

The evaluation of the incidence of extreme monthly precipitation totals across central-eastern Poland (1971–2020)

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Abstract: This study investigates the temporal and spatial variability of extreme monthly precipitation sums in central-eastern Poland over the period 1971–2020. The analysis is based on records from six IMGW-PIB stations over a 50-year span. Monthly precipitation totals were examined using the Mann–Kendall trend test in conjunction with Sen’s slope estimator. Extreme value behaviour was assessed through the 95th and 99th percentiles and extreme value analysis (EVA) employing the Gumbel distribution. To identify common modes of variability, principal component analysis (PCA) was applied. The findings reveal substantial variability in monthly precipitation totals. The most pronounced extremes occurred in the summer months (July and August), whereas spring and autumn exhibited a lower frequency of extreme events. The highest risk of extreme precipitation and the greatest projected rainfall values (T2) were observed in Białowieża, Legionowo, and Pułtusk. Decadal analysis highlighted fluctuations ranging from deficit periods in the 1980s to relative stabilisation in the most recent decade (2011–2020). The Mann–Kendall test did not identify statistically significant trends for most months and stations, except for a notable increase in May precipitation at Szepietowo. Results of PCA confirmed a clear distinction between moderate extremes (P95) and the most intense episodes (P99), underscoring the dominant role of spring-summer P99 extremes in shaping overall precipitation variability across the region.

Keywords: atmospheric precipitation, extreme values, long-term period, spatial distribution, variability

INTRODUCTION

Extreme precipitation totals pose a significant threat to water management, infrastructure, and agriculture, and have significant social and economic consequences (Kalbarczyk and Kalbarczyk, 2024). Extreme weather events are highly likely to undergo change in the future (Wang, Zwiers and Swail, 2004; Kharin and Zwiers, 2005). In Poland, an increasing frequency of such events has been observed, including a rise in the number of days with heavy precipitation during the winter and autumn-winter months (Szwed, 2019).

Nidzgorska-Lencewicz, Mąkosza and Czarnecka (2024) demonstrated that, between 1991 and 2020, the West Pomeranian Voivodship exhibited considerable spatial variability in annual

precipitation totals, ranging from values below 600 mm in the western counties to more than 800 mm in the north-eastern part of the region. In most poviats¹, changes in the precipitation regime were statistically insignificant, although the greatest variability was observed in spring. Significant negative trends in spring precipitation were identified in the poviats of Białogard, Kamień, Sławno, and Koszalin, while a decline in the proportion of spring precipitation within the annual total was recorded across an even broader area of the region.

The analysis of extreme monthly precipitation totals can reveal finer changes in spatial and seasonal distribution that

¹ Powiat (Pl: powiat) – the intermediate level of the Polish administrative system.

remain undetectable in annual-scale assessments (Wibig and Jędruszkiewicz, 2025). Extreme monthly precipitation totals are defined as cases in which the total precipitation for an entire month exceeds a locally high threshold (e.g. the 95th–99th percentile or specific absolute values). Such totals integrate the influence of both the number of wet days and the intensity of individual events (Liu *et al.*, 2024). It is important to investigate this parameter from the perspective of hydrology, flood risk management, and agricultural planning, as a single month with extreme precipitation can have long-lasting impacts (Groisman *et al.*, 2005).

The distribution of extremes is strongly regional: the southern and south-western parts of Poland (the Carpathians, foothills, and the Sudetes region) reveal a higher frequency of extreme events than the north-eastern areas of the country. Long-term studies reveal a complex, non-stationary pattern of changes in extreme monthly precipitation totals in Poland (Kalbarczyk and Kalbarczyk, 2024). Recent multi-station analyses (covering periods up to 2020–2024) indicate that changes are not uniform across the annual cycle – certain months (particularly January and February) show significant increases in precipitation totals, whereas others (e.g. April, June, November) more frequently exhibit decreases (Wibig and Jędruszkiewicz, 2025). Earlier analyses (e.g. for the period 1951–2006) showed regional decreases in extremes in some months and increases in others, indicating the absence of a simple, universal upward trend for the entire country. More recent studies, based on longer and more up-to-date series and alternative extreme indices, consistently report increased variability and, in some indicators, an intensification of extremes (Pińskwar *et al.*, 2019).

