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Determining the yield responses of maize plant under different irrigation scenarios with AquaCrop model

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Abstract

The AquaCrop simulation model is a significant implementation used to determine the response of crop yield to water and accordingly build up new strategies to improve agricultural irrigation management. Since determining the appropriate irrigation program in the field researches will require many years and labor; it becomes convenient with the AquaCrop to determine the adaptation of crops to the cultivating conditions and to examine the impact of possible variables such as drought on crop production. In this study, different irrigation scenarios were created, and yield predictions were made with the AquaCrop 6.1 model for maize plant which irrigated by drip irrigation method in Adana conditions, Turkey. These scenarios were created by determining four different depletion levels of readily available water (RAW) amount in the soil. These depletion levels were 25%(S1), 50%(S2), 75%(S3) and 100%(S4). The highest grain yield value was found in S1 as 10.075 ton/ha and the lowest grain yield in the S4 as 9.837 ton/ha. The amount of seasonal irrigation water simulated for different irrigation schedules varied between 348.5–390.7 mm, and the evapotranspiration (ET) varied between 411.5-426.5 mm. As a result, S3 scenario has been recommended considering the amount of irrigation water and the yields achieved.

Keywords: AquaCrop, Maize, Modelling, Irrigation scheduling, Yield estimation

Introduction

Maize (*Zea mays* L.) has a significant role among the grains found in the world. Since it can grow in tropical, subtropical and temperate climates, it can be cultivated almost anywhere in the world except Antarctica. The production quantity of maize has shown a significant acceleration in the rate of increase at the beginning of the 20th century, and the production data for the world is 1147 million tons in 2018 and Turkey has 0.49% of this amount with 5.7 million tons (FAO, 2018). One of the most suitable areas for maize agriculture in Turkey is Çukurova plain. According to the statistical data of 2019; Adana (located in Çukurova Plain) is the one of the provinces (second one after Konya) with highest amounts of harvested area (66 564 ha) and production (717 802 tons) of maize in Turkey (TURKSTAT, 2019). Since maize plant grows in the hottest period of the year, water consumption is high. Besides, it is a plant that uses water most effectively among field crops; that is, produces the highest amount of dry matter per unit of water.

It is essential to determine the appropriate irrigation time for the plant. When irrigation is delayed, because the plant is sensitive to water stress, the yield decreases even if the amount of water applied at the next irrigation time increases. Rather than planning the irrigation to a fixed irrigation calendar, the

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irrigation time and the water needs differ according to the plant's development periods should be determined (Doorenbos and Pruitt, 1977). Some researchers have been conducted to determine these values for the maize plant. Braunworth and Mack (1989) investigated the effect of water deficit on maize yield and quality. They determined that the yield value was close to each other in irrigation conditions without consuming 50% of the RAW. Oğretir (1993) conducted a study on the water-yield relationship in maize under Central Anatolian conditions in Turkey and determined the effect of water deficit on grain yield. The researcher determined the irrigation water need as 440 mm and the crop evapotranspiration as 659 mm in the treatment with full irrigation, and the highest efficiency is obtained by irrigating four times. Gençoğlan and Yazar (1999), conducted a study in Adana to determine the effects of deficit irrigation applications on water use efficiency and yield values. As a result of the study, they reported that the amount of water they applied varied between 102 mm and 823 m, and the plant water consumption values varied between 343 mm and 1052 mm. Besides, the yield values achieved 10.02 ton/ha in the first year and 10.04 ton/ha in the second year of the study. Shaozhong et al. (2000) found the crop evapotranspiration of maize to be 442.72 mm in their studies conducted in Hong Kong. Vural and Dağdelen (2008) investigated the effects of different irrigation programs on agronomic properties in their studies. The amount of irrigation water they reached at the end of the research varied between 234 mm and 571 mm for different treatments, and the crop evapotranspiration values varied between 130 mm and 609 mm. Yuan et al. (2019) determined the effect of 3 different irrigation levels on the maize plant yield in their study. They reported the highest yield from the treatments with 370 mm irrigation water.

The effects of different irrigation strategies can also be understood using agricultural-hydrological simulation models (Li et al., 2020). With the models' help, irrigation schedule scenarios can be created. The dynamics of crop growth under different meteorological factors and soil water content can be followed. Together with the necessary calibrations and accurate data, these simulation models provide you with access to yield and irrigation programs according to climatic conditions anywhere in the world. The models involving plant water relationships; AquaCrop, SWAP, soil and water balance simulation model, Hydrus are popular simulation models used to simulate the water needs for the growth periods of the plant or the water consumption/supply of farmland (Xu et al., 2019; Ran et al., 2018; Li et al., 2017a; Li et al., 2017b). The AquaCrop model was developed in 2009 by the Food and Agriculture Organization of the United Nations (FAO). The model's main primary purpose is to predict plant growth and yield in restricted, supportive irrigation levels and rainfall-dependent conditions (Steduto et al., 2009). The model has already been run for different crops and obtained acceptable results compared to yields in field conditions. However, it is important to determine the AquaCrop model's suitability by testing it under alternative irrigation programs in different climatic, soil or plant conditions (Yiğit and Candoğan, 2019). This study's objectives were to estimate yield and irrigation water need and to create different irrigation schedules using the AquaCrop model for maize plant and Adana province conditions in Turkey.

