Determination of Water Requirement and Crop Coefficient of Wheat Crop in Central Ethiopia

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Abstract

Accurately estimating a crop's seasonal water needs is pivotal for effective irrigation project design, establishment, and management, as well as for scheduling irrigation. This study aimed to ascertain the seasonal crop evapotranspiration (ETc) and crop coefficient (Kc) of wheat across various developmental stages. The research was carried out at the Debre Zeit Agricultural Research Center in central Ethiopia during the dry season of 2021/22. The crop considered for the experiment was durum wheat of Utuba variety. Two non-weighing lysimeter units were employed to measure the water balance components. The soil moisture was monitored using gravimetric method on daily basis conducted both before and after each irrigation event at various depth intervals. Using weather data and the modified Penman Monteith method, reference crop evapotranspiration (ETo) was determined, while crop evapotranspiration was calculated employing the water balance equation. The study found that during the initial, development, middle, and late stages of growth, water requirements were 40.35 mm, 82.44 mm, 238.66 mm, and 31.3 mm, respectively. Additionally, crop coefficients for the early, development, middle, and late stages of wheat growth were computed as 0.51, 0.83, 1.29, and 0.52, respectively. These findings provide valuable insights for precise water resource planning and management in wheat cultivation.

Keywords: wheat; reference evapotranspiration; crop evapotranspiration; crop coefficient; non-weighing lysimeter

Introduction

Water is considered a key natural resource, essential for sustaining life and propelling the socioeconomic development nations (Abebe Shenkut *et al.*, 2013). The increasing pressure on water and the environment, as a result of the rapid expansion of the population around the world, is becoming an issue of great concern (Yenesew Mngistu, 2015). Water use among sectors is occasionally competitive in terms of quantity and quality due to its non-uniform distribution and availability (Ketema Tezara *et al*., 2019). Agriculture is the key contender among different users, since it consumes a significant percentage of freshwater to provide a secure food supply for the ever-increasing population. Consequently, the agricultural sector needs special consideration and scientific research on how to increase its output (Bashir *et al*., 2017; Abebe Shenkut *et al*., 2013).

Worldwide inefficient water use wastes a significant amount of water, which is already scarce. Particularly, the careless use of it for agriculture is making the water deficit worse in many places. This poor use of water is leading to a greater than necessary increase in fresh water withdrawals and could result in unneeded competition between various industries. The introduction and use of new and existing technology to optimize water use efficiency in the agricultural sector, which uses a significant amount of fresh water, is one of the alternatives that can address these issues (Nair *et al*., 2013).

Optimizing water use in irrigated agriculture involves balancing the crop's need for water with the amount of water that is actually applied to the crop. Achieving adequate water management is necessary to maximize yield production and water use efficiency. Deficit irrigation and alternate irrigation, along with other irrigation forms, can increase water use effectiveness. Due to their affordability and technical simplicity, these technologies can also be used by commercial farmlands and individual farmers. However, the crop water requirement and crop coefficient—two highly important parameters are necessary for the application of these technologies. These variables play a major role in every irrigation and drainage design strategy. Therefore, establishing these parameters in areas with potential for irrigation, such as central Ethiopia, will be useful in maximizing water use efficiency (Callejas Moncaleano *et al*., 2021; Daniel G.Eshete *et al*., 2020).

Wheat (*Triticum aestivum* L.) has served as the staple diet for most major civilizations around the world (Curtis, B.C et al., 2002). Based on grain acres, it is the most significant grain in the world, and it comes in second place in terms of overall output volume. It is also a crucial source of calories for humans. Hence, the population numbers of different regions are showing rapid growth, and wheat is one of the major crops in the food chain system; the desire to enhance its productivity is becoming the first priority of different organizations and agricultural firms. In the Ethiopian context, wheat (*Triticum aestivum* L.) is one of the major cereal food crops grown. Covering about 13.25% of the total cultivated area under grain crops, wheat is the fourth most important crop in area coverage, following Tef, maize, and sorghum (Ketema Tezara *et al*., 2019).

Numerous studies have shown that, when it comes to irrigated crop production, knowing the exact quantity of crop water requirements during the crop growing season and the crop coefficient for a specific growth stage is crucial for proper planning and management of irrigation (Pakparvar *et al.*, 2014; Piccinni *et al.*, 2007; Ketema Tezara *et al.*, 2019; Yarami *et al.*, 2011). Currently, irrigated wheat production is given the highest priority in Ethiopia. However, there is a lack of site- and crop-specific data needed for planning and management of irrigated wheat crops. Thus, field measurement-based determination of the crop water requirement (ETc) and crop coefficient (Kc) of wheat (*Triticum aestivum* L.) is urgently needed. Therefore, the purpose of this study was to determine the water requirement and crop coefficient of the wheat crop in the Bishofitu area in central Ethiopia.

