Developing and Testing Simple Weighable Lysimeter for Measurement of Crop Water Requirement and Evaluation of Crop Evapotranspiration Estimation Models

Nigusie Kebede Degefu

A Dissertation Submitted to the Department of Water Resources Engineering,

School of Civil Engineering and Architecture

Presented in Partial Fulfilment of the Requirement for the Degree of Doctor of Philosophy in Water Resources Engineering (Specialization in Irrigation Engineering)

Office of Graduate Studies

Adama Science and Technology University

March, 2025

Adama, Ethiopia

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2. Habtamu Beri (PhD)

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DECLARATION

I hereby declare that this dissertation entitled "Developing and Testing Simple Weighable Lysimeter for Measurement of Crop Water Requirement and Evaluation of Crop Evapotranspiration Estimation Models" 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 used for this thesis have been duly acknowledged through appropriate citations.

Nigusie Kebede Degefu	____________________	______________________
Name of the student	Signature	Date

APPROVAL BY SUPERVISORS

We hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled “Developing and Testing Simple Weighable Lysimeter for Measurement of Crop Water Requirement and Evaluation of Crop Evapotranspiration Estimation Models” by Nigusie Kebede Degefu.

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APPROVAL BY BOARD OF EXAMINERS

We the undersigned, members of the board of examiners of the dissertation open defence by Nigusie Kebede Degefu have read and evaluated the dissertation entitled “Developing and Testing Simple Weighable Lysimeter for Measurement of Crop Water Requirement and Evaluation of Crop Evapotranspiration Estimation Models” and examined the candidate during open defence. This is, therefore, to certify that the dissertation is accepted for partial fulfilment of the requirement of the degree of Doctor of Philosophy in Irrigation Engineering.

Chairperson	Signature	Date
Internal Examiner	Signature	Date
External Examiner 1	Signature	Date
External Examiner 2	Signature	Date

Final approval and acceptance of dissertation is contingent upon submission of its final copy to the office of Postgraduate Studies (OPGS) through the candidate’s Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head	Signature	Date
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BIOGRAPHICAL SKETCH

Nigusie Kebede Degefu was born on May 24, 1983, in Weliso Town, South West Shoa Zone, Ethiopia. He is the son of Mr. Kebede Degefu and Mrs. Aregash Bereded. He began his early education at Gobena Dachie Primary and Secondary School and later attended Geresu Dhuki Secondary and Comprehensive School in Weliso Town for his secondary and high school education.

His higher education journey commenced in 2005 when he earned a diploma in natural resource management from Maichew ATVET College. In 2011, he earned a Bachelor of Science (BSc) degree in Water Resource and Irrigation Management from Mekele University. Continuing his academic pursuits, he completed a Master of Science (MSc) degree in Hydraulic Engineering from Jimma University in 2016. In 2020, he joined Adama Science and Technology University to pursue a Doctor of Philosophy (PhD) in Water Resources Engineering, specializing in Irrigation Engineering.

Nigusie embarked on his professional career in 2005 as a development agent at the Weliso Wereda Agricultural Development Office, a role he held until March 2012. He then worked as an irrigation engineer in the same office until July 2013. From July 2013 to September 2017, he served as a water engineer at the Weliso Wereda Irrigation Development Authority. His expertise led him to become the Study, Design, Supervision, and Contract Administration Team Leader at the same institution from September 2017 to September 2018. He later transitioned into academia, joining Ambo University as a lecturer, where he worked from September 2018 to September 2020.

Throughout his career, Nigusie has been dedicated to advancing sustainable water resource management and irrigation engineering, making significant contributions to both the practical and academic aspects of the field.

DEDICATION

This dissertation is dedicated to my beloved wife, Yenienesh Endale, whose unwavering support, patience, and encouragement have been my greatest source of strength throughout this journey. I also dedicate this work to our lovely children, Hewan Nigusie and Natanim Nigusie, whose presence continues to inspire me.

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LIST OF ABBREVIATIONS

cm	Centimeter
CSA	Central Statistical Agency
Dp	Deep percolation
ET	Evapotranspiration
ETc	Crop evapotranspiration (actual)
ETo	Reference evapotranspiration
FAO	Food and Agricultural Organization
GDP	Gross Domestic Product
IA	Index of Agreement
Kc	Crop coefficient
kg	Kilogram
m	Meter
MARC	Melkasa Agricultural Research Center
masl	Meter above sea level
MBE	Mean Bias Error
mm	Millimeter
PVC	Polyvinyl chloride
PWP	Permanent Wilting Point
RAW	Readily Available Water
RMSE	Root Mean Square Error
TAW	Total Available Water

