INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2023, 37, 425-433
doi: 10.31545/intagr/171945

Assessment of maize water requirements and precipitation deficits and excesses in central-eastern Poland

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Received June 27, 2023; accepted September 6, 2023

A b s t r a c t. Satisfying the water needs of the maize crop in central-eastern Poland was assessed in the years 2001-2021 using meteorological data obtained from seven Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) stations located at Białowieża, Legionowo, Pułtusk, Siedlce, Szepietowo, Terespol and Warszawa. During maize growing season water reserves were assessed based on the climatic water balance. The optimum precipitation for every month of the maize growing season was determined by means of the method offered by Klatt. Precipitation deficits and excess were calculated on the basis of the average monthly air temperatures and monthly atmospheric precipitation totals for moderately firm soils. The trends method with linear regression equations was applied in order to determine changes in the examined parameters. In central-eastern Poland, during the maize growing seasons in 2001-2021, water deficits were most frequent in May (on average 12 events occurred throughout the study period). The highest values for the precipitation deficits occurred in the Pułtusk area. The average deficit from May to September was 135 mm. Maize water demand was most satisfactorily met in the Terespol area. An analysis of the linear trend gradient revealed that at Siedlce, the greatest tendency for an increase in water deficits occurs in May (on average, by 22 mm per 10 years). Also, at Terespol a positive tendency was noted in August, the trend gradient being 2.83.

K e y w o r d s: maize, climatic water balance, optimum precipitation, water deficits, central-eastern Poland

1. INTRODUCTION AND OBJECTIVE OF THE WORK

Progressing climate change is contributing to a global increase in air temperature and altering atmospheric precipitation patterns. Also, extreme atmospheric events are becoming increasingly frequent. Future climate change scenarios show that agriculture will suffer from water shortages with increasing frequency. Agricultural operation planning will have to accommodate any changes, by *e.g.* introducing earlier sowing dates and crop plant harvest times (Marcinkowski and Pniewski, 2018). Moreover, the projected increases in temperatures due to climate change will increase crop water demand (Nelson *et al*., 2009). An increasing frequency of droughts would pose a challenge for water resource management whereas increases in the demand for food stimulates competition among water users. From the perspective of food production, maize is the main crop cultivated in the world (Huang, 2007). It is, however, very sensitive to prolonged water shortages (Mueller *et al*., 2013). At present, drought is the most serious threat to maize cultivation (Campos *et al*., 2013; Lobell *et al*., 2014; Sammons *et al*., 2014), 20-25% of all the fields where maize is grown around the world are being affected by pressure from drought (Golbashy *et al*., 2010). Drought reduces maize leaf area and the leaf content of chlorophyll, it affects photosynthesis, and eventually yield performance is reduced (Athar and Ashraf, 2005). Plants which are

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subjected to a moderate but prolonged drought event switch off their metabolism and finally die due to stomata closure and the inhibition of gas exchange (Jaleel *et al*., 2007). The closure of stomata reduces the water availability for cells because of poor hydraulic conductivity from the roots to the leaves. Although declining hydraulic conductivity reduces the nutrient supply to the stem, it also prevents embolism in the xylem and may become an adaptive response. Osmotic regulation is another method whichplants adopt in order to cope with drought-related stress. The synthesis of dissolved substances, such as polyols and proline, under the stress conditions caused by drought prevents water loss from cells, and plays an important part in turgor pressure maintenance (Blum, 2005; DaCosta and Huang, 2006). Also, the occurrence of drought at the initial stages of development (plant emergence) leads to poor crop condition and, under extreme conditions, it may result in a total crop failure (Ibrahim *et al*., 2001; Yang *et al*., 2004). On a global scale, drought may contribute to a diminished maize yield performance which is potentially as much as 50% lower (Tai *et al*., 2011; Wang *et al*., 2003). Maize has a very well-developed root system which makes it possible for the crop to acquire water from deeper soil strata and, as a result, maize suffers less than other plant species from short-term water shortages (Fageria, 2013; Paluszek, 2011). Chen *et al*. (2020) has demonstrated that sporadic deep ploughing encourages maize root development in clay soil, and this is a useful technique while developing strategies for counteracting seasonal drought-related stress. The operation may increase the water content of soil during stress events because it enhances soil hydraulic properties through the homogenisation of the rhizosphere in the soil profile.

Drought-related stress is the most important abiotic factor limiting crop plant growth, development and yield potential (Bruce *et al*., 2002; Khalili *et al*., 2013; Abolhasani and Saeidi, 2004; Banziger *et al*., 2002). The estimation of crop plant water demand is of importance from the standpoint of both water management and sustainable agriculture (Djaman *et al*., 2018). Many authors have suggested various methods for determining agricultural drought (Jędrejek *et al*., 2022; Kędzior and Zawadzki, 2017; Kuśmierek-Tomaszewska and Żarski, 2021; Łabędzki and Bąk, 2014; Pińskwar *et al.,* 2020; Ziernicka-Wojtaszek, 2021). Plant water demand may be defined as the amount of water necessary to produce high yields, and its level may be expressed *e.g.* by means of the optimum precipitation. The highest water demand for all plants occurs at the final stages of vegetative growth and at the beginning of generative development. These are the widely known critical stages of water demand and they are different for individual species and cultivars of crop plants. A shortage or excess of actual precipitation as compared with optimum precipitation may result in reduced yields (Dzieżyc, 1988). Maize water requirements are substantial even with effective management and a low transpiration coefficient. Nevertheless, long-term precipitation totals do not necessarily fully meet maize water demands because actual precipitation abundance is to a great extent affected by its distribution throughout the growing season (Sulewska, 2007). Observations which have been made in recent years have confirmed the thesis that, under Polish conditions, maize yields were affected by precipitation totals rather than by the average air temperature during the growing season. Also, it was demonstrated that excessive precipitation of over 350-400 mm (from May to September) resulted in lower maize grain yields, particularly when accompanied by low air temperatures (Sulewska, 2004). In order to meet an increased water demand, it is necessary to precisely estimate the quantity of water used by crops.

