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Challenge of Rainfall Uncertainty in the Study of Deficit Irrigation

Ligalem Agegn Asres*, Melaku Adugnaw Walle
Faculty of Water Resources and Irrigation Engineering, Arba Minch Water Technology Institute, Arba Minch University, Ethiopia

***Corresponding author:** ligalemagegn@gmail.com

One of the alternative methods for managing irrigation water is deficit irrigation, particularly alternate furrow irrigation (AFI). This deficit in irrigation is affected by uncontrolled rainfall. In line with this, rainfall uncertainty causes a variation between the measured actual crop evapotranspiration and the theoretical crop evapotranspiration. Let us imagine that rain falls during the deficit irrigation research, and the soil moisture under the deficit experiment is then raised to the soil field capacity. It is incorrect to report the result as a deficit. Thus, there is a research gap on the effect of rainfall uncertainty on the quantity of theoretical and actual crop evapotranspiration under deficit irrigation. This study was carried out at the Arba Minch University demonstration site on onion crops. Using CROPWAT 8.0 software, the reference evapotranspiration (ETo) was calculated using the Penman-Monteith formula. The crop coefficient and ETo were used to calculate the theoretical crop evapotranspiration. In contrast, actual crop evapotranspiration was calculated using soil moisture measurements before and after each irrigation event after applying theoretical crop evapotranspiration. As a result, there is a significant difference between the calculated theoretical crop evapotranspiration and actual crop evapotranspiration from a deficit study. Thus, the calculated seasonal theoretical crop evapotranspiration was 201.72 mm. On the other hand, the actual crop evapotranspiration was 275.82 mm. This revealed that the actual crop evapotranspiration was greater than the calculated theoretical crop evapotranspiration by 36.7%. Uncontrolled rainfall was identified as the output's cause. This has an evident effect on the deficit in experimental research. Hence, conducting the deficit experiment in a greenhouse is more reasonable. In addition, it is possible to assess actual crop evapotranspiration based on daily soil moisture measurements and report the deficit level based on the measured amount.

Keywords: actual crop evapotranspiration, deficit irrigation, rainfall, soil moisture, theoretical crop evapotranspiration.

Introduction

Water is essential for both crops and people. Crops receive either natural or artificial watering. Irrigation is an artificial water delivery method used to feed crops in agricultural fields. Irrigated agriculture is linked to many environmental issues (Kamali et al., 2022). Fluctuations in climatic factors are one of the major obstacles. Crops are heavily dependent on climate like temperature, rainfall uncertainty, and amount of rainfall (Lobell et al., 2011). Rainfall variability in Ethiopia has demonstrated that unreliable occurrences in adequate amounts and delayed beginning dates cause crop yields to diminish by a respectable amount in practically all regions (Godswill et al., 2007).

Deficit irrigation, or purposefully under-watering a crop, is a technique for conserving farm water and directing it toward municipal, industrial, or agricultural growth (Shammout et al., 2018). Profitability has been the focus of research on this method, although the findings are inconsistent. Agronomic and legal considerations are also significant in enhancing agricultural operations, and they go beyond economic issues when determining the feasibility of deficit irrigation (Varzi and Grigg, 2019). In actuality, applying deficit irrigation during the late phase might not produce the anticipated results. The site might not respond to irrigation for various reasons. These include the presence of perched or regional water tables, deep soil with high water-holding capacity from rainfall (Li et al., 2021), weather conditions such as rain and/or low temperatures that result in low evaporative demand (Blanco et al., 2020), and a lack of accurate soil water monitoring that makes it difficult to accurately predict changes in soil water content during periods of reduced irrigation (McCarthy et al., 2002). While increasing the amount of annual rainfall, these changing conditions will alter expected rainfall patterns and increase extreme climatic events such as torrential rain, which does not count as effective rain that benefits the agronomical system because it cannot be collected (Choo et al., 2019; Nie et al., 2020).

