DOI:10.28974/idojaras.2020.1.7

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 124, No. 1, January – March, 2020, pp. 129–141

Statistical and geostatistical analysis of spatial variation of precipitation periodicity in the growing season

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(Manuscript received in final form April 25, 2019)

Abstract— This work presents the variation in the spatial distribution of atmospheric precipitation determined by means of multidimensional analyses. Precipitation data observed at nine stations of the Institute of Meteorology and Water Management (IMGW) located in central-eastern Poland in the period 1971–2005 are analyzed. Precipitation periodicity index was calculated for each station (measurement point). The index was subjected to descriptive analysis by calculating the average value for the long-term period and the average rate of change. Multidimensional analyses were used to examine the spatial differentiation of precipitation variation. Periodicity indexes in months associated with the first and second principal component were found to account for over 70% variation between the measurement points. The months were as follows: April, May, July, and October. Cluster analysis was performed based on principal components, and it yielded three groups of measurement points with different distribution of precipitation periodicity indexes. The first group consisted of localities characterized by a low precipitation periodicity index in July and October. The second cluster included measurement points which had the lowest precipitation periodicity in May, June, August, and September. The third cluster was formed by only one locality (Białowieża), whose precipitation periodicity index was the highest in every month of the growing season. Both principal component analysis and cluster analysis may be used for an assessment of spatial variation of precipitation periodicity. Their results agree with findings based on the method of isoline interpolation.

Key-words: precipitation periodicity index, multidimensional analysis, variation, spatial distribution

1. Introduction

Atmospheric precipitation is a basic element of climate, which is characterized by substantial temporal and spatial variations. The literature on the subject contains many parameters which describe this phenomenon, and suggests numerous methods of determining their variation (*Friederichs,* 2010*; Huang et al.,* 2018; *Łupikasza,* 2001; *Miler,* 2018; *Nikulin,* 2011).The annual distribution of atmospheric precipitation in the zone of temperate latitudes is commonly believed to be their most important characteristic. Poland has a temperate climate which is changeable, uneven and characterised by, among others, spatial and temporal precipitation variation *(Paul* and *David,* 2006; *Twardosz et al.,* 2011; *Żarski* and *Dudek,* 2000).

Precipitation distribution varies throughout the growing season, and the same season of the year may see many days without rain or longer periods of excessive rainfall (*Dzieżyc et al.,* 2012). Spatial and temporal changes in precipitation distribution negatively affect agriculture, afforestation, and water reserves. As the frequency of extreme phenomena has been on the increase in recent years, much more attention is paid to precipitation at present. Scientists all over the world have raised the subject of precipitation variation for many years, particularly in the context of climate change and increased frequency of weather anomalies (*Banaszkiewicz et al.,* 2004; *Olechowicz – Bobrowska et al.,* 2005*, Paul* and *David,* 2006).

Progressing warming is an empirically confirmed symptom of climate change. The warming, which is most evident in spring, is not accompanied by statistically significant changes in the amount of precipitation (*Ziernicka-Wojtaszek et al.,* 2015; *Żmudzka,* 2009). Modern climatic forecasts, including research by IPCC experts (2007)*,* indicate that central Europe will see an increase in the winter precipitation and a decline in the summer rainfall. Precipitation conditions in Poland have changed in the last 50 years as well. A decline in the proportion of summer (June-August) precipitation sum in the annual sum has been observed. According to *Degirmendžić et al.* (2004) and *Zawora* and *Ziernicka* (2003), the main features of the continental climate are becoming less and less pronounced. Variation in precipitation is to a great extent the result of the effect of atmospheric circulation, which favours continental or oceanic influences and thus impacts the climate at a global and local scale (*Twardosz et al.,* 2011).

In meteorology and climatology, spatial analysis is almost exclusively based on measurements taken at certain points − mainly various types of meteorological stations. As a result, the analysis requires that the data collected at these points are transformed into surfaces of certain meteorological elements. The spatial distribution of precipitation types in Europe, particularly in the Mediterranean area, is well known. However, little attention has been paid in literature to the long-term variation of this precipitation characteristics.

The objective of this work was to analyze the variation in one of the indicators of annual precipitation variation (irregularity index) in the central-eastern part of Poland by means of multidimensional analyses.

2. Materials and methods

2.1. Study area

The present work draws on data on daily atmospheric precipitation sums for the period 1971–2005 obtained from nine IMGW stations located in the central-eastern part of Poland (*Table 1* and *Fig. 1*).

