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TRENDS IN THE COURSE OF HYDROLOGICAL DROUGHT ON THE VISTULA RIVER (POLAND)

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Abstract. Poland is considered a country with limited water resources compared to other European countries. Hydrological droughts have become increasingly frequent in recent years, occurring on the country's main rivers, including the Vistula. The Vistula is the longest river in Poland (1,022 km), and its basin accounts for 54% of Poland's area. Droughts are most often defined as periods of time during which water flow is below a certain threshold, which can be attributed to water shortages. In this study, the standardized flow index (SRI) was used to determine hydrological drought, which uses average monthly flow values for the multi-year period 1953-2022. SRI values were calculated for eight hydrological stations located along the Vistula River for time scales of 1, 3, 6, 9, and 12 months. Trends across time scales were observed using the Mann-Kendall test, the trend significance test, and Sen's slope estimator. Results indicated that periods of mild drought and precipitation were the most reproducible categories based on the percentage of occurrences. Different parts of the basin experienced droughts on different standard timescales, with this being particularly evident during the period 1988–2022. Decreasing trends were observed throughout the basin. This trend is particularly significant in April, especially at the Torun and Tczew stations located in the river's lower course. The results of this study are expected to contribute to a better understanding of hydrological drought dynamics in the Vistula River Basin, which plays a crucial role in water resources and sustainable livelihoods in the region.
Keywords: hydrological drought, trends, Standardized Runoff Index, Vistula, Poland

1 INTRODUCTION

Drought is a natural phenomenon that affects the environment, society, and various sectors of the national economy, including water supply, agriculture, and industry (Messis et al., 2025). Droughts are an inherent part of climate, which means they occur in various regions of the world and can occur at any time of the year (Meilutytė-Lukauskienė et al., 2024). Droughts are most often considered in four categories: meteorological, agricultural, hydrological, and socioeconomic. Hydrological drought refers to the reduction or scarcity of surface and groundwater resulting from a prolonged lack of rainfall. Among all extreme phenomena, hydrological drought is considered the least understood, despite significant progress in scientific research (Kubiak-Wójcicka and Jamorska, 2022). Unlike other natural hazards, such as floods, the onset and end of drought are not clearly defined, making their characterization difficult. Furthermore, changing climatic conditions, including precipitation and air temperature, influence the variability of hydrological conditions.

Climate change observed in recent years has become a reality. Research conducted in Europe has shown that hydrological droughts will change in Europe with increasing global warming (Cammalleri et al., 2020) and increased precipitation variability. Climate change will accelerate hydrological processes in the landscape, leading to changing spatial and temporal patterns of hydrological drought occurrence. Poland is characterized by low water resources compared to other European countries. These limited water resources, combined with their high variability in time and space, lead to the risk of water deficit. This study focuses on the Vistula River, which is the longest river in Poland, and its basin comprises 54% of the country's area. The main objective of this study is to determine trends in hydrological drought using the Stream Drought Index (SRI) and average monthly flow data from eight stations located along the Vistula River. The analysis was conducted for 1, 3, 6, 9, and 12 months of cumulative rainfall over the 1953-2022 multiyear period, as well as for the 1953-1987 and 1988-2022 multiyear periods. The modified Mann-Kendall test (MMK trend test) and Sen's slope were used to determine drought trends. In addition to determining hydrological drought trends, basic drought parameters such as drought intensity, drought frequency, drought duration, and drought severity were characterized.

2 METHODS

2.1 Study area

The Vistula is the longest river in Poland (1022 km), draining an area of approximately 194,000 km² (Kubiak-Wójcicka and Bąk, 2018). The river originates from the Barania Góra Mountains in the south of Poland and flows into the Baltic Sea near Gdańska. Most of the basin's surface is characterized by plains that do not exceed an altitude of 300 m a.s.l. (Figure 1). The maximum altitude is 2,499 m a.s.l. in the Tatra Mountains, south of the basin. The study area is characterized by annual precipitation varying on average between 500 mm in the north and 1200 mm in the south. Average annual temperatures range from 5°C in the south to 9°C in the center of the basin (Figure 2).

