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# Climatic and anthropogenic drivers of zero-flow events in intermittent rivers in Poland

Agnieszka Rutkowska[1)], Marzena Osuch[2)], Mirosław Żelazny[3)], Kazimierz Banasik[4), 5)], Mariusz Klimek[3)]

[1)] University of Agriculture in Krakow, Department of Applied Mathematics, Balicka St, 253C, 30-198 Kraków, Poland

[2)] Institute of Geophysics Polish Academy of Sciences, Warsaw, Poland

[3)] Jagiellonian University in Kraków, Institute of Geography and Spatial Management, Kraków, Poland

[4)] Warsaw University of Life Sciences – SGGW, Department of Water Engineering and Applied Geology, Warsaw, Poland

[5)] Institute of Technology and Life Sciences – National Research Institute, Falenty, Poland

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**Abstract:** River intermittence was studied based on data from hydrological monitoring in Poland. We screened the entire state database and two another data sources applying the criterion for zero-flow event: discharge less than 0.0005 $m^3 \cdot s^{-1}$, and found five intermittent rivers with catchment area from 9.2 to 303.7 $km^2$. We aimed at finding associations between intermittence and climatic driving forces (temperature and precipitation), and between intermittence and anthropogenic activity. We used the Spearman correlation coefficient, circular statistics, and statistical tests for trend.

The concentration of zero-flow days, mostly in summer, and the decreasing trend in the standardised precipitation evapotranspiration index (*SPEI*) in all catchments at various aggregation levels, and an increasing trend in the total number of zero-flow days and in the maximum length of zero flow events in two rivers, were detected. The strong negative correlation ($-0.62 \le \rho < 0$) between intermittence and the *SPEI* backward lagged in time showed that intermittence resulted from prolonged deficits in climatic water balance due to increasing evapotranspiration. The reaction of the Noteć catchment, amplified by the anthropogenic pressure (brown coal mines), was reflected in the atypical shape of the rose diagram and in inhomogeneities in river discharges.

The results show that the rose diagram can serve as an indicator of the degree of anthropogenic impact on runoff conditions.

**Keywords:** circular statistics, climatic and anthropogenic impacts, river flow intermittence, standardised evapotranspiration index, trend in flow intermittence

## INTRODUCTION

In recent years the cessation of flow in Poland has been noticed more frequently, mainly in small or mid-sized catchments. Unfortunately, like in other countries, there is a lack of flow measurements in most such rivers because the intermittence has been observed only occasionally for years and rarely documented in the literature. Recently, some projects were undertaken by state institutions, e.g. Stop Drought (PGW Wody Polskie, 2018) supported by E.U. funds, to prevent the effects of drought in river basin districts.

The main objective of the paper is to answer questions about whether observed drying showed an increasing tendency, what might be the drivers of the tendency, and how anthropogenic activity can affect the reaction of a catchment to drought conditions in the selected intermittent rivers in Poland. Two variables were studied at the annual and seasonal scale: the total number of days with zero-flow and the maximum length of zero-

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flow events. The long-term trend in the variables and the metrics of intermittence, such as metrics of frequency, duration and timing, were investigated. The timing of intermittence was estimated using circular statistics that are often used in assessing the dates of drought, flood or intermittence events, seasonality of precipitation and runoff (Bayliss and Jones, 1993; Burn, 1997; Castellarin, Burn and Brath, 2001; Parajka *et al.*, 2009; Rutkowska, Kohnová and Banasik, 2018).

For the explanation of causes of intermittence, the correlation with the standardised evapotranspiration index (*SPEI*) was assessed (Vicente-Serrano, Begueria and Lopez-Moreno, 2010), where the elements of climate, such as precipitation and temperature, are involved. It is used as an indicator of drought conditions by measuring drought severity and identifying the onset and end of drought episodes. Examples of the use of the *SPEI* are: finding links between meteorological drought indices and streamflows (Laaha *et al.*, 2016), assessment of moisture conditions in Poland (Wibig, 2012), and the relation between the *SPEI* and zero-flow occurrence in 452 intermittent rivers in Europe (Tramblay *et al.*, 2021) where a strong correlation was revealed in many stations.

In addition, the influence of human activity on river intermittence was studied. The results of the study can improve the management of such rivers through adaptation to water scarcity.

## MATERIALS AND METHODS

The entire database (1076 gauging stations) of the Institute of Meteorology and Water Management National Research Institute (Pol. Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy, IMGW–PIB), Poland was screened. The institution is responsible for maintaining the hydro-meteorological network in Poland. Their geographical coverage adequately represents the spatial variability in the hydrological conditions of Poland. However, intermittence was not observed very often in previous decades and it was not a criterion in establishing gauging stations by IMGW–PIB. Therefore, the flow observations from two additional sources were also studied. Daily river flows were used in the study. The criterion for intermittence was that the length of the data series must be at least 25 years and that the series must contain at least one event with flows lower than 0.0005 $m^3 \cdot s^{-1}$ and a record of five consecutive days with such a discharge. Periods with such flows are defined as zero-flow events in this study. The problem of establishing the most representative threshold level was considered carefully (Delso, Magdaleno and Fernandez-Yuste, 2017) because the rivers differ by discharge conditions and discharge magnitudes. Various thresholds have been used in the literature, from 0.0001 to 0.005 $m^3 \cdot s^{-1}$ (Delso, Magdaleno and Fernandez-Yuste, 2017). The main cause behind the choice was that the accuracy of the data from IMGW–PIB was 0.01 or 0.001 $m^3 \cdot s^{-1}$ (it depends on periods of monitoring) thus the discharge less than 0.0005 $m^3 \cdot s^{-1}$ was always registered as zero. As a result, five gauging stations were selected that fulfil intermittence criteria (river/gauging station): Noteć/Łysek, Czarna/Struga, Morwawa/Iskrzynia from the IMGW–PIB database, Zagożdżonka/Wygoda from the Department of Water Engineering and Applied Geology, Warsaw University of Life Sciences – SGGW, and Stara Rzeka/Łazy from the Institute of Geography and Spatial Management, Jagiellonian University in Kraków, Poland. The catchment characteristics are shown in Table 1 and the location of the stations is presented in Figure 1. The Noteć, Czarna, and Zagożdżonka catchments are