Materials and Methods

Description of the Study Area

The experiment was conducted at the Debre Zeit Agricultural Research Center (DZARC) in the off-season from 24th December to 22 April 2021. The study site is located at 8°73′ latitude and longitude of 39°98′, with an altitude varying between 1931 and 2017 above mean sea level and found at a distance of 46 km to the southeast of Addis Ababa (Figure 1). The mean annual rainfall is about 801.3 mm and has a single rainy season that extends from March to October and peaks in July. The mean annual maximum temperature is 25.5 °C, with variations between 23.7 °C and 27.7 °C in July and May, respectively. The mean annual minimum temperature is about 10.5 °C, with the coolest temperature of about 7.4 °C in July.

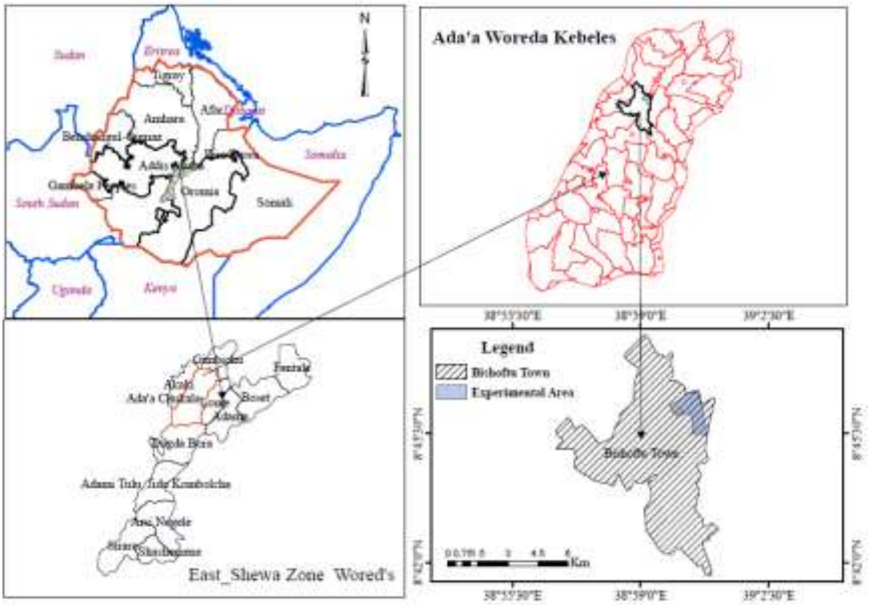

Figure 1. Location of the study area.

Experimental Material and Set up

Experimental set up

The experiment was implemented on two non-weighing lysimeters. The lysimeters were constructed near to observatory meteorological station at a distance of 20 m. It was constructed with an air tube that was used as an aeration pipe to facilitate air movement at the root zone, and there was a concrete bund of 10 cm height above the ground surface to avoid the inflow and outflow of water from the system. The net area of a single lysimeter was 4 m2 (2 m width by 2 m length) and 1 m depth to allow unrestricted root growth.

Sowing of the seed was done in double rows with a row spacing of 20 cm and a furrow width of 40 cm for proper irrigation water application and agricultural practices. Three furrows and four ridges with a length of 2 m inside each lysimeter and 2 m from the outside in each direction of the lysimeter (buffer zone) were constructed, and similar planting procedure with the lysimeter was applied. Furrows were arranged from the northern to the southern directions. The buffer area was used to maintain the natural environment consistent with the experimental plots, whereby the same crop was planted on 32 m2, excluding the lysimeter area (Figure 2). The buffer zone helped to observe the difference between the crop growth that was planted in and outside the lysimeter. The same treatment was applied to the lysimeters with respect to irrigation and fertilizer application as well as pest and weed management.

Experimental material

An experimental wheat variety called Utuba was used. The variety was released by the Debre Zeit Agricultural Research Center Durum Wheat Breeding Department in 2015. It takes approximately 120 days to reach maturity, and it has a high protein content and high yield potential relative to early-released varieties (Mekuria Temtme, 2018). Urea and NPS were used as sources of nitrogen, phosphorus, and other required fertilizer, within recommended rate with respect to the crop variety. A furrow irrigation system was applied in order to irrigate the experiment and a calibrated watering can to feed water inside the furrow.

