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Variability of drought occurrence during the maize (*Zea mays* L.) growing season in Central-Eastern Poland

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Abstract: This study aimed to analyse the variability of precipitation deficits and excesses during the maize (*Zea mays* L.) growing season in Central-Eastern Poland from 1971 to 2020. Meteorological data were obtained from IMGW-PIB stations located in Siedlce, Włodawa, Legionowo, Pułtusk, Szepietowo, and Białowieża. The water balance was calculated based on crop evapotranspiration (ET_c), determined using a modified Hargreaves equation and crop coefficients (k_c). Results indicate that spring precipitation excesses predominated during the first two decades, whereas from the 1990s onwards, water deficits became increasingly pronounced, particularly in June and July – critical months for maize yield formation. At many stations, average deficits during this period exceeded 50 mm, with localised values dropping below 75 mm. Principal component analysis (PCA) explained nearly 67% of total variance and revealed a clear shift in hydroclimatic conditions. Early decades (1971–1990) were characterised by relatively stable conditions, while the period after 1990 showed increasing variability, including more frequent alternation of deficit and excess events. The most recent decades (2001–2020) were marked by strong intra-decadal variability and intensified fluctuations in the water balance. Spatial differentiation was also noted: precipitation excesses were more frequent in the north-eastern part of the region, whereas central locations were mainly affected by deficits. These trends are consistent with broader climatic patterns in Central Europe, showing increasing drought frequency alongside more intense precipitation events. The results highlight growing instability in water availability and confirm the need for adaptive water management strategies, particularly during the most sensitive growth stages of maize.

Keywords: climatic variability, maize (*Zea mays* L.), precipitation deficit, water balance, water requirements

INTRODUCTION

Climate change observed in Poland over recent decades has led to increasingly frequent and intense extreme events, including meteorological, agricultural, and hydrological droughts (Demietiew, 2018; Borek, 2021; Krogulec, 2024). Climatic analyses indicate a significant warming trend in Poland, with annual, seasonal, and monthly mean air temperatures between 1991 and 2020 being significantly higher than those recorded during 1961–1990, with differences ranging from 1.0 to 1.3°C depending on location (Tomczyk and Bednorz, 2022). This changing climate in Poland is reflected not only in rising average temperatures but also in increased precipitation variability. Although total annual precipitation shows no clear downward trend, its temporal distribution has shifted. Rainfall events have become more intense but less frequent, reducing the effectiveness of soil moisture replenishment (Karaczun and Kozyra, 2020; Skałecka, 2023). The growing variability and extreme nature of precipitation may result in more frequent droughts with extensive spatial coverage and severity (Łabędzki, 2006; Kuchar *et al.*, 2015). Water balance analyses show that during summer, evapotranspiration in many regions of Poland exceeds precipitation levels, leading to soil water deficits (Ziernicka-Wojtaszek, 2015; Kuśmierek-Tomaszewska *et al.*, 2018; Żarski, Kuśmierek-Tomaszewska and

Dudek, 2018; Kuśmierek-Tomaszewska and Żarski, 2021; Żarski and Kuśmierek-Tomaszewska, 2023).

In Poland, the area devoted to maize cultivation has expanded considerably over recent decades. According to Statistics Poland (GUS, no date), during the past twenty years the sown area of maize (*Zea mays* L.) for grain has increased approximately threefold – from about 412 thous. ha in 2004 to more than 1.25 mln ha in 2023 (excluding maize grown for silage). This amounts to nearly 1.9 mln ha of total maize cultivation (grain and silage combined) in 2023. From a historical perspective, a more rapid expansion occurred between 2000 and 2013, when the combined maize area increased more than fourfold, from 152 to 614 thous. ha.

Maize, one of Poland's most important cultivated crops, has a high water demand, particularly during its period of rapid growth and flowering, which typically occurs in June and July. Water shortages during this critical phase significantly limit ear development and reduce yields (Széles *et al.*, 2023; Poudel, 2023; Król-Badziak, Kozyra and Rozakis, 2024a). Moreover, precipitation variability and the increasing vapour pressure deficit (VPD) have an equally strong, or even stronger, impact on maize productivity than temperature alone (Zhang *et al.*, 2024).