According to *Woś* (1993), the study area belongs to the 19th Polish climatic region − the Podlasie-Polesie region. Compared with other climatic regions in Poland, the number of days with moderately warm and cloudy weather in the area is low − around 70 days per year. The number of moderately warm days with precipitation is about 55 per year, and the number of moderately warm, cloudy days with precipitation is only 26 per year. The days when the weather is rather frosty and sunny without precipitation are more frequent than in other regions.

Table 1. Geographic coordinates of synoptic and climatic IMGW stations in central-eastern Poland

Station	**Geographic coordinates**		**H_s m a.s.l.**
	φ	**λ**	
Ostrołęka	53 ° 05’	21 ° 34’	95
Białowieża	52 ° 42’	23 ° 51’	164
Włodawa	51 ° 33’	23 ° 32’	163
Szepietowo	52 ° 51’	22 ° 33’	150
Legionowo	52 ° 24’	20 ° 58’	93
Biała Podlaska	52 ° 02’	23 ° 05’	133
Sobieszyn	51 ° 37’	22 ° 09’	135
Pułtusk	52 ° 44’	21 ° 06’	95
Siedlce	52 ° 11’	22 ° 16’	146

Explanations: φ – latitude, λ – longitude, H_s – elevation above sea level.

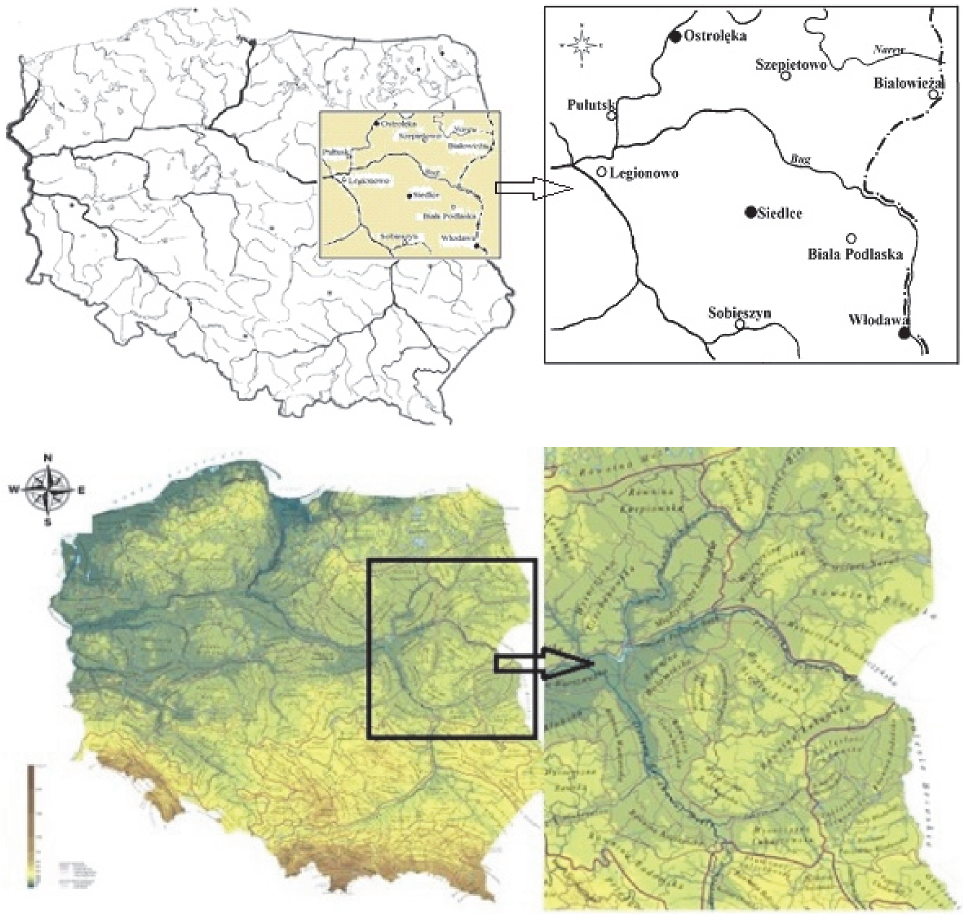


Fig. 1. Location of the meteorological stations included in the study.