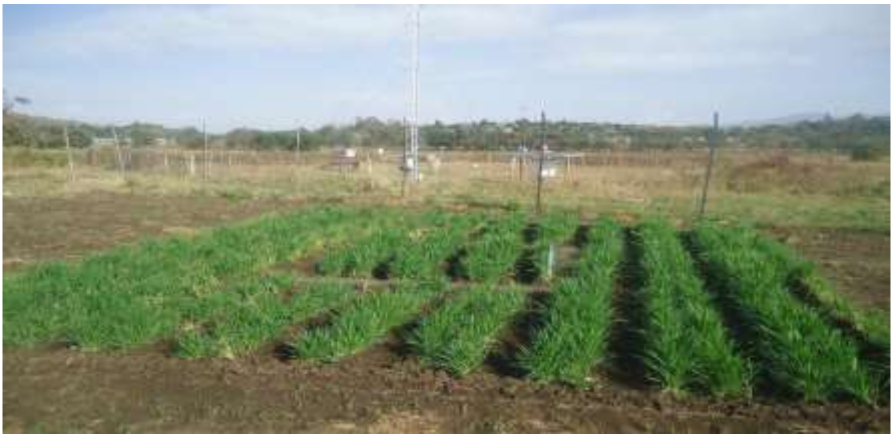

Figure 2. Overview of the experimental site during the crop development stage.

Soil Sampling and Analysis

Soil samples were collected from the lysimeter unit as well as from the buffer zone with similar procedures. The samples were taken up to a depth of 60 cm with an interval of 0–15 cm, 15–30 cm, and 30–60 cm using augurs and sample collecting bags. The collected samples were subjected to the analysis of physical parameters of the soil. These include the field capacity, permanent welting point, soil texture, electric conductivity, and pH. For bulk density analysis, undisturbed sample was collected using core samplers of known dimensions which was 5 cm depth and diameter of 4 cm from the same depth intervals described above. The analysis was conducted in the DZARC soil laboratory.

Data Analysis

Moisture holding capacity of the soil and permanent welting point.

The water holding capacity and permanent welting point of the soil were determined following standard soil laboratory procedures. The acquired samples were dried naturally in a soil sample drying storage and ground by hand. The ground sample was weighted and immersed in water until saturation was reached for 24 h before being extracted using a syringe. Following that, the sample was placed in a pressure plate for 24 h to drain excess water, which is until the drainage ceases that corresponds to field capacity. The evaluation is then performed using Equation (1). Permanent wilting point was determined using pressure plate. The pressure plate was set to 0.33 bar for the field capacity (FC) and 15 bar for the permanent welting point (PWP) determination.

$$\text{FC\%} = \frac{\text{Wet soil (gm)} - \text{Dry soil (gm)}}{\text{Dry soil (gm)}} \times 100 \qquad (1)$$

Bulk density is given by Equation (2) as follows:

$$\rho b = \frac{Ms}{Vt} \qquad (2)$$

where FC is the field capacity of the soil, PWP is the permanent wilting point of the soil, ρb is the dry bulk density (gm/cm3), Ms is the mass of the dry soil in gram, and Vt is the total sample volume (cm3).

Soil moisture content

Depending on the stage of crop growth, the soil moisture was monitored both before and after (24 hrs later) each irrigation treatment at various depths. The upper 30 cm of depth contains 61–68% of the effective root depth of wheat (Fan *et al.*, 2016). Thus, soil moisture was monitored up to 60 cm depth using gravimetric method. Accordingly, the soil moisture content was evaluated using Equations (3)–(6):

$$\text{moisture content on weight bassis, W (\%)} = \frac{\text{Wwet}-\text{Wdry}}{\text{Wdry}} \times 100 \quad (3)$$

$$\text{Moisture content on volumetric basis, } \theta = \frac{W(\%)}{100} \times \text{bulk density} \quad (4)$$

$$\text{Depth of moisture content, d} = \theta \times Z_r \quad (5)$$

$$\Delta\theta = \text{SMC} = \theta_{t1} - \theta_{t2} \quad (6)$$

where W=wet is the weight of wet soil (w/w), W=dry is the weight of dry soil (w/w), θ is the volumetric moisture content (%), Zr is the soil depth (mm), W is the soil moisture content in on weight basis, Δθ is the change in soil moisture in mm, and θt1 and θt2 are the soil moisture content between consecutive days (mm).
Effective Rainfall (Pe).

