitional climate zone, the studied catchments are alternately influenced by marine and continental air from the Atlantic Ocean and Eurasian continent, respectively. We believe that in such areas characterised by variable inflow of air masses, each dry period should be considered and analysed individually.

During the dry period that started at the beginning of the hydrological year 1990 and lasted until 1994, or even until the end of 1995 (Brda and Wda), the S circulation indices took negative values, indicating the domination of the inflow of air masses from the north. On the other hand, the latest drought – the most intense in the entire study, which for most of the analysed rivers began in the mid-2014 hydrological year (except Zgłowiączka – in January 2013 and Skrwa Prawa – in January 2015) – was characterised by positive and high values of the indices, meaning that the inflow of air masses from the south prevailed. Although it was not the longest drought in the studied period, the SSI-12 indices reached extremely minimal values for virtually all the analysed rivers. Additionally, the number of months quantified as extremely dry was the highest and ranged from 11 (Skrwa Prawa River) to 22 (Drwęca River).

Discussion and summary

The number and duration of dry periods in the analysed rivers varied. It is hardly surprising as, although placed in one physical and geographical unit, they differ in local climatic conditions or the catchment area. Moreover, the differences in the time of occurrence and length and intensity of dry periods in the studied catchments may result from their inertia. As shown in Kasprzyk (2005), the occurrence of long-term low flows is influenced by not only climatic factors (low totals of precipitation and negative climatic water balance) but also features of a given catchment, such as lithology, water abundance and catchment retention. Additionally, Kasprzyk (2005) points at the level of development of a catchment area. Wrzesiński (1999) also proved that the duration of low flows is up to the catchment morphometry and lithology. Longer-lasting low flows characterise lower-lying catchments with little diversification, slight slopes and clay subsoil.

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Wrzesiński (1999) found that limited forest cover and a clay substrate generally result in more profound low flows. Tomaszewski (2015) also points out the importance of various features of a catchment area in the occurrence of low flows. In his opinion, they take longer to develop in lake catchment areas, where lakes act as a buffer, and in catchments rich in groundwater.

