Abstract: Climate warming increases the water needs of plants. The aim of this study was to estimate the water needs of grapevines in central Poland. Water needs were calculated using the crop coefficients method. Reference evapotranspiration was assessed by the Blaney–Criddle’s equation, modified for climate conditions in Poland. Crop coefficients were assumed according to the Doorenbos and Pruitt method. Water needs were calculated using the data from four meteorological stations. Rainfall deficit with the probability occurrence of normal years, medium dry years, and very dry years was determined by the Ostromęcki’s method. Water needs of grapevines during the average growing season were estimated at 438 mm. Upward time trend in the water needs both in the period of May–October and June–August was estimated. Temporal variability in the water needs was significant for all of the provinces. These changes were mainly impacted by a significant increasing tendency in mean air temperature and less by precipitation totals that did not show a clear changing tendency. Due to climate change, vineyards will require irrigation in the near future. The use of resource-efficient irrigation requires a precise estimate of the grapevines’ water needs. The study identified the water requirements for grapevines in central Poland.

Keywords: crop evapotranspiration; irrigation; precipitation; rainfall deficit; reference evapotranspiration; *Vitis vinifera* L.

1. Introduction

Despite the unfavorable climatic conditions, the tradition of viticulture in Poland dates back to the Middle Ages. Nowadays, the largest number of vineyards in Poland is located in the south-eastern, south-western, and southern provinces of the country, where the most favorable climatic conditions for viticulture are [1–4]. However, many new vineyards are also planted in eastern and central Poland, despite the fact that there are much less satisfactory climatic environments for viticulture [4,5]. The development of new vineyards in Poland is the effect of improving economic conditions and changes in consumer preferences, as well as the increase of ecological agro-tourism, including oeno-tourism activities. A large increase in interest in viticulture in Poland is also the result of great progress in breeding programs that aim to obtain new cultivars with low...
susceptibility to fungal diseases and frost damage and the gradual warming of the climate in Poland [2,3,6–13].

Orchard plantations in central Poland are exposed to the largest deficit of precipitation during the growing season [14,15]. According to Rzekanowski [15], in the case of fruit plants, the highest water deficits occur in the great valleys area, i.e., central Poland, while more favorable water conditions are in the southern and northern region of the country. The most important factors that limit the development of vineyards in central Poland are minimum winter temperature (−30 °C occurring at least once in 10 years), as well as spring and autumn frosts [16]. The sum of active temperatures (SAT) above 10 °C is considered to be the most important climatic criterion, which is particularly useful for assessing the conditions of viticulture [16–18]. In the last few decades, climate change that is favorable for viticulture has been observed in Poland. As reported by Lisek [16], in central Poland in the years 1981–2000, the average SAT was almost 2500 °C, while in 2003 the SAT was over 2700 °C, and in 2006 the SAT was up to 2900 °C. For comparison, the SAT in northeastern Poland is about 2200 °C, 2600 °C in the highlands of central Poland, and 2700 °C in the south-west and west part of the country [17,18].

According to Lisek [16], as the result of climate change, especially due to the increase in temperature in the period from 1 May to 30 September, nowadays viticulture in central Poland is much more effective than twenty years ago. Due to climate warming, the subsequent phenological stages of plant development occur earlier, which increases the quality of fruit of the grapevines grown in central Poland. An increase in the average summer (May–September) temperature of 1 °C raises the water needs of grapevines by 50 mm of annual precipitation, assuming that at least 50% of annual precipitation occurs during the growing season [19,20].

The purpose of the present study was to estimate the water needs of grapevine plants grown in central Poland. The results of the research will help to develop a program of resource-efficient irrigation of vineyards in the central provinces of the country.

2. Materials and Methods

In the present study, crop evapotranspiration was applied as a measure of grapevine (Vitis vinifera L.) water needs [21]. Consequently, the water requirements of grapevines were determined by the crop coefficients method. The reference evapotranspiration was calculated by the Blaney–Criddle equation, which is based on air temperature and was modified for Polish environmental conditions [22–24]. The crop coefficients for grapevine plants (adjusted to the reference evapotranspiration that was considered by the Blaney–Criddle method) were assumed according to Doorenbos and Pruitt [25]. It was presumed that the soil in the middle of the growing season is covered with plants at a level of 40–50%. It was also assumed that the grapevines are grown in regions with a cold winter and with spring and autumn frosts; the first leaves appear in early May, while the harvest begins in mid-September.