The greatest factor in the water balance equation, rainfall, fluctuates in both time and space. It is reasonable to believe that rainfall is independent of vegetation type in most hydrological applications (Coe et al., 2009). Evapotranspiration, which is directly related to vegetation features, is the second largest element in the water balance equation. In humid locations, evapotranspiration is constrained by the amount of energy available, while it almost always equals rainfall in arid and semiarid regions (Silva-Junior et al., 2021). Crop evapotranspiration (ETc) is a complex process comprising transpiration from vegetation to the atmosphere as well as evaporation from land surfaces and water bodies (Allen et al., 1998). Without the appropriate correction, the traditional method for calculating actual crop evapotranspiration, which uses multitemporal crop coefficients (Kc), cannot be used in water-limited conditions (Chiesi et al., 2018; Wanniarachchi and Sarukkalige, 2022). Theoretically, this correction may be obtained using measurements of soil water content (Chiesi et al., 2018). Accurate evapotranspiration calculation is crucial because it plays a major role in agriculture (Gao et al., 2018; Khan et al., 2010; Rawat et al., 2019).

To calculate actual crop evapotranspiration, several methods have been developed. One of the more popular methods was the Penman-Monteith (PM) approach, which is based on meteorological parameters (Allen et al., 1998). Crop evapotranspiration can also be calculated using the water balance approach by quantifying it and using it as the residual in the water balance equation (Long et al., 2014; Wan et al., 2015). Effective calculation of actual evapotranspiration in an irrigated field can be done using the soil water balance approach (Libardi et al., 2015). This method is simple and potentially valid as long as other components of the water balance can be measured properly. It ensures an accurate computation of ET (Wan et al., 2015). Rainfall is one of the factors used in this water balance equation to calculate actual crop evapotranspiration (Hasenmueller and Criss, 2013). This rainfall varies throughout time, which is problematic for agriculture. It has two separate effects on crops: heavy rainfall and low rainfall. Irrigation makes it almost possible to avoid low rainfall, but excessive rainfall at the end of the crop season causes yield damage (Alam et al., 2011). Therefore, the main objective of this study was to evaluate the impact of rainfall uncertainty on crop evapotranspiration on a deficit study in the experimental area.

