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Analysis of Crop Water Requirements for Apple Using Dependable Rainfall

Yusuf Ucar [1], Joanna Kocięcka [2], Daniel Liberacki [2,*] and Roman Rolbiecki [3]

[1] Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Isparta University of Applied Sciences, 32260 Isparta, Turkey
[2] Department of Land Improvement, Environment Development and Spatial Management, Faculty of Environmental Engineering and Mechanical Engineering, Poznań University of Life Sciences, Piątkowska 94, 60-649 Poznań, Poland
[3] Department of Agrometeorology, Plant Irrigation and Horticulture, Faculty of Agriculture and Biotechnology, Bydgoszcz University of Science and Technology, 85-029 Bydgoszcz, Poland
* Correspondence: daniel.liberacki@up.poznan.pl

Abstract: Rainfall expected to occur in a given period is defined as dependable rainfall. The increasing pressure on freshwater resources necessitates efficient water use in the agricultural sector, where water is used the most globally. Therefore, dependable rainfall values in dry (80%), normal (50%) and wet (20%) periods, which are used in the planning and operation stages of irrigation networks, can be determined by analysis. In this study, the change in the irrigation water requirement of apple trees was investigated based on the dependable rainfall of Warsaw and Isparta, two important apple production regions of Poland and Turkey. For this purpose, dependable rainfall values in both locations between 1984 and 2021 were calculated monthly and annually with the Rainbow program. Then, using the climate parameters of the relevant years, plant water consumption and irrigation water requirements were calculated with the help of Cropwat software. As a result of the research, rainfall values expected to occur in the dry, normal and rainy years in Warsaw are 466 mm, 532 mm and 604 mm, respectively, while, in Isparta, these values are 422 mm, 520 mm and 602 mm, respectively. Crop water requirements calculated based on dependable rainfall are 363 mm, 237 mm and 108 mm in Warsaw during the dry, normal and wet periods, while these values are 452 mm, 367 mm and 277 mm, respectively, in Isparta. The application of appropriate irrigation rates that take into account water requirements will optimize the use of water resources and also improve apple yields. This is extremely important for these research areas in particular, as Turkey and Poland are among the largest apple producers in the world.

Keywords: apple production; crop water requirements; climate analysis; Cropwat; Rainbow; rainfall; Turkey; Isparta; Poland; Warsaw

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1. Introduction

One of the largest challenges facing agriculture today is ongoing climate change and the occurrence of water shortages. Rational water management in terms of crop irrigation is, therefore, extremely important. Irrigation systems that deliver water to agricultural lands are complex, with many uncertainty factors, such as temporal and spatial variations in hydrological elements, fluctuation in economic parameters, and errors in estimating crop yields [1]. Achieving the expected benefit from the irrigation system depends on the realistic planning of the irrigation scheduling and its implementation. With a good irrigation schedule, water and fertilizer are used effectively, plant yields and quality are increased, and production costs are reduced thanks to water, energy and fertilizer savings [2]. Optimizing irrigation scheduling significantly improves irrigation efficiency in a field or plantation, as evidenced by previous researchers' results [3,4]. In order to perform irrigation scheduling, it is necessary to know the crop water requirements (CWR), rainfall, plant characteristics and the depth of the soil to be wetted. It is also important to determine the soil's water-holding capacity, the moisture level at the start of irrigation and the amount of water to be applied in each irrigation.

Climate parameters such as temperature, humidity and wind speed are fundamental factors in determining irrigation water amounts and the operation of irrigation systems. These parameters interact with rainfall to influence evapotranspiration (ET), one of the basic criteria that should be determined to obtain correct irrigation scheduling and calculate crop water requirements. While the ET values of a region change very little from year to year, the amount of rainfall in the region can vary significantly from year to year. Regarding irrigation scheduling and crop water requirements, the amount, duration, intensity and distribution of rainfall during the plant growing period and their probabilities are important [5,6]. For this reason, it is also significant to use dependable rainfall instead of average rainfall in irrigation scheduling [7] and the associated crop water requirement. Dependable rainfall is rainfall that is expected to occur with a certain probability. Akcay et al. [8] stated that the expected rainfall amounts in any dry, normal and wet period (year, month, ten days) could be determined by rainfall frequency analysis. In addition, these analyses are performed for statistically different probability levels by using the rainfall measured in any period in the previous years. In studies on irrigation, authors stated that an 80% probability level is used when determining the expected rainfall amount in any dry period, and a 20% probability level is used when determining the expected rainfall amount in the wet period [9,10]. Especially in the design of irrigation systems, dependable rainfall is recommended instead of using average rainfall values, which is expected to decrease with an 80% probability in the period when water is most needed. For dependable rainfall analysis for irrigation purposes, rainfall data with an observation period of at least 15 years should be used [11]. In this way, the irrigation system will be able to distribute the water needed even in the most critical period in terms of rainfall.

Although the apple's homeland is Central Asia, it is a fruit that can be grown almost anywhere in the world. Turkey and Poland are two important apple producers. According to FAO data, Turkey ranks third in world apple production, with 4,300,486 tons, and Poland ranks fourth, with 3,554,300 tons [12]. In terms of apple species, Poland is dominated by the Idared variety, which covers 18.2% of the total area of apple trees. Popular varieties are also Szampion, Jonagold and Ligol, which account for 10.1%, 9.4% and 7.9%, respectively [13]. Furthermore, a systematic increase in the apple harvest in Poland has been observed for many years. This results in the need to export apples or allocate fruit for processing. It is estimated that between 40 and 60% of the Polish apple harvest is destined for the processing industry and between 20 and 30% for export [14]. Regarding Turkey, the regions with the highest apple production are Isparta and Karaman, which account for 33.6% of the total production [15]. The main varieties grown in this country are Starking, Golden, Amasya and Granny Smith. These represented 70% of total production in the 2019/2020 season [16]. In various studies, the evapotranspiration of apples varies between 500 and 700 mm, depending on the region of growth in Turkey and the apple variety, while this value is between 600 and 700 mm in Poland [17,18]. As in other plants, it is crucial to fully meet the crop water requirement in apples. Moreover, it is extremely important to do this when the plant is least sensitive to water in case of water deficits in terms of obtaining the maximum yield from the unit area. Estimating crop water requirements by performing dependable rainfall analyses is one of the elements that will facilitate the efficient use of water in agriculture. In addition, water allocated for irrigation is decreasing due to climate change and increasing water demands in non-agricultural areas. Therefore, analyzing the water requirement of apples based on dependable rainfall and analyzing the relationship between rainfall and apples' water requirements is vital to conserve the diminishing water resources. Such calculations for apple in countries with high apple production, such as Turkey and Poland, will help to optimize irrigation. Moreover, it will increase water savings, which is extremely important in the face of climate change.