Materials and Method

AquaCrop

The model used in the study is AquaCrop version 6.1 programmed in Delphi by FAO in 2009. The AquaCrop estimates the yield that can be obtained as a function of water consumption under dry conditions with convenient, deficit irrigation or full water applications (Steduto et al., 2009; Andarziana et al., 2011). The model requires input climate data, crop characteristics, soil properties and irrigation parameters. Inputs; climate, plant, soil and management files are kept and can be easily accessed and changed by the user (Raes et al., 2018a). The main inputs and outputs of the complete model are shown in Figure 1.

Climate

In Adana, located in the Mediterranean Region's south-east, summers are sweltering and dry; winters are warm and rainy. The long-term climate data (1929-2019) (MGM, 2020; Gaisma, 2020) of some climate elements provided from the Adana Province central meteorology station affiliated to the General Directorate of State Meteorology Affairs and the NASA-Langley-Gaisma weather database given in Table 1. The total annual precipitation is 645.7 mm.

To obtain the climate data required running the model, average lowest and highest air temperatures, reference crop evapotranspiration (ETo), precipitation, and annual average CO_2 concentration in the atmosphere were used as inputs. CO_2 concentration data in the atmosphere were taken from the Hawaiian Mauna Loa Observatory records, which included in the program (Raes et al., 2018a). The AquaCrop 6.1 model does not include the reference crop evapotranspiration calculation. Therefore, to get the reference crop evapotranspiration values, the ETo calculator on the FAO's official website was used in the calculation. To calculate ETo, relative humidity; insolation, the monthly average for many years' highest and lowest temperature values were used as inputs (Raes, 2012). Different methods have been developed to calculate ETo and the performances of different these equations have been analyzed. The FAO Penman-Monteith method has been recommended as the standard method for ETo calculations (Allen et al., 1998). The original Penman-Monteith method used by the ETo calculator is the following equation.

In the equation;

ETo : Reference evapotranspiration (mm day^{-1}),

R_n : Net radiation at the crop surface (MJ m^{-2} day^{-1}),

G : Soil heat flux density (MJ m^{-2} day^{-1}),

T : Mean daily air temperature at 2 m height (°C),

u_2 : Wind speed at 2 m height (m s^{-1}),

e_s : Saturation vapor pressure (kPa),

e_a : Actual vapor pressure (kPa),

$e_s – e_a$: Saturation vapor pressure deficit (kPa),

Δ : Slope vapor pressure curve (kPa $°C^{-1}$),

γ : Psychometric constant (kPa $°C^{-1}$).