GENERAL ABSTRACT

*Scarcity of water is a growing challenge in agriculture, making efficient irrigation planning and management essential. Accurately determining crop water requirements is critical for optimizing irrigation, with direct lysimeter measurements providing the most precise results. However, lysimeter-based experiments are often limited due to high costs, lack of laboratory facilities, and equipment constraints. As an alternative, the Kc-approach, which estimates crop water needs by multiplying reference evapotranspiration (ETo) with crop coefficient (Kc), is commonly used in data-scarce regions. In line with this, the current study was aimed at developing and testing simple weighable lysimeter for measurement of crop water requirement and evaluation of crop evapotranspiration estimation models. The developed lysimeter was tested for its performance in 2023 and 2024, successfully detecting soil moisture variations as small as 0.2 mm, ensuring precise water requirement and crop coefficient measurements. Field experiments at the Melkasa Agricultural Research Centre were conducted to determine water requirements and crop coefficients of onion (*Allium cepa *L.) and the result revealed a seasonal crop evapotranspiration of 460.27 mm, with crop coefficient values of 0.68, 0.89, 1.03, and 0.86 for the initial, developmental, mid-, and late-season stages, respectively. Additionally, ten ETo models were assessed for their accuracy, and the Hargreaves and Blaney-Criddle equations were calibrated in the Kc-approach, using lysimeter-measured onion (*Allium cepa *L.) evapotranspiration. The calibration significantly enhanced the accuracy of both the Hargreaves and Blaney-Criddle equations, with the Hargreaves coefficient increasing by 48% (from 0.0023 to 0.0034) and the Blaney-Criddle coefficient decreasing by 9% (from 1 to 0.9135). The results indicated that the calibrated Hargreaves and Blaney-Criddle models were the most accurate alternatives for estimating ETo in the study area and regions with similar climatic conditions. Overall, this study provides valuable tools for optimizing irrigation management in data-scarce regions, contributing to improved water resource utilization and irrigation scheduling in semi-arid climates.*

***Keywords**: Weighable lysimeter, Crop coefficient, Evapotranspiration, Kc-approach, ETo-models, Onion, Semi-arid regions, Calibration.*

1. GENERAL INTRODUCTION

1.1. Background

The development of the economy and social progress is strongly influenced by water resource availability and management (Sullivan, 2002). Especially, for those countries in which their overall economic growth and social sector development are reliant on the agriculture sector. More specifically, in the arid and semi-arid regions, in which water is one of the most important limiting factors in the development of agriculture (Hend et al., 2019). For instance, in Ethiopia, agriculture contributes 40% of the GDP, 80% of the total employment, and 70% of the export earnings (Qureshi et al., 2018). In such countries, the resource becomes more important.

In many countries, especially in developing countries, the water share for irrigation is decreasing continuously, and the resource is becoming scarce. The competitive need for water for different uses (industries and domestic) is one of the cause (Dingre & Gorantiwar, 2020). On the other hand, limitations to develop new water resources because of high cost requirements, absence of appropriate sites for the storage reservoir, complexities of water delivery, and environmental concerns (Pereira, 2005), desertification, and overexploitation of the existing water resources (Bachour, 2013) are among the technical and economic reasons. In addition, climate change impacts on water availability for agriculture with respect to time and space with more emphasis in the arid and semi-arid regions (Halasuru Jayaram, 2018). Moreover, low efficiencies in irrigated agriculture also increase irrigation water demand (Yadeta et al., 2021b); all are the causes for scarcity of the resource.

Thus, in the context of water scarcity for agriculture, the precise management of available water for irrigation is important. Dependency on rainfall for future crop production has become a major constraint for sustainable food production in the developing countries (Adeboye et al., 2009). So effective planning and management of irrigation water and increasing irrigation efficiency is important and achieved through accurate estimation of water requirements of crops (Holzapfel et al., 2010; Wickramaarachchi et al., 2011).

Accurate water requirement determination is more important for vegetable crops that require frequent irrigation and are highly sensitive to water stress, like onion. Onion (*Allium cepa* L.) is a major vegetable crop cultivated in arid and semi-arid regions worldwide (Hend et al., 2019), including Ethiopia. In these regions, onion production relies entirely on irrigation. While irrigation enables year-round production, water availability remains the most limiting factor (Bossie et al., 2009). Additionally, onions have high water requirements (Lo´pez-Urrea et al., 2009), which constrains their production and expansion in such areas. Given these challenges, accurately determining the water needs of crops like onions is essential, as even small water savings can result in significant additional water availability (Yadeta et al., 2021a).

Crop water requirement determination is more accurate with direct measurement using lysimeters. However, such experiments are rarely undertaken due to high costs, lack of instruments, and laboratory facilities (Yadeta et al., 2021a). When direct measurement is not possible, the indirect method, which uses the Kc approach, in which crop water requirement is determined as a product of ETo and Kc is used. In this case, the accuracy of the water requirement determined depends on the method used to estimate the ETo. The FAO-56 Penman-Monteith method is used as a standard equation for estimating ETo for different climatic conditions of the world. However, data required in the Penman-Monteith method are not always available, especially in developing countries (Hunduma et al., 2020) in general and specifically in Ethiopia. Therefore, considering the large input data requirement of the FAO-56 Penman-Monteith method, the best performing model from the available alternatives with a limited input data requirement needs to be selected (Song et al., 2019) and calibrated to be used at a specific area of interest. From this perspective, this study aimed at developing and testing a simple weighable lysimeter for measuring of crop water requirement, crop coefficient and evaluating crop evapotranspiration estimation methods to be used for irrigation scheduling and management.