Currently, there is a lack of studies attempting to comprehensively compare climatic conditions and the water needs of apples among the world's leading producers. Previous work has focused, among other aspects, on analyses of the imports and exports of fruit, vegetables and their products between Turkey and Poland. They show that these countries differ in the number of apples consumed per capita. In Turkey, the value is almost 30 kg per year, while in Poland, it is lower, estimated at around 13–15 kg of apples per capita per year [19]. It has also been found that running organic apple production systems in Turkey can support environmental protection and reduce non-renewable energy consumption compared to conventional production systems [20]. Furthermore, previous studies clearly show that properly irrigating these fruits is extremely important in both Turkey and Poland. For example, an experiment in the Düzce region (Turkey) showed that despite the occurrence of summer precipitation, which would seem to meet water needs, it is essential to plan for adequate irrigation in apple orchards [21]. Furthermore, during a two-year experiment on apples in Isparta, a significant effect of irrigation frequency on yield was noted [22]. Moreover, in Poland, many studies show that irrigation is an important element influencing the production volume and quality [18,23]. However, proper irrigation of apples cannot be carried out without prior climatic analyses and accurate estimation of their water needs. The present study is intended to fill the knowledge gap in analyses and comparisons of climatic conditions in the context of apple cultivation in Turkey and Poland.

The main objective of this study was to investigate the change in water requirements for apple irrigation based on dependable rainfall in Warsaw and Isparta, which are two important apple production regions in Poland and Turkey. First, analyses were carried out for meteorological data for the period 1984–2021 in the Rainbow software. Then, dependable rainfall was calculated according to 80% (dry), 50% (normal) and 20% (wet) probability values. Estimating dependable rainfall values is extremely important as they are used in the planning and operation of irrigation networks. Furthermore, this study aimed to calculate the plants' water consumption and accurately determine the irrigation water requirements for apples in the Isparta and Warsaw regions. Finally, the results were analyzed to show potential changes in water demand over the years and compare the values received between the world's leading apple producers, Turkey and Poland. This research on water demand is fundamental and should be used as source material to develop future-oriented assumptions in making changes and adjustments to enable the more precise and economical use of irrigation water in apple cultivation. This is extremely important in view of the adverse climate changes recorded in the countries analyzed. The implementation of adaptation measures is crucial for these countries, as water deficits can reduce yields. A reduction in apple production in Turkey, the world's third-largest producer of apples, and Poland, the fourth-largest producer, could result in insufficient fruit to satisfy the consumer demand.

2. Materials and Methods

The two cities used as study sites are located in important apple production areas: Warsaw (Poland) and Isparta (Turkey). Warsaw (52°13′ N, 21°00′ E) is the capital of the country and also the central city of the Mazowieckie Voivodship. Approximately 43% of Poland's apple cultivation area is located in this voivodship [14], which is why this region was chosen for the study. The country is dominated by light, sandy soils and the growing season lasts around 205 days [24]. According to the United States Department of Agriculture, Isparta is the largest apple-producing province in Turkey, with around 850,000 MT of apples per year [16]. Therefore, Isparta (37°45′ N; 30°33′ E) was chosen as the study area in Turkey for this study. The growing season in this region is considered to be from May to October, as confirmed by previous studies of apple water consumption [17]. In the region of Isparta, there are soils such as clay, clay loam, sandy clay loam, silty clay and silty clay loam [25]. Climate parameters used in this work, such as maximum temperature, minimum temperature, relative humidity, wind speed and sunshine duration and rainfall, were obtained from the Polish Institute of Meteorology and Water Management and the Turkish

State Meteorological Service. While the Isparta-Eğirdir basin has a climate type between a steppe and humid climate according to the De Martonne drought index [26], Warsaw has a semi-humid climate type according to the same classification [27]. Raes et al. [28] stated that 30 years of rainfall data are sufficient for calculating dependable rainfall. In this study, a 38-year data set was used. For this reason, it is considered that the selected period is sufficient for dependable rainfall calculation.

2.1. Calculation of the Dependable Rainfall

Rainbow software was used to analyze observed annual and monthly rainfall values. With this software, the homogeneity test of time series and probability distribution analysis can be performed with different approaches. Different dependable rainfall values obtained for the probabilities are shown in a table or graphically [28]. In order to analyze rainfall with the software, the stages were as shown in Figure 1. Then, dependable rainfall data were transferred to the MS Excel program, and dry (80%), normal (50%) and wet (20%) months and years were determined.