Maize is a thermophilic crop and requires an adequate supply of heat (expressed as the sum of effective temperatures) for proper development. Ghamghami *et al.* (2019) report that the base temperature for calculating growing degree days (GDD) is approximately 6°C, with germination occurring at a soil temperature of around 10°C. For the production of fully developed grain, a thermal accumulation of about 1,550–2,200°C-days (based on a 6°C threshold) is required, depending on the length of the growing season and the cultivar type. Under Polish conditions, Król-Badziak, Kozyra and Rozakis (2024b) indicate that a threshold of 6°C has been adopted as the basis for GDD calculations for maize. They further emphasise that achieving full maturity of plants in the Polish climate requires exceeding the necessary GDD sum for the respective cultivar groups (e.g. FAO210, FAO240, FAO290) within a given season.

Changing climatic conditions and their influence on soil water balance underscore the need for research into drought variability in the context of agricultural production. This is particularly relevant for Central-Eastern Poland, where maize is a key component of the cropping structure. Analysing trends during the maize growing season may provide valuable insights for planning adaptive strategies in agriculture.

The aim of this study was to analyse the variability of precipitation deficits and excesses during the maize growing season in Central-Eastern Poland from 1971 to 2020.

MATERIALS AND METHODS

The study area encompasses the valleys of the Vistula, Bug, and Narew rivers, comprising extensive agricultural and forested landscapes. The region is characterised by a moderately warm continental climate with oceanic influences. Average summer temperatures range from approximately 18.0–18.5°C. Annual precipitation levels are among the lowest in Poland, amounting to around 500 mm in the central part of the region and up to 600 mm along its periphery. These conditions – relatively warm summers and a temperate continental climate – significantly influence the water requirements of crops (Błaś and Ojrzyńska, 2024). The analysis was based on meteorological data from six IMGW-PIB stations located in Central-Eastern Poland: Siedlce (52°16'N, 22°29'E), Włodawa (46°00'N, 24°00'E), Legionowo (52°25'N, 20°56'E), Pułtusk (52°67'N, 21°42'E), Szepietowo (48°00'N, 22°00'E) and Białowieża (23°31'N, 24°21'E). The study covered the period from 1971 to 2020. Monthly values of mean, minimum, and maximum air temperature, as well as total precipitation, for the maize growing season (April–October) were analysed. Reference evapotranspiration (*ETo*) was calculated using a version of the Hargreaves equation modified for Polish conditions (Bogawski and Bednorz, 2014). Potential crop evapotranspiration (ET_c) was obtained by multiplying *ETo* by crop coefficients (k_c, defined as the ratio of evapotranspiration measured under conditions of adequate soil moisture to reference evapotranspiration) corresponding to the successive developmental stages of maize (Tab. 1).

$$ETo = 0.408 \cdot 0.001(T_a + 17.0) \cdot (T_{\max} - T_{\min})^{0.724} \cdot R_a \tag{1}$$

where: T_a = mean air temperature (°C), $T_{\max}$ = maximum air temperature (°C), $T_{\min}$ = minimum air temperature (°C), R_a = extraterrestrial radiation ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$).

Solar radiation reaching the Earth's atmosphere (R_a) is constant for a given time and location; it is obtained from standard reference tables. The calculated reference evapotranspiration (*ETo*) was subsequently used to estimate crop evapotranspiration (ET_c) using crop-specific coefficients (k_c):

$$ETp = k_c \cdot ETo \tag{2}$$

Precipitation deficits and excesses during the maize growing season were identified, along with their frequency and intensity, by comparing ET_c values with monthly precipitation totals. To determine spatial-temporal patterns in the occurrence of water excesses and deficits during the maize growing season, principal component analysis (PCA) was conducted using decadal intervals. Components with eigenvalues greater than 1 were selected for analysis (Rodríguez-Sánchez, 2015). The analysis included the following variables: mean precipitation excess (*E*, mm), mean precipitation deficit (*D*, mm), and the number of months per decade with excess (*NME*) and deficit (*NMD*) precipitation. Results were presented in the form of a biplot.