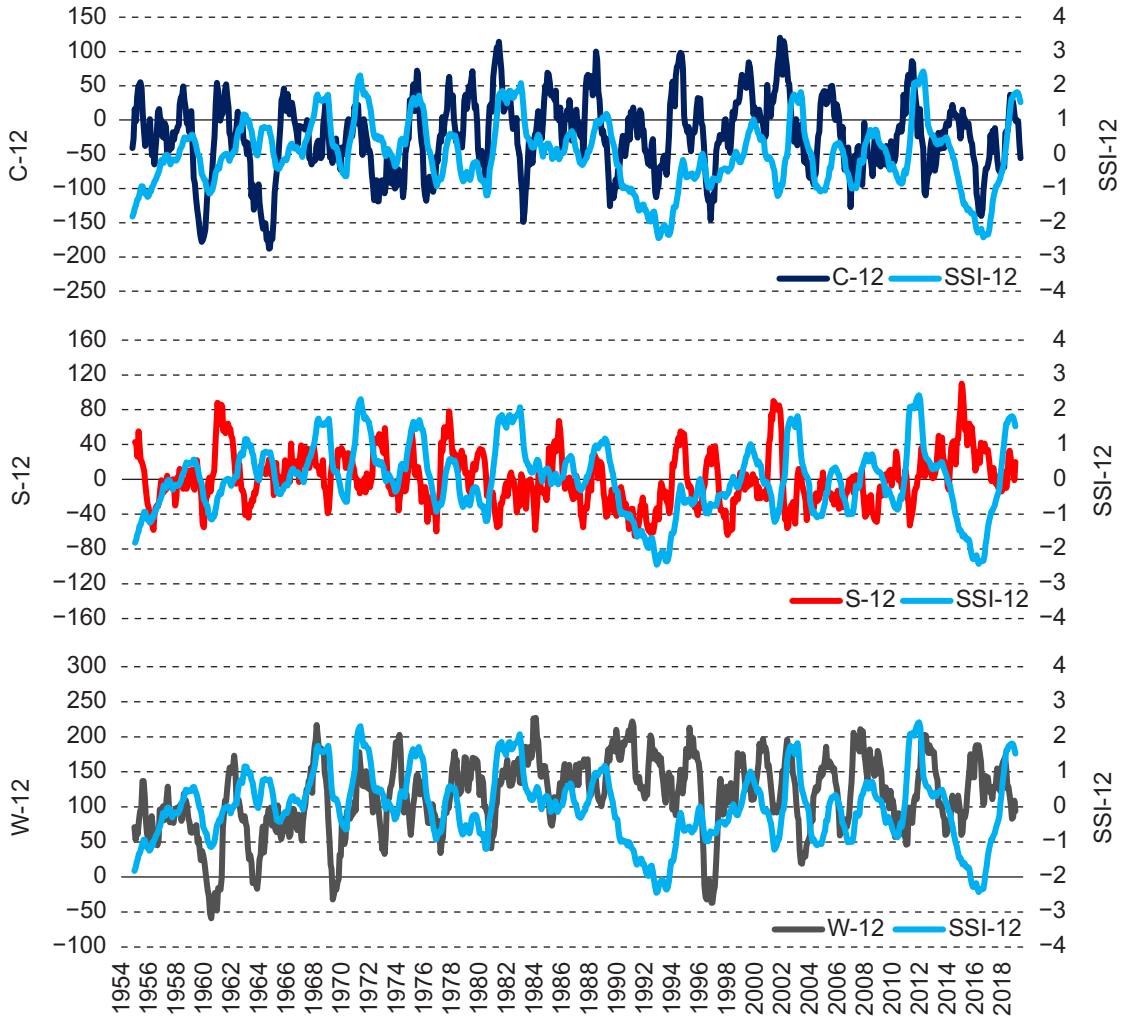

Fig. 6. The course of monthly indices of atmospheric circulation (C-12, S-12, W-12) and SSI-12 exemplified by the Brda River in 1954–2018. SSI, Standardised Streamflow Index.

Table 5. Relationship between dry periods in the analysed rivers and atmospheric circulation indices in 1954–2018.

No.	River	SSI-12/C-12		SSI-12/S-12		SSI-12/W-12	
		Spearman's Corelation Coefficient	*p*-value	Spearman's Corelation Coefficient	*p*-value	Spearman's Corelation Coefficient	*p*-value
1	Skrwa Prawa	**0.44**	**<0.0001**	0.03	0.6677	**−0.20**	**0.0050**
2	Zgłowiączka	**0.36**	**<0.0001**	**0.19**	**0.0117**	**−0.51**	**<0.0001**
3	Drwęca	**0.34**	**<0.0001**	**−0.34**	**<0.0001**	−0.13	0.1034
4	Brda	**0.35**	**<0.0001**	0.08	0.2605	**−0.16**	**0.0267**
5	Wda	**0.40**	**<0.0001**	−0.09	0.2494	0.03	0.6647
6	Osa	**0.17**	**0.0134**	**−0.29**	**<0.0001**	−0.09	0.1644
7	Wierzyca	**0.35**	**<0.0001**	**−0.30**	**<0.0001**	−0.02	0.7747

SSI, Standardised Streamflow Index.
Bold values denote statistical significance at the $p < 0.05$ level.

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Bobiński and Meyer (1992a) report that Poland experienced two extremely dry periods in the second half of the 20th century. The first one lasted 15 (1950–1964) and the other 10 years (1982–1991). Moreover, the whole period 1965–1981 saw a higher discharge than the multi-year average.