The objective of the present work is to analyse the climatic water balance, and estimate the precipitation deficits during the maize growing season in central-eastern Poland

2. MATERIALS AND METHODS

The boundary between the areas of western and eastern Europe runs through the teritory of Poland and its location is connected with both climatic and biogeographical factors which translate into the differences between the oceanic and continental type of the climate. According to Kondracki (1994), the study area includes the Mazowsze-Podlasie Lowlands which are classified as sub-provinces of the Central Polish Lowlands, and they also include the Southern Podlasie Valley and the southern part of the Northern Podlasie Lowland as well as the following mesoregions: the Lower Narew Valley, Warszawa Basin and Włodawa Hump. In the west of the study area, the Vistula River constitutes the hydrographic border, the Narew and its tributary, the Wkra are the northern border, the Bug, which connects with the Narew, constitutes the boundary in the east and the Wieprz in the south-east of the area. The Oder glaciation encompassed the whole of the Mazowsze-Podlasie Lowlands (Fig. 1). The mesoclimate of the region displays variations due to surface features. Continental characteristics are increasingly prevalent in the easterly direction, they are associated with the length of the winter period and extreme temperatures during the winter months. The Southern Podlasie Lowland reaches an elevation of 150-200 m above sea leval, it even reaches above 200 m in several places. The lowland is a part of the colder climatic

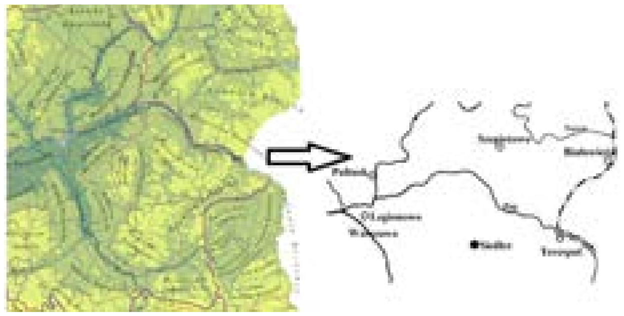

Fig. 1. The study area.

districts in contrast with the lowlands located further to the west. The dominant effect here is manifested by the temperatures measured during the winter months. The average annual precipitation total is slightly higher as compared with that of central Poland, and amounts to around 550 mm. The Northern Podlasie Lowland is a sub-province of the Podlasie-Belarus Plateau due to, among other reasons, the continental characteristics of the climate. In terms of surface features, the Lowland is similar to the Central Polish Lowlands and remain within reach of the Warta glaciation. The continental features of the climate include the lowest temperatures of the winter months while the summer temperatures are similar to values experienced in the west of the country. The average amplitude of the air temperatures may be as high as 23°C. The average annual precipitation totals fluctuate at around 550 mm and snow cover remains for 80-100 days.

The work is based on meteorological data for the years 2001-2021 pertaining to the average monthly air temperature, the monthly values of the relative air humidity and the monthly totals of atmospheric precipitation from seven IMGW-BIP stations: Białowieża, Legionowo, Pułtusk, Siedlce, Szepietowo, Terespol and Warszawa (Table 1). In order to display the dynamics of changes in temperature and precipitation during the growing season of the maize crop in the study years, the following basic descriptive statistics were calculated: arithmetic mean, minimum and maximum values and the coefficient of variation:

$$V = \frac{S}{X} 100 \,, \tag{1}$$

where: V is the coefficient of variation (%), S is the standard deviation and X is the arithmetic mean.

The monthly values of the climatic water balance (*CWB*) were calculated for each maize growing season. Following an analysis of the input data, the meteorological conditions contributing to drought were determined, based on *CWB*, as the difference between atmospheric precipitation (*P*) and potential evapotranspiration (*PET*) for three stations: Siedlce,

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°	
Białowieża	52°42'	23°51'	164
Legionowo	52 °24	20°58'	93
Pułtusk	52°44'	21°06'	95
Terespol	52°04'	23°37'	131
Siedlce	52°11'	22°16'	146
Szepietowo	52°51'	22°33'	150
Warszawa	52°13'	21°01'	113

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

Warszawa and Terespol (Doroszewski *et al*., 2007, 2008 and 2012; Kanecka-Geszke and Smarzyńska, 2007; Legates and McCabe, 2005; Łabędzki, 2006):

$$CWB = P - PET \,, \tag{2}$$

where: *CWB* is the climatic water balance (mm), *P* is the atmospheric precipitation (mm) and *PET* is the potential evapotranspiration (mm).

In order to calculate the potential evapotranspiration, the following Ivanov's formula was used:

$$PET = 0.0018(25 + t)^2(100 - f) \,, \tag{3}$$

where: t is the mean monthly air temperature (°C), f is the mean monthly relative humidity (%).

The maize crop water requirements in each month of the growing season were determined using the method suggested by Klatt (after Nyc, 2006):

$$Popt = \beta \, \{Pk + 5(ta - tk)\} \,, \tag{4}$$

where: *Popt* is the optimum precipitation per real unit (mm), *Pk* is the optimum (monthly) precipitation for the maize crop according to the table by Klatt (mm), ta is the mean monthly air temperature at the unit (°C), *tk* is the mean monthly air temperature (°C) for which Klatt determined an optimum precipitation (*Pk*), β is the coefficient taking into account the soil type (for light soils $\beta = 1.15$).