Table 1. Crop coefficients (k_c) for maize

Month	Maize development stage	k_c
April	emergence and early development	0.30–0.40
May	intensive vegetative growth	0.70–0.80
June	pre-flowering development and ear formation	1.00–1.15
July	flowering stage with peak water demand	1.15–1.20
August	kernel formation and grain maturation	0.90–1.00
September	ripening phase with declining transpiration	0.60–0.70
October	emergence and early development	0.40–0.50

Source: own elaboration based on: Allen *et al.* (1998).

RESULTS AND DISCUSSION

Analysis of decadal data reveals significant changes in the distribution of precipitation excesses and deficits during the maize growing season between 1971 and 2020 (Fig. 1). In the first two decades (1971–1980 and 1981–1990), precipitation excesses predominated in April and May, while June and July were characterised by a high incidence of deficits, particularly in central locations such as Legionowo and Pułtusk.

In subsequent decades, a pronounced trend towards rainfall deficits in June and July, critical months for the intensive growth phase of maize, became increasingly evident. This observation aligns with the findings of Łabędzki and Bąk (2014), who highlighted the growing risk of atmospheric drought during this period. Between 2001–2010 and 2011–2020, most locations exhibited a clear predominance of precipitation deficits in June, often occurring in 8–10 years per decade. This pattern reflects a broader trend of increasing frequency of dry summer episodes across central Europe (Spinoni, Naumann and Vogt, 2015; Hänsel *et al.*, 2019). Concurrently, numerous instances of precipitation excess were recorded in September and October, particularly in Białowieża and Włodawa. These findings are consistent with projections outlined in the IPCC (2021) report, which mentions a rising risk of extreme weather events, including droughts, even in temperate zones. They are further corroborated by Polish climate studies, which point to a shortening of the winter season and an earlier onset of dry, warm summer months (Wibig, 2012). Regional differences are evident across the analysed stations. In the north-eastern part of the region (Szepietowo, Białowieża), spring precipitation excesses were more frequent, whereas in central locations (Pułtusk, Siedlce), deficits during key summer months dominated. These findings support the findings of Żarski, Kuśmierek-Tomaszewska and Dudek (2018), who identified substantial spatial variability in the water balance of maize cultivation in Poland.

Over the study period, precipitation deficits were much greater than excesses (Tabs. 2, 3), confirming a trend towards more frequent drought conditions. At most stations, cumulative deficits during the maize growing season exceeded several hundred millimetres, whereas excesses were typically several times smaller.