Materials and Methods

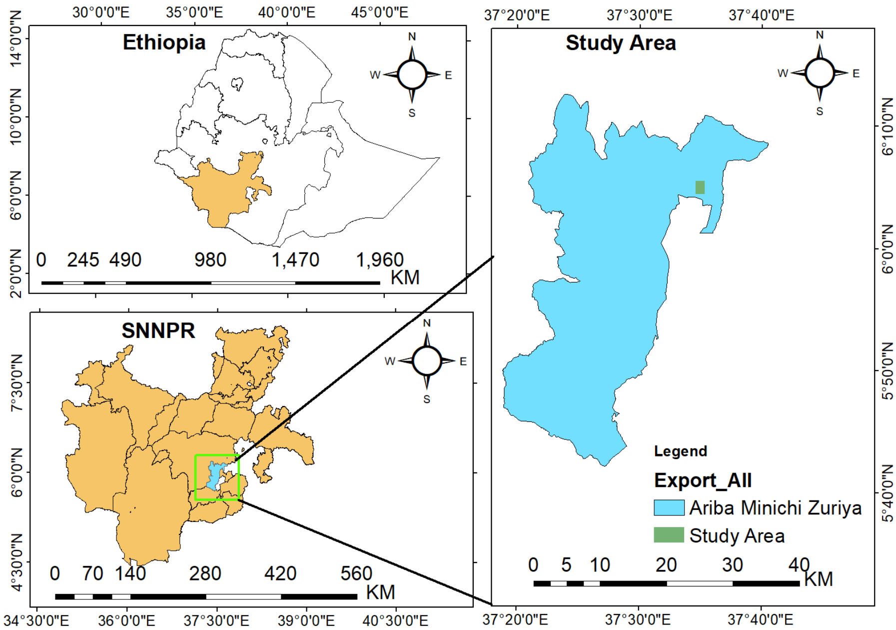
Description of the study area

The demonstration farm at Arba Minch University served as the study site. The study region is situated geographically at an altitude of 1203 m.a.s.l., 6°04’ N latitude, and 37°33’ E longitude. The time frame for this study was from August to November 2019. *Fig. 1* shows the study location map. The soil texture, bulk density, field capacity and permanent wilting point of the study site were silty clay, 1.26 g/cm^3, 36% and 20.1%, respectively (Asres et al., 2022).

Data collection

The Arba Minch University Meteorological Station provided the climate data (maximum and minimum temperature, relative humidity, sunshine, wind speed and rainfall). The climate data were collected from 1987 to

Fig. 1. *A map of the study area location*



2018 and the crop grown time from August to November of 2019. The FAO paper was used to gather onion crop coefficients (Allen et al., 1998). Field and laboratory analyses were performed on significant soil physical data, including soil texture, bulk density, field capacity, and permanent wilting point. Soil moisture of each irrigation event was measured both before and after irrigation. For this study, an onion crop was employed as a test crop. The onion crop is commonly grown in the agro-ecological zone of the study area. The agro-ecological zone of the study area is classified as dry low land. The behavior of dry low land includes an average altitude range of 500–1400 m.a.s.l. and an average annual rainfall below 900 mm (MOA, 2000).

Reference evapotranspiration and theoretical crop evapotranspiration

The previously developed Penman-Monteith method was used to determine reference evapotranspiration using CROPWAT 8.0. Mathematically, it can be expressed using *Equation 1*:

$$ET_O = \frac{0.408(Rn-G)+\gamma\frac{900}{T+273}U_2(es-ea)}{\Delta+\gamma(1+0.34U_2)} \quad (1)$$

Where ETo is reference evapotranspiration (mm/day); Rn is net radiation at the crop surface (MJ/m^{2}day); G is soil heat flux density (MJ/m^{2}day), which could be neglected at daily scale (Allen et al., 1998); γ is psychrometric constant (kPa/°C) which is equal to 0.0674 kPa/°C; T is mean daily air temperature at 2 m height (°C); U2 is wind speed at 2 m height (m/s); es is saturation vapor pressure (kPa); ea is actual vapor pressure (kPa); Δ is slope vapor pressure curve (kPa/°C).

Theoretical crop evapotranspiration was calculated based on reference evapotranspiration and crop coefficients that are accessible for different crops in an FAO document (Allen et al., 1998). This can be stated using *Equation 2*:

$$ETc = Kc \times ETo \quad (2)$$

Where: ETc is theoretical crop evapotranspiration; Kc is crop coefficient and ETo is reference evapotranspiration.

The initial, development, mid, and late seasons of the maize crop in the arid climate had growing lengths of 20, 30, 30, and 10 days, respectively, with Kc values of 0.7, 1.15, and 0.35 for the initial, mid, and late growth stages (Allen et al., 1998).

Using *Equation (3)*, the net irrigation water requirement of crops (NIR) was calculated (Micheal, 2007):

$$\mathrm{NIR} = \mathrm{ETc} - \mathrm{Pe} - \mathrm{GW} \tag{3}$$

Where: NIR is net irrigation water requirement (mm); ETc is crop evapotranspiration (mm); Pe is effective rainfall (mm); GW is groundwater contribution to crop water (mm), but not contributed at the time of the study.