Rainfall data were obtained from an observatory weather station located close to the experiment. The effective rainfall was then computed using Equations (7) and (8) as per the FAO CropWAT8.0 version model (FAO, 1992):

$$Pe = 0.6 \times P - 10 \text{ if P is } \leq 70 \quad (7)$$

$$Pe = 0.8 \times P - 24 \text{ if P is } > 70 \quad (8)$$

where P is the rainfall and Pe is the effective rainfall in mm.
Estimation of Crop evapotranspiration (ETc)
The water balance Equations (9) and (10) were used to compute the crop's evapotranspiration, as suggested and indicated by (Tilahun Hordofa, 2020; Abebe Shenkut *et al.*, 2013; Ketema Tezara *et al.*, 2019; Belay Yadeta *et al.*, 2021) and the components of water balance have been presented in the figure below (Figure 3):

$$(I + Pe) = - ETc \pm \Delta\theta - Dp - \Delta R \quad (9)$$

$$ETc = (I + Pe) - Dp \pm \Delta\theta \quad (10)$$

where ETc is the crop evapotranspiration (mm/day), I is the irrigation (mm), Pe is the rainfall (mm), Δθ is the change in soil moisture, Dp is the drainage water depth in mm, and ΔR is the change in runoff in mm.

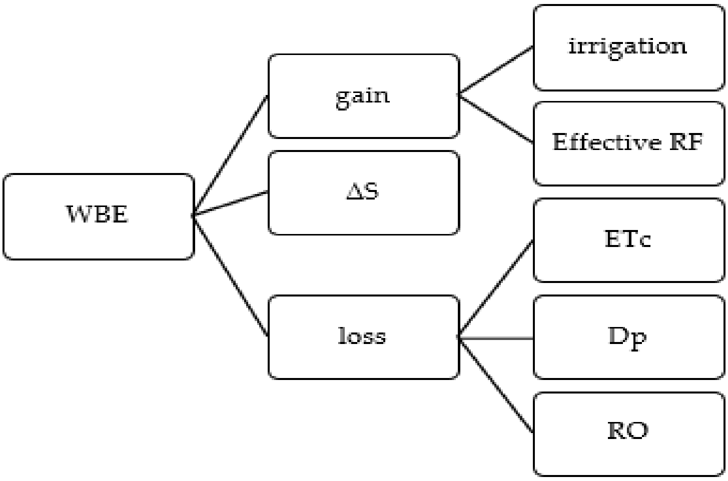

Figure 3. Water balance equation components.

Estimation of Reference Evapotranspiration (ETo)

The FAO-supplied model (CropWAT) and FAO Penman–Monteith method were utilized in order to estimate reference evapotranspiration because they can produce reliable results (Allen & Food and Agriculture Organization of the United Nations, 1998). The formula for the FAO Penman–Monteith equation is shown in the equation below:

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{Rn} - \mathrm{G}) + \gamma\left(\frac{900}{\mathrm{T} + 273}\right)\mathrm{U2}(\mathrm{es} - \mathrm{ea})}{\Delta + \gamma(1 + 0.34\mathrm{U2})} \qquad (11)$$

where ETo is the reference evapotranspiration (mm/day), Rn is the net radiation at the crop surface (MJ m−2), G is the soil heat flux density (MJ m−2 day−1), T is the mean daily air temperature at 2 m height (°C), U2 is the wind speed at 2 m height (ms−1), es is the saturation vapor pressure (KPa), ea is the actual vapor pressure (KPa), es − ea is the saturation vapor pressure deficit (KPa), Δ is the slop vapor pressure curve (KPa), and γ is the psychometric constant (KPa °C−1).

Estimation of Crop Coefficient (Kc)

Several authors have used Equation (12) to derive growing stage crop coefficient (Allen & Food and Agriculture Organization of the United Nations, 1998; Tilahun Hordofa, 2020; Abebe Shenkut *et al.*, 2013; Ketema Tezara *et al.*, 2019; Belay Yadeta *et al.*, 2021):

$$k_{Ci} = \frac{ET_{ci}}{ET_{oi}} \qquad (12)$$

where k_{ci}, ET_{ci}, and ET_{oi} are the crop coefficient, crop evapotranspiration, and reference evapotranspiration during the i-th crop growth stage.

Results and Discussions

Soil physical properties

The results of the soil physical properties of the study area (Table 1) revealed that the soil texture was found to be clay and there was no salinity threat as both the buffer zone and lysimeter showed salinity levels of 0.105 ds/m. The result agreed with soil analysis result conducted previously by the Debre Zeit Agricultural Research Center (DZARC) (self-observed).

