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Assessment of the Water Needs of Fruit Plants in the Perspective of Climate Change

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Abstract: The paper includes a detailed water need forecasting analysis of fruit plants: apple trees, pear trees, cherry trees and plum trees, for the area of Poland with particular water deficits. The assessment was carried out for the multiannual period of 1989-2018, using three methods developed by Press, Grabarczyk and Rzekanowski, and Treder. The greatest water needs in the multiannual period (1989-2018) were demonstrated by apple and plum trees. The average water needs of apple trees in the multiannual period were 485 mm (Press method), 599 mm (Rzekanowski and Grabarczyk) and 558 mm (Treder), respectively. The average amount of water needs of plum trees was 506 mm (according to Press), 590 mm (Rzekanowski and Grabarczyk) and 548 mm (Treder). In practice, each of the methods presented should be used to forecast the water needs of fruit plants. This will minimise the risk of water shortages and will also enable determination of irrigation doses.

Keywords: fruit plants, water deficit areas, irrigation needs, water needs

1. Introduction

In Central Poland, where water shortages are frequent, intensive vegetable and fruit growing is exclusively dependent on the course and distribution of precipitation and air temperature. Spatial and temporal variability of precipitation is a characteristic feature of the Polish climate, which makes it difficult to estimate water needs of plants and forecast water balance (Kuchar & Iwański 2011). The studies carried out so far have shown that fruit plants in Poland require annual precipitation of 700 to 800 mm (Słowik 1973) and even 800 to 900 mm (Hołubowicz et al.1993) for optimal growth and yielding.The average amount of precipitation over multiannual period is 602 mm, with deviations from the average of +/-30% in some years (Rzekanowski 2009). The vegetation period is prolonged, which has a positive effect on fruit farming, but is associated with a higher risk of water deficit for fruit trees. Water needs of fruit plants are very high, especially at the time of growth and ripening of fruits. In Poland, irrigation is not developed on a wider scale. The development of irrigation systems should primarily concern fruit plants and vegetables. This is linked to the need to increase the modernity and competitiveness of farms and the projected climate changes (Bac & Rojek 1979). Water needs of fruit plants are assessed as high (Słowik 1973, Drupka 1976, Hołubowicz et al.1993). The demand for water increases as the period of growth and ripening of fruits is extended. On the other hand, water needs of fruit plants grow with the shallowing of the root system, which depends on the species and type of rootstock. Therefore, it is assumed that out of all fruit plants, berry plants have the greatest water needs, and among them blueberry, strawberry and wild strawberry, followed by raspberry, currant and gooseberry (Rzekanowski, 2009). Moreover, the analysis of water needs of fruit plants indicates that fruit trees also have relatively high water needs (Drupka 1976). Among the trees, especially on dwarf and semi-dwarf rootstock, apple and plum have high water needs; peach, cherry, pear and walnut have medium water needs;, and apricot and cherry trees have relatively low needs (Rzekanowski 2009). There is, therefore, a great need to adapt models to practice based on simple meteorological measurements such as air temperature and humidity. This condition is met by the following models: Grabarczyk, Rzekanowski and Treder and others (Treder et al. 2013). The use of models allowing the calculation of reference evapotranspiration to estimate water needs of not only fruit plants requires the determination of plant coefficients, depending on the plant species and development phase (Treder et al. 2013). There is no information in Polish scientific literature on the calculation of water needs of fruit plants. In this part of Poland, as opposed to countries located in warmer climate zones, plant irrigation is of an interventional nature. Its purpose is to supplement periodic precipitation deficits in relation to the water demand of cultivated plants (Żarski et al. 2013). This applies especially to the lowland part of the country, defined as an area particularly scarce in water for agriculture (Ballif 1995, Treder & Pacholak 2006). These areas include light and very light soils located in the lowland, central part of Poland, in the zone of in the summer half-year precipitation(IV-IX) limited by the 350 mm isohyet. Rzekanowski (2009) believes that these areas show the greatest need for irrigation in Poland as they meet the climatic criterion of irrigation application. They cover the central lowland part of Poland, defined by Romer as the Land of the Great Valleys. These areas are characterised by the lowest precipitation during the growing season, extremely unfavourable climatic water balances and an increased frequency of long-term rain-free periods. In Polish literature on estimating water needs of fruit trees, the amounts of precipitation necessary to obtain high yields are given, described as optimal precipitation according to Kemmer and Schulz (Słowik 1973, Hołubowicz et al.1993, Święcicki 1981) and Press (Rzekanowski 2009, Łabędzki 2009, Rzekanowski et al 2011). Water needs of fruit trees according to Drupka (Rzekanowski et al 2011, Drupka 1986) were defined as water consumption from a controlled moisture layer. These formulas enable calculation of water needs of fruit trees in each month of the growing season (IV-IX) for two soil species: cohesive and sandy. In rain-free periods, these values represent a shortage of water needed to cover the potential evapotranspiration of fruit trees. Water needs of fruit trees according to the Treder model are estimated in three stages: estimation of Reference Evapotranspiration (ETo), estimation of evapotranspiration of a specific species (ETr) and estimation of the evapotranspiration of a specific planting taking into account the size of trees (ETr). The formula for reference evapotranspiration given by Treder, using the coefficient α and plant coefficients k adapted to this equation, makes it possible to determine the evapotranspiration of plums, pears, apple trees and cherries during the period IV-X. The formulas for reference evapotranspiration according to Hargreaves modified by Droogers and Allen and Hargreaves modified by Bogawski and Bednorz, as well as the Blaney-Criddle formula modified by Żakowicz (Treder et al 2010, Dzieżyc 1988, Bogawski & Bednorz 2014), using plant coefficients k according to Doorenbos and Pruitt, allow for determination evapotranspiration of: peach, cherry, pear, apple, apricot, plum and cherry in the period IV-X and evapotranspiration of vines in the period V-X. The comparison of thermal and rainfall conditions of a given region of Poland with water needs determined by the developed formulas may be helpful in the estimation of rainfall deficits for fruit trees in relation to such needs. The presented methods may also be helpful in the estimation of orchard irrigation needs and in making decisions on the location of irrigation equipment and possible use of irrigation in orchards and vineyards in Central Poland. The aim of the study was to predict water needs of fruit plants typical for Central Poland: apple trees, pear trees, cherry trees and plum trees.

