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

Abstract. 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.

Keywords: 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...
subjected to a moderate but prolonged drought event switched off their metabolism and finally die due to stomatal closure and the inhibition of gas exchange (Jaleel et al., 2007). The closure of stomata reduces 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 vessel–tracheid response. Osmotic regulation is another method plants adopt in order to cope with drought-related stress. The synthesis of dissolved substances, such as polysols and proline, under the stress condition, causes a 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 potential 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 growth in sandy soil, and this may be 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 (Bruel et al., 2002; Khadil et al., 2013; Abolhasani and Saedi, 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 (Dyban et al., 2018). Many authors have suggested various methods for determining agricultural drought (Jędrzejek et al., 2022; Kędzior and Zawadzki, 2017; Kuśmierek-Tomaszewska and Zarzyki, 2021; Łabędzki and Bąk, 2016; Pintkowski et al., 2020; Ziemnicka-Wejnowski, 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 (Drzazęcy, 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 and excesses 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 territory 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 Mazowieze-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 Narw and its tributaries, the Warta and its tributaries, the Bug, which connects with the Narw, constitute the boundary in the east and the Wisłrz in the south-east of the area. The Oder glaciation encompassed the whole of the Mazowieze-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 rises to an elevation of 150-200 m above sea level, it even reaches above 200 m in several places. The lowland is a part of the colder climatic 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 Belaus 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 is 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, Terospol 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: 

\[ \text{V} = \frac{s}{X} \times 100 \]  

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, Warszawa and Terospol (Doroszewski et al., 2007, 2008 and 2009; Kaneczka-Gusek and Smarzynka, 2007; Legates and McCabe, 2005; Łabędzki, 2006).

\[ \text{CWB} = P - PET, \]

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:

\[ \text{PET} = 0.0018(25 + t(100 - t)), \]

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):

\[ \text{Popt} = \beta(0.5 + 5a - \delta), \]

where: \( \text{Popt} \) is the optimum precipitation per real unit (mm), \( \beta \) is the optimum (monthly) precipitation for the maize crop, \( a \) is the mean monthly air temperature at the unit (°C), \( \delta \) is the mean monthly air temperature (°C) for which Klatt determined an optimum precipitation (PET) and \( \gamma \) 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 monthly differences between the monthly atmospheric precipitation total, following the formula:

\[ \text{Pd} = P - \text{Pa}, \]

where: \( \text{Pd} \) is the precipitation deficit/excess (mm), \( \text{Pa} \) is the optimum precipitation according to Klatt and \( \text{Pa} \) is the actual precipitation (mm).

The negative differences denote the precipitation deficits 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 (\( \sigma \)) of the obtained differences (\( Pd - \text{Pa} \)) were also calculated. Based on these values, three classes of precipitation deficits and excesses for maize were identified by assuming the following value (\( Pd - \text{Pa} \) = 0). Next, the frequency of each class was calculated. The classes included the following conditions:

\begin{itemize}
  \item a) optimum in terms of precipitation sufficiency for values in the range from -0.5 to -0.25 mm,
  \item b) moderately dry for deficit values ranging from -0.5 to -1.0 mm,
  \item c) dry for precipitation deficits below -1.0 mm (Skowron et al., 2016).
\end{itemize}

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

![Fig. 1. The study area.](image-url)
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% 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 (Jemal, 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 Terepol 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

### 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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Białowieża</th>
<th>Legionowo</th>
<th>Pułtusk</th>
<th>Siedlce</th>
<th>Szepietowo</th>
<th>Terepol</th>
<th>Warszawa</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>242</td>
<td>13</td>
<td>172</td>
<td>15</td>
<td>175</td>
<td>14</td>
<td>233</td>
</tr>
<tr>
<td>Min</td>
<td>239</td>
<td>13</td>
<td>172</td>
<td>15</td>
<td>175</td>
<td>14</td>
<td>233</td>
</tr>
<tr>
<td>Max</td>
<td>368</td>
<td>15</td>
<td>368</td>
<td>15</td>
<td>379</td>
<td>15</td>
<td>379</td>
</tr>
<tr>
<td>V</td>
<td>21</td>
<td>4</td>
<td>30</td>
<td>5</td>
<td>29</td>
<td>4</td>
<td>26</td>
</tr>
</tbody>
</table>