Local factors, e.g. topography and the availability of moisture from Mediterranean regions, also influence the direction and spatial pattern of trends (Barcikowska *et al.*, 2020; Diodato, Seftigen and Bellocchi, 2025). Extreme monthly precipitation totals may increase as a result of a greater number of wet days in a month, an increase in the intensity of individual heavy precipitation days, or a combination of both. Polish studies indicate that both seasonal mechanisms (e.g. summer convection) and synoptic-scale cycles contribute to these proportions (Michalska, 2001).

Ziernicka-Wojtaszek and Kopcińska (2020) report that the lowest precipitation occurred in February, while the highest was recorded in July. The seasonal distribution amounted to: 22, 37, 23 and 17% in spring, summer, autumn and winter, respectively, with distinctive spatial patterns characteristic of each season. While numerous studies have investigated extreme daily precipitation (Szalińska and Otop, 2012; Diemientew, 2018; Walkowska, Pórolniczak and Kolendowicz, 2022), the structure of extremes at the monthly scale and their regional differentiation remain understudied. The monthly perspective represents a less frequently employed yet complementary approach, as monthly precipitation totals integrate both the number of days with rainfall and the intensity of individual events. This enables the identification of phenomena that have no equivalent in daily analyses, where single, short-lived events determine the classification of an occurrence as extreme. By contrast, extreme monthly totals may also arise as a result of the accumulation of days with moderately intensive precipitation. The rationale for this study stems from the growing need for adaptation to the impacts of

climate change and the limited number of investigations focusing on monthly precipitation extremes and their spatial distribution.

The aim of the present study is to evaluate the temporal of extreme monthly precipitation totals in central-eastern Poland. Specifically, the objectives are to identify months with extreme precipitation totals, to examine long-term trends in the frequency and intensity of monthly extremes, and to analyse the spatial distribution of extreme precipitation in order to identify particularly vulnerable areas.

MATERIALS AND METHODS

The study was conducted in central-eastern Poland. The boundaries of the region were defined based on physical-geographical criteria (Kondracki, 2002), incorporating the coverage of meteorological stations with complete data series. This area is situated within a transitional zone between maritime and continental climates, resulting in considerable temporal and spatial variability in weather conditions, particularly in precipitation and air temperature. From a physical-geographical perspective, the study area belongs to the Mazovian Lowland and, in part, to Podlasie. Central-eastern Poland exhibits a temperate warm transitional climate, with marked continental influences. The mean annual air temperature in the region is approximately 8.0–8.5°C, while the annual precipitation total ranges between 500 and 600 mm – some the lowest values recorded in Poland (Błaś and Ojrzyńska, 2024). The highest precipitation occurs in the summer months (June–August), while the minimum is observed in winter and early spring. The notable spatial-temporal variability of precipitation results in the region frequently experiencing both drought periods and episodes of heavy rainfall leading to local flooding.

The study utilised meteorological data covering the period 1971–2020, providing a sufficiently long time series for the evaluation of climatic trends. The primary data source consisted of monthly precipitation totals from meteorological stations of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) situated in Siedlce, Włodawa, Legionowo, Pułtusk, Szepietowo, and Białowieża (Fig. 1). The study focused exclusively on the months of the growing season (from April to October), as this period corresponds to greatest variability and dynamics of precipitation in central-eastern Poland and carries the highest hydrological and economic significance. Extreme monthly precipitation totals were defined as values exceeding the 95th percentile of the distribution of monthly precipitation totals for a given station over the entire study period. In addition, the 99th percentile threshold was also analysed, denoting the most extreme months. The 95th percentile threshold enables the identification of months with distinctly elevated precipitation totals, whereas the 99th percentile captures the rarest events, corresponding to approximately 1% of the highest values in the entire measurement series. The application of both thresholds allows for the analysis of “moderate extremes” as well as the most severe episodes, thereby facilitating a comprehensive assessment of the nature and structure of variability in monthly precipitation totals within the study region. The choice of the 95th and 99th percentile thresholds was guided by international standards in the investigation of extreme climatic

