Measurement of Crop Water Requirement and Developing Crop Coefficient (Kc) for Irrigation Scheduling of Wheat Crop Using Lysimeter at Bishofitu

Mahlet Wogu Amdneh

A Thesis Submitted to

Department of Water Resources Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Water Resources Engineering (Irrigation Engineering)

Office of Graduate Studies

Adama Science and Technology University

Jun, 2022

Adama, Ethiopia

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Mekonen Ayana Gebul (PHD)

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## APPROVAL PAGE OF M.SC. THESIS

I, the advisors of the thesis entitled "**Measurement of Crop Water Requirement and Developing Crop Coefficient (Kc) for Irrigation Scheduling of Wheat Crop Using Lysimeter at Bishofitu**" and developed by Mss. Mahlet Wogu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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| Major Advisor | Signature | Date |

## APPROVAL OF BOARD OF EXAMINERS

We, the undersigned, members of the Board of Examiners of the thesis by Mss. Mahlet Wogu have read and evaluated the thesis entitled "**Measurement of Crop Water Requirement and Developing Crop Coefficient (Kc) for Irrigation Scheduling of Wheat Crop Using Lysimeter at Bishofitu**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Water Resources Engineering (Irrigation Engineering).

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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## DECLARATION

I hereby declare that this Master Thesis entitled "**Measurement of Crop Water Requirement and Developing Crop Coefficient (Kc) for Irrigation Scheduling of Wheat Crop Using Lysimeter at Bishofitu**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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| Ms. Mahlet Wogu | ______________________ | ______________ |
| Name of the student | Signature | Date |

## RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Measurement of Crop Water Requirement and Developing Crop Coefficient (Kc) for Irrigation Scheduling of Wheat Crop Using Lysimeter at Bishofitu**" prepared under my/our guidance by Mss. Mahlet Wogu submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Water Resources Engineering (Irrigation Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

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| Mekonen Ayana (PHD) | ____________________ | ______________ |
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# Table of Contents

## List of Table

## List of Figure and Illustrations

## List of Acronyms and Abbreviations

AI   After Irrigation

BI   Before Irrigation

DAS   Day After Sowing

DSS   Day Starting Sowing

DZARC   Debre Zeit Agricultural Research Center

ETc   Crop Evapotranspiration

ETo   Reference Evapotranspiration

FAO   Food and Agriculture Organization

FC   Field Capacity

Kc   Crop coefficient

PWP   Permanent Welting Point

SMS   Soil Moisture Content

## ABSTRACT

*With rapid population growth, pressure on natural resources such as water is aggravating. Consequently, shortage of water also competition for the available water is increasing in many regions. Scarcity of fresh water for agricultural use is forcing the society to look for different planning and management options. This requires knowledge of crop specific parameters that are needed for irrigation development and management. The objectives of this research were to determine the crop evapotranspiration, develop crop coefficient and irrigation scheduling for wheat crop. The study was conducted in Bishoftu, at Debre Zeit Agricultural Research Center (DZARC).The experiment was conducted during the dry season (Bega) of 2021/22 with sample crop of Utuba variety durum wheat. For this purpose, two non-weighing lysimeter units were used for measuring water balance components on daily basis from which crop evapotranspiration was calculated and then crop coefficient. The total crop growing length was 115 day starting from day after sowing which was assigned 20, 30, 42, and 23 days for initial, development, mid, and late stage respectively. The reference evapotranspiration was estimated with CropWAT8.0 model and Microsoft excel was used for the data analysis. The soil moisture content was monitored with gravimetrical method and monitoring was carried out before and after every irrigation applications with different depth interval. The results indicated that the crop evapotranspiration of 40.35 mm, 82.44 mm, 238.66 mm, and 31.3 mm was recorded for initial, development, mid, and late growing stage respectively with total seasonal water requirement of 392.75 mm. The crop coefficient was estimated to be 0.51, 0.83, 1.29, and 0.52 for initial, development, mid, and late stage of wheat growth respectively and fourth degree polynomial equation was developed for the relationship between DGS and kc also sixth degree with DAS. As the findings indicated, there is variation on kc result from FAO recommended values ranging between -30 % to +63.5 %. The irrigation scheduling was developed based on peak daily crop evapotranspiration and the result indicated 10, 12, 27, and 9 days interval is required for initial, development, mid, and late season of the crop growing stages respectively. As of the result of this study, parameters to be calibrated and validated with respect to desired location if it is different from the conditions under which they are developed for. Therefore, crop water requirement, crop coefficient and irrigation scheduling are essential parameters for efficient irrigation water management, planning and precise water application.*



***Keywords**: reference evapotranspiration, crop evapotranspiration, crop coefficient, irrigation scheduling, non-weighing lysimeter*

# 1. NTRODUCTION

## 1.1 Background of the Study

Water is one of essential natural resource up on which all lives and socio-economic development of every country depends (Shenkut *et al*., 2013). Recently, due to the rapid growth of population throughout the globe, the pressure on different natural resources and existing environment is becoming a serious problem in many regions. From these natural resources, water is the most important element which faces huge pressure to provide most of essential services in order to live healthy life as well as providing critical desires for the rapidly raising population among others (Yihun, 2015).

Water resource is have being used in varies sectors such as agriculture, domestic use and industries. Due to its nature of non-uniformity in distribution, water usage competition between different sectors is arising from time to time both in quantity and quality (Tezera *et al*., 2019). Among this competitor agriculture is the one. As agriculture uses large portion of water resource for producing food in order to feed the growing population and maintain secured food system, the pressure caused by this sector on water resources is the most crucial area that need attention in addition to scientific studies (Beshir, 2017; Shenkut *et al*., 2013).

As Shenkut *et al*. ( 2013) pointed out, 60% annual precipitation which reaches to the earth's surface will be lost in the form of evapotranspiration(ET) from agricultural lands. Because agriculture uses high amount of water demand for food production and non-uniform distribution of water availability, providing sufficient amount of food with available rainfall became impossible. Also, agriculture was often hampered due to irregular, insufficient also uncertain rain occurrence. So, providing proper irrigation system becomes an option which can provide secured and uninterrupted agriculture.

Irrigation practice implies the application of water for the crop with different techniques when there is shortage of rainfall or no rainfall at all. The importance of irrigation practice is tremendous especially when it is applied with proper way of management. While comparing the productivity, irrigated land is much better than un-irrigated land as irrigation make it possible for multi-cropping season which can't achieved with agriculture that only depend on rainfall. The other importance of irrigation is that, it can enhance crop production on areas under different climate condition. Crop production under variable climate condition is becoming widely practicable after introducing modern irrigation practices. Areas such as arid and semi-arid were difficult to use them for crop production in previous time but provision of modern irrigation system solved the problem hence they are under agricultural practices.

According to Gebul, (2021) report, Ethiopian modern irrigation development started in 1950s at the time of imperial government. The government initiated irrigation projects in a collaboration with Dutch Company in order to produce fruit for export and gain foreign currency. Later, at the Derg regime, through long process all private irrigation schemes transferred to the government in order to build up sustainable food production to control the disaster caused by frequent drought throughout the country. Even though, modern irrigation development has a history of fifty years in Ethiopia, irrigated wheat production have been implemented in recent years.

Agriculture is the cornerstone of Ethiopian economy as it contributes 43% of GDT, 80% of human labor employment and 75% of export commodity values (Gebul, 2021; Mehari, 2019). Despite its importance, contribution and long history in Ethiopia, still the productivity of agriculture on nationwide level is very low. Studies that have been done on Ethiopian agricultural productivity indicated that, due the limitation of information on basically required data, enhancing the productivity couldn't be achieved for the last several decades (Fitsume *et al*., 2017). As a result, the country is losing billions of dollars every year on the importing agricultural products especially durum wheat (Tezera *et al*., 2019).

Wheat (*Triticum aestivum L*.) is one of the first domesticated food crop and has been the basic stable food of the major civilization in most part of the world (Curtis *et al*., 2002). It is the most important grain worldwide based on grain acreage and is ranked second when it comes to the total production volume and it is an essential source of calories in human diet. Hence the population number of different regions is showing rapid growth and wheat is source is one of the major crop in food chain system, the desire enhancing its productivity is becoming first priority of different organizations and agricultural firms.

In Ethiopian context, wheat (*Triticum aestivum L*.) is one of the major cereal food crops grown highly, which ranks the country in the second place from sub-Saharan African countries in terms of the total wheat area coverage and production. Among cereals, wheat is the fourth most important crop in area coverage following to Tef, maize and sorghum holding 13.25 % out of the total grain crops cultivation area in the country level (Tezera *et al.*, 2019). Also, world-grain.com reported that, wheat is the first ranked cereal production in Ethiopia with estimated production rate of 4.6 million tons in 2019/20. Other report from U.S department of agriculture said that the domestic demand of the nation couldn't be covered even though other reports mentioned that Ethiopia is one of in the top three wheat producer in Africa (world-grain.com). Hodson *et al.* (2020) also reported that though Ethiopia is the largest producer of wheat at the same time wheat importing by the government is taking billions of dollars every year just to fill the gap between the demand and supply. Therefore, in order to be self-sufficient in wheat supply, the government of Ethiopia has initiated new program related to expanding irrigated wheat production in different locations through enhancing of productivity of irrigation schemes and adding of varies inputs (Tezera *et al*., 2019).

Regardless of the initiated program of enhancing wheat production and productivity to achieve the goal set, still irrigation practices for this crop are traditional and the application of water isn't considering optimized usage procedure because the information on water requirement, crop coefficient and irrigation schedule of wheat is still limited and (Fitsume *et al*., 2017). Numerous studies indicated that, in the case of crop production, knowing the proper amount of crop water requirement during its growing season and crop coefficient for particular growth stage is important for planning of proper agricultural water management so that, there will be enhancement of water productivity and yield production as well as irrigation water usage efficiency (Piccinni *et al*., 2007; Pakparvar *et al*., 2014; Tezera *et al*., 2019; Yarami *et al*., 2011). Therefore, determination of the exact crop water requirement (ETc) and crop coefficient (kc) of wheat (*Triticum aestivum L*.) as well as irrigation scheduling will have a great importance to enhance irrigated wheat productivity and overall irrigation planning also management practices to save water.

For the determination of ETc, different kind of techniques and methods have been developed up to present date. The most reliable and old method is the use of lysimeter to measure water balance components and estimate crop evapotranspiration from the water balance equation. Lysimeter is one the technique that can be used to measure crop water requirement, reference evapotranspiration and crop coefficient. The system was developed before 300 years and is still providing the most accurate data in the measurement of crop water requirement and crop coefficient (Howell *et al*., 1991). Accuracy of the lysimeter result is directly proportional to the surface area and the data collected.

Scholars like Piccinni *et al*. (2007); Shenkut *et al.* (2013); Tezera *et al*. (2019); Yadeta *et al*. (2021); Yarami *et al.* (2011); and Yihun, (2015) used lysimeters (weighing/non-weighing) to determine water requirement and crop coefficient of different crops including Tef. Wheat, Sugarcane, and Sorghum in different locations of Ethiopia as well as the globe. In non-weighing or drainage lysimeter, the determination of crop water requirement is a residual of all measuring water balance components including water input (rainfall and irrigation), output (drainage and runoff), and change in soil water storage. But since the system is isolated and there is no outflow or inflow of runoff to the system, most of the time the runoff component will be ignored. Also the technique requires additional moisture monitoring device to measure the daily loss of water and change in soil moisture of the irrigated lysimeter and these device can be neutron probe, TDR and Diviner 2000, and gravimetric method or other available moisture sensors (Shenkut *et al*., 2013; Tezera *et al*., 2019). Therefore, as of scholars witnessed, using lysimeter for this particular project of determining crop water requirement and crop coefficient of wheat will provide relatively accurate data.

### 1.2 Statement of the problem

Agricultural water management is all about the effective and efficient use of available water resource where and when it is needed. To achieve this target, knowing the accurate amount of water needed by a specific crop is important. Hence, determination of crop water requirement and crop coefficient is the first step need to be done to prepare better agricultural water management strategies.

In Ethiopia, Crop water requirement of wheat have been studied by different scholars at different area but they are limited in number and are less available. As crop water requirement and crop coefficient are dependent on climate condition, soil type and crop variety the study should be done in diverse conditions to have more accurate data and information for further planning, designing and management purpose (Hordofa *et.al*., 2020). There a number of studies conducted to determine crop coefficient and crop water requirement across the world by different scholars and scientists. But, because of the variation in conditions those affect these two major input for irrigation management they can’t be applied in different location without critical considerations and validations. Also FAO provided information on these parameters after intensive studies throughout the globe, studies indicated that those recommended values are sometimes underestimated other times overestimated based on location difference. Fan *et al*. (2016), mentioned that, method which applied for the determination of these parameters will change the output of the study. Therefore, every research result need to validated and checked before using it at different location other than the area covered by the study.

Crop water requirement of wheat was studied by Tezera *et. al*. (2019) at Melkassa using lysimeter and by Fitsume *et al.* (2017) using CropWAT8.0. But as mentioned by different researchers the soil type variation and climate condition between Melkassa and Bishofitu will cause the variation of crop water requirement and crop coefficient as they have different climate and soil type. Even though, Fitsume *et al*. (2017) studied the wheat water requirement for Bishofitu area, they only focused FAO CropWAT8.0 model and literature values for crop coefficient in the determination of crop water requirement which makes it more of theoretical can't be applied without experimental justification as their recommendation also Kumar *et al*. (2012) suggestion.

Therefore, this study has filled these gaps by providing appropriate information with respect to experimentally determined crop water requirement, crop coefficient and irrigation scheduling for wheat crop.

### 1.3 Objective

The general objective of this study was to determine the crop water requirement, crop coefficient and develop equation to estimate crop coefficient for irrigation scheduling of wheat crop.

The specific objectives of the study were:

- to determine crop water requirement and crop coefficient of wheat crop,
- to develop equation to determine crop coefficient for different area, and
- to develop irrigation schedule for wheat crop under the conditions of the study area.

### 1.4 Significance of the study

Many studies have been done by different scholars and researches on the determination of crop water requirement for a variety of crops but wheat. Though it is true that wheat (*Triticum* *aestivum L*.) is the most important crop in Ethiopia, but there is limitation of information on water requirement and crop coefficient therefore, this study was required. The experiment determined required amount of water for wheat production and also developed crop coefficient so that it can be used in planning of irrigation management. The study result will help to enhance water productivity and yield optimization with appropriate application of limited water resource. It also will improve management practices in the study area as the area has high potential foe wheat production.

### 1.5 Scope of the Study

The study has focused on the determination of water requirement, crop coefficient for irrigation scheduling of wheat crop which is applicable without any calibration only at the study area. As the study was conducted only for one season because of the time limitation, it is better to repeat it for having reliable results and need to be validated before applying for further purpose. Also, parameter such as infiltration capacity of the soil should be studied in the future to make the information full and applicable for the planning and management purpose.

# 2. LITERATURE REVIEW

## 2.1 Wheat Production and Its Adaptations

Wheat is one of the first domesticated food crop and has been the basic stable food of the major civilization in most part of the world. It is successful at the area of latitude between $30^0$ and $60^0$ N and $27^0$ & $40^0$ S, of course it can be produced beyond this limit too. The optimal growth temperature is about $25^0$C which is between minimum and maximum temperature of $3^0$ & 4 $^0$C and $30^0$ & $32^0$C respectively (Curtis *et al*., 2002; and Bouras *et al*., 2019). Wheat is the most important grain worldwide based on grain acreage and is ranked second when it comes to the total production volume and it is an essential source of calories in human diet. The need for wheat worldwide is aggravating from time to time because of rapid population growth.

According to different scholar reports, wheat may show different responses for varies type of exposure. The exposure might be climate, water growing season and sometime it might be soil type where it will be cultivated. With reference to Alam and Hossain, (2014), the response of wheat for temperature rise will vary from variety to variety. They also reported that, wheat production under heat stress will fasten the growth season and might force it to complete the life cycle much faster than under normal condition. As a consequence, biomass production will be reduced.

Du *et al*. (2022) reported that, high temperature in wheat production especially at development and grain filling stage may reduce the final production. But as they investigated, the effect might be positive or negative based on growing season which is whether it is on spring or winter. Based on the finding out warmer climate will benefit winter wheat through shortening growth phase and providing sufficient amount of growth length in grain fill stage and ultimately the grain yield will be increased.

