The frequency of drought events in Skierniewice, central Poland, over the last century

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Highlights

- Authors analysed drought frequency and intensity in Skierniewice over 100 years.
- *SPI*, *HTC*, *Ped*, and *CWB* were used to assess meteorological or agricultural drought.
- Severe droughts were recorded in both early and recent decades of the study.
- *HTC* and *CWB* better identify dry periods linked to agricultural drought.

Abstract: In the context of climate change, the frequency, intensity, and spatial distribution of drought events have become a critical area of research. Water scarcity can restrict plant development, reduce yields, and, under severe conditions, lead to total crop failure. This study investigates the occurrence and frequency of drought events in Skierniewice, central Poland, over the past 100 years (1923–2022), using historical meteorological data. Drought assessment was conducted using the standardised precipitation index (*SPI*), hydrothermal coefficient (*HTC*), thermal-precipitation index (Ped drought index) and climatic water balance (*CWB*). Based on the *SPI* classification, 34 dry years were identified during the study period. However, linear correlation analysis did not reveal statistically significant trends in *SPI* values over time, either on an annual basis or for individual months of the growing season. In contrast, correlation analyses of *HTC* and *CWB* values across the growing season showed a statistically significant negative linear trend for August, indicating increasing precipitation deficits during this month. Across all months, more periods are classified as dry according to *HTC* compared to *SPI* and Ped index, suggesting a greater sensitivity of this index to drought conditions. In the context of Skierniewice, the adopted *HTC* and *CWB* thresholds appear to accurately reflect drought conditions during spring and summer but may be overly restrictive for the later part of the growing season. Regardless of the index or classification criteria applied, droughts in Skierniewice have occurred relatively frequently, with severe events recorded both in the early and recent decades of the study period.

Keywords: climate change, climatic water balance (*CWB*), hydrothermal coefficient (*HTC*), Ped index, standardised precipitation index (*SPI*)

INTRODUCTION

Drought is one of the most significant natural hazards, impacting ecosystems, agriculture, water resources, and human societies worldwide. The availability of water in agricultural systems significantly influences crop growth and productivity, while water scarcity during key phenological stages may restrict plant development, decrease yields, and, under severe conditions, cause complete crop failure (Lipiec *et al.*, 2013; Klamkowski, Treder and Wójcik, 2015; Dietz, Zörb and Geilfus, 2021). With ongoing climate change, mean global temperatures are expected to rise over the coming decades, resulting in increased global aridity and greater crop water demand (Feng and Fu, 2013). Drought and its consequences for agriculture and water resources have become increasingly prevalent in many countries, including Poland (Treder *et al.*, 2009; Treder *et al.*, 2013). In the context of climate change, the frequency, intensity, and spatial distribution of drought events have become critical areas of research. Understanding historical drought patterns is essential for predicting future trends and developing effective adaptation strategies.

The study of drought has gained significant attention in recent decades due to its profound socio-economic and environmental impacts. Droughts are typically classified into meteorological, agricultural, hydrological, and socio-economic categories, each reflecting different aspects of water scarcity. Standardised precipitation index (*SPI*), climatic water balance (*CWB*) and other metrics are widely used to quantify and monitor drought conditions globally (Łabędzki and Bąk, 2014).

In Poland, research on drought has primarily focused on its impact on agriculture, as the sector is particularly vulnerable to water shortages. Studies have highlighted an increasing trend in the frequency and severity of droughts in the country, attributed to rising temperatures and changes in precipitation patterns. For instance, Łabędzki (2007) emphasised the growing need for effective drought risk management in Polish agriculture, while studies by Treder *et al.* (2004) and Kędziora *et al.* (2014) analysed the role of soil and vegetation in mitigating drought impacts.

Skierniewice, located in central Poland, with its long history of agricultural research, has been a focal point for studies on climatic variability and its effects on crop production. Its location offers a unique case study for analysing drought frequency due to its geographical location and climatic conditions (Treder *et al.*, 2024). Situated in a region characterised by a transitional climate, it experiences a mix of oceanic and continental influences, making it particularly sensitive to climatic variability. According to Doboszyński and Doboszyńska (1963), the location of Skierniewice is such that the data can be considered characteristic of a larger area of central Poland. Research by Doroszewski *et al.* (2014) underscored the region's vulnerability to drought due to its dependence on rainfall for agriculture. Additionally, studies have highlighted the importance of historical data for understanding the cyclical nature of droughts and their relationship with broader climatic phenomena, such as the North Atlantic Oscillation and El Niño-Southern Oscillation.

This study aims to investigate the occurrence and frequency of drought events in Skierniewice over the last 100 years (1923–2022). By analysing historical meteorological data, this research seeks to identify long-term trends and variations in drought patterns, contributing to a broader understanding of regional climate dynamics and their implications for water resource management and agriculture. The study also seeks to fill gaps in the literature by integrating long-term meteorological records with modern analytical techniques, offering insights into historical trends and future challenges posed by climate change.

MATERIALS AND METHODS

STUDY MATERIAL

The drought assessment was made for Skierniewice, located in central Poland (51.96° N, 20.16° E; 125 m a.s.l.). Meteorological drought was assessed using the standardised precipitation index (*SPI*), hydrothermal index (*HTC*), and thermal-precipitation index (Ped drought index). The occurrence of agricultural drought was assessed using the climatic water balance (*CWB*). The indices were calculated for a 100-year data series. The source material consisted of meteorological measurements in 1923–2022, recorded at a station located at the SGGW Experimental Field and at a station situated in the Pomological Orchard of the National Institute of Horticultural Research. The distance between the stations is approximately 500 m across open space. Data from the first station were available for 1923–2014, and data from the second station for 2015–2022. Weather data for certain months in 1939, 1940, and 1945 were not available due to wartime disruptions (1939: September–December; 1940: January–May; 1945: January–July).

STANDARDISED PRECIPITATION INDEX (*SPI*)

The *SPI* was designed to evaluate deviations in precipitation from the historical mean, providing a standardised measure of drought severity (McKee, Doesken and Kleist, 1993). The index is calculated by standardising precipitation values for a given time period and location. This process involves several steps:
1) distribution fitting: long-term precipitation data are fitted to an appropriate probability distribution, most often a gamma distribution, to account for the skewness of the precipitation data;
2) transformation into a normal distribution: after fitting a gamma distribution, precipitation values are transformed to a normal distribution using appropriate transformations, such as the cube root, to obtain a symmetrical data distribution;
3) standardisation: after transformation, the values are standardised, meaning that the mean is subtracted from each value and divided by the standard deviation; the formula for *SPI* can be written as:

$$SPI = \frac{f(P) - \mu}{\delta} \tag{1}$$

where: $f(P) = P^{1/3}$ normalised rainfall total, μ = average value of normalised precipitation series, δ = average standard deviation of the normalised precipitation series.