The precipitation deficit and excess were calculated based on the mean monthly air temperature and the monthly atmospheric precipitation total, following the formula:

$$Pd/e = Popt - Pa \,, \tag{5}$$

where: *Pd*/*e* is the precipitation deficit/excess (mm), *Popt* is the optimum precipitation according to Klatt and *Pa* is the actual precipitation (mm).

The negative differences denote the precipitation deficit whereas the positive differences point to excessive precipitation. The mean minimum and maximum values were calculated in addition to the frequency of precipitation shortages during maize growing season.

The standard deviations (σ) of the obtained differences (*Popt* – *Pa*) were also calculated. Based on these values, three classes of precipitation deficits and excesses for maize were identified by assuming the following value: (*Popt* – *Pa*) = 0. Next, the frequency of each class was calculated. The classes included the following conditions:

a) optimum in terms of precipitation sufficiency for values in the range from –0.5σ to 0.5σ,

b) moderately dry for deficit values ranging from –0.5σ to –1σ,

c) dry for precipitation deficits below –1σ (Skowera *et al*., 2016).

3. RESULTS AND DISCUSSION

Figure 2 presents the mean values of the air temperature and atmospheric precipitation totals during the growing season of the maize crop (April-September) in central-eastern

Poland, and Table 2 displays their variation. The highest mean totals of atmospheric precipitation for the 2001-2021 growing seasons of the maize crop were recorded in the northern part of the region (Pułtusk – 378 mm, Szepietowo – 379 mm, Białowieża – 395 mm), the lowest long-term mean precipitation total being 352 mm for Legionowo. At Pułtusk and Białowieża, the maximum values of the precipitation totals for April-September were 598 and 599 mm, respectively. Of all the analysed stations, the lowest precipitation total in the study years (172 mm) was recorded at Pułtusk. The atmospheric precipitation in the study region was very variable, with the coefficient of variation ranging from 21%

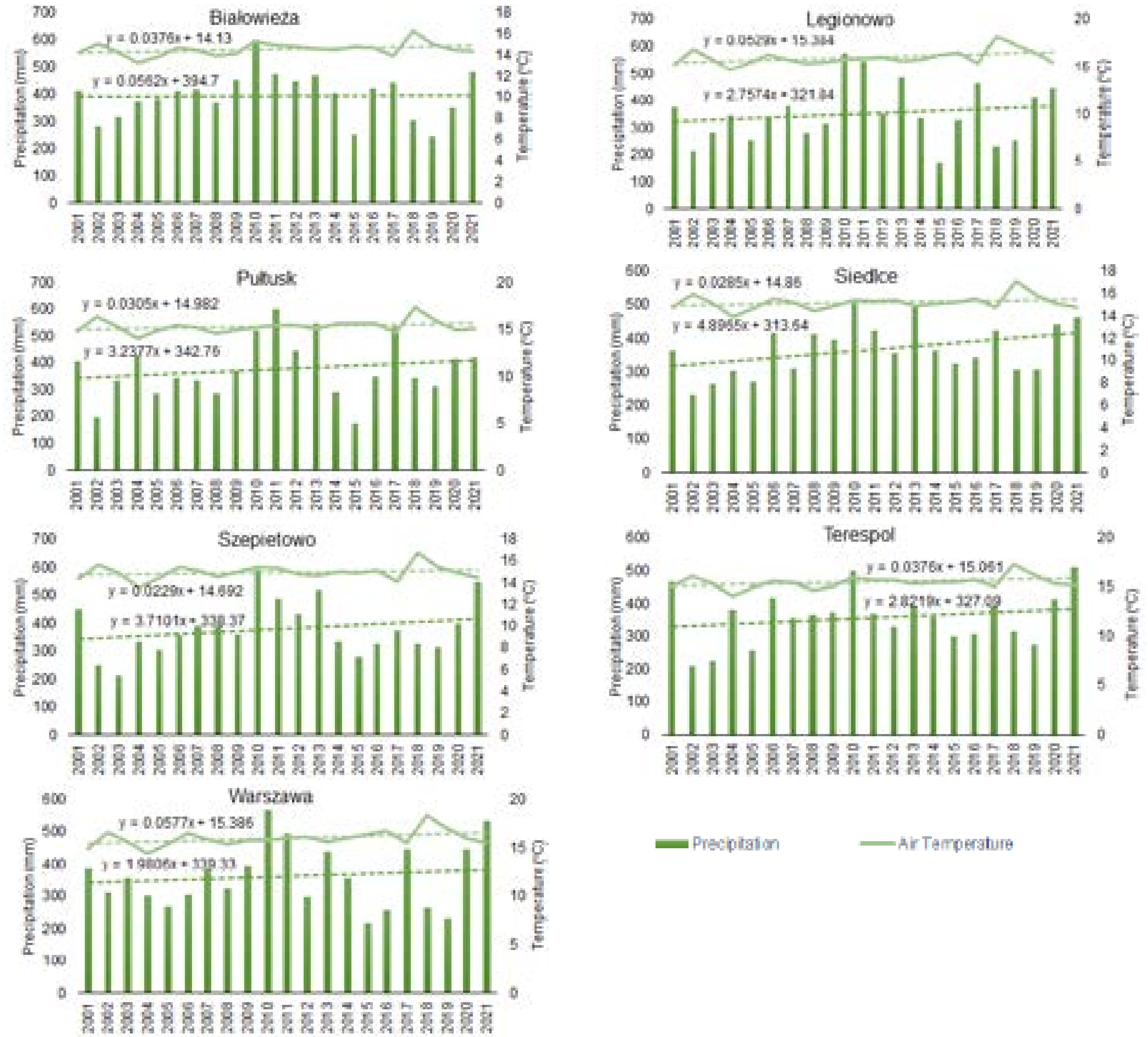

Fig. 2. Mean air temperatures and atmospheric precipitation sums in central-eastern Poland in 2001-2021.

