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Variability of the lowest monthly precipitation sums in the Silesian and Żywiec Beskids

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Abstract: The study was based on monthly precipitation sums from at eight precipitation stations in the Silesian and Żywiec Beskids, covering the period 1951–2022. The data were obtained from the Institute of Meteorology and Water Management – National Research Institute. The frequency and year-to-year variability of the precipitation sums, as well as seasonal variability, based on Colwell's predictability index (*P*) and its components: constancy (*C*) and seasonality (*M*). The results show that low precipitation occurred in all months of the year, with the highest frequency in October, and sporadically recorded in May, June, and July. The majority of the lowest monthly precipitation sums ranged between 30–50 mm, although in some, values exceeded 65 mm. Dry months were recorded in the study period of 1951–2022, notably October 1951, when precipitation sums at the stations did not exceed 3.5 mm, and November 2011, when they did not exceed 1.5 mm. Compared to the long-term average, these precipitation sums accounted for less than 5%. No significant trend was observed in the lowest monthly precipitation sums, though short-term fluctuations were present. Analysis of Colwell's indices showed that the predictability of the lowest annual precipitation sums was below average, at approximately 0.40 across the analysed stations. Seasonality (*M*) was the dominant component of predictability, accounting for an average of 71% of the total predictability. The research findings may contribute to the understanding of the variability and forecasting of extreme meteorological droughts in the Polish Carpathians, particularly with implications for agriculture and forestry.

Keywords: climatic variability, Colwell's indices, dry spells, extreme weather, Mann-Kendall test, Polish Carpatians, precipitation, seasonality

INTRODUCTION

Precipitation shortages result from weather anomalies, and prolonged periods without rainfall can lead to atmospheric and soil drought, low-flow conditions, and even hydrological drought (Cebulska, 2018; Twardosz and Cebulska, 2020). The agricultural and hydrological impacts of insufficient precipitation are particularly severe during summer periods, when high air temperatures contribute to increased evaporation. These conditions negatively affect plant vegetation as well as the quantity and quality of crop yields (Koźmiński, 1986; Kundzewicz and Kozyra, 2011). Rain-free or low-precipitation periods occur irregularly and periodically (Łabędzki, 2006) and can extend over areas with diverse topography. The Polish Carpathians, where the Beskids are located, exhibit significant temporal and spatial variability in precipitation, ranging from complete absence to 500 mm per month (Twardosz and Cebulska, 2020). According to research by Kostrakiewicz (1977a), low precipitation sums also occur in river and stream valleys, except for deep valleys in the Tatra Mountains. This phenomenon may be influenced not only by meteorological factors but also by the physiography of the terrain. Factors such as elevation, landform, and particularly the orientation of mountain ranges relative to moist air masses play a significant role (Kostrakiewicz, 1967; Hess, 1968). Studies by Kostrakiewicz (1977a; 1977b) and Czemerda, Kostrakiewicz and Hess (1980) demonstrated that regions such as the Pogórze and Silesian Beskids, which are exposed to rain-bearing winds, experience the highest annual precipitation sums in the Polish Carpathians.

Moreover, precipitation amounts at comparable elevations decrease progressively from west to east across the Polish Carpathians. Slopes exposed to rain-bearing winds serve as orographic barriers and play a significant role in generating extreme precipitation events. The effects of these events are evident in hydro-geomorphological processes. The studied area is considered the most precipitation-rich region in the Polish Carpathians. However, with ongoing climate change, water shortages are also becoming an issue. This aligns with the well-known observation: "too much water, too little water, water pollution – all may intensify in a changing climate" (Kundzewicz and Kowalczak, 2008). As a result, studies have focused on atmospheric droughts, periods without precipitation or with only weak rainfall, as well as dry spells accompanied by intense summer rainfall, particularly in the Upper Vistula basin and the Carpathians (Kowanetz, 1981; Cebulska, 2018; Markiewicz, 2021). In Poland, is observed strong seasonality in precipitation and corresponding drought indices (Karamuz *et al.*, 2021). This behaviour becomes evident when monthly data are analysed. A very important question is: Do time series of monthly P_{min} also show seasonality? The lowest monthly precipitation sum (P_{min}) is defined as the minimum monthly precipitation sums. It is an important question in case future projections of meteorological conditions, especially for extremes events.

Against the backdrop of global warming, the aim of this study is to analyse multi-year and annual trends of the P_{min} in the Silesian Beskids and the Żywiec Beskids. The study assesses the frequency and year-to-year variability of these precipitation events, the significance of the P_{min} trend, and seasonal variability using Colwell's indices: predictability (P) and its components – constancy (C) and seasonality (M).