2. Materials and methods

This fact prompted the author of this paper to undertake a comprehensive estimation of water needs of four species of fruit trees (apple, pear, cherry and plum) in the first five years after planting, based on field water consumption and models for which plant coefficients were determined. On their basis the potential evapotranspiration during the vegetation period was calculated. The obtained results can be used to calculate the water needs of these species of fruit trees in the conditions of central Poland, in an area particularly scarce in water. Based on Press, Rzekanowski and Grabarczyk and Treder methods, rainfall deficits were calculated as water needs of four selected fruit plants (apple, pear, cherry and plum). The calculations used meteorological data (precipitation amount and average air temperatures) from the IMGW stations in Toruń, Bydgoszcz and from the meteorological stations of KWB "Konin" in Lubstów and Kleczew in the years 1989-2018. The objects of the research were typical orchard farms in Kujawy, in Topolinek, 20 km from Bydgoszcz and eastern Wielkopolska (Gutowo near Września, Komorowo near Kleczew). The facilities that are located in the area with the lowest precipitation in Poland were selected (Fig. 1).

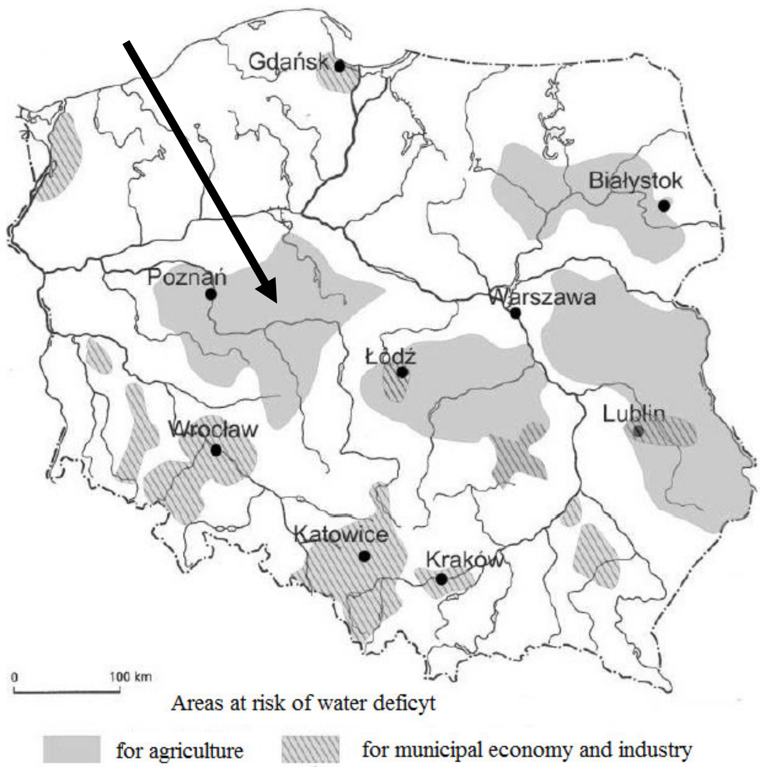

Fig. 1. Areas at risk of water deficit for agriculture, for municipal economy and industry