Another study conducted in Ethiopia, indicated the water stress in wheat production at different growth stage has different effect. According to the result, wheat shouldn't be stressed at development and mid stage in order to have optimum water use efficiency while avoiding significant loss of grain yield. Similar study was reported by Qadir *et al*. (1998) from Pakistan on assessing the effect of water stress on growth and yield performance of wheat with four different cultivars. The result indicated that the response of wheat to water stress varied among the varieties. But, in general, water stress during vegetation and reproductive stage can affect yield. Therefore, water stress should be avoided to have maximum biologically potential yield.

Regarding to water demand, as of any crop the water demand of wheat vary from season to season. When the growing season became long the total water demand will increased. This is true for wheat production in winter season. Due to low temperature in this particular season the growth stage required by the crop is long. Therefore, due to elongation of the season there is increment of water demand. As mention in the above paragraph, existence of high temperature will minimize the growth stage of crop but not always minimization of growth stage will decrease the water demand as there is high temperature, there will be high chance for more evaporation occurrence.

According to world-grain.com report, wheat is the first ranked cereal production in Ethiopia with estimated production rate of 4.6 million ton from the previous year (2018/19). As U.S department of agriculture report the domestic demand of the nation couldn't be covered even though other reports mentioned that Ethiopia is one of in the top three wheat producer in Africa (world-grain.com). As per Tezera *et al*. (2019) report, it is commonly grown crop in the highlands at altitudes ranging from 1500 to 3000masl. Major wheat production areas in the country are Arsi, Bale, Shewa, Ilubabor, Western Harerghe, Sidama, Tigray, Northern Gondar, and Gojam regions.

Hodson *et al.* (2020) reported that though Ethiopia is the largest producer of wheat at the same time wheat importing by the government is taking billions of dollars every year just to fill the gap between the demand and supply. Even if the reports indicated the need of wheat production increment in the future, the parameters which limit its productivity and production are not well studied and irrigation practices are still traditional (Fitsume *et al*., 2017). As reports indicated the need of wheat production increment in the future. Therefore, there are works on improving of durum wheat in yield production yield quality. Despite this, the parameters which limit its productivity and production of durum wheat are not well studied and irrigation practices are still traditional which is "apply water if there is water don't worry about the amount"(Fitsume *et al*., 2017).

## 2.2 Crop Water Requirement

Different scholars suggested different methodologies to determine crop water requirement and crop coefficient around the world. As a result, models, empirical formulas, structures and instruments have been developed for the last many decades and even some of them have history of centuries. Nouri *et al.* (2013) explained about weather-based methods, soil-moisture measurement, surface energy balance approach, and remote sensing method. Regarding to his finding, the remote sensing method is the best one as it can provide area based estimation of water requirement for multi-vegetation at once also can be updated frequently in easy way. Ewaid et al. (2019) also reported that remote sensing (RS) approach is currently more practical method to estimate water requirement while considering wide range of parameters which are very influential on the growth and development of any crop.

There are also models those can be used to determine crop water requirement and crop coefficient such as; CropWAT and AquaCrop. These models were developed by Food and Agricultural Organization of United Nation (FAO) to determine net as well as gross crop water requirement and they are still in use by numerous scholars and institutes for planning and management purpose.

Despite these findings, the method of lysimeter which is collaborated with water balance approach have been one of the best used by different scholars and organizations until now (Allen *et al*., 1998; Ewaid *et al*., 2019; Yadeta *et al*., 2021). Experimental studies done in different part of the world including Ethiopia, used lysimeter to estimate crop water requirement and crop coefficient as it can provide accurate result if it is handled and managed accordingly (Babaee *et al*., 2019; Dirirsa *et al*., 2017; Fitsume *et al*., 2017; Haile Tefera and Tamene Mitiku, 2021; Nouri *et al*., 2013; Onyancha *et al*., 2017; Surendran *et al*., 2019).

Different types of crops have different amount of water requirement to maintain optimal yield. Their water requirement vary from location to location. Even if the crop is similar, there will be variation in water depth requirement due to difference in climate and soil type.

### 2.2.1 Previous studies on crop water requirement:-

Yadeta *et al.* (2021) determined the water requirement and crop coefficient of sugarcane using non-weighing lysimeter at Melkassa agricultural research center and the result of daily crop water requirement found to be 3.1-6.7 mm/day , 2.8-5.2 mm/day, 4.0-6.3 mm/day and 4.5-7.5

mm/day for emergency, tillering, grand formation and ripening stages respectively. This indicates that, the climate condition during ripening stage was hot or drier comparing to development stage hence the soil characteristics throughout the growing season remain the same.

Determination of crop water requirement and crop coefficient of Tef for wet season was conducted by Hordofa *et a*l. (2020). The experiment took place for three years (2015-2018) on non-weighing lysimeter, and the result shown variation in value in those three different years. The crop water requirement was found to be ranging between 346 mm and 378.4 mm for those three experimental years and the average value was determined to be 363.68±13.36 mm.

Similarly, Yihun, (2015) conducted experiment on the same field (Melkassa) for the same crop between 2010-2012 on a dry season. The result of ETc was varied between 299 and 342 mm with the average value of 319 mm. Ewaid *et al*. (2019) studied the water requirement of wheat in Iraq using CropWAT8.0 version with climate data from CLIMWAT which incorporated with CropWAT model to provide meteorological data for specific station. They used the crop parameters needed by the model from FAO-56 manual then the planting and harvesting date information from the Iraq agricultural operation guideline. The result pointed out, the seasonal crop water requirement (ETc) was 1239.1 mm per season and the irrigation water requirement was 1142 mm per season.

Other study done by Bouras *et al*. (2019) in Morocco using FAO AquaCrop model indicated that the seasonal water requirement of wheat in Mediterranean region is 323 mm, 382 mm and 404 mm for early, intermediate and late sowing date which is quite small comparing to Ewaid *et al*. (2019). And the difference between those two results indicate that the variation of place and climate condition highly affects ETc.

Study carried out by Irmak *et al*. (2015) for two wheat growing season reported that, at the early stage of winter wheat ETc was low due to low temperature and the value was varied from 0 mm/day to 9.5 mm/day which was recorded on summer time and the averaged value for ETc was 2.1 mm/day . They also reported that the seasonal crop evapotranspiration was determined to be 600 mm and 490 mm for two consecutive study years. As their report, ETc was increased to the maximum at full crop development and reproduction stage and, declined towards the end of the growing season (harvesting date). In their repot they also mentioned that, the temperature in the crop growing season has high dominancy in determining the daily and stage based crop evapotranspiration. The same study from Ethiopia conducted by Tezera *et al*. (2019) at Melkassa using lysimeter to determine crop water requirement and crop coefficient of wheat. The result pointed out that, the growth stage water requirement of wheat was 52.2 mm, 97.1 mm, 191.5 mm and 73.2 mm for initial, development, mid and late stage respectively. Other study conducted in Uzbekistan by Kenjabaev *et al*., (2014) reported the seasonal water requirement of wheat to be 509±27 mm. Laaboudi A, and Mouhouche B, (2012) conducted an experiment between 2004/2005-2006/2007 under arid climate condition using lysimeter and found, the seasonal ETc of 592 mm, 615 mm and 604 mm for the first, second and the third season respectively. water requirement of wheat in the study area was reported by Fitsume *et al*., (2017). The study was based on the CropWAT model and the result presented that total water requirement of wheat for the current study area is 489.9 mm/season for planting date of January 15.

### 2.3 Estimation of Reference Evapotranspiration (ETo)

Crop evapotranspiration refers as the loss of water from cropped area in the form of evaporation and transpiration (Allen *et al*., 1998). This parameter can be affected by; climate, crop characteristics, management practices and environmental aspects (Savva & Frenken, 2002). Among these aspects, climate condition has major effect on the determination of crop water requirement. Therefore, parameter was developed to determine the effect of climate on crop water requirement with the help of reference crop and the parameter known as reference evapotranspiration (ETo). However they are different models and equations those have been developed to determine ETo, the well-known also relatively accurate equation which integrated with different models is FAO Penman-Monteith equation. FAO Penman-Monteith equation approach known for its accuracy and acceptance among different scholars. It is an integrated method with multiple models in order to determine crop water requirement and irrigation scheduling through estimation of reference evapotranspiration and area calibrated or FAO recommended crop coefficient for almost all type of crops (Allen *et al*., 1998.; Dingre & Gorantiwar, 2020).

## 2.4 Estimation of Crop Coefficient (Kc)

Crop coefficient is the coefficient which express the characteristics of the crop. They are many factors need to be considered which is including; crop type, changing crop characteristics over the growing season (stages of growth) and, to a limited extent, the prevailing weather conditions during estimation. As evaporation is part of crop evapotranspiration, conditions affecting soil evaporation will also affect kc. The value of crop coefficient highly depend on the growth stages. The Kc during this initial stage ($kc_{in}$) is large when the soil is wet from irrigation and rainfall and is low when the soil surface is dry. It reaches to the maximum at mid stage and starts to fall up to harvesting date (Allen *et al*., 1998.; Dingre & Gorantiwar, 2020).

After determination each stage kc value, kc curve will be developed for further usage of ETc estimation and irrigation scheduling. From the crop coefficient curve, the kc value for any period during the growing period can be determined also. Once the kc values have been derived, the crop evapotranspiration (ETc) can be calculated by multiplying the kc values with corresponding ETo values. This parameter can be determined using the same methods as crop evapotranspiration using empirical formula. Different researchers worked on the estimation of crop coefficient for varies crops among them some of them have been summarized as the following.

### 2.4.1 Findings of crop coefficient from previous studies for different crops:-

The crop coefficient of sugarcane was studied and was reported to be 0.42, 0.93, 1.26 and 1.05 for emergency, tillering, grand formation and ripening stage respectively by Yadeta *et al.* (2021). As Hordofa *et a*l. (2020) report the crop coefficient (kc) was estimated as 0.46, 0.88, 1.03 and 0.57 for initial, development, mid and late stage. The author also found fifth-order polynomial function so that the result can be used on areas with similar agro-climate condition as Melkassa for irrigation scheme design and water management practices. Other study by Yihun, (2015) reported that, the kc of Tef was found for initial, development, mid-season and late season was 0.6, 0.8, 1.2 and 0.8 respectively. The same as Hordofa *et al*. (2020), found fifth-order polynomial function relationship between Kc and day after sowing (DAS) was developed. The difference in results found by these two researcher, may have been caused by the seasonal variation of the experiment activity or the variety of the Tef they have been used for their experiment. Furthermore, the time gap between these studies can be the cause for differences between in results. According to Irmak et al., (2015) from USA, the crop coefficient of wheat for early, mid, and late season crop growing stage was estimated to be 0.6, 1.3 and 0.3 respectively. As stated by Tezera *et al*. (2019), the crop coefficient of wheat estimated to be 0.54, 1.15 and 0.67 for initial, mid and late stage of wheat growth period respectively. In accordance with their result, there is value variation between FAO recommendation and the estimated one at Melkassa for initial and late stage which justifies that determination of crop coefficient for specific location is compulsory in order to have better management practice. Kenjabaev *et al*., (2014) from Uzbekistan conducted an experiment by integrating soil water balance budget and FAO-56 manual to determine ETc and Kc of wheat and pointed out that the crop coefficient of wheat to be 0.27, 1.03 and 0.89 for initial, mid and late stage respectively.

Laaboudi A, and Mouhouche B, (2012) conducted an experiment for the aim of determining ETc and kc. Their finding reported that, kc of wheat for the growing season which carried out between 2004/2005-2006/2007 under arid climate condition, kc was determined for each critical stage of wheat growing period. The result was ranged from 0.48 to 1.44. Based on their finding, 0.61 was recorded during initial stage which was referred up to three leaves development (initial stage), 1.07 for stage of tiller formation (development stage), 1.35 from stem elongation up to milk-soft dough formation (mid-stage), and lastly, 0.88 for hard dough or known as late stage.

All the above reviews indicated that, ETc and kc are highly dependent on location, soil type, crop type and variety and finally on climate condition of the area. Which explains that using the result that have been experimented on some area shouldn’t be used for other area without calibration or justification using experiment.

Therefore, doing this experiment was an important task for future planning of irrigation development in the area and can be used to enhance irrigation effectiveness and efficiency as experimental study will provide area specified crop water requirement (ETc) as well as crop coefficient (kc) of wheat.

### 2.5 Irrigation Scheduling

Scheduling irrigation is a major activity in irrigated agriculture and it provides information on how to irrigate, how much to irrigate and when to irrigate to achieve best yield and water productivity. It is one of the factor that influence the agronomy and economic viability of small farms and also its importance is high in water saving and improving crop yield. Proper scheduling of irrigation uses for enhancement of efficiency in water use as well as optimization of yield productivity. Different scholars and research findings suggest various type of irrigation scheduling techniques. But every techniques developed up to present day requires continuous monitoring of the crop and climate condition also condition of the soil (Harisson, 2012). He mentioned that, water balance method is currently under usage for irrigation scheduling as it provide information between input and output of water balance in the plant root zone.

A varies techniques and tools have been developed in concern of supplying water in more accurate way. Ali and Talukder (2001) reported that in order to provide appropriate scheduling, conditions such as; level of technology of the farm, condition of water availability and water supply, financial capability of the farmer, and value of the product on market should be considered. He also mentioned that, irrigation scheduling should aim minimizing wasteful loss of water and optimization of yield.

Food and Agricultural Organization of United Nation, FAO also provided different methods to determine irrigation scheduling within drainage and irrigation technical papers (FAO- irrigation and drainage paper-33 and 56; FAO training manual: irrigation scheduling, 1998). Namely;

(i) Plant observation method: - this method is applicable when the farmer or irrigator has adequate knowledge about the circumstance of the location and also the characteristics of the soil texture. The method used to determine when the plant need to be irrigated and it works solely based on observing of changes in plant leaves. The change may include changing color and curling of leaves and ultimately plant welting may appear. To use this method as irrigation scheduling method in a successful way it need to be applied with best experience.

(ii) Estimation method: - FAO provides this method with developed tables' consideration of soil type and climate of the area. It estimates irrigation scheduling based on the peak water demand. In this method, after scheduling estimation there must be adjustment for non-peak demand as the first one is based on peak demand. The adjustment also required based on growth stage, climate condition and lastly soil condition.

(iii) Simple calculation methods: - simple calculation method follows step wise procedure to determine irrigation scheduling and it requires data like; soil type, root depth, application efficiency of the system with respect to irrigation methods to be applied. As similar to estimation method, simple calculation method also requires adjustment. But here the adjustment is for peak demand rather than non-peak demand as estimation method.

Kerry Harisson, (2012) mentioned that water balance method for irrigation scheduling is the most acceptable and currently applied principle. As the major principle of water balance is obtaining the balance between the ingoing and outgoing soil water it can help to know how much water is lost and how much need to be supplied and when to be supplied the correct amount of water in order to maintain balanced water content in the soil where crop grown. FAO-irrigation and drainage paper -33 also provides simple calculation procedure to calculate irrigation scheduling which focuses in determination of net depth of irrigation and interval of irrigation in days.

Because of variation in soil characteristics and climate condition, irrigation scheduling that have been designed in one location can't be applied on other location. Also irrigation scheduling may vary from season to season and from one month to another month. Therefore, it requires to be adjusted with the location, water availability, man power, season and demand of irrigation water need with respect to crop type and variety.

Determination of irrigation scheduling for wheat in Ethiopian condition was conducted by Fitsume *et al*. (2017) using CropWAT model for Bishofitu. But, hence the scheduling was done with historical data applying it for real time scheduling may cause disadvantage for gaining optimum yield and water productivity. Hossain *et al*. (2015) suggested that irrigating wheat 17-20 days after sowing (DAS) at initial stage and (45-50 DAS) at booting stage can increase the yield performance of wheat yield. But this may not work in other location as it is area specified. There is no any experimentally developed irrigation scheduling at the study area up to date therefore, this research result will give a hint about the importance of irrigation scheduling on water productivity and yield optimization.