STUDY AREA, DATA, METHODS

STUDY AREA

The study area includes the Silesian Beskids and the Żywiec Beskids, located within the Upper Vistula River Basin in the Polish Carpathians. This basin encompasses not only high and low mountains but also mid-elevation mountain ranges, including the compact mountain groups of the Silesian and Żywiec Beskids (Starkel, 1991). In 2018, the Żywiec Beskids were subdivided into three mesoregions: the Żywiec-Orawa Beskids, the Kysuce Beskids, and the Orawa Ranges. The total area of the Żywiec Beskids is 687.2 km^2, with the highest peak being Diablak (1,725 m a.s.l.) in the Babia Góra massif (beskidy.infopl.info, 2025b). The area of the Silesian Beskids is 479.9 km^2 (beskidy.infopl.info, 2025a), with Skrzyczne (1,257 m) and Barania Góra (1,215 m) as the highest peaks. The Beskids are characterised by significant elevation differences (400–800 m), distinct ridges, steep slopes, and narrow, shallow valleys (Klimaszewski, 1967). Due to the diverse ridge systems in both the Silesian and Żywiec Beskids, the area is divided into compact mountain groups, deeply dissected by valleys with steep, straight, or convex slopes (Izmaiłow *et al.*, 1995). The study area lies within a mountain climate region (Hess, 1965), which exhibits substantial precipitation variability influenced by topographic exposure, terrain shape, and the degree of climate continentality (Twardosz and Cebulska, 2020). The average annual precipitation in this region ranges from 900 to 1,400 mm. Locations receiving over 1,400 mm of annual precipitation include: Skrzyczne (1,461 mm) and Wisła-Przysłup (1,434 mm) in the Silesian Beskids, Markowe Szczawiny (1,496 mm) in the Babia Góra range of the Żywiec Beskids. Along the foothills of the Beskids, the 900 mm isohyet runs from 700 mm in Sanok to 1,200 mm in Wisła (Niedźwiedź and Obrębska-Starklowa, 1991).

DATA – SOURCE MATERIAL

The study incorporates monthly precipitation sums from eight stations located within the Upper Vistula River Basin, including three in the Silesian Beskids and four in the Żywiec Beskids (Fig. 1).

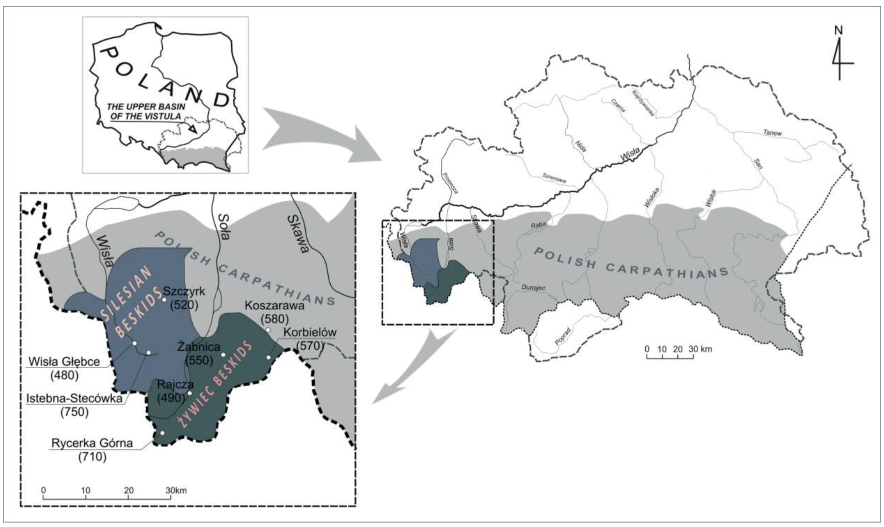


Fig. 1. Location of meteorological stations in the Silesian Beskids and Żywiec Beskids (precipitation station elevation in parentheses); source: own study

These stations are situated in Istebna-Stecówka, Korbielów, Rajcza, Rycerka Górna, Szczyrk, Żabnica, and Wisła-Głębce, as well as in Koszarawa, which is in close proximity to the Żywiec Beskids. The highest station, Istebna-Stecówka (750 m a.s.l.), and the lowest, Wisła-Głębce (480 m a.s.l.), were selected based on data from the Precipitation Yearbook (IMGW, 1977). Precipitation data from the period 1951–2022 were obtained from the database of the Institute of Meteorology and Water Management – National Research Institute (Pol.: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy). Only precipitation stations with homogeneous data spanning 72 years were included in the study. From the compiled database of monthly precipitation sums for each station, the lowest monthly precipitation total ($P_{\min}$) was selected for each year across the multi-year period.