The water needs of the grapevine plants were calculated on the basis of measurement data collected from four meteorological stations located in Bydgoszcz, Warszawa, Poznań, and Łódź, which were representative of the considered provinces situated in central Poland: Kuyavian–Pomeranian province (K–P), Masovian province (M), Greater Poland province (G–P), and Lodz province (L), respectively (Table 1, Figure 1). Due to the long data series, these stations were considered as representative of the studied regions. In the entire examined area and period, the long-term average sum of active temperatures (SAT) exceeded 2500 °C, which is assumed as suitable for moderately early and late ripening of grapevines [3,26]. The calculations were carried out for the vegetation period of grapevines in Poland, considered from 1 May to 31 October in the years 1981–2020.

The statistical methods used in the study were trend analysis at different significance levels (p ≤ 0.01 and p ≤ 0.05) and descriptive characteristics (minimum, maximum, median, standard deviation, and variability coefficient) [27]. All calculations were performed using Microsoft Excel 2013 software.
standard deviation, and variability coefficient) [27]. All calculations were performed using Microsoft Excel 2013 software.

Figure 1. Location of analysed provinces of central Poland: geographical location of Poland (a), location of meteorological stations (b) and isolines of SAT—long-term average sum of active temperatures (c).

Table 1. Geographical position of the meteorological stations.

| Province               | Station     | Altitude a | Longitude | Latitude |
|------------------------|-------------|------------|-----------|----------|
| Kuyavian–Pomeranian    | Bydgoszcz  | 46         | 18°01’    | 53°08’   |
| Masovian               | Warszawa    | 106        | 20°59’    | 52°09’   |
| Greater Poland         | Poznań      | 86         | 16°50’    | 52°25’   |
| Łódz                   | Łódź        | 184        | 19°24’    | 51°44’   |

a Meters above mean sea level.
The amounts of precipitation deficit (N) with the occurrence probability of the normal years (N50%), medium dry years (N25%) and very dry years (N10%) were determined for the six-month period of intensive development of grapevine plants (from 1 May to 31 October) by the Ostromęcki method [28,29].

3. Results

Within the analyzed forty years in all studied provinces, there was the tendency of increased mean air temperature, both during the entire grapevine growing season and during the period of intense plant development (June–August). The significant (at \( p \leq 0.01 \)) trend in increased mean air temperature was observed in all examined provinces (Table 2).

Table 2. Equations of mean air temperature trend in the grapevine vegetation period in 1981–2020 in central Poland.

| Period         | Trend Equation | \( R^2 \) | Tendency (°C·Decade\(^{-1}\)) |
|----------------|----------------|----------|---------------------------------|
| Kuyavian–Pomeranian Province |               |          |                                 |
| May–October    | \( y = 0.0272x + 15.070 \) \( R^2 = 0.2007 \) *** 0.3 | | |
| June–August    | \( y = 0.0406x + 17.874 \) \( R^2 = 0.1982 \) *** 0.4 | | |
| July           | \( y = 0.0262x + 19.006 \) \( R^2 = 0.0339 \) n.s. 0.3 | | |
| Masovian Province |               |          |                                  |
| May–October    | \( y = 0.0396x + 14.987 \) \( R^2 = 0.3887 \) *** 0.4 | | |
| June–August    | \( y = 0.0577x + 17.720 \) \( R^2 = 0.3848 \) *** 0.6 | | |
| July           | \( y = 0.0477x + 18.813 \) \( R^2 = 0.1277 \) ** 0.5 | | |
| Greater Poland Province |               |          |                                  |
| May–October    | \( y = 0.055x + 14.310 \) \( R^2 = 0.4967 \) *** 0.6 | | |
| June–August    | \( y = 0.0739x + 16.813 \) \( R^2 = 0.448 \) *** 0.7 | | |
| July           | \( y = 0.0607x + 17.906 \) \( R^2 = 0.1516 \) ** 0.6 | | |
| Lodz Province  |               |          |                                  |
| May–October    | \( y = 0.0351x + 14.312 \) \( R^2 = 0.3518 \) *** 0.3 | | |
| June–August    | \( y = 0.0572x + 16.821 \) \( R^2 = 0.3726 \) *** 0.6 | | |
| July           | \( y = 0.0490x + 17.794 \) \( R^2 = 0.1123 \) ** 0.5 | | |

n.s.—not significant; **—significant at \( p \leq 0.05 \); ***—significant at \( p \leq 0.01 \).