### 2.6 Lysimeter

Lysimeter is a device which used to measure crop evapotranspiration through providing mechanism to measure the soil moisture in the root zone and deeply percolated water beyond the effective root zone. It can be weighing or non-weighing type (Piccinni *et a*l., 2007). Both have the same function with different techniques and methodologies to apply in measuring the crop evapotranspiration and they are field level measuring devices. The non-weighing one is constructed directly on the ground. Whereas, the weighing one is constructed on the tanker which is installed directly on the subsurface within standardized depth and used as an outer tanker in order to isolate the instrument from the natural environment and avoid any lateral moisture movement and it serves as a structure which carry the weighing lysimeter also contains load cells for weighing purpose (Fisher, 2014).

In non-weighing or drainage lysimeter, the determination of crop water requirement is a residual of all measuring water balance components including water input (rainfall and Irrigation), output (drainage and runoff), and change in soil water storage. But since the system is isolated and there is no outflow or inflow to the system the runoff component will be ignored. Also the technique requires additional moisture monitoring device to measure the daily loss of water and change in soil moisture of the irrigated lysimeter and these device can be neutron probe, TDR and Diviner 2000 or other available moisture sensors (Shenkut *et al*., 2013; Tezera *et al*., 2019).

Lysimeter is one of the best method or system that can be used to measure crop water requirement and crop coefficient. The system was developed before 300 years and is still providing the most accurate data in the measurement of crop water requirement and crop coefficient (Howell *et al.,* 1991). The accuracy of the result found from lysimeter is directly proportional to the surface area and the data to be collected.

Scholars like Piccinni *et al*., ( 2007); Shenkut *et al.*, (2013); Tezera *et al*., (2019); Yadeta *et al*., (2021); Yarami *et al.*, (2011); and Yihun, (2015) used lysimeter to determine water requirement and crop coefficient of different crops including Tef, Wheat, Sugarcane, and Sorghum in different locations of Ethiopia as well as the globe. Their result indicated that the technique can provide accurate and acceptable result when it is managed with care and skill.

# 3. MATERIALS AND METHODS

## 3.1 Description of the study area

The experiment was conducted at Debre Zeit Agricultural Research Center (DZARC). It is located in East-Shewa of Ethiopia with latitude of 8.73$^0$ N and longitude 39.03$^0$ E at altitude varying between 1810 and 1908 amsl at 46 km distance to the southeastern of Addis Ababa (Figure 3:1). Mean annual rainfall is 801.3 mm and have one-season rainfall pattern with extended rainy season from March to October. The rainfall distribution has its peak in July. The mean annual maximum temperature is 25.5 $^0$C with monthly value range between 23.7 $^0$C and 27.7 $^0$C in July and May respectively. The mean annual minimum temperature is 10.5 $^0$C with monthly value range of 7.4 $^0$C and 12.1 $^0$C for July and August respectively. The study area has the dominant slop varies between 0 % and 2 % and clay soil type which dominate the area up to depth of 150 cm.

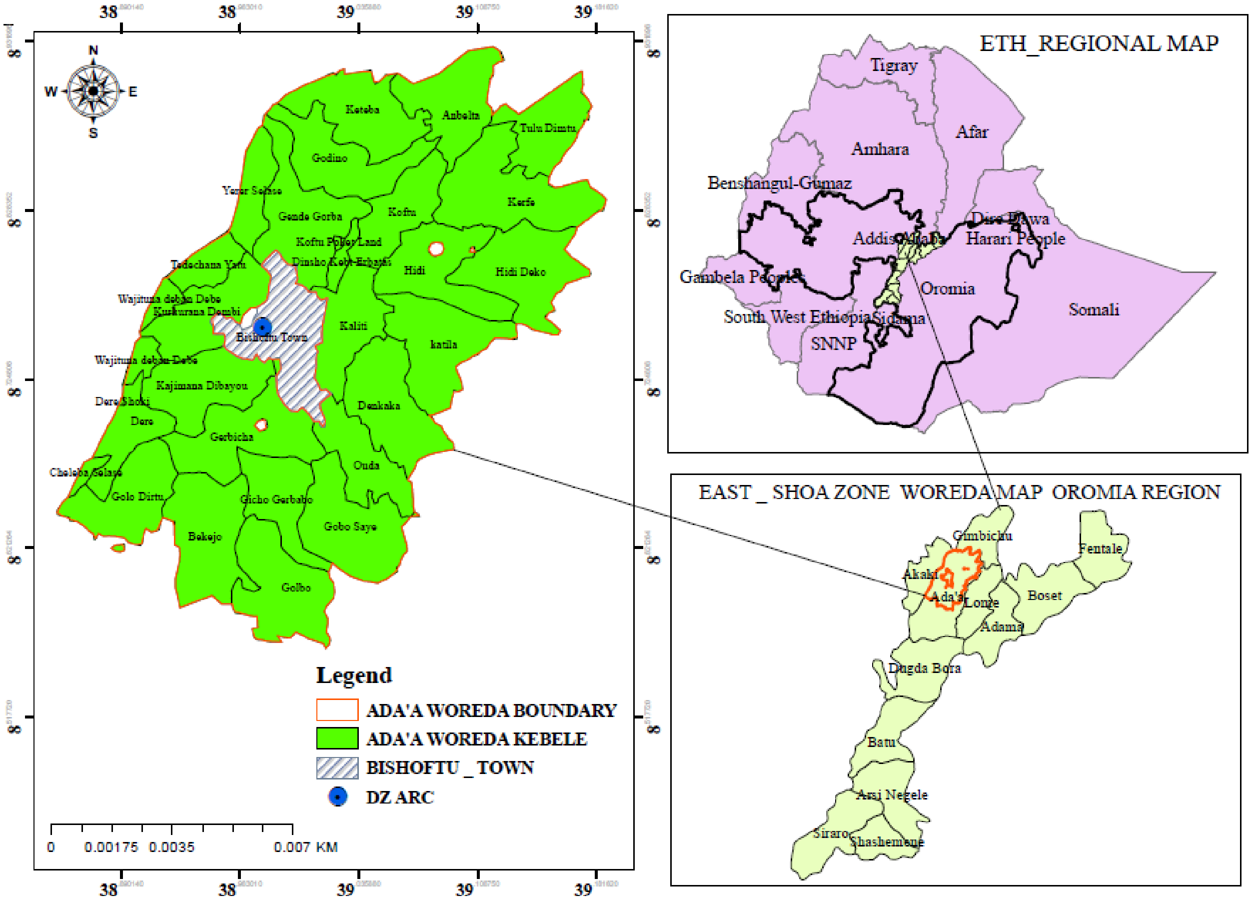


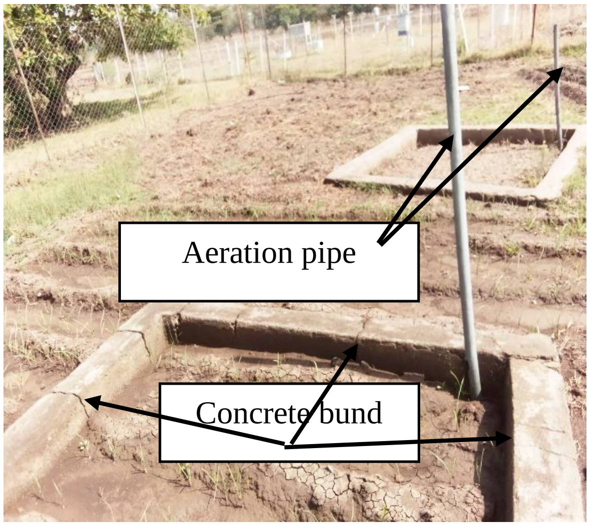

Figure 3:1: Location of the study area

### 3.2 Experimental Setup

The experiment was conducted on two non-weighing lysimeter. The lysimeter was constructed near to the observational meteorological station within a distance of 20 m. It was constructed with air tube used as aeration pipe to facilitate air movement at the root zone and there was concrete bund of 10 cm above the ground surface to avoid inflow and outflow of water in the system. The net area of a single lysimeter was 2 m by 2 m (4 $m^2$) and 1 m of depth to allow unrestricted root growth.

Sowing of the crop was in double row with row spacing of 20 cm and furrow width of 40 cm for proper irrigation water application. Furrow was constructed with 2 m length inside the lysimeter and 6 m outside of the lysimetere structure (buffer zone) then 1.8 m of it was covered with the crop and the remaining kept as open area 10 cm for both side. Sowing took place from Northern to southern direction. The buffer was provided to maintain the natural environment consistent, the same crop have been planted around the lysimeters on 6 m by 6 m (32 $m^2$ excluding the lysimeter area) to serve as a buffer zone (Figure 3:2). The buffer zone helped to observe the difference between the crop growth that was planted on the naturally undisturbed soil and disturbed soil of the lysimeter and the same treatment was applied as the lysimeter with respect to irrigation and fertilizer application as well as pest and weed management.

Figure 3:2: Experimental layout and crop growth



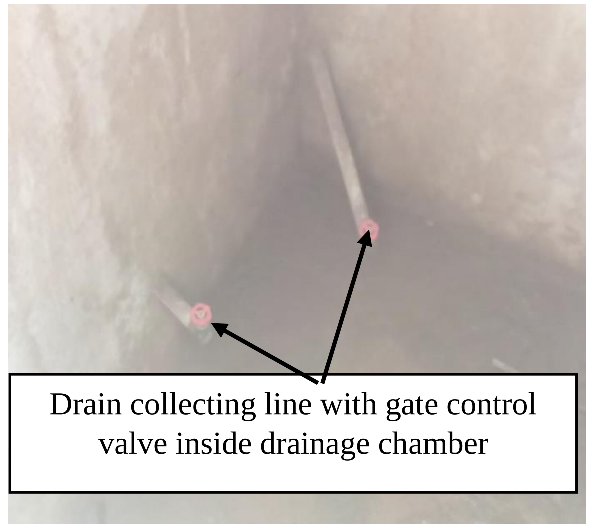



Figure 3:3: Components of non-weighing lysismeter

**3.3 Crop Experimental Design**

Utuba is one of the durum wheat variety produced at Debre-Zeit Agricultural Research Center. Utuba (IDON-MD-2009_off/53/2009) was released by Debre-Zeit Agricultural Research Center durum wheat breeding department in 2015. It takes approximately about 108 days up to maturity stage and it has high protein content and high yield potential relative to early released varieties (Temtme *et al*., 2018). The growing duration can be longer or shorter based on the weather condition of growing area. For this experimental study it has taken one hundred sixteen days up to harvesting date (116). The period that have been taken by the crop to initial stage which is from sowing up to 10% of ground coverage up to developing two leaves was 20 days. The next development was designed to be 30 days based on FAO- irrigation and drainage paper 56 and 33 with recommendation of taking as development stage when the ground cover reaches to 60 up to 80%, maturity, and late stage took, 42, and 23 respectively (Allen *et al.*, 1998). The agronomic data that have been collected at the starting of maturity stage shows that the average height of the crop was 57 cm while the height for this particular variety given to be 82 cm at the end of maturity stage.

The fertilizer application took place on sowing date. The rate for DAP was 120 kg/ha and Urea, 250 kg/ha was applied. The urea application, one third of the rate was applied during sowing and the remaining third fourth was applied on thirty days after sowing. The seed rate was based on the recommendation for the study area and 150 kg/ha was used.

### 3.4 Soil Sampling and Analysis

3.4.1 Soil sampling:-

Soil samples were collected from the lysimeter unit and the buffer zone with similar procedures. The samples were taken up to the depth of 60 cm with interval of 0-15 cm, 15-30 cm, 30-60 cm with Auguring procedure have been followed to collect the soil sample for every mentioned depth. A single auger and sample collecting bags have been used. The collected sample were used to analyze the physical parameters of the soil. These includes; field capacity, permanent welting point, soil texture, electric conductivity and pH value. For the case of bulk density analysis, the sample was collected with core sampler of known dimension up to the depth of 60 cm with the interval of 0-15, 15-30, 30-60 cm.

Figure 3:4: Soil sampling

3.4.2 Soil sample analysis:-

The soil analysis was done for both the lysimeters and the buffer zone to make sure they exhibited similar hydraulic characteristics and property.

A. Water holding capacity

The collected samples were dried with natural condition in soil sample drying store and was grinded manually. The grinded sample was weighted and soaked in water up to saturation point and kept for 24 hours then excess water have been removed with the help of syringe. After that, it was placed into pressure plate for 24 hours in order to remove over saturated water to maintain to the point of field capacity and permanent welting point with applying pressure rather than gravitational force. For the field capacity (FC) the pressure plate set to 3 bar and 15 bar for the permanent welting point (PWP). Then the sample was removed from the pressure plate and immediately weighted the wet soil and put it in drying oven at 105 $^{0}$C for another 24 hours. After removing from the drying oven and waited till it becomes cool and weighted again to find the dry weight of the sample. The final procedure was calculating the FC and PWP in percentage with the following formula NRCS (1996). Also soil water characteristics software was used to check the viability of the result used analyzed soil texture.

$$\mathrm{FC\%} = \frac{\text{Wet soil (gm)} - \text{Dry soil (gm)}}{\text{Dry soil (gm)}} * 100 \tag{3.1}$$

$$P\mathrm{WP}\ \% = \frac{\text{Wet soil (gm)} - \text{Dry soil (gm)}}{\text{Dry soil (gm)}} * 100 \tag{3.2}$$

Where,

FC is field capacity of the soil

PWP is permanent welting point of the soil

Wet soil is at FC (gm), and

Wet soil is at PWP (gm)

B. Bulk density analysis

The collected soil sample with core sampler was measured in the soil laboratory including the core sampler. After weighting it have been kept in oven dry for 24 hours at 105$^{0}$C. The next step was measuring the dry weight of the sample soil to determine the bulk density and the following formula have been used to determine bulk density,

$$\rho\mathrm{b} = \frac{\mathrm{Ms}}{\mathrm{Vt}} \tag{3.3}$$

Where,

$\rho_b$ is dry bulk density (gm/cm$^3$),

Ms is mass of the dry soil (gm), and

Vt is total sample volume (cm$^3$)

C. Soil texture analysis

Particle size distribution was recorded as a percentage of total sample mass for sand, silt, and clay. The procedures followed for determining particle size distribution were adopted from Kilmer and Alexander (1949). Different time length has been sat to identify the particle size of the soil in order to classify the soil texture category of the study area. Throughout the whole analysis of soil texture appropriate procedure of soil texture analysis have been followed.

### 3.5 Soil Moisture Monitoring and Irrigation Water Application

3.5.1 Soil Moisture Monitoring:-

The soil moisture monitoring process was carried out before and after every irrigation application up to different depth based on the crop growth stage. According to result reports by Fan *et al*. (2016), 61-68% of effective root distribution of wheat exist at upper soil profile which is 30 cm. Therefore, the total effective root zone up to harvesting date was considered to be 60 cm and soil moisture was monitored up to this depth. Because of its accuracy and accessibility, gravimetrical method have been used to assess the daily moisture content of the soil in the lysimeter. The monitoring depth interval set to be 0-15, 15-30, and 30-60 cm. the total moisture content was calculated based on provided equation (3.4).

3.5.2 Irrigation water application:-

Because there was no well-studied and well-developed irrigation scheduling or optimum depletion level information for wheat at the study area, the irrigation water was applied based on soil moisture monitoring at the root zone while considering keeping the soil moisture level near to the field capacity throughout the crop growing season. Water Cane with known volume was used to Irrigate and the calculated volume of water applied in the form furrow irrigation method and directly applied inside the furrow. The interval of the irrigation application was monitored by soil moisture depletion. The depleted amount of water from the field capacity level was calculated and was changed in to volumetric unit as indicated in (Equation 3.8). Irrigation was terminated after starting of late stage which was in the first decade of April.

The soil moisture was estimated as below;

$$\mathrm{MC}\ (\%) = \frac{\mathrm{Wwet} - \mathrm{wdry}}{\mathrm{wdry}} \tag{3.4}$$

$$\mathrm{VMC}\ (\%) = \mathrm{MC}\% * \rho_b \tag{3.5}$$

$$\theta\mathrm{i} = \text{ Volumetric MC} * \mathrm{D} \tag{3.6}$$

$$\Delta\theta = \mathrm{SMC} = \theta 1 - \theta 2 \tag{3.7}$$

Where,

Wwet is weight of wet soil (w/w),

Wdry is weight of dry soil (w/w),

VMC is volumetric soil moisture content (%),

D is Soil depth (mm),

MC is soil moisture content,

$\Delta\theta$ is change in soil moisture in mm

$\theta 1$ and $\theta 2$ are soil moisture content between consecutive days (mm)

Then, the depth of the water loss was changed in to volume in order to apply the irrigation water using water cane with known volume.

$$V = \Delta\theta * A \tag{3.8}$$

Where,

V is the volume of the water (Liter), and

A is area of the lysimeter ($m^2$).