**Table 1.** Intermittent rivers and catchment characteristics

| No. | River/Gauging station | Longitude | Latitude | *A* ($km^2$) | *FR* | *BR* | Study period | Regime |
|---|---|---|---|---|---|---|---|---|
| | | | | | % | | | |
| 1 | Noteć/Łysek | 18°30’ | 52°24’ | 303.7 | 16.4 | 2.8 | 1961–2018 | strongly modified |
| 2 | Czarna/Struga[1)] | 21°08’ | 52°22’ | 201.6 | 29.5 | 11.2 | 1956–2018 | weakly modified |
| 3 | Zagożdżonka/Wygoda | 21°26’ | 51°25’ | 9.2 | 64.3 | 2.0 | 1980–2018 | natural |
| 4 | Stara Rzeka/Łazy | 20°30’ | 49°58’ | 22.4 | 47.3 | 7.3 | 1993–2019 | natural |
| 5 | Morwawa/Iskrzynia | 21°52’ | 49°41’ | 107.9 | 32.0 | 4.8 | 1973–2018 | natural |

[1)] Empty data record in 1517 days in Czarna in years 1990–1992, 2005–2006.
Explanations: No. = number of the river, *A* = catchment area, *FR* = forest ratio, *BR* = ratio of built-up areas + roads.
Source: own elaboration.

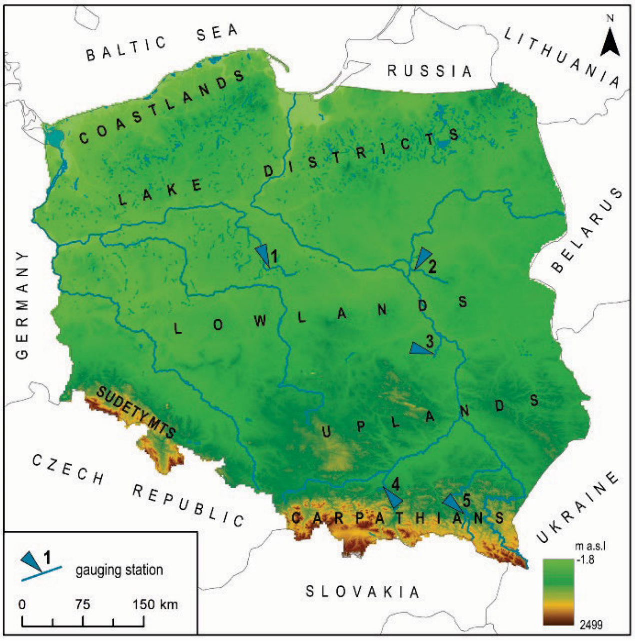


**Fig. 1.** Location of stations that fulfil intermittence criteria; *1–5* = number of river/gauging stations as in Tab. 1; source: own elaboration

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lowland catchments, while the Stara Rzeka and Morwawa are typical mountainous catchments with high precipitation totals.

The Noteć catchment is located in an area where droughts are very common, e.g. Bąk and Łabędzki (2002). The region is under anthropogenic pressure as brown coal mines were established there during the 20th and 21st centuries to supply lignite to the nearby power station. This led to a large cone of depression and a lowering of the groundwater table. In the Noteć River, the recorded zero-flow events occurred in the years 2015 and 2016, although the dry period might have been longer but was not recorded (missing data till 2017). This was actually one an extremely long event lasting at least 391 days, interrupted by several flow episodes.

The Czarna River flows through a forest reserve in its lower course. The river regime is weakly modified, as the catchment has a high ratio of artificial areas due to its proximity to Warsaw, the capital city.

In the Zagożdżonka catchment, local depressions constitute a significant part of the area. The discharge observations have been carried out since 1963 at the Płachty Stare and Czarna gauging stations and periodically since 1980 at Wygoda, the most upstream-located station. A dry river bed was reported at Wygoda for eight years during the period 1980–2018. Due to the lack of continuous observations, the data record for Wygoda used in the study was obtained using the transfer polynomial function between daily river discharge at Płachty Stare and Wygoda (Banasik *et al.*, 2019).

Time series plots of logs of river discharges that fulfil intermittence criteria are shown in Figure 2. In the plots, the zero-flow events are marked by red crosses.

A year is defined as starting on 1st April and finishing on 31st March, a summer season from 1st April to 30th September, and a winter season from 1st October to 31st March. Such a choice can guarantee that zero-flow events are not disrupted between years (Laaha and Blöschl, 2006) as in Poland's climatic conditions, low flows occur very rarely between March and May.

The series of $X_1$, the total number of zero-flow days, and $X_2$, the maximum length of zero-flow events were established at the annual scale and seasonal scale: for summer and winter. The samples were selected from the series of daily river flows and applying the criterion for intermittence. The metrics of frequency included: the frequency of years when the discharge was below the threshold level 0.0005 $m^3 \cdot s^{-1}$, among all years in the series and the frequency of days with such a discharge. The metrics of duration were: the mean and standard deviation of the annual (seasonal) number of zero-flow days and the mean and standard deviation of the annual (seasonal) maximum length of zero-flow events. The onset dates (the date of the first day in a year when discharge was below a threshold), and all dates of intermittence were analysed using circular statistics i.e. metrics of timing. The metrics of the timing of intermittence include: (i) the mean date of zero-flow events onset, (ii) the mean date of all zero-flow days, and (iii) the mean resultant length of the dates of all zero-flow days. All formulas for the metrics of timing are available e.g. in Fisher (1993), Rutkowska, Kohnová and Banasik (2018), Mardia and Jupp (2000). The pattern of intermittence was shown in rose diagrams. The comparison between rose diagrams for various catchments has provided important information on the difference between runoff conditions, e.g. human impact.