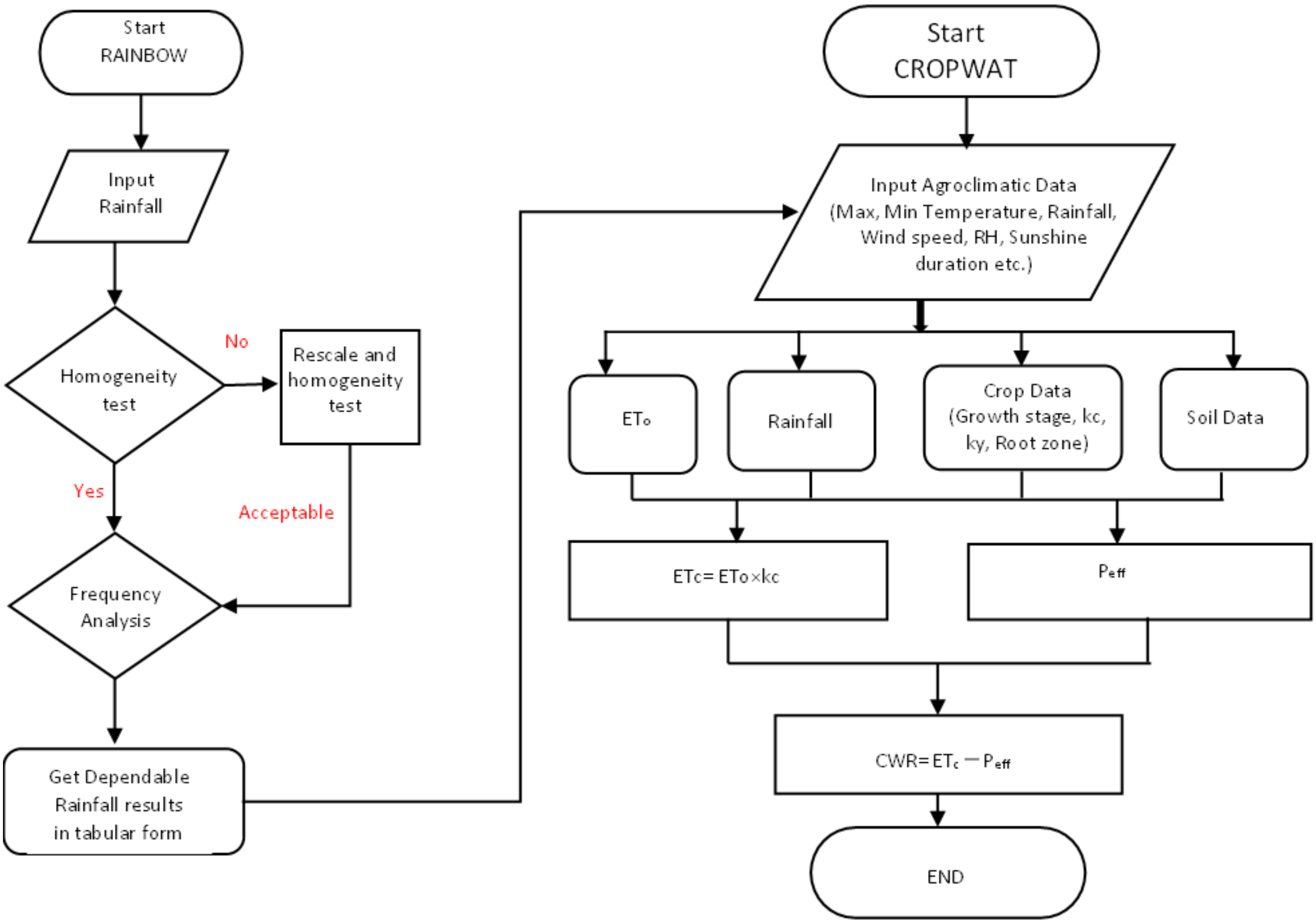

Figure 1. Flowchart of the methodology (Cropwat section of the flowchart was adapted from Kattak et al. [29]). ETo: reference evapotranspiration, ETc: evapotranspiration of the crop, Peff: effective rainfall, RH: relative humidity, kc: crop coefficient, ky: yield response to water, CWR: crop water requirement.

2.2. Calculation of Crop Water Requirements

The monthly water requirement of rice was calculated by using the Single Crop Coefficient method [30].

Evapotranspiration [30] and crop water requirements are calculated by Equations (1) and (2) below.

$$ET = kc \times ETo \tag{1}$$

where:

ET—evapotranspiration [mm month^{-1}];
kc—crop coefficient (kc_{ini}: 0.50; kc_{mid}: 1.20, kc_{end}: 0.95) [30];
ETo—reference evapotranspiration [mm month^{-1}] [30];

$$CWR = ET - Re \tag{2}$$

where:

ET—evapotranspiration [mm month^{-1}];
Re—effective rainfall [mm month^{-1}];
CWR—crop water requirement [mm·month^{-1}].

The ETo estimation methodology used in this study is applied in scientific research and recommended for use by the FAO [5,31–34]. Reference evapotranspiration, evapotranspiration and crop water requirements were calculated with the Cropwat software (version 8). This software was developed by the Food and Agriculture Organization (FAO) as a tool to assist scientists, agronomists and engineers in performing typical irrigation calculations, as well as for managing and designing irrigation systems [35]. The application allows the development of irrigation schedules under different farming and water supply conditions and is widely used in research [36–39]. Furthermore, to better understand the research process, each step of the methodology was depicted on a flowchart (Figure 1).

2.3. Statistical Analyses

The Mann–Kendall test [40,41] was applied for statistical analyses of the results. This method is widely used for determining trends in hydro-meteorological time series [42–44].

3. Results and Discussion

3.1. Dependable Rainfall Analysis

This study analyzed the monthly and annual average rainfall values observed in Warsaw and Isparta between 1984 and 2021 and the dependable rainfall expected to occur in wet, dry and normal months and years with the Rainbow software (Table 1). Warsaw's average annual rainfall for the analyzed years is 541 mm, while Isparta's is 508 mm. Analyses carried out in this study have shown a difference of 33 mm between the mean annual rainfall values in the investigated regions. Furthermore, they indicated that the mean annual rainfall tends to increase ($p < 0.031$) in Warsaw, while there is no increasing or decreasing trend in Isparta. As can be seen from Table 1, the amount of rainfall during the growing period in Warsaw was higher than in Isparta. Furthermore, the analyses also highlighted a difference in rainfall distribution over the year between the regions. According to the long-term average, the wettest month in Warsaw is July, with 80 mm, followed by June, with 67 mm. The least wet month in Warsaw is March (28 mm). Meanwhile, the wettest months in Isparta are December (68 mm) and January (66 mm), and the least rainfall occurs in August, with 15 mm. For apples between April and October, which is the vegetation period in both locations, 71% of the annual rainfall (385 mm) is realized in Warsaw, while this rate is 44% in Isparta (222 mm). The closeness in annual mean rainfall values in Warsaw and Isparta is even more pronounced for the dependable rainfall values (wet (20%), normal (50%) and dry (80%)). While the dependable rainfall values in Warsaw in wet, normal and dry years are 604 mm, 532 mm and 466 mm, respectively, in Isparta, these values are 602 mm, 520 mm and 422 mm, respectively. In Warsaw, in terms of the wet year (20%), the expected maximum and minimum rainfall values by month are 116 (July)–38 mm (January, February and March), and in the normal year (50%), these values are 67 (July)–25 mm (February); the highest and lowest rainfall in the dry year (80%) varied between 39 (July) and 13 mm (October). In Isparta, in terms of the wet year (20%), the expected maximum and minimum rainfall per month is 104 (December)–24 mm (July); in the normal year (50%), it is 55 (January)–8 mm (July), while the highest and lowest rainfall in the dry year (80%) varied between 26 (March) and 0 mm (July). The analyses show that the rainfall distribution during the year in Isparta differs from that in Warsaw. Differences in rainfall distribution in these regions can be seen for wet, normal and dry years.

Table 1. Monthly and annual rainfall analysis results in Warsaw and Isparta (mm).

Months	Warsaw				Isparta			
	Average	20% (Wet)	50% (Normal)	80% (Dry)	Average	20% (Wet)	50% (Normal)	80% (Dry)
January	29	38	25	15	66	100	55	26
February	28	38	25	14	53	78	47	24
March	28	38	27	18	56	82	49	26
April	34	52	31	15	51	74	42	23
May	56	73	50	34	54	80	47	24
June	66	100	61	31	33	52	28	11
July	80	116	67	39	16	24	8	0
August	63	90	54	32	15	26	11	2
September	50	75	45	23	17	26	9	3
October	36	57	31	13	36	60	30	9
November	36	51	33	19	44	67	37	17
December	35	53	36	18	68	104	49	22
Year	**541**	**604**	**532**	**466**	**508**	**602**	**520**	**422**