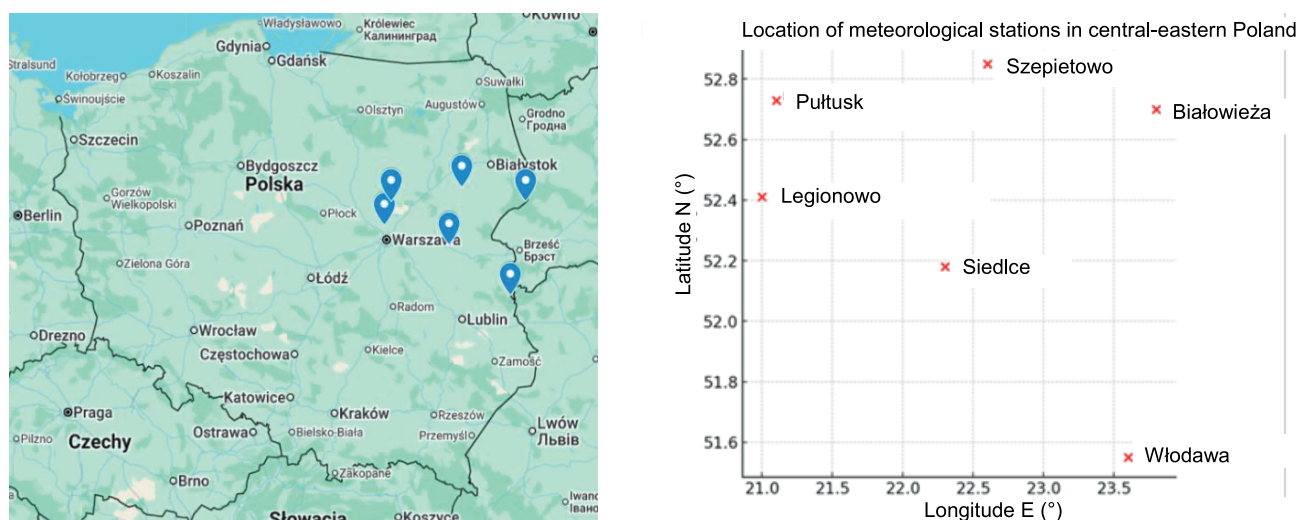


Fig. 1. Meteorological stations in central-eastern Poland; source: own elaboration

phenomena, such as those established by the ETCCDI (Expert Team on Climate Change Detection and Indices).

To assess the direction and statistical significance of changes in monthly precipitation totals, the non-parametric Mann-Kendall (MK) trend test was employed. This method is widely used for investigating hydrological and meteorological time series, facilitating the detection of monotonic trends without assuming normality of the distribution or linearity of the variables. Statistical significance was assessed at $\alpha = 0.05$ level. The analysis was performed separately for each month of the growing season (April–October) and for each meteorological station. This approach enabled both seasonal and spatial differentiation of potential trends to be identified. To assess the magnitude of trend changes (positive or negative) in the analysed time series, Sen's slope estimator (Q_s) was calculated, which remains robust even in the presence of extreme months (exceptionally wet or dry).

In order to deepen the analysis, an extreme value analysis (EVA) was conducted for each station using the Gumbel distribution (GEV Type I). Empirical non-exceedance probabilities were calculated by means of the Weibull method. The model parameters – slope (β) and intercept (α) – were estimated using Gumbel linear regression, and the goodness of fit was evaluated with the coefficient of determination R^2 (RSQ). Subsequently, based on the estimated parameters, projected rainfall levels were calculated for return periods of $T = 2, 5, \text{ and } 10$ years.

To explore the major patterns of covariability, principal component analysis (PCA) was conducted using a correlation matrix of the variables (Rodríguez-Sánchez *et al.*, 2015). Calculations were executed in the Statistica 13.0 software package, and the results were presented as a biplot.

RESULTS AND DISCUSSION

PRECIPITATION CHARACTERISTICS OF THE REGION

Analysis of measurement 1971–2020 data covering the period from April to October, demonstrated significant variability in monthly precipitation totals across the stations in central-eastern Poland (Tab. 1). Mean monthly precipitation values at individual

stations ranged between approximately 34 mm to 41 mm in April, 68–87 mm in July, and 39–50 mm in October. The highest monthly precipitation totals, reaching extreme values at individual stations, reflect marked local differences in climatic conditions.

The highest precipitation totals during the growing season occurred in Białowieża (445 mm), where maximum monthly totals ranged between 94 mm in April to 238 mm in October. At other stations, the highest monthly totals varied between 76 mm (Szebietowo, April) and 319 mm (Legionowo, July). Minimum monthly precipitation totals also displayed considerable variation. In April, some stations recorded as little as 1–8 mm, suggesting drought periods or nearly rainless early-spring days. During the summer and autumn months, minimum totals were higher, reflecting the seasonal nature of precipitation in the region. The variability analysis demonstrates the highest relative heterogeneity of monthly precipitation totals in October, with coefficients of variation exceeding 60% in Pułtusk and Szebietowo, while in the summer months variability was moderate, generally below 50%.