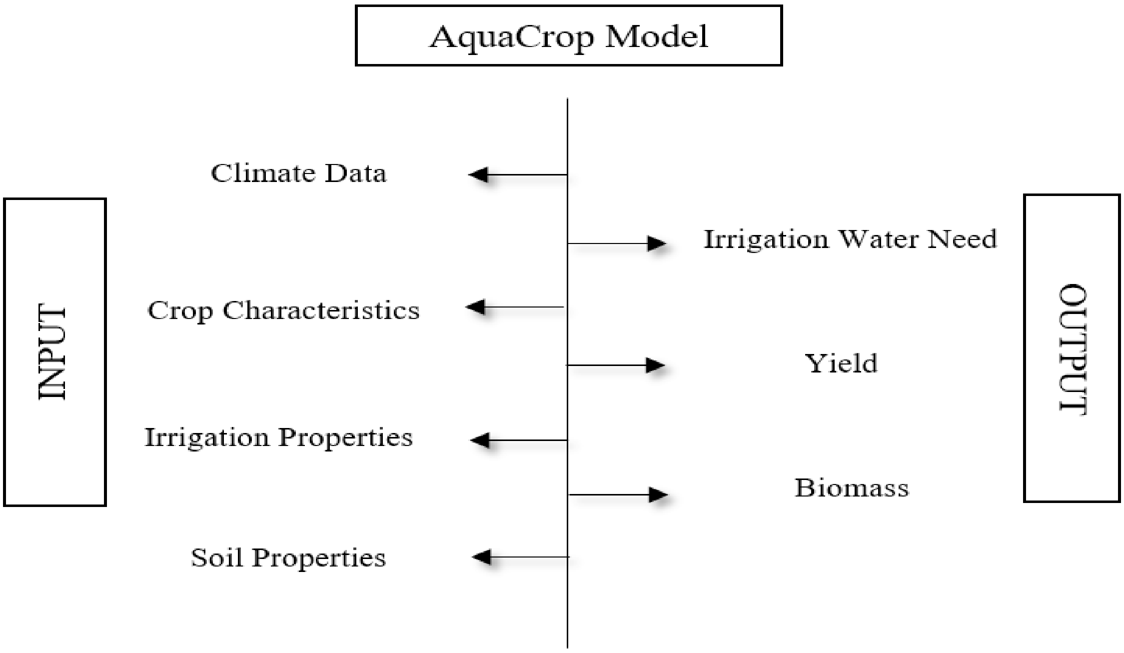

Figure 1. Inputs and outputs of the model

Table 1. Long term (1928-2019) monthly averages climate data

Months	Avg. max. temperature (°C)	Avg. min temperature (°C)	Avg. Insolation (hours)	Rainfall (mm)	Wind speed (m s^{-1})	Relative humidity (%)
January	15.1	5.5	4.4	105.1	3.33	66.0
February	16.1	5.9	5.1	85.1	3.02	64.0
March	19.5	8.5	5.5	60.4	3.00	65.0
April	23.8	12.3	6.5	50.3	2.63	68.0
May	28.2	16.2	8.5	42.8	2.55	67.0
June	31.7	20.4	10.2	19.3	2.52	68.0
July	33.7	23.9	10.2	9.4	2.66	71.0
August	34.6	24.2	9.6	7.0	2.58	71.1
September	33.2	21.0	8.3	15.1	2.58	65.0
October	29.2	16.4	7.1	47.9	2.50	62.0
November	22.0	10.7	5.3	82.6	2.19	66.0
December	16.8	7.0	4.2	120.7	2.63	68.0
Avg./Total	25.3	14.3	7.08	645.7	2.68	66.75

Plant Material

In this study, the maize which is one of the most used plants in agricultural production in Turkey, is defined as plant material. AquaCrop version 6.1 offers some data which contains parameters suitable for the simulation of maize. Some of these parameters are not universal and need to be adjusted to similar climate conditions or the soil contents. To minimize the margin of error of the results, the data was collected from different sources. The default parameters for the maize plant taken from the AquaCrop model are given in Table 2. In contrast, the parameters taken from different researches to adapt to study site conditions are given in Table 3. The values of the AquaCrop default database parameters were also created by taking into account the previous studies for maize. It was assumed that there were not too many variables and did not affect the results (Raes et al., 2009).

Table 2. Conservative parameters used in simulation (Raes et al., 2009)

Parameters	Values
Minimum effective rooting depth (Z_n) (m)	0.30
Shape factor describing root zone expansion	1.30
Crop coefficient when the canopy is complete but prior to senescence ($K_cT_{r,x}$)	1.05
Water productivity normalized for ETo and CO_2 (WP) (g/m^2)	33.70
Water productivity normalized for ETo and CO_2 during yield formation	100
Reference harvest index (HI_0) (%)	50
Possible increase (%) of HI due to water stress before flowering	None
Excess of potential fruits (%)	Small
Coefficient describing the positive impact of restricted vegetative growth during yield formation on HI	Small
Coefficient describing the negative impact of stomatal closure during yield formation on HI	Strong
The allowable maximum increase of specified HI (%)	15
Soil water depletion level for canopy expansion - Upper level	0.14
Soil water depletion level for canopy expansion - Lower level	0.72
Shape factor for Water stress coefficient for canopy expansion	2.90
Soil water depletion level for stomatal control - Upper level (p_{sto})	0.69
Shape factor for Water stress coefficient for stomatal control	6
Soil water depletion level for canopy senescence - Upper level	0.69
Shape factor for Water stress coefficient for canopy senescence	2.70
Soil water depletion level for the failure of pollination - Upper level	0.80
The electrical conductivity of the saturated soil-paste extract: lower threshold (ECe_n)	1.70
The electrical conductivity of the saturated soil-paste extract: upper threshold (ECe_x)	10

Table 3. The crop characteristics of maize

Parameters	Values	References
Base temperature (°C)	10	Lee, 2007
Upper temperature (°C)	28	Sanchez et al., 2014
Planting date	02 June	Sahin, 2001
Max. effective rooting depth (Z_x) (cm)	90	Kuscu et al., 2013
Leaf Area Index	6	Koca and Turgut, 2012
Emergence (days)	8	Ritchie et al., 1993
Crop Coefficient (K_c)	0.6	Piccini et al., 2009
Senescence (days)	80	Borrás et al., 2003
Maturity (days)	120	FAO, 2020
Duration Flowering (days)	20	Durand et al., 2012
From day 1 after sowing to flowering (days)	60	Durand et al., 2012
1000 seed mass (g)	345.7	Kılınc et al., 2018
Row space (cm)	70	Kuscu and Demir, 2012
Inter-row spacing (cm)	20	Kuscu and Demir, 2012
Germination rate (%)	95	Khodarahmpour et al., 2012