2.2. Meteorological analysis

The following parameters were calculated for each station:

- the average atmospheric precipitation sum for the growing season (April-October) through the long-term period,
- the monthly atmospheric precipitation sum for the growing season (April-October), and
- the monthly index of precipitation periodicity in the growing season (April-October).

The precipitation periodicity index is a general characteristics of the precipitation continentality which suitably reflects the degree of the development of land-related precipitation characteristics in areas of temperate latitudes (*Woś,* 1993).

The precipitation periodicity index is calculated according to the following formula:

$$W = (\Sigma \left| mi - Rs \right| * 100)/R, \quad (1)$$

where *mi* is the average precipitation in the *i*th month, *R*s is the average precipitation sum for the studied period, and *R* is the precipitation sum for the studied period.

The index of precipitation periodicity may range from 0 to about 183%. Based on the value of the *W* index, *Wilgat* (1948) distinguished the following precipitation types:

- fairly even precipitation, when *W* is less than 25%,
- slightlyperiodic precipitation, when *W* is between 25–50%,
- clearly periodic precipitation, when *W* is between 50–75%,
- distinctly periodic precipitation, when *W* is between 75–100%, and
- extremely periodic precipitation, when *W* is more than 100%.

Schulze (1956) termed the above indicator the annual distribution index, whereas *Chromow* (1977), who used the unitless parameter (not percentages), called it the periodicity index. According to *Kożuchowski* and *Wibig* (1988), such a formula should be termed the non-proportionality index. *Walsh* and *Lawler* (1981) used this parameter to develop maps of seasonal precipitation variation in the tropical Africa, the British Isles, Brazil, and India.

2.3. Geostatistical analysis

The spatial interpolation of precipitation periodicity was based on the kriging method. A few types of kriging can be distinguished based on the detailed calculation used by the algorithm, from which the ordinary kriging is the most popular. Many traditional climatological approaches accept it as the only spatial interpolation method. The description of kriging can be found in many works, including textbooks on individual geostatistical programs. In generally, kriging assumes that there is internal stationarity in the whole spatial process. Explaining values (variables) are based on linear equations calculated from observed data accompanied by corresponding weights. The weights depend on the spatial correlation which exists between these points. Linear coefficients are determined so that the estimated variance error is the lowest (the so-called kriging variance). Due to this, kriging is believed to be the most universal method of spatial analysis.

2.4. Statistical analysis

Multi-dimensional principal component analysis (PCA) and cluster analysis were carried out to compare the measurement points in terms of precipitation periodicity. The principal component analysis is a dimension reduction technique, which transforms the original correlated variables into new, non-correlated variables called principal components. They maximally explain the total variance of a group of p primary variables $x_1, \ldots, x_p$, that is

$$\sum_{j-1}^{p} S_j^2 = tr\,(S), \tag{2}$$

where S is the covariance matrix for a sample, tr is the trace of the matrix, and s_j^2 is the variance of the variable x_j, $j = 1, \ldots, p$ (*Krzyśko,* 2010).

The number of components considered was selected based on the Kaiser's criterion, according to which only the variables with the value of more than 1 are analyzed. Such components carry only the most significant information which reflects the variation of the objects, thus they were used in the second part of the analysis, in the cluster analysis. Euclidean distance was used as a measure of distance between objects and Ward's procedure as an agglomeration method. The intersection point was determined applying the Mojena's rule:

$$d_{i+1} > \bar{d} + ks_d, \tag{3}$$

where $\bar{d}$ is the mean value, s_{d} is the standard deviation d_i, and k is a constant value = 1.25 (*Milligan* and *Cooper,*1985).

Statistical analysis was performed using Statistica 12.0 PL for Windows.

3. Results and discussion

The highest atmospheric precipitation sum for the growing season in central-eastern Poland was recorded in 1974 (630 mm), while the lowest in 1982 (248 mm) (*Fig. 2*). In Białowieża, the precipitation sum spanning from April to October declined by as much as 48 mm per 10 years, on average. The precipitation for the April-October period dropped by less than 10 mm per 10 years only in Pułtusk. Many authors confirmed that precipitation patterns have been changing both in Poland and Europe (*Boryczka* and *Stopa –Boryczka,* 2004; *Mousavi et al.,* 2018; *Pauling et al.,* 2005).