The *SPI* was calculated for individual years and months using Rain-Based Drought Index Calculation and Severity Assessment software (https://www.agrimetsoft.com). Since the variability of precipitation in Poland is very high (high standard deviation), the following classification of drought conditions was

adopted (Łabędzki, 2007): ≤−2.00 – extreme drought, −1.99 ≤ SPI ≤ −1.50 – severe drought, −1.49 ≤ SPI ≤ −0.50 – moderate drought.

HYDROTHERMAL INDEX (HTC)

The assessment of hydrothermal conditions for the period in which the research was carried out was based on the hydrothermal index (HTC) of Selyaninov (Kuchar et al., 2017).

$$HTC = \frac{10 \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} T_i} \qquad (2)$$

where: n = length of the period (days), P_i = rainfall on the i-th day (mm), T_i = average air temperature on the i-th day (°C); the values of each HTC rating class are as follows (based on Kuchar et al. (2017): ≤0.4 – extremely dry; 0.4 < HTC ≤ 0.7 – very dry; 0.7 < HTC ≤ 1.0 – dry; 1.0 < HTC ≤ 1.3 – quite dry

THERMAL-PRECIPITATION INDEX

The thermal-precipitation index (known also as Ped drought index) uses mean values and standard deviations of air temperature and precipitation. Positive values of Ped index correspond to the dry time or a warmer temperature regime, while negative values correspond to the wet weather. This index is calculated as follows (Podstawczyńska, 2007; Krawczyk, 2025):

$$Ped = \sum_{i=1}^{n} \left(\frac{Ti - Tm}{\sigma t} - \frac{Pi - Pm}{\sigma p} \right) \qquad (3)$$

where: Ti = mean monthly air temperature (°C), Tm = long-term mean monthly temperature (°C), σt = standard deviation of monthly temperature, Pi = monthly precipitation sum (mm), Pm = long-term mean monthly precipitation (mm), σp = standard deviation of monthly precipitation. Classification of the thermal-precipitation index values (according to Koleva and Alexandrov (2008) is presented as follows: $Ped < 0$ – wet period; $0 \leq Ped < 1$ – normal; $1 \leq Ped < 2$ – light drought; $2 \leq Ped < 3$ – moderate drought; $Ped \geq 3$ – extreme drought.

CLIMATIC WATER BALANCE (CWB)

The CWB is an indicator used to assess the moisture conditions of the environment by evaluating available water resources. It is calculated as the difference between precipitation and evapotranspiration over a specific period:

$$CWB = P - ETo \qquad (4)$$

where: P = precipitation (mm), ETo = evapotranspiration (mm).

Due to the lack of some meteorological inputs (solar radiation measurements were not available for part of the study period), ETo (acc. to Penman–Monteith method) was estimated with the help of an AI model. An artificial neural network (ANN) technique was applied due to the high quality of ETo prediction, as presented by Treder et al. (2023). Machine learning models offer advantages over empirical equations since they require no knowledge of internal variables and provide simple solutions for nonlinear and multi-variable functions. The usefulness of the machine learning methods for determining evapotranspiration when access to meteorological data is limited was demonstrated by Adnan et al. (2017), Antonopoulos and Antonopoulos (2017), and El-Magd, Baraka and Eid (2023). The ANN algorithm comprises three layers: an input layer, a hidden layer, and an output layer. In the ANN algorithm, data are placed in the input layer to train the model, weights are determined in the hidden layer, and prediction results are generated in the output layer (Xu et al., 2018). This method learns from a training dataset and stores the data pattern as weighted neuron connections. After training, when new data are applied, the ANN recognises and classifies patterns based on the input data. To set up the model, the meteorological variables were used as inputs: mean and maximum air temperatures, average air humidity, vapour pressure deficit (VPD), average solar radiation, extra-terrestrial solar radiation, and day of year. A negative CWB value signifies that evapotranspiration surpasses precipitation, leading to potential water deficits. This metric is particularly useful in climatological and hydrological analyses, as well as in operational activities of agrometeorological services. The values of each CWB rating class (based on long-term own observations according to Wójcik, Treder and Zbudniewiek (2018)) are presented as follows: $CWB \leq -70$ extremely dry; $-70 < CWB \leq -50$ – very dry; $-50 < CWB \leq -30$ – dry; $-30 < CWB \leq -20$ – quite dry.

RESULTS AND DISCUSSION

CLIMATE TRENDS AND DROUGHT RISK IN SKIERNIEWICE

Meteorological drought is a significant atmospheric phenomenon that constrains agricultural development in numerous regions, often leading to reduced crop yields (Reinermann et al., 2019; Rolbiecki et al., 2022). Although it has been the focus of extensive scientific research, forecasting meteorological drought remains challenging (Vicente-Serrano et al., 2022). Typically, meteorological drought is assessed retrospectively using historical data (Przybylak et al., 2020; Bartoszek et al., 2021).

Over the past century (1923–2022), Skierniewice, located in central Poland, has experienced a significant increase in average air temperature (Treder et al., 2024) – see Figure 1. This trend aligns with the broader phenomenon of global climate change, marked by rising temperatures worldwide. Despite this pronounced warming, regional precipitation levels have not exhibited a similar upward trend (Treder et al., 2025) – see Figure 1. The lack of a rising trend in rainfall, combined with higher temperatures, has exacerbated the risk of droughts, posing challenges for agriculture, water management, and local ecosystems. This imbalance between temperature and precipitation trends highlights the pressing need to understand the frequency and intensity of droughts in Skierniewice over the past 100 years. Such understanding is essential for developing effective adaptation strategies to mitigate the adverse impacts of climate change in the region.