Irrigation Management Data

In this study, the drip irrigation method was used to estimate the yield of the maize plant. The 25%, 50%, 75% and 100% depletion levels of ready water available (RAW) were determined to starting irrigation applications in the model as scenario 1 (S1), scenario 2 (S2), scenario 3 (S3) and scenario 4 (S4), respectively. To put it another way, the irrigation scheduling for the S1, S2, S3 and S4 scenarios were set to start irrigation applications when 25%, 50%, 75% and 100% of the RAW value is depleted. Soil water content has been reached to field capacity after all irrigation applications, and the percentage of wetting soil surface was accepted as 30%.

In order to ensure the uniformity between scenarios during the emergence periods and to keep the soil water content at the field capacity, first 4 irrigation applications were applied to all scenarios at the same time and amount. Following the irrigation application on June 24, different irrigation scenarios were started according to the soil water content.

It is assumed that the RAW value lies between field capacity and the stomatal closure point (p_{sto}.TAW) by model. Besides, when the upper level of soil water depletion for stomatal closure is multiplied by field capacity, the found value is an upper level of depletion of root zone ($Dr_{sto,\ upper}$) (Raes et al., 2018b). As seen in Table 2, the upper level (p_{sto}) was accepted as 0.69 for maize plants (Raes et al., 2018c).

Soil Data

The soil texture used in the study has been assumed considering the soil characteristics of Adana. The AquaCrop model includes different soil textures and soil texture has been taken from these available profiles, and its properties are given in Table 4. 30 cm soil layers were taken into account for 0-120 cm soil depth.

Table 4. Soil properties used in the model as input

Type of Soil	Soil Depth (cm)	FC[1] (%)	PWP[1] (%)	SAT[2] (%)	TAW (mm/m)	Ksat[3] (mm/day)	τ (Tau)[4]
Sand	0-30	13	6	36	70	3000	1
Silty Clay	30-60	50	32	54	180	100	0.43
Silty Clay	60-90	50	32	54	180	100	0.43
Silty Clay	90-120	50	32	54	180	100	0.43

[1]In percentage of volume, [2]Water content in soils as percentage by volume, [3]Hydrolic Conductivity [4]Drainage coefficient

Monitoring the soil water content is an important part of the model. In the study the soil water content (Wr) in the root zone and the corresponding water stress were followed daily by model to calculate soil water balance. The root zone was defined as the part where the soil was held and calculations were made on the amount of water retained in this part. The change of soil water content is determined by tracking the amount of water incoming to the root and outgoing. Incoming water can be defined as rain and irrigation, and some section of the rain disappears due to runoff. Another option for water transportation is a capillary rise, which is transported from a shallow groundwater layer to the root zone. The outgoing waters are; soil evaporation, crop transpiration, and deep percolation losses. The soil water balance used by the model is based on this logic and is expressed in the following equation (Raes, 2017).

$$Wr_{t+1} = Wr_t + (P - RO) + I + CR - E - Tr - DP$$

In the equation;

Wr_{t+1}, Wr_t : Water contents in the root zone (at the time "t" and "t+1")
P : Rainfall
RO : Runoff
I : Irrigation
CR : Capillary rise
E : Evaporation
Tr : Transpiration of the crop
DP : Deep percolation losses

After severe rainfalls or over irrigations; If the water content in the soil exceeds the field capacity (Wr_{FC}), deep percolation losses (DP) will occur.

$$DP = Wr_{FC} - Wr$$

Root zone depletion (Dr); refers to the difference between the WR_{FC} value and the soil water content (Wr) after water depletion in the root zone.

$$Dr = Wr_{FC} - Wr$$

Results and Discussion

Reference Crop Evapotranspiration

Daily average ETo values for each month were calculated with the ETo calculator software developed by FAO, using Adana's monthly average climate data for long term years as input. As a result of these calculations, it was found that the highest ETo value was in July with 6.2 mm/day, while the lowest ETo value was in December with 1.7 mm/day. The annual ETo changes calculated with the ETo calculator are given in Figure 2. The annual average ETo value was found to be 1425 mm.

Simulation Results for Different Scenarios

The biomass and grain yield values calculated by model is given in Figure 3. As a result of the simulations, biomass yields varied between 20.842-21.435 ton/ha and grain yield values changed between 9.83-10.07 ton/ha. For both yield parameters, the highest values were obtained at S1 scenario while the lowest yields were obtained at S4 scenario.