LONG-TERM TRENDS

The analysis of decadal totals of extreme precipitation revealed marked temporal differentiation across the five decades examined. The highest values were recorded in the period 1971–1980, particularly in Białowieża and Szebietowo, indicating an especially intense character of precipitation during this period. The subsequent decade, 1981–1990, was characterised by the lowest values across all stations, suggesting a general weakening of extreme events. In 1991–2000 and 2001–2010, a renewed increase in precipitation totals was observed, although the values remained spatially differentiated, with the strongest growth noted in Włodawa and Szebietowo. The final decade, 2011–2020, brought another intensification of extremes, though without reaching the record-breaking levels of the 1970s. Variability between decades proved more pronounced than differences between stations, indicating that temporal factors exert a dominant influence on the character of extreme precipitation in the region (Fig. 2).

For each of the seven months (April–October) and for all six stations, the non-parametric Mann-Kendall test was employed to identify monotonic trends in monthly precipitation totals during

Table 1. Maximum, minimum, and mean monthly precipitation totals, and their coefficients of variation, in central-eastern Poland for the period 1971–2020

Station	April	May	June	July	August	September	October	Sum/mean April-October
Maximum (mm)								
Siedlce	91	153	194	204	257	167	180	178
Włodawa	91	174	221	253	269	126	243	197
Legionowo	111	176	239	319	233	145	166	198
Pułtusk	114	184	197	332	183	146	178	191
Szepietowo	76	149	168	198	189	235	218	176
Białowieża	94	186	209	205	219	171	238	189
Minimum (mm)								
Siedlce	6	14	16	8	3	14	2	9
Włodawa	8	13	5	12	3	8	5	8
Legionowo	2	15	6	5	5	10	3	7
Pułtusk	1	21	9	11	4	3	3	7
Szepietowo	2	5	6	7	3	8	1	5
Białowieża	3	5	18	9	4	8	3	7
Mean (mm)								
Siedlce	35	57	73	70	65	54	40	395
Włodawa	37	58	70	81	63	53	40	402
Legionowo	35	54	70	75	64	50	42	391
Pułtusk	34	57	77	75	64	51	40	399
Szepietowo	34	57	66	68	64	59	39	395
Białowieża	41	64	77	87	67	58	50	445
Coefficient of variation (%)								
Siedlce	46	40	40	44	42	51	62	46
Włodawa	37	38	44	43	44	47	60	45
Legionowo	52	34	40	45	46	53	60	47
Pułtusk	53	36	47	51	41	50	64	49
Szepietowo	50	38	40	41	48	58	64	48
Białowieża	44	37	41	39	51	48	58	45

Source: own study.

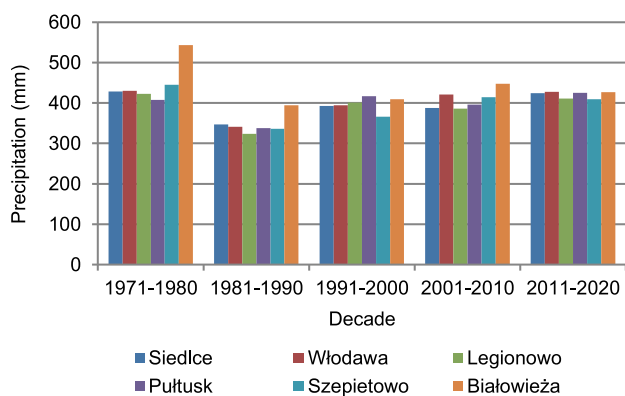


Fig. 2. Precipitation totals by decade for the period 1971–2020 in central-eastern Poland; source: own study

the growing season. The results indicate no statistically significant monotonic trends (across the set of stations and months analysed) – Table 2. The only statistically significant change ($p < 0.05$) was noted for May at the Szepietowo station ($S = 268$, $z = 2.233$, $p = 0.0255$), indicating a pronounced increase in May precipitation totals over the study period. In most cases, the p -values are greater than 0.05, indicating that the observed changes represent tendencies rather than statistically significant trends. The greatest increase in Q_s values was recorded in May (e.g., Siedlce: $Q_s = 0.382$; Włodawa: $Q_s = 0.409$; Legionowo: $Q_s = 0.388$; Szepietowo: $Q_s = 0.540$). This suggests that May is the month in which the rate of increase in precipitation is the highest. The most negative Q_s values, indicating a downward tendency, occurred in June (for all stations except Szepietowo) and September (for most stations). The largest decline in precipitation