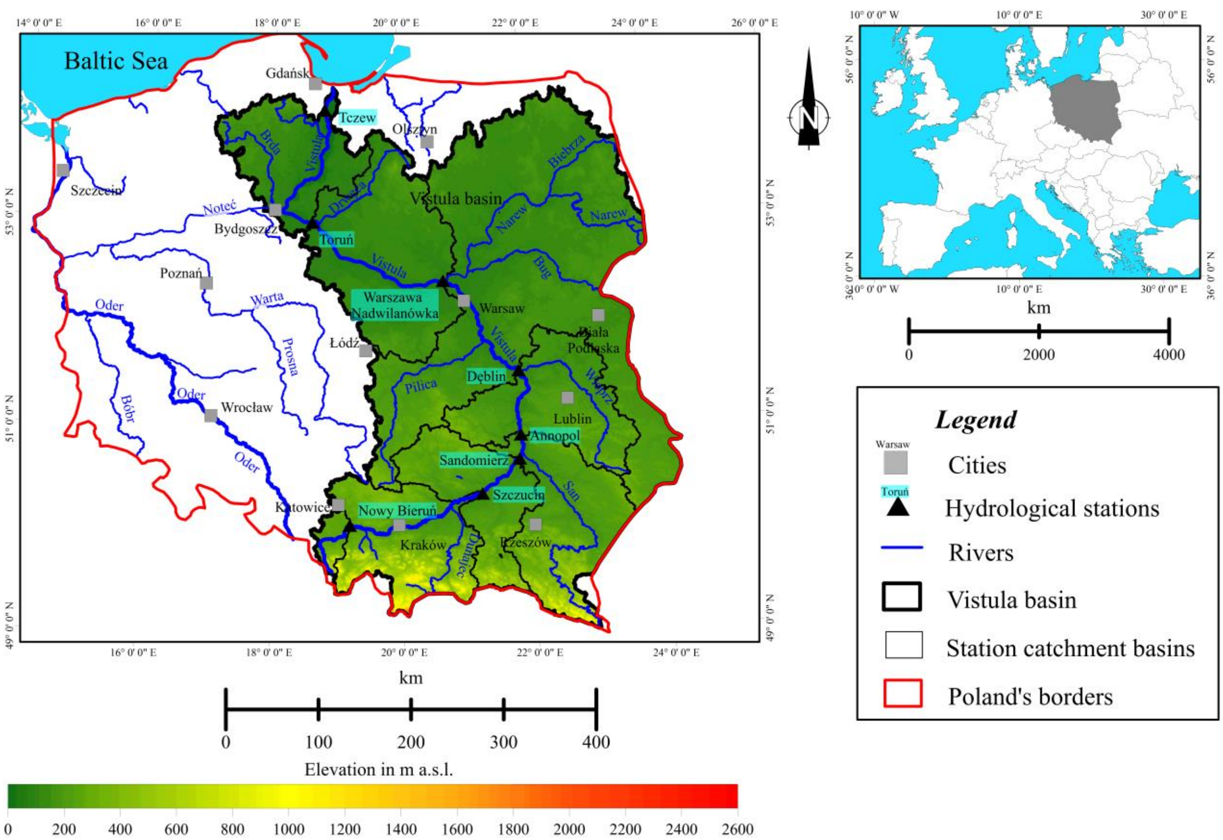

Figure 1. Vistula River Basin

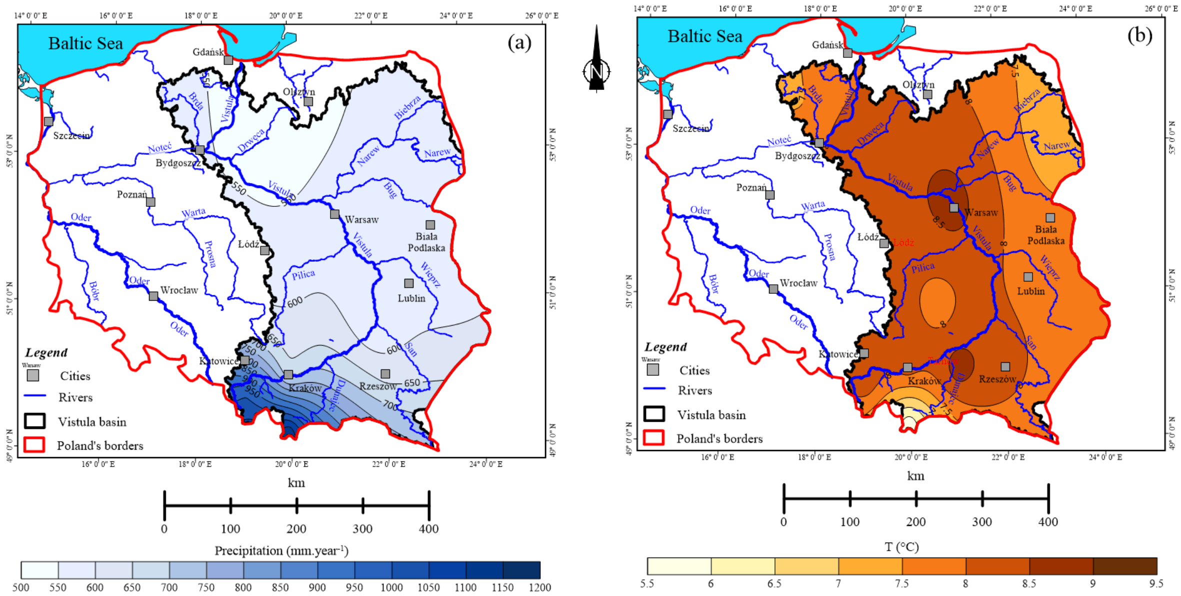

Figure 2. Spatial distribution of climate parameters on an annual basis (1953–2022): (a) average sum of precipitation; (b) average temperature

2.2 Data

Monthly streamflow data are available from the Institute of Meteorology and Water Management-National Research Institute. Data from eight hydrological stations is collected for the period 1953-2022. The average flow of the Vistula increases with the basin area. The coefficient of variation of annual discharges indicates that the greatest variability is observed in the upper reaches of the river, while the lowest variability is observed in the lower reaches of the Vistula.The characteristics of the eight stations collected are summarized in Table 1.

Table 1. The characteristics of the selected hydrological stations

Hydrological station	Area (km²)	Average Altitude (m a.s.l.)	Average annual flow for the multi-year period 1953-2022 (Q in $m^3 \cdot s^{-1}$)	Coefficient of variation of annual flows in the years 1953-2022 (CV in %)
Nowy Bieruń	1776.64	335.96	21.19	28.60
Szczucin	20110.46	411.92	233.42	24.30