The yearly atmospheric precipitation sum in the study area was primarily affected by the location of the measurement point. It was the highest (610 mm) in the north (Białowieża) and the lowest (518 mm) in the south (Włodawa). A similar relationship was found for the growing season. The sum for April-October was the highest in the north and amounted to 414 mm in Białowieża and 410 mm in Ostrołęka. At the remaining points, the precipitation sum did not exceed 400 mm throughout the growing season. In Poland, substantial differences between precipitation amounts are recorded even in relatively small areas (*Banaszkiewicz et al.,* 2004, 2008). Precipitation unevenness, analyzed on the basis of periodicity indexes, was also confirmed by *Paul* and *David* (2006).

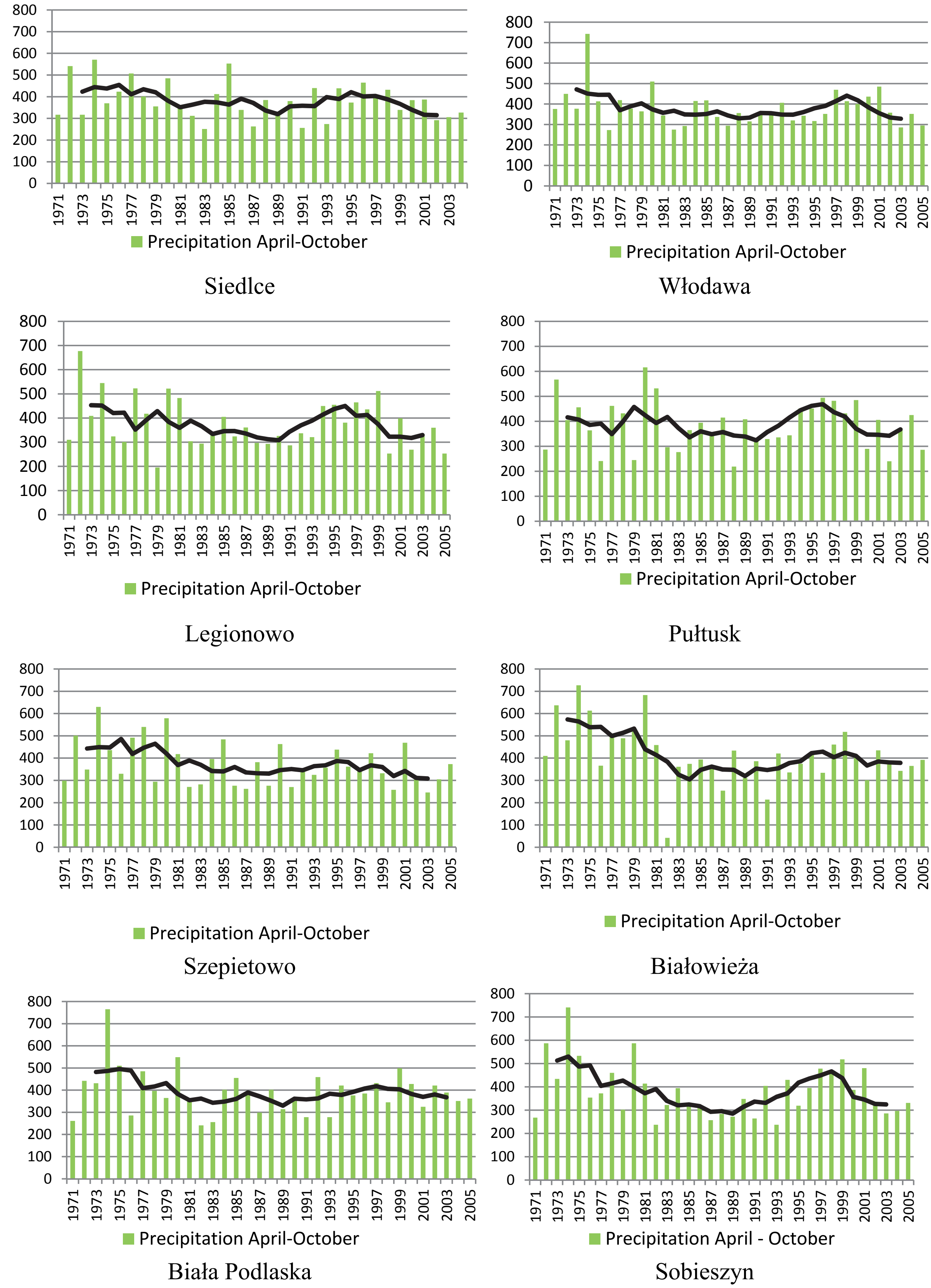
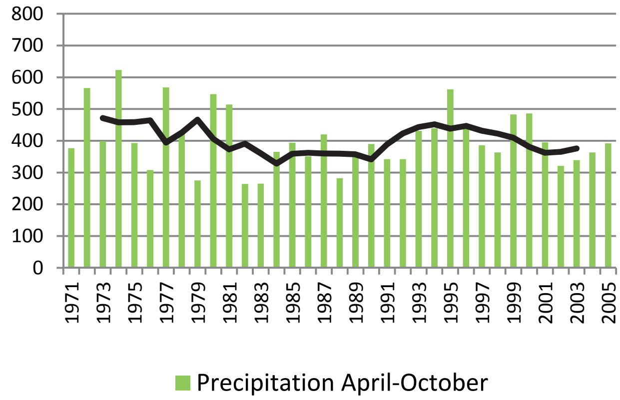