Among the studied provinces in central Poland, in each month of the growing season, the lowest standard deviation of the grapevines’ water needs, which is a measure of the diversity of monthly sums of the water requirements, was estimated to occur in the Masovian province (Table 3). During the growing period, the highest standard deviation of the grapevine water needs was noted in July and ranged from 6.4 mm to 7.5 mm, depending on the province. The lowest standard deviation of the water needs ranged from 3.1 mm to 3.5 mm, depending on the province, was assessed in May.

The variability coefficient, as a measure of the relative diversity of monthly sums of the grapevines’ water needs in the period from May to August ranged from 5.1% to 7.4% (Table 3). In September, its values increased to the range between 7.3% and 10.3%. The highest variability coefficient of grapevine water requirements (from 12.6% to 14.2%) was noted in October. Among the studied provinces, during the entire growing season the highest diversity in the grapevines’ water needs was estimated to occur in the Greater Poland province.
Table 3. Statistical characteristics of grapevine water requirements (mm) in 1981–2020 in central Poland.

| Characteristic | Province | May  | June | July | August | September | October |
|---------------|----------|------|------|------|--------|-----------|---------|
| Minimum (mm)  | K–P \(^a\) | 39   | 80   | 103  | 91     | 51        | 19      |
|               | M        | 41   | 79   | 101  | 92     | 52        | 21      |
|               | G–P      | 37   | 76   | 98   | 90     | 50        | 20      |
|               | L        | 37   | 75   | 96   | 88     | 48        | 19      |
| Maximum (mm)  | K–P \(^a\) | 57   | 109  | 133  | 119    | 70        | 34      |
|               | M        | 55   | 106  | 132  | 121    | 68        | 34      |
|               | G–P      | 54   | 106  | 133  | 121    | 86        | 35      |
|               | L        | 52   | 103  | 127  | 118    | 67        | 35      |
| Median (mm)   | K–P \(^a\) | 48   | 89   | 116  | 104    | 60        | 27      |
|               | M        | 48   | 88   | 115  | 105    | 61        | 28      |
|               | G–P      | 47   | 85   | 114  | 103    | 60        | 28      |
|               | L        | 45   | 84   | 110  | 102    | 58        | 27      |
| Standard deviation (mm) | K–P \(^a\) | 3.5  | 5.3  | 6.9  | 5.6    | 4.4       | 3.7     |
|               | M        | 3.1  | 5.2  | 6.4  | 5.4    | 4.4       | 3.5     |
|               | G–P      | 3.4  | 5.8  | 7.5  | 6.2    | 6.3       | 3.7     |
|               | L        | 3.2  | 5.2  | 7.0  | 5.4    | 4.6       | 3.6     |
| Variability coefficient (%) | K–P \(^a\) | 7.4  | 6.0  | 6.0  | 5.4    | 7.4       | 14.2    |
|               | M        | 6.5  | 5.9  | 5.6  | 5.1    | 7.3       | 12.6    |
|               | G–P      | 7.4  | 6.8  | 6.7  | 6.0    | 10.3      | 13.1    |
|               | L        | 7.0  | 6.2  | 6.3  | 5.3    | 7.8       | 13.5    |

\(^a\) K–P = Kuyavian–Pomeranian province; M = Masovian province; G–P = Greater Poland province; L = Lodz province.

The average water needs of grapevines during the growing season, considered from 1 May to 31 October in the years 1981–2020 in central Poland were estimated to be 438 mm (Figure 2a). The highest daily water requirements of grapevines (equal 3.7 mm) were calculated in July (Figure 2b). A little lower values of daily grapevines’ water needs (3.4 mm) were estimated to occur in August, as well in June (2.9 mm). The lowest water requirements of grapevines were assessed to occur in May (1.5 mm) and in October (0.9 mm).