STANDARDISED PRECIPITATION INDEX

The SPI values showed high variability on an annual basis during the 100-year study period (Fig. 2). The analysis of the linear correlation between SPI values and time did not reveal statistically
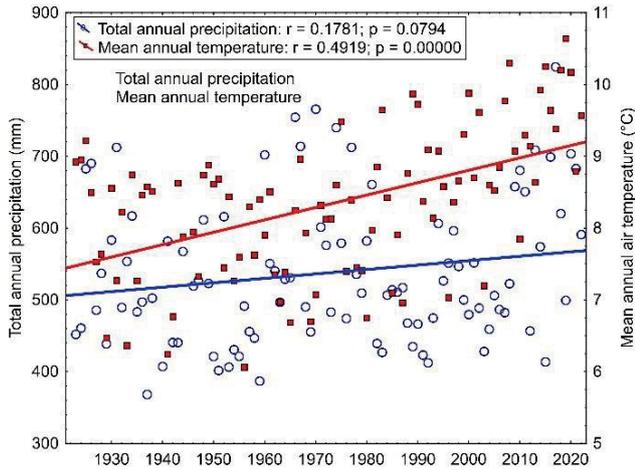
Fig. 1. Course of average annual air temperature and total annual precipitation in Skierniewice, 1923–2022; source: own study

Fig. 2. Course of standardised precipitation index (*SPI*) values in Skierniewice from 1923 to 2022; circles indicate pronounced sequences of dry years (*SPI* threshold of –0.5 is marked with a yellow line); source: own study

significant long-term trends on an annual scale. Similarly, no significant temporal trends were observed in monthly *SPI* values during the vegetation period. For all months of the vegetation period, the probability of error for the calculated correlation coefficients between study years and *SPI* values exceeded 5% (Fig. 3). A statistically significant increase in *SPI* value was confirmed only for the winter months (Fig. 4), which is likely related to the rising winter precipitation totals. Overall, the presented *SPI* analysis for Skierniewice does not support an opinion the drought frequency has increased during the growing season.

     According to the adopted classification, 34 dry years were identified in the 1923–2022 period (Tab. 1). Of these, three were
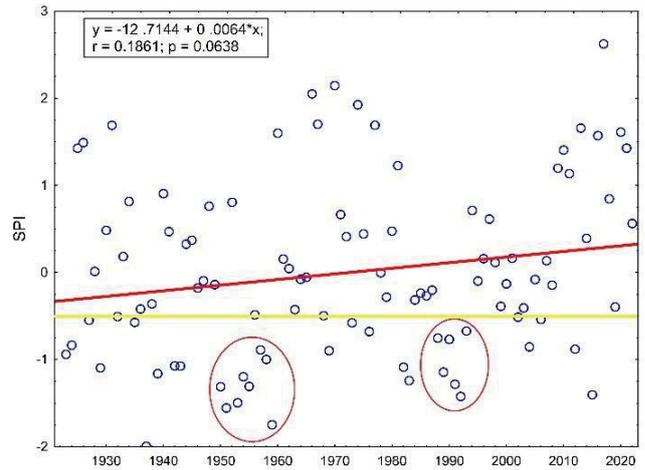
classified as severely dry (1951, 1953 and 1959) and one as extremely dry (1937). Consecutive dry years (sequences of dry years) are very unfavourable for the economy, especially for agriculture. During the study period, four two-year sequences of summer drought were recorded (1923–1924, 1942–1943, 1950–1951 and 1982–1983) and two three-year sequences (1953–1955 and 1957–1959). These two-year sequences were separated only by 1956, when the *SPI* value was –0.484, i.e. at the borderline between normal and moderately dry. During the decade of 1950–1959, as many as eight years were classified as dry. The longest
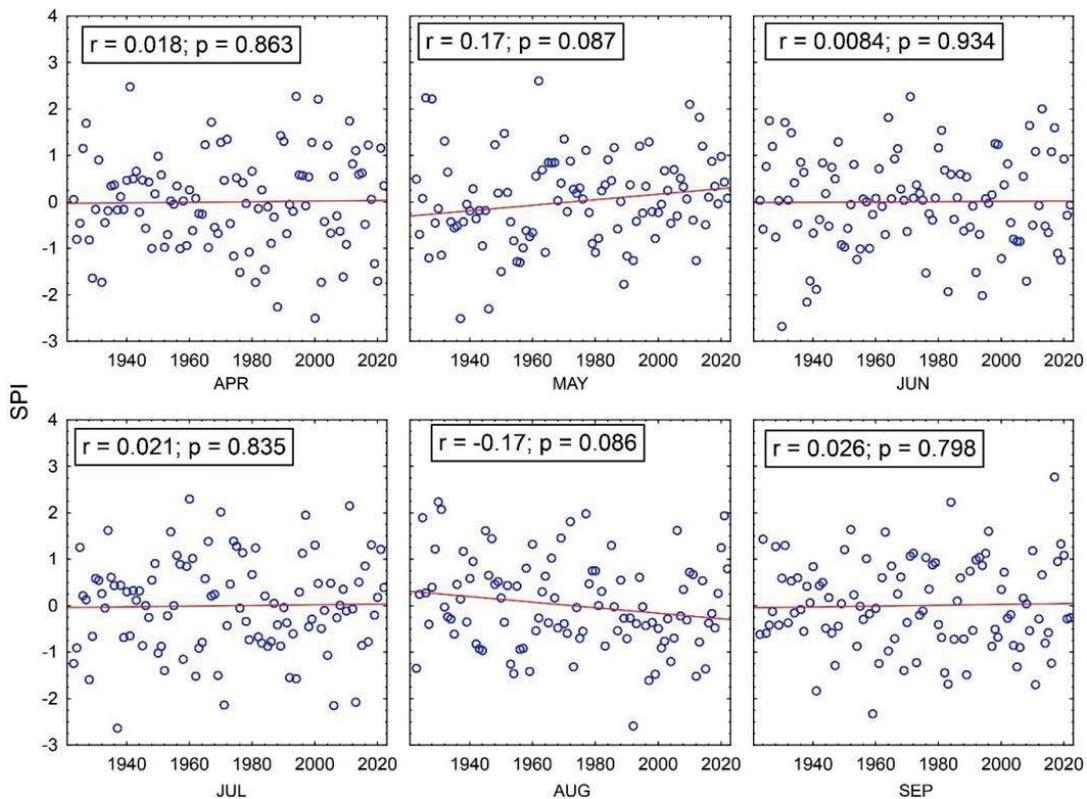