The hypothesis about the monotonic trend in the variables $X_1$, $X_2$ was verified using the Mann–Kendall test (MK test) (Kendall, 1938; Mann, 1945) at the annual and seasonal scale. The time series were tested for autocorrelation first to make sure that the version of the MK test for uncorrelated variables could be used. Additionally, two rank-based tests, the Cucconi test (C test) (Cucconi, 1968; Marozzi, 2013; Rutkowska and Banasik, 2016) and the Lepage test (L test) (Lepage, 1971) were used to test the hypothesis that there is a step trend in both location and scale parameters (location-scale trend) in the series of river flow characteristics. This test was used to confirm an abrupt change in river flows at a station where additional water transfers were documented.

The *SPEI* data with 1, 6 and 12 months aggregation time (*SPEI*1, *SPEI*6, *SPEI*12) were obtained from the *SPEI* database (https://spei.csic.es/spei_database). It is calculated based on atmospheric water balance, as the difference between precipitation and potential evapotranspiration, standardised to the normal distribution, where the former captures the water supply while the latter captures the atmospheric water demand. The *SPEI* values are negative when atmospheric demand exceeds precipitation; values

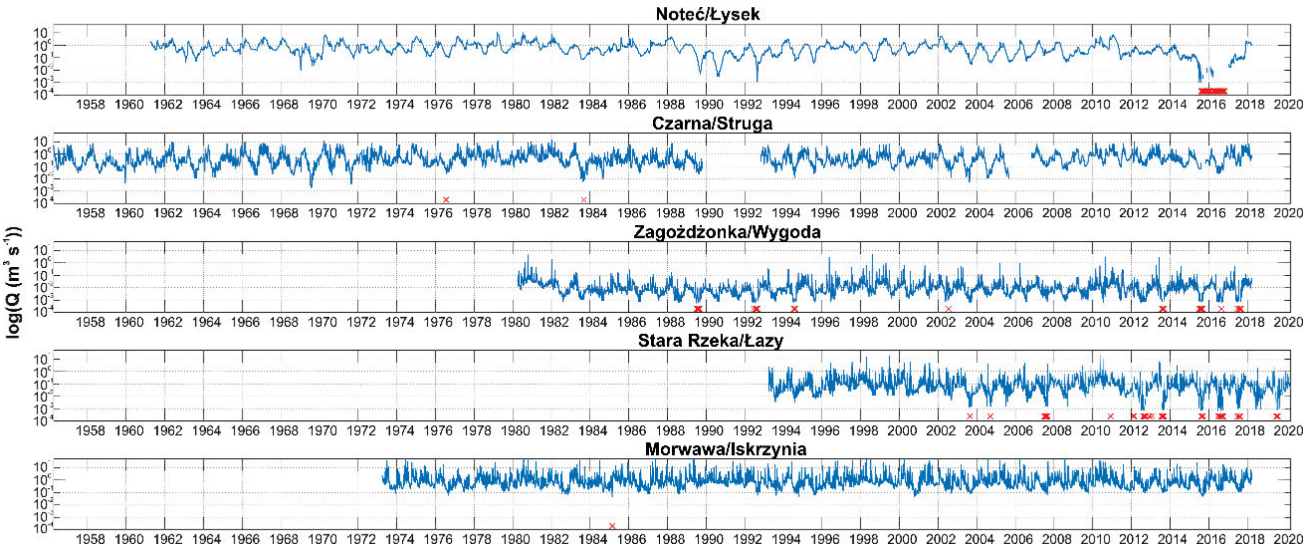


**Fig. 2.** Time series plots of log($Q$) where $Q$ are daily discharges; the zero-flow events are marked by red crosses; source: own study

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less than zero show deficits in climatic water balance, while values less than –1 show moderate, severe or extreme drought conditions.

The Spearman correlation coefficient between the series of $X_1$, $X_2$ at the annual and seasonal scale and the 12-month *SPEI*12 (current and lagged backwards) and 6-month summer/winter *SPEI*6 (current and backward lagged), respectively, were tested for significance with one-sided alternatives in order to check the influence of current and previous precipitation and evapotranspiration conditions on the intermittence. All tests were carried out at $\alpha$ = 0.05 and calculations were performed in the R programme (Agostinelli and Lund, 2017; R Core Team, 2021; Tsagris *et al.*, 2021). Symbols and abbreviations are listed at the end of the paper.

## RESULTS AND DISCUSSION

### METRICS OF FREQUENCY, DURATION, AND TIMING

The metrics of frequency, duration and timing are presented in Table 2. The values of $f_y$ are very low in the Noteć, Czarna and Morwawa rivers, where the zero-flow events were recorded rarely, and larger in the Zagożdżonka and Stara Rzeka rivers, where these events occurred more often. According to $f_d$, the rivers could be grouped into the set with the Noteć, Zagożdżonka and Stara Rzeka rivers and the set with the Czarna and Morwawa rivers. The grouping is similar to the results of $N_0$. All the measures: $m_{1A}$, $m_{1S}$, $m_{1W}$, $m_{2A}$, $m_{2S}$, $m_{2W}$, $s_{1A}$, $s_{1S}$, $s_{1W}$, $s_{2A}$, $s_{2S}$, $s_{2W}$ are higher in the first set than in the second set. There is, however, also a difference in the structure of $X_1$, $X_2$ in the first set, as all zero-flow events are clustered in two years in the Noteć River and are more dispersed in the Zagożdżonka and Stara Rzeka rivers. The causes of the long zero-flow event in the Noteć River will be discussed in the next sections.