RESEARCH METHODS

Trend of changes in the lowest monthly precipitation sums

To determine trends in the lowest monthly precipitation sums in both the Silesian Beskids and the Żywiec Beskids, the widely used Mann–Kendall (MK) test was applied (Kendall, 1975; Banasik and Hejduk, 2012; Jeneiová, Kohnová and Sabo, 2014; Blain, 2015; Młyński, Cebulska and Wałęga, 2018). The test was applied to detect monotonic trends in meteorological or hydrological data series. The null hypothesis (H_0) states that the data come from a population with identically distribution. The alternative hypothesis (H_A) posits that the data follow a monotonic trend. Let X_1, …, X_n be a time series and let

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(X_j - X_i\right) \tag{1}$$

where: sgn = sign function.

The standardised MK test statistics (Z) can be estimated as follows:

$$Z = \frac{S - \operatorname{sgn}(S)}{\sqrt{\operatorname{var}(S)}} \tag{2}$$

where:

$$\operatorname{var}(S) = \frac{1}{18}\left(n(n-1)(2n+5) - \underbrace{\sum_{j=1}^{p} t_j\left(t_j - 1\right)\left(2t_j + 5\right)}_{\mathrm{T}} + \underbrace{\frac{2(2n+5)}{n-2}\sum_{i=1}^{n-1}(n-i)(n-i-1)(n-i-2)\rho_s(i)}_{\mathrm{A}} \right) \tag{3}$$

Equation (3) for the variance includes a correction term (T) to due to repeated values in the dataset, with p representing the number of tied groups and t_j denoting the number of data points in the j-th group. It also includes a correction for the autocorrelated data (term A) proposed by Hamed and Rao (1998), where $\rho_s(i)$ is the autocorrelation coefficient of the i order in the series of ranks R_1, …, R_n corresponding to X_1, …, X_n and is given by the Equation (4):

$$\rho_s(i) = \frac{\sum_{t=1}^{n-i}(R_t - \bar{R})(R_{t+i} - \bar{R})}{\sum_{t=1}^{n}\left(R_t - \bar{R}\right)^2} \tag{4}$$

where: $\bar{R}$ = average of the ranks.

If H_0 is true, the statistic Z (Eq. 2) follows approximately a standard normal distribution $N(0,1)$.

A positive value of S indicates an "upward trend" and a negative value indicates a "downward trend", $S = 0$ indicates no trend.

Seasonality of the occurrence of the lowest monthly precipitation sums

Among various methods used to analyse seasonality in time series, the Colwell indicators can be particularly useful. This method analyses three key parameters: predictability (P), constancy (C), and the seasonality index (M) (Kennard *et al.*, 2010, Wałęga and Młyński, 2017; Młyński, Cebulska and Wałęga, 2018). Colwell's indices are widely used to study the recurrence of hydrological phenomena, including flow velocity (Riddell and Leggett, 1981), precipitation seasonality (Miller, 1984), river basin classification based on flow regime (Webb, Thoms and Reid, 2012; Zhang *et al.*, 2012), and as an indicator influencing habitat conditions for macroinvertebrates (Wałega *et al.*, 2022).

Determining Colwell's indices requires categorising observational series to obtain a matrix ($s \times t$) describing the analysed process. The columns of the matrix represent fixed time steps, while the rows describe the state of a given phenomenon. Let N_{ij} denote the number of occurrences when the variable reaches state i at time step j, X_j be the sum of columns for each time j, Y_i be the sum of all rows for each state i, and Z denote the total number of observations analysed. Then, seasonality M is defined as (Eq. 5) (Colwell, 1974):

$$M = \frac{H(x) + H(y) - H(xy)}{\log(s)} \tag{5}$$

where: s = number of matrix rows, $H(x)$, $H(y)$ and $H(xy)$ = uncertainties with respect to state, time, and state-time interaction, respectively, given by the Equations (6), (7) and (8):

$$H(x) = -\sum_{j=1}^{t} \frac{X_j}{Z} \log \frac{X_j}{Z} \tag{6}$$

$$H(y) = -\sum_{i=1}^{s} \frac{Y_i}{Z} \log \frac{Y_i}{Z} \tag{7}$$

$$H(xy) = -\sum_{i=1}^{s} \sum_{j=1}^{t} \frac{N_{ij}}{Z} \log \frac{N_{ij}}{Z} \tag{8}$$

Constancy (C) (Eq. 9) and predictability (P) (Eq. 10) are defined as:

$$C = 1 - \frac{H(y)}{\log(s)} \tag{9}$$

$$P = C + M \tag{10}$$

Constancy (C) represents the tendency of a variable to remain unchanged throughout the year. It reaches its maximum value (C = 1), when the variable has the same value in every analysed period. The seasonality index (M) reaches its maximum value (M = 1) when the variable exhibits a fully deterministic pattern over time, meaning that its values appear at consistent, predictable intervals, even if they vary between periods. The predictability index (P) measures the overall variability across successive analysed time steps, with its maximum value equal to 1 (Kennard *et al.*, 2010).