Sandomierz	33198.41	348.28	288.43	24.32
Annopol	51448.60	331.75	429.06	24.03
Dęblin	68007.67	297.21	494.58	22.68
Warszawa Nadwilanówka	153934.28	223.76	573.00	22.59
Toruń	179131.99	206.01	965.40	23.01
Tczew	193368.43	197.15	1035.07	21.56

2.3 Standardized Runoff Index (SRI)

The Standardized Runoff Index is developed by Shukla & Wood (2008). It is based on the same concept as that of McKee et al. (1993) used to estimate meteorological drought with SPI (Standardized Precipitation Index). It is used to process flow measurements from a watershed. The SRI measures the anomaly in the runoff generated, which includes both surface runoff and base flow (Shukla and Wood, 2008). This index is used in several research projects around the world (Bayer Altin and Altin 2021; Kubiak-Wójcicka et al., 2021; Ho et al., 2021; Li et al., 2022; Lin et al., 2023; Meresa et al., 2023). The calculation of the index is indicated in the following formula:

$$SRI_{i,j} = \frac{f(Q_{i,j}) - \mu}{\sigma} \quad (1)$$

Where:

$f(Q_{i,j})$: Transformed mean of streamflow (Q) for month i on time scale j;

μ: Mean of normalized values of Q;

σ: Standard deviation of normalized values of Q.