As regards the metrics of timing, the values of $\bar{\Theta}$, $\bar{\Theta}_0$ show that most zero-flow events occurred in the months Jul–Sep. The value of $\bar{\rho}$ is higher in the Zagożdżonka River, where the intermittence was observed only in summer, than in the Stara Rzeka River where it was observed in summer and winter. In the Noteć River, the large dispersion of the dates is reflected in a low $\bar{\rho}$ value. The dispersion of zero-flow days can be more biased in the Czarna and Morwawa rivers, where the samples are much less numerous.

The rose diagrams of the dates of intermittence were presented in Figure 3. The shapes of the Zagożdżonka and Stara Rzeka diagrams reflect the seasonality of intermittence, summer for the former and winter for the latter. The shape for Noteć/Łysek is unlike the shapes for other gauging stations. It reflects a strong anthropogenic influence on the runoff conditions.

### TREND IN INTERMITTENCE AND TREND IN THE *SPEI*

A significant increasing trend was detected in $X_{1A}$, $X_{2A}$, $X_{1S}$, $X_{2S}$ in the Stara Rzeka River and in $X_{1A}$, $X_{2S}$ in the Zagożdżonka River. The analysis was not conducted for the Noteć River, where results would not be reliable due to the concentration of all zero-flow days in two years (2015 and 2016), and in the Czarna and Morwawa rivers due to a very low number of zero-flow days in data records.

The trend analysis was conducted for the *SPEI*1, *SPEI*6, and *SPEI*12 in all five catchments for each month separately. The periods of the *SPEI* corresponded with the periods of discharge data (case 1). An alternative analysis was carried out for the *SPEI* from 1902 to 2018, the whole period when data were available (case 2), to consider the long-term tendency of the *SPEI* in each catchment. As regards case 1, a decreasing trend was detected in the *SPEI*1 in April, May, August, and November for Noteć, in April and August for Czarna, in June for Zagożdżonka, in April for Stara Rzeka, and in April for Morwawa. An increasing trend was identified in the *SPEI*1 in January for Noteć and in January and February for Zagożdżonka. A decreasing trend in the *SPEI*6 was shown in May, June, July, August, and September for Noteć, in July, August, September and October for Czarna, and in August, September and October for Morwawa. The *SPEI*6 showed an increasing trend in February and March in Stara Rzeka. As regards the *SPEI*12, a decreasing trend was shown from April to December in Noteć, in all months in Czarna, and in September, October and December in Morwawa. To summarise, the decreasing trends dominate in the summer months, and such trends were found more often than the increasing trends (45 against 5 months).

**Table 2.** Metrics of frequency, duration and timing of intermittence in studied rivers

| Parameter | Noteć/Łysek | Czarna/ Struga | Zagożdżonka/ Wygoda | Stara Rzeka/Łazy | Morwawa/Iskrzynia |
|---|---|---|---|---|---|
| $N_0$ | 391 | 10 | 165 | 173 | 8 |
| $f_y/f_d$ | 3.51/1.89 | 3.23/0.05 | 21.05/1.19 | 40.74/1.78 | 2.22/0.05 |
| $m_{1A}/m_{1S}/m_{1W}$ | 6.9/4.1/2.8 | 0.2/0.2/0 | 4.3/4.3/0 | 6.4/4.9/1.5 | 0.2/0/0.2 |
| $m_{2A}/m_{2S}/m_{2W}$ | 4.9/3.9/1.6 | 0.1/0.1/0 | 3.0/3.0/0 | 3.4/2.4/1.4 | 0.2/0/0.2 |
| $s_{1A}/s_{1S}/s_{1W}$ | 36.4/24.8/17.1 | 1.0/1.0/0 | 10.6/10.6/0 | 10.0/8.5/4.8 | 1.2/0/1.2 |
| $s_{2A}/s_{2S}/s_{2W}$ | 29.0/24.2/8.8 | 0.7/0.7/0 | 7.6/7.6/0 | 5.5/4.2/4.4 | 1.2/0/1.2 |
| $\bar{\Theta}_0$ / calendar date | 1.09 / Jun 3 | 2.24 / Aug 9 | 1.81 / Jul 14 | 2.10 / Jul 31 | 5.66 / Feb 23 |
| $\bar{\Theta}$ / calendar date | 2.78 / Sep 9 | 2.07 / Jul 30 | 2.25 / Aug 9 | 2.53 / Aug 26 | 5.71 / Feb 26 |
| $\bar{\rho}$ | 0.32 | 0.96 | 0.96 | 0.57 | 1.00[1)] |

[1)] The more accurate value is $\bar{\rho}$ = 0.9991696.
Explanations: symbols and units are listed at the end of the paper.
Source: own study.