Fig. 2. Atmospheric precipitation sums for the growing season (April-October) and the 5-year moving average in central-eastern Poland from 1971 to 2005.



Ostrołęka

Fig. 2. Continued

In the study area, average values of precipitation variation index ranged from 42% in Włodawa to 48% in Szepietowo. The average area values of this parameter in individual months of the growing season ranged from 35% in May to 61% in October. According to *Czarnecka* and *Nidzgorska-Lencewicz* (2012), the greatest spatial and temporal variations in precipitation occur in autumn. *Marosz et al.,* (2013) claim that spatial variation of the average value (from 1971 to 1990) of the 90th percentile of daily precipitation sums shows relatively low variation, while seasonal and monthly values are cyclic. The sum of the monthly precipitation tended to change significantly in August in Koszalin, and a seasonal trend of precipitation change was observed only in the cool season of the year in Poznań (*Skowera et al.,* 2014).

In central-eastern Poland, only two types of precipitation periodicity (slightly and clearly periodic) were found in the growing season of the long-term period studied (*Fig. 3*).

Analysis of the periodicity index revealed that at each measurement point, precipitation was slightly periodic in April, May, September (excluding Włodawa), and October, and clearly periodic in June and July. Precipitation periodicity in August depended on the measurement point and was clearly periodic for five points, and poorly periodic for four locations. According to *Wilgat* (1948), precipitation in Europe is quite even compared with other areas in the world resulting from a strong impact on the Atlantic. The yearly precipitation pattern becomes surprisingly smooth in eastern and south-eastern Europe, although continental properties of precipitation should strengthen eastwards − precipitation should be higher in the summer season. Probably, precipitation concentration declines in eastern Europe due to a general shortage of and seasonal fluctuations in water vapor transportation (*Łupikasza,* 2001). Variation in precipitation results from the effect of atmospheric circulation, which is behind the domination of continental or oceanic influences (*Tylkowski* and *Hojan,* 2018).