Table 2. Distribution of variation in mean air temperature (*t*) (°C), atmospheric precipitation sums (*P*) (mm) and coefficients of variability (V) (%) in 2001-2021 in central-eastern Poland

Parameters	Białowieża		Legionowo		Pułtusk		Siedlce		Szepietowo		Terespol		Warszawa	
	P	*t*	*P*	*t*	*P*	*t*	*P*	*t*	*P*	*t*	*P*	*t*	*P*	*t*
Mean	395	15	352	16	378	15	368	15	379	15	358	15	361	16
Min.	242	13	172	15	175	14	233	14	212	14	209	14	219	15
Max.	598	16	576	18	599	17	510	17	588	17	510	17	566	18
V	21	4	30	5	29	4	21	4	26	4	22	4	27	5

for Białowieża and Siedlce to 29% for Pułtusk and 30% for Legionowo. The gradient values of the linear trend in precipitation changes during the growing season of the maize crop were positive although they did not exceed 5 mm. Czarnecka and Nidzgorska-Lencewicz (2012) have claimed that long-term changes in the level of seasonal atmospheric precipitation do not reveal a statistically significant linear trend. In turn, a common phenomenon which has occurred in most of the Polish area is a tendency for an increase in precipitation during the spring and autumn season coupled with a declining share of summer rainfall in the yearly total.

Both spatial and temporal variations in air temperature were relatively minor in the study area. The coefficient of variation for all of the stations ranged between 4 and 5%. Also, no substantial differences in mean air temperatures (April-September) were found between the stations, the values for this parameter falling within the range of 15-16°C. Due to the short (21-year) period of the observations, the gradient values of the linear trend in air temperature changes were positive but they were also relatively minor. Marosz *et al*. (2023) claimed that in Poland in most years (in terms of both the annual and seasonal values) the highest positive values of anomalies in air temperatures occurred in the last 20-year period (2001-2021). Variations in thermal conditions in Poland have generally been similar to the tendencies in Europe (World Meteorological Organisation) and in the rest of the world during the last decades (Ustrnul, 2021).

Figure 3 shows the monthly values of the trends in such changes whereas Table 3 presents the variations in the distribution and frequency of the negative values of climatic water balance in central-eastern Poland. The climatic water balance for the stations was generally negative in April (at Siedlce in July as well). Moreover, in April the lowest mean monthly values of this parameter were recorded at all of the stations (this also occurred in June at Warsaw). The Siedlce and Terespol stations had the lowest frequency (57%) of negative *CWB* values in May whereas at Warsaw such a situation was noted in September (71%). The highest

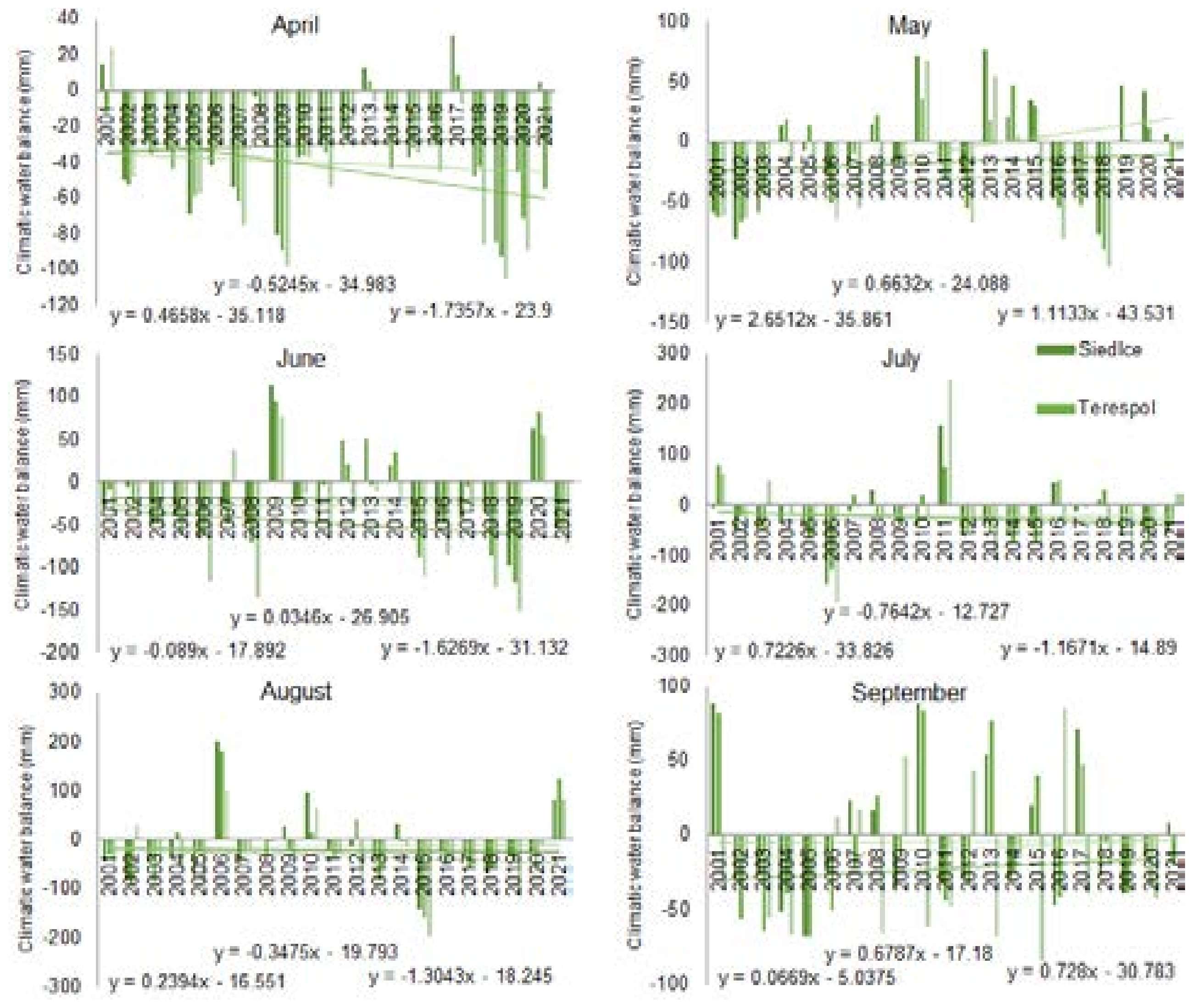

Fig. 3. Climatic water balance in central-eastern Poland in 2001-2021.