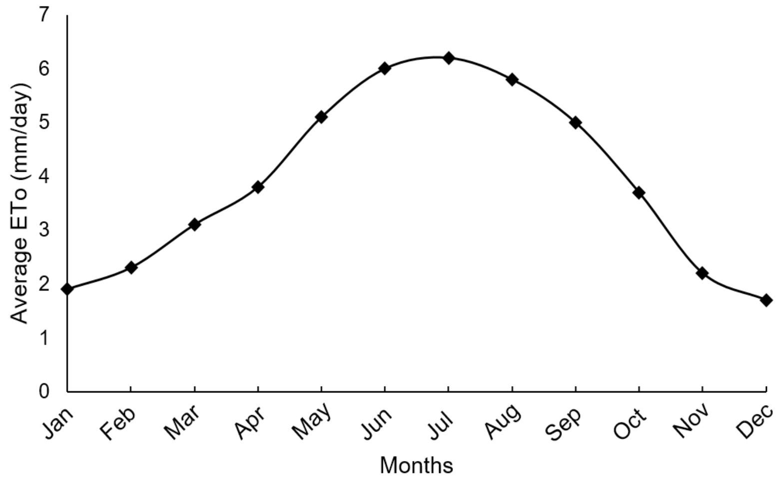

Figure 2. Annual reference crop evapotranspiration (ETo) changes of the study site

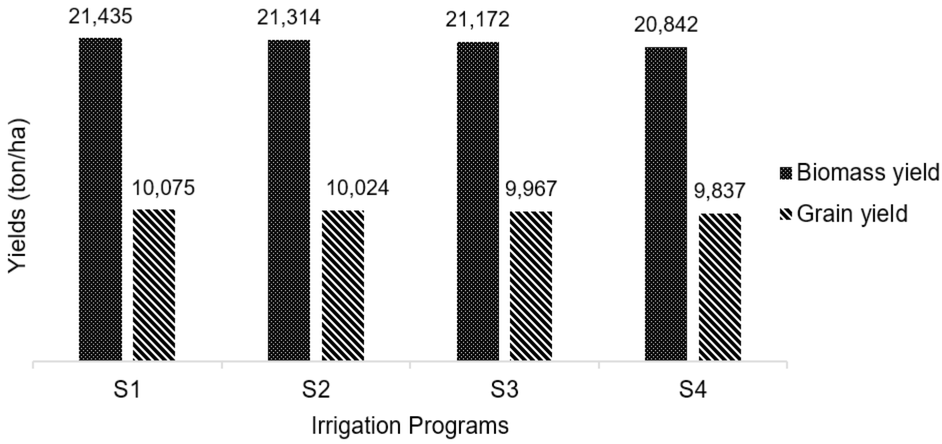

Figure 3. The biomass and grain yields obtain from different scenarios

The net amount of irrigation water for the S1 scenario was estimated to be 390.7 mm. This amount is distributed over 20 irrigation applications and is the highest irrigation water amount reached among allscenario. After the start of irrigation applications considering the soil water content, the amount of water simuleted in each scenario varied between 4.1 mm and 26.7 mm and the irrigation intervals were minimum 4 and maximum 8 days. The irrigation water applications for the S1 scenario are given in Table 5 in detail. The total evapotranspiration (ET) has been estimated as 426.5 mm and water use efficiency (WUE) as 2.38 kg/m^3. Also, evaporation and transpiration values in the model were estimated at 56.6 mm and 370.3 mm, respectively. Total yields, transpiration (Tr), cover percentage development (CC), root zone water depletion (Dr) simulations of the S1 irrigation scenario are given in Figure 4.

According to the model's simulation results, there were 12 irrigation events in S2 scenario and net irrigation water amount to be applied in the total was calculated as 378.4 mm. After the start of irrigation applications considering the depletion values of RAW, irrigation intervals were formed as minimum 7 and maximum 12 days and the lowest irrigation water amount applied was 35.5 mm and the highest was 48.7 mm. The amount of irrigation water to be applied for S2 is given in Table 6 in detail. When the data obtained were evaluated, the total ET was found to be 418.3 mm and the WUE was calculated as 2.41 kg/m^3. Evaporation and transpiration values for scenario S2 were estimated as 50.4 mm and 368.1 mm, respectively. The simulation results of yields, Tr, CC and Dr for scenario S2 are given in Figure 5.