The orchard farms of various areas ranging from 30 ha to 75 ha were located on luvisols of IVa valuation class, which are characteristic soils of this part of Poland. In this area, the climatic risk of fruit plant cultivation is particularly high, which translates into the need for irrigation systems and, above all, precise determination of irrigation doses. On the basis of the daily and monthly air temperatures obtained, water needs for apples, pears, cherries and plums were read from a table prepared by Press for each month of the vegetation period. Next, the dependencies developed by Grabarczyk on potential evapotranspiration of ETp and Rzekanowski on actual evapotranspiration of ETr were used.

In this method, the Grabarczyk formula was used to calculate the amount of potential evapotranspiration (Grabarczyk & Żarski 1992):

$$ETp = 0.32 (\Sigma d + 1/3 \Sigma t) \quad (1)$$

where:
ETp – potential evapotranspiration (mm),
Σd – sum of average daily air humidity deficiency (hPa),
Σt – sum of average daily air temperatures (t°C).

The Press method was used to determine the water needs of fruit trees as optimal precipitation (Żakowicz 2010). For pear, apple and plum trees, the water requirements were calculated for the growing season (April-September) and for cherry trees for the period from April to August. According to Press (Ostromęcki 1973), three variants of water requirements are possible in each month of the growing season, depending on the height of the average air temperature.

Table 1. Monthly values of the plant k coefficient of fruit plants (Treder et al 2010)

	plant factor k	apple	pear	cherry	plum
IV	0.28	0.50	0.45	0.45	0.45
V	0.21	0.75	0.75	0.75	0.75
VI	0.19	1.10	1.05	1.00	1.10
VII	0.18	1.20	1.15	1.10	1.20
VIII	0.17	1.20	1.15	1.10	1.15
IX	0.16	1.15	1.10	0.90	1.15

When the temperature rises by 2°C, the amount of precipitation or artificial rainfall in the form of irrigation should be higher by 5 to 10 mm to provide the plants with the sufficient amount of water The potential ETp evapotranspiration for all months of the growing season was calculated according to the formula. Then, for each fruit plant studied, the actual evapotranspiration was calculated by multiplying it by the plant coefficient k (Table 1) according to Rzekanowski's formula (Rzekanowski 2009): $ETr = k \times ETp$, (2), where: ETr – actual evapotranspiration (mm), k – plant coefficient depending on the development phase and the condition and type of vegetation (Table 1), ETp – potential evapotranspiration (mm). Using the Rzekanowski formula (Rzekanowski 2009), the values of actual evapotranspiration and the amount of precipitation, precipitation deficits were calculated: $N = ETp – P$, (3), where: N – precipitation deficit in the absence of water reserves in the soil (mm), ETp – potential evapotranspiration (mm), P – precipitation during the growing season (mm).