Based on daily crop evapotranspiration, the amount of effective rainfall between the two irrigations was calculated using *Equation 4* (Asres, 2022; Setu et al., 2023):

$$\begin{aligned} &\mathrm{Pe} = \sum \mathrm{ETc} \quad \text{if} \sum \mathrm{ETc} < \text{rainfall or} \\ &\mathrm{Pe} = \text{rainfall} \;\; \text{if} \sum \mathrm{ETc} > \text{rainfall} \end{aligned} \tag{4}$$

Where: ∑ ETc is the sum of crop evapotranspiration from previous irrigation to the time of rain (mm).

Based on net irrigation and measured application efficiency to the field (64%), gross irrigation water to the field was estimated. The depth of irrigation for alternate furrow irrigation is calculated using the estimated gross depth of irrigation water. Plants are spaced 10 cm apart from one another, with a furrow-to-furrow distance of 40 cm.

Actual crop evapotranspiration

Based on the applied theoretical crop evapotranspiration, the measured soil moisture before and after each irrigation in the crop root zone (0–30 cm and 30–60 cm) was used to calculate actual crop evapotranspiration for this study (*Equation 5*):

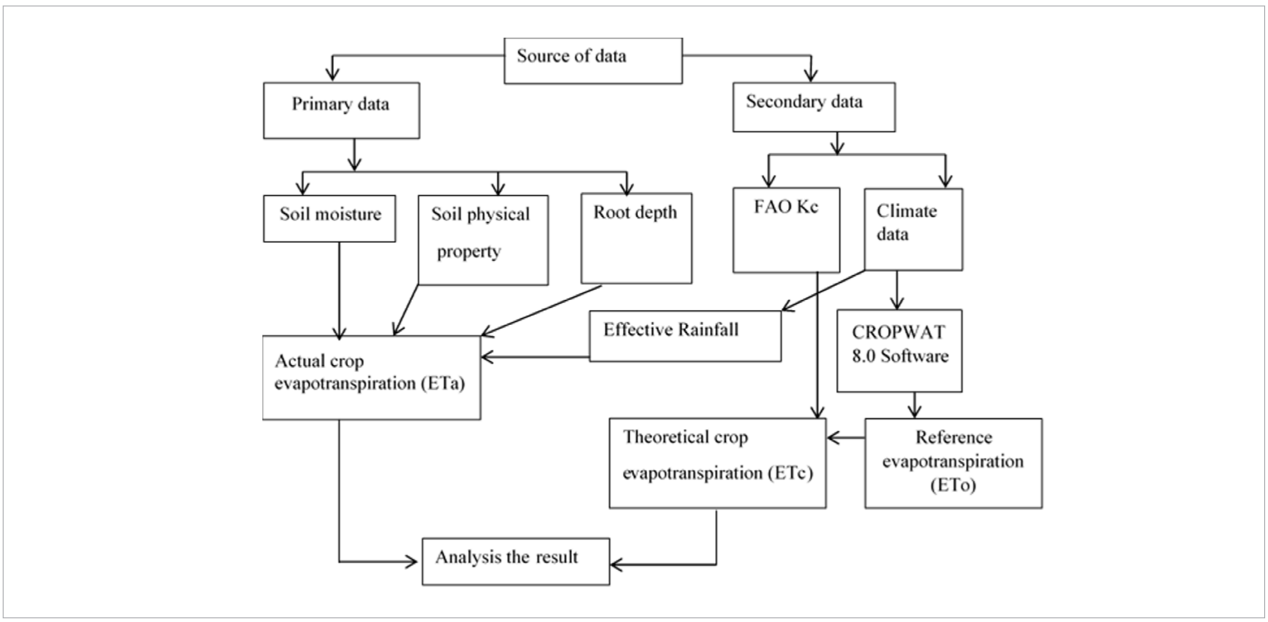
$$\mathrm{ETa} = (\omega_{ai} - \omega_{bi})\mathrm{As_i} \times \mathrm{Zr_i} + \mathrm{Pe} + \mathrm{E_1} \tag{5}$$

Where: ETa is actual evapotranspiration between two irrigations (mm)’ ωai is gravimetric soil moisture content after irrigation for ith soil layer (fraction); ωbi is gravimetric soil moisture content before the next irrigation for ith soil layer (fraction); Zri is crop root depth for ith soil layer (mm); Asi is the apparent specific gravity for ith soil for layer; Pe is effective rainfall between soil moisture measurements (mm); i is soil layer; E1 is crop evapotranspiration for one day after the next irrigation (mm).