1.2. Statement of the Problems

Water scarcity in arid and semi-arid regions is one of the most important limiting elements in the development of agriculture (Hend et al., 2019). Thus, managing the available water is necessary, which is achieved through accurate determination of the water requirements of crops (Holzapfel et al., 2010; Wickramaarachchi et al., 2011). However, water requirements and locally determined crop coefficient (Kc) values are not available for many important vegetable crops, including onion, in Ethiopia. Lysimeters have been used for many years to directly determine crop water requirements (ETc) and crop coefficient (Kc) (Khan et al., 1993; Martin et al., 2001; Ünlü et al., 2010; Lasisi et al., 2019; Nicolás-Cuevas et al., 2020). Determination of ETc and Kc requires that the soil water balance components be determined for short time intervals like in days. This in turn requires that the lysimeters are either weighable or soil moisture sensors available to monitor change in moisture content per unit of time. Due to the unavailability of these facilities, ETc and Kc for different crops are rarely determined in Ethiopia. Thus, the design and operation of irrigation systems heavily depend on literature values, which undermine local conditions.

So far, in the country, a limited number of lysimeters are available (at Melkasa, Werer, and Bishoftu Agricultural Research Centers). In all sites, the type of lysimeter is a non-weighing type; soil moisture change is monitored using a neutron probe, which is expensive.

Most often, crop water requirements are estimated using indirect methods. That means reference evapotranspiration is determined using climate data and an appropriate estimation method, which is then adjusted to crop water requirements (ETc) using crop coefficient (Kc) values from literature for the crops considered (Doorenbos & Pruitt, 1977; Allen et al., 1998). The FAO-56 Penman-Monteith method is considered as a standard method, which is universally used but requires large climate data, which are not measured in most meteorological stations (Hunduma et al., 2020). Although there are several evapotranspiration estimation methods in the literature, which are developed for specific areas, there is no specific method calibrated for the different agro-climatic conditions of Ethiopia. In this perspective, this study was focused on developing a simple and low-cost weighable lysimeter to be used for measuring water requirements and crop coefficients of shallow-rooted vegetable crops. Moreover, the study attempted to evaluate and calibrate selected evapotranspiration estimation models using experimentally generated data to be used under data-scarce conditions of semi-arid climatic areas of Ethiopia.

1.3. Objectives of the Study

1.3.1. General objective

The main objective of this study was to develop simple weighable lysimeter and evaluate and calibrate selected evapotranspiration estimation methods to be used under data scarce conditions in Ethiopia.

1.3.2. Specific objectives

The specific objectives of the study were:

- ➢ To develop and test a weighable lysimeter to measure soil water balance components grown with shallow-rooted crops.
- ➢ To determine water requirements and develop a crop coefficient of onion crops.
- ➢ To evaluate and calibrate selected evapotranspiration estimation model based on measured data to be used under data-scarce conditions.

1.4. Research Questions

To address the objectives of the study the following research questions were formulated:

- ✓ How can a weighable lysimeter be developed and tested to accurately measure soil water balance components for shallow-rooted crops?
- ✓ What are the water requirements and crop coefficient values for onion crops under the given agro-climatic conditions?
- ✓ How accurate are selected evapotranspiration estimation models when evaluated and calibrated against measured data, and how suitable are they for use under data-scarce conditions?

1.5. Scope and Limitations of the Study

The study was conducted at Melkasa Agricultural Research Center, located in the semi-arid region of Melkasa, Ethiopia, over two consecutive years (2022/23–2023/24). It focused on the development and evaluation of a simple weighable lysimeter for measuring soil water balance components. The research specifically aimed to determine the water requirements and crop coefficient (Kc) of the Nafis onion variety, which is widely cultivated in the region. In addition, it included the evaluation of ten ETo models and the calibration of the Hargreaves and Blaney-Criddle equations using the Kc approach with experimentally derived onion ETc data. The study then identified the best-performing model and enhanced the accuracy of the Hargreaves and Blaney-Criddle equations for use under data-scarce conditions.

This study was significant as it focused on developing and testing a simple, cost-effective weighable lysimeter for measuring soil water balance components in shallow-rooted crops. By generating precise data on onion crop water requirements and crop coefficients, this research aimed to improve irrigation efficiency and support better water resource management. Additionally, the study evaluated and calibrated selected evapotranspiration estimation models using measured data, ensuring their applicability in data-scarce regions of Ethiopia.

The findings contributed to more reliable irrigation scheduling, reducing water wastage and improving crop productivity. Moreover, the development of a practical and affordable lysimeter provided a valuable tool for researchers and farmers, enabling more improved water management practices. Ultimately, this study enhanced agricultural sustainability by improving water use efficiency and addressing the challenges posed by limited water resources in semi-arid regions of Ethiopia.