Fig. 3. Standardised precipitation index (*SPI*) values in the months of April–September in Skierniewice, 1923–2022; *r* = correlation coefficient, *p* = *p*-value; source: own study
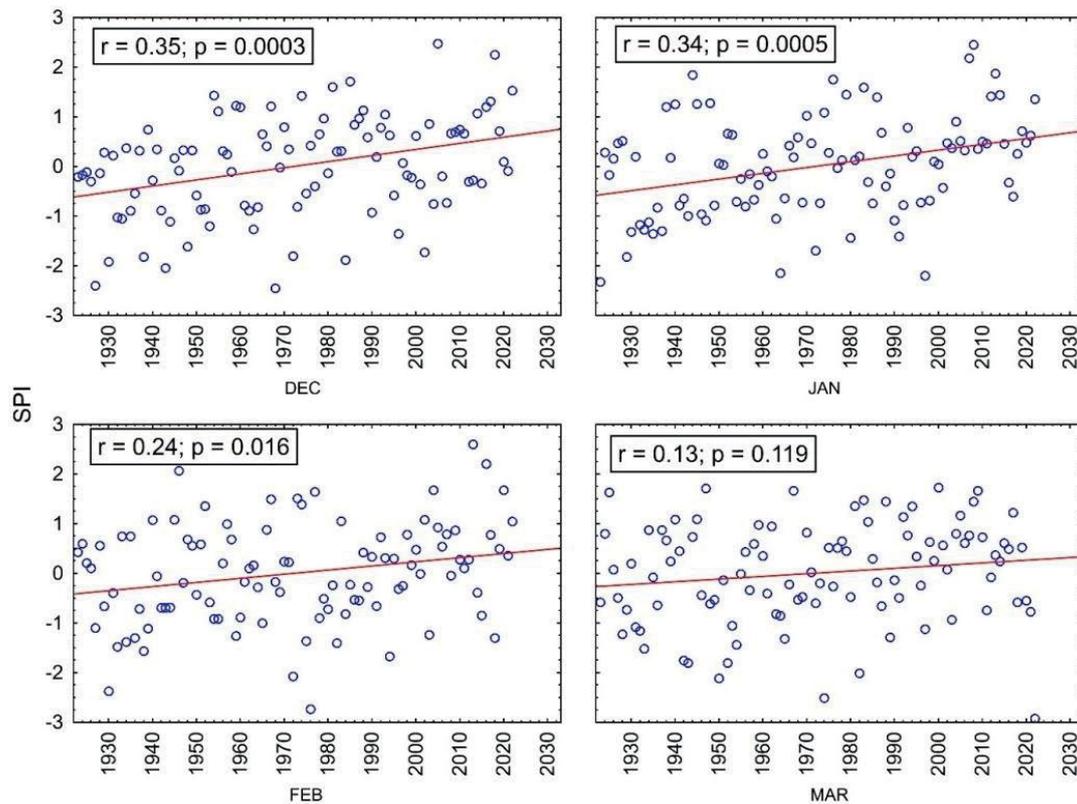
Fig. 4. Standardised precipitation index (*SPI*) values in the period December–March in Skierniewice, 1923–2022; *r* = correlation coefficient, *p* = *p*-value; source: own study

Table 1. Frequency of drought occurrence (period 1923–2022) based on the adopted standardised precipitation index (*SPI*) classification

Period	Number of months in drought category (year)			
	moderately dry	severely dry	extremely dry	total
Apr	21	7 (1929, 1932, 1976, 1981, 2002, 2009, 2020)	2 (1988, 2000)	30
May	22	2 (1950, 1989)	3 (1937, 1946, 1947)	27
Jun	23	6 (1939, 1941, 1976, 1983, 1992, 2008)	3 (1930, 1938, 1994)	32
Jul	22	5 (1928, 1962, 1969, 1992, 1994)	4 (1937, 1971, 2006, 2013)	31
Aug	25	2 (1997, 2012)	2 (1984, 1992)	29
Sep	27	3 (1941, 1983, 2011)	2 (1951, 1954)	32
Years 1923–2022	30	3 (1951, 1953, 1959)	1 (1937)	34

Source: own study.

period of consecutive dry years (six years) occurred from 1988 to 1993 (Fig. 2).

In the monthly analysis, June and September were most frequently classified as dry months (32 times), while May was least frequent (27 times). July had the highest frequency of extreme droughts (four cases: 1937, 1971, 2006, 2013). June and July were categorised as severely or extremely dry on nine occasions (Tab. 1).

The *SPI* has certain limitations; for instance, since it is based solely on a precipitation, it does not reflect actual soil moisture conditions and therefore cannot be directly linked to plant water needs. Nevertheless, due to its simplicity, flexibility, and ability to effectively capture precipitation anomalies, the *SPI* remains a widely used and valued indicator (Łabędzki, 2007). The results presented above provide important insights into the climatic characteristics of central Poland, a region long regarded as prone

to frequent droughts. The *SPI* calculated at various timescales illustrates the relationship between the number of drought-affected months and the frequency and duration of drought periods. These findings are consistent with those of Łabędzki (2007), who demonstrated that *SPI* is a reliable tool for identifying and characterising local drought events. The use of multiple timescales enables the detection of both the frequency and duration of meteorological droughts caused by precipitation deficits in preceding months.

Łabędzki's (2007) study in the Bydgoszcz region (central Poland), based on 145 years of monthly precipitation data, showed that approximately 30% of months experienced drought conditions across the 3-, 6-, 12-, 24-, and 48-month timescales. These results are consistent with other regional studies. Kuśmierek-Tomaszewska and Żarski (2021), using *SPI* to examine drought frequency and intensity in central Poland over a 60-year period (1961–2020), reported no significant increase in either meteorological drought frequency or intensity, corroborating the findings of this study. According to their analysis, the frequency of meteorological drought during the active plant growth period was 30.0%, with severe and extreme droughts comprising 6.7%. A detailed analysis of seasonal *SPI* variability in Poland (spring, summer, and autumn) was conducted by Kalbarczyk and Kalbarczyk (2022) using data from 1951 to 2020. They found that droughts occurred more frequently in spring and autumn, approximately every four to five years, than in summer, where they occurred roughly every seven years. In areas affected by extreme drought, precipitation typically fell to 50% of the climatic norm, while air temperatures fluctuated above or below the norm between –1.0°C and +1.0°C. Differences in reported drought frequency between studies mainly result from analyses conducted over varied timeframes and different regions of Poland.