### 3.6 Data Collection

The lysimeter uses water balance equation method in order to determine water requirement and crop coefficient of specified crop type all required parameters should be collected accordingly. Hence, parameters of irrigated water depth, effective rainfall, drainage water from lysimeter, and soil moisture change per unit time were collected. The procedures are outlined in the following sections.

3.6.1. Irrigation water depth (I):-

The irrigation amount from every application day was recorded on the data recording sheet as well as on Microsoft excel sheet in terms of mm in depth. Depth of irrigation was estimated based on the equation provided in (Equation 3.7).

3.6.2 Effective Rainfall (Pe):-

Though, it is true that the season for the experiment was off-season, but, small amount of rainfall appeared during growth period and recorded data was collected from the weather station which found by near to the experimental area and effective rainfall was calculated using FAO CropWAT8.0 version model (FAO, 1992).

$$Pe = 0.6*P - 10 \qquad \text{if } Pe \text{ is} \leq 70 \tag{3.9}$$

$$Pe = 0.8*P - 24 \qquad \text{if } P \text{ is} > 70 \tag{3.10}$$

Where,

P is rainfall and Pe is effective rainfall in mm

3.6.3 Drained Water (Dp):-

As the effective root zone consideration was up to 60 cm (Fan *et al.*, 2016) and the activity took place in dry season (no rainfall) also the irrigation water depth was applied considering only up to this depth drainage was neglected at this effective root zone.

3.6.4 Change in Soil Moisture (Δθ):-

Daily soil moisture change data have been collected and recorded from the soil moisture recording data sheet. The soil moisture was monitored with gravimetrical method with varies time interval. The procedure followed to determine soil moisture change have been explained in section 3.5.2.

3.6.5 Climate and agronomic data collection:-

3.6.5.1 Climate data:-

The daily climate maximum and minimum temperature and rainfall data were collected from DZARC meteorological station which is installed about 20m distance from the experimental lysimeter unit. The data was used to determine the reference evapotranspiration (ETo) with FAO Penman-monteith equation with application of CropWAT8.0 model. Because the climate data wasn't complete, the analysis option in the software was assigned to estimate the remaining climate data from temperature data.

3.6.5.2 Agronomic data:-

Major agronomic data those were important and major parameters in stage wised estimation of crop coefficient and crop water requirement were collected. Sowing took place on December 23, 2021 and harvested on April 18, 2022. The sowing rate for wheat was 150 kg/ha and fertilizer rate was for Urea 250 kg/ha and DAP 120kg/ha. These rates are as per the recommendation provided for the specified crop variety (Temtme *et al.,* 2018). Major agronomical data such as; sowing date, date for emergence, development, maturity, and late season, every irrigation application rate and date, growth stage length, and finally harvesting date were collected.

## 3.7 Data Analysis

All the data analysis processes were carried out with Microsoft excel.

3.7.1 Estimation of Crop evapotranspiration (ETc):-

The crop water requirement/ crop evapotranspiration was determined from water-balance /water-budget equation as indicated and recommended by (Hordofa *et al*., 2020; Shenkut *et al*., 2013; Tezera *et al*., 2019; Yadeta *et al*., 2021)

$$(I + Pe) = -ETc \pm \Delta S - Dp - \Delta R \qquad (3.11)$$

Where,

ETc is the crop evapotranspiration (mm/day)

I is irrigation (mm),

Pe is rainfall (mm),

$\Delta S$ is change in soil moisture for equation (3.7),

Dp is dranage water depth in mm, and

$\Delta R$ is change in runoff in mm.

Because, the analysis was restricted at soil layer up to 60 cm and irrigation water depth was restricted to the effective root zone, the value of Dp was neglected also $\Delta R$ was neglected as there is bund which control any runoff from or to the system. The equation that have been adopted for this particular study was;

$$ETc = (I + Pe) \pm \Delta S \tag{3.12}$$

3.7.2 Estimation of Reference Evapotranspiration (ETo):-

For the purpose of estimating reference evapotranspiration, FAO already mentioned software used. As the meteorological station found at Debre-Zeit Research Center has a problem with sunshine hour data recording, only maximum and minimum temperature was collected and the remaining climate data have been estimated by the model after setting in the model option into using only maximum and minimum temperature and estimate the remaining parameters and FAO Penman-monteith method have been applied to estimate ETo as it can provide reliable result (Allen *et al.*, 1998). The equation for FAO Penman-monteith have been indicated in equation (3.13).

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{Rn}-\mathrm{G})+\gamma\left(\frac{900}{\mathrm{T}+273}\right)\mathrm{U2}(\mathrm{es}-\mathrm{ea})}{\Delta+\gamma(1+0.34\mathrm{u2})} \tag{3.13}$$

Where,

ETo is reference evapotranspiration (mm/day),

Rn is net radiation at the crop surface (MJ $m^{-2}$)

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

T is Mean daily air temperature at 2 meter height ($^{0}$C),

$U_2$ is wind speed at 2 meter height ($ms^{-1}$),

$e_s$ is Saturation vapor pressure (KPa),

$e_a$ is actual vapor pressure (KPa),

$e_s$ - $e_a$ is saturation vapor pressure deficit (KPa),

Δ is Slop vapor pressure curve (KPa), and

γ is Psychometric constant (KPa $^0C^{-1}$).

3.7.3 Estimation of Crop Coefficient (Kc):-

The time series crop coefficient was determined using the formula provided in equation (2.2) as recommended by (Allen *et al*., 1998; Hordofa *et al.*, 2020; Shenkut *et al.*, 2013; Tezera *et al.*, 2019; and Yadeta *et al*., 2021).

$$\mathrm{kc} = \frac{\mathrm{ETc}}{\mathrm{ET0}} \tag{3.14}$$

3.7.4 Development of Crop Coefficient (kc) equation:-

For the development of kc equation, first, double regression analysis with Microsoft excel was carried out between kc and days of growth stage (DGS) as well as days after sowing (DAS). Then coefficient of determination was analyzed with the same material. Finally, the equation was validated to see its performance further analysis was conducted to see the variation between the real result and result from developed equation.

3.7.5 Determination of irrigation scheduling:-

For the determination of irrigation scheduling, step-wise procedure was applied and the scheduling was based on the peak demand on the cropping season. Equation (3.14) was applied to determine the irrigation interval and equation (3.14) to determine net and gross irrigation depth with consideration of application efficiency 100% because the irrigation application was with hand and there was no any loss of water due to application process. Additionally, irrigation interval (Ii) need to be integer number therefore, the final value have been decided to be the lower integer number of calculated value (i.e. if the calculation result is 10.4 then it will be 10 days interval).

$$\mathrm{Ii\ (daya)} = \frac{\mathrm{dnet}}{\mathrm{ETcj}} \tag{3.14}$$

$$dnet, adj = i * ETcj \tag{3.16}$$

Where, Ii is irrigation interval in days, ETcj is peak demand of the season in mm/day, dnet stands for net irrigation need in mm, and dnet,adj is adjusted net irrigation depth based on irrigation interval in mm.

The whole activity which have been covered with this particular study have been summarized in the following flow chart. Each activity was interrelated to each other and the input of one activity was the output of other activity.

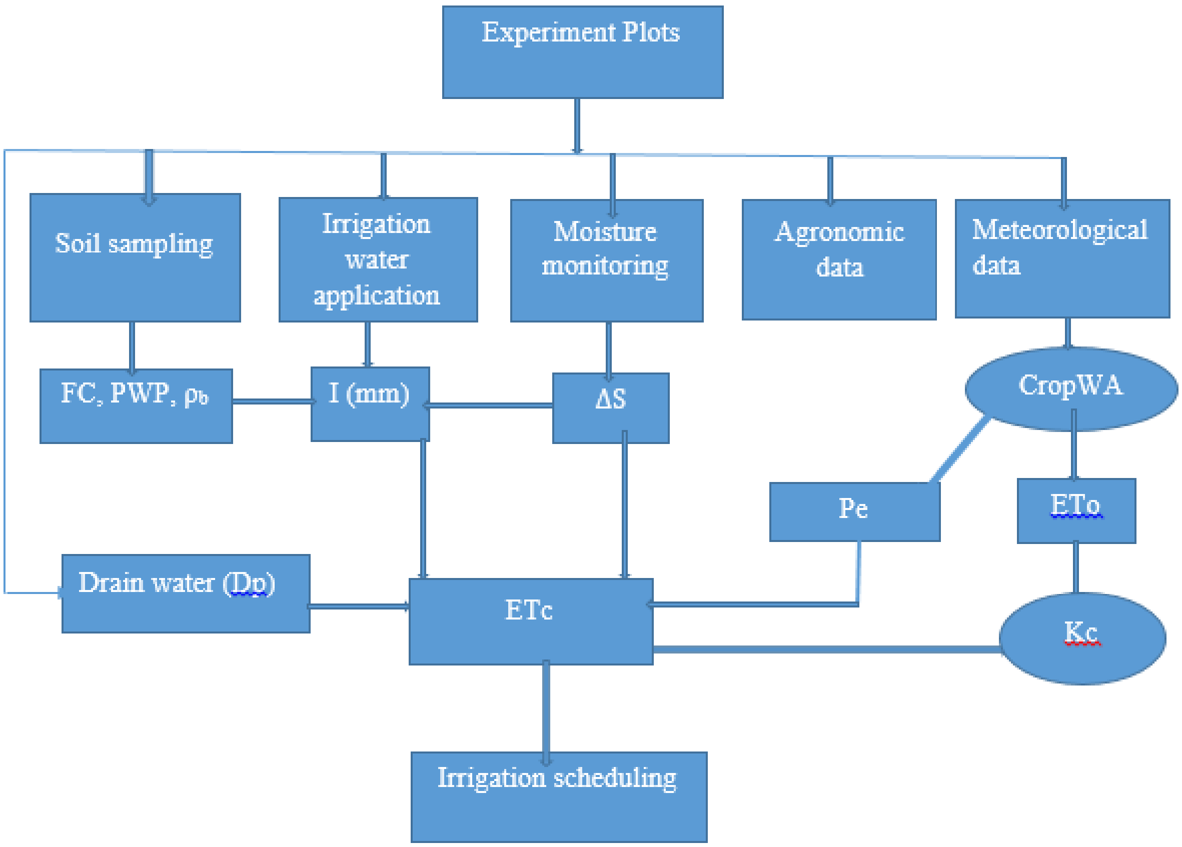



Figure 3:5: Flow chart of the total experimental activities

# 4. RESULTS AND DISCUSSIONS

## 4.1 Soil Analysis

The result of the soil analysis showed that the soil texture of the experimental site is clay and there was no salinity behavior as the salinity analysis result indicated the salinity content of 0.105 ds/m on both lysimeter and buffer zone. The averaged bulk density of the soil determined to be 1.15 gm/cm$^3$ up to 1.2 m and 1.1 for 60 cm depth and the field capacity of the lysimeter ranged from 50.0 % to 51.8 % on different soil depth. Averaged total available water (TAW) was estimated to be 113.4 mm/60 cm. the result of soil laboratory analysis was presented in Table (4:1) shows. As the result indicated the soil found on the experimental lysimeter has good capacity to hold moisture for long time comparing to other soil types. As a consequence, the irrigation interval can be reasonably long of course with consideration of crop growth stage.

Table 4:1 Soil analysis result of the Lysimeter

| S.No. | Depth (cm) | FC (%) | PWP (%) | $\rho_b$ (gm/cm$^3$) | TAW (mm) | Soil texture | Particle proportion (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Clay | Silt | Sand |
| 1 | 0-15 | 51.80 | 35.80 | 1.09 | 26.16 | Clay | 54.4 | 24 | 21.6 |
| 2 | 15-30 | 51.57 | 34.10 | 1.09 | 28.56 | Clay | 50.4 | 34 | 15.6 |
| 3 | 30-60 | 50.00 | 32.35 | 1.16 | 61.42 | Clay | 52.4 | 30 | 17.6 |
| 4 | 0-60 | 51.12 | 34.08 | 1.11 | 116.14 | Clay | 51.4 | 30 | 18.6 |

Note: TAW = total available water content.

## 4.2 Weather Condition During Crop Growing Season

The experimental site is well-known for its dual rainy (bimodal) season but for this particular cropping season there wasn’t considerable amount of rainfall and the maximum rainfall amount recorded was 14.5mm/24hr in January which was during initial stage of the crop growth. The weather condition in the growing season was very hot and dry which might cause high amount of reference evapotranspiration compared to previous seasons. The average minimum and maximum temperature of the growing season have been recorded to be 7.3$^0$C and 27.78$^0$C.

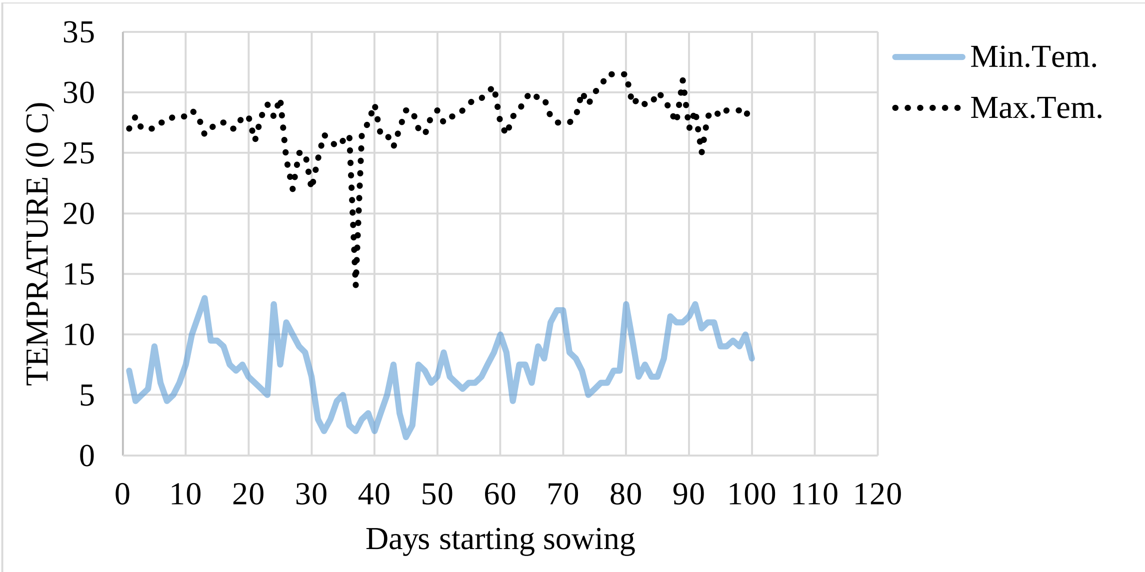



Figure 4:1: Trend of temperature during growing season of the crop (maximum & minimum temperature)

**4.3 Seasonal Soil Moisture Content**

The soil moisture content was kept near to the field capacity level throughout the growing season up to root depth of 60cm. Therefore, monitoring the soil moisture content continuously was essential in order to provide optimal moisture level to avoid any production loss due to stress. The moisture level of the soil was monitored and the data was recorded and tried to show it in the following graph, Figure 4.2.