Table 2 shows the dry, normal and rainy months and years of Warsaw. For Warsaw, the total annual rainfall for a year with the annual rainfall classed as "dry" should be less than or equal to the dependable expected rainfall for that year, 466 mm; meanwhile, in the year classified as "wet", this value must be greater than or equal to 604 mm. According to the total dependable rainfall data for many years, within 38 years (1984–2021), 6 years are classified as dry (1990, 1993, 1996, 2015, 2018, 2019), 9 years as wet (1994, 1998, 2009, 2010, 2011, 2013, 2017, 2020, 2021) and 23 years as normal years. Furthermore, the analysis carried out in this work has shown that rainfall in Warsaw ranges from 390 to 456 mm in the dry year, while rainfall in the rainy year is between 604 and 798 mm. In 2010, the wettest year, only 1 month was classified as dry. On the other hand, in the least wet year of 2019, 4 months were classified as dry months, while 1 month was classified as a wet month. In Warsaw, 2018 and 2019 were classified as dry years for two consecutive years, and 2009, 2010 and 2011 were classified as wet years for 3 consecutive years. Although 2012 was a normal year in Warsaw, no months in this year were classified as dry. Table 3 shows Isparta's dry, normal and wet months and years. The annual rainfall class for Isparta was determined as "dry", while the total annual rainfall for a year in Isparta should be less than or equal to 422 mm, which is the expected dependable rainfall value of that year, and this value must be more than or equal to 602 mm in the year classified as "wet". According to the total dependable rainfall data for many years, within 38 years (1984–2021), 8 years were classified as dry (1986, 1989, 1990, 1992, 1993, 1999, 2008, 2011) and 10 years as rainy (1988, 1998, 2001, 2003, 2006, 2009, 2010, 2012, 2013, 2014), while 20 years are classified as normal years. It can therefore be concluded that normal years prevailed for Isparta during the analyzed period. In this region, rainfall values in the dry year vary between 284 and 400 mm, while rainfall values in the wet year are between 612 and 687 mm. In 1998, the rainiest year, only 1 month (July) was classified as dry. While the least wet year of 2008 contained 4 dry months, it also included 1 rainy month. In Isparta, 2012, 2013 and 2014 were classified as wet years for two consecutive years, and both 1989 and 1990, and 1992 and 1993, were classified as dry years for two consecutive years. Although 1994 and 2019 were classified as normal years in Isparta, no months in these years were classified as dry. Özfidaner and Gönen [45] emphasized that not all of the months in a year classified as normal can be classified as normal months and that there can be dry and wet months in normal years. The same is true for years classified as dry and wet. While there may be dry months in a year classified as rainy, it is possible to have wet months in a year classified as dry. In other words, it is not possible for all the months in a dry year to be dry or for all the months in a wet year to be wet. Considering this situation, Özfidaner and Gönen emphasized that it is better to use dependable rainfall values instead of monthly dependable rainfall values in agricultural drought studies [45]. In addition, monthly or ten-day dependable rainfall values are considered important in monitoring the intensification of drought, in which months or ten-day periods are considered over several years, and precautions can be taken accordingly. For example, in June, July and August, when irrigation water is largely needed in Warsaw and Isparta, 20 months were classified as dry.

Table 2. Dry, normal and wet months in Warsaw.

Year	**Months**												**Total**
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	
1984	23	16	24	5	99	48	101	32	92	18	28	7	**493**
1985	13	20	35	37	58	74	48	59	50	23	23	67	**508**
1986	33	7	17	14	87	51	48	74	52	30	22	32	**467**
1987	14	13	23	28	60	126	63	36	30	17	45	43	**497**
1988	16	32	44	5	31	102	64	78	17	4	47	43	**482**
1989	16	21	14	55	26	114	46	51	28	42	33	37	**480**
1990	10	22	26	46	23	39	63	70	77	13	49	16	**456**
1991	16	17	14	28	44	108	62	44	40	18	60	39	**488**
1992	12	31	43	33	25	40	25	25	79	48	63	59	**484**
1993	48	17	25	24	39	51	67	38	37	23	19	66	**454**
1994	40	9	65	93	89	20	32	73	59	69	39	65	**652**
1995	25	35	34	46	45	77	61	54	138	18	25	16	**571**
1996	5	17	11	29	61	36	100	72	64	27	25	6	**454**
1997	1	21	24	27	57	61	214	23	38	55	39	28	**589**
1998	22	43	41	56	45	114	94	52	24	55	40	31	**617**
1999	21	29	23	76	47	122	24	29	20	41	31	22	**484**
2000	29	42	41	14	38	14	120	62	53	5	66	40	**524**
2001	18	19	31	61	41	36	139	38	73	37	34	19	**545**
2002	38	72	37	17	44	55	23	141	31	64	29	3	**553**
2003	31	5	11	27	45	43	133	54	52	63	23	47	**535**
2004	24	57	35	57	58	47	79	43	17	37	52	17	**523**
2005	34	34	39	22	60	48	84	22	33	5	29	81	**490**
2006	21	30	14	35	38	15	20	165	31	40	43	26	**479**
2007	79	30	27	16	44	134	73	60	58	36	31	13	**602**
2008	68	28	39	28	35	22	88	87	61	15	29	37	**537**
2009	19	33	44	6	79	149	88	60	13	67	51	45	**652**
2010	25	37	24	39	116	87	92	143	89	3	109	34	**798**
2011	39	21	8	34	48	49	295	62	7	9	0	32	**604**
2012	47	35	21	55	44	63	73	35	28	58	29	31	**519**
2013	49	25	23	48	133	85	20	60	92	30	28	19	**613**
2014	48	14	35	44	90	74	73	68	8	6	16	82	**555**
2015	38	6	30	35	39	19	59	8	58	40	53	17	**404**
2016	21	67	33	31	28	56	71	61	11	110	41	63	**593**
2017	19	39	39	48	49	86	90	48	127	83	45	33	**705**
2018	30	7	19	13	35	22	85	63	45	52	11	51	**433**
2019	34	31	28	3	79	18	37	34	60	16	13	38	**390**
2020	29	43	13	8	67	166	48	95	64	80	9	26	**646**
2021	31	28	18	58	65	56	154	171	32	10	35	19	**676**
Average	**29**	**28**	**28**	**34**	**56**	**66**	**80**	**63**	**50**	**36**	**36**	**35**	**541**

Red color indicates dry months and years, green color indicates wet months and years, and white color indicates normal months and years.

Table 3. Dry, normal and wet months in Isparta.