Table 2. Evaluation of trends in monthly precipitation totals based on the Mann–Kendall test

Station	Parameter	April	May	June	July	August	September	October
Siedlce	S	109	174	50	–21	42	–136	3
	z	0.903	1.447	–0.844	–0.167	0.342	–1.129	0.016
	p	0.366	0.147	0.398	0.867	0.731	0.258	0.986
	Qs	0.175	0.382	–0.285	–0.071	0.142	–0.263	0.002
Włodawa	S	31	200	–58	–5	113	–115	139
	z	0.250	1.664	–0.476	–0.033	0.936	–0.953	1.154
	p	0.801	0.095	0.633	0.973	0.348	0.340	0.248
	Qs	0.031	0.409	–1.42	–0.028	0.318	–0.304	0.263
Legionowo	S	–125	207	–129	–65	87	–8	93
	z	–1.037	1.723	–1.070	–0.535	0.719	–0.058	0.769
	p	0.299	0.084	0.284	0.592	0.471	0.953	0.441
	Qs	0.210	0.388	–0.384	–0.193	0.111	0.002	0.200
Pułtusk	S	–42	198	–29	55	58	–25	72
	z	–0.342	1.647	–0.234	0.451	0.476	–0.200	0.593
	p	0.731	0.099	0.814	0.651	0.633	0.840	0.552
	Qs	–0.095	0.357	–0.09	0.210	0.143	–0.055	0.181
Szepietowo	S	50	268	50	–21	147	–32	25
	z	–0.066	2.233	0.058	–0.167	1.221	–0.259	0.200
	p	0.946	0.025*	0.953	0.867	0.221	0.795	0.840
	Qs	0.002	0.540	0.238	–0.071	0.475	–0.091	0.043
Białowieża	S	–151	79	–163	–28	41	–137	–73
	z	–1.254	–1.355	–1.355	–0.225	0.334	–1.137	–0.602
	p	0.209	0.514	0.175	0.821	0.737	0.255	0.546
	Qs	–0.300	0.178	–0.542	0.080	0.142	–0.411	–0.181

Explanations: S = Mann–Kendall test statistic, z = standardised value of the test statistic, p = probability value (p-value), * = statistical significance at $p \leq 0.05$, Qs = Sen's slope estimate.

Source: own study.

was observed in June at the Białowieża station ($Q_s = -0.542$) and at Włodawa ($Q_s = -1.42$).

Overall, small and statistically insignificant S values (both positive and negative) are predominant, suggesting the absence of a uniform, strong directional trend in monthly precipitation totals in the study area.

Regional analyses for Poland reveal a complex and irregular pattern of changes in the precipitation regime. The results obtained here are in alignment with the broader context of observed and projected changes in precipitation extremes in Europe and Poland. Synthesis reports (IPCC) mention an increase in the intensity and frequency of extreme precipitation in many regions of the world, including Europe, resulting from atmospheric warming and the increased capacity of air to hold water vapour. These changes are seasonally differentiated and locally heterogeneous (IPCC, 2007). Case studies for the central-eastern region of Poland confirm seasonal differences in precipitation totals and increases in certain months in recent decades (Mikołajewski *et al.*, 2025).

ASSESSMENT OF EXTREME PRECIPITATION RISK

To evaluate the risk of extreme precipitation in central-eastern Poland, the 95th and 99th percentile analyses were employed. Percentiles are positional measures that define threshold precipitation values exceeded by only a specified proportion of observations – 5 and 1% of monthly precipitation totals, respectively. This method enables the identification of rare but potentially hazardous precipitation events (Pińskwar, 2022). The data indicate that the highest 95th and 99th percentile values occurred in Białowieża, as well as in Legionowo and Pułtusk, indicating an increased likelihood of extreme precipitation in these locations. The use of percentiles also facilitates the evaluation of precipitation distribution asymmetry. At most stations, the 99th percentile values are much higher than those of the 95th percentile, reflecting the presence of distinct, high-intensity extreme events. The largest contribution to extreme precipitation totals is observed in July and August (Fig. 2). Extreme precipitation in June and September also plays

a significant role, although to a lesser extent than in July and August. The smallest contribution to extreme totals occurs in the spring months (April and May) and in October. The difference between the 95th and 99th percentiles primarily results from the fact that, at the higher threshold (99th), the dominance of the summer months becomes even more evident. The distribution is similar across locations, indicating a general climatic trend for the region. July and August consistently demonstrate the highest extreme precipitation totals which, in June and September, are also prominent in Legionowo, Pułtusk, and Szepietowo. Białowieża exhibits a high share of August extremes, indicating a shift in the peak of extreme precipitation. Siedlce and Włodawa exhibit the most typical distribution, with minimal deviations. Although all locations exhibit broadly similar distributions of extreme precipitation, variations remain in the dominance of summer months: July (Pułtusk), July and August (Siedlce, Włodawa), or August (Białowieża).