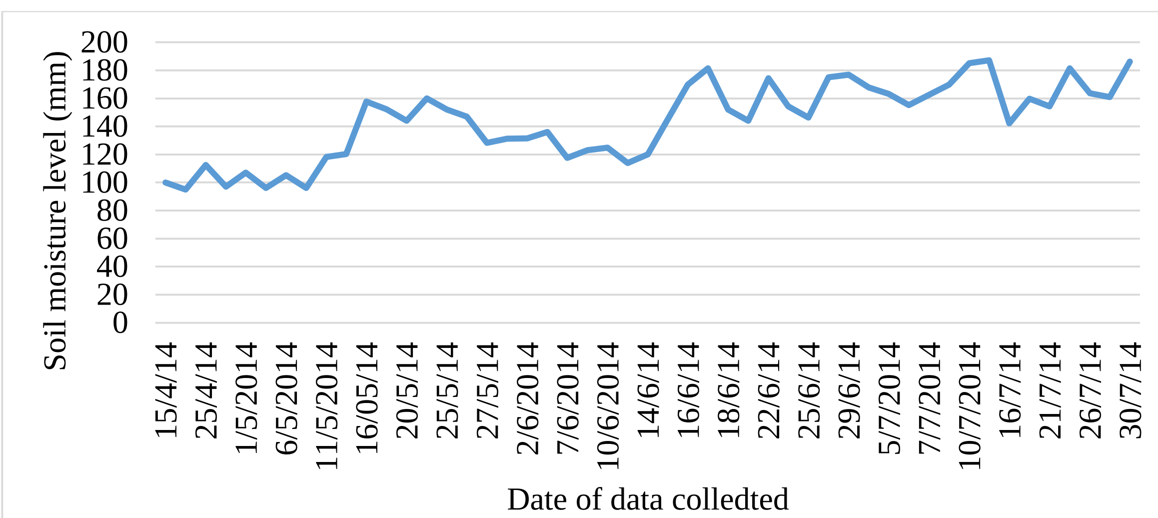



Figure 4:2: Growing seasonal trend of soil moisture content

As can be seen from Figure 4.2, the moisture level was higher at mid and late stage as storage of moisture increased due to increasing days after sowing and water application. Moisture at development stage was high compared to initial stage which indicates the soil moisture depletion at initial stage was higher as the canopy coverage at this time was very low relative to the remaining growth stages.

The soil moisture level during maturity stage showed rapidly decreasing which caused frequent irrigation application and continuous monitoring in order to maintain optimally measured ETc value. The main reason for the rapid loss of moisture at this level is the increasing of water demand as the crop growth progresses. The moisture depletion of the soil at the last stage of the crop growth showed decreasing rapidly at the upper layer on the soil strata. Therefore, frequent irrigation was required during starting of late stage because of the weather condition and the temperature at the time can be seen in appendix (5) which indicated that irrigation interval is affected by the weather condition of the stage as it can lead to peak demand. But the total moisture level within considered effective root zone was higher than the other growth stages. Gradually, irrigation was terminated before eleven days of harvesting date.

The soil moisture before every irrigation and after irrigation have been monitored and presented below with the help of graph in (Figure 4:3).

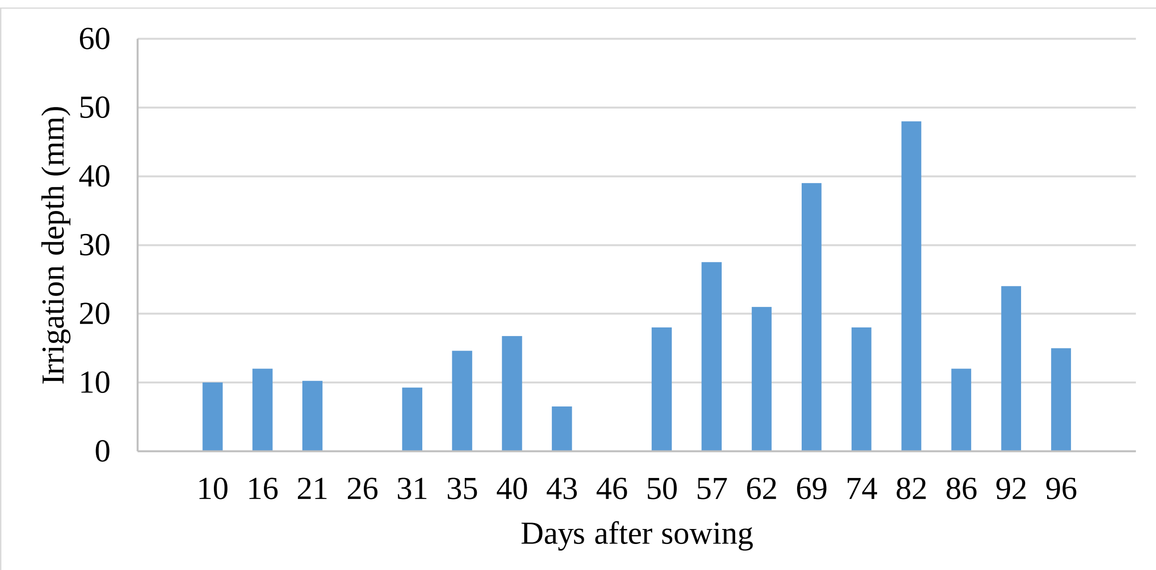
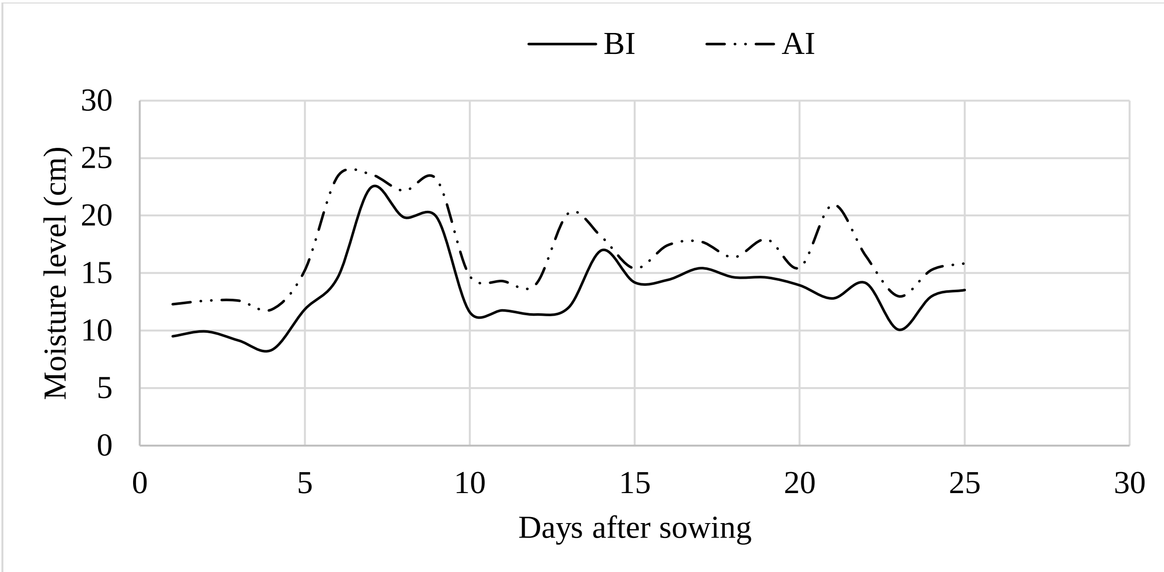



Figure 4:3: Depth of irrigation applied




Note: BI is before irrigation and AI is after irrigation

Figure 4:4: Moisture level before and after irrigation

As it can be observed from the above graphs (Figure 4:3), the irrigation application frequency have been increased while the growing stage of the crop moved from initial to the mid stage and there was high demand of water during maturity stage then declined towards the late stage when the green leave on the crop started to change their color to yellow. The irrigation application frequency at the initial stage for many crop is high relative to other crop growth stage as the root depth at this particular stage is small and the same is true for wheat crop. But the depth of irrigation is very small which resulted the water requirement for initial stage small compared to development and mid stage.

### 4.4 Crop Evapotranspiration (ETc)

For the determination of daily as well as stage-wise crop evapotranspiration, the water balance method expressed in equation (3.12) was used and the result are summarized in Table (4:1) and Figure (4.5). As the result indicated, the water requirement of wheat increased from initial stage to mid-stage and gradually decreased to the late stage (harvesting date). The water requirement at initial stage which is from day after sowing to day starting development stage (the first 20 days) was 40.35 mm. As the ground cover at this stage was small, it was believed that, the largest portion of this water demand was used by evaporation loss. At development stage, the demand increased to be 82.44 mm as indicated in the result Table (4:2). At this moment, evaporation from the soil surface started showing decrement while transpiration increment takes place due to increasing canopy cover on the ground. The daily water demand wasn't constant at this particular stage rather showed gradual increment as indicated Figure (4:5).

When the crop growth hits mid-stage, the water requirement attained to the maximum value 238.66 mm. Mid-stage is a stage when the crop start forming grain and the canopy coverage is almost 100%. Therefore, more water have been lost as transpiration rather than as evaporation and the amount of water required for metabolism was higher at this stage comparing to other stages. The crop late growth stage is when the leaf senescence took place and transpiration starts to decline. Hence, the water requirement at this stage showed decrement and became 31.3 mm. At this stage formation of grain ceases and hard dough formation takes place. In late stage water amount need to be minimized and gradually terminated in order to allow optimum and quality yield achievement. The result lined up with different similar studies and FAO working papers in trend of increasing as well as decreasing of water requirement in different stages (Allen *et al*., 1998; Kenjabaev *et al*. 2014; Tezera *et al*., 2019).

The finding of this study, when compared with the result of the study conducted by Tezera *et al*. (2019) in Melkassa, there was less water requirement at initial, development and late stage for the current study. But, the water requirement at mid-stage was higher in the current study. The total water requirement was recorded to be 392.75 mm/season which is less than their study output (413.8 mm/season). The difference in required water amount might have been caused by seasonal differences in climate and location specific conditions. More specifically, Such conditions might be; difference in climatic condition between the two locations, the season when the cultivation took place, the variety which have been used as experimental crop, the soil type, or the management practice of cultivation.

Table 4:2: Seasonal crop evapotranspiration (ETc)

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

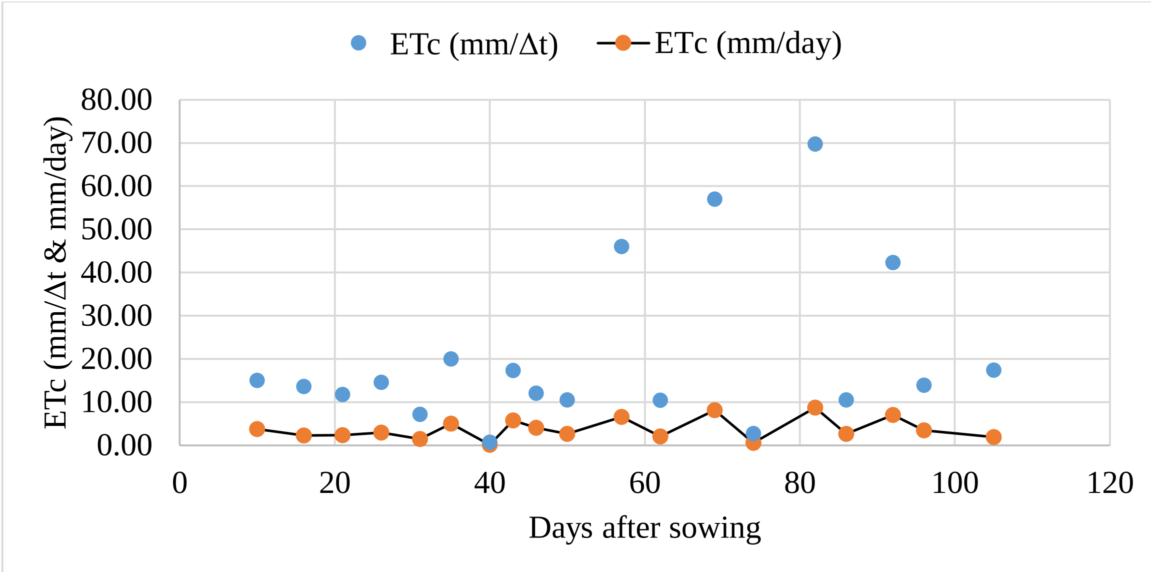



Figure 4:5: Crop evapotranspiration rate for growing season

Other studies conducted by different scholars in different location similarly showed variation with the current result (Table 4.3). These results have higher water requirement than the current output (Kenjabaev *et al.*, 2014; Laaboudia A, and Mouhouche B, 2012). The variation was expected as water requirement is very dependent on different physical parameters.

Table 4:3: Comparison of crop evapotranspiration determined by different authors for wheat crop

| Authors | ETc | | | | |
|---|---|---|---|---|---|
| | Initial | Development | Mid-stage | Late-stage | Total ETc (mm/season) |
| Current result | 40.35 | 82.44 | 238.66 | 31.3 | 392.75 |
| Tezera et al. (2019), Ethiopia | 52.2 | 97.1 | 191.5 | 73 | 413.8 |
| Laaboudia A, and Mouhouche B, (2012), Algeria | - | - | - | - | 603.67 |
| Irmak et al., (2015), USA | - | - | - | - | 490 to 600 |
| Kenjabaev et al. (2014), Uzbekistan | - | - | - | - | 509 |

As Fitsume *et al*. (2017) and Tezera *et al*. (2019)reported, due to the absence of well-studied and documented data about the water requirement of wheat in the study area; parameters adopted from FAO manual were under usage for planning and designing purpose up to present date. As a result, some irrigators are applying excess water which can cause water logging at the root zone and may leads to decreasing in yield (Tiryakioğlu *et al*., 2015) and others are supplying less water to their crop which may leads to water stress and ultimately there may be yield reduction (Jemal *et al*., 2019). In both case, there will be yield reduction and mismanagement of precious natural resource (water). In order to have optimum usage of this limited resource; planning and designing with accurate data is essential.

4.4.1 Comparison of ETc values based on FAO recommended kc and current result:-

FAO provides different kc value based on crop growing stage for various crop and from these crop wheat is among others. In order to analyze the variation between these two kc results (FAO and current result) on ETc amount two method were used. The first one was using simple calculation which is multiplication of kc value with total ETo of the desired growth stage which was drived from equation (2.2). The result indicated that, the total water requirement of the season is 497.77 mm/season and it was greater than the current result by 26.7%. The result for initial, development, mid and late stage were estimated to be 67.19 mm, 152.3 mm, 249.6 mm and 28.68 mm respectively. the result was lined up with by Fitsume *et al*. (2017) that reported 489.9 mm for the total growing season.

Other result from CropWAT software provided maximum ETc value. In the software, all used parameters similar to the current study including; root depth, total available water, soil type, climate data which was restricted to only under the growing season. Output of the analysis indicated the total water requirement of wheat growing season was 597.5 mm/season which is significantly higher than both from the experimental result and simple estimation method.

Table 4:4: Comparison of ETc value from different estimation methods

| | Growth stages ETc (mm) | | | | |
|---|---|---|---|---|---|
| ETc estimation methods | Initial | Development | Mid | Late | Total |
| lysimeter result | 40.3 | 82.44 | 238.66 | 31.3 | 392.75 |
| FAO kc by ETo | 67.19 | 152.3 | 249.16 | 28.68 | 497.8 |
| CropWAT | 74.9 | 152.4 | 256.5 | 113.7 | 597.5 |

## 4.5 Reference Evapotranspiration (ETo)

The averaged reference evapotranspiration (ETo) of the growing season found to be 5.1 mm/day which was estimated with CROPWAT model. The trend of the reference evapotranspiration during the growing season is presented in Figure 4.5. As indicated in the Figure (4:6), the maximum and minimum reference evapotranspiration of the growing season was determined to be 6.19mm/day and 2.8mm/day respectively.