![Figure 2](image-url)
and 309 mm (K–P) and 308 mm (M) in the period of increased crop water needs. The lowest water needs of grapevines, 427 mm in the period of May–October and 296 mm in the period of June–August, were noted in the Lodz province. In both analyzed periods and in all of the provinces, grapevine water demands were higher than precipitation totals (Figure 3a,b), which indicates the necessity of supplementary irrigation.

In the studied forty-year period in each considered province of central Poland, there was a visible tendency of the increased water needs of grapevines— both in the growing season (May–October) (Figure 4a–d) and during the period of increased crop water needs (June–August) (Figure 5a–d), as well as in July, the month with the highest water requirements (Figure 6a–d).

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**Figure 3.** Average water needs of grapevines and the average precipitation in the growing season (a) and in the period of increased crop water needs (b) in the considered provinces in central Poland (K–P = Kuyavian–Pomeranian, M = Masovian, G–P = Greater Poland, and L = Lodz).

**Figure 4.** Time trend of precipitation totals and grapevine water needs in the period of May–October in the considered provinces in central Poland: Kuyavian–Pomeranian (a), Masovian (b), Greater Poland (c) and Lodz (d).
Figure 4. Time trend of precipitation totals and grapevine water needs in the period of May–October in the considered provinces in central Poland: Kuyavian–Pomeranian (a), Masovian (b), Greater Poland (c) and Lodz (d).

Figure 5. Time trend of precipitation totals and grapevine water needs in the period of June–August in the considered provinces in central Poland: Kuyavian–Pomeranian (a), Masovian (b), Greater Poland (c) and Lodz (d).

Figure 6. Time trend of precipitation totals and grapevine water needs in July in the considered provinces in central Poland: Kuyavian–Pomeranian (a), Masovian (b), Greater Poland (c) and Lodz (d).

There was also tendency of increased precipitation totals, especially during the entire grapevine vegetation period (May–October) (Figure 4a–d). In general, the trend of changes was not significant due to high variability in precipitation from year to year. An exception
was Masovian province, where a significant increasing trend was recorded (Table 4). In the period of increased water demands for grapevines (June–August) a slight decreased tendency was recorded in Lodz province (Figures 5a–d and 6a–d).

**Table 4.** Time trend equations of the rainfall in the years 1981–2020 in central Poland.

| Period       | Provinces          | Linear Correlation Coefficient (r) | Tendency of Rainfall (mm decade$^{-1}$) |
|--------------|--------------------|-----------------------------------|---------------------------------------|
|              | Kuyavian–Pomeranian | Masovian                          | Greater Poland                        | Lodz       |
| May–October  | 0.191 n.s.         | 0.450 ***                         | 0.194 n.s.                            | 0.196 n.s. |
| June–August  | 0.080 n.s.         | 0.261 n.s.                         | 0.028 n.s.                            | 0.068 n.s. |
| July         | 0.117 n.s.         | 0.185 n.s.                         | 0.127 n.s.                            | 0.030 n.s. |
| May–October  | 15.5               | 38.3                              | 14.9                                  | 15.2       |
| June–August  | 5.1                | 16.5                              | 1.7                                   | −3.9       |
| July         | 4.1                | 8.7                               | 5.5                                   | −1.2       |

n.s.—not significant; ***—significant at $p \leq 0.01$.

In the entire studied area of Poland, a significant temporal variability in grapevines’ water needs was noted (Table 5). This indicates that in the growing season (May–October) and during the years 1981–2020, the grapevine water requirements increased in each decade from 11.5 mm in Greater Poland province to 5.8 mm in Kuyavian–Pomeranian province (Figure 4a–d, Table 5). In the months June–August, during the period of increasing water needs by plants, the crop evapotranspiration rose in each following decade from 8.4 mm in Greater Poland province to 4.6 mm in Kuyavian–Pomeranian province (Figure 5a–d, Table 5). In July, the month when the water needs of the grapevines are the highest, the crop evapotranspiration increased in the range from 2.5 mm in Greater Poland province to 1.1 mm in Kuyavian–Pomeranian province (Figure 6a–d, Table 5).