In the scenario S3, 9 irrigations were made and a total of 348.5 mm irrigation water was calculated. The maximum irrigation water amount applied were obtain 69.4 mm on 21 August and the minimum irrigation water amount was 53.3 mm on 18 July. In the applications made after the start of different irrigation simulations for each scenario, the irrigation intervals were between 11-14 days. Detailed information about irrigation is given in Table 7. The total ET was found to be 415.5 and the highest WUE value of the study was calculated as 2.42 kg/m^3 in the S3 scenario. According to the data obtained, evaporation and transpiration values for the S3 scenario were 49.4 mm and 365.6 mm, respectively. Biomass and grain yields, Tr, CC and Dr simulations of S3 irrigation scenarios are given in Figure 6.

Table 5. The irrigation applications of S1 scenario

Number of applications	Days after sowing	The Date	Net irrigation water application (mm)
1	2	03 June	9.0
2	6	07 June	4.1
3	11	12 June	5.0
4	23	24 June	9.8
5	34	05 July	14.2
6	40	11 July	15.5
7	45	16 July	21.2
8	49	20 July	21.4
9	53	24 July	23.4
10	57	28 July	24.1
11	61	01 August	24.4
12	65	05 August	24.4
13	69	09 August	24.2
14	73	13 August	23.7
15	77	17 August	23.3
16	81	21 August	22.8
17	86	26 August	26.7
18	91	31 August	24.5
19	97	06 September	25.3
20	105	14 September	23.9
Total			390.7

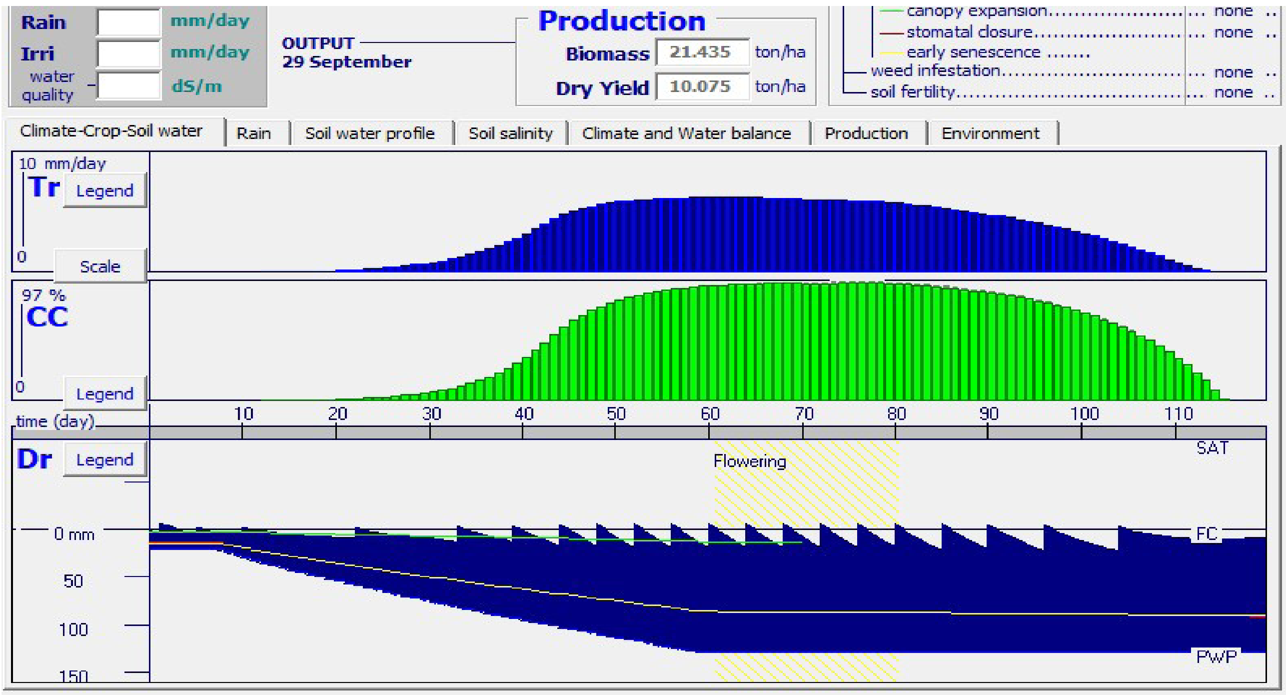

Figure 4. Simulation of crop development for scenario S1

Table 6. The irrigation applications of S2 scenario

Number of applications	Days after sowing	The Date	Net irrigation water Application (mm)
1	2	03 June	9.0
2	6	07 June	4.1
3	11	12 June	5.0
4	23	24 June	9.8
5	43	14 July	35.5
6	51	22 July	41.4
7	58	29 July	41.7
8	66	06 August	48.7
9	74	14 August	47.6
10	82	22 August	45.6
11	91	31 August	45.6
12	103	12 September	44.3
Total			378.4