While the study provided valuable insights and tools for improving irrigation scheduling and water use efficiency, some limitations should be noted. The scope was limited to development of a weighable lysimeter for shallow-rooted crops, limiting their applicability for measuring ETc and Kc for deep-rooted crops. Moreover, the economic feasibility of the developed weighable lysimeter was not analysed. The findings for onion ETc and Kc were for a specific agro-climatic zone, which may affect the generalizability of the results to other crops or regions with different environmental conditions. However, the study provides a valuable foundation for broader applications and future research. By focusing on low-cost, practical methodologies, this study supports improved water resource management in semi-arid regions facing similar constraints.

1.6. Organization of the Dissertation

This dissertation is structured into six chapters as follows:

Chapter 1: Introduction

This chapter provides a general introduction to challenges related to irrigation water resources, crop water requirement determination methods, and the determination of onion water requirements and crop coefficients. It also presents the requirement of ETo model evaluation and calibration. Additionally, this chapter outlines the background, objectives, problem statement, significance, and scope of the study.

Chapter 2: Literature Review

This chapter presents a comprehensive review of relevant literature, summarizing previous research findings and key conclusions on related topics. It establishes the foundation for the study by covering aspects such as onion and its water requirement, weighing lysimeter development for ETc determination, performance testing and validation methods, and results of past studies.

Chapter 3: Methodology

This chapter describes the overall methodological approach, including details about the study area: its location, soil type, farming systems, and climatic conditions. It also details the overall research method and design.

References: A list of references cited in the above chapters is provided at the end.

Chapter 4-6 present the results and discussions related to the specific objectives of the study, which have also been published in peer-reviewed journals. Each article includes the background of the study, methodology, results and discussions, conclusions, and recommendations, followed by a list of references.

Chapter 4: Development and Testing of a Weighable Lysimeter

This chapter presents the results of the first specific objective entitled "Development and testing of a simple weighable lysimeter to measure soil water balance components grown with shallow-rooted crops."

Chapter 5: Determination of Onion Water Requirements and Crop Coefficients

This chapter presents the results of the second specific objective entitled "Determination of water requirement and crop coefficient of onion using a weighing lysimeter at Awash Melkasa, semi-arid of Ethiopia."

Chapter 6: Evaluation and Calibration of Evapotranspiration Estimation Models

This chapter presents the results of the third specific objective entitled "Evaluation and calibration of selected evapotranspiration models using measured data for semi-arid areas of Ethiopia under data-scarce conditions."

2. LITERATURE REVIEW

2.1. Crop Water Requirement

Crop water requirement, or evapotranspiration (ETc), is defined as the combined processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration (Allen et al., 1998). Quantifying crop evapotranspiration is important in agriculture for irrigation scheduling (Abebe et al., 2021), designing and managing irrigation as well as drainage systems (Shenkut et al., 2013; Hunduma & Kebede, 2020), and designing hydraulic structures (Tukimat et al., 2012). Therefore, determining the evapotranspiration of a crop is very important.

Of course, many studies of crop water requirements have been undertaken for a variety of crops in different locations, and crop water requirements and crop-coefficient curves are developed from these studies. However, the results from one environment may not be readily transferable to another because the crop evapotranspiration rate depends on climatic and environmental conditions, as well as the development stage of the crop (Pérez-Ortolá & Knox, 2015).

Onion (Allium cepa L.) and its water requirement

Onion (Allium cepa L.) is one of the major vegetable crops grown in arid and semi-arid regions across the world (Hend et al., 2019). Worldwide land dedicated to onion (Allium cepa L.) production has doubled in the last 20 years, reaching 3.10 million ha. The average yield also increased from 12 ton ha^{-1} in the early 1960s to 18.4 ton ha^{-1} in 2004 (López-Urrea et al., 2009). Global annual production was around 97.8 million tons from 5.2 million ha of land (Hend et al., 2019).

In Ethiopia, onion is a high-value bulb crop produced by small farmers and commercial growers for both local and export markets (Bossie et al., 2009). The country produces 273,859 tons from 36,373 hectares of land with an average yield of 7.5 ton ha^{-1} in 2019 (CSA, 2020). The total production and the total cultivated area for the crop grew by 18.7% and 59.7%, respectively, between 2015 and 2020 (Miruts et al., 2021). It has a vital role in the human diet as well as having a medicinal function (Rodríguez Galdón et al., 2008). It is an indispensable part of the Ethiopian daily meal as it improves the taste and scent of the food.

In arid and semi-arid regions, the production of onion is entirely dependent on irrigation. As irrigation water is available, onion can be produced throughout the year; however, in these areas, water availability is the most limiting factor for onion production (Bossie et al., 2009). Moreover, being water requirements for onions are very high (Lo´pez-Urrea et al., 2009), restricts the production and expansion of the crop in such areas. Provided these limitations, it is necessary to determine the water requirement of crops such as onion. Because saving small percentages brings an extra availability of significant volumes of water (Yadeta et al., 2021a).