The field capacity of the soil in the lysimeters ranged from 50.0% to 51.8%. Moisture content at wilting point is relatively high (32.35–35.80%). As a result, the total available water over 60 cm of root zone is 116 mm. The average bulk density ranged from 1.09–1.16 gm/cm^3 for 60 cm soil depth.

Table 1. Physical properties of the lysimeter soil.

Depth (cm)	FC (%)	PWP (%)	ρ_b (gm/cm^3)	TAW (mm)	Particle Proportion (%)			
					Clay	Silt	Sand	Soil Texture
0–15	51.80	35.80	1.09	26.16	54.4	24	21.6	Clay
15–30	51.57	34.10	1.09	28.56	50.4	34	15.6	Clay
30–60	50.00	32.35	1.16	61.42	52.4	30	17.6	Clay
0–60	51.12	34.08	1.11	116.14	51.4	30	18.6	Clay

Note: TAW = total available water content.

Weather Condition of the Experimental Site during Crop Growing Season

The average minimum and maximum temperature of the growing season was 7.3 °C and 27.78 °C, respectively (Figure 4). The maximum rainfall recorded was 14.5 mm in January, which was during the initial stage of the crop growth, and the remaining growing season was totally dry.

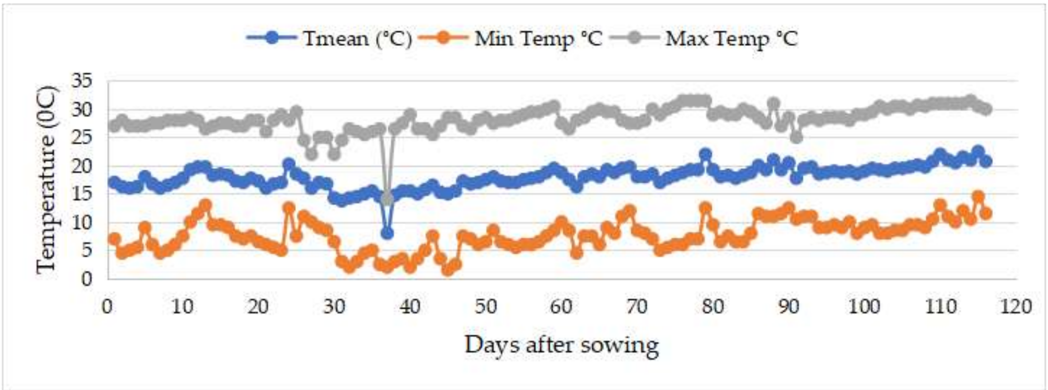

Figure 4. The mean temperature during the growing season of the crop (25 December to 18 April).

Soil moisture content

The soil moisture was monitored as explained in the methodology, and moisture throughout the growing season is presented in Figure 5. Keeping the soil moisture in the effective root zone was considered the best option while applying irrigation water. As the results indicate, the moisture content during the mid- and late season was found to be high compared to the initial and development stages. The reason behind this phenomenon might be due to the reduction of evaporation from the soil as ground coverage was at its maximum at this growth stage or the increase the depth of irrigation as root growth increased.

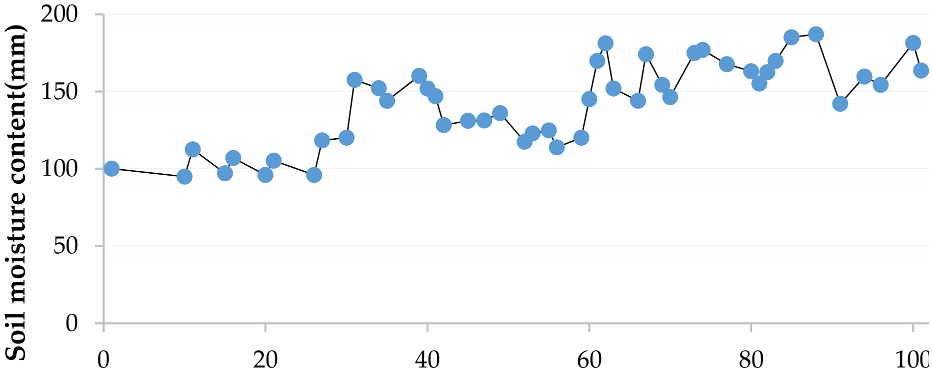

Figure 5. Growing seasonal trend of the soil moisture content over 60 cm depth.

Reference Evapotranspiration (ETo)

The averaged reference evapotranspiration (ETo) of the growing season was found to be 5.1 mm/day, which was estimated using CROPWAT model. The value of the reference evapotranspiration during the growing season was ranged between 6.19 mm/day and 2.8 mm/day.