The best time to measure soil moisture depth in loamy soil after irrigation should be about 24 hours when soil saturation has drained to full capacity (Herrerra and White, 2002; Shortt et al., 2011). It may take 36 hours in heavy soil and about 16 hours in sandy soil. Therefore, in this study, the soil moisture after irrigation was measured after 24 hours; however, until that time, the crop consumed water. This is the reason why the one-day crop evapotranspiration value was added to the equation.

A general flow chart of this study is presented in *Fig. 2*.

Fig. 2. *A general flowchart of the methodology of the study*



Results and Discussion

Based on calculated amounts of reference evapotranspiration (ETo) and crop coefficients, the theoretical crop evapotranspiration (ETc) for the onion crop was calculated. *Table 1* provides the theoretical ETc and actual ETa values for the onion crop for each irrigation event across the crop base period. As shown in *Table 1*, the actual evapotranspiration of the crop during the irrigation event that lasted six days was 18.27 mm, compared with the crop's theoretical evapotranspiration of 7.86 mm. This showed that unmanaged rainfall is the cause of this overestimation of actual crop evapotranspiration. This rain is complicating the studies on deficit irrigation. However, during the examination of the experiment, the other supplementary sources for crop evapotranspiration were absent.

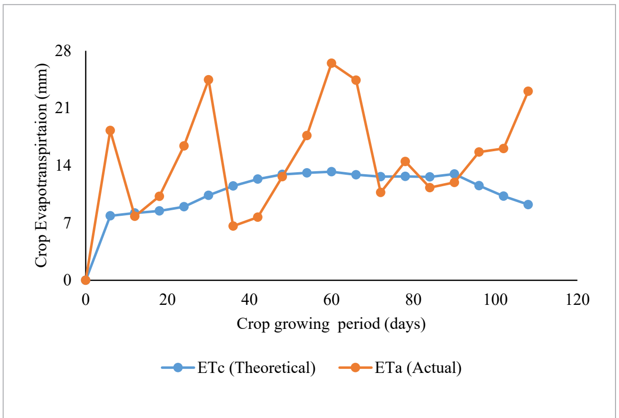
Table 1. *Theoretical crop evapotranspiration, effective rainfall and actual crop evapotranspiration*

Interval (days)	Theoretical approach						ETa (mm)
	*ETo (mm)	Kc	ETc (mm)	ETc at DI (mm)	RF (mm)	Pe (mm)	
09–14 Aug	22.45	0.7	15.72	7.86	18.2	8.33	18.27
14–20 Aug	23.44	0.7	16.41	8.2	0	0	7.8
20–26 Aug	24.18	0.7	16.93	8.46	3.9	3.9	10.24
26–01 Sept	24.03	0.75	17.94	8.97	14.6	14.6	16.39
01–07 Sept	25.38	0.82	20.73	10.36	11.8	10.3	24.45
07–13 Sept	25.94	0.89	23	11.5	0	0	6.61
13–19 Sept	25.8	0.96	24.68	12.34	2	2	7.69
19–25 Sept	25.15	1.03	25.82	12.91	2.4	2.4	12.64
25–01 Oct	24.95	1.05	26.2	13.1	9.3	9.3	17.65
01–07 Oct	25.21	1.05	26.47	13.24	77.9	26.47	26.47
07–13 Oct	24.52	1.05	25.75	12.87	44.6	17.2	24.41
13–19 Oct	24.07	1.05	25.27	12.64	10.9	5.4	10.71
19–25 Oct	24.14	1.05	25.35	12.67	17.4	9.6	14.49
25–31 Oct	24.02	1.05	25.22	12.61	5	5	11.3
31–06 Nov	24.69	1.05	25.92	12.96	6	4.8	11.93
06–12 Nov	24.3	0.95	23.09	11.54	10.9	6.2	15.64
12–18 Nov	24.14	0.85	20.52	10.26	8.5	3.4	16.07
18–24 Nov	24.61	0.75	18.46	9.23	0	0	23.06
Total			403.48	201.72	243.4	128.9	275.82