Year	Months												Total
	January	February	March	April	May	June	July	August	September	October	November	December	
1984	52	63	103	154	10	2	4	6	6	0	45	20	**464**
1985	97	93	45	43	15	28	0	4	2	31	56	56	**469**
1986	70	85	10	13	41	12	1	20	19	21	18	73	**381**
1987	51	79	79	59	47	83	9	27	1	5	68	51	**559**
1988	8	80	121	72	27	12	53	21	12	51	82	73	**612**
1989	12	17	60	13	34	25	3	0	0	72	49	34	**320**
1990	7	25	19	38	71	23	11	1	6	7	12	101	**321**
1991	35	71	17	87	74	8	58	12	12	46	14	164	**598**
1992	2	10	95	47	46	40	13	13	3	5	51	60	**384**
1993	37	38	62	22	106	1	0	1	2	10	60	26	**364**
1994	85	29	58	27	49	18	36	42	6	109	36	30	**524**
1995	48	28	127	34	26	26	87	9	5	24	46	15	**475**
1996	43	99	42	51	62	32	19	11	17	29	3	132	**542**
1997	28	23	30	77	36	53	0	44	41	65	30	70	**494**
1998	97	29	169	46	82	27	2	0	19	20	55	140	**687**
1999	63	79	26	24	9	16	2	45	5	10	13	22	**312**
2000	33	42	44	77	63	17	0	5	10	33	66	39	**428**
2001	62	31	21	58	68	3	6	3	10	0	157	218	**637**
2002	22	10	51	135	46	1	11	9	74	5	38	99	**501**
2003	23	107	48	133	90	36	0	3	4	52	14	152	**661**
2004	201	50	5	77	21	26	14	7	0	14	44	15	**474**
2005	105	88	36	58	34	17	30	1	38	21	44	23	**495**
2006	54	28	106	39	44	26	4	21	72	141	80	0	**613**
2007	90	43	26	26	19	25	11	10	3	30	91	85	**459**
2008	10	15	34	51	13	4	3	36	20	31	61	5	**284**
2009	125	70	55	40	67	27	18	0	26	18	52	169	**667**
2010	68	137	33	47	32	65	40	0	30	79	14	84	**629**
2011	35	52	50	55	43	62	2	1	13	50	0	37	**400**
2012	148	89	21	53	107	18	1	35	16	39	26	70	**623**
2013	59	102	25	60	67	34	88	15	3	104	68	29	**654**
2014	61	23	79	45	107	43	1	10	99	57	37	109	**671**
2015	127	58	112	26	68	92	3	43	8	23	18	6	**583**
2016	102	33	60	48	88	12	26	45	32	2	49	34	**529**
2017	88	4	74	26	150	31	13	20	6	47	42	32	**531**
2018	89	32	69	6	63	69	4	14	2	32	49	107	**537**
2019	97	55	40	51	34	53	10	3	27	10	29	45	**454**
2020	74	71	41	24	92	43	2	25	1	49	27	35	**484**
2021	88	16	45	8	2	145	8	1	14	13	22	125	**487**
Average	**66**	**53**	**56**	**51**	**54**	**33**	**16**	**15**	**17**	**36**	**44**	**68**	**508**

Red color indicates dry months and years, green color indicates wet months and years, and the white color indicates normal months and years.

3.2. Reference Evapotranspiration (ETo) and Evapotranspiration (ET) of Apple in Warsaw and Isparta

In order to calculate the evapotranspiration for any plant using empirical equations, the reference evapotranspiration must first be calculated. The reference evapotranspiration is one of the main components of evapotranspiration and reflects climate characteristics. Considering all months of the year, the average total ETo was 777 mm in Warsaw and 839 mm in Isparta (Figure 2). When the ETo values for both locations were analyzed monthly, while the ETo values in Isparta were higher in May and June, the ETo values in Warsaw were higher in July, August, September and October. For the years 1984–2021, the average ETo was 604 mm in Warsaw, while it was 636 mm in Isparta between May and October, which is the apple-growing season. Calculating the reference evapotranspiration for particular research areas allows coefficients to be reliably applied to specific apple crops. The actual evapotranspiration can then be determined, providing information on the amount of water loss for each crop. It is then possible to intervene effectively by supplementing the required water in crop irrigation.

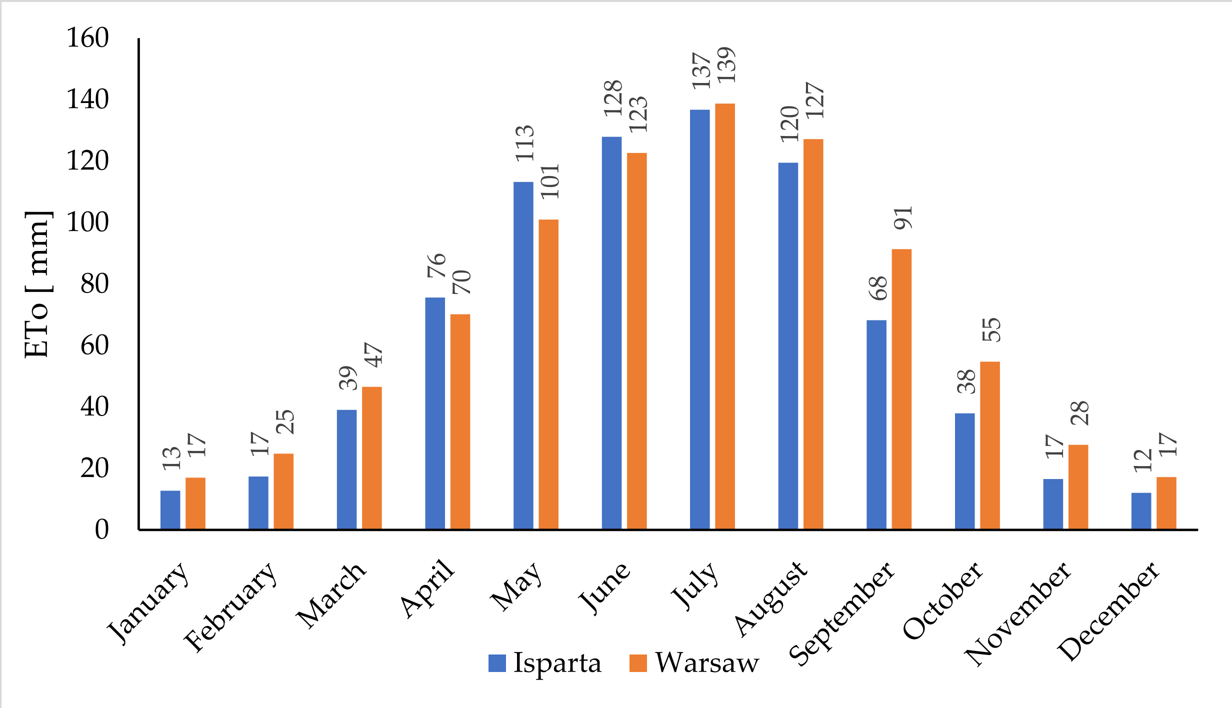

Figure 2. Change in ETo for both regions by month.