**Table 5.** Time trend equations of the grapevine water needs in the years 1981–2020 in central Poland.

| Period       | Provinces          | Linear Correlation Coefficient (r) | Tendency of Water Needs (mm decade$^{-1}$) |
|--------------|--------------------|-----------------------------------|------------------------------------------|
|              | Kuyavian–Pomeranian | Masovian                          | Greater Poland                           | Lodz       |
| May–October  | 0.456 ***          | 0.644 ***                         | 0.701 ***                               | 0.610 ***  |
| June–August  | 0.429 ***          | 0.614 ***                         | 0.660 ***                               | 0.598 ***  |
| July         | 0.184 n.s.         | 0.357 **                          | 0.389 **                                | 0.335 **   |
| May–October  | 5.8                | 8.4                               | 11.5                                    | 7.6        |
| June–August  | 4.6                | 6.6                               | 8.4                                     | 6.5        |
| July         | 1.1                | 2.0                               | 2.5                                     | 2.0        |

n.s.—not significant; **—significant at $p \leq 0.05$; ***—significant at $p \leq 0.01$.

The highest rainfall deficit in the studied six-month period of the grapevine development (from 1 May to 31 October) with the occurrence probability of the normal years ($N_{50\%}$) and medium dry years ($N_{25\%}$) was noted in the Kuyavian–Pomeranian province and amounted to 133 mm and 254 mm, respectively (Table 6). The highest rainfall deficit with the occurrence probability of the very dry years ($N_{10\%}$) was found in the Masovian province (363 mm). In the three-month period (June–August), during the increased water needs by plants, the highest rainfall deficit in the normal years ($N_{50\%}$) and medium dry years ($N_{25\%}$) was observed in the Kuyavian–Pomeranian province (117 mm and 200 mm, respectively) and the highest rainfall deficit in the very dry years ($N_{10\%}$) was noted in the Masovian province (303 mm). In July, the rainfall deficits $N_{50\%}$, $N_{25\%}$, and $N_{10\%}$ were evenly balanced. Generally, with the exception of the very dry years ($N_{10\%}$), the lowest
rainfall deficit in the normal years (N50%) and medium dry years (N25%) was found in the Lodz province.

Table 6. Rainfall deficit (mm) in grapevines cultivation in 1981–2020 in central Poland. N—amounts of precipitation deficit.

| Probability of Rainfall Deficit Occurrence | Provinces          | Kuyavian–Pomeranian | Masovian | Greater Poland | Lodz |
|-------------------------------------------|---------------------|---------------------|----------|---------------|------|
| May–October                               |                     |                     |          |               |      |
| N50% = normal years                       | 133                 | 100                 | 126      | 103           |      |
| N25% = medium dry years                   | 254                 | 251                 | 262      | 232           |      |
| N10% = very dry years                     | 330                 | 363                 | 296      | 300           |      |
| June–August                               |                     |                     |          |               |      |
| N50% = normal years                       | 117                 | 92                  | 106      | 95            |      |
| N25% = medium dry years                   | 200                 | 194                 | 194      | 175           |      |
| N10% = very dry years                     | 260                 | 303                 | 225      | 242           |      |
| July                                      |                     |                     |          |               |      |
| N50% = normal years                       | 37                  | 35                  | 31       | 30            |      |
| N25% = medium dry years                   | 95                  | 87                  | 81       | 88            |      |
| N10% = very dry years                     | 129                 | 122                 | 99       | 132           |      |

4. Discussion

In Poland, atmospheric precipitations are the primary source of water for viticulture [3]. In areas suitable for the grapevine cultivation, the annual precipitation totals ranged between 500 mm and 800 mm [3,4]. Rzekanowski [15], studying the water deficit during the growing season in Poland on the basis of data from 27 meteorological stations, stated that the highest water deficits in the fruit plants’ cultivation occurs in central Poland (in the great valleys area). More favorable water conditions were noted in the southern and northern region of the country [15]. The highest need for irrigation supplementing precipitation was observed just in central Poland [30–35]. A clearly negative effect of drought periods on the yield of grapevine plants grown in Poland was published by Treder and Pacholak [36]. The water deficit occurring during the drought period contributed to the weak growth of shoots and fruits, drying shoots growing from the buds in the corners of leafstalks, and yellowing leaves [3]. Consequently, the vineyards located in central Poland should be irrigated, especially during periods of drought. Drip irrigation of the grapevine plantings in Poland was recommended [3,36].