It is noted that the streamflow values are fitted to the logarithmic function.

SRI values were calculated for eight hydrological stations located along the Vistula River for time scales of 1, 3, 6, 9, and 12 months. To define the intensity of periods for each time scale, a drought classification system was introduced based on the SRI: Extremely humid (EH ≥ 2); Severely humid (SH: 1.5 to 1.99); Moderately humid (MH: 1 to 1.49); Close to normal (CN: -0.99 to 0.99); Moderately dry (MD: -1.49 to -1); Severely dry (SD: -1.99 to -1.5); Extremely dry (ED ≤ -2).

2.4 Trend analyses

In this study, we applied the test to the monthly and annual flow series, taking into account the entire period (1953–2022) and two separate periods (1953–1987 and 1988–2022). The same test was applied to SRI values at different time scales (1, 3, 6, 9, and 12 months). The non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975), which is commonly used in hydrological analyses, was used to detect trends in Vistula flows and determine their statistical significance. The Mann-Kendall Z-statistic and the directional coefficient β expressed by the Theil-Sen estimator (Theil, 1950; Sen, 1968) were calculated for periods covering every possible combination of starting and ending year for the multi-year period under study. The 35-year period used in hydrological calculations (Kubiak-Wójcicka, 2020) was taken as the length of the calculation period.

The Mann-Kendall S-statistic was calculated using the formula:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \quad (2)$$

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \quad (3)$$

where:

x_j and x_k-values of the variable in individual years j and k, where j > k,

n - number of years.

The S statistic tends to move rapidly towards normality, and for n > 10 the statistic has an approximately normal distribution with mean 0 and variance described by the formula:

$$\operatorname{Var}(S) = [n(n-1)(2n+5)]/18 \quad (4)$$

The standardised test statistic Z was calculated using the formula:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (5)$$

In the Mann-Kendall test, the null hypothesis is that there is no significant trend in the data series. A trend is significant if the null hypothesis cannot be accepted. The region of acceptance at the significance level α = 0.05 is defined by the interval -1.96 ≤ Z ≤ 1.96 (no significant trend), while the region of rejection is given by Z < -1.96 (significant decreasing trend) and Z> 1.96 (significant increasing trend), where Z is the standardised test statistic.

The directional coefficient β expressed by the Theil-Sen estimator (β) was calculated from the formula:

$$\beta = \operatorname{Median}((x_j - x_k)/(j - k)) \quad (6)$$

A positive value of β indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

3 RESULTS

3.1 Variability of drought using SRI

The frequency of drought at different time scales is summarized in the table 2. We found that months with near-normal drought conditions (CN) occurred more frequently (35%-38% throughout the period). A significant increase is observed in 1988-2022 across all time scales and across the eight hydrological stations, with the exception of extreme drought events, which have decreased. The increase in the frequency of moderate droughts between 1988 and 2022 is very significant, particularly over a 12-month period at Dęblin (from 7.62 in 1953-1987 to 18.33 % in 1988-2022), Warszawa Nadwilanówka (from 8.33 in 1953-1987 to 18.10 % in 1988-2022), and Toruń (from 6.67 in 1953-1987 to 13.57 % in 1988-2022). Severe droughts occur repeatedly at all stations, but with greater frequency in the period 1988–2022. They vary between 2% and 5% throughout the study period. Their occurrence is greater on a 6–9-month scale, which corresponds well with seasonal hydrological deficits and prolonged droughts. Extreme droughts remain rare (<2%) at most stations and periods. However, slightly more frequent occurrences are noted in the early period (1953–1987), particularly in Nowy Bieruń and Sandomierz (~3–5%). In recent years, they have tended to decrease, which may reflect a shift toward "moderate" and "severe" droughts rather than extreme ones.