The estimated two-year precipitation values (T_2) describe the maximum rainfall events occurring during the growing season that can be expected statistically every other year (Tab. 3). In the study region, these values range from 107.2 mm in Legionowo to 119.8 mm in Białowieża. The β parameter in Białowieża is moderately high (39.3), resulting in the highest T_2 value, which

Table 3. Estimated Gumbel distribution parameters and extreme precipitation values during the growing season for selected return periods (T_2 , T_5 , T_{10}) in central-eastern Poland

Parameter	Białowieża	Legionowo	Pułtusk	Siedlce	Szepietowo	Włodawa
β	39.3	43.5	42.6	38.2	36.2	40.9
α	105.4	91.2	101.5	96.0	95.4	94.7
R^2	0.98	0.97	0.95	0.96	0.99	0.93
T_2	119.8	107.2	117.1	110.0	108.7	109.7
T_5	164.5	156.5	165.4	153.3	149.7	156.2
T_{10}	194.0	189.2	197.4	181.9	176.8	186.9

Explanations: β = slope, α = intercept, R^2 = coefficient of determination, T_2 , T_5 , T_{10} = return periods of two, five, and ten years, respectively. Source: own study.

indicates that even relatively frequent maxima during the growing season are greater there than at the other stations. The lowest T_2 values in Legionowo stem from a lower baseline α , and despite a high β , extreme precipitation is somewhat smaller than in the other locations. The T_5 values are clearly higher than T_2 and reveal more pronounced spatial variability, ranging from 149.7 mm in Szepietowo to 165.4 mm in Pułtusk and Białowieża. The β parameter in Legionowo and Pułtusk is high (>42), meaning that T_5 increases dynamically, suggesting that heavy rainfall occurs less frequently but is more intense. At Szepietowo, the lower β (36.2) results in a smaller increase between T_2 and T_5 . The ten-year precipitation values (T_{10}) indicate the maxima that can be expected on average once per decade during the growing season. In central-eastern Poland, these values are relatively high and spatially consistent, ranging from 176.8 mm in Szepietowo to 197.4 mm in Pułtusk. Particularly high T_{10} values in Legionowo (189.2 mm) and Pułtusk (197.4 mm) suggest that these areas, located close to larger agglomerations or within their zones of influence, may be more exposed to intense annual extremes of precipitation.

In the first decade (1971–1980), the growing season had relatively high precipitation totals across the entire region, with mean values ranging between 407 mm in Pułtusk and 543 mm in Białowieża (Fig. 3). The highest totals in Białowieża reflect a local influence of climatic factors favouring intense precipitation in the eastern part of the region. In the subsequent decade (1981–1990), a notable decline in precipitation totals occurred at all stations, with the greatest deficit recorded in Legionowo (323 mm), while Białowieża maintained a relatively high value of 394 mm. During 1991–2000, a partial recovery in precipitation totals was observed, with mean values ranging between 365 mm and 417 mm. In 2001–2010, variability between stations was notable, with the highest totals recorded in Białowieża (447 mm) and Włodawa (414 mm). The most recent decade (2011–2020) showed a stabilisation of precipitation totals, with mean values ranging between 408–427 mm.

IDENTIFICATION OF PATTERNS IN EXTREME PRECIPITATION

In order to compare the variability of the P95 and P99 percentiles across individual months and to identify the main patterns of co-variability among the six meteorological stations, a principal component analysis (PCA) was conducted. The first