RESULTS AND DISCUSSION

VARIABILITY OF LOWEST MONTHLY PRECIPITATION SUMS IN ANNUAL AND MULTI-YEAR TRENDS

In the annual course of the lowest monthly precipitation sums ($P_{\min}$) from 1951 to 2022, $P_{\min}$ occurred at every station and in every month, except for the meteorological stations located in Koszarawa and Rajcza. At these two stations, $P_{\min}$ was not observed in May or June over the multi-year period. At the remaining measurement stations, only one occurrence of $P_{\min}$ was recorded in these months. In July, the lowest precipitation was also sporadic in the study area, with three cases (4.2%) in Wisła Głębce and four cases (5.6%) in Szczyrk. In the other months, its frequency was higher – particularly in February and October, where it reached 13 cases (18.1%). Thus, $P_{\min}$ occurred least frequently in May, June, and July, while it was most frequent in October and February. Based on the lowest monthly precipitation sums, characteristic values of these precipitation events were determined (Tab. 1, Fig. 2), as well as their percentage relative to the corresponding long-term monthly average (Tab. 2). The lowest monthly precipitation values showed significant variation, ranging from 0 to over 77 mm. As shown in Table 1, the highest $P_{\min}$ was recorded in Szczyrk in August 1998. Across the entire study area, most of the lowest monthly precipitation sums ranged from 30 to 50 mm. However, in some months, precipitation exceeded 65 mm, particularly in Rycerka Górna (68 mm), Wisła Głębce (68.6 mm), and Szczyrk (77.5 mm) (Fig. 3). Meanwhile, precipitation below 5 mm occurred only 29 times over the 72-year study period, with the highest number of such cases (seven) recorded in Żabnica, located at an elevation of 550 m a.s.l.

Table 1. Statistical characteristics of lowest monthly precipitation sums ($P_{\min}$) in the years 1951–2022

Specification	Istebna-Stecówka	Korbielów	Koszarawa	Rajcza	Rycerka Górna	Szczyrk	Wisła Głębce	Żabnica
Year of occurrence (1)	2011	1951	2011	1951, 2011	1951	2011	1951	1951
1	1.2	0	0.3	0	0.1	0.8	0	0
2	30.6	25.6	27.0	22.3	29.6	30.1	30.2	24.9
3	60.3	54.8	56.1	47.2	68.0	77.5	68.6	58.3
Year of occurrence (3)	1981	1967	2016	1998	1970	1998	1967	2016

Explanations: 1 – the lowest monthly precipitation sum (mm) among $P_{\min}$ in the years 1951–2022; 2 – precipitation as the average value of $P_{\min}$ (mm); 3 – the highest monthly precipitation sum (mm) among $P_{\min}$ in the years 1951–2022.
Source: own study.

During December to September, none of the analysed stations recorded a lack of precipitation. However, in October and November, four stations reported zero precipitation (Tab. 1). October 1951 was classified as a dry month across all stations, with extremely low or absent precipitation levels (Tab. 1). This drought affected not only the Silesian and Żywiec Beskids and the entire Upper Vistula basin but also most of Europe. Despite being dry, it was also a cool month, and the meteorological drought that occurred had a continental reach (Cebulska and Twardosz, 2010). Another extreme meteorological drought also occurred in November 2011. Across the entire study area, the total monthly precipitation did not exceed 1.2 mm, with precipitation sums contributing only up to 1.7% of the long-term average (Tab. 2). According to Cebulska (2018), the longest precipitation-free period, lasting 40 days, occurred in places such as Szczyrk from 21 October to 29 November 2011. This took place under anticyclonic circulation types – southern (Sa) and anticyclonic ridge (Ka). However, as noted by Obrębska-Starklowa *et al.* (1995), the frequency and intensity of dry spells decrease with altitude.

In the Mała Wisła catchment, at least one station was identified each month where the given month was classified as dry, with varying intensities of meteorological drought. In April of the years 1984, 1988, 2002, 2007–2009, and 2013, meteorological drought occurred across almost the entire Mała Wisła catchment. During these years, precipitation shortages were recorded at nearly all measurement stations. For example, in April 2009, the entire study area experienced low precipitation, with amounts reaching up to 13.2 mm in Istebna-Stecówka (Cebulska, 2016).