Water requirements of onion depend on different factors such as variety, planting density, crop husbandry techniques, expected yield, local soil, agro-climatic conditions, irrigation application, and scheduling. As reviewed by Pérez-ortolá and Knox (2015), onion water requirements ranges from 225 to 1040 mm to produce a mean yield of 10 to 77 ton ha^{-1} in different locations, soil type, agro-climatic areas and with irrigation systems of varying efficiency. The reported figures represent net irrigation needs; there is an additional requirement to account for system efficiency depending on the water application method.

2.2. Estimation of ET

ET can be determined using direct and indirect methods (Evett et al., 1989). Determining ET using soil water balance and lysimeters are among the direct methods, while those methods use meteorological data to compute ET classified as indirect methods (Allen et al., 1998).

2.2.1. Evapotranspiration determination using direct methods (lysimeters)

Among the direct methods used for the determination of evapotranspiration are lysimeters devices that have an isolated structure where the soil and vegetation do not interfere externally. Thus, it is possible to control all inputs and outputs of water in the system (Fenner et al., 2019). Both weighing and non-weighing types of lysimeters have been developed (designed, constructed, and installed) for measuring evapotranspiration (Khan et al., 1993; Martin et al., 2001; Ünlü et al., 2010; Lorite et al., 2012; Schmidt et al., 2013; Lasisi et al., 2019; Nicolás-Cuevas et al., 2020). Lysimeters are considered the standard for evapotranspiration measurements (Ünlü et al., 2010) and calibrating other evapotranspiration estimation methods (Sanches et al., 2017).

Determination of evapotranspiration using lysimeters involves measuring the various components of the soil water balance. The method consists of assessing the incoming and outgoing water flux into the crop root zone over some time interval. Irrigation and rainfall add water to the root zone while part of it might be lost by deep percolation (Allen et al., 1998).

The data for the three components of the soil water balance, i.e., rainfall (P), is obtained from the weather station, irrigation (I), and deep percolation (Dp) directly measured from the amount of water applied and during excess rainfall events at the drainage collection chamber, respectively, for both types of lysimeters. What makes difference between the two types of lysimeters (weighing and non-weighing) is the data acquisition method for the fourth component, i.e., change in soil moisture content.

Soil moisture measurement in lysimeters

Method for soil moisture change measurement in lysimeters bases on the type of lysimeter. In weighing-type lysimeters, the soil moisture change is directly measured by the change of mass (Payero & Irmak, 2008). Determining the variation in weight of a cropped soil, i.e., the crop including the soil zone supplying water to the crop, within a given time interval. Without irrigation or rain, weight variation is almost entirely due to ET. Plant matter varies to a minimal extent compared to water (Rana & Katerji, 2007). The soil moisture change for a given time interval is computed as the difference in mass of the lysimeter, i.e., the current mass of the set and the previous mass of the set for the time interval considered (Da Silva et al., 2020).

In non-weighing type lysimeters, changes in soil moisture are measured volumetrically for a given time interval (Scharifi et al., 2019). In this type of lysimeters, soil moisture change for a given time interval is traditionally determined by means of soil sampling and gravimetric analyses. However, in the past decades, sensor technologies largely replaced this method because soil water sensors enable monitoring of water content at short time intervals without destructive and laborious soil sampling (Nolz, 2016). A neutron probe is one of the sensor-based devices used to determine the soil moisture content. Different authors used the device to monitor the change in soil moisture after calibration following the standard procedure for neutron probe calibration given in the user manual for the model (Shenkut et al., 2013; Dirirsa et al., 2015; Abebe et al., 2021). Time Domain Reflectometry (TDR) is the other device used to monitor soil moisture change to compute soil water balance. Different authors used this device to compute the evapotranspiration of crops (Quezada et al., 2011; Carvalho et al., 2016). Tensiometer is also used to monitor the moisture change in soil (Quezada et al., 2011).

2.2.2. Evapotranspiration determination using indirect methods

On the other hand, owing to the difficulty of obtaining field measurement data, ET is computed indirectly from weather data by the crop coefficient approach. In the crop coefficient approach, the crop evapotranspiration, ETc, is computed as a product of the reference crop evapotranspiration, ETo, and crop coefficient, Kc (Doorenbos & Pruitt, 1977; Allen et al., 1998).

This method is the most widely accepted two-step approach, which includes the quantification of the atmospheric demand through the computation of reference evapotranspiration (ETo), and the surface characteristics through a crop factor called a crop coefficient (Kc), and is generally followed in the estimation of crop evapotranspiration.

2.3. Reference Evapotranspiration (ETo)

Reference evapotranspiration, ETo, is defined as the rate of evapotranspiration from an extensive surface of 8 cm to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground, and not short of water (Doorenbos & Pruitt, 1977). According to Allen et al. (1998), ETo is the rate of ET from a hypothetical crop with a height of 0.12 m, albedo (0.23), and fixed canopy resistance (70 sm^{-1}). As described by Parisi et al. (2009), ETo can be estimated by means of empirical models or instrumental proxies like evaporation from atmometers or pan evaporimeters.