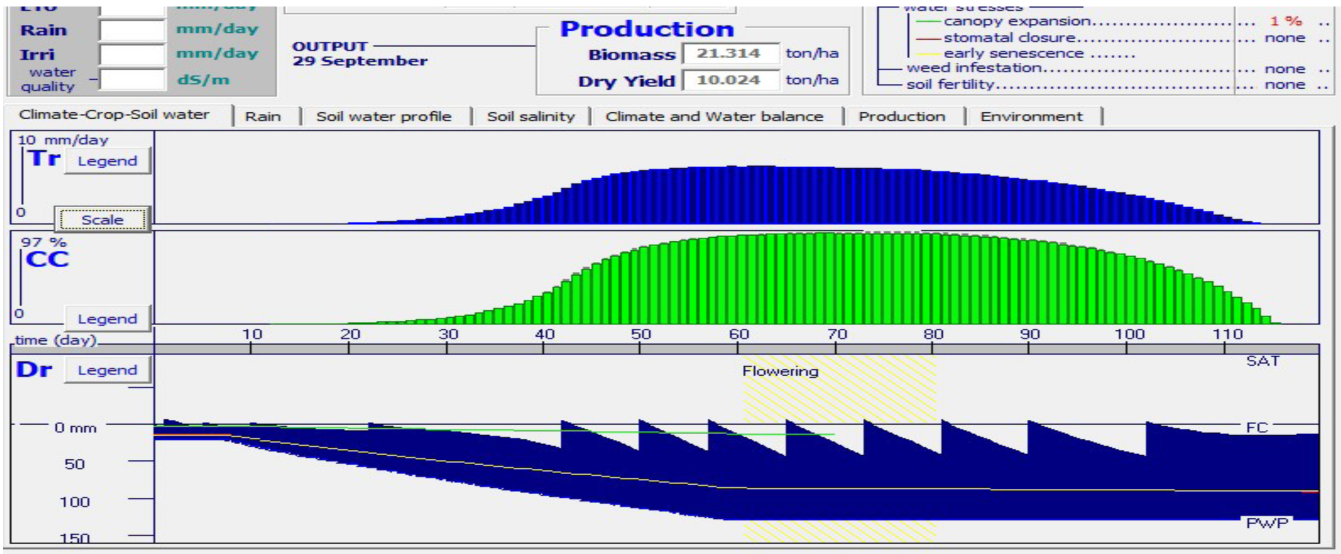

Figure 5. Simulation of crop development for scenario S2

Table 7. The irrigation applications of S3 scenario

Number of applications	Days after sowing	The Date	Net irrigation water Application (mm)
1	2	0 June	9.0
2	6	07 June	4.1
3	11	12 June	5.0
4	23	24 June	9.8
5	47	18 July	53.3
6	58	29 July	63.1
7	69	09 August	66.5
8	81	21 August	69.4
9	95	04 September	68.3
Total			348.5

When the results for scenario 4 are examined, it is seen that a total of 8 irrigations were made and 376.4 mm of irrigation water was found. Following the irrigation applied according to depletion levels, the irrigation intervals of these 8 application varied between 3-15 days and the irrigation water amount applied at once maximum 91.4 mm and minimum 79.1 mm. Detailed information on irrigation practices is given in Table 8. The ET for scenario 4 was determined as 411.5 mm and the WUE was calculated as 2.41 kg/m^3. According to the data obtained, evaporation and transpiration values for the S4 scenario were 51.2 mm and 359.9 mm, respectively. Simulations results of S4 irrigation scenarios are given in Figure 7.

Table 8. The irrigation applications of S4 scenario

Number of applications	Days after sowing	The Date	Net irrigation water Application (mm)
1	2	0 June	9.0
2	6	07 June	4.1
3	11	12 June	5.0
4	23	24 June	9.8
5	52	23 July	79.1
6	67	07 August	88.5
7	83	23 August	91.4
8	106	15 September	89.5
Total			376.4