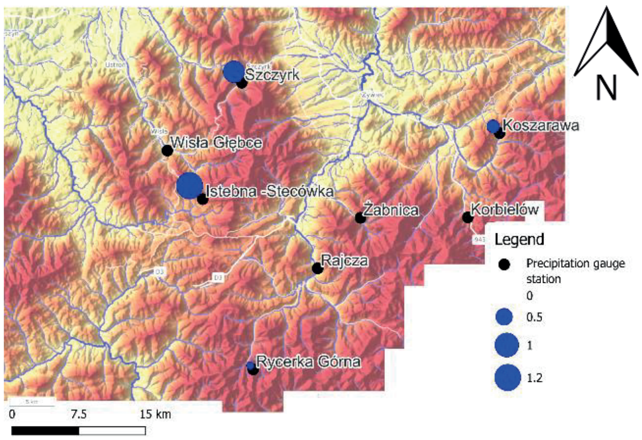


Fig. 2. The lowest monthly precipitation sum (mm) among $P_{\min}$ in the years 1951–2022; source: own study

TREND OF LOWEST MONTHLY PRECIPITATION SUMS CHANGES

The course of the lowest monthly precipitation sums at individual stations was analysed to identify potential linear trends. The Mann–Kendall test (Kendall, 1975) was used to assess the statistical significance of the trend values. No significant increasing trend in

Table 2. The lowest monthly precipitation sums P_{min} (%) in the average monthly precipitation

Station	Month											
	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Istebna-Stecówka	15.4	8.9	7.8	13.4	32.7	14.6	29.8	17.7	8.9	2.9	1.3	10.9
Korbielów	20.5	13.5	4.9	1.9	23.2	30.8	20.9	17.5	11.3	0.0	1.7	9.7
Koszarawa	14.7	8.7	2.1	4.8	34.9	25.1	14.5	19.1	11.8	0.9	0.4	13.0
Rajcza	20.4	11.0	4.3	12.2	24.0	33.2	17.7	19.0	10.6	0.0	0.0	11.6
Rycerka Górna	21.5	13.6	12.6	10.6	32.2	14.0	22.9	18.9	18.9	0.1	0.7	7.8
Szczyrk	21.3	7.1	7.9	4.7	28.8	20.4	10.7	3.3	4.1	3.7	0.9	9.5
Wisła Głębce	20.7	7.5	11.5	13.8	31.6	22.4	22.9	16.5	8.0	0.0	0.6	10.4
Żabnica	17.5	4.0	9.8	5.5	17.2	21.0	19.0	7.6	12.2	0.0	0.6	9.2

Source: own study.

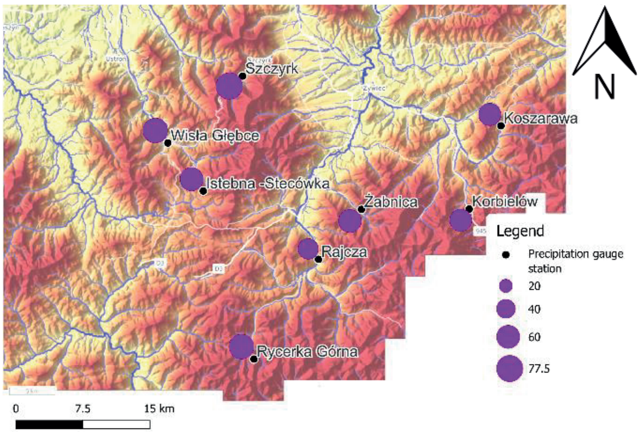
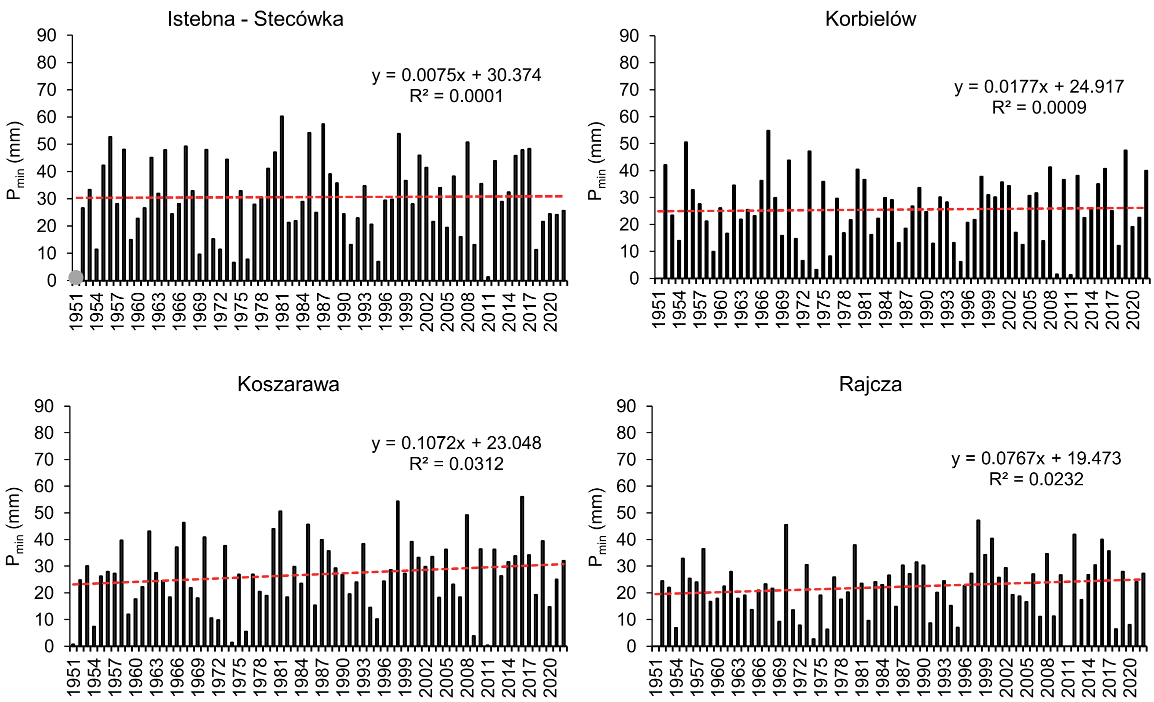