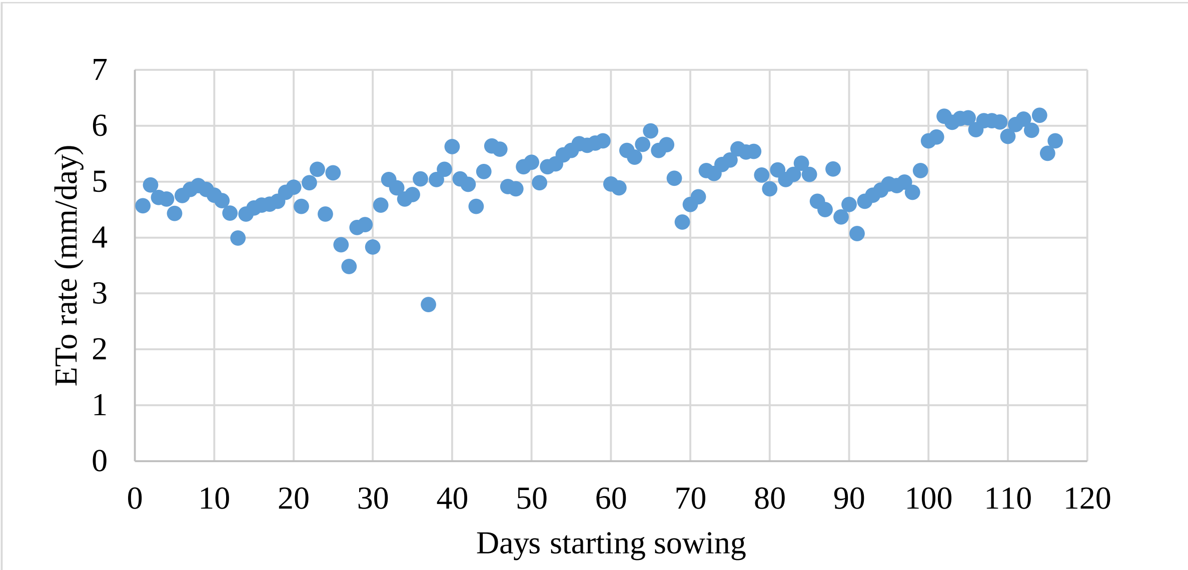



Figure 4:6: Rate of reference evapotranspiration during crop growing season (mm/day)

As we can see from Table (4.4), the reference evapotranspiration of the season is greater at mid stage as the length of the stage is longer relative to other stages. Despite being the smallest in growth length in days, ETo at the initial stage recorded to be higher relative to late stage.

Table 4:5: Copping season reference evapotranspiration (ETo)

| Parameters | Growth stages | | | | Total |
|---|---|---|---|---|---|
| | Initial | Development | Mid | Late | |
| Growth Length (days) | 20 | 30 | 42 | 23 | 115 |
| ETo (mm/growth stage) | 79.05 | 138.44 | 217.05 | 71.7 | 525.25 |

<u>4.5.1 Comparison of seasonal and stage based ETc and ETo:-</u>

Reference evapotranspiration (ETo) and crop evapotranspiration (ETc) are parameters which are related to one another. The result of one is always dependent on other.

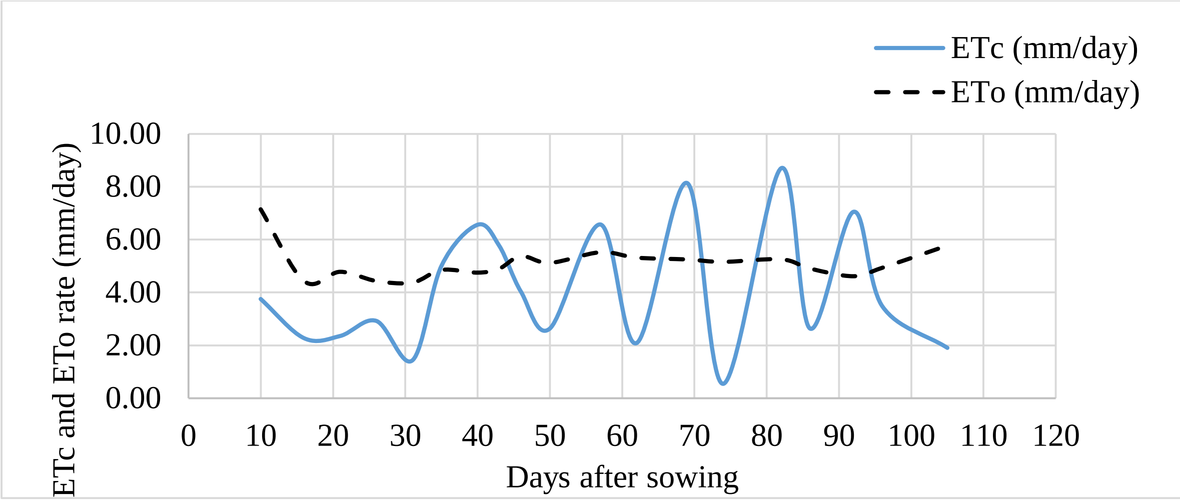



Figure 4:7: ETc and ETo rate over the growing season

As it can be seen from Figure 4.6, the reference evapotranspiration of the growing season was higher than crop evapotranspiration for the first two growth stages (initial and development) and showed decreased at the mid stage. The averaged stage based ETc and ETo have been summarized and presented in Figure 4.7.

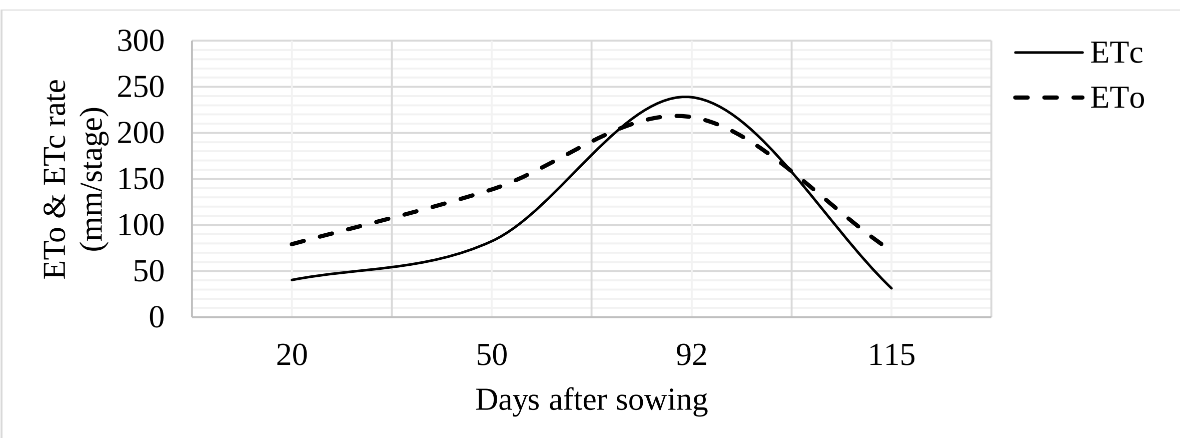



Figure 4:8: Stage based averaged ETc and ETo rate value for the whole growing season

**4.6 Crop Coefficient (kc)**

As crop coefficient is the ratio between crop evapotranspiration and reference evapotranspiration, the estimated value for the whole growing season was below other studies result. The results of kc are summarized and presented table (4.5).

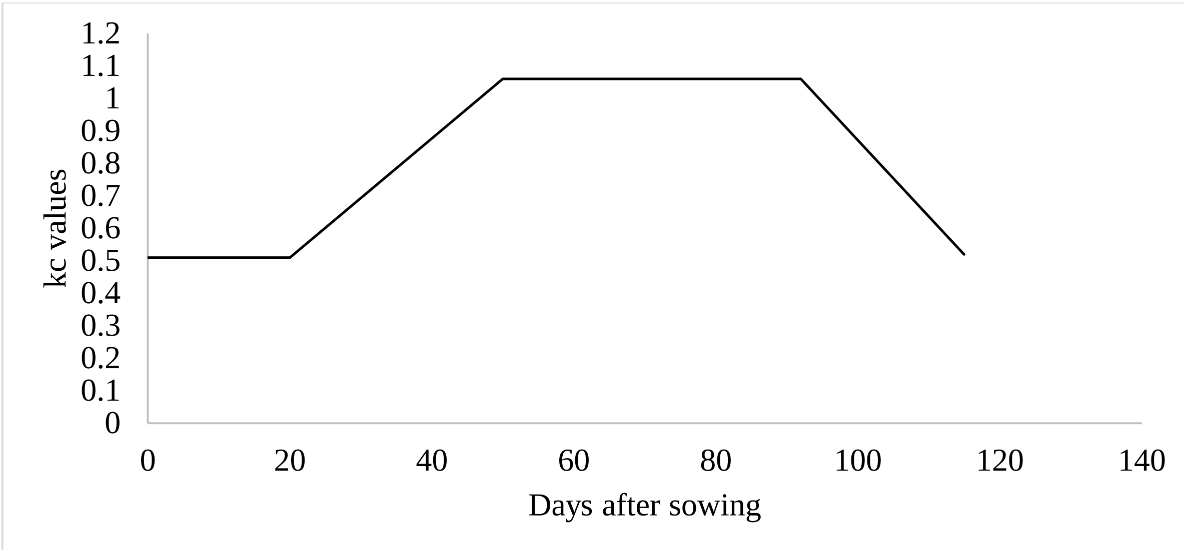



Figure 4:9: Stage based average kc value for different growth stages

The crop coefficient is the ratio of crop evaporation to reference evapotranspiration as explained in methodology part and the kc of durum wheat was determined from parameters of crop evapotranspiration (ETc) and reference evapotranspiration (ETo) as presented in equation (3.14) and the value ranged from 0.51 initial stage to 1.29 mid stage as indicated in Table (4.5). Figure (4.10) shows that the kc value increased from initial stage to development stage continuously and the increment was maximum when the crop growth reached to mid stage. There was gradual declination up to harvesting date referred as late stage.

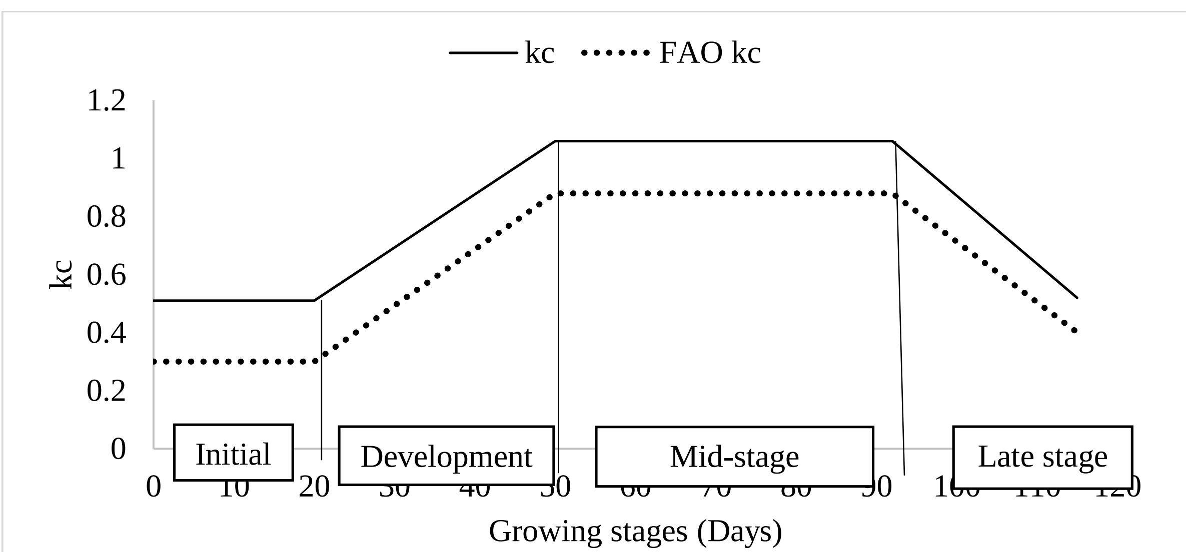



Figure 4:10: Comparison of kc values between current study and FAO recommendation

The result showed significant variation from the value given in FAO manual which have been used for the last long period of time as representative kc value at the study area especially at mid stage. As the value of kc is very dependent on parameters like crop type and variety, climate condition, soil type, and moisture condition of the soil surface, the variation was expected (Ali *et al*. 2007).

The crop coefficient at initial stage was estimated to be 0.51 which less than FAO recommended value (0.6-1.1) by 66.6 % for frequently irrigated with depth range of 10-40 mm and ETo variation between 3 mm/day and 5 mm/day considering the average value between 0.6 and 1.1 and greater than 0.3 by 70% which was recommended for normal condition (Allen *et al*., 1998). At mid stage, the averaged kc value between development stage and maturity stage for this particular experiment have been estimated to be 1.06 which is again greater than the value of FAO recommendation (0.93) by 13.98 %. The possible reason for variation in those result can be; variation in climate condition, soil type, crop type and variety also managerial practice in the field level.

Table 4:6: Result of seasonal and daily crop and reference evapotranspiration (ETc & ETo) with averaged crop coefficient (kc) value

| 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 |
| ETc (mm/day) | 2.02 | 2.75 | 5.68 | 1.36 |
| ETo (mm/stage) | 79.05 | 138.44 | 217.05 | 71.7 |
| ETo (mm/day) | 3.95 | 4.61 | 5.17 | 3.12 |
| Average kc | 0.51 | 0.83 | 1.29 | 0.52 |

Table 4:7: 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 |
| FAO (1998) | 0.6-1.1 | 0.5-0.7 | 1.15 | 0.4 |
| Tezera et al. (2019) | 0.54 | - | 1.15 | 0.67 |
| Laaboudia A, Mouhouche B, (2012) | 0.48 | 0.74 | 1.3 | 0.88 |
| Kenjabaev et al. (2014) | 0.27 | - | 1.03 | 0.89 |

The result of kc at the development stage (0.83) was compared with the study finding by Laaboudia A, and Mouhouche B (2012) and observed to be greater by 0.09 or 12.16%. The same study carried out by Tezera *et al*. (2019) on crop coefficient of wheat pointed out 0.54, 1.15, and 0.67 for initial, mid and late stage on crop growing season. In relation to FAO recommendation, estimated kc value of their finding showed exactly the same at mid stage with variation for initial and late stage. Irmak *et al*., (2015) also found that the kc value for winter and spring wheat to be 0.6, 1.3, and 0.3 for early, mid and late season respectively. The output of this study showed similarity with the current study for mid stage and no significant difference for initial stage either. The initial, mid, and late season crop growing stage of wheat reported to be 0.27, 1.03, and 0.89 respectively by Kenjabaev *et al*. (2014).

Ali *et al*. (2007) also determined winter wheat kc value in Bangladesh Ishurdi with different ETo estimation methods. The result reported to be 0.82, 1.19, 1.55, and 1.00 for initial, development, mid, and late stage respectively with similar ETo estimation method as the current study. The values of kc for different growth stages of this study significantly higher comparing to current research outcome. They also reported that, the value of kc is very dependent the nature of moisture content. Based on their finding the kc value will be less for stressed crop and high with good moisture condition.

All the study results those have been mentioned above justified that, calibration of crop coefficient with respect to desired location is required to provide accurate crop evapotranspiration amount and then optimum usage of available water for better yield and water productivity.

### 4.7 Crop Coefficient, Day of Growth Sowing (DGS) and Days After Sowing (DAS)

Regression analysis was conducted between crop coefficient kc and days of growth stage DGS. The analysis gave fourth order polynomial equation with high coefficient of determination $r^2$ = 0.999. The developed relation can help for prediction of crop coefficient in planning and designing irrigation systems on areas which have similar climate and soil condition other than the study area.

$$kc = 5E\text{-}08\,(DGS)^4 - 1E\text{-}05(DGS)^3 + 0.0012(DGS)^2 - 0.0186(DGS) + 0.51$$

$$R^2 = 0.999$$

The equation was used to determine kc values for those four growth stages and showed compatibility with the result that have been developed using formula. There is some numerical difference between the study result and kc value estimated from the above equation. But, the variation wasn't significant which indicates one can use the equation to estimate kc value known length of each growing stages.

Table 4:8: Comparison of kc values between experimental resultt one and kc from the developed equation

| Growth stages | Determined kc | Kc from developed eq. | Variation |
|---|---|---|---|
| Initial | 0.51 | 0.55 | + 7.8% |
| Development | 0.83 | 0.8 | - 3.75% |
| Mid-stage | 1.29 | 1.26 | - 2.38% |
| Late-stage | 0.52 | 0.6 | + 15.8% |

Similarly, equation was developed for days after sowing and kc. The result gave sixth degree polynomial equation with coefficient of determination $r^2 = 0.66$. Related study by Kang *et al*. (2003) developed fifth order polynomial equation with coefficient of determination $r^2 = 0.96$ for winter wheat. Hordofa *et al*. (2020) and Yihun, (2015) also developed relation between DAS and kc, then proposed fifth order polynomial equation for Tef crop at Melkassa.

$$kc = 4E\text{-}06(DAS)^6 - 0.0003(DAS)^5 + 0.0077(DAS)^4 - 0.0983(DAS)^3 + 0.6349(DAS)^2 - 1.8346(DAS) + 2.3384$$

$$R^2 = 0.664$$

**4.8 Irrigation Scheduling**

Irrigation scheduling for this particular study was carried out based on the net water requirement of particular stage rather than scheduling with assumption. Scheduling was designed based on growth stage to avoid yield loss due to water stress or water logging. The scheduling result have been summarized and presented in Table (4.7).