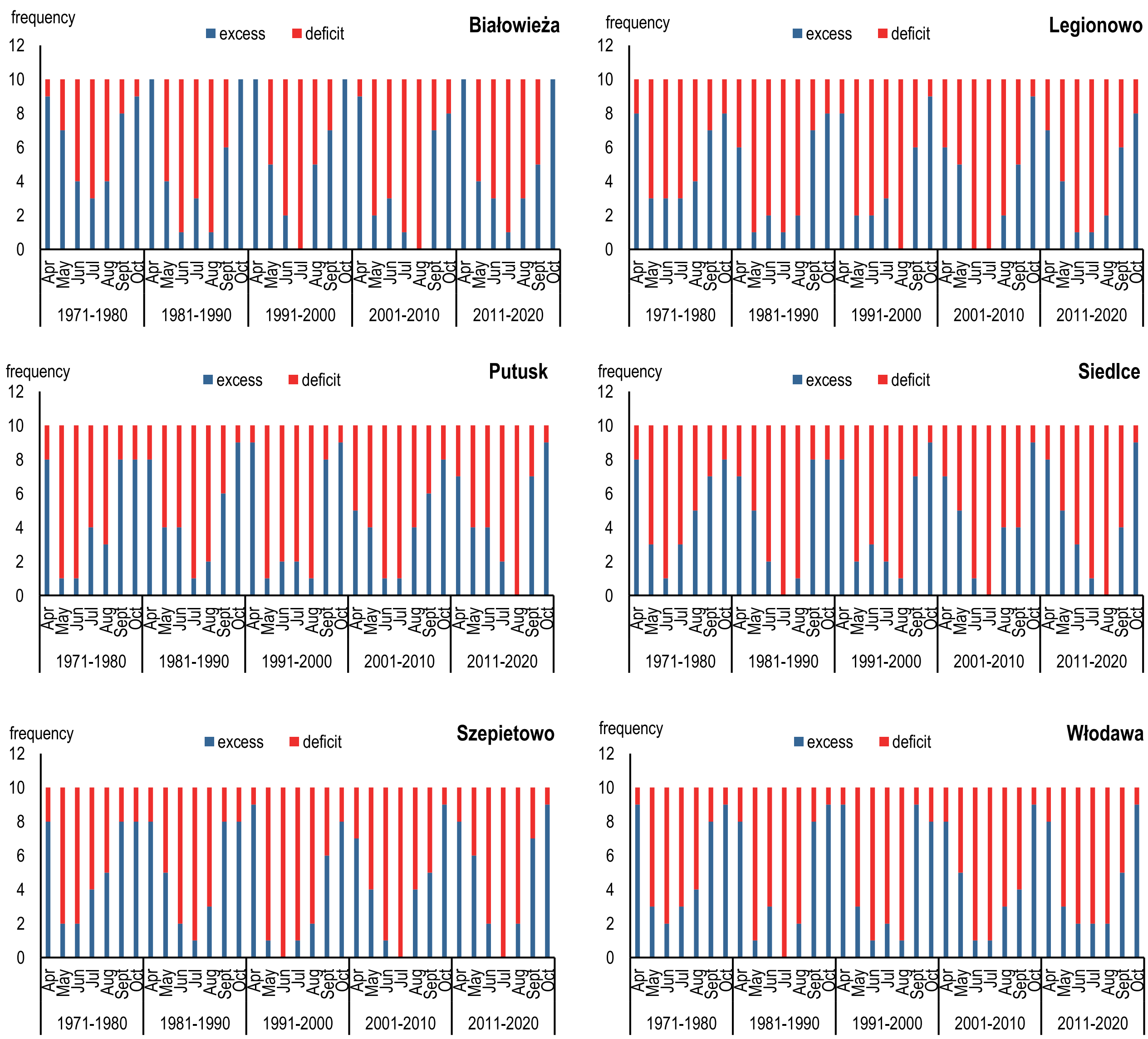

Fig. 1. Frequency of precipitation deficits and excesses during the maize growing season at analysed stations; source: own study

Table 2. Mean precipitation excesses (mm) during the growing season at analysed stations

Period	Excess in the month						
	April	May	June	July	August	September	October
Białowieża							
1971–2020	48.3	44.8	45.3	36.0	23.1	38.2	33.8
1971–1980	38.6	59.2	58.8	47.4	12.6	56.1	48.6
1981–1990	71.6	38.5	95.0	13.6	1.4	36.3	22.3
1991–2000	37.5	18.6	24.2	0.0	23.5	23.7	43.9
2001–2010	49.4	85.5	13.7	102.5	0.0	30.0	26.0
2011–2020	43.3	38.4	56.5	2.3	43.5	43.9	28.1
Legionowo							
1971–2020	28.3	22.7	38.6	50.4	55.3	40.3	39.4
1971–1980	32.0	16.6	20.4	16.9	70.5	35.3	59.4
1981–1990	23.5	0.3	12.7	27.2	19.7	32.4	21.8
1991–2000	36.3	14.3	87.4	36.8	0.0	52.8	29.9
2001–2010	22.9	32.7	0.0	0.0	73.8	35.2	34.8
2011–2020	23.7	24.6	47.4	215.3	41.8	47.0	53.0
Pułtusk							
1971–2020	26.1	28.1	46.1	44.5	40.4	36.3	36.9
1971–1980	26.7	23.6	0.3	24.7	68.6	31.0	61.3
1981–1990	15.9	11.2	54.9	8.8	6.2	39.8	18.2
1991–2000	34.1	48.7	82.5	51.2	2.3	49.3	36.6
2001–2010	21.9	39.6	44.0	5.9	45.9	29.2	32.4
2011–2020	30.0	29.3	31.2	114.5	0.0	30.7	38.2
Siedlce							
1971–2020	24.6	24.0	41.6	44.0	49.5	45.4	36.0
1971–1980	22.2	3.5	12.7	16.5	54.4	42.0	60.1
1981–1990	17.6	24.1	90.7	0.0	5.1	28.3	19.5
1991–2000	31.8	24.9	9.4	56.7	29.9	49.5	24.4
2001–2010	16.6	18.6	81.2	0.0	59.4	72.7	28.4
2011–2020	33.2	41.3	37.4	101.5	0.0	51.1	48.4
Szepietowo							
1971–2020	24.6	24.0	41.6	44.0	49.5	45.4	36.0
1971–1980	22.2	3.5	12.7	16.5	54.4	42.0	60.1
1981–1990	17.6	24.1	90.7	0.0	5.1	28.3	19.5
1991–2000	31.8	24.9	9.4	56.7	29.9	49.5	24.4
2001–2010	16.6	18.6	81.2	0.0	59.4	72.7	28.4
2011–2020	33.2	41.3	37.4	101.5	0.0	51.1	48.4
Włodawa							
1971–2020	22.8	32.4	51.2	51.7	36.0	36.4	34.4
1971–1980	23.8	27.9	55.8	39.2	28.5	33.9	47.5
1981–1990	17.7	18.6	27.3	0.0	19.4	28.8	18.8
1991–2000	32.2	24.6	2.3	56.3	3.0	34.5	32.9
2001–2010	9.4	24.4	121.1	10.6	72.5	63.8	32.8
2011–2020	29.7	62.9	71.7	86.3	29.4	34.4	40.0