Many researchers pointed at the 1989–1994 dry period as Poland's longest and most intense one in the second half of the 20th century. The atmospheric drought that most of the country experienced in 1982–1984 is believed to have been the main reason for its occurrence (Meyer 1984). Rainfall deficits from mid-1982 to mid-1992 in Central Poland amounted to, e.g., 759 mm (Poznań – annual norm 519 mm) to 923 mm (Płock – annual norm 543 mm) (Bobiński, Meyer 1992a). Individual wet years that sparsely occurred during that period failed to counterbalance the deficit. The periodically lower precipitation coincided with rising air temperature (Przybylak et al. 2007, Limanówka et al. 2012), which promoted evapotranspiration and, thus, negative Climatic Water Balance (Mager et al. 1999). The consequent soil and agricultural drought (Łabędzki 2004, 2006a, 2006b, Łabędzki et al. 2008, Daroszewski et al. 2014) later evoked a hydrological and hydrogeological one (Bobiński, Meyer 1992a, 1992b, The drought… 1992, Mager et al. 1999, Tomaszewski 2012). The development of the dry period at that time followed classic paradigms of drought build-up presented in papers by Stahl (2001), Tallaksen and Van Lanen (2004), Tokarczyk (2010), Tomaszewski (2012) and Van Loon (2015).

Somorowska (2009) showed a significant relationship between the Palmer index (sc-PDSI) and the discharge of rivers throughout Poland. This dependence concerned not only small catchments but also those with substantial surface and underground retention. Moreover, she noticed an increased number of dry months in the last two decades of the 20th century and also the fact that the Palmer index values were lower in 1991–2000 than in the reference period 1961–1990. In her opinion, it proves that hydrological droughts are growing in intensity. This intensification of dry periods in Poland may be related to the growing inflow of air masses from the south (south-east or south-west) observed since the beginning of the 1990s. Ustrnul and Wypych (2011) reported that maximum air temperatures recorded in Poland in 1951–2006 occurred at various circulations. However, in most cases, a high-pressure system without clear advection or with airflow from the southern sector was dominant. Similarly, Tomczyk (2014) stated that the heat waves in Poznań in 1981–2010 were related to the inflow of hot air masses from the south-west and continental air masses from the eastern sector. These findings are confirmed by Wibig (2008) in a study pertaining to Central Poland and Wibig et al. (2009) in a study concerning the whole country. The above analyses show that heat waves occur when high-pressure systems dominate over Central Europe or when there is strong advection of air from the south. The incoming air is usually hot and dry and, in our opinion, directly affects the hydrological system.

The continuous and rapid increase in air temperature has already reduced water resources in Poland. Calculations by Kędziora et al. (2014) performed for Greater Poland (central part of Poland) prove that in each year from 1996 to 2006, evaporation from free water surface exceeded the total precipitation. The annual evaporation increased from 600 mm in 1996 (mean annual air temperature 8°C) to 1000 mm in 2006 (mean annual air temperature 10°C). Kędziora et al. (2014) concluded that it was the increased evaporation that resulted in a decrease in lake water level by approx. 1 m, and in groundwater level by approx. 3–4 m in that period.

The 2014–2017 drought and its causes have been given thorough consideration in the literature. It was in the summer of 2015 when Central Europe experienced the lowest precipitation since 1901 (Orth et al. 2016). This finding is also confirmed by Ionita et al. (2017), who conclude that it was the hottest and the driest summer since 1950 in the area stretching from the Eastern Czech Republic to Ukraine. The climax of highly unfavourable conditions (low precipitation, high air temperature and evapotranspiration, low soil moisture) across Eastern Europe happened in August 2015, which is reported to have been the hottest month ever for most of Poland, Ukraine and Belarus (Ionita et al. 2017). Such atmospheric conditions were brought about by four heat waves, all associated with persistent blocking situations and the northbound deviation of storm tracks over the Atlantic Ocean, and were quickly