Fig. 3. The highest monthly precipitation sum (mm) among P_{min} in the years 1951–2022; source: own study

P_{min} was observed at the precipitation stations within the study area (Rajcza, Szczyrk, and Wisła Głębce), nor at the nearby Koszarawa station, located near the border of the Żywiec Beskids. The lowest precipitation values exhibited considerable variability between stations from year to year (Fig. 4), as well as significant differences in P_{min} values among stations. For example, in Szczyrk in the early 1950s, P_{min} was noticeably lower compared to other measurement stations. In Żabnica, between 1991 and 1995, P_{min} did not exceed 10 mm, whereas at other stations, P_{min} only occasionally fell below 10 mm. In Rycerka Górna and Szczyrk, significantly higher P_{min} sums appeared in 1998.

SEASONALITY OF LOWEST MONTHLY PRECIPITATION SUMS

Analysis of minimum precipitation in the years 1951–2022 at the analysed stations showed low seasonality (M) at the level of 21–33% (below 50%), while predictability was at the level (P) of 32–43%, and constancy (C) 5–11% (Fig. 5, Fig. 6). The analysis



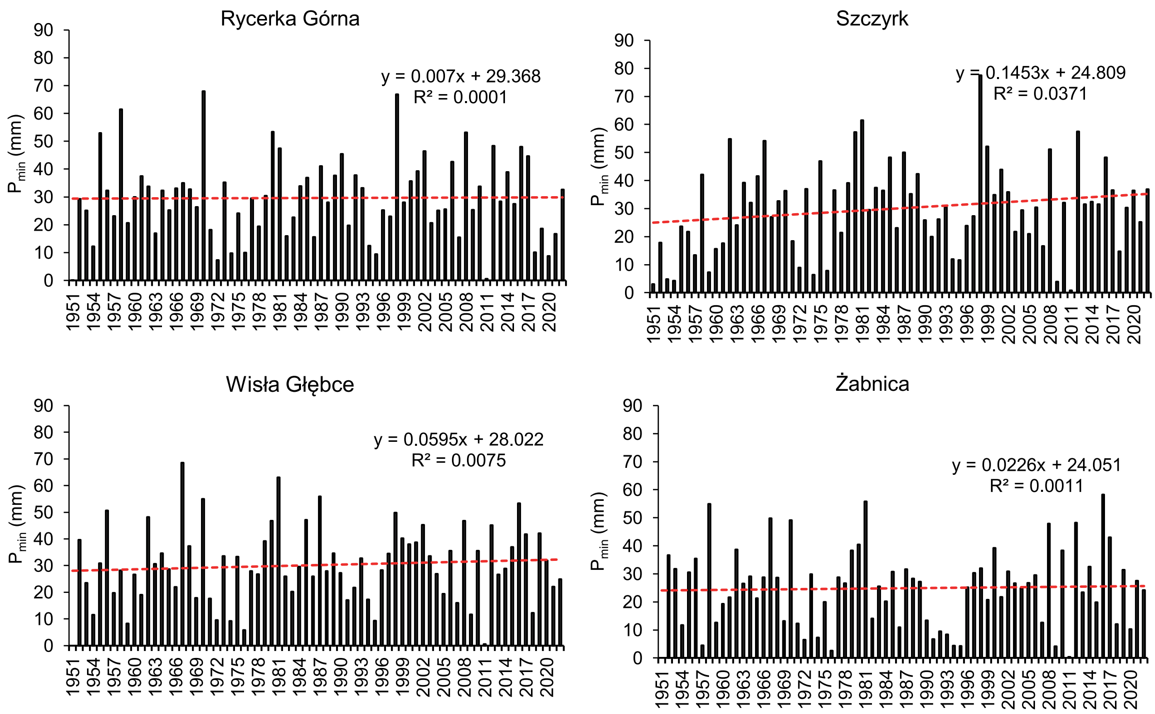


Fig. 4. Long-term course of the lowest monthly precipitation sums (P_{min}) in the years 1951–2022 with a trend line; source: own study