3.2 Drought trend analysis

The Mann–Kendall test with Sen's slope applied to the Standardized Runoff Index (SRI) highlighted marked spatial and temporal differences in hydrological drought evolution across the Vistula River Basin (Table 3). In the upstream stations (Nowy Bieruń, Szczucin, and Sandomierz), no significant trends were observed during the early period (1953–1987). However, in the recent decades (1988–2022), these stations exhibited significant positive trends at most timescales, with Sen's slopes increasing with the accumulation period (up to 0.0024 at 12 months). Positive SRI trends correspond to reduced drought intensity and/or increased runoff, suggesting that the upper basin has become less drought-prone since the late 1980s.

In contrast, midstream stations (Annopol, Dęblin, and partly Warszawa Nadwilanówka) displayed significant long-term negative SRI trends, particularly at 6–12 month scales for the entire 1953–2022 period. Although trends within the individual subperiods were weaker, the cumulative negative slopes indicate an intensification of hydrological drought conditions over the long term.

The downstream stations (Toruń and Tczew) showed the most striking regime shift. Over the full 1953–2022 period, both exhibited strong and significant negative SRI trends across all timescales, with Sen's slopes ranging from –0.0003 to –0.0006. When split into subperiods, however, the first period (1953–1987) was dominated by significant positive trends (up to 0.0024), while the second period (1988–2022) showed negative but mostly non-significant slopes. This inversion indicates that the lower basin experienced a transition from improving to worsening drought conditions after the late 1980s.

Table 2. Occurrence of hydrological drought (in %) by class at different time scales (1, 3, 6, 9, and 12 months)

Drought class		CN (0 to -0.99)			MD (-1.0 to -1.49)			SD (-1.5 to -1.99)			ED (<=-2.0)		
Stations	Time scale (months)	1953-2022	1953-1987	1988-2022	1953-2022	1953-1987	1988-2022	1953-2022	1953-1987	1988-2022	1953-2022	1953-1987	1988-2022

Nowy Bieruń	1	37.74	35.71	39.76	10.36	11.43	9.29	2.50	3.57	1.43	1.79	2.86	0.71
	3	33.81	34.76	32.86	9.17	10.00	8.33	5.36	4.52	6.19	1.43	2.62	0.24
	6	32.02	31.19	32.86	10.83	10.48	11.19	3.57	3.10	4.05	2.26	3.57	0.95
	9	32.14	32.14	32.14	7.74	5.71	9.76	5.83	5.48	6.19	2.38	3.81	0.95
	12	30.00	28.33	31.67	9.40	6.19	12.62	3.10	3.10	3.10	3.93	5.24	2.62
Szczucin	1	37.86	38.33	37.38	12.14	9.05	15.24	2.98	3.10	2.86	0.71	1.19	0.24
	3	34.64	34.29	35.00	10.60	10.48	10.71	4.88	3.10	6.67	0.95	1.43	0.48
	6	36.19	36.90	35.48	11.79	10.71	12.86	4.05	2.38	5.71	0.71	1.19	0.24
	9	34.64	32.38	36.90	12.74	12.62	12.86	4.05	2.86	5.24	0.95	1.43	0.48
	12	32.14	27.86	36.43	12.50	11.19	13.81	4.64	4.76	4.52	0.60	0.71	0.48
Sandomierz	1	36.90	36.67	37.14	12.50	10.00	15.00	3.33	4.05	2.62	0.60	0.95	0.24
	3	34.40	34.05	34.76	10.83	10.24	11.43	3.93	3.10	4.76	1.19	1.67	0.71
	6	35.24	35.48	35.00	11.79	10.95	12.62	4.17	2.86	5.48	0.83	1.43	0.24
	9	34.52	33.10	35.95	12.74	11.67	13.81	3.21	2.62	3.81	0.83	1.67	0.00
	12	32.26	29.76	34.76	12.50	9.76	15.24	3.57	3.33	3.81	1.07	2.14	0.00
Annopol	1	35.83	33.10	38.57	12.02	12.14	11.90	3.33	2.62	4.05	0.95	1.67	0.24
	3	34.52	34.29	34.76	11.55	8.81	14.29	4.64	5.48	3.81	0.95	1.19	0.71
	6	35.00	33.10	36.90	12.86	11.43	14.29	3.81	3.57	4.05	0.71	0.95	0.48
	9	34.52	33.81	35.24	12.38	9.05	15.71	3.81	3.33	4.29	0.83	1.67	0.00
	12	34.76	31.90	37.62	13.33	9.76	16.90	3.81	3.81	3.81	0.24	0.48	0.00
Dęblin	1	37.14	35.48	38.81	12.50	10.95	14.05	2.62	3.10	2.14	0.83	1.43	0.24
	3	34.88	34.05	35.71	11.79	9.76	13.81	3.81	4.52	3.10	1.43	1.90	0.95
	6	35.24	32.62	37.86	13.45	11.19	15.71	2.98	3.10	2.86	0.71	1.43	0.00
	9	35.71	35.24	36.19	12.50	8.57	16.43	3.10	3.33	2.86	0.95	1.90	0.00
	12	34.64	34.29	35.00	12.98	7.62	18.33	3.21	3.33	3.10	0.71	1.43	0.00