**Eto, Reference crop evapotranspiration; Kc, crop coefficient; ETc, theoretical crop evapotranspiration; DI, deficit irrigation; RF, rainfall; Pe, effective rainfall; Eta, actual crop evapotranspiration.*

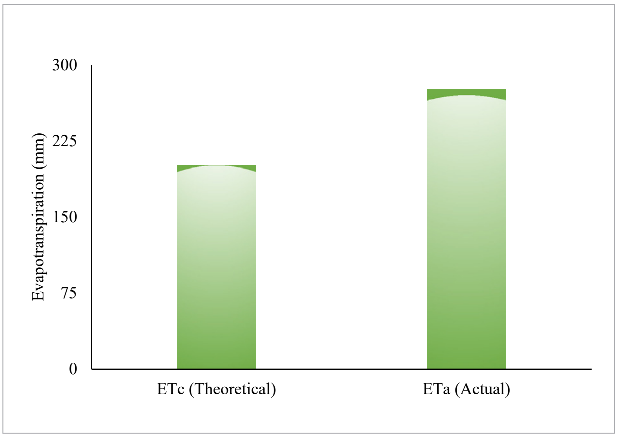
Under deficit irrigation conditions, the calculated ETc and measured ETa varied depending on the irrigation event. *Fig. 3* showed the measured ETa and calculated ETc. The two variables in the relationship oscillate one another, so that the maximum theoretical crop evapotranspiration is oscillated with the actual crop evapotranspiration. The results of this investigation are completely different. With the exception of five irrigation events, every irrigation event's actual crop evapotranspiration is overestimated compared with the theoretical crop evapotranspiration.

Fig. 3. *Theoretical and measured crop evapotranspiration*



The following graphical outputs (*Fig. 4*) are the results of an analysis and observation of seasonal theoretical and actual crop evapotranspiration for onion crop under deficit conditions. The seasonal actual and theoretical crop evapotranspiration observed in the field was measured at 275.82 mm and 201.73 mm, respectively. In accordance with this, the measured actual crop evapotranspiration is 36.7% more than the calculated theoretical crop evapotranspiration. The question is where this much water is lost through crop evapotranspiration.

Fig. 4. *Seasonal theoretical and actual crop evapotranspiration for onion crop under deficit irrigation*



As mentioned clearly in the water balance components, it is obvious that this water comes from supplemental sources (soil moisture, rainfall, and groundwater input through capillary rise). Input (rainfall, irrigation, and groundwater), storage (soil water storage), and output/loss (evapotranspiration, runoff, and drainage) all contribute to the water balance (Cui and Zornberg, 2008; Libardi et al., 2015; Tilahun and John, 2012; Todorovic, 2016). However, the crop in this study does not receive groundwater input by capillary rise. Groundwater has no contribution to crops if the level of groundwater is more than one meter below the crop root zone (Allen et al., 1998). In keeping with this, throughout the research at the experimental site, the groundwater level was not visible up to 2 m below the soil surface. On the other hand, only irrigation is controlled from input; natural rainfall is not. According to Liu et al. (2020), rainfall is a fundamental component of the water cycle and a key factor in the equation for the water balance. This greatest factor in the water balance equation fluctuates in both time and space (Coe et al., 2009), which has an effect on agricultural productivity. Although irrigation serves as insurance for rain-fed agriculture in the event of irregular rainfall, rainfall (particularly excess rainfall) is not required in the experimental study of deficit irrigation. It is not only disadvantage for the experimental area, but also a negative effect on crop production if it is raining over crop water requirement. The majority of crops are susceptible to this extreme moisture, which can have a major effect on yields. Therefore, deficit irrigation is one of the management practices that discourage unmanaged rainfall, which results in the fluctuation of theoretical and actual crop evapotranspiration.