Measured Crop Evapotranspiration (ETc)

The water balance Equations (10) and (11) were applied to determine the water demanded by the wheat crop. As depicted in Table 2, the water requirement at the initial stage was 40.35 mm and increased to 82.44 mm during the development stage. As the ground cover at initial stage was small, the largest portion of water loss might be accounted to evaporation. The demand continuously increased till it showed a decrease at a late stage, which proved that the water demand of a crop is highly dependent on the greenness of the plant, and when the plant changes its green color, the water requirement tends to decrease (Figure 6).

Table 2. Seasonal crop evapotranspiration (ETc).

Parameters	Growth Stages				
	Initial	Development	Mid-Stage	Late-Stage	Total (mm/GS)
Growth Length (day)	20	30	42	23	115
ETc (mm/stage)	40.35	82.44	238.66	31.3	392.72
ETc (mm/day)	2.02	2.75	5.68	1.36	

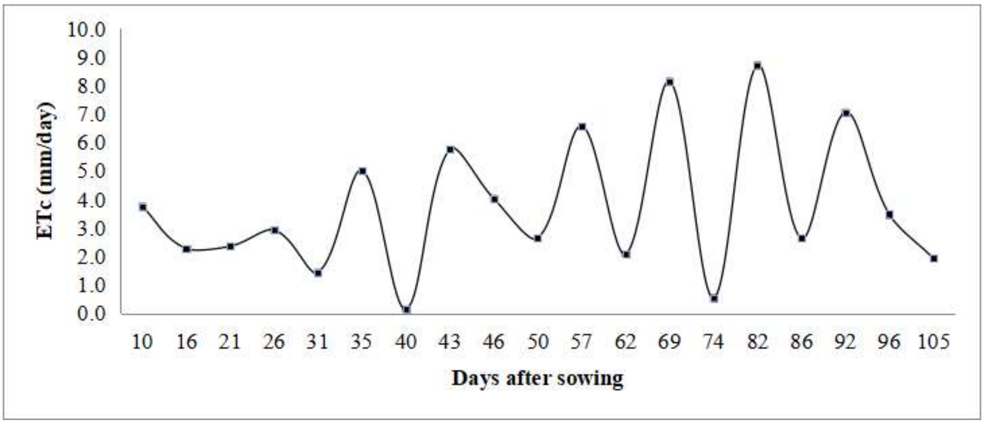

Figure 6. Crop evapotranspiration rate for the growing season.

As shown in Figure 7 below, the water demand of wheat at different growth stages varied continuously with respect to growth stage. This demonstrates that applying the same amount of water throughout the growth stage without distinguishing the crop growth stage can result in a significant loss of water that could be used to expand the area to crop additional crops. During the growing season, observations revealed that when the weather was exceptionally sunny and hot, the water demand was significant and the soil moisture dries rather quickly, and vice versa.

The results of this investigation showed that less water was used at the beginning, development, and end of the experiment when compared to the findings of the study conducted by (Ketema Tezara *et al.*, 2019) in Melkassa. However, the current study had a higher water demand at the mid-stage. Their study showed that the seasonal water demand of the crop was found to be 413.8 mm, which is a bit greater than our result (392.75 mm). Obviously, seasonal variations in climate and site-specific variables contribute to the variations in the amount of crop water requirement. More specifically, these factors could include the climate differences between the two places, the season in which the cultivation took place, the species of crop employed as an experimental crop, the soil type, or the cultivation management technique.

Other studies conducted by different scholars in different locations similarly showed variations from the current result (Table 3). These results have a higher water requirement than the current results (Kenjabaev *et al*., 2014; Laaboudi *et al*., 2015). The variation was expected, as water requirements are dependent on different physical parameters, particularly soil type and climate conditions.

Measure crop evapotranspiration and estimated reference evapotranspiration based on local climate parameters are necessary to develop crop coefficient. Figure 7 indicates the curves of these two important variables over the growing season of the wheat crop.

As it can be seen from (Figure 7), the reference evapotranspiration (ETo) during the growing season was higher than crop evapotranspiration (ETc) for the first two growth stages (initial and development) and the late growing stage. However, during the mid-growth stage, the water loss through crop evapotranspiration was higher than the reference evapotranspiration. This shows that as crop progresses in its development and reaches maximum physiological development, its water demand becomes greater than that dictated by evaporative demand of the atmosphere.