The evapotranspiration is a function of the reference evapotranspiration (ETo), reflecting the climate parameters and the plant coefficient (kc) (ET = ETo × kc). While the apple evapotranspiration was between 430 and 659 mm (average 534 mm) in Warsaw, it was between 445 and 556 mm (average 510 mm) in Isparta. Evapotranspiration values changed in a narrower range in Isparta, while the change in Warsaw was in a broader range. The minimum evapotranspiration was similar in both regions; however, the difference between them in terms of maximum values was around 100 mm (Figure 3 and Table 4). According to the Mann–Kendall test results, the trend of change in evapotranspiration in apples was significant in both regions. Evapotranspiration in Warsaw showed an increasing trend ($p < 0.001$), while, in Isparta, it had a decreasing trend ($p < 0.0001$) (Table 4). A field study on evapotranspiration estimation conducted in Isparta on Gala Galaxy apples in 2007 and 2008 found the highest evapotranspiration in young dwarf fruit trees, 608.2 mm and 631.9 mm, respectively, in a facility without a water deficit [17]. On the other hand, evapotranspiration in young dwarf apple trees irrigated frequently (3 days) varied between 491.5 and 600.5 mm in 2007–2008. In apple trees with a longer irrigation interval (10 days), evapotranspiration in the specified years was 400.7–440.2 mm, respectively [22]. Kucukyumuk et al. [46] measured the evapotranspiration of Braeburn apple cultivars in Egirdir-Isparta as 506.2 mm, 501.9 mm and 513.5 mm, respectively, between 2010 and 2012 under full irrigation conditions. Stachowski et al. [47] estimated the water needs of apples in Central Poland using three methods, and they ranged from 435 mm (press method) to 729 mm (Grabarczyk and Rzekanowski method). Irrespective of the calculation method, they proved that rainfall in the last thirty years has not been able to meet plants' water needs. According to Rolbiecki et al. [48], the water requirements of apple trees throughout the vegetation period (April–October) were much higher (by 120%) in the Isparta region than in the Bydgoszcz region (Poland). It is thought that the difference between the evapotranspiration values is due to the different climatic conditions, cultivation techniques, apple varieties, amount and quality of irrigation water and irrigation method.

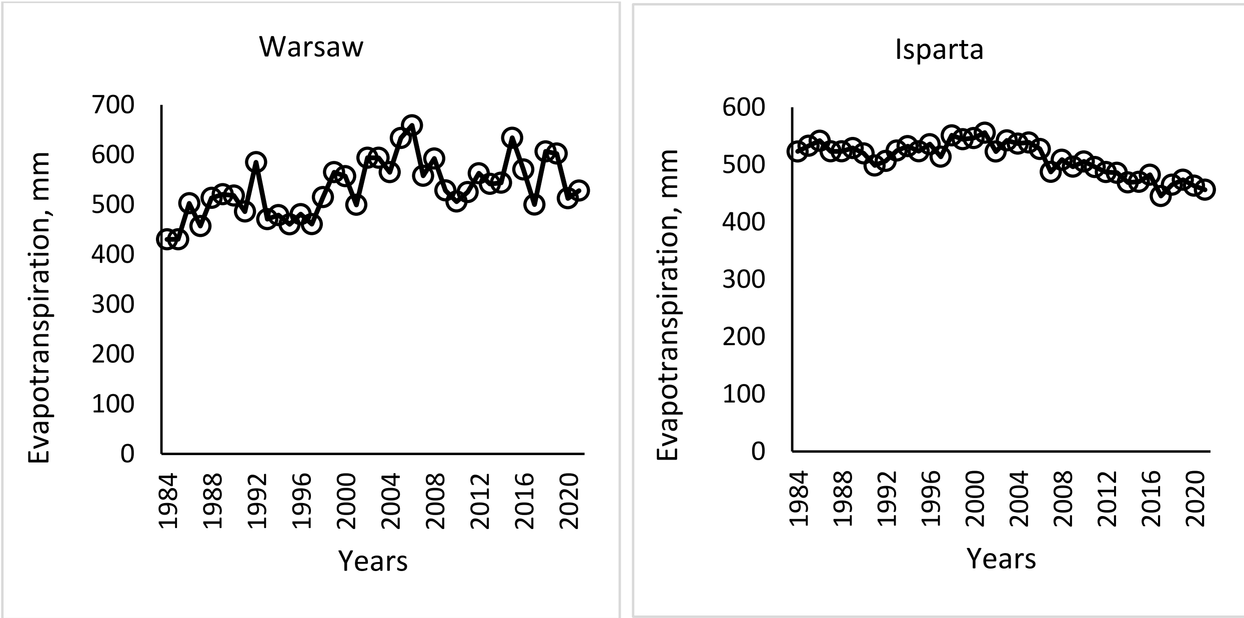

Figure 3. The change in the evapotranspiration of apples between 1984 and 2021 in Warsaw and Isparta.

Table 4. Trend changes of ET and rainfall.

Regions	Min	Max	Mean	SD	Kendall's t	S	*p*	α	Trend
					Rainfall				
Warsaw	390	798	541	87.345	0.246	173	0.031 *	0.05	↑
Isparta	284	687	508	111.013	0.169	119	0.138 ns	0.05	-
					Apple's evapotranspiration				
Warsaw	430	659	534	56.998	0.387	272	0.001 ***	0.05	↑
Isparta	445	556	510	29.494	−0.494	−347	0.0001 ***	0.05	↓

Min: minimum, Max: maximum, SD: standard deviation, S: Kendall statistics; statistically significant at: * p <0.05, ** $p < 0.01$, *** $p < 0.001$; ns: non-significant.

3.3. Crop Water Requirements (CWR) According to the Dry, Normal and Wet Years in Warsaw and Isparta

Accurate determination of climatic conditions and precise estimation of crop water use is becoming a priority for water management and agricultural planning. With the development of agriculture and the emergence of large farms, estimating water requirements has become crucial. Scientists evaluate crop water requirements to achieve two main objectives. The first is long-term planning, where an average or probability climate can be used to estimate CWR. The second is to determine water requirements for real-time management, where climate data from the current season are used to identify the required values [49]. According to the Mann–Kendall test results, the plant water requirement in dry, normal and wet conditions in Warsaw is increasing, while, in Isparta, it has shown a decreasing trend in all three conditions (Table 5). The increase in Warsaw and the decrease in Isparta are related to the increase and decrease in evapotranspiration in these regions. The CWR in Warsaw in the dry year varied between 259 and 488 mm (average: 363 mm). In normal year conditions, it ranged from 135 to 363 mm (average: 237 mm), and in wet years, it ranged between 24 and 215 mm (average: 108 mm). In Isparta, the amount of irrigation water was between 388 and 498 mm (average: 452 mm) in the dry year, 305–412 mm (average: 367 mm) in the normal year and 219–391 mm (average: 277 mm) in the wet year. Although evapotranspiration values have been higher in Warsaw in recent years, the irrigation water requirement of apples in Isparta is higher than in Warsaw in terms of dry, normal and wet years. This is because Warsaw has more rainfall during the vegetation period. Therefore, parallel to the evapotranspiration values, while the CWR increases in Warsaw, it decreases in Isparta. In Warsaw, the ratio of rainfall to evapotranspiration (average: 534 mm) under dry, normal and wet conditions is 32%, 56% and 80%, while, in Isparta (average: 510 mm), these ratios are 11%, 28% and 46%, respectively. Although there were no large differences between the regions in terms of total rainfall, there was a difference in the ratio of evapotranspiration supply by rainfall. This is because rainfall is high in Warsaw in the middle of the growing period, around July, whereas it is low in Isparta during these months.