The *SPI* may be considered a primary index for initial drought hazard evaluation in a given region. However, to achieve a more accurate understanding of agricultural drought impacts, it is necessary to employ additional indices that account for evapotranspiration, soil moisture, groundwater depth, and crop productivity. It is important to emphasise that using multiple drought indices, rather than relying on a single one, provides a more comprehensive assessment of drought events. Further research into other indicators is essential to develop a system that most accurately reflects drought conditions in specific areas. Additionally, it is crucial to determine which *SPI* timescale best captures agricultural and hydrological drought under the climatic conditions of central Poland.

HYDROTHERMAL INDEX

The correlation analysis between *HTC* values for consecutive months of the growing season (May–Sep) and the subsequent study years revealed a significant negative linear correlation coefficient only for August ($r = -0.28$, $p = 0.0049$) – Figure 5. This significant decrease in *HTC* over time indicates increasing precipitation deficits in August.

The category of dry months most frequently included September (62 occurrences) and June (60 occurrences) – Table 2. According to this classification, over the past century, September and June were recorded as extremely dry in 11 and 9 instances, respectively.
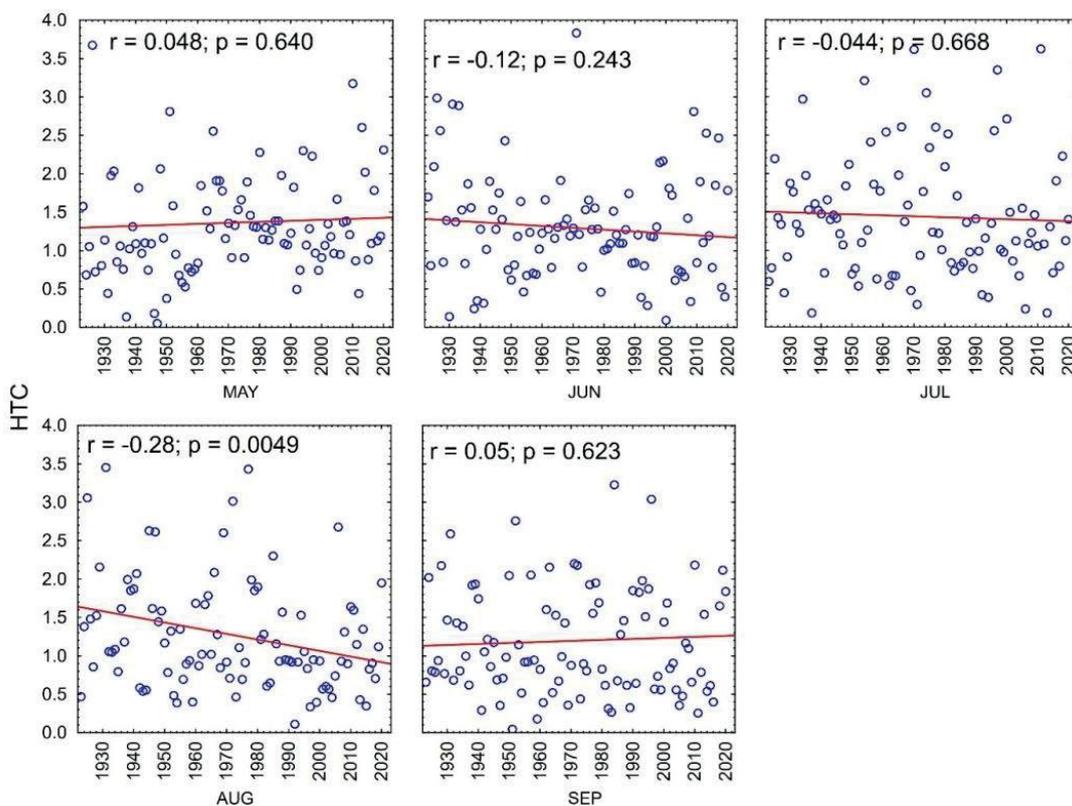

Fig. 5. Hydrothermal index (*HTC*) values in the months of May–September in Skierniewice, 1923–2022; r = correlation coefficient, p = *p*-value; source: own study

Table 2. Frequency of drought (1923–2022) based on the hydrothermal index (*HTC*) classification

Month	Number of months in drought category (year)				
	quite dry	dry	very dry	extremely dry	total
May	25	21	7 (1924, 1931, 1954, 1955, 1956, 1992, 2012)	4 (1937, 1946, 1947,1950)	57
Jun	27	16	8 (1950, 1954, 1955, 1958, 1979, 2003, 2006, 2018)	9 (1930, 1938, 1939, 1941, 1992, 1994, 2000, 2008, 2019)	60
Jul	16	16	11 (1923, 1928, 1930, 1932, 1958, 1962, 1963, 1964, 1969, 1992, 2004)	5 (1937, 1971, 1994, 2006, 2013)	48
Aug	15	24	15 (1923, 1942, 1943, 1944, 1953, 1956, 1973, 1975, 1983, 1984, 2001, 2002, 2003, 2004, 2013)	5 (1954, 1992, 1997, 1999, 2015)	59
Sep	7	24	20 (1923, 1932, 1937, 1946, 1954, 1964, 1966, 1973, 1981, 1985, 1988, 1991, 1997, 1999, 2004, 2006, 2009, 2014, 2015, 2016)	11 (1941, 1947, 1951, 1959, 1961, 1969, 1982, 1983, 1989, 2005, 2011)	62

Source: own study.

The Selyaninov hydrothermal coefficient is used in practice as a quantitative indicator of the heat-to-moisture ratio. It has been employed to analyse the occurrence of meteorological droughts in various parts of Poland. Skowera (2014) assessed trends in hydrothermal conditions during the intensive vegetation period using *HTC*, based on data from 1971–2010. During this time, the highest drought frequency in each month was observed in central and midwestern Poland (Warsaw, Łódź, Poznań), while lower drought frequencies were reported in northern and southeastern regions. August and September were the driest months of the vegetation period. In the present study, conducted in Skierniewice (located approx. 50 km from Łódź), a significant long-term decrease in *HTC* in August confirms an increasing precipitation deficit in this month. A study by Samborski (2024) in Zamość (eastern Poland) reported rising air temperatures and declining precipitation over 47 years (1976–2022), resulting in a downward trend in *HTC*. According to his findings, extremely dry conditions were observed in the second half of the growing season (July–October). In general, more meteorological drought occurrences in Poland have been identified using *HTC* compared to other indices such as *SPI* (Baryła *et al.*, 2016; Szyga-Pluta, 2018). This discrepancy can be attributed to the stricter classification criteria of the *HTC* index.