Table 4:9: Scheduling irrigation parameter result

| Parameters | Growth stages | | | |
|---|---|---|---|---|
| | Initial | development | Mid-stage | late-stage |
| dnet (mm) | 40.35 | 82.44 | 238.66 | 31.3 |
| ETc (mm/day) | 3.75 | 6.56 | 8.7 | 3.4 |
| Interval (days) | 10.76 | 12.57 | 27.43 | 9.2 |
| Adj. Interval (days) | 10 | 12 | 27 | 9 |
| dnet, adj (mm) | 37.5 | 78.72 | 234.9 | 30.6 |

The result presented in Table 4:9 indicates, the irrigation interval for initial, development, mid, and late season estimated to be 10, 12, 27, and 9 days respectively. The time required to apply the irrigation depth have been omitted from the study as it requires development of infiltration curve which is beyond the scope of the study. In general, to produce wheat on one hectare of land one needs 3927.5 $m^3$ of net irrigation water Gross water requirement highly depends on the application efficiency of the irrigation system as well as the irrigation applicator. Therefore, it needs critical attention in order to improve the efficiency so that better water productivity can be achieved.

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

Knowing the correct amount of water to apply and when to apply is crucial for proper irrigation development and management. In order to have these knowledge, information on; crop type, soil type, season of cultivation, climatic condition of the area, and method of irrigation to be applied are required. The objective of this study was to determine crop water requirement and develop crop coefficient of wheat grown in Bishofitu,

Despite the potential of the area for irrigated wheat production, information required were not well-studied or generated. Therefore, this study was required to fill the gap of lacking appropriate information regarding wheat water requirement and crop coefficient as well as irrigation scheduling for irrigated wheat. To determine crop water requirement of wheat, non-weighing lysimeter was used in order to assess inflow and outflow components of water balance equation and water balance equation was implemented.

The result of the study showed that, the total net water requirement of wheat is 392.75 mm/season and 380.45 mm of net irrigation water requirement per a single season. Particularly, 40.35 mm, 82.44 mm, 238.66 mm, and 31.3 mm for initial, development, mid-stage, and late stage respectively. The amount doesn't consider any loss during irrigation application as the efficiency considered to be 100%. The gross water requirement of wheat production at the area may vary depending on irrigation methods and efficiency of the irrigation system.

The crop coefficient (kc) of the study was found to be 0.51, 0.83, 1.29, and 0.52 for initial, development, mid-stage, and late stage respectively. Equation was developed for both length of growth stage and days after sowing with relation to kc. Fourth and sixth order polynomial equation have been developed for days of growth stage (DGS) and days after sowing (DAS) with coefficient of determination ($r^2$) 0.999 and 0.66 respectively.

Regarding irrigation scheduling, water application will be every 10, and 12, 27, and 9 days interval for initial, development, mid and late stage respectively. This interval may vary from area to area based on the soil type and weather condition of the area. Scheduling was carried out with consideration of peak daily water requirement rather than average crop water demand of the stage.

Generally, the result showed that parameter like kc and ETc need to be calibrated locally before applying theme for any other area other than same location.

### 5.2 Recommendations

The finding out of this study clearly showed that, experimental studies are crucial to provide proper irrigation management and enhancing water productivity. Calibration of parameters with respect to the desired location is the first turning point of providing proper planning and management of irrigated agriculture. If one use correct data, then the result will be expected to be real and correct too. Every irrigation manager need to give proper attention while designing as well as managing new and already existing systems with respect to the most critical parameters so that productivity can be enhanced.

Finally, it is recommended to repeat the experiment to have most accurate results as increasing replication decreases error. Also, cost of construction for lysimeter is high which is why they are limited in country level. Therefore, searching less costly mechanisms should be considered in order to make it more accessible in every corner of the country so that local based kc value can be developed to enhance water productivity. Also, this result shouldn't be used for design purpose directly as it is, due to the specification of area and season also it used a single season climate parameter to estimate seasonal water requirement of wheat. But, it can be used as a source of information for further studies.

# REFERENCES

Ali, M. H., M.R. Hoque, A. A. Hassan and M.A. Khair (2007). "Crop coefficient of winter wheat at different growth stages in a humid sub-tropic environment". Int. J. Bio-Research, 2(1): 36 – 46

Allen, R. G., and Food and Agriculture Organization of the United Nations, eds., (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Rome: Food and Agriculture Organization of the United Nations.

Allen, Richard G, Luis S Pereira, Dirk Raes, and Martin Smith, (1998). "Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - FAO Irrigation and Drainage Paper 56."

Babaee, Maryam, Ahmad Shokat-Naghadeh, Hedieh Ahmadpari, and Mohammad Nabi-Jalali, (2019). "Comparison of Different Methods with Lysimeter Measurements in Estimation of Rice Evapotranspiration in Sari Region." Revista INGENIERÍA UC 26(2): 175–84.

B. C Curtis, S. Rajaram, H. Gomez Macharson, (2002). "Bread wheat improvement and production". FAO plant production and protection series No. 30.

Beshir, Siraj. (2017). "Review on Estimation of Crop Water Requirement, Irrigation Frequency and Water Use Efficiency of Cabbage Production." Journal of Geoscience and Environment Protection 05(07): 59–69.

Bouras, E., Jarlan, L., Khabba, S., Er-Raki, S., Dezetter, A., Sghir, F., & Tramblay, Y. (2019). Assessing the impact of global climate changes on irrigated wheat yields and water requirements in a semi-arid environment of Morocco. Scientific Reports, 9(1), 19142. https://doi.org/10.1038/s41598-019-55251-2

Dingre, S. K., and S. D. Gorantiwar. (2020). "Determination of the Water Requirement and Crop Coefficient Values of Sugarcane by Field Water Balance Method in Semiarid Region." Agricultural Water Management 232: 106042.

Dirirsa G, Bekele D, Hordofa T., (2017). Crop Coefficient and Water Requirement of Tomato (Melka Shola Variety) at Melkassa, Central Rift Valley of Ethiopia. Acad. Res. J. Agri. Sci. Res. 5(5): 336-340

Du, Xiong, Gao Zhen, Sun Xiaonou, Bian Dahong, Ren Jianhong, Yan Peng, Cui Yanhong, (2022). "Increasing Temperature during Early Spring Increases Winter Wheat Grain Yield by Advancing Phenology and Mitigating Leaf Senescence." Science of The Total Environment 812: 152557.

Ewaid, Abed, and Al-Ansari, (2019). "Crop Water Requirements and Irrigation Schedules for Some Major Crops in Southern Iraq." Water 11(4): 756.

Fan, Jianling, Brian McConkey, Hong Wang, and Henry Janzen (2016). "Root Distribution by Depth for Temperate Agricultural Crops." Field Crops Research 189: 68–74.

Fisher, Daniel K. (n.d) "Simple and Inexpensive Lysimeters for Monitoring Reference and Crop-ET." :

Fitsume Yemenu Desta, Kidist Abera, Michael Eshetu, Richard, K., & Molla Mekonnen Alemu, (2017). Irrigation water planning for crops in the central highlands of Ethiopia, aided by FAO CROP WAT MODEL. African Journal of Agricultural Research, 12(28), 2329–2335. https://doi.org/10.5897/AJAR2016.11659

Gebul, Mekonen Ayana, (2021). "Trend, Status, and Challenges of Irrigation Development in Ethiopia—A Review." Sustainability 13(10): 5646.

Haile Tefera, Ashebir, and Demeke Tamene Mitiku, (2021). "Models Comparative Study for Estimating Crop Water Requirement and Irrigation Scheduling of Maize in Metekel Zone, Benishangul Gumuz Regional State, Ethiopia." International Journal of Agricultural Economics 6(2): 59.

Hodson, D. P., Jaleta, M., Tesfaye, K., Yirga, C., Beyene, H., Kilian, A., Carling, J., Disasa, T., Alemu, S. K., Daba, T., Alemayehu, Y., Badebo, A., Abeyo, B., & Erenstein, O. (2020). Ethiopia's transforming wheat landscape: Tracking variety use through DNA fingerprinting. Scientific Reports, 10(1), 18532. https://doi.org/10.1038/s41598-020-75181-8

Hossain, Belal, Khandakar Faisal Ibn Murad, and Sariful Bin Ekram, (2015). “Irrigation Scheduling of Wheat Using Pan Evaporation Method.” International Journal of Innovative Research in Advanced Engineering 2(10): 6.

Howell, Terry, A.D. Schneider, and Marvin Jensen, (1991). “History of Lysimeter Design and Use for Evapotranspiration Measurements.” Lysimeters for Evapotranspiration and Environmental Measurements: 1–9.

Jemal, M. Hassen, Wondimu, T., Fikadu, R. Borena, Kebede, N., Niguse, A., Elias, K. Hailu, (2019). “Wheat Response to Water Stress Condition at Different Growth Stages in Amibara, Ethiopia.” African Journal of Agricultural Research 14(32): 1493–98.

Kang, Shaozhong, Binjie Gu, Taisheng Du, and Jianhua Zhang, (2003). “Crop Coef®cient and Ratio of Transpiration to Evapotranspiration of Winter Wheat and Maize in a Semi-Humid Region.” Agricultural Water Management: 16.

Kenjabaev, Shavkat, Yvonne Dernedde, Hans-Georg Frede, and Galina Stulina, (2014). “Determination of Actual Crop Evapotranspiration (ETc) and Dual Crop Coefficients (Kc) for Cotton, Wheat and Maize in Fergana Valley: Integration of the FAO-56 Approach and BUDGET.”

Ketema Tezera, Gobena Dirirsa and Tilahun Hordofa, (2019). Determination of Wheat (Triticum Aestivum L) Seasonal Water Demand and Crop Coefficient for Effective Irrigation Water Planning and Management in Semi-Arid, Central Rift Valley of Ethiopia. International Journal of Environmental Sciences & Natural Resources, 21(1). https://doi.org/10.19080/IJESNR.2019.21.556054.

Kilmer, V. J., & Alexander, L. T. (1949). Methods of Making Mechanical Analyses of Soils. Soil Science, 68(1), 15–24. http://doi.org/10.1097/00010694-194907000- 00003

Kumar, R., M. K. Jat, and V. Shankar. 2012. “Methods to Estimate Irrigated Reference Crop Evapotranspiration – a Review.” Water Science and Technology 66(3): 525–35.

Laaboudi, A., Allaoua, C., Hafuounda, L., Ballague, D., Sbargoud, S., Meterfi, J., and Herda, F., (2015). “Crop Coefficient and Water Requirement for Wheat (Triticum Aestivum) in Different Climate Regimes of Algeria.” International Journal of Agricultural Policy and Research Vol.3 (8), pp. 328-336 http://dx.doi.org/10.15739/IJAPR.057

Laaboudi A., Mouhouche B, (2012). “Water Requirement Modelling for Wheat under Arid Climatic Conditions.” Hydrology Current Research 3(130). doi:10.4172/2157-7587.1000130.

Md. Nur Alam, Md. Bodruzzaman1, Md. Monwar Hossain, Md. Sadekuzzaman, (2014). "Growth performance of spring wheat under heat stress conditions." International Journal of Agronomy and Agricultural Research (IJAAR) ISSN: 2223-7054 (Print) 2225-3610 (Online) http://www.innspub.net Vol. 4, No. 6, p. 91-103

Mehari, Hagos. 2019. “Review on: impact of climate change on crop water requirement in Ethiopia.” 6(5): 12.

Mekuria, T., Wasihun L, Shitaye H, Asenafi G., (2018). "Durum wheat (Triticum durum Desf) Variety “Utuba” Performance in Ethiopia". Agri Res& Tech: Open Access J.; 18(4): 556063. DOI: 10.19080/ARTOAJ.2018.18.556063.

M.H. Ali and M.S.U. Talukder (2001). Methods or Approaches of Irrigation Scheduling – An Overview. J. of the Institute of Engineers, Bangladesh, Vol. 28/AE, No.1: 11 – 23

Nouri, H. et al. 2013. “Remote Sensing Techniques for Predicting Evapotranspiration from Mixed Vegetated Surfaces.” Hydrology and Earth System Sciences Discussions 10(3): 3897–3925.

NRCS. (1996). Soil Survey Laboratory Methods Manual, (42), 716. http://doi.org/10.1021/ol049448l

Onyancha, D M, C Gachene, and G Kironchi, (2017). “Model-Based Estimation of The Crop Water Requirement Of Major Crops In Machakos County.” 4(2).

Pakparvar, M., Cornelis, W., Pereira, L. S., Gabriels, D., Hosseinimarandi, H., Edraki, M., & Kowsar, S. A. (2014). Remote sensing estimation of actual evapotranspiration and crop coefficients for a multiple land use arid landscape of southern Iran with limited available data. Journal of Hydroinformatics, 16(6), 1441–1460. https://doi.org/10.2166/hydro.2014.140

Piccinni, G., Ko, J., Wentz, A., Leskovar, D., Marek, T., & Howell, T. (2007). Determination of crop coefficients (kc) for irrigation management of crops.

Qadir, Ghulam, Muhammad Saeed, and Mumtaz Akhtar Cheema. 1998. “Effect of Water Stress on Growth and Yield Performance of Four Wheat Cultivars.” Pakistan Journal of Biological Sciences 2(1): 236–39.

Savva, Andreas P, and Karen Frenken. (2002) “Planning, Development Monitoring and Evaluation of Irrigated Agriculture with Farmer Participation.” : 1164.

Shenkut, A, K Tesfaye, and F Abegaz. 2013. “Determination of Water Requirement and Crop Coefficient for Sorghum (Sorghum Bicolor L.) at Melkassa, Ethiopia.” Science, Technology and Arts Research Journal 2(3): 16.

Surendran, U., Sushanth, G. M., Joseph, E. J., Al-Ansari, Nadhir, and Yaseen, Zaher Mundher, (2019). “FAO CROPWAT Model-Based Irrigation Requirements for Coconut to Improve Crop and Water Productivity in Kerala, India.” Sustainability 11(18): 5132.

Tilahun Hordofa, Gobena Dirirsa, Tatek Wondimu, Abera Tersfaye and Ketema Tezera, (2020). Crop Water Requirement and Crop Coefficient of Tef (Eragrostis tef) in Central Rift Valley of Ethiopia. Journal of Natural Sciences Research, 11(15), 34.

TiRyakiOğlu, Murat, Sema Karanlik, and Mehmet Arslan. “Response of Bread-Wheat Seedlings to Waterlogging Stress.” Turk J Agric For: 11.

S. Irmak, K. Djaman, V. Sharma, (2015). “Winter Wheat (Triticum Aestivum L.) Evapotranspiration and Single (Normal) and Basal Crop Coefficients.” 2015. Transactions of the ASABE: 1047–66.

Yadeta, Belay, Mekonen Ayana, Muluneh Yitayew, and Tilahun Hordofa. 2021. “Determination of Water Requirement and Crop Coefficient for Sugarcane Using Lysimeter Experiment under Semiarid Climatic Conditions of Ethiopia.” Journal of Irrigation and Drainage Engineering 147(11): 04021051.

Yarami, N., A. A. Kamgar-Haghighi, A. R. Sepaskhah, and Sh. Zand-Parsa. 2011. “Determination of the Potential Evapotranspiration and Crop Coefficient for Saffron Using a Water-Balance Lysimeter.” Archives of Agronomy and Soil Science 57(7): 727–40.

Yihun, Yenesew Mengiste. 2015. Agricultural Water Productivity Optimization for Irrigated Teff (Eragrostic Tef) in a Water Scarce Semi-Arid Region of Ethiopia. Leiden: CRC Press/Balkema.