2.3.1. Reference evapotranspiration (ETo) models

In-situ measurement of ETo is expensive and time-consuming (Muhammad et al., 2019; Yadeta et al., 2021a). In this regard, a large number of models have been developed for estimating reference crop evapotranspiration from meteorological data (Hargreaves & Samani, 1985; Allen et al., 1998; Droogers & Allen, 2002; Irmak et al., 2003; Trajkovic, 2007; Tabari & Talaee, 2011; Tabari et al., 2013; Berti et al., 2014; Heydari & Heydari, 2014; Dorji et al., 2016; Ahooghalandari et al., 2016; Christian & Andrés, 2021). The models are categorized based on the weather parameters that play the dominant role in the model. It ranges from the complex energy balance equations to simpler equations, which require limited meteorological data.

Models are classified as temperature-based models, radiation-based models, mass-transfer models, and combination models, which are based on the energy balance and mass transfer principles (Adeboye et al., 2009).

Some of the methods are only valid under specific climatic and agronomic conditions. Therefore, the developed models require local calibration to validate their usage. From the models developed, the FAO Penman-Monteith method is recommended as the standard equation for the estimation of the reference evapotranspiration for different climates of the world. However, this equation needs full weather data, but few stations with complete weather data exist in different parts of the world, especially in developing countries (Hunduma et al., 2020).

During the selection of models for reference evapotranspiration computation, the availability of meteorological data is a major consideration (Al-Ghobari, 2000). Temperature and radiation-based methods are simple with a low number of input variable requirements (Rácz et al., 2013).

2.3.2. Calibration of ETo models

Accurate estimation of reference evapotranspiration (ETo) is essential for water resource management, irrigation planning, and climate impact studies. The FAO-56 Penman-Monteith model (Allen et al., 1998) is widely regarded as the most reliable method; however, its high data requirements often necessitate the use of empirical models such as Hargreaves-Samani, Blaney-Criddle, and Priestley-Taylor in regions with limited meteorological data. To enhance their accuracy, researchers have extensively studied calibration, adjusting model parameters to reflect local climatic conditions.

One of the most common approaches in model calibration is modifying the empirical coefficients of temperature-based models like Hargreaves-Samani, Blaney-Criddle, and Priestaley-Taylor (Heydari et al., 2015; Metcalfe et al., 2019). Studies in arid and semi-arid regions have shown that these models tend to overestimate ETo due to extreme temperature fluctuations and low humidity. (Djaman et al., 2015) assessed temperature-based models in the Sahel region, finding that uncalibrated models tend to overestimate ETo due to high radiation and low humidity. Their study demonstrated that modifying empirical coefficients in the Hargreaves-Samani model significantly improved accuracy. Similarly, (Majeed et al., 2017) evaluated the Hargreaves-Samani equation in Pakistan, recommending adjustments to account for regional wind speed variations, which are often ignored in temperature-based models. Cobaner et al. (2017) and Ogunrinde et al. (2022) also highlighted the need for regional coefficient tuning, showing that calibration improves the Hargreaves-Samani model's performance across different climatic sub-regions. The other study by Tabari and Talaee (2011) calibrated the Hargreaves model in Iran and found significant improvements in ET_0 estimation when adjusting the empirical coefficients. Similarly, (Cobaner et al., 2017) calibrated the Hargreaves-Samani model for high-altitude regions by modifying the empirical coefficients, leading to improved performance in the Centeral European climate conditions.

The Blaney-Criddle model, initially developed in 1950 and later modified by FAO (Doorenbos & Pruitt, 1977), estimates ET_0 based on temperature and daylight hours. This model also benefits from calibration to enhance its applicability across diverse environments. A study in Turkey by (Gharehbaghi & Kaya, 2022) showed that locally adjusted coefficients significantly improved the model's accuracy in estimating ET_0. Furthermore, a study in Iran (Fooladmand & Ahmadi, 2009) and in Jordan (Mohawesh, 2010) highlighted the importance of spatial calibration in arid and semi-arid regions to minimize estimation errors.

Comparative studies have assessed the performance of these models against the FAO-56 Penman-Monteith standard. For example, Trajkovic, (2007) evaluated different temperature-based models and found that calibration of both Hargreaves and Blaney-Criddle models improved their correlation with FAO-56 estimates. A study conducted by (Heydari et al., 2015) reported similar result. In conclusion, the calibration of the Hargreaves and Blaney-Criddle models is critical for improving ET_0 estimation across different climatic conditions. Several studies have demonstrated that regional parameter adjustments significantly enhance the performance of these models, making them more reliable alternatives in data-scarce regions.