Table 3. Distribution of variation in climatic water balance (mm) in central-eastern Poland in 2001-2021

Parameters	Siedlce	Terespol	Warszawa
	April		
Mean	–30.0	–40.8	–43.0
Min.	–84.6	–92.9	–104.5
Max.	31.4	8.0	23.8
Negative *CWB* frequency (%)	81.0	90.5	95.2
	May		
Mean	–6.7	–16.8	–31.3
Min.	–80.5	–88.8	–104.2
Max.	75.7	46.4	67.0
Negative *CWB* frequency (%)	57.1	57.1	81.0
	June		
Mean	–19.7	–28.1	–49.3
Min.	–98.7	–118.6	–150.3
Max.	113.1	95.0	76.5
Negative *CWB* frequency (%)	76.2	81.0	85.7
	July		
Mean	–25.9	–21.8	–32.3
Min.	–157.7	–127.3	–194.4
Max.	157.0	79.9	247.3
Negative *CWB* frequency (%)	81.0	61.9	81.0
	August		
Mean	–13.9	–23.6	–32.6
Min.	–142.5	–160.8	–194.8
Max.	200.4	181.3	97.8
Negative *CWB* frequency (%)	71.4	76.2	81.0
	September		
Mean	–4.3	–9.7	–19.9
Min.	–68.5	–68.8	–84.7
Max.	87.7	84.3	84.7
Negative *CWB* frequency (%)	61.9	71.4	71.4

mean monthly *CWB* values occurred at all of the stations in September and they were as follows: –4.3 mm at Siedlce, –9.7 mm at Terespol and –19.9 mm at Warszawa. The values of the directional coefficients of the trend in changes in the climatic water balance were variable and depended on both the month and the station concerned. May and September were the only months when the coefficients were positive, which indicates that there was a slight tendency for evaporation to decline in those months. Also, Wibig (2012) has claimed, based on an analysis of the linear trend, that changes in CWB are very gradual (the trend gradients were slight) and because of this, apart from several exceptions, all of the coefficients were negative, this was indicative of the fact that evaporation exceeded precipitation. At present, a certain tendency is being observed for droughts to increase during the summer which accommodates most of the growing season, thus posing a threat to farming. Also, Ziernicka-Wojtaszek (2015) has reported that the dry area in Poland is increasing in terms of climatic water balance with values from –90 mm to –120 mm from 34% of Poland in the years 1971-2000 to 52% in the years 1981-2010. In a study by Łabędzki (2007), who analysed droughts in central Poland, it was observed that drought occurred in the entire region from late June to early July in the years 1983, 1994, 2005, 2006 and 2008. Dry periods lead to reduced crop yields of poorer quality (Łabędzki and Bąk, 2017). According to Żarski *et al*. (2017), regional yield losses and maize harvest reductions caused by drought in the June-July period averaged around 13%, the maximum value being 27%.

The greatest number of days with water deficit in the individual months of the maize crop growing season was recorded in the northern part of the region (Białowieża,

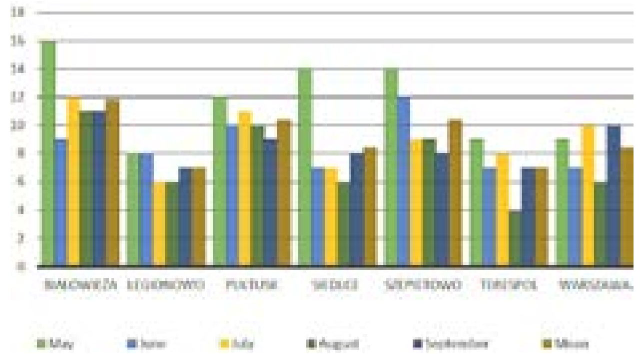

Fig. 4. Number of days with precipitation shortages during maize growing seasons in centraleastern Poland in 2001-2021.

Pułtusk, Szepietowo) (Fig. 4) where, in each month of the growing season, there were over 10 days with deficits. The maize water requirement was most often satisfied at Terespol and Legionowo. Of all the months of the growing season, the greatest number of days with precipitation shortages in the whole study area occurred in May. At Białowieża, Siedlce and Szepietowo, the deficit prevailed for two weeks in May on average. Żarski and Dudek (2009) examined the frequency of drought events during the period of increased water demand by maize grown for grain in the Kujawy-Pomorze region, and found that there was a necessity to irrigate the maize in 21 out of the 30 years analysed.