3. Results and discussion

Potential evapotranspiration ETp was calculated using the following meteorological data: sum of daily average air temperatures and sum of daily average air humidity deficits. In order to determine the average monthly air humidity deficiency, the difference between saturated steam pressure value (from the table) and average monthly water vapour pressure value was calculated. Next, the actual evapotranspiration ETr for apple, pear, cherry and plum trees was determined by multiplying the value of potential evapotranspiration ETp obtained from Grabarczyk's formula by the plant factor. The third method of determining the water needs of fruit plants was the Treder's method (Drupka 1986). The value of index evapotranspiration ($ET_{0)}$ of each plant for each month obtained using the method of Grabarczyk was multiplied by the plant factor *k*, obtaining the actual evapotranspiration value (ETr). Water needs of the analysed fruit plants according to the Treder's model were calculated using the Web-based Decision Support System (Treder et al. 2010, www.nawa-dnianie.inhort.pl/eto/26-eto-temp). The results were developed through the statistical determination of the following values: mean, median, maximum and minimum, standard deviation and coefficient of variation. An attempt was also made to determine possible tendencies (trends) towards changes in the examined index of water needs of fruit plants in the Kujawy and eastern Wielkopolska regions. The methodology proposed by Rolbiecki was used here (Rolbiecki 2018). In the analysed period, no tendencies towards changes in precipitation levels were observed. For the analysed period of thirty years (1989-2018), the average amount of precipitation for the period between April and September was 343 mm. The lowest amount of precipitation occurred in 1989 (145 mm) and was by 198 mm lower than the long-term average, and the highest amount of precipitation was observed in 2010 (565 mm) and was by 222 mm higher than the average. In the analysed period of years, the amount of precipitation satisfied the water needs of apple trees only in 3 vegetation periods. In 2001, the precipitation was higher than the water needs of apple trees (by 79 mm), in 2010 (by 55 mm) and in 2017 by 29 mm. The water needs of apple trees calculated using the Press method ranged from 435 mm in the 1991 vegetation period to 560 mm in the 2002 vegetation period. The water needs of pear trees were lower than those of apple trees. In the evaluated period of thirty years, the amounts of precipitation were greater than the water needs of pear trees thirteen times. On the other hand, only in seven vegetation periods the amounts of precipitation met the water needs of pear trees: in 1993 (49 mm), in 2000 (11 mm), in 2001 (154 mm), in 2007 (12 mm), in 2010 (150 mm), in 2013 (32 mm), and in 2017 (124 mm). For cherries, the growing season is by one month shorter (IV-VIII), compared to apple, pear and plum trees, which results in a lower water requirement. In the analysed period, the lowest demand for water occurred in 1991 (315 mm) and the highest in 2002 (400 mm). The highest water deficit for cherry orchards was found in 1989 (185 mm). Higher amounts of precipitation in relation to the demand for water of cherry trees occurred in 2010. (by 200 mm). In fourteen growing seasons from 1989 to 2018, the amount of precipitation was higher than the water demand of the cherry trees. The highest water demand of plum tree occurred in 2002 (580 mm) and the lowest in 1991 (455 mm). The amount of precipitation in the analysed growing seasons was higher than the water needs of plums in: 2001 (by 59 mm), in 2010 (by 30 mm), and in 2017 (14 mm). The differences between the amount of precipitation during the growing seasons and the water demand of fruit trees over the long-term period (1989-2018) show that plum tree is the most demanding in terms of water demand among all fruit plants (from 455 mm in 1991 to 580 mm in 2002). Whereas the smallest water needs according to the Press method were observed in cherry tree (from 315 mm in 1991 to 400 mm in 2002). The greatest water shortages occurred in the periods from April to September 1989 and amounted to: 315 mm for apple trees, 240 mm for pear trees, 185 mm for cherry trees and 345 mm for plum trees. Water needs calculated with the use of the method of Rzekanowski and Grabarczyk in the growing periods from 1989 to 2018 were from 471 mm to 729 mm for apple trees, from 451 mm to 700 mm for pear trees, from 427 mm to 660 mm for cherry trees, and from 462 mm to 718 mm for plum trees. In 2001 and 2010, the water needs of fruit plants were met by precipitation (Fig. 2). For apple, pear, cherry and plum trees, the lowest water demand was in April 1997 and it amounted to 23 mm for apple trees, and 21 mm for pear, cherry and plum trees. The highest water needs were observed in July 2006: for apple and plum trees they amounted to about 174 mm, for pear trees 167 mm and cherry trees 160 mm (Table 2). The lowest water needs in the growing seasons 1989-2018 in relation to precipitation were observed in 1990 and the highest in 2002. The water demand of apple trees ranged from 498 mm to 643 mm, of pear trees from 476 mm to 618 mm, cherry trees from 450 mm to 585 mm, and of plum trees from 489 mm to 632 mm. The calculations carried out using the Treder's method showed a clear shortage of precipitation in the analysed period. The water needs of apple trees calculated using the method of Press ranged from 435 mm (in 1991) to 560 mm (in 2002), method of Rzekanowski and Grabarczyk – from 471 mm (in 1996) to 729 mm (in 2018), and the method of Treder from 498 mm (in 1990) to 643 mm (in 2002).