# APPENDICES

Appendix 1: Pictures of soil sample collection

Appendix 2: Status of crop on the field

Appendix 3: Sample collection activity

Appendix 4: Water balance components raw data and results

| DAS | I (mm) | Pe (mm) | ΔS (mm) | ETc (mm) | Δt | ETc (mm/day) | ETo (mm/day) | ETo (mm/day) | kc |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 10 | 0 | -5 | 15 | 4 | 3.75 | 28.59 | 7.15 | 0.52 |
| 16 | 12 | 0 | -1.6 | 13.6 | 6 | 2.27 | 26.56 | 4.43 | 0.51 |
| 21 | 10.25 | 0 | -1.5 | 11.75 | 5 | 2.35 | 23.9 | 4.78 | 0.49 |
| 26 | 0 | 5.4 | -9.2 | 14.6 | 5 | 2.92 | 22.15 | 4.43 | 0.66 |
| 31 | 9.25 | 0 | 2.09 | 7.16 | 5 | 1.43 | 21.86 | 4.37 | 0.33 |
| 35 | 14.62 | 0 | -5.41 | 20.03 | 4 | 5 | 19.4 | 4.85 | 1.03 |
| 40 | 16.77 | 0 | 16.03 | 0.74 | 5 | 6.56 | 23.74 | 4.75 | 1.38 |
| 43 | 6.5 | 0 | 23.8 | 17.3 | 3 | 5.77 | 14.69 | 4.90 | 1.18 |
| 46 | 0 | 0 | -12.08 | 12.08 | 3 | 4.03 | 16.13 | 5.38 | 0.75 |
| 50 | 18 | 0 | 7.47 | 10.53 | 4 | 2.63 | 20.47 | 5.12 | 0.51 |
| 57 | 27.5 | 0 | -18.5 | 46 | 7 | 6.57 | 38.65 | 5.52 | 1.19 |
| 62 | 21 | 0 | 10.58 | 10.42 | 5 | 2.08 | 26.58 | 5.32 | 0.39 |
| 69 | 39 | 0 | -18.01 | 57.01 | 7 | 8.14 | 36.73 | 5.25 | 1.55 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 74 | 18 | 0 | 20.7 | 2.7 | 5 | 0.54 | 25.78 | 5.16 | 0.10 |
| 82 | 48 | 0 | -21.71 | 69.71 | 8 | 8.7 | 42.03 | 5.25 | 1.66 |
| 86 | 12 | 0 | 22.51 | 10.51 | 4 | 2.63 | 19.61 | 4.90 | 0.54 |
| 92 | 0 | 6.9 | -35.41 | 42.31 | 6 | 7.05 | 27.67 | 4.61 | 1.53 |
| 96 | 15 | 0 | 1.1 | 13.9 | 4 | 3.475 | 19.73 | 4.93 | 0.70 |
| 105 | 24 | 0 | 6.6 | 17.4 | 9 | 1.9 | 51.97 | 5.77 | 0.33 |

Appendix 5: Soil moisture content raw data

| Date | SMC | θi – θa |
|---|---|---|
| 15/4/2014 | 100 | |
| 24/4/2014 | 95.00 | -5 |
| 25/4/2014 | 98.60 | |
| 30/4/2014 | 97.00 | -15.6 |
| 1/5/2014 | 97.60 | |
| 5/5/2014 | 96.10 | -11 |
| 6/5/2014 | 105.30 | |
| 10/5/2014 | 96.10 | -9.2 |
| 11/5/2014 | 118.33 | |
| 15/5/2014 | 120.42 | 1.87 |
| 16/5/2014 | 157.66 | |
| 19/5/2014 | 152.25 | -5.41 |
| 20/5/2014 | 144.08 | |
| 24/5/2014 | 160.11 | 16.03 |
| 25/5/2014 | 152.09 | |
| 27/5/2014 | 128.29 | -23.8 |
| 28/5/2014 | 143.29 | |
| 30/5/2014 | 131.21 | -12.08 |
| 1/6/2014 | 128.64 | |
| 4/6/2014 | 136.11 | 7.47 |

| | | |
|---|---|---|
| 5/6/2014 | 142.39 | |
| 11/6/2014 | 123.89 | -18.5 |
| 12/6/2014 | 124.30 | |
| 16/6/2014 | 134.88 | 10.58 |
| 17/6/2014 | 181.41 | |
| 23/6/2014 | 163.40 | -18.01 |
| 24/6/2014 | 154.36 | |
| 28/6/2014 | 175.06 | 20.7 |
| 29/6/2014 | 176.98 | |
| 6/7/2014 | 155.27 | -21.71 |
| 7/7/2014 | 162.59 | |
| 10/7/2014 | 185.10 | 22.51 |
| 11/7/2014 | 177.60 | |
| 16/7/2014 | 142.19 | -35.41 |
| 17/7/2014 | 135.20 | |
| 20/7/2014 | 136.30 | 1.1 |
| 21/7/2014 | 154.37 | |
| 29/7/2014 | 160.97 | 6.6 |
| 30/7/2014 | 186.36 | |

Appendix 6: Seasonal climate raw data

| DSS | Min Temp | Max Temp | Humidity | Wind | Sun | Rad | ETo |
|---|---|---|---|---|---|---|---|
| | °C | °C | % | m/s | hours | MJ/m?/day | mm/day |
| 1 | 7 | 27 | 64 | 2 | 11.7 | 24 | 4.57 |
| 2 | 4.5 | 28 | 61 | 2 | 13.2 | 26.1 | 4.94 |
| 3 | 5 | 27 | 62 | 2 | 12.6 | 25.2 | 4.72 |
| 4 | 5.5 | 27 | 63 | 2 | 12.4 | 24.9 | 4.69 |
| 5 | 9 | 27 | 66 | 2 | 10.8 | 22.8 | 4.43 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | 6 | 27.5 | 63 | 2 | 12.4 | 25 | 4.75 |
| 7 | 4.5 | 27.5 | 61 | 2 | 13 | 25.8 | 4.86 |
| 8 | 5 | 28 | 62 | 2 | 13 | 25.9 | 4.93 |
| 9 | 6 | 28 | 62 | 2 | 12.6 | 25.3 | 4.86 |
| 10 | 7.5 | 28 | 64 | 2 | 12 | 24.5 | 4.76 |
| 11 | 10 | 28.5 | 66 | 2 | 11.1 | 23.3 | 4.66 |
| 12 | 11.5 | 28 | 68 | 2 | 10.1 | 22 | 4.44 |
| 13 | 13 | 26.5 | 72 | 2 | 8.6 | 19.9 | 3.99 |
| 14 | 9.5 | 27 | 67 | 2 | 10.6 | 22.7 | 4.42 |
| 15 | 9.5 | 27.5 | 66 | 2 | 10.9 | 23.1 | 4.53 |
| 16 | 9 | 27.5 | 66 | 2 | 11.1 | 23.4 | 4.58 |
| 17 | 7.5 | 27 | 65 | 2 | 11.5 | 24.1 | 4.6 |
| 18 | 7 | 27 | 64 | 2 | 11.8 | 24.4 | 4.65 |
| 19 | 7.5 | 28 | 64 | 2 | 12 | 24.8 | 4.81 |
| 20 | 6.5 | 28 | 63 | 2 | 12.4 | 25.4 | 4.9 |
| 21 | 6 | 26 | 64 | 2 | 11.8 | 24.5 | 4.56 |
| 22 | 5.5 | 28 | 62 | 2 | 12.8 | 26.1 | 4.98 |
| 23 | 5 | 29 | 61 | 2 | 13.5 | 27 | 5.22 |
| 24 | 12.5 | 28 | 69 | 2 | 9.7 | 21.7 | 4.42 |
| 25 | 7.5 | 29.5 | 63 | 2 | 12.6 | 25.9 | 5.16 |
| 26 | 11 | 24.5 | 71 | 2 | 8.7 | 20.3 | 3.87 |
| 27 | 10 | 22 | 73 | 2 | 7.8 | 19.2 | 3.48 |
| 28 | 9 | 25 | 68 | 2 | 9.9 | 22.2 | 4.18 |
| 29 | 8.5 | 25 | 68 | 2 | 10.2 | 22.6 | 4.23 |
| 30 | 6.5 | 22 | 68 | 2 | 9.7 | 22 | 3.83 |
| 31 | 3 | 24.5 | 62 | 2 | 12.5 | 26 | 4.58 |
| 32 | 2 | 26.5 | 60 | 2 | 13.7 | 27.8 | 5.04 |
| 33 | 3 | 26 | 61 | 2 | 13.1 | 27 | 4.89 |
| 34 | 4.5 | 25.5 | 63 | 2 | 12.3 | 25.8 | 4.69 |
| 35 | 5 | 26 | 63 | 2 | 12.3 | 25.9 | 4.77 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 36 | 2.5 | 26.5 | 61 | 2 | 13.5 | 27.7 | 5.05 |
| 37 | 2 | 14 | 72 | 2 | 7.9 | 19.7 | 2.8 |
| 38 | 3 | 26.5 | 61 | 2 | 13.3 | 27.6 | 5.04 |
| 39 | 3.5 | 27.5 | 61 | 2 | 13.5 | 27.9 | 5.22 |
| 40 | 2 | 29 | 59 | 2 | 14.7 | 29.7 | 5.63 |
| 41 | 3.5 | 26.5 | 61 | 2 | 13.1 | 27.5 | 5.05 |
| 42 | 5 | 26.5 | 63 | 2 | 12.5 | 26.6 | 4.95 |
| 43 | 7.5 | 25.5 | 66 | 2 | 11 | 24.4 | 4.56 |
| 44 | 3.5 | 27 | 61 | 2 | 13.4 | 28 | 5.18 |
| 45 | 1.5 | 28.5 | 59 | 2 | 14.8 | 30.1 | 5.64 |
| 46 | 2.5 | 28.5 | 59 | 2 | 14.4 | 29.6 | 5.58 |
| 47 | 7.5 | 27 | 65 | 2 | 11.7 | 25.7 | 4.91 |
| 48 | 7 | 26.5 | 64 | 2 | 11.7 | 25.8 | 4.87 |
| 49 | 6 | 28 | 62 | 2 | 12.8 | 27.4 | 5.27 |
| 50 | 6.5 | 28.5 | 62 | 2 | 12.8 | 27.5 | 5.35 |
| 51 | 8.5 | 27.5 | 65 | 2 | 11.5 | 25.6 | 4.98 |
| 52 | 6.5 | 28 | 63 | 2 | 12.6 | 27.3 | 5.27 |
| 53 | 6 | 28 | 62 | 2 | 12.8 | 27.7 | 5.32 |
| 54 | 5.5 | 28.5 | 62 | 2 | 13.2 | 28.4 | 5.48 |
| 55 | 6 | 29 | 62 | 2 | 13.3 | 28.5 | 5.56 |
| 56 | 6 | 29.5 | 61 | 2 | 13.5 | 28.9 | 5.68 |
| 57 | 6.5 | 29.5 | 62 | 2 | 13.3 | 28.6 | 5.65 |
| 58 | 7.5 | 30 | 62 | 2 | 13.1 | 28.4 | 5.69 |
| 59 | 8.5 | 30.5 | 63 | 2 | 12.9 | 28.1 | 5.73 |
| 60 | 10 | 27.5 | 67 | 2 | 10.8 | 25.2 | 4.96 |
| 61 | 8.5 | 26.5 | 66 | 2 | 11.1 | 25.6 | 4.89 |
| 62 | 4.5 | 28 | 61 | 2 | 13.5 | 29.3 | 5.56 |
| 63 | 7.5 | 28.5 | 63 | 2 | 12.5 | 27.8 | 5.44 |
| 64 | 7.5 | 29.5 | 63 | 2 | 12.9 | 28.5 | 5.67 |
| 65 | 6 | 30 | 61 | 2 | 13.8 | 29.8 | 5.91 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 66 | 9 | 29.5 | 64 | 2 | 12.3 | 27.6 | 5.56 |
| 67 | 8 | 29.5 | 63 | 2 | 12.7 | 28.3 | 5.66 |
| 68 | 11 | 28 | 67 | 2 | 10.7 | 25.3 | 5.06 |
| 69 | 12 | 27.5 | 69 | 2 | 9.6 | 21.3 | 4.28 |
| 70 | 8.5 | 27.5 | 65 | 2 | 11.3 | 23.6 | 4.59 |
| 71 | 8 | 28 | 64 | 2 | 11.7 | 24.2 | 4.73 |
| 72 | 7 | 30 | 62 | 2 | 13 | 26 | 5.2 |
| 73 | 5 | 29 | 61 | 2 | 13.4 | 26.6 | 5.15 |
| 74 | 5.5 | 30 | 61 | 2 | 13.6 | 26.9 | 5.31 |
| 75 | 6 | 30.5 | 61 | 2 | 13.6 | 26.9 | 5.39 |
| 76 | 6 | 31.5 | 60 | 2 | 14 | 27.5 | 5.59 |
| 77 | 7 | 31.5 | 61 | 2 | 13.6 | 27 | 5.53 |
| 78 | 7 | 31.5 | 61 | 2 | 13.6 | 27.1 | 5.54 |
| 79 | 12.5 | 31.5 | 66 | 2 | 11.3 | 23.9 | 5.12 |
| 80 | 9.5 | 29 | 65 | 2 | 11.5 | 24.2 | 4.87 |
| 81 | 6.5 | 29.5 | 62 | 2 | 13 | 26.4 | 5.21 |
| 82 | 7.5 | 29 | 63 | 2 | 12.4 | 25.5 | 5.04 |
| 83 | 6.5 | 29 | 62 | 2 | 12.8 | 26.2 | 5.13 |
| 84 | 6.5 | 30 | 61 | 2 | 13.3 | 26.8 | 5.33 |
| 85 | 8 | 29.5 | 63 | 2 | 12.4 | 25.7 | 5.13 |
| 86 | 11.5 | 28.5 | 67 | 2 | 10.4 | 22.9 | 4.65 |
| 87 | 11 | 27.5 | 68 | 2 | 10.2 | 22.6 | 4.5 |
| 88 | 11 | 31 | 65 | 2 | 11.8 | 24.9 | 5.23 |
| 89 | 11.5 | 27 | 69 | 2 | 9.7 | 22 | 4.37 |
| 90 | 12.5 | 28.5 | 69 | 2 | 10 | 22.4 | 4.59 |
| 91 | 10.5 | 25 | 70 | 2 | 9.2 | 21.4 | 4.07 |
| 92 | 11 | 28 | 67 | 2 | 10.4 | 23.2 | 4.65 |
| 93 | 11 | 28.5 | 67 | 2 | 10.7 | 23.6 | 4.76 |
| 94 | 9 | 28 | 65 | 2 | 11.4 | 24.6 | 4.85 |
| 95 | 9 | 28.5 | 65 | 2 | 11.6 | 25 | 4.96 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 96 | 9.5 | 28.5 | 65 | 2 | 11.4 | 24.7 | 4.93 |
| 97 | 9 | 28.5 | 65 | 2 | 11.6 | 25.1 | 4.99 |
| 98 | 10 | 28 | 66 | 2 | 11 | 24.2 | 4.81 |
| 99 | 8 | 29 | 63 | 2 | 12.3 | 26.2 | 5.2 |
| 100 | 9 | 29 | 64 | 2 | 12.3 | 28.7 | 5.73 |
| 101 | 9.5 | 29.5 | 64 | 2 | 12.3 | 28.7 | 5.8 |
| 102 | 8 | 30.5 | 62 | 2 | 13.5 | 30.4 | 6.17 |
| 103 | 8 | 30 | 63 | 2 | 13.3 | 30.1 | 6.06 |
| 104 | 8.5 | 30.5 | 63 | 2 | 13.3 | 30.1 | 6.13 |
| 105 | 8.5 | 30.5 | 63 | 2 | 13.3 | 30.1 | 6.14 |
| 106 | 9.5 | 30 | 64 | 2 | 12.6 | 29.1 | 5.93 |
| 107 | 9.5 | 30.7 | 63 | 2 | 12.9 | 29.6 | 6.09 |
| 108 | 9 | 30.5 | 63 | 2 | 13.1 | 29.8 | 6.09 |
| 109 | 10.5 | 31 | 64 | 2 | 12.6 | 29.1 | 6.07 |
| 110 | 13 | 31 | 67 | 2 | 11.5 | 27.3 | 5.81 |
| 111 | 11 | 31 | 65 | 2 | 12.4 | 28.8 | 6.02 |
| 112 | 10 | 31 | 64 | 2 | 12.9 | 29.5 | 6.12 |
| 113 | 12 | 31 | 66 | 2 | 12 | 28 | 5.92 |
| 114 | 10.5 | 31.5 | 64 | 2 | 12.9 | 29.5 | 6.19 |
| 115 | 14.5 | 30.5 | 69 | 2 | 10.5 | 25.7 | 5.51 |