At all of the stations and during all of the months of the maize crop growing season, the maximum values of the deficit were always higher than the values of excess precipitation (Table 4). The highest excess was recorded in August at all of the stations. However, the values were much lower than the deficit which was close to 80 mm. The highest precipitation shortages for maize crop throughout the study years were recorded in July. At Pułtusk, Legionowo and Warszawa, the deficit in July exceeded 200 mm. This month is a critical period determining cultivation success, the determinants during this time period being the weather pattern and water availability at the stage of maize panicle formation and flowering, regardless of whether the crop is grown for silage or grain. Drought in this period contributes to problems with cob maturation and grain formation; additionally, it poses a threat to pollen viability and may contribute to pollen decline. As a protective response to water deficit, maize stops supplying the uppermost grains on the cob with nutrients. The longer

Table 5. Frequency (%) of individual water deficit classes during the growing season of maize crop

Water deficit classes	May	June	July	August	September	Average
Optimum	29	36	29	28	22	29
Moderately dry	13	12	10	6	4	9
Dry	21	22	20	13	13	18

the water deficit-related stress lasts, the greater the number of grains that cease to develop, which eventually leads to their drying out (Guo *et al*., 2008). Also, water deficit has been found to contribute to a lower maize plant height in the stand, a lower index of leaf area and poorer root growth (Hirich *et al*., 2012; Payero *et al*., 2006).

Based on the calculated frequency of atmospheric precipitation deficits and excesses in the obtained classes, it was found that the conditions associated with precipitation sufficiency for maize, *i.e.*, in the range from –0.5σ to 0.5σ were the most common (Table 5). The frequency of moderately dry and dry growing seasons was 9% and 18%, respectively. Based on the standard deviation values, the months identified as dry were May (21%), June (22%), and July (20%), May and June were also the months most frequently classified as moderately dry. By contrast, Żarski and Dudek (2009) observed that in the period 1971-2005, precipitation deficits for maize occurred in 80.0-97.1% of the years studied, depending on the soil type. Moreover, Żarski *et al*. (2004) reported that the period from late July to early August, corresponding to the tasselling stage of maize, is the period of thegreatest water demand.

4. CONCLUSIONS

1. The precipitation and temperature conditions in 2001-2021 varied significantly. The average precipitation totals during the growing season of the maize crop was 370 mm, and the air temperature was 15°C. The variation in precipitation amounted to 25%, while for the temperature, it was 4%. Long-term changes in atmospheric precipitation tended to increase slightly.

2. The climatic water balance exhibited a substantial temporal variation. However, in each month of maize vegetative growth, there occurred a precipitation deficit which lasted for 10 days on average. Based on a linear trend analysis, it

Table 4. The highest values of precipitation excess and deficit (mm) during maize growing season

Month	Białowieża		Legionowo		Pułtusk		Siedlce		Szepietowo		Terespol		Warszawa	
	excess	deficit	excess	deficit	excess	deficit	excess	deficit	excess	deficit	excess	deficit	excess	deficit
May	33.8	–59.7	47.3	–120.5	48.9	–133.9	45.8	–85.8	30.3	–94.7	42.5	–56.3	39.6	–73.2
June	50.7	–149.1	49.8	–39.2	56.4	–93.7	56.4	–103.6	51.6	–76.5	48.2	–94.5	71.8	–90.7
July	54.9	–129.8	90	–248.6	64.5	–261.9	81.4	–134.2	76.5	–159.6	57.3	–77	79.6	–225
Aug.	75.8	–153.8	85.4	–108.3	80.7	–112.5	73.1	–185.5	82.1	–118.5	79.2	–179.1	86.6	–105.6
Sept.	30.6	–136.3	41.7	–87.5	39.2	–75.1	41.6	–78.4	33	–141.4	44.8	–78.9	52.2	–77.2

was found that in May and September, the gradient values of the linear trend for changes in the climatic water balance were positive. However, these changes occurred very slowly as indicated by the modest gradient values.

3. As a result of the progressive increase in air temperature, the water requirements of maize have been rising. The average precipitation deficit during the growing season of the maize crop was 117 mm, – the highest precipitation deficits occurring in July and August which are the months when maize requires the most water. Based on the calculated frequency of the atmospheric precipitation deficits in the obtained classes, it was recorded that dry months occurred with a frequency of 18%, while for moderately dry months the frequency was 9%.

4. In recent years, a steady increase in the area cropped with maize has been observed in Poland. The crop grown in the majority of this area suffers from relatively poor development due to water deficits experienced during the growing season. Climate change is an additional contributor to this problem as it increases drought frequency, intensity and adverse effects. There is little likelihood of precipitation shortages becoming less of a problem. Hence, further efforts should be made to ensure the sustainable use of water in agriculture. The results of the present work may be used for projecting maize production and planning its irrigation.

Conflict of interest: The authors declare no conflict of interest.

5. REFERENCES

Abolhasani K. and Saeidi G., 2004. Relationships between agronomic characteristic of safflower under water stress and control. Iran Jour. Field Cops Res., 1, 127-138.

Athar H.R. and Ashraf M., 2005. Photosynthesis under drought stress. In: Handbook of Photosynthesis (Ed. M. Pessarakli), Taylor and Francis, New York, 793-804.

Banziger M., Edmeades G.O., and Lafitte H.R., 2002. Physiological mechanisms contributing to the increased N stress tolerance of tropical maize selected for drought tolerance. Field Crops Res., 75(3), 223-233, https://doi.org/10.1016/S0378-4290(02)00028-X

Blum A., 2005. Drought resistance, water-use efficiency, and yield potential: are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res., 56, 1159-1168, https://doi.org/10.1071/AR05069

Bruce W.B., Edmeades G.O., and Barker T.C., 2002. Molecular and physiological approaches to maize improvement for drought tolerance. J. Exp. Bot., 53, 13-25, https://doi.org/10.1093/jexbot/53.366.13

Campos H., Cooper M., Edmeades G., Löffler C., Schussler J., and Ibanez M., 2006. Changes in drought tolerance in maize associated with fifty years of breeding for yield in the U.S. Corn Belt. Maydica 51, 369-381.

Chen J., He Y., and Li P., 2020. Effects of tillage alteration on soil water content, maize crop water potential and grain yield under subtropical humid climate conditions. Int. Agrophys., 35(1), 1-9, https://doi.org/10.31545/intagr/131668

Czarnecka M. and Nidzgorska-Lencewicz J., 2012. Multiannual variability of seasonal precipitation in Poland (in Polish). Water-Environment-Rural Areas, 12(2), 45-60.