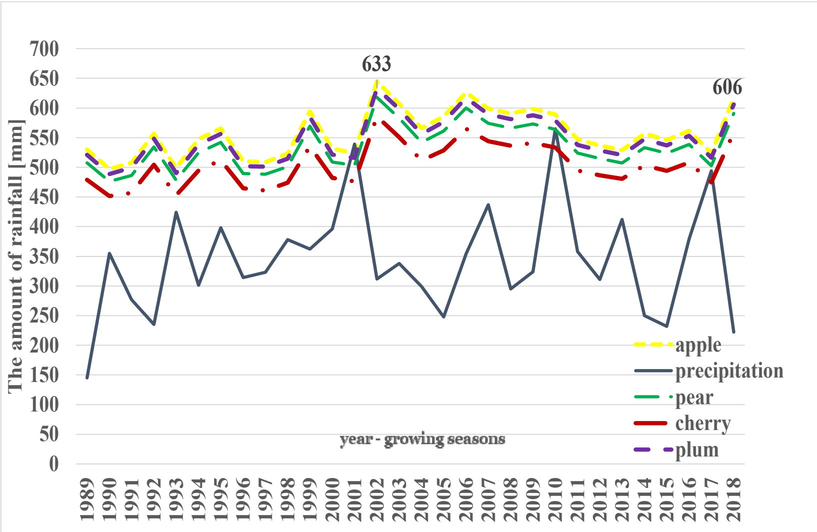

Fig. 2. Water needs of apple, pear, cherry and plum trees determined by the Rzekanowski and Grabarczyk method plotted against the background of atmospheric precipitation during the growing season (1989-2018) (own elaboration)

Table 2. Minimum and maximum values of the water needs of fruit plants in 1989-2018 determined by means of the Treder's method (own elaboration)

	apple		pear		cherry		Plum	
	min	max	min	max	min	maxi	min	max
IV	**23**	55	21	50	21	50	21	50
V	49	92	49	92	49	92	49	92
VI	94	131	90	125	86	119	94	131
VII	107	**174**	103	**167**	98	**160**	107	**174**
VIII	105	160	101	153	96	147	101	153
IX	59	102	56	97	46	79	59	102

Average water requirements of apple trees for the studied long-term period were 485 mm, 599 mm and 558 mm respectively. The obtained results are consistent with the calculated water needs of fruit trees according to Drupka (1986). The water needs of pear trees according to the method of Press ranged from 356 mm (1990) to 455 mm (2002). According to the method of Rzekanowski and Grabarczyk they ranged from 451 mm (1996) to 700 mm (2018) and to the method of Treder from 476 mm (1990) to 618 mm (2002). Average water requirements of pear trees for the methods were respectively: 399 mm, (Press), 575 mm (Rzekanowski & Grabarczyk) and for the method of Treder

534 mm (Fig. 3). The results obtained are consistent with the water needs of fruit trees determined by means of the Kemmer and Schulz method (500-710 mm) (Rolbiecki 2018).

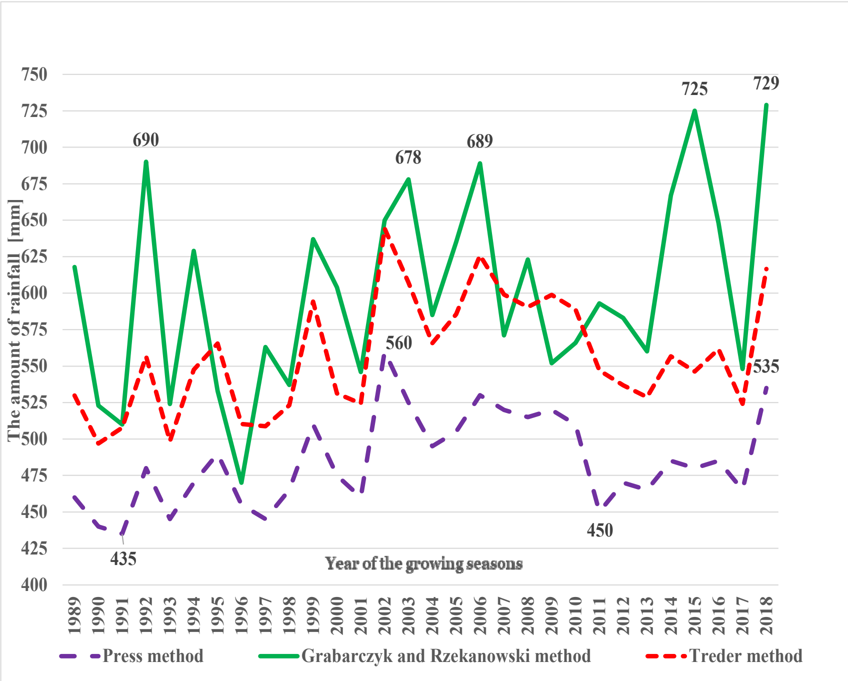

Fig. 3. Apple water needs calculated by three methods in the growing seasons (1989-2018) (own elaboration)