The Selyaninov hydrothermal coefficient distinguishes four drought severity classes, whereas the *SPI* distinguishes only three. For all growing season months, the number of drought classifications was significantly higher when using *HTC* than *SPI* (Tab. 2). While the number of dry months identified depends on the adopted classification thresholds, the high frequency of September droughts indicated by *HTC* requires further explanation. As indicated by the *HTC* formula, the index is calculated using a fixed ratio between air temperature and precipitation. For instance, to reach the threshold for the first drought category (*HTC* ≤ 1.3), monthly precipitation must be less than or equal to 3.9 mm per 1°C of average air temperature. This threshold is applied uniformly to all months of the growing season and does not account for incoming solar radiation.

In Skierniewice, September often features relatively high temperatures and low precipitation. However, this period is generally less critical for most crops, since shorter days and reduced solar radiation lead to lower transpiration rates. Thus, the current drought threshold for late summer (end of the growing season) may be too stringent. A similar issue has been noted in the construction of climadiagrams illustrating drought periods. A potential solution would be to adopt differentiated drought thresholds for various stages of the growing season, an approach already proposed by Klamkowski and Treder (2019) for climadiagrams.

THERMAL-PRECIPITATION INDEX (PED DROUGHT INDEX)

The thermal-precipitation index proposed by Ped (1977), which takes into account mean air temperature and total precipitation, enables the identification of dry and wet periods against long-term climatic norms (Podstawczyńska, 2010). In the present study, correlation analysis of Ped drought index values for successive months of the growing season and subsequent study years revealed a statistically significant positive linear relationship in June ($r = 0.30$, $p = 0.0019$) and August ($r = 0.37$, $p = 0.0001$) – Figure 6. The observed increase in the index over time points to a progressive intensification of rainfall deficits during June and August.

Dry months were most frequently observed in April, July, and September (26 cases), representing values markedly lower than those derived from the *HTC* index, yet comparable to those obtained using the *SPI*. Based on the Ped drought index, extreme droughts were relatively rare over the past century, occurring twice in May, July and August, and never in September (Tab. 3). Across all months of the growing season, substantially fewer drought classifications were identified when applying the Ped index than with the *HTC*.

Under Polish conditions, Krawczyk (2025) identified periods of drought and evaluated the efficacy of various drought indices (Ped, *HTC*, *SPI*) using data from 46 meteorological stations for 1966–2020 (April–September). The frequency of dry
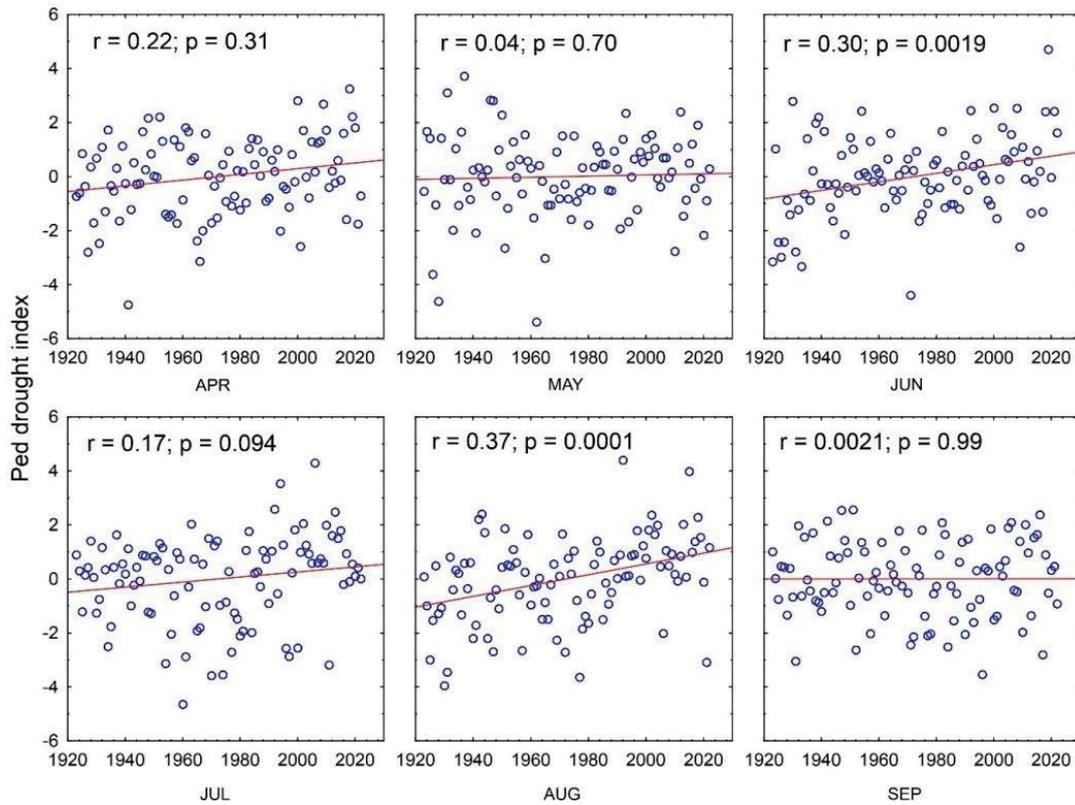
Fig. 6. Thermal-precipitation index (Ped drought index) during the vegetation period in Skierniewice, 1923–2022; r = correlation coefficient, p = p-value; source: own study

Table 3. Frequency of drought occurrence (period 1923–2022) based on the adopted Ped drought index classification

Month	Number of months in drought category (years)			
	light drought	moderate drought	extreme drought	total
Apr	20	5 (1948, 1952, 2000, 2009, 2019)	1 (2018)	26
May	17	5 (1946, 1947, 1950, 1993, 2012)	2 (1931, 1937)	24
Jun	14	8 (1930, 1939, 1954, 1992, 2000, 2008, 2018, 2021)	1 (2019)	23
Jul	20	4 (1963, 1992, 2002, 2013)	2 (1994, 2006)	26
Aug	16	5 (1942, 1943, 2002, 2013, 2018)	2 (1992, 2015)	23
Sep	19	7 (1942, 1947, 1951, 1982, 2006, 2011, 2016)	0	26

Source: own study.

conditions varied depending on the index applied. The author observed that dry conditions were detected less frequently by the *SPI* than by the other indices, suggesting that *SPI* may underestimate drought severity. For the Ped index, the frequency of dry months gradually increased until August and then decreased in September. In the present study, the increase in this index over time reflects intensifying rainfall deficits, particularly in June and August. A significant rise in precipitation deficits in August was also confirmed by the *HTC*.