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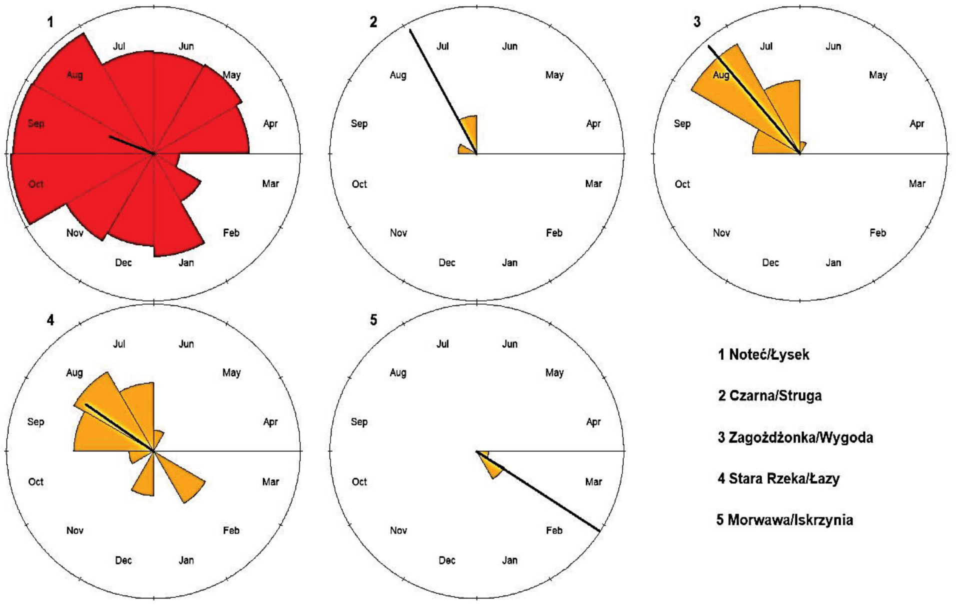


**Fig. 3.** Rose diagrams of the dates of intermittence in the five catchments; the highest bar = the month with the largest frequency of zero-flow events, the black arm = the mean date of intermittence while its length is the mean resultant length $\bar{\rho}$ (the longer the arm, the larger the concentration of dates), the red diagram for Noteć/Łysek = flow intermittence was observed throughout the whole year; source: own study

As regards case 2, only decreasing trends, mainly in summer, in the *SPEI*1, *SPEI*6, and *SPEI*12 were detected. August was the month with the decreasing trend in all catchments at all *SPEI* scales. A similar situation was in April and September when a decrease in all *SPEI*s dominated. November and December were the months with a frequent decreasing tendency. Of note is that the trend in *SPEI*12 was decreasing in all months in three catchments (Noteć, Zagożdżonka, Stara Rzeka) and nearly all months in two catchments (Czarna, Morwawa) which shows that all catchments experienced strong drying conditions.

## IDENTIFICATION OF CLIMATIC DRIVERS: CORRELATIONS WITH THE *SPEI*

The Spearman correlation coefficient was negative between the *SPEI*12 and $X_{1A}$ and $X_{2A}$, between the *SPEI*6 and $X_{1S}$ and $X_{2S}$, and between the *SPEI*6 and $X_{1W}$ and $X_{2W}$ in the Stara Rzeka catchment. It was also negative between the *SPEI*12 and $X_{1A}$ and $X_{2A}$, and between the *SPEI*6 and $X_{1S}$ and $X_{2S}$ in the Zagożdżonka catchment, and when the series of the *SPEI*12 and *SPEI*6 values were lagged backwards.

This indicates that current and previous long zero-flow events occurred when evapotranspiration surpassed precipitation (negative *SPEI* values, deficits in water balance). It was observed that some zero-flow events are linked with the *SPEI* of less than –1 (drought conditions). The correlation coefficients *r* between $X_1$, $X_2$ and the current and previous *SPEI*12 (Apr–Mar), and the summer *SPEI*6 (Apr–Sep), and the winter *SPEI*6 (Oct–Mar) values for lag = 1, …, 11 (for *SPEI*12) and lag = 1, …, 5 (for *SPEI*6) were depicted in Figure 4. The coefficient is significantly lower than zero in the following cases in the Stara Rzeka River: between $X_{1A}$ and the current *SPEI*12 and between $X_{1A}$ and the *SPEI*12 backward lagged by 1, ..., 9 months (Fig. 4a); between $X_{2A}$ and the current *SPEI*12 and between $X_{2A}$ and the *SPEI*12 backward

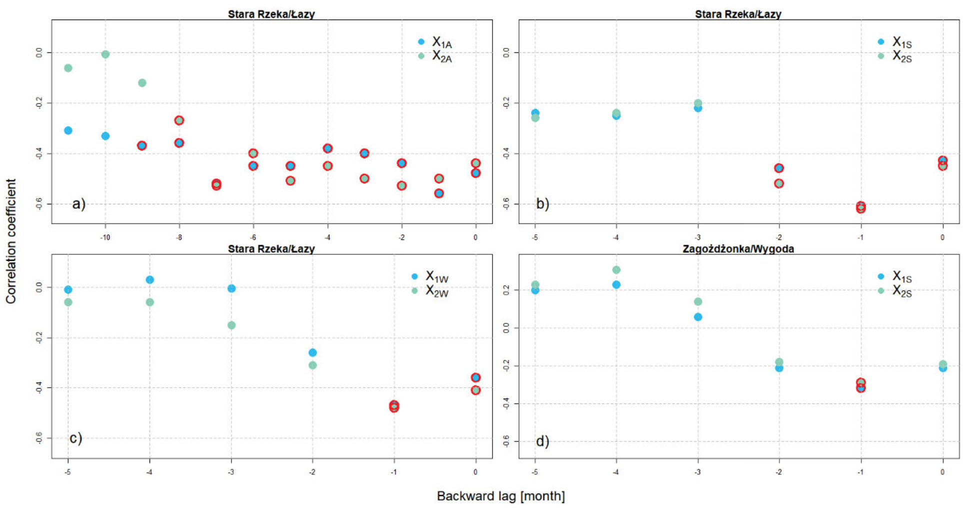


**Fig. 4**. The Spearman correlation coefficient between $X_1$, $X_2$ and the *SPEI* for various backward lags of the *SPEI*; red circles = correlation coefficient significantly lower than zero; source: own study

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lagged by 1, ..., 8 months (Fig. 4a); between $X_{1S}$, $X_{2S}$ and the current *SPEI*6 and between $X_{1S}$, $X_{2S}$ and the *SPEI*6 backward lagged by 1, 2 months (Fig. 4b); between $X_{1W}$, $X_{2W}$ and the current *SPEI*6 and between $X_{1W}$, $X_{2W}$ and the *SPEI*6 backward lagged by 1 month (Fig. 4c). In the Zagożdżonka River, it is significantly lower than zero between $X_{1S}$, $X_{2S}$ and the *SPEI*6 backward lagged by 1 month (Fig. 4d), and between $X_{1A}$, $X_{2A}$ and the *SPEI*12 backward lagged by 7 months.