2.4. Crop Coefficient (Kc)

Crop coefficient, Kc, is the ratio between crop evapotranspiration (ETc) and reference evapotranspiration (ETo), and it represents an integration of the effects of four essential qualities (albedo or reflectance of the crop soil surface, crop height, canopy resistance, and evaporation from the soil) that differentiate the crop from reference grass (Allen et al., 1998). The crop coefficients developed in one region often do not transfer exactly to another region because the values for the same crop may vary from place to place; thus, crop coefficient values should be developed for those crops commonly grown in a given climatic condition (Evett et al., 2009). As described by Doorenbos and Pruitt (1977), crop characteristics, crop planting or sowing date, rate of crop development, length of growing season, soil evaporation, and climate are the main factors affecting the value of the crop coefficient.

Due to the ET differences during the growth stages, the Kc for the crop will vary over the developing period, which can be divided into four distinct stages: initial, crop development, mid-season, and late season. For instance, the author suggested kc values for onion (dry) were 0.7, 1.05, and 0.75 for the initial stage, mid-season stage, and end of late season respectively. However, these values are for sub humid climates with an average minimum relative humidity (RH_{min}) of 45% and a wind speed (U_2) of 2 m/s, so the Kc (mid) and Kc (end) values need to be corrected following the correction procedure for more or less humid and/or more or less windy conditions.

In the last 15 years, many authors have shown that the adoption of Kc values proposed in the FAO documents, even if adjusted to account for local conditions, may lead to inaccurate estimates of crop water requirements. This is mainly because, from a theoretical point of view, the tabulated Kc curve is designed to reflect ETc in optimum agronomic and water management conditions, but in practice, Kc values depend on the environmental and management conditions under which they were obtained. Even the application of the adjustments proposed by FAO-56 is often not sufficient to make the Kc curve truly site-specific (Facchi et al., 2013).

For instance, as reported by Abebe et al. (2021), measured Kc values of onion were significantly different from the FAO-56 reported values, and the author recommends local calibration of crop coefficients is essential for efficient irrigation water management and precise water applications. Moreover, the use of on-site microclimatological data and crop coefficients enables growers to determine crop water use in a reliable, usable, and affordable format (Piccinni et al., 2009). Different authors have suggested developing an on-site Kc value for agricultural crops based on lysimeter data and local climatic conditions, which would be more relevant for quantifying site-specific crop water requirements and for initiating sustainable management of water resources (Shenkut et al., 2013; Dirirsa et al., 2015; Dingre & Gorantiwar, 2020; Abebe et al., 2021).

2.5. Weighing Lysimeter Development for ETc Determination

2.5.1. Weighing lysimeters

Lysimeters are containers or tanks filled with soil in which plants are grown and used to measure the amount of water consumed in evapotranspiration by a vegetated surface. It is also used in water quality studies to determine the movement of chemicals in the soil profile (Martin et al., 2001). Lysimeters for ET research are usually classified as monolithic or reconstructed soil profiles, weighing or non-weighing, and gravity or vacuum drainage (Kohnke, H.; Dreibelbis, 1940). Different types of lysimeters have been reported (Gifford et al., 1982; Khan et al., 1993; Martin et al., 2001; Payero & Irmak, 2008; Parisi et al., 2009; Lorite et al., 2012; Fisher, 2012; Nicolás-Cuevas et al., 2020; Soler-m et al., 2021). Basically, lysimeters are two types: weighing and non-weighing (Parisi et al., 2009).

Weighing lysimeters are standard tools (Ünlü et al., 2010) and the most reliable method to measure crop ET (Johnson et al., 2005) and are used to verify or calibrate weather-based reference-ET estimation models. These are true as long as they are properly constructed, installed, operated, and managed (Bryla et al., 2010; Sanches et al., 2017). It gives data on the average soil water content change (ΔS), which is given by the difference in the weight of the lysimeter before and after a given period of time (Δt) (Nicolás-Cuevas et al., 2020). This ΔS with other components of the soil water balance (irrigation, precipitation, and drainage) over Δt provides the average evapotranspiration rate of the crop.

Based on the time interval between two consecutive weight measurements, weighing lysimeters are of two types: continuous weighing and intermittent weighing (weighable lysimeters) (Howell et al., 1991). Even if the former are accurate and precise (Howell et al., 1985), they are not widely used due to the high installation costs and skilled personnel requirements. Its weighing mechanism and the lysimeter are permanently installed, and measurements are taken at intervals as short as one minute (Zupanc et al., 2012). For weighable lysimeters, the weighing system is movable and moved to the lysimeter every time to take measurements. The time interval between two consecutive measurements is generally one day or longer (Type & Silva, 2022).

Lysimeters main objective in ET determination is to create a controlled environment for the measurement of water into and out of the system. This requires matching the soil-plant system inside the lysimeter with the surrounding area in terms of soil water content (Shenkut et al., 2013), plant density, and soil (nutrient availability) (Khan et al., 1993), etc. However, matching the soil and water conditions inside and outside the lysimeter is difficult. For instance, the volume of soil in the tank may limit a normal rooting profile of the plant. Additionally, more moisture is available at the bottom soil profile of a lysimeter relative to the surrounding area of the same depth, unless an efficient drainage system removes the excess water (Tanner, 2015). To minimize this problem, great concern is required at all steps of lysimeter design, construction, installation, and management in the field.