Warszawa Nadwilanówka	1	38.81	39.05	38.57	10.83	8.81	12.86	3.93	5.00	2.86	1.19	1.90	0.48
	3	35.95	35.95	35.95	10.83	8.81	12.86	4.05	4.76	3.33	1.31	1.90	0.71
	6	32.86	33.10	32.62	12.14	9.76	14.52	4.29	5.48	3.10	0.60	1.19	0.00
	9	34.76	33.10	36.43	12.50	10.00	15.00	3.33	4.05	2.62	0.83	1.67	0.00
	12	34.52	32.14	36.90	13.21	8.33	18.10	3.57	5.00	2.14	0.71	1.43	0.00
Toruń	1	36.67	34.29	39.05	12.02	10.00	14.05	3.21	3.81	2.62	1.07	1.19	0.95
	3	38.10	34.05	42.14	9.29	7.62	10.95	4.76	4.29	5.24	1.19	1.43	0.95
	6	35.36	28.33	42.38	11.55	10.95	12.14	4.64	4.05	5.24	0.48	0.71	0.24
	9	35.36	30.00	40.71	11.43	8.81	14.05	5.36	5.24	5.48	0.36	0.24	0.48
	12	36.31	31.67	40.95	10.12	6.67	13.57	5.60	6.43	4.76	0.00	0.00	0.00
Tczew	1	36.55	33.57	39.52	11.67	10.48	12.86	3.81	4.29	3.33	0.95	0.95	0.95
	3	36.90	33.10	40.71	8.93	6.90	10.95	5.12	5.71	4.52	1.43	1.43	1.43
	6	35.24	27.14	43.33	10.48	11.19	9.76	5.48	5.00	5.95	0.48	0.24	0.71
	9	34.29	26.67	41.90	12.14	10.48	13.81	4.76	5.48	4.05	0.48	0.24	0.71
	12	34.88	29.29	40.48	12.50	11.19	13.81	4.88	3.57	6.19	0.71	0.95	0.48

Table 3. Results of the Mann-Kendall test and Sen's slope for SRI series' at different time scales (1, 3, 6, 9 and 12 months) during the periods 1953-2022, 1953-1987 and1988-2022