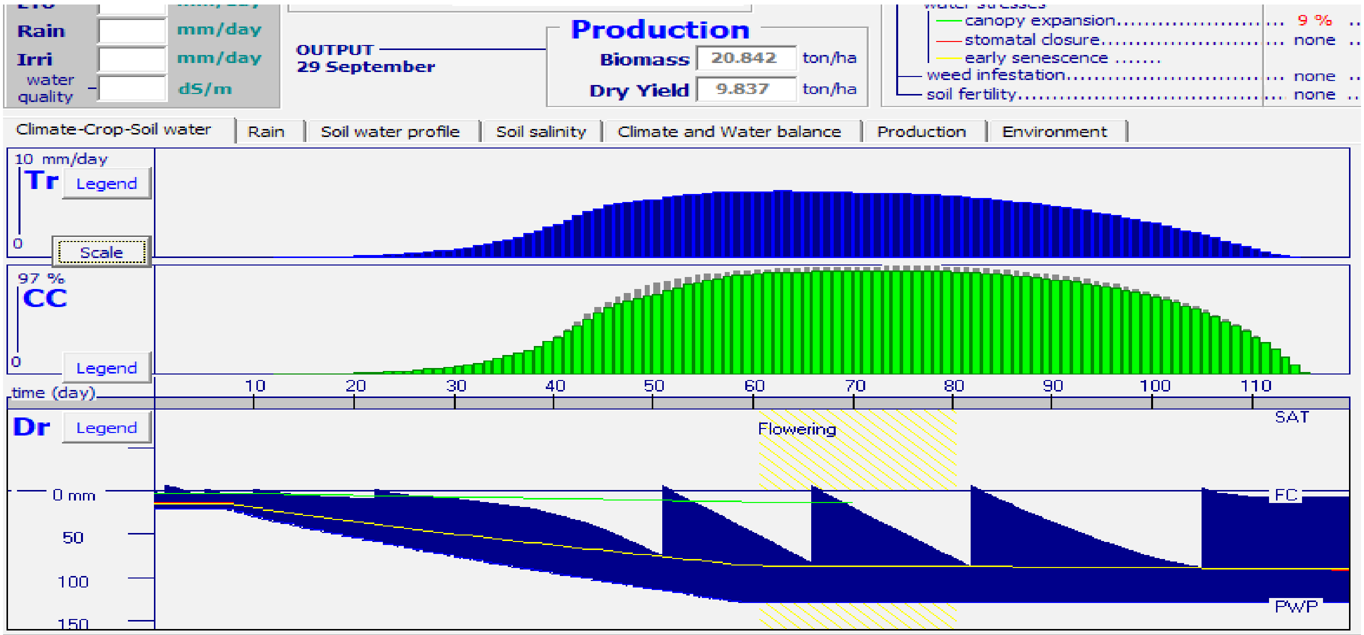

Figure 7. Simulation of crop development for scenario S4

When the data of 2019 are examined, the yield obtained from Adana maize production is seen as 11.4 t/ha TURKSTAT, 2019). Demirok and Tuylu (2019), in their study with the drip irrigation method under the conditions of the Harran Plain, varied between 6.98 t/ha and 11.51 t/ha. Gönülal and Soylu (2020) achieved a yield of 9.93 t/ha in their study. Gençoğlan and Yazar (1999), achieved yield values of 10.02 ton/ha in the first year of their research and 10.04 ton/ha in the second year of their research stated in Adana. Uçak et al. (2010), stated that the average yield of maize plant under Çukurova conditions in the years between 1996-2006 as 11.37 ton/ha. The results show that the obtained yields are parallel with the simulation results obtained from the AquaCrop model.

ET values calculated by the model for S1, S2, S3 and S4 scenarios are respectively 426.5, 418.3, 415.5 and 411.5 mm. Zhang et al. (2018) stated after their study were carried in China, total evapotranspiration values varied between 430.0 and 497.4 mm. Barbieri et al. (2012) stated that as a result of their research seasonal ET ranged from 389 to 486 mm. Gökçel and Yazar (2008), in their study carried in Adana, determined

ET values for maize plant with different irrigation methods and their results were varied between 375 mm and 677 mm. ET values predicted by the AquaCrop model with irrigation programs are similar to the above study.

Conclusion

The results obtained from the AquaCrop 6.1 model simulation show that there are no remarkable differences in yields between the 4 scenarios. When the simulation result graphs of each scenario are examined, it is seen that the root zone depletion (Dr) values of S3 scenario are the most efficient irrigation program. For the case where irrigation intervals are set as specified in the study, S3 scenario, which has the lowest irrigation water amount and the highest water use efficiency can be recommended as a proper irrigation program. There was 108 kg grain yield difference between S1 with the highest yield value and the recommended S3 scenario. In regions where there is no water shortage and in conditions where irrigation applications can be performed more frequently, the irrigation schedule of the S1 treatment can also be used. Even in cases where there is no water shortage, it is expedient to use the irrigation schedule of the S3 scenario in terms of effective use of water resources and reduction of labor with long irrigation intervals. The biomass and grain yield values obtained in the S3 scenario are respectively 21.172 t/ha and 9.967 t/ha. Besides, the total evapotranspiration was estimated to be 415.5 mm and WUE 2.42 kg/m3. It can be said that the irrigation program applied in the S3 scenario applicable under similar climate and soil conditions for the maize plant.

Compliance with Ethical Standards

Conflict of interest

The authors declared that for this research article, they have no actual, potential or perceived conflict of interest.

Author contribution

The contribution of the authors to the present study is equal. All the authors read and approved the final manuscript. All the authors verify that the Text, Figures, and Tables are original and that they have not been published before.

Ethical approval

Not applicable.

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Data availability

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Consent for publication

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