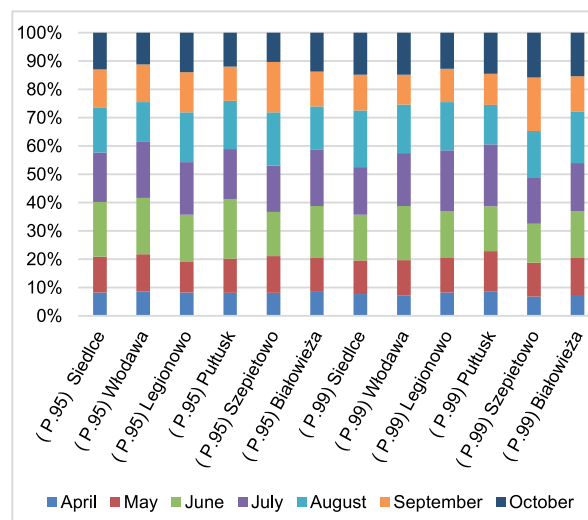


Fig. 3. Percentage share of individual months in extreme precipitation totals for selected percentiles in central-eastern Poland, 1971–2020; (P.95) = 95th percentile, (P.99) = 99th percentile; source: own study

two principal components together explained 77.51% of the total variability, indicating the high effectiveness of the applied dimensionality reduction method (Tab. 4). The first principal component (PC1), accounting for 52.11% of the variability, was strongly associated with P95 values in the spring-summer months (April–July). Legionowo deviated significantly from this pattern, displaying the highest positive PC1 score. In contrast, Szepietowo, Siedlce, and Białowieża exhibited strongly negative PC1 coordinates, suggesting their conformity with the dominant seasonal pattern. The second principal component (PC2), explaining 25.40% of the variability, emphasised the influence of extreme P99 values in the summer months (May–July). Pułtusk and Białowieża recorded high positive PC2 scores, which may indicate their greater susceptibility to extreme conditions during this period.

To better illustrate the relationships between the variables and the meteorological stations, the PCA results were presented in a biplot, which enables the simultaneous interpretation of case coordinates and the directions of influence of individual variables on the principal components.

The biplot displays the results of principal component analysis (PCA) conducted on a set of variables reflecting the total precipitation during the growing season (SP) and monthly extremes defined as the 95th (P95) and 99th (P99) percentiles

for the stations analysed (Fig. 4). The length of the arrows (variables) indicates the strength of their contribution to the first two principal components, while the angles between the vectors represent correlations (Jolliffe and Cadima, 2016). The first two principal components together explain 77.5% of the total variance of the factors analysed. This high proportion indicates a good representation of the data structure in a two-dimensional space and facilitates its graphical interpretation.

The biplot demonstrates a clear separation between variables linked to the 95th percentile (P95) and those associated with the 99th percentile (P99). The first principal component (PC1) primarily groups P95 values (from April to October) together with the total precipitation for the entire growing season (SP), representing the common distribution of seasonal precipitation conditions linked to typical, intense, but not extreme rainfall.

In contrast, PC2 differentiates the 99th percentile values, which represent the most extreme precipitation episodes. The highest positive factor loadings for this component occur for May P99, June P99, April P99, and July P99, indicating the dominant role of spring-summer extremes. By contrast, September P99 (strongly negative values for PC2) and October P99 exhibit a different character, suggesting a distinct structure of extreme events in the autumn months.

Table 4. Correlation coefficients between principal components (PC1–PC3) and variables, and variance explained by the components

Variable	PC1	PC2	PC3	Variable	PC1	PC2	PC3
Apr P95	-0.967	0.239	-0.077	Apr P99	0.518	0.706	0.315
May P95	-0.981	0.109	-0.025	May P99	0.089	0.876	0.389
June P95	-0.817	0.523	-0.038	Jun P99	0.317	0.708	-0.516
July P95	-0.895	0.380	-0.195	Jul P99	0.659	0.649	0.378
Aug P95	-0.933	-0.010	0.323	Aug P99	0.018	-0.136	-0.871
Sept P95	-0.912	-0.343	0.191	Sep P99	-0.313	-0.793	0.439
Oct P95	-0.882	0.362	-0.184	Oct P99	-0.889	0.268	0.137

Explanations: percentage of variance explained: PC1 = 52.11%, PC2 = 25.40%, PC3 = 13.2%.
Source: own study.

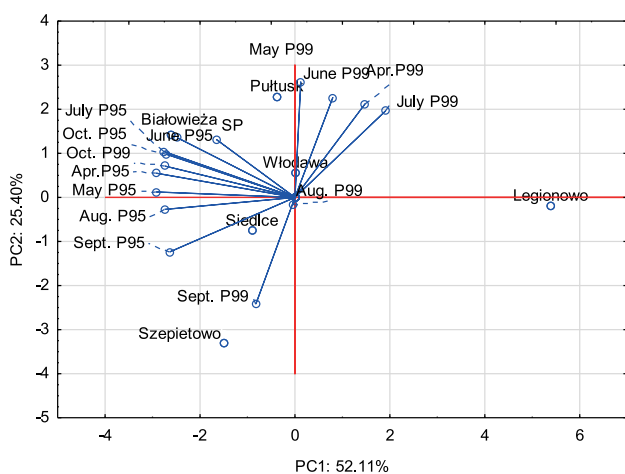


Fig. 4. Principal component analysis biplot for precipitation totals across the growing season (SP) and the 95th and 99th percentile; P95 and P99 = values of the respective percentiles of monthly precipitation totals; source: own study