Generally, in many European countries and around the world, irrigation is a common cultivation treatment in vineyards [37]. Several scientists report the beneficial effects of micro-irrigation, including deficit irrigation, on the development and yield of grapevine plants [37–47]. In studies carried out in Spain, comparing to the rain-fed treatment, all applied irrigation methods increased the yield of grapevine fruit, even by 58% [45].

The effects of climate change on grapevine physiology and wine characteristics are already visible and will very likely continue in the coming decades in all the grape growing regions of the world. The first observed and forecasted effect of climate change was an advance in development stages, with a ripening occurring under warmer meteorological conditions. This can significantly modify the quality of berries, which will likely contain less anthocyanin, fewer acids, more sugars, and presumably fewer aroma compounds. The effects of climate change on grapevine yield potential are more difficult to predict [48].

The results of studies in Germany depicted an increasing spring frost risk for potential viticulture areas in eastern Germany as well as in the southernmost areas of viticulture. This effect in northern and eastern Germany is due to earlier bud burst and stronger continental air masses’ influence, but for the southern and western regions of Germany, it is mainly due to the even earlier bud burst. This could modify the regionally nuanced character of German wines [49].
Climate change studies for Italy [50,51], France [52], Germany [49,53], and Luxembourg [54], among others, hint at an increase in the growing season mean temperature.

The expected further climate changes may cause an increase in water needs of the plants, also including grapevines [13,24,55–57]. Therefore, some adaptation measures should already be taken today to protect plant crops against the effects of rising air temperature. These adaptation activities include irrigation treatments, particularly the resource-efficient drip irrigation systems. The results of the research presented in this paper will allow for precise programming of irrigation treatments for vineyards located in central Poland. It was found that the water needs of grapevines during the growing season in the study area amounted to 438 mm, and this value was not covered by rainfall.

In the present research, the observations of the temporal variability analyzed on the basis of the forty-year period showed a significant gradual increase in grapevine water needs in all of the studied provinces in central Poland. The importance of the irrigation treatments in Poland will gradually increase along with the intensification of adverse climate changes [7,8,35,58–62] and the foreseen rising temperature in the range of 2 ºC to 4 ºC [7,8]. It should be noted that individual scenarios for temperature and precipitation changes, developed for Poland in the actual decade of the 1920s and following (2050 and 2080) years, differ significantly, especially in the summer months (from June to August). In fact, all scenarios assumed an increase in air temperature. It is expected that the average monthly air temperature in July and August may exceed even 25 ºC. Some scenarios predict an increase in precipitation, while the others assume a decrease in precipitation. This research has shown that in vineyards located in central Poland, there is already a significant deficit in precipitation.

Grapevines are considered to be drought tolerant plants [63], but most current cultivation areas are located in the regions with decreasing water availability and a potential risk of high drought stress during the growing season [64]. In future scenarios, the current winemaking regions in southern Europe may undergo a decline in their viticulture suitability, mainly due to severe dryness [65]. These regions may indeed become too dry for high-quality winemaking [66] and, in some of the most extreme cases, will require intensive irrigation [65].

5. Conclusions

Based on the estimates carried out in present study, it was found that during the growing season, i.e., from 1 May to 31 October, the average value of water needs of grapevines cultivated in vineyards in central Poland is estimated to be 438 mm and it is not covered by rainfall. Both in the growing season and during the period of increased water needs by plants, i.e., from 1 June to 31 August, an upward time trend in the water needs of grapevines was noted. A significant temporal variability in water needs was found for each province. Regardless of the occurrence probability of the normal, medium, or dry years, the rainfall deficit in the growing season in grapevine cultivation was recorded in the entire studied area of central Poland. These changes are mainly impacted by a significant increasing tendency in mean air temperature and less by precipitation totals, which do not show a clear changing tendency. The presented research results may constitute the basis for designing resource-efficient irrigation programs necessary for agricultural and horticultural crops in the light of the observed global climate change.

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