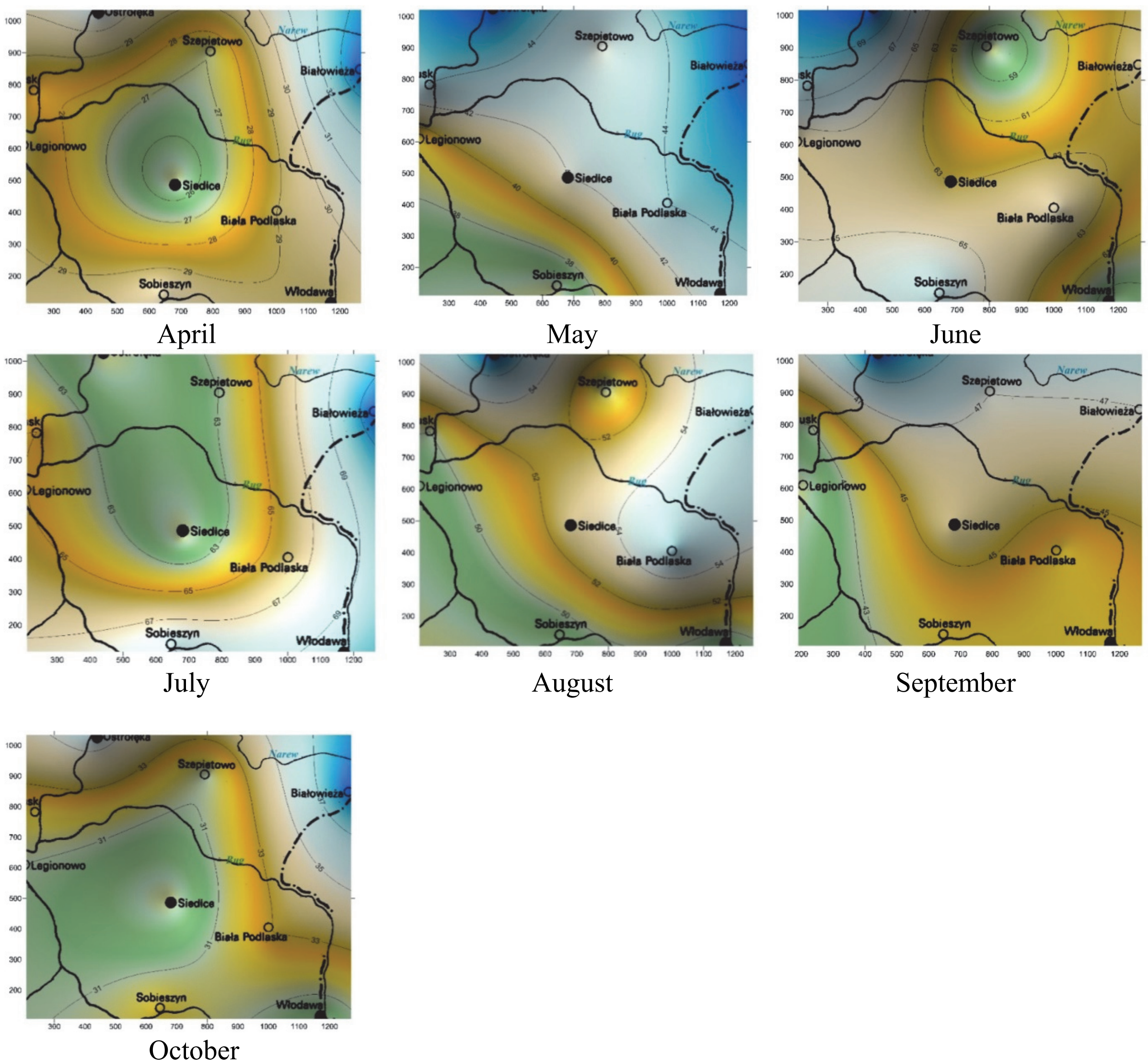


Fig. 3. Distribution of atmospheric precipitation periodicity types in the growing season in central-eastern Poland.

Łupikasza (2001) observed that the precipitation periodicity index was constantly on the increase mainly in western Europe (the British Isles, Denmark, western France), Romania, and some stations located in the east of Europe, whereas in central Germany, south-eastern France and southern Norway the opposite trend was observed (the index *W* was constantly on the decline).

Principal component analysis demonstrated that the first two principal components accounted for over 70% of variation in the types of precipitation periodicity between measurement points (*Table 2*). The precipitation periodicity index for April, May, and October had the greatest influence on spatial variation, as indicated by correlation coefficients between the first principal component and the indicators analyzed. The second principal component was the most strongly correlated with precipitation periodicity in July, and accounted for over 20% of variation between measurement points.

Table 2. Factor loads, eigenvalues, and proportion of the total variance of precipitation periodicity index, as explained by the first two principal components

Characteristics	PC1	PC2
X1 – periodicity index in April	-0.827	-0.441
X2 – periodicity index in May	-0.837	0.186
X3 – periodicity index in June	-0.734	0.194
X4 – periodicity index in July	-0.420	-0.874
X5 – periodicity index in August	-0.683	0.272
X6 – periodicity index in September	-0.726	0.340
X7 – periodicity index in October	-0.827	-0.441
Eigenvalue of principal components	3.09	1.22
Explainded proportion of the total variance (%)	51.53	20.33
Comulative proportion of the total variance (%)	51.53	71.87

Measurement points were divided into three groups based on cluster analysis (*Fig. 4*).