For comparison, the average annual (I-XII) water needs of cherry trees in the medium soil in the Bydgoszcz region determined by means of the method of Kemmer and Schulz for the period 1981-2015 constituted 532 mm (Kielak 1986). In turn, the annual water requirements for cherry trees determined by Rzekanowski (1989) for the north-western Kujawy region in the period 1981-1985 ranged from 473 mm to 539 mm (495 mm on average). During the forty-year period (1976-2015) analysed by Rolbiecki (2018), the water needs of cherry trees during the growing season in medium soils (IV-VIII) were 316 mm in the Bydgoszcz region and 326 mm in the Wrocław region. The average water needs of cherry trees were 379 mm in the Bydgoszcz area and 391 mm in the Wrocław area, while their maximum values reached 424 mm and 432 mm respectively. Thus, the average precipitation deficits in light soils were 115 mm (maximum 160 mm) in the Bydgoszcz area and 72 mm (maximum 113 mm) in the Wrocław area. According to Rzekanowski (2009), the highest water deficits occur in the case of fruit plants in the central strip of Poland (the Land of Great Valleys) and for sour and sweet cherry trees (in medium soils) they are from 20 to 42 mm. In order to obtain positive production effects in cherry growing in this area, sprinkling (Treder et al 2018), drip irrigation (Rojek 2006, Rolbiecki & Piszczek 2016a, 2016b) and sub-irrigation (Rolbiecki & Piszczek 2016c) should be performed. The water needs of plum trees varied: for the Press method from 455 mm (in 1991) to 580 mm (in 2002), for the Rzekanowski and Grabarczyk method from 462 mm (in 1996) to 718 mm (in 2018), and for the Treder method from 489 mm (in 1990) to 632 mm (in 2002). The average annual water needs of plum trees calculated by the Press method were as follows: 506 mm, 590 mm using Rzekanowski and Grabarczyk's method and 548 mm using Treder's method. The analyses conducted show that between 1989 and 2018, the water needs of fruit plants increased by 4.1 mm in each decade. (apple), 3.3mm (pear) and from 3.5 mm to 3.9 mm (cherry and plum) in each decade. As a result of similar analyses carried out by Rolbiecki (2018) over the years 1976-2015, the water needs of cherry trees in each decade increased by 3,9 mm on heavy soils, 4.9 mm on medium soils and 5.9 mm on light soils in the Bydgoszcz region and 8.6 mm on heavy soils, 10.7 mm on medium soils and 12.8 mm on light soils in the Wrocław region.

4. Conclusions

A detailed analysis of the results obtained allows us to conclude that in the meteorological conditions prevailing in this part of Poland, the amount of precipitation during the vegetation period in the last thirty years did not meet the water needs of the fruit plants analysed. Therefore, an urgent need arose to forecast and estimate the amount of water to be supplied to them by irrigation in order to cover their water needs. Apple trees and plum trees had the greatest water needs throughout these years (1989-2018). The detailed analysis of water needs showed that the average water needs of apple trees over the years amounted to 485 mm (Press method), 599 mm (Rzekanowski & Grabarczyk) and 558 mm (Treder), respectively. The average amount of water needs of plum trees was 506 mm (according to Press), 590 mm (Rzekanowski & Grabarczyk) and 548 mm (Treder). The obtained results confirmed the observations of other authors (Rolbiecki 2018, Treder et al 2018, Bąk Łabędzki 2014a) that cherry trees had the lowest water needs. The average water needs varied from 347 mm (Press method), 542 mm (Rzekanowski & Grabarczyk) and 505 mm (Treder). In practice, each of the methods presented should be used to forecast the water needs of fruit plants. Their use should minimise the risk of water shortages and, above all, enable a more precise determination of the irrigation doses. They can be particularly helpful in assessing the irrigation needs of orchards, plantations, and vineyards in Central Poland, equipment in this area of the country. Especially since, according to Rzekanowski et al. (2011), by 2025, irrigation should cover an area of approx. 1 million ha in Poland and should be located mainly on light soils of the Land of the Great Valleys.

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