Table 5. Trend changes of crop water requirements according to the dry, normal and wet years.

Rainfall	Min	Max	Mean	SD	Kendall's t	S	*p*	α	Trend
				Warsaw					
Dry	259	488	363	56.995	0.387	272	0.001 ***	0.05	↑
Normal	135	363	237	55.220	0.343	241	0.003 **	0.05	↑
Wet	24	215	108	47.747	0.419	294	0.000 ***	0.05	↑
				Isparta					
Dry	388	498	452	29.494	−0.494	−347	0.0001 ***	0.05	↓
Normal	305	412	367	28.808	−0.499	−351	<0.0001 ***	0.05	↓
Wet	219	391	277	32.603	−0.521	−366	<0.0001 ***	0.05	↓

Min: minimum, Max: maximum, SD: standard deviation, S: Kendall statistics; statistically significant at: * p <0.05, ** $p < 0.01$, *** $p < 0.001$; ns: non-significant.

Kodal et al. [7] emphasized that the dry year's rainfall values determine the maximum water requirements of irrigation schemes. Furthermore, the normal year's rainfall values are used to develop performance indicators of irrigation schemes, reservoir operation plans and scheduling; the wet year's rainfall values are used to determine whether irrigation is necessary. Therefore, correctly determining the amount of water required to irrigate apple trees is extremely important in producing this fruit. Studies carried out to date show that adequate drip irrigation can increase the marketable yield of apple trees by an average of 22% [50]. Furthermore, the type of irrigation system is also important. Research conducted in the Isparta region demonstrated that switching from flood irrigation for apples to drip irrigation positively affects vegetative growth and fruit quality [51].

In order to predict crop water requirements in dry, normal and wet years, 3- and 5-year moving averages and their R^2 values were obtained and are shown in Figure 4. In particular, 5-year moving averages in Warsaw give the best results in dry, normal and wet conditions (R^2 = 0.5182; R^2 = 0.5222; R^2 = 0.5278). On the other hand, in Isparta, the 3-year moving average gave the best result in all dry, normal and wet conditions (R^2 = 0.5632; R^2 = 0.564; R^2 = 0.5815).

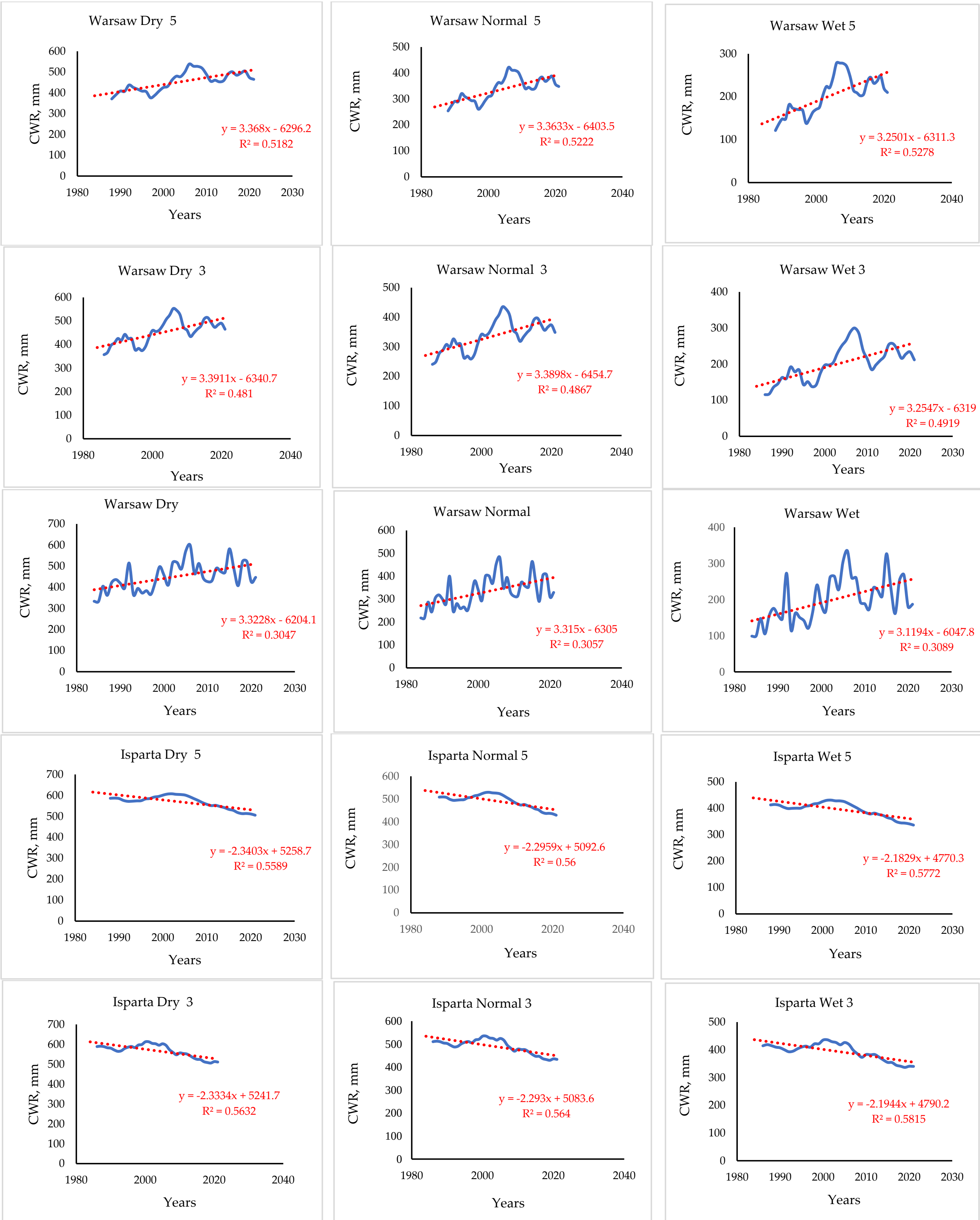

Figure 4. *Cont.*

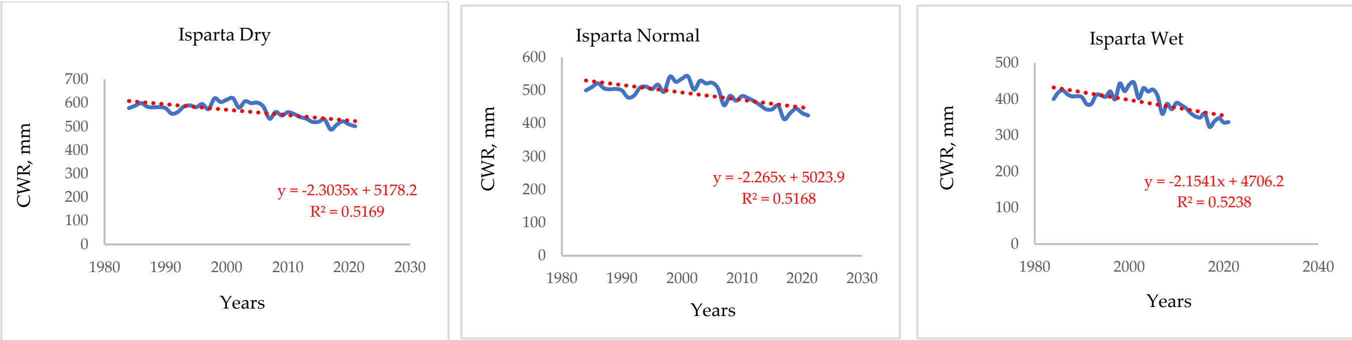

Figure 4. Crop water requirements of apples according to dry, normal and wet years, mm. CWR: crop water requirement, mm; 3: three-year moving average; 5: five-year moving average.