Source: own study.

Table 3. Mean precipitation deficits (mm) during the maize growing season at analysed stations

Period	Deficit in the month						
	April	May	June	July	August	September	October
Białowieża							
1971–2020	12.4	21.3	43.9	72.2	40.8	14.6	3.8
1971–1980	11.0	38.9	43.6	69.1	30.8	13.3	1.0
1981–1990	0.0	14.0	34.3	78.9	34.3	14.3	0.0
1991–2000	0.0	24.6	51.9	70.5	44.3	12.5	0.0
2001–2010	13.7	17.4	40.2	79.5	39.9	13.7	5.2
2011–2020	0.0	22.5	51.1	64.1	56.7	17.2	0.0
Legionowo							
1971–2020	9.9	25.3	52.0	64.7	38.7	14.3	5.0
1971–1980	3.1	19.9	53.0	40.2	48.9	10.9	3.8
1981–1990	8.7	23.6	31.8	67.4	32.7	22.2	4.8
1991–2000	11.0	28.8	59.4	77.3	38.4	12.0	10.2
2001–2010	9.6	26.1	58.5	66.2	40.3	15.8	8.6
2011–2020	15.7	29.1	55.3	69.7	36.0	11.2	2.2
Pułtusk							
1971–2020	12.1	23.7	57.2	75.0	36.6	20.2	6.1
1971–1980	5.3	19.0	40.4	69.5	38.8	17.7	2.0
1981–1990	10.4	29.8	47.4	72.0	33.2	17.1	6.8
1991–2000	21.3	21.6	57.5	87.4	29.2	26.8	6.4
2001–2010	12.7	24.5	66.8	74.3	60.0	14.9	8.0
2011–2020	13.7	26.9	77.2	71.0	30.3	28.4	9.1
Siedlce							
1971–2020	9.1	28.8	51.6	67.4	37.2	10.8	5.8
1971–1980	7.4	23.8	37.7	53.3	51.7	5.3	1.2
1981–1990	8.0	29.2	44.0	58.3	36.3	13.6	3.7
1991–2000	2.6	34.3	58.1	91.7	24.9	9.5	10.7
2001–2010	12.6	28.5	56.2	71.3	46.3	12.6	10.3
2011–2020	13.9	27.2	65.8	62.6	36.6	11.2	10.0
Szepietowo							
1971–2020	9.0	24.3	50.4	63.7	42.6	10.6	5.1
1971–1980	6.1	24.8	49.7	54.9	55.0	3.7	4.6
1981–1990	7.4	20.9	40.7	66.8	40.4	20.0	4.2
1991–2000	2.3	30.0	53.9	70.1	45.6	11.1	4.4
2001–2010	13.0	19.1	49.0	65.3	39.5	10.8	5.8
2011–2020	10.8	22.9	57.8	58.7	35.9	8.0	8.2
Włodawa							
1971–2020	4.9	25.3	57.7	62.8	41.8	16.7	5.0
1971–1980	1.3	23.3	43.7	44.8	46.5	8.2	5.3
1981–1990	1.2	27.6	64.4	52.1	35.9	14.5	5.7
1991–2000	1.5	22.3	55.1	78.1	44.5	0.1	4.6
2001–2010	5.2	21.1	48.8	64.4	28.0	20.5	7.5
2011–2020	12.0	30.4	78.5	75.1	53.2	19.7	2.6

Source: own study.