The drought conditions can be amplified in the first half of winter in all five catchments due to positive temperatures observed during the last dozen years or so. In the Zagożdżonka catchment, the process of drying was also intensified by natural land use alterations, an increase in forested areas and a decrease in arable land (Krajewski *et al.*, 2021).

The results indicate that the current zero-flow episodes might have resulted from drought conditions for over a dozen previous months in the Stara Rzeka River. The association was weaker in the Zagożdżonka River, however, previous water deficits might have also impacted the current summer zero-flow episodes in this catchment. As regards the other catchments, the *SPEI*6 and *SPEI*12 often dropped below –1 during the years 2015–2016 in the Noteć catchment, which could considerably amplify the river's drying. Similarly, the *SPEI*12 and *SPEI*6 were lower than –1 in several months before the zero-flow events in the Morwawa catchment. In the Czarna catchment, the *SPEI*12 values lower than –1 occurred during the whole year before zero-flow events. This shows that all catchments experienced strong drying conditions.

## CLIMATIC AND ANTHROPOGENIC IMPACT OF RUNOFF CONDITIONS IN THE VICINITY OF THE ŁYSEK GAUGING STATION

The Noteć River catchment is located in one of the driest areas in Poland, where the relatively low contribution of forested areas in land cover can enhance the effect of drying (see Tab. 1). The susceptibility to drying was amplified in recent years due to climatic water imbalance, reflected in decreasing trends in the *SPEI*. The very long zero-flow event started as a result of very unusually low precipitation in 2015 and continued until October 2017. From the other side, the Łysek gauging station is located 7 km to the south of the Tomisławice open-cast mine that has been working since 2011 and 3 km to the north-east from the Lubstów open-cast mine where coal was extracted till 2009, and which has been recultivated and filled with water from neighbouring catchments. All of this has considerably reduced the discharge at Łysek due to lowering groundwater levels in neighbouring water reservoirs and caused changes in water relations in the region (Przybyłek, 2018). After mining was halted at Lubstów, due to the mine filling with water, the discharge between Łysek and a station located downstream (8 km distance) was reduced between May and October 2011 by 39%, on average (Wachowiak, 2015). In the future, the Tomisławice mine will be closed and energy production will turn to other sources. The locations of the Łysek station and the Tomisławice and Lubstów mines, and other mines in the region are shown in Figure 5.

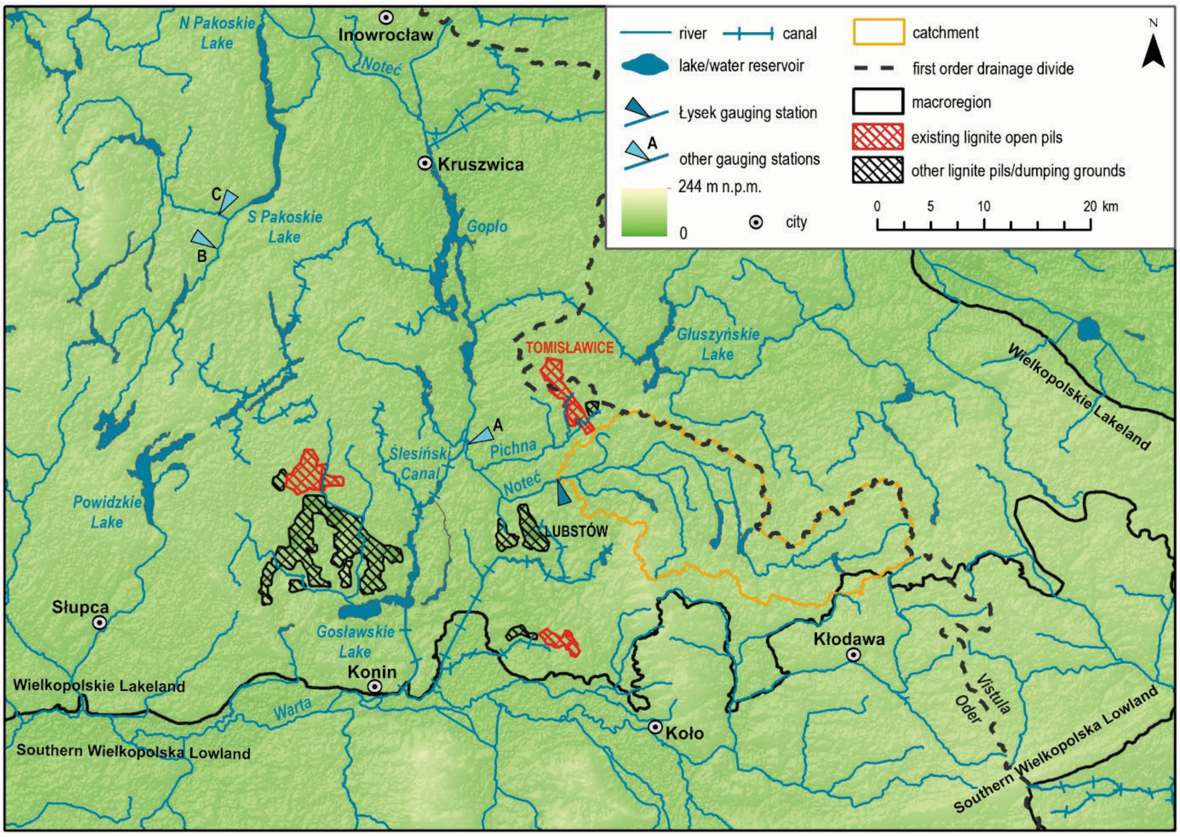


**Fig. 5.** The location of the open-cast brown coal mines (Tomisławice, Lubstów and others) and the gauging stations; the Łysek gauging station, and the three other gauging stations; *A* = Noteć/Noć Kalina, *B* = Mała Noteć/Gębice, *C* = Panna/Goryszewo; source: own elaboration