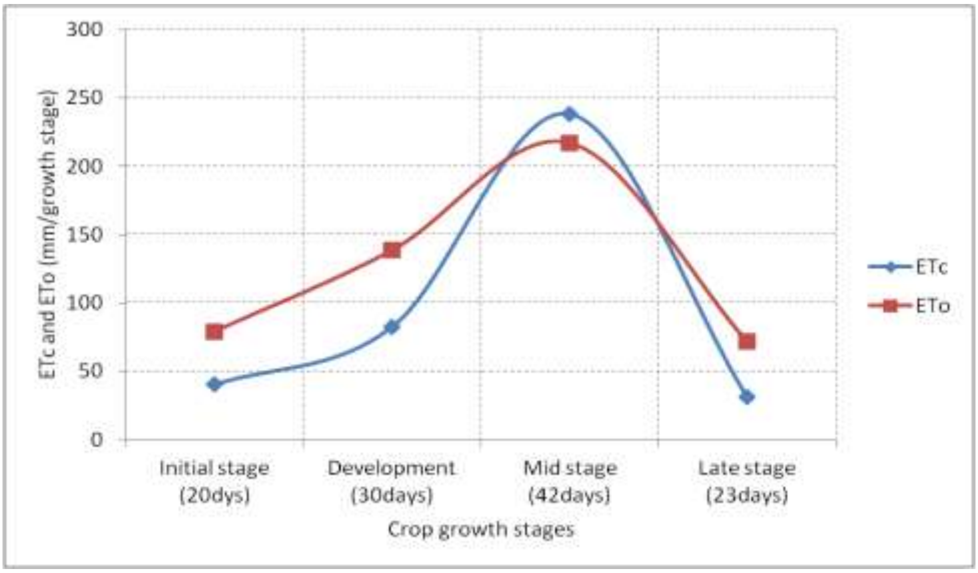

Figure 7. Stage-based ETc and ETo rate over the growing season.

Table 3. Comparison of crop evapotranspiration of wheat as determined by different authors.

Authors	ETc				
	Initial	Development	Mid-Stage	Late-Stage	Total ETc (mm/Season)
Current result	40.35	82.44	238.66	31.3	392.75
(Ketema Tezara *et al*., 2019)	52.2	97.1	191.5	73	413.8
(Laaboudi *et al*., 2015)	-	-	-	-	603.67
(Irmak *et al*., 2015)	-	-	-	-	490–600
(Kenjabaev *et al*., 2014)	-	-	-	-	509

Crop Coefficient (Kc)

The results of field measurement of the crop coefficient for wheat are presented in (Table 4 and Figure 8). The crop coefficient is a parameter estimated from ETc and ETo. When the value of ETc drops during the growth stage due to weather fluctuations, Kc becomes small, and vice versa. The Kc values found in this study were 0.51, 0.83, 1.29, and 0.52 at the initial, development, middle, and late stages, respectively. The result indicated that increasing the growth date (stage) of the crop also increased the crop coefficient until it reaches the late stage. While the crop reaches its late growing stage, the plant loses its greenness and gradually ceases photosynthesis process. At this stage, the reference evapotranspiration becomes higher than crop evapotranspiration, and as a result, Kc value becomes smaller than the previous two growing stages (Allen *et al*., 1998).

Table 4. Crop coefficient of wheat as derived from growth stage values of ETc and ETo.

Parameters	Growth Stages			
	Initial	Development	Mid-Stage	Late-Stage
Length of growing stage (day)	20	30	42	23
ETc (mm/stage)	40.35	82.44	238.66	31.3
ETo (mm/stage)	79.05	138.44	217.05	71.7
Kc	0.51	0.83	1.29	0.52