Similar observations were reported by Podstawczyńska (2007) for Łódź (approx. 50 km from Skierniewice). The author

evaluated long-term data from 1904–2000 in terms of thermal-precipitation conditions using the Ped drought index. Among the months showing the strongest trends across all analysed precipitation characteristics, August stood out as the month in which maximum daily precipitation totals decreased, while the Ped index increased.

Skowera, Wojkowski and Ziernicka–Wojtaszek (2016) characterised thermal-precipitation conditions in the Opole Voivodeship based on mean monthly air temperature and precipitation data from 1981–2010. The authors observed that from June to August, the value of the Ped index increased, while

in January it decreased, which indicates an increasing drought risk in summer months and more humid conditions in winter. Comparable results were obtained by Treder *et al.* (2025) for Skierniewice, who recorded a significant increase in precipitation only during winter months.

Differences in drought assessments using various indices were also reported by Kopcińska *et al.* (2018). Based on data from the Opole Voivodeship for May–September 1981–2010, the authors found higher frequencies of dry conditions according to the *HTC* (36% on average) compared with the *SPI* (35%) and, in particular, the Ped index (25%). Since air temperature has changed significantly in recent years (Treder *et al.*, 2024), it is essential to consider the thermal influence on drought occurrence. An advantage of the Ped and *SPI* indices lies in their ability to compare a given period with long-term values characteristic of a specific area, provided that an adequately long measurement series is available. However, Kopcińska *et al.* (2018) emphasised that both indices do not account for the systematic increase in precipitation variability documented, for example, by Kożuchowski (1996). This limitation may reduce their usefulness in detecting the evolving nature of droughts under changing climatic conditions.

CLIMATIC WATER BALANCE

Agricultural drought is closely linked to plant cultivation conditions. Therefore, the most appropriate criterion for its assessment seems to be the climatic water balance. Currently, due to a marked increase in air temperature leading to enhanced evapotranspiration, the concept of *CWB* is commonly used to assess drought risk. It also serves as a basis for estimating crop irrigation needs (Treder *et al.*, 2023). This index is employed in the Agricultural Drought Monitoring System managed by the Institute of Soil Science and Plant Cultivation (Pol.: Instytut Uprawy, Nawożenia i Gleboznawstwa – IUNG-PIB) in Puławy, which identifies areas in Poland where drought conditions cause crop losses. Moreover, *CWB* is featured in the Irrigation Decision Support System dedicated to horticultural crops, developed by the National Institute of Horticultural Research (Pol.: Instytut Ogrodnictwa – Państwowy Instytut Badawczy) in Skierniewice (Treder *et al.*, 2013).

The *CWB* is a comprehensive indicator, incorporating key meteorological variables essential to drought formation – namely, precipitation and evaporation. The balance between these two components is also crucial for understanding the transition from meteorological drought to more advanced stages, such as soil, agricultural, and hydrological drought. Unlike indices based solely on precipitation, the climatic water balance can weaken or strengthen drought evaluation through the incorporation of additional information about moisture conditions (Łabędzki and Bąk, 2014).

As with the *HTC* analysis, a significant decreasing trend in *CWB* for August was observed ($r = -0.24$, $p = 0.0178$) – Figure 7. The second index statistically confirms the increasing precipitation deficit in August.

Although air temperatures have risen, precipitation levels in Poland have not demonstrated significant long-term trends since the 1980s (Żmudzka, 2002; Wibig, 2009). However, precipitation variability has increased, with the coefficient of variation rising from 10% (1861–1990) to 16%, and then to 19% during 2001–2018 (Kożuchowski, 1996; Ziernicka-Wojtaszek and Kopcińska,
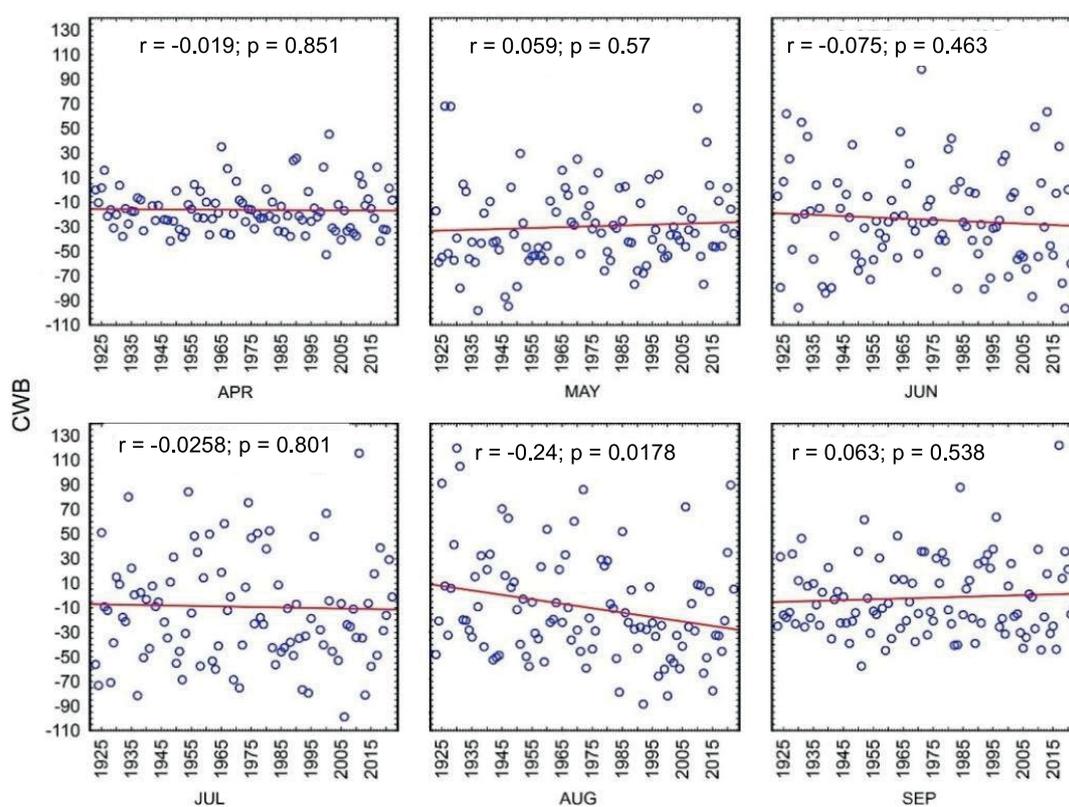

Fig. 7. Climatic water balance (*CWB*) values during the vegetation period in Skierniewice, 1923–2022; *r* = correlation coefficient, *p* = *p*-value; source: own study

2020). This rising variability contributes to more frequent extreme events, including both intense rainfall and droughts.