DaCosta M. and Huang B., 2006. Osmotic adjustment associated with variation in bentgrass tolerance to drought stress. J. Am. Soc. Hortic. Sci., 131(3), 338-344, https://doi.org/10.21273/JASHS.131.3.338

Djaman K., O'Neill M., Owen C.K., Smeal D., Koudahe K., Wes M., and Irmak S., 2018. Crop evapotranspiration, irrigation water requirement and water productivity of maize from meteorological data under semiarid climate. Water, 10(4), 405, https://doi.org/10.3390/w10040405

Doroszewski A., Jadczyszyn J., Jóźwicki T., Koza P., Kozyra J., Łopatka A., Mizak K., Nieróbca A., Pudełko R., and Stuczyński T., 2007. Frequency of agricultural droughts in Poland in 1959-2006. Puławy, 1-59.

Doroszewski A., Jadczyszyn J., Kozyra J., Pudełko R., Stuczyński T., Mizak K., Łopatka A., Koza P., Górski T., and Wróblewska E., 2012. Fundamentals of the agricultural drought monitoring system (in Polish). Water-Environment-Rural Areas, (IV-VI), 12, 2(38), 77-91.

Doroszewski A., Kozyra J., Pudełko R., Stuczyński T., Jadczyszyn J., Koza P., and Łopatka A., 2008. Agricultural drought monitoring in Poland (in Polish). Wiad. Mel. i Łąk., 51(1), 35-38.

Dzieżyc J., 1988. Agriculture under irrigation conditions. PWN, Warszawa.

Fageria N.K., 2012. The role of plant roots in crop production. CRC Press. Taylor & Francis Group. eBook, https://doi.org/10.1201/b12365

Golbashy M., Ebrahimi M., Khavari Khorasani S., and Choukan R., 2010. Evaluation of drought tolerance of some corn (*Zea mays* L.) hybrids in Iran. Afr. J. Agric. Res., 5(19), 2714-2719.

Guo J., Su G., Zhang J., and Wang G., 2008. Genetic analysis and QTL mapping of maize yield and associate agronomic traits under semi-arid land condition. Afr. J. Biotech., 7, 1829-1838.

Hirich A., Rami A., Laajaj K., Choukr-Allah R., Jacobsen S-E., El Youssfi L., and El Omari H., 2012. Sweet corn water productivity under several deficit irrigation regimes applied during vegetative growth stage using treated wastewater as water irrigation source. World Acad. Sci., Engin. Technol., 61, 840-847, https://doi.org/10.5281/zenodo.1057043

Huang C.L., 2007. Maize and grace: Africa's encounter with a New World crop, 1500-2000 – by James C. McCann. Dev Econ., 45(2), 242-5, https://doi.org/10.1111/j.1746-1049.2007.00041_2.x

Ibrahim M., Zeid N.A., and Semary E., 2001. Response of two differentially drought tolerant varieties of maize to drought stress. Pak. J. Biol. Sci., 4(7), 779-784, https://doi.org/10.3923/pjbs.2001.779.784

Jaleel C.A., Manivannan P., Sankar B., Kishorekumar A., Gopi R., Somasundaram R., and Panneerselvam R., 2007. Water deficit stress mitigation by calcium chloride in *Catharanthus roseus*: Effects on oxidative stress, proline metabolism and indole alkaloid accumulation. Colloids and surfaces B: Biointerfaces, 60(1), 110-116, https://doi.org/10.1016/j.colsurfb.2007.06.006

Jędrejek A., Koza P., Doroszewski A., and Pudełko R., 2022. Agricultural drought monitoring system in Poland – farmers' assessments *vs.* monitoring results (2021). Agriculture, 12(4), 536, https://doi.org/10.3390/agriculture12040536

Kanecka-Geszke E. and Smarzyńska K., 2007. Assessing meteorological drought in some agro-climatic regions of Poland by using different indices. Acta Sci. Pol. Formatio Circumiectus, 6(2), 41-50.

Khalili M., Naghavi M.R., Aboughadareh A.P., and Rad H.N., 2013. Effects of drought stress on yield and yield components in maize cultivars (*Zea mays* L.). Int. J. Agron. Plant Prod., 4(4), 809-812.

Kondracki J., 1994. Geography of Poland. Physico-geographic mesoregions (in Polish). Wyd. Nauk. PWN, Warszawa.

Kuśmierek-Tomaszewska R. and Żarski J., 2021. Assessment of meteorological and agricultural drought occurrence in central Poland in 1961-2020 as an element of the climatic risk to crop production. Agriculture, 11(9), 855, https://doi.org/10.3390/agriculture11090855

Kędzior M. and Zawadzki J., 2017. SMOS data as a source of the agricultural drought information: Case study of the Vistula catchment, Poland. Geoderma, 306, 167-182, https://doi.org/10.1016/j.geoderma.2017.07.018

Legates D.R., Lins H.F., and McCabe G.J., 2005. Comments on "Evidence for global runoff increase related to climate warming" by Labat *et al*. Adv. Water Res., 28(12),1310-1315, https://doi.org/10.1016/j.advwatres.2005.04.006

Lobell D.B., Roberts M.J., Schlenker W., Braun N., Little B.B., Rejesus R.M., and Hammer G.L., 2014. Greater sensitivity to drought accompanies maize yield increase in the US Midwest. Science, 344(6183), 516-519. https://doi.org/10.1126/science.1251423

Łabędzki L., 2006. Agricultural droughts. An outline of the problem and monitoring and classification methods. Rozpr. Nauk. Monografie, IMUZ, Falenty, Water-Environment-Rural Areas 17, 1-107.