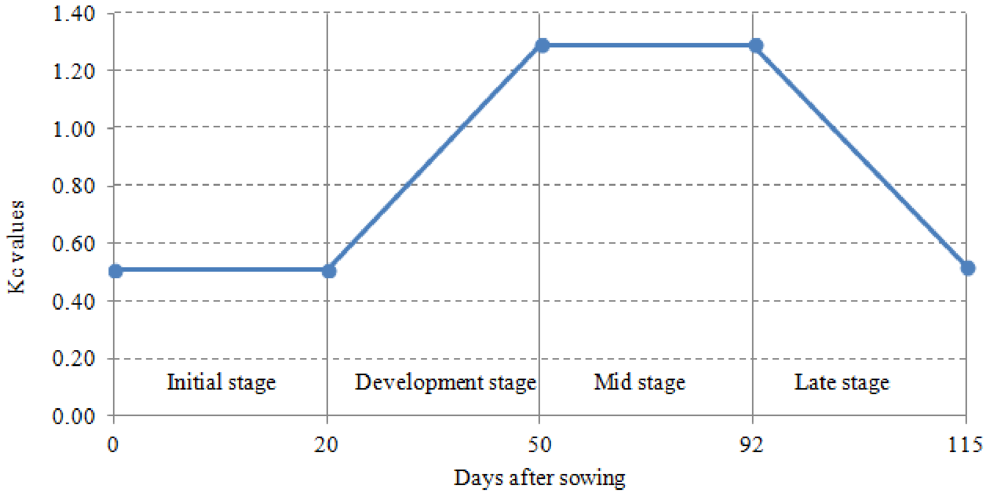

Figure 8. Kc values for different growth stages.

Similar experimental studies conducted in different parts of the world have shown that there is a variation in Kc values which might be sue to the differences in climatic conditions of the areas (Table 5). For instance, research conducted by (Ketema Tezara *et al.*, 2019) on the wheat crop coefficient identified 0.54, 1.15, and 0.67 for the early, middle, and late stages of the crop growing season. Ref. (Irmak *et al.*, 2015) also discovered that the Kc values for early-, middle-, and late-season winter and spring wheat were 0.60, 1.3, and 0.30, respectively. The findings of this study are more or less in line with many of the previous results. According to (Kenjabaev *et al.*, 2014), the wheat crop's Kc values at early, middle, and late season growing stages were 0.27, 1.03, and 0.89, respectively, which was different from the current result.

Table 5. Comparison of Kc results from different scholar findings.

Sources	**Kc Value**			
	Initial	**Development**	**Mid-Stage**	**Late Stage**
Current study averaged Kc result	0.51	0.83	1.29	0.52
(Allen *et.al* 1998)	0.6–1.1	0.5–0.7	1.15	0.4
(Ketema Tezera *et. al*, 2019)	0.54	-	1.15	0.67
(Laaboudi *et al*., 2015)	0.48	0.74	1.3	0.88
(Kenjabaev *et al*., 2014)	0.27	-	1.03	0.89

All these variations show the importance of calibration and validation of crop coefficient to the specific areas of interest before using the values given in different research papers. The graphical representation of the Kc values over the growth stage and season is portrayed in Figure 8.

Crop Coefficient as a Function of Days of the Growing Season (DGS)

Crop coefficient Kc values as a function of days of growth stage (DGS) were fitted to a regression equation. As a result, a fourth-order polynomial equation with a high coefficient of determination, $R^2 = 0.999$, was developed. The established relationship can be used to anticipate crop coefficients when constructing and planning irrigation systems in locations outside of the research area that have similar climate and soil conditions. The equation has the following form:

$$Kc = 5 \times 10^{-8} (DGS)^4 - 1E\text{-}05(DGS)^3 + 0.0012(DGS)^2 - 0.0186(DGS) + 0.51$$

where $R^2 = 0.99$.

The equation was tested using the Kc data generated by the current study and results are presented in Table 6 below. There is a little numerical discrepancy between the study's findings and the Kc value predicted by the equation. The difference, however, was not statistically significant, indicating that one may use the equation to estimate the Kc value for the known length of developing stage.

Table 6. Comparison of Kc values from the experimental result and developed equation.

	Kc Values		
Growth Stages	**Measured from Lysimeter Data**	**Estimated Using the Suggested Equation**	**Deviation (%)**
Initial	0.51	0.55	+7.8%
Development	0.83	0.80	−3.75%
Mid-stage	1.29	1.26	−2.38%
Late-stage	0.52	0.60	+15.8%

Conclusions

The results indicated that the seasonal net water requirement of the wheat crop was found to be 392.75 mm. The crop evapotranspiration during initial, development, mid-stage, and late stages was 40.35 mm, 82.44 mm, 238.66 mm, and 31.3 mm, respectively. The crop coefficient (Kc) was determined to be 0.51, 0.83, 1.29, and 0.52 for the initial, development, mid, and late growth stages, respectively. A regression equation that predicts Kc values as a function of crop growth stage developed in this study can also be used to estimate Kc under data-scarce conditions.

The results further revealed that considering the climate of the area and the soil condition must be a priority in order to have better water conservation in crop production, especially cereal crops. Additionally, the result indicated that for areas similar to the experimental site regarding agro-ecology and crop variety, already-developed Kc equations can be used to estimate the crop water requirement and crop coefficient. As the results presented in this paper are based on one season experiment, repetition of the experiment would be recommended to generate reliable information useful efficient and effective management of irrigation.

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