A detailed analysis of *CWB* trends and spatial patterns in Poland during 1951–1980, 1971–2000, 1981–2010, and 1991–2020 was performed by Ziernicka-Wojtaszek (2023). According to the author, the period 1971–2000 represented a transitional phase, during which temperature changes began to manifest. The subsequent periods saw a systematic temperature increase, which led to a significant rise in field evaporation (Bartczak, Krzemiński, and Araźny, 2024). Consequently, the share of wet or optimally moist areas in Poland decreased from 70% to only 31% between 1951 and 2020 (Ziernicka-Wojtaszek, 2023).

Data for 1923–2022 from Skierniewice indicate that, based on the *CWB* classification, May (67 cases) and June (59 cases) were most frequently classified as dry months, while September was least frequent (23 cases) – Table 4. Over the past century, May and June were classified as extremely dry 7 and 13 times, respectively, while September was not classified as extremely dry at all. The high frequency of months labelled as dry stems from the

crops such as cereals have been reported when the water table is at a depth of 150–200 cm (Kahlown and Ashraf, 2005). Observations in spring 2025 (March–April) in the experimental orchard in Skierniewice showed groundwater levels below 2 m (unpublished data). Under Skierniewice conditions, the adopted threshold for "extremely dry" months is appropriate for summer, but appears too high for the late growing season (e.g., September). To enhance the accuracy of drought frequency assessments, it is necessary to consider additional factors, such as rooting depth, soil water-holding capacity, and crop coefficients (K_c) used to estimate actual crop evapotranspiration (ET_c).

Regardless of the assessment index or classification thresholds applied, droughts in Skierniewice have occurred relatively frequently. Severe droughts were observed both a century ago and in recent years. By analysing the data presented in the Tables 1–2 and 4, it is possible to identify years in which the same months were simultaneously classified as "very dry" (severe drought) or "extremely dry" across the *SPI*, *HTC*, and *CWB* indices; a total of 23 such cases were recorded (Tab. 5). When months classified as

Table 4. Frequency of drought occurrence (period 1923–2022) based on the climatic water balance (*CWB*) classification

Month	Number of months in drought category (year)				
	quite dry	dry	very dry	extremely dry	total
Apr	20	25	1 (2000)	0	46
May	9	29	22 (1924, 1925, 1927, 1929, 1934, 1936, 1954, 1955, 1956, 1958, 1959, 1964, 1971, 1979, 1980, 1981, 1990, 1992, 1993, 1999, 2000, 2011)	7 (1931, 1937, 1946, 1947, 1950, 1989, 2012)	67
Jun	13	17	16 (1935, 1949, 1950, 1951, 1955, 1963, 1970, 1976, 1990, 2003, 2004, 2005, 2006, 2010, 2015, 2022)	13 (1924, 1930, 1938, 1939, 1941, 1954, 1983, 1992, 1994, 2000, 2008, 2018, 2019)	59
Jul	8	19	11 (1923, 1939, 1950, 1952, 1958, 1962, 1963, 1969, 1983, 2004, 2015)	8 (1924, 1928, 1937, 1971, 1992, 1994, 2006, 2013)	46
Aug	16	19	13 (1942, 1943, 1954, 1959, 1973, 1983, 1997, 1999, 2001, 2002, 2004, 2012, 2013)	4 (1984, 1992, 2000, 2015)	52
Sep	16	6	1 (1951)	0	23

Source: own study.

the adopted classification thresholds, which may not always reflect actual environmental conditions. The criterion used in this study for classifying early growing season months as "quite dry" and "dry" (–20 mm to –50 mm) may be too lenient, considering lower evapotranspiration rates and higher soil moisture after winter. In contrast, for summer months, when evapotranspiration increases and soil water reserves are often depleted, this threshold more accurately reflects plant water status.

A key factor in water balance is the contribution of groundwater, which should be acknowledged as part of the crop's water supply. The effectiveness of groundwater support diminishes with increasing distance between root zone and water table (Hopmans, Grismer, and Grimes, 2002). Optimal yields for

Table 5. Years in which specific months were classified as "very dry" or "extremely dry" according to the standardised precipitation index, hydrothermal index, and climatic water balance

Month	Year
May	1937, 1946, 1947, 1950
Jun	1930, 1938, 1939, 1992, 1994, 2008
Jul	1928, 1937, 1962, 1969, 1971, 1992, 1994, 2006, 2013
Aug	1984, 1992, 1997
Sep	1951

Source: own study.

"moderate" or "extreme drought" according to the Ped index were also included, consistency with the remaining indices was found in only 14 cases: 1937, 1946, 1947, and 1950 (May); 1930, 1939, 1992, and 2008 (June); 1992, 1994, 2006, and 2013 (July); 1992 (August); and 1951 (September).

CONCLUSIONS

Climatic changes observed in central Poland have substantial implications for regional water resources, particularly during the spring and summer months. These changes intensify drought conditions and pose a serious threat to agricultural productivity. Over the past century (1923–2022), Skierniewice has experienced a significant increase in average air temperature. Despite this pronounced warming trend, precipitation levels have remained relatively stable, failing to offset the effects of increased evapotranspiration. This imbalance heightens the risk of drought, creating major challenges for agriculture, water management, and local ecosystems. The analysis revealed that the hydrothermal coefficient (*HTC*) classified more periods as dry compared to the standardised precipitation index (*SPI*) and the Ped index. The Ped index identified fewer extreme drought events, indicating that it provides a more conservative assessment of drought severity under the climatic conditions of central Poland. While the *SPI* effectively describes deviations in precipitation, it does not account for thermal conditions and therefore underestimates plant water demand. Consequently, indices such as the *HTC* and climatic water balance (*CWB*), which integrate both precipitation and temperature, are more suitable for identifying agricultural drought periods. The results for Skierniewice indicate that the adopted *HTC* and *CWB* thresholds accurately reflect drought conditions during spring and summer, although they may be overly restrictive for the later part of the growing season.

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CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interest.

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