Łabędzki L., 2007. Estimation of local drought frequency in Central Poland using the standardized precipitation index SPI. Irrig. Drain., 56, 67-77, https://doi.org/10.1002/ird.285

Łabędzki L. and Bąk B., 2014. Meteorological and agricultural drought indices used in drought monitoring in Poland: a review. Meteorol. Hydrol. Water Manag. Res. Operat. App., 2(2), 3-13, https://doi.org/10.26491/mhwm/34265

Łabędzki L. and Bąk B., 2017. Impact of meteorological drought on crop water deficit and crop yield reduction in Polish agriculture. J. Water Land Dev., 34, 181-190, https://doi.org/10.1515/jwld-2017-0052

Marcinkowski P. and Piniewski M., 2018. Effect of climate change on sowing and harvest dates of spring barley and maize in Poland. Int. Agrophys., 32(2), 265-271, https://doi.org/10.1515/intag-2017-0015

Marosz M., Miętus M., and Biernacik D., 2023. Features of multiannual air temperature variability in Poland (1951-2021). Atmosphere, 14, 282, https://doi.org/10.3390/atmos14020282

Mueller N.D., Gerber J.S., Johnston M., Ray D.K., Ramankutty N., and Foley J.A., 2013. Closing yield gaps through nutrient and water management. Nature, 490, 254-157, https://doi.org/10.1038/nature11420

Nelson G., Rosegrant M., Koo J., Robertson R., Sulser T., Zhu T., Ringler C., Msangi S., Palazzo A., Batka M., Magalhaes M., Valmonte-Santos R., Ewing M., and Lee D., 2009. Climate change: Impact on agriculture and costs of adaptation. Intl. Food Policy Res. Inst., 21, 1-57, https://doi.org/10.2499/0896295354

Nyc K., 2006. An introduction of irrigation systems. In: Plant Irrigation (Eds. S. Karczmarczyk and L. Nowak), PWRiL, Poznań, 7, 157-174.

Paluszek J., 2011. Criteria of Polish cultivated soil physical quality assessment (in Polish). Acta Agrophysica. Rozprawy Monografie, 2, 5-136.

Payero J.O., Melvin S.R., Irmak S., and Tarkalson D., 2006. Yield response of corn to deficit irrigation in a semiarid climate. Agric. Water Manag., 84(1-2), 101-112, https://doi.org/10.1016/j.agwat.2006.01.009

Pińskwar I., Choryński A., and Kundzewicz Z.W., 2020. Severe drought in thes of 2020 in Poland – More of the same? Agronomy, 10(11), 1646, https://doi.org/10.3390/agronomy10111646

Sammons B., Whitsel J., Stork L.G., Reeves W., and Horak M., 2014. Characterization of drought-tolerant maize MON 87460 for use in environmental risk assessment. Crop Sci., 54, 719-729, https://doi.org/10.2135/cropsci2013.07.0452

Skowera B., Kopcińska J., Ziernicka-Wojtaszek A., Wojkowski J., 2016. Precipitation deficiencies and excesses during the growing season of late potato in the opolskie voivodship (1981–2010). Acta Sci. Pol. Form. Circumiectus, 15(3), 137-149, https://doi.org/10.15576/ASP.FC/2016.15.3.137

Sulewska H., 2004. Environmental requirements of maize and opportunities of its cultivation in Poland. In: Technologies of Maize Production (Ed. A. Dubas), Wyd. Wieś Jutra Warszawa, 16-23.

Sulewska H., 2007. Environmental requirements of maize. In: Integrated Production of Maize (Eds Z. Kaniuczak, S. Pruszyński), Wyd. IOR, Poznań, 6-9.

Tai F.J., Yuan Z.L., Wu X.L., Zhao P.F., Hu X.L., and Wang W., 2011. Identification of membrane proteins in maize leaves, altered in expression under drought stress through polyethylene glycol treatment. Plant Omics J., 4, 250-256.

Ustrnul Z., Wypych A., and Czekierda D., 2021. Air temperature change. In: Climate change in Poland past, present, future (Ed. M. Falarz). Springer Climate. Springer, Cham., 275-330, https://doi.org/10.1007/978-3-030-70328-8_11

Wang W., Vinocur B., and Altman A., 2003. Plant responses to drought, salinity and extreme temperature: towards genetic engineering for stress tolerance. Planta, 218, 1-14, https://doi.org/10.1007/s00425-003-1105-5

Wibig J., 2012. Moisture conditions in Poland in view of the SPEI index (in Polish). Water-Environment-Rural Areas, 12(2), 329-340.

Yang J., Zhang J., Wang Z., Xu G., and Zhu Q., 2004. Activities of key enzymes in sucrose-to starch conversion in wheat grains subjected to water deficit during grain filling. Plant Physiol., 135, 1621-1629, https://doi.org/10.1104/pp.104.041038

Ziernicka-Wojtaszek A., 2015. Climatic water balance in Poland in the light of the present day climate change. Water-Environment-Rural Areas, 15, 4(52), 93-100.

Ziernicka-Wojtaszek A., 2021. Summer drought in 2019 on Polish territory – A case study. Atmosphere, 12(11), 1475, https://doi.org/10.3390/atmos12111475

Żarski J., Dudek S., and Grzelak B., 2004. Role of water and thermal factors in shaping the corn yield. Acta Agroph., 3(1), 189-195.

Żarski J., Dudek S., Kuśmierek-Tomaszewska R., and Żarski W., 2017. Effects of agricultural droughts in the province of Kujawsko-Pomorskie and possibilities of minimizing their impact. Infrastructure and Ecology of Rural Areas, II(2), 813-824.

Żarski J. and Dudek S., 2009. Time variability of selected plants irrigation needs in the region of Bydgoszcz. Infrastructure and Ecology of Rural Areas, 3, 141-149.