Actual crop evapotranspiration in non-irrigated locations typically does not exceed rainfall, with a small temporal buffer dependent on the soil capacity to retain water. Because some water will be lost by percolation or surface drainage, actual crop evapotranspiration will typically be less than rainfall (Hasenmueller and Criss, 2013). In areas with deficit irrigation, rainfall may not result in significant percolation and drainage, because the voids of the deficit experiment are more air than water. After the soil moisture deficit is filled, runoff or deep percolation occurs. Up until the field's capacity, all rainfall is successfully stored in the crop root zone. This indicates that rain is captured in the root zone of the crop and expelled by evapotranspiration. There is no percolation out of the bottom of the soil layer until the moisture deficit is eliminated (Datta et al., 2017; ITRC, 2003). That is the reason for the observed overestimation of 36.7% from actual crop evapotranspiration. Therefore, rainfall in studying deficit irrigation is quite difficult. Accordingly, during periods of heavy rainfall, the deficit in soil moisture reaches or exceeds the field's capacity. The experimental design, however, only considers the theoretical crop evapotranspiration. The main challenges, according to Capra et al. (2008), are that deficit irrigation requires precision watering and some challenges are related to the lack of expertise necessary. Because rainfall that happens throughout the growing season has a direct impact on agricultural yield, weather uncertainty puts farmers at a considerable risk (Wibowo et al., 2019). It is preferable to undertake deficit irrigation studies in a greenhouse to manage rainfall uncertainties. The undesired rain is effectively monitored in a greenhouse. In a greenhouse, Mao et al. (2003) conducted research on deficit irrigation for a cucumber crop and found accurate results. In line with this, the water balance equation used to estimate crop evapotranspiration does not take rainfall into account (Mao et al., 2003; Chand et al., 2020). According to Trout and Jonge (2021), both the effect of the current soil water shortage on water uptake and stomatal resistance and the effect of the previous water stress on plant growth had an impact on crop evapotranspiration. When the soil water deficit exceeded 25% of the total plant accessible water, the measured evapotranspiration was lower than the potential crop evapotranspiration.

Deficit irrigation is a technology to manage irrigation water. During testing, uncontrolled rainfalls happened and significantly affected the result as well as the report of research. When only deficit irrigation is taken into account, the crop yield is good due to the crop getting enough water at the time of rain. Therefore, in relation to this, it is recommended to ignore the theoretical approach of crop evapotranspiration estimation and follow actual soil moisture measurement to monitor deficit irrigation and apply the irrigation water to the crop based on the measurement of soil moisture only.

Conclusions

Irrigated agriculture is associated with various environmental challenges. The fluctuations in meteorological variables, including rainfall, are among the key obstacles. The measurement of actual crop evapotranspiration was significantly impacted by rainfall in the deficit irrigation research. According to this study, the difference between actual and theoretical crop evapotranspiration is overstated by up to 36.7%. In keeping with this, it has an impact on the deficit irrigation naming (level) at the end of the experiment. Therefore, it is better to re-adjust the level of deficit irrigation based on the consumed water compared with the control treatment at the end of the season. The uncontrolled rainfall is what causes the observed overvalue of the actual crop evapotranspiration. Accordingly, the most difficult water balance factor in the research of deficit irrigation is rainfall. To evaluate the impact of deficit irrigation on any agronomic parameters, it is therefore preferable to employ a greenhouse. The unwanted rainfall can be adequately monitored in this greenhouse.

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