Progressive climate change is leading to a reduction in the amount of water in the environment in many regions of the world, which is a major element influencing the amount of crop and livestock production. Climate change is associated with numerous temperature and precipitation fluctuations [52,53]. This is forcing farmers and fruit growers to introduce new varieties resistant to climate change and methods of growing crops under periodic water shortages. It should be noted that under the conditions of an ever-warming climate, plants that, until recently, were usually dormant in the winter period may start to grow, which may result in shoot damage later in the season. Short-term water stress can also lead to the development of large numbers of barren flowers and poorly formed fruit. However, the most negative effect of soil water deficiency becomes apparent in small trees after planting, where the ratio between the root system and the above-ground part is disturbed [54]. Therefore, selecting optimum apple varieties resistant to temperature fluctuations and temporary water shortages is crucial. Water shortages make optimal water management extremely important in apple cultivation. In order to achieve the optimum yield and, at the same time, save water, it is necessary to accurately determine the water requirements of plants at different developmental stages. This information is crucial for irrigation and crop planning in different agroclimatic regions [55]. A study in Central Poland showed that the amount of precipitation occurring during the growing seasons between 1989 and 2020 did not meet the water needs of many types of fruit trees [47]. This indicates that irrigation is essential for proper growth and beneficial results in apple production. It is essential to compensate for the plant's water deficits by irrigation during the months when rainfall cannot meet the apple trees' water needs. In Poland, usually, at the time of the highest water demand for apple trees, there is also the highest rainfall deficit. This situation very often occurs in August. Treder [18] estimated that the average water requirement for Central Poland is at least 2.5–3 mm·day^{-1}. However, these values may not be sufficient when high temperatures and droughts occur. It was found that in dry years, the necessary amount of water to irrigate apple trees in Central Poland can be as high as 1200–2000 m^3·ha^{-1} [18]. Furthermore, because of the drought threat, researchers stress that Turkey is also a country that needs to take steps to use water resources more efficiently [56,57]. One possible measure is the use of water-efficient irrigation systems. Studies in the Isparta region show that switching from flood irrigation to drip irrigation contributes to lower water consumption. Moreover, it positively affects apple trees' vegetative growth and fruit quality [51]. This is an extremely important result in light of the need to save water resources in this region. With agriculture being one of the world's major water consumers, the need to reduce water use and improve water resource management is a priority for major food-producing countries [58]. Moreover, in Poland, measures should be taken to optimize water consumption. A survey carried out by Treder et al. [59] showed that as many as 80% of fruit growers use an indicative frequency and amount of irrigation that is not supported by any reliable criteria. Therefore, it is essential to popularize the principles of optimizing water management among fruit growers. In order to achieve this, emphasis should be placed on implementing tools that facilitate the estimation of water needs. A good irrigation effect and the productive use of irrigation water are only possible if an optimal irrigation regime is applied, which should follow the cultivated crop's requirements [60,61]. Numerous scientific studies show that estimating water needs is crucial to increasing the yields of many crops and for their adaptation to climate change [47,62,63].

This paper focuses on the issue of optimizing water use in agriculture, which is of particular attention and concern in light of the increasing competition for freshwater resources. This problem is especially relevant in semi-arid regions or those with periodic rainfall deficits [64]. In order to address the above-mentioned issue, it is necessary to develop effective plans and tools through which measures related to the quantity and availability of water for irrigation will be implemented. Scientists emphasize that research on efficient water resource use should be directed towards accurate irrigation under the increasing trend of reference evapotranspiration [65]. The present work provides new knowledge from the analysis of climatic conditions and rainfall patterns in two important countries in apple production. Furthermore, it estimates the water requirements of apples. All the results obtained in this work can be helpful for the development of appropriate water management plans and the need to optimize irrigation in apple production in the face of ongoing climatic changes.

4. Conclusions

This study showed that the crop water requirements calculated based on dependable rainfall are 363 mm, 237 mm and 108 mm in Warsaw during dry, normal and wet periods. Meanwhile, for Isparta, they are 452 mm, 367 mm and 277 mm, respectively. Furthermore, the results indicate that the average annual rainfall and average annual evapotranspiration values are close in both regions. In addition, there is a difference in the distribution of rainfall during the year between the regions. In Warsaw, rainfall is higher in the summer, which is the apple-growing period under dry, normal and wet conditions, while, in Isparta, spring rainfall is higher. The difference in rainfall distribution causes a difference in the crop water requirement of apples under dry, normal and wet conditions between Warsaw and Isparta. The ratio of rainfall to evapotranspiration for apples during the growing period of apple under dry, normal and wet conditions is 32%, 56% and 80% in Warsaw, respectively, while it is 11%, 28% and 46% in Isparta, respectively. According to these results, the crop water requirement of apples in Warsaw and Isparta is greatly affected by the agreement among the rainfall distribution.

As a result, crops are exposed to many unpredictable and complex hydrological phenomena, such as rainfall during the growing period. The study's results reveal that knowledge of the amount and distribution of rainfall, which is a major climatic parameter, for different conditions such as dry, normal and wet, is very important for the correct calculation of crop water requirements. To avoid yield losses in apple-growing areas, finding a balance between rainfall and crop water demand is necessary. In order to establish this balance, soil moisture monitoring and smart irrigation systems need to be widely used in fruit-growing areas. The results show that the amount of irrigation water needed in both regions is quite different in wet, normal and dry years, determined based on dependable rainfall. Considering that irrigation scheduling in these countries is usually based on normal years, there is a possibility that less water is applied to plants in dry years and more water is applied in wet years, which is undesirable in terms of water resource management and plant cultivation. In this case, fluctuations in world apple production may lead to a deterioration in the supply–demand balance. Therefore, the use of dependable rainfall in irrigation scheduling, both for sustainable apple production and for soil and water resource management, will help to optimize water management and maintain apple production at current levels.

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draft preparation, Y.U., J.K. and D.L.; R.R. writing—review and editing, Y.U. and J.K.; visualization, Y.U.; supervision, R.R. All authors have read and agreed to the published version of the manuscript.

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