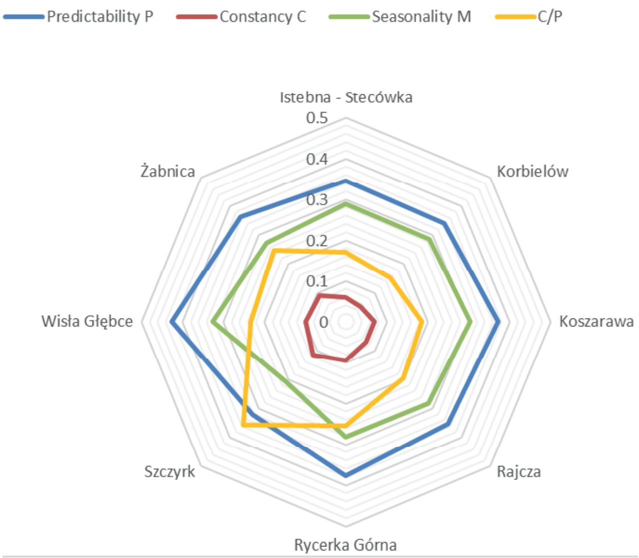


Fig. 5. Predictability, constancy and seasonality of lowest monthly precipitation sums (P_{min}) in the years 1951–2022 at individual stations; source: own study

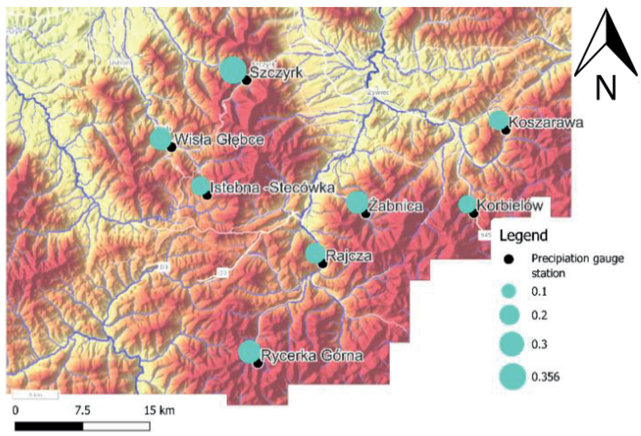


Fig. 6. Variation in the ratio of Colwell's indices – constancy (C) to predictability (P) for lowest monthly precipitation sums (P_{min}) at individual stations; source: own study

indicates that constancy dominates over the seasonality of P_{min}. The highest predictability value occurred at the Wisła Głębce station (43%), while the lowest value occurred at the Szczyrk station (32%). The highest seasonality occurred at the Wisła Głębce station (33%), and the lowest at the Szczyrk station (21%). Constancy reached the highest value at the Szczyrk station (11%) and the lowest value at the Korbielów station (5%). Minimum precipitation is characterised by low variability, which affects the lack of seasonality in their occurrence in individual years. It can be assumed that the values of P_{min} are more determined by the location of the station than by the course of atmospheric conditions. This is also related to the terrain, where the amount of minimum precipitation varies between summer and cooler months. The highest predictability values were observed at stations located in the Silesian Beskids (Wisła Głębce) and Żywiec Beskids (Rycerka Górna, Koszarawa, Żabnica).

The analysis of the relationship between the standard deviation of P_{min} and Colwell's indices (Fig. 7) indicated a correlation between these parameters. In the case of predictability and seasonality, the relationship with standard deviation can be described by a second-degree polynomial. With a large standard deviation exceeding 13 mm, a decrease in P and M is observed, which is caused by an increase in precipitation variability. In the case of constancy, an increase in constancy is visible with an increase in the standard deviation value. The values of determination coefficients R^2 explain over 40% of the variability of C, C/P from the standard deviation, and about 20% of the variability of P from the standard deviation. The strongest