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The results indicate that changes in the Noteć River are more severe than in other catchments. Therefore we suspect that they result not only from varying climatic conditions but also anthropogenic activity in the area, namely from the operation of two open-cast mines located in the proximity of the Łysek gauging station. In order to confirm the findings, we made a comparison of flows with other gauging stations located in very similar climatic conditions: Noteć/Noć Kalina (10 km downstream, the same *SPEI* grid), Panna/Goryszewo, and Mała Noteć/Gębice (approx. 50 km distance, the adjacent *SPEI* grid). A comparison of flows at Łysek and the three other stations is shown in Figure 6. It is visible that the curves were similar up to 2011. After that, the flows at Noć Kalina station are larger and have had less variability since 2012. Such changes correspond well to the start of water transfers because since 2009, the discharge from the Tomisławice mine was directed through the Pichna River to the Noteć River just above the Noć Kalina station.

The causes of the long zero-flow event in the Noteć River were climatic and anthropogenic. The decreasing tendency of the summer *SPEI*1, *SPEI*6, and *SPEI*12 reflect the water deficit due to increasing air temperature and low precipitation in the region. The increasing evapotranspiration and low precipitation can be quantified as climatic causes, while the establishment of the open-cast brown coal mines at Tomisławice and Lubstów can be accounted for anthropogenic impacts. The drying up of the Noteć River bed is an example of how negative consequences of anthropogenic activity were amplified by the meteorological drought in 2015 with extremely low rainfall totals. The large water deficits at Noteć/Łysek were prolonged to October 2016 (or longer to 2017). According to Vicente-Serrano *et al.* (2015), rivers are most endangered in months with very low *SPEI* values due to severe and extreme drought. The three months with decreasing *SPEI*6 values (August, September, October) coincide with the months with the largest number of zero-flow days shown in Figure 5 at Noteć/Łysek. There is also a match in the timing between the zero-flows and very low *SPEI*12 values; the *SPEI*12 was less than –1.5 in 11 months during the 13 months of the zero-flow period. Results are consistent with Somorowska (2016) where a strong decreasing tendency in the SPEI3 and SPEI12 was shown and with Okoniewska and Szumińska (2020), where an increase in temperature and a decrease in relative humidity were detected.

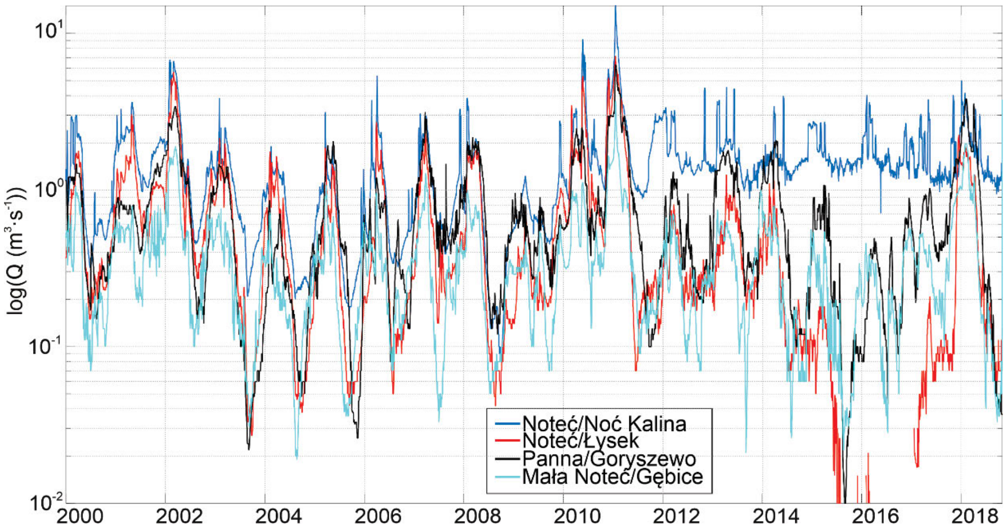


**Fig. 6.** The hydrographs at Noteć/Łysek, Noteć/Noć Kalina, Panna/Goryszewo, and Mała Noteć/Gębice; the discharge $Q$ is in logarithmic scale; source: own study

To inhomogeneity in river flow at the Noć Kalina station due to additional discharge from the Tomisławice mine was confirmed with the C and L tests for the location-scale step trend in the annual series (years 1972–2019). The additional discharge caused a huge increase in the mean values of the minima and 1st quartiles (larger than 100%) and of the means and medians (larger than 30%), and a decrease (larger than 40%) in standard deviations of the 1st quartiles, medians, and means. The year of change of all annual characteristics was 2012, when discharges were more stabilised.

It is noteworthy that human activity strongly affected water relations in the region due to establishing canals to water transfers from open-cast mines. The identified changes were only observed at a local scale, namely in the areas adjacent to the mines.

## DISCUSSION

Results of the analysis enabled the identification of driving forces of intermittence and comparison of responses from neighbouring catchments to drought conditions in various flow regimes.