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

Fig. 3. Climatic water balance in central-eastern Poland in 2001-2021.
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 trends 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 found that the period from late July to early August, corresponding to the tasselling stage of the maize crop, is a critical period for maize yield formation. The longer the water deficit-related stress lasts, the greater the number of grains that cease to develop, which eventually leads to their drying out (Gao 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 –0.5 to 0.5%, 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, Ziarnicka-Wojtaszek and Dudek (2009) observed that in the period 1971-2005, precipitation deficits for maize occurred in 80.9-97.1% of the years studied, depending on the soil type. Moreover, Ziarnicka et al. (2004) reported that the period from late July to early August, corresponding to the tasselling stage of maize, is the period of the greatest water demand.

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Siedlce</th>
<th>Terespol</th>
<th>Warszawa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>–30.0</td>
<td>–40.8</td>
<td>–43.0</td>
</tr>
<tr>
<td>Min.</td>
<td>–84.6</td>
<td>–92.9</td>
<td>–104.5</td>
</tr>
<tr>
<td>Max.</td>
<td>31.4</td>
<td>8.0</td>
<td>23.8</td>
</tr>
<tr>
<td>Negative CWB frequency (%)</td>
<td>81.0</td>
<td>90.5</td>
<td>93.2</td>
</tr>
<tr>
<td>May</td>
<td>–4.7</td>
<td>–16.8</td>
<td>–31.3</td>
</tr>
<tr>
<td>June</td>
<td>–5.0</td>
<td>–88.8</td>
<td>–104.2</td>
</tr>
<tr>
<td>July</td>
<td>57.5</td>
<td>46.4</td>
<td>67.0</td>
</tr>
<tr>
<td>Negative CWB frequency (%)</td>
<td>57.1</td>
<td>57.1</td>
<td>81.0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Water deficit classes</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum</td>
<td>29</td>
<td>36</td>
<td>28</td>
<td>22</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Moderately dry</td>
<td>13</td>
<td>12</td>
<td>10</td>
<td>6</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Dry</td>
<td>21</td>
<td>22</td>
<td>20</td>
<td>13</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Number of days with precipitation shortage during maize growing seasons in central-eastern Poland in 2001-2021.

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

<table>
<thead>
<tr>
<th>Month</th>
<th>Białowieża</th>
<th>Legionowo</th>
<th>Pułtusk</th>
<th>Siedlce</th>
<th>Szepietowo</th>
<th>Warszawa</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>–9.7</td>
<td>–49.3</td>
<td>–94.8</td>
<td>57.9</td>
<td>–134.2</td>
<td>79.6</td>
</tr>
<tr>
<td>June</td>
<td>–6.7</td>
<td>–43.1</td>
<td>–134.2</td>
<td>79.6</td>
<td>–159.6</td>
<td>86.6</td>
</tr>
<tr>
<td>July</td>
<td>–22.6</td>
<td>–64.9</td>
<td>–194.8</td>
<td>97.8</td>
<td>–225</td>
<td>97.8</td>
</tr>
<tr>
<td>August</td>
<td>–15.0</td>
<td>–28.1</td>
<td>–194.4</td>
<td>97.8</td>
<td>–225</td>
<td>97.8</td>
</tr>
<tr>
<td>September</td>
<td>–14.3</td>
<td>–16.0</td>
<td>–194.4</td>
<td>97.8</td>
<td>–225</td>
<td>97.8</td>
</tr>
</tbody>
</table>

ASSESSMENT OF MAIZE WATER REQUIREMENTS AND PRECIPITATION DEFICITS AND EXCESSES

Paltusk, 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 of 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. Ziarnicka and Dudek (2009) examined the frequency of drought events during the period of increased water demand by maize grown for grain in the Kujawy-Pomeranian 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, whether the crop is grown for silage or grain. Drought in this period contributes to problems with crop 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 the period of increased water demand by maize grown for grain in the study area, regardless of whether the crop is grown for silage or grain, the water deficit-related stress lasts, the greater the number of grains that cease to develop, which eventually leads to their drying out (Gao 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).

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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