The highest water surpluses were generally recorded in spring (April–May), locally exceeding 80 mm, for example in Białowieża (May 2001–2010: 85.5 mm) and Włodawa (May 2011–2020: 62.9 mm). These values contrast with deficits ranging from 20 to 30 mm in the same months during other decades and in other stations (e.g., Siedlce: May 1971–1980: 23.8 mm). During the summer period, critical for maize development, negative water balances predominated. Average deficits in June and July frequently exceeded 50 mm, and in Pułtusk and Siedlce, values in some decades fell below 75 mm. Exceptionally high precipitation excesses during this period occurred sporadically (e.g., Włodawa, June 2001–2010: 121.1 mm; Legionowo, July 2011–2020: 215.3 mm), highlighting the increasing irregularity in rainfall distribution. In autumn (September–October), the water balance was more stable and uniform.

From a spatial perspective, precipitation excesses tended to occur in the north-eastern part of the region (Białowieża, Szepietowo), whereas central stations (Pułtusk, Siedlce) more frequently recorded pronounced summer deficits. Similar regional differences have been described by Szwed (2019), Łabędzki and Bąk (2014), and Łabędzki and Bąk (2017), who emphasised that local precipitation conditions can significantly influence the risk of soil drought and yield losses.

To identify spatial-temporal patterns in the formation of water excesses and deficits during the maize growing season, a principal component analysis (PCA) was conducted using decadal intervals (Fig. 2). The first two principal components explain nearly 67% of the variance in the dataset. The first component (PC1) represents a "drought-water surplus" gradient axis. Positive values correspond to decades dominated by water deficits (high values of *D* and *NMD*), while negative values indicate decades with a greater prevalence of excesses (high values of *E* and *NME*). The second principal component (PC2) differentiates decades based on internal variability. High positive values suggest frequent co-occurrence of both excesses and deficits within the same decade, whereas negative values reflect greater stability in water conditions. The biplot reveals distinct clustering of decades. The periods 1971–1980 and 1981–1990 are located on the right side of the plot, indicating a dominance of deficits and a high number of months with water shortages. The decade 1991–2000 is positioned on the opposite side (negative PC1 values), reflecting an increased frequency of water excess episodes. The years 2001–2010 are characterised by a high PC2 value, indicating substantial intra-decadal variability and the simultaneous occurrence of both excess and deficit events. The most recent decade (2011–2020) occupies a position in the area of positive values for both components, suggesting an intensifying amplitude of water balance fluctuations and the presence of both deficit and surplus periods.

These findings indicate a clear shift in climatic conditions over the study period. The first two decades were dominated by water deficits; after 1990, the frequency of excess episodes increased, while the last two decades have been marked by pronounced variability and instability in the water balance – features characteristic of contemporary climatic conditions in Poland.

Białowieża was characterised by a higher frequency of precipitation excess episodes, whereas central stations (Legionowo, Pułtusk, Siedlce) more commonly experienced water deficits. Szepietowo exhibited the greatest variability between decades. This region lies at the intersection of continental and Atlantic climatic influences, resulting in alternating decades of wetter and drier conditions. An additional factor is the pronounced seasonality of precipitation, which leads to the co-occurrence of surplus periods (spring and early summer) and deficit periods (August and September). The results are consistent with observed climatic trends in Poland and Central Europe where recent decades have been marked by an increase in the frequency and intensity of drought episodes in certain areas, alongside a rise in