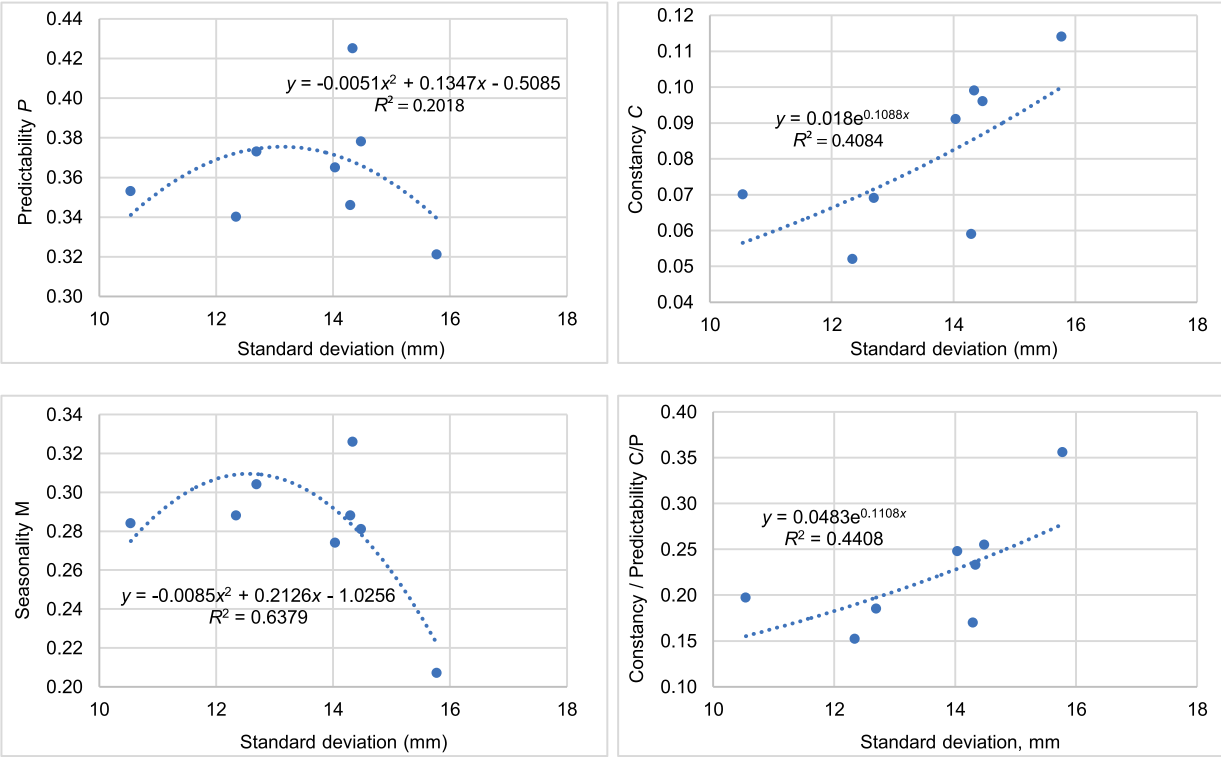


Fig. 7. Standard deviation of lowest monthly precipitation sums (P_{min}) in relation to the values of Colwell's indices; P = predictability, C = constancy, M = seasonality; source: own study

relationship at the level of R^2 = 0.64 is observed between M and the standard deviation. The relationships between standard deviation and predictability, constancy and constancy-to-predictability ratio are statistically insignificant at the α = 0.05 level (p_{value} = 0.264 for P, p_{value} = 0.088 for C, p_{value} = 0.073 for C/P). Only the relationship between seasonality and standard deviation was statistically significant (p_{value} = 0.017). This confirms the earlier observation that the variability of P_{min} influences the seasonality of their course (Dong *et al.*, 2020).

CONCLUSION

In the Żywiec Beskids and the Silesian Beskids, the lowest monthly precipitation sums (P_{min}) can occur throughout the year, though with the lowest frequency during the summer months. The fewest occurrences of P_{min} are observed in May, June, and July. Notably, in Rajcza and Koszarawa, P_{min} did not occur in May or June over the 72-year period. The highest number of lowest precipitation sums was recorded during the cold half-year, particularly in February. Across the entire study area, most of the lowest monthly precipitation sums ranged between 30 and 50 mm, although some months recorded higher sums. At each precipitation station, up to 10 months in the August–April period had precipitation below 10 mm. Dry months were observed during the study period. Extreme dry months included October 1951, when total precipitation did not exceed 3.5 mm, and November 2011, with a total of up to 1.2 mm. Similarly, dry months were February 1976, March 1974, as well as April 2009 and April 2020. P_{min} also occurs during the growing season; however, the number of observed cases did not exceed 10/72. No completely dry months were recorded in the warm half-year, although some months had precipitation below 10% of the long-term average, and in Szczyrk, September precipitation even fell below 4% of the average. The Colwell's indices analysis indicated that annual minimum precipitation was characterised by low predictability and seasonality. The highest predictability of P_{min} was observed at stations located in the Beskid Żywiecki. In the case of stations where P_{min} values had a large standard deviation, precipitation seasonality decreased.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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