Stations	Time scale (months)	1953-2022		1953-1987		1988-2022	
		P. value	Sen's slope	P. value	Sen's slope	P. value	Sen's slope
Nowy Bieruń	1	0.0847	0.0002	0.5851	0.0002	**0.0232**	**0.0009**
	3	0.0876	0.0003	0.8461	0.0001	**0.0001**	**0.0015**
	6	0.2193	0.0002	0.9149	0.0001	**<0.0001**	**0.0019**
	9	0.3809	0.0001	0.9492	<0.0001	**<0.0001**	**0.0021**
	12	0.4758	0.0001	0.8745	0.0001	**<0.0001**	**0.0024**
Szczucin	1	0.5609	-0.0001	0.1100	0.0006	0.4848	0.0003
	3	0.8542	<0.0001	0.0960	0.0007	0.0756	0.0007
	6	0.9201	<0.0001	**0.0203**	**0.0010**	**0.0089**	**0.0010**
	9	0.5576	-0.0001	**0.0342**	**0.0009**	**0.0021**	**0.0012**
	12	0.1922	-0.0002	**0.0535**	**0.0008**	**0.0011**	**0.0013**
Sandomierz	1	0.8797	<0.0001	0.1848	0.0005	0.2984	0.0004
	3	0.9216	<0.0001	0.2583	0.0005	**0.0334**	**0.0008**

	6	0.9979	<0.0001	0.1433	0.0006	**0.0049**	**0.0011**
	9	0.7171	-0.0001	0.1926	0.0006	**0.0007**	**0.0013**
	12	0.3776	-0.0001	0.2123	0.0006	**0.0004**	**0.0014**
Annopol	1	0.2088	-0.0002	0.3458	0.0004	0.8404	-0.0001
	3	0.1414	-0.0002	0.5008	0.0003	0.7613	0.0001
	6	**0.0492**	**-0.0003**	0.3305	0.0005	0.6107	0.0002
	9	**0.0084**	**-0.0004**	0.3078	0.0005	0.7089	0.0001
	12	**0.0020**	**-0.0005**	0.3357	0.0005	0.5535	0.0002
Dęblin	1	0.2400	-0.0002	0.4461	0.0003	0.5277	-0.0002
	3	0.1410	-0.0002	0.7271	0.0002	0.8644	-0.0001
	6	**0.0422**	**-0.0003**	0.6098	0.0002	0.9382	<0.0001
	9	**0.0115**	**-0.0004**	0.5662	0.0003	0.8534	0.0001
	12	**0.0034**	**-0.0004**	0.5137	0.0003	0.7465	0.0001
Warszawa Nadwilanówka	1	0.9864	<0.0001	0.1240	0.0006	0.4551	-0.0003
	3	0.4337	-0.0001	0.5410	0.0003	0.6353	-0.0002
	6	0.5059	-0.0001	0.5605	0.0003	0.8518	-0.0001
	9	0.1108	-0.0002	0.5728	0.0002	0.8665	-0.0001
	12	0.0635	-0.0003	0.4729	0.0003	0.9919	<0.0001
Toruń	1	0.0666	-0.0003	**0.0101**	**0.0011**	0.1935	-0.0005
	3	**0.0086**	**-0.0004**	**0.0180**	**0.0010**	0.1926	-0.0005
	6	**0.0008**	**-0.0005**	**0.0078**	**0.0012**	0.2491	-0.0004
	9	**0.0001**	**-0.0006**	**0.0089**	**0.0012**	0.3403	-0.0004
	12	**0.0173**	**-0.0003**	**0.0017**	**0.0015**	0.4271	0.0008
Tczew	1	0.0935	-0.0002	**0.0002**	**0.0016**	0.0982	-0.0006
	3	**0.0201**	**-0.0003**	**0.0002**	**0.0016**	0.0915	-0.0006
	6	**0.0068**	**-0.0004**	<**0.0001**	**0.0019**	0.1712	-0.0005
	9	**0.0015**	**-0.0005**	<**0.0001**	**0.0020**	0.2310	-0.0004
	12	**0.0009**	**-0.0005**	<**0.0001**	**0.0024**	0.3445	-0.0004

* Values in bold are statistically significant

4 DISCUSSION

The combined analysis of drought frequency and trend behavior across the Vistula River Basin (1953–2022) reveals a complex, spatially variable evolution of hydrological drought regimes. Notably, the region has transitioned from sporadic extreme droughts toward more persistent moderate and severe events, with pronounced basin segmentation in upstream, midstream, and downstream zones.