The drivers of zero-flow events at Zagożdżonka/Wygoda and Stara Rzeka/Łazy were mostly climatic. In the Zagożdżonka catchment, the *SPEI* values lower than 0 often coincided with large $X_{1S}$ and $X_{2S}$ values while the largest $X_{1S}$ was detected in summer with the *SPEI*6 (May–Oct) as low as around –2. Similarly, very large $X_{1S}$ and $X_{2S}$ values in the Stara Rzeka River appeared at months with the *SPEI*6 (May–Oct) lower than –0.5 while the largest $X_{1W}$ and $X_{2W}$ values at months with the *SPEI*6 (Nov–Apr) lower than –1. The dates of zero-flow events in the two catchments often coincided with very low *SPEI*12 values in July, August and September. The increase in $X_{1S}$ and $X_{2S}$ can be linked with the decrease in the *SPEI*1 in June (Zagożdżonka) and in April (Stara Rzeka) and the increase in $X_{1W}$ and $X_{2W}$ with the decrease in the *SPEI*1 in December (Stara Rzeka). The increase in

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the *SPEI*1 in the second half of winter: in January (Noteć), January and February (Zagożdżonka), and February and March (Stara Rzeka) can be assigned to negative temperatures when evapotranspiration is low. The drought conditions can be amplified in the first half of winter in all five catchments due to positive temperatures observed during the last dozen years or so. In the Zagożdżonka catchment the increase in the mean annual temperature (1951–2015), but no decrease in precipitation was noticed (Krajewski *et al*., 2019). The process of drying was also intensified by natural land use alterations that were comprised of an increase in forested areas and a decrease in arable land (Krajewski *et al*., 2021). An increase in air temperature in the Vistula River Basin, where the Stara Rzeka catchment is located, was also documented, e.g. by Kubiak-Wójcicka (2020), while an increase in temperature in the Bieszczady Mountains, around 200 km to the south-west from the Stara Rzeka, was revealed by Mostowik *et al*. (2019).

Similar climatic drivers and the increasing tendency to intermittence that were identified in the catchments under study were found in other regions. The increasing trend in the number of zero-flow days and the correlation between the river intermittence and the *SPEI* was recognised in most of the 452 rivers in Europe by Tramblay *et al*. (2021) while the reaction of many basins was masked by local climatic conditions or anthropogenic influence. Sauquet *et al*. (2021) indicated the aridity index as the explanatory factor of flow intermittence based on the study of river flows from 471 rivers from Western Europe, Australia, and USA. This factor represented climatic drivers of intermittence. The upward trend was identified in most of basins. In the study of Palmer and Hondula (2014), in turn, the compensatory mitigation methods for the reduction of negative consequences of coal mining in Southern Appalachia were shown. The mitigation was completed successfully on over 100 intermittent rivers and ephemeral streams. It shows the efficiency of restoration actions in intermittent rivers.

The analysis shows that zero-flow events in the Noteć, Zagożdżonka, and Stara Rzeka rivers were associated with increasing evapotranspiration that surpassed precipitation. The possible cause behind the higher evapotranspiration in the three catchments was the increasing temperature due to climate change. Another effect of climate change is that, because of warmer winters with less snow, less water is stored as snowpack, groundwater is not replenished by spring melts, and that soil accumulates less water in summer because rainstorms become more intense and brief.

The patterns of intermittence, depicted in rose diagrams, considerably differed in the Stara Rzeka and Zagożdżonka rivers from the pattern in the Noteć River. The pattern in the Stara Rzeka and Zagożdżonka is an example of how catchment with natural or nearly natural flow regime can respond to climatic drivers such as increased temperature or low precipitation. The pattern in the Noteć River is an example of how catchments with anthropogenic influence can respond to climatic drivers.

## CONCLUSIONS

The temperature and evapotranspiration, represented by the standardised precipitation evapotranspiration index (*SPEI*), were found to be very important factors in river flow intermittence. The conclusion can be drawn that in areas where drying up of rivers was not very common in the past, zero-flow events can be associated with global warming due to climate change. Usually, river intermittence is a consequence of prolonged water deficits in the past.

Another factor that can cause intermittence is anthropogenic pressure. The establishment of open-cast brown coal mines and intra- or interbasin water transfers, enhanced by current and previous drought climatic conditions, might result in river intermittence.

The rose diagram reflects the anthropogenic influence on runoff conditions. Therefore, the conclusion can be drawn that its shape can indicate the degree of anthropogenic pressure that results in river intermittence.

The investigation presented in the paper is important from the point of view of water management when catchments experience strong drying conditions due to climate changes and human impact.

## ABBREVIATIONS

| | |
|---|---|
| $f_y$, $f_d$ | frequency of years, days with discharge <0.0005 $m^3 \cdot s^{-1}$ (%) |
| $m_{1A}$, $m_{1S}$, $m_{1W}$ | mean annual, summer, winter total number of zero-flow days (day) |
| $m_{2A}$, $m_{2S}$, $m_{2W}$ | mean annual, summer, winter maximum length of zero-flow event (day) |
| $N_0$ | total number of zero-flow days in the data record (day) |
| $\bar{\rho}$ | sample mean resultant length (–) |
| $r$ | Spearman correlation coefficient (–) |
| $s_{1A}$, $s_{1S}$, $s_{1W}$ | standard deviation of the annual, summer, winter total number of zero-flow days (day) |
| $s_{2A}$, $s_{2S}$, $s_{2W}$ | standard deviation of the annual, summer, winter maximum length of zero-flow event (day) |
| $\bar{\Theta}$, $\bar{\Theta}_0$ | mean date of all zero-flow events, mean date of annual onsets (rad) |
| $X_{iA}$, $X_{iS}$, $X_{iW}$ | annual, summer, winter total number of zero-flow days (if $i$ = 1), maximum length of zero-flow event ($i$ = 2) (day) |

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