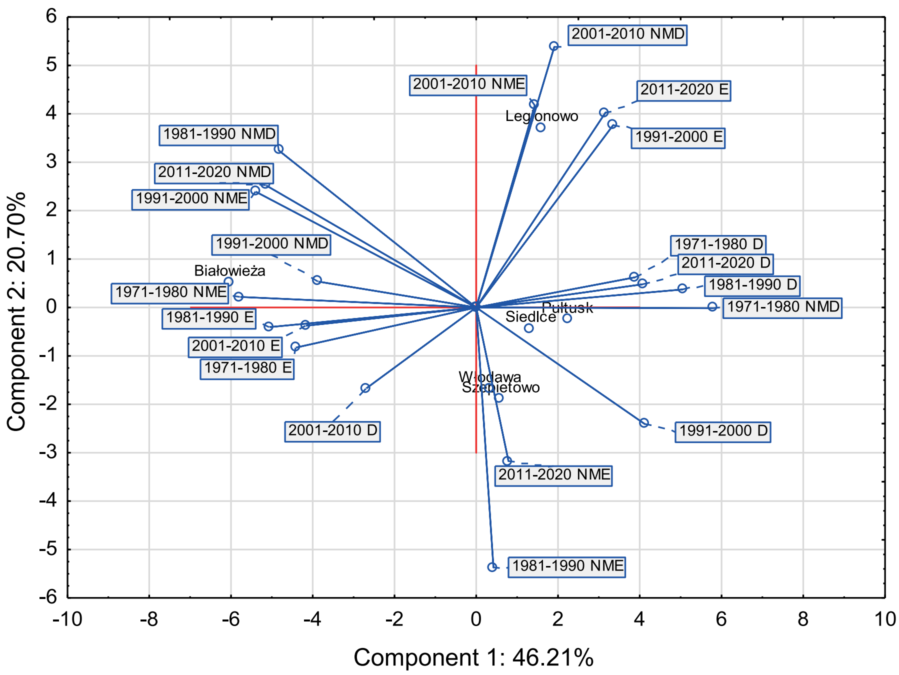

Fig. 2. Biplot illustrating the spatial-temporal analysis of precipitation excesses and deficits during the maize (*Zea mays* L.) growing season; *D* = rainfall deficiency, *E* = excess rainfall, *NME* = number of days with excess rainfall, *NMD* = number of days with insufficient rainfall; source: own study

the severity of extreme precipitation events in others, confirming greater fluctuations between dry and wet periods.

The results obtained are of considerable practical importance for maize producers in east-central Poland, as they confirm that during the period of intensive growth and flowering (June–July) precipitation deficits predominate, frequently exceeding 50 mm. Such conditions lead to a decline in actual evapotranspiration and a reduction in yield, particularly on light soils with low water-holding capacity.

According to data from the agricultural drought monitoring system of IUNG-PIB (https://susza.iung.pulawy.pl), in the years 2011–2020 agricultural drought in maize cultivation occurred in east-central Poland in as many as 7–8 years of the decade, with the greatest severity in 2015, 2018 and 2019. In central regions, including the stations at Siedlce, Pułtusk and Legionowo, the climatic water balance (*CWB*) fell below –150 mm, indicating a high risk of yield losses exceeding 30%. On light and very light soils, typical of Mazovia and Podlasie, drought risk was assessed as the highest in the country, whereas on heavier soils (e.g. in the areas of Włodawa and Białowieża) the deficits were less severe.

These findings confirm the need for continued monitoring of local water balances and for integrating meteorological data with soil assessments. In practical terms, the results presented in this paper may support advisory and decision-making activities in agricultural water management. They enable the identification of areas particularly vulnerable to water deficit during the critical developmental phases of maize, which may serve as a basis for local planning of water retention, the development of drainage and irrigation infrastructure, and the adaptation of agronomic technologies to the soil and climatic conditions of the region.

CONCLUSIONS

The research reported here demonstrates that, between 1971 and 2020, the distribution of precipitation during the maize growing season in Central-Eastern Poland considerably irregular. Precipitation deficits, particularly in June and July, frequently exceeded 50 mm and posed the greatest risk of yield reduction. Precipitation excesses occurred mainly in spring, yet they were insufficient to offset the negative summer water balance. Principal component analysis (PCA) confirmed increasing variability; within the same decade, years with both severe drought and excessive rainfall became more common. The results clearly indicate a growing amplitude of water balance fluctuations and an increasing risk of agricultural drought in the study area.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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