Near-normal conditions (CN) prevailed in approximately 35–38% of months across the study period. From 1988 onward, there was a statistically significant surge in moderate and severe droughts, particularly at multi-month scales, while extreme droughts became less frequent. This pattern—shifting from rarer but more severe events to more persistent but moderate stress—is especially crucial for water resource management due to the cumulative socio-economic and ecological impacts of recurring deficits.

This shift aligns with broader trends across Europe: since the 1970s, meteorological and hydrological drought frequency have increased in many regions, including Poland, influenced by climate change (e.g., precipitation deficits and heightened evapotranspiration) (Kubiak-Wójcicka and Bąk, 2018). The drop in extreme droughts relative to moderate/severe events may also mirror evolving climatic forcing's, with slow-onset droughts becoming more dominant in the hydrological response.

The spatial analysis of drought trends across the Vistula River Basin highlights marked contrasts between upstream, midstream, and downstream regions. Research conducted by Baran-Gurgul and Wałega (2025) confirmed that hydrological drought has a strong spatial distribution and five main regions with homogeneous drought duration and volume can be distinguished. At hydrological stations located upstream (Nowy Bieruń, Szczucin, Sandomierz), no significant changes were observed prior to 1987, but the emergence of positive SRI trends after 1988 suggests improved runoff conditions and reduced drought exposure, possibly due to localized increases in precipitation and groundwater buffering (Stahl et al., 2010; Spinoni et al., 2017). By contrast, the midstream stations (Annopol, Dęblin, Warszawa Nadwilanówka) exhibited persistent negative long-term SRI trends, particularly over 6–12 month scales, reflecting intensifying drought severity and increased vulnerability to cumulative precipitation deficits (Kubiak-Wójcicka and Bąk, 2018). This is confirmed by research conducted by Krawczyk (2025) for the multiannual period 1966-2020, which showed that meteorological drought particularly affects Central and South-Western Poland, especially in April and from June to August. The downstream reaches (Toruń, Tczew) reveal the most striking regime shift: strong positive trends during 1953–1987 gave way to negative slopes after 1988, accompanied by a higher frequency of moderate droughts. This reversal points to growing hydrological stress in the lower basin, likely influenced by reduced snowmelt inputs, altered river regulation, and higher evapotranspiration under warming conditions (Kubiak-Wójcicka and Bąk, 2018, Kubiak-Wójcicka, 2020). However, warmer winters have shortened the snow accumulation season and reduced snowpack, leading to weaker and earlier melt peaks (Beniston, 2012). As a result, downstream flows are increasingly exposed to summer precipitation variability, amplifying the occurrence of prolonged hydrological droughts.

5 CONCLUSION

This study provides a comprehensive assessment of hydrological drought dynamics in the Vistula River Basin over the period 1953–2022 using the Standardized Runoff Index (SRI). The findings highlight a clear spatial and temporal differentiation in drought evolution along the river system. While the upstream basin has shown signs of recovery with reduced drought intensity since the late 1980s, midstream and downstream sections experienced a worsening of drought conditions, particularly at longer timescales. A general shift was observed from rare extreme droughts toward more persistent moderate and severe events, underscoring a transition toward chronic hydrological stress.

The regime shift in the lower Vistula after the 1980s appears closely linked to broader climatic drivers, including reduced snow accumulation, earlier snowmelt peaks, and enhanced evapotranspiration under warming conditions. This change has amplified the dependence of downstream flows on variable summer precipitation, heightening water scarcity risks. These spatial contrasts emphasize the need for regionally differentiated water management strategies, as the upper, middle, and lower parts of the basin are subject to distinct drought dynamics.

Overall, the results underline that hydrological drought in the Vistula Basin is not only intensifying but also transforming in character. This evolving drought regime poses significant challenges for water resources, ecosystems, and socio-economic activities dependent on the river. Improved understanding of these dynamics is essential for adapting water management and resilience strategies to ongoing climatic and hydrological changes in Poland and Central Europe.

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