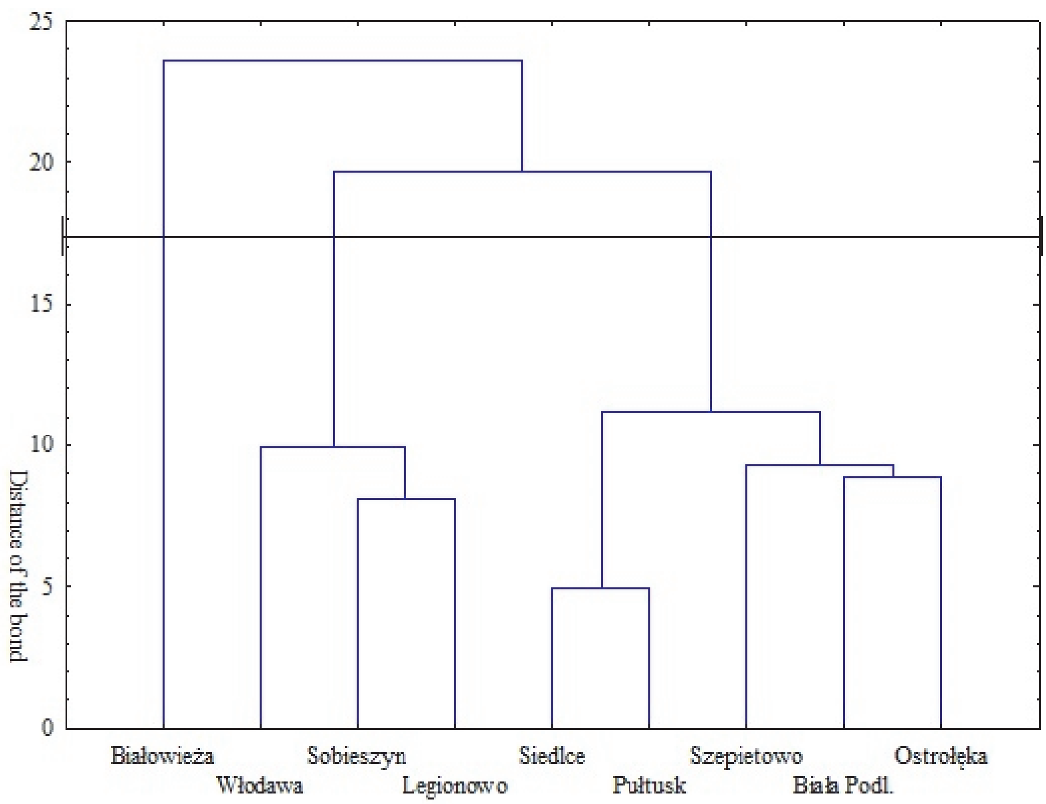


Fig. 4. Dendrogram for nine measurement points obtained for the first two principal components.

The first group included stations located in Siedlce, Pułtusk, Szepietowo, Biała Podlaska, and Ostrołęka. The second group included stations situated in Włodawa, Sobieszyn, and Legionowo, while the Białowieża station is the only object in the third group.

The region represented by stations in cluster 1 had a low periodicity index in July and October. The region formed by points from cluster 2 was characterized by the lowest periodicity index in May, June, August, and September. Cluster 3 with only Białowieża in it had the highest precipitation periodicity index in every month of the growing season (*Table 3*).

Table 3. Average values of precipitation periodicity index in the three clusters

Characteristic	**Cluster 1**	**Cluster 2**	**Cluster3**
April	36.358	36.910	44.260
May	54.290	49.710	59.480
June	70.628	67.530	77.200
July	70.226	74.790	80.680
August	63.452	58.083	65.870
September	55.840	54.070	58.500
October	36.358	36.910	44.260

Principal component analysis and cluster analysis may be used for an assessment of spatial variation of precipitation periodicity, because their results agree with the results of the isoline interpolation method.

4. Conclusions

1. Average values of precipitation periodicity index ranged from 42 to 61%, and in the period 1971–2005, only two types of it were observed: the slightly and the clearly periodic precipitation.

2. The index of precipitation periodicity in April, May, and October had the greatest influence on the differences between the analyzed locations.

3. Based on cluster analysis, the study area was divided into three groups. The first cluster comprised stations in Siedlce, Pułtusk, Szepietowo, Biała Podlaska, and Ostrołęka, which had low precipitation periodicity indexes in July and October. The second cluster, formed by stations located in

Włodawa, Sobieszyn, and Legionowo, was characterized by the lowest precipitation periodicity in May, June, August, and September. Białowieża, which was the sole object in the third cluster, had the greatest precipitation periodicity in almost all of the months.

4. Principal component analysis and cluster analysis may be used for an assessment of spatial variation of precipitation periodicity, because their findings agree with the results of the spatial interpolation method.

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