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reflected in the hydrological situation, including river discharges, in many parts of Europe (Laaha et. al. 2017). Southern Germany was identified as the geographical centre of the hydrological extreme in terms of water deficit, while the area surrounding the Czech Republic was most severely afflicted with low river flows whose return period was 100 years or more. Additionally, the authors would like to point at the southern part of Poland as the region which also experienced a hydrological drought of considerable severity. Moreover, our analyses prove that hydrological droughts expressed with SSI-12 also occurred in Central and Northern Poland. This fact sheds more light on this extreme weather event. However, according to Garcia-Herrera et al. (2019), it was from July 2016 to July 2017 that Europe's most severe drought occurred. It concerned more than 90% of Central and Western Europe and reached record values for 1979–2017 on 25% of the continent's area. This catastrophic hydro-climatic situation was largely driven by limited transport of humidity from the Atlantic to Northern and Central Europe. Consequently, these parts of the continent experienced precipitation scarcity and longer exposure to sunshine. On the other hand, Garcia-Herrera et al. (2019) argue that in Southern Europe, these were thermodynamic processes associated with high temperatures and the resulting increased atmospheric evaporative demand (AED) that played a crucial role. Moravec et al. (2021) found that the 2014–2018 dry period in Central Europe was the record one in terms of aggregated deficit of soil moisture in 253 years (1766–2018). It can be argued, then, that according to the numerous researchers quoted above, the extreme drought in the discussed period, and particularly in 2018, was related to more factors than merely decreased precipitation. We ought to consider a coincidence of several events. Destabilised and weakened jet streams, combined with blocking weather events, effectively curbed the inflow of humidity from the Atlantic Ocean to Central Europe. This, in turn, paved the way for the hot and dry air coming from the eastern and southern sectors bringing record-breaking air temperatures, which strongly promoted evapotranspiration and soil drying. This situation must have diminished water resources in vast areas of the continent. Schubert et al. (2016) stress that agricultural and hydrological droughts in Europe are triggered by long precipitation deficits. Spinoni et al. (2017), on the other hand, point at spring and summer air temperature in Central Europe as the main driver of drought events.

Conclusion

The phenomenon of hydrological drought is multidimensional, and there seems to be no single cause that triggers it. It begins with a lengthy lack of precipitation leading to a meteorological and soil drought. A number of studies in the literature indicate that it is air circulation in the upper atmosphere that is responsible for this state of affairs. In Poland, drought events tend to be an aftermath of the anticyclonic atmospheric circulation connected with the inflow of warm and dry air masses.

In our opinion, the occurrence of a given type of atmospheric circulation (higher or lower frequency of particular types/indices) promotes the development of droughts. The observed changes in the atmospheric circulation regime are a direct consequence of climate change and their separation seems highly doubtful.

The increase in global air temperature is a well-evidenced process, the consequence of which is a growing frequency and intensity of extreme phenomena not only in Poland but across the globe.

Considering the research period of 65 years, the longest-lasting dry period for most of the analysed rivers happened between 1990 and 1995. However, the most intense droughts in the lower Vistula tributaries occurred in 2014–2017.

Drought-wise, the study area is most affected by anticyclonic systems. We believe, though, that the influence of air circulation should be subject to an individual analysis for each event of a drought. For example, during the 1990–1995 dry spell, the air advection from the north and the west was dominant. However, the 2014–2017 drought seems to have been triggered by the coincidence of the high-pressure system, the advection of dry air from the Eurasian continent and the inflow of hot air from the south.

We believe that the presented analyses showing the relationship between a type of atmospheric circulation and the occurrence of extreme hydrological events may contribute to the

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development of mitigation pathways that can prepare and adapt endangered areas to the anticipated further climate change.

Acknowledgements

The authors thank the Institute of Meteorology and Water Management – National Research Institute for kindly providing the Polish meteorological data. The research work of Andrzej Araźny was supported by funds from the Nicolaus Copernicus University (1665/2020/IDUB.EF – Global environmental changes).

Author's contribution

AB: Conceptualisation, methodology, formal analysis, writing – original draft, writing – review and editing, visualisation; AA: Conceptualisation, methodology, formal analysis, writing – original draft, writing – review and editing, visualisation, MK: Methodology, formal analysis, writing – review and editing, RM: Methodology, resources, writing – review and editing.

Conflict of interest

The authors have no conflicts of interest to declare.

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