Most stations (Włodawa, Siedlce, Pułtusk) cluster near the zero point, evident of a shared regional trend and moderate local differences. The isolation of Legionowo along PC1 suggests a local specificity of this station, in alignment with the observation that the regional background can be strongly modulated by local factors, and that extremes exhibit high spatial heterogeneity (Majewski *et al.*, 2021). The position of Szepietowo and September P99 points to differences in the variability structure between early summer and autumn.

The alignment of SP with the vectors for June P99 and July P99 indicates that the most intense, short convective rainfall events in the warm half of the year make a notable contribution to monthly totals in Poland. The most recent analyses of heavy rainfall episodes substantiate the dominance of intense events in the warm half-year and the high spatial-temporal variability of their intensity and duration (Mikołajewski *et al.*, 2025).

The biplot also demonstrates that in some periods, totals above the 95th percentile decrease, while those above the 99th percentile increase, suggesting a growing share of the rarest, most

intense events alongside no increase in moderate extremes. Studies conducted for Poland and Central Europe report strong seasonal differentiation in the mechanisms of extreme precipitation (Kundzewicz, 2014; Wypych and Ustmul, 2024). Earlier research for Poland indicated no clear trends in precipitation extremes in the second half of the 20th century, while more recent studies from the last few decades more frequently report an increase in the frequency of the most intense episodes in the warm half-year, in alignment with the position of P99 along the main axis of variability in the biplot.

CONCLUSIONS

The analysis of extreme monthly precipitation totals in central-eastern Poland provides a complementary perspective to studies focused on daily or annual scales. The monthly approach integrates both the number of days with rainfall and the intensity of individual events, thereby capturing the accumulation of moderately intense precipitation events that are not visible in daily analyses. The study revealed that the highest extreme monthly precipitation totals are concentrated in July and August, with the greatest risk observed in Białowieża, Legionowo, and Pułtusk. In Białowieża, not only were the highest totals of the growing season recorded (445 mm), but also the highest estimated two-year return precipitation ($T_2 = 119.8$ mm). The application of extreme value analysis (EVA) to assess projected precipitation (T_2 , T_5 , T_{10}) based on monthly maxima represents a key and innovative element of this work. The results indicate clear spatial variability in the rate of increase of extremes. A high slope estimator in Legionowo and Pułtusk suggests that rarer events (e.g., T_5 , T_{10}) are more intense relative to their frequency of occurrence (i.e., heavy rainfall occurs less often but is more severe). Conversely, the lower slope estimator in Szepietowo (36.2) indicates a smaller increase in precipitation for these rarer return periods. This constitutes a novel contribution to understanding the structure of precipitation intensity in the region.

The PCA analysis enabled a clear separation of variability associated with moderate extremes (P95) from the most intense episodes (P99). This differentiation suggests that the processes shaping these two classes of events are distinct. It should be noted that, although this study provides valuable insights, it has certain limitations with respect to broader regional inference. The analysis is based on data from six meteorological stations. Although these points are strategically distributed across central-eastern Poland, their limited number may not fully capture the local heterogeneity of extreme phenomena, which is particularly relevant in the case of convective precipitation. Nevertheless, the results have concrete practical implications for hydrology, agriculture, and water resource planning in the region. The estimated projected precipitation values for rare events provide specific data for water engineering. The highest values for the ten-year return period (T_{10}) were recorded in Pułtusk (197.4 mm) and Legionowo (189.2 mm). These areas are therefore most exposed to rare but very intense monthly precipitation events during the growing season, necessitating higher standards in the design of local drainage and flood protection infrastructure. The findings confirm the substantial contribution of extreme events in July and August, which is crucial for managing retention and flash flood risk. The observation that extreme events (P99) are increasing, while

moderate ones (P95) are not, highlights the need to orient adaptation strategies not only towards drought mitigation (common in this region), but above all towards preparedness for short-lived, intense downpours that determine monthly extremes.

CONFLICT OF INTERESTS

All the authors declare that they have no conflict of interests.

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