The other concern in developing a lysimeter for ET determination is its representativeness. The representativeness of the lysimeter depends on the soil profile type of the lysimeter, i.e., monolithic or reconstructed. Many weighing lysimeters have utilized reconstructed soil profiles (Howell et al., 1991). With respect to small, reconstructed lysimeters, large, monolithic lysimeters are more representative. Size is one of the main determinants of its cost in association with the types of equipment, labour, and materials used in the lysimeter construction (Schneider et al., 1998). Therefore, how well a lysimeter represents the field condition is dependent on a compromise between costs and management under field conditions.

2.5.2. Design and construction of weighing lysimeters

Regarding the design and construction of lysimeters, there is no universal methodology; rather, it is based on specific requirements that might be obeyed by crop, soil, climate, availability of materials and technology, skill of users, and cost involved (Khan et al., 1993). Kohnke et al. (1940) strengthened this idea by cautioning, "That no one construction should be regarded as standard in a lysimeter and that a proper design can be made only by having an accurate knowledge of both the purpose of the experiment and of the pedologic, geologic, and climatic conditions." Due to its specificity, lysimeters have been made following numerous designs (Sołtysiak & Rakoczy, 2019) or designs have been copied or duplicated (Howell et al., 1991).

Even if there is no universal standard in designing lysimeters, ease of fabrication, simple installation, low maintenance requirements, and low cost are important considerations (Fisher, 2004). According to Martin et al. (2001), in designing lysimeters, two points are very important: the lysimeters had to be large enough to represent field conditions, yet small enough not to require expensive equipment for lifting and weighing. In the other hand, farmers' needs are also considered as a design requirement. Nicolás-Cuevas et al. (2020) reported that small dimensions for ease of installation and integration in the field framework, easy transport, an affordable cost, and good performance under farming operations are among the lysimeter characteristics required to achieve farmer needs.

As a main component, a weighable lysimeter comprises an inner tank, an outer tank, a drainage system, and a weighing mechanism (Fisher, 2004; Schmidt et al., 2013; Jayaram et al., 2018). Issues related to the design and construction of these components are pointed out in this section.

1. Inner and outer tank

Materials used

Different materials are used to construct the inner and outer tanks of a weighing lysimeter. For the inner tank steel materials (Schmidt et al., 2013; Fenner et al., 2019) and plastic material (plastic drum) (Parisi et al., 2009; Wickramaarachchi et al., 2011; Lasisi et al., 2019) are among them. Currently, columns of materials resistant to moisture, such as PVC and stainless steel, are used (Sołtysiak & Rakoczy, 2019). While for the outer tank, reinforced fiberglass (Mariano et al., 2015), masonry work (Schmidt et al., 2013), and steel materials (Sołtysiak & Rakoczy, 2019) have been used to minimize heat conduction down the lysimeter walls and to retain the soil around the lysimeter.

Shape

As reviewed by Howell et al. (1991), the shapes of weighing lysimeters are of two types: rectangular, and circular. Many weighing lysimeters are rectangular but circular lysimeters are inherently much stronger per unit container mass.

Dimensions or size

The basic parameters that differ in the lysimeter size are surface area (diameter or width and length, based on the shape) and depth (Sołtysiak & Rakoczy, 2019). Surface area over 29 m^2 and depth up to 2.7m have been reported (Howell et al., 1991). However, in recent years, small cylindrical weighing lysimeters have been available on the market, such as Smart Field

Lysimeter (SFL) and Ready-To-Go lysimeter, having a size as small as 30 cm in diameter and 30 cm in depth, (Doležal et al., 2018). In non-weighing type lysimeters having a diameter and depth of 30 cm (Halasuru Jayaram, 2018), 0.3 m diameter and 0.5 m depth (Wickramaarachchi et al., 2011) have been reported. In general, weighing lysimeters having different sizes has been reported (Gifford et al., 1982; Fisher, 2004; Parisi et al., 2009; Sanches et al., 2017; Fenner et al., 2019; Fenner et al., 2019; Soler-m et al., 2021).

Depth is a critical design parameter, and for ET measuring lysimeters, it depends on the root depth of the crop in concern. Even if root depth is one of the determinant factors of the lysimeter depth, for normal rooting of the crops, it is not an economically sound criterion for designing a lysimeter. Consideration of root density rather than maximum root length can substantially decrease the cost of construction with insignificant loss of accuracy in the measurement of ET (Khan et al., 1993). For instance, onion having a root depth of 50 cm; ninety percent of the root system concentrated in the top 40 cm of soil depth (Bossie et al., 2009), an experimental plot depth of 40 cm was used (Lo´pez-Urrea et al., 2009).

In determining the depth of a lysimeter, the rim is one of its components. Rim is the height of the lysimeter above the surrounding soil surface (edge of the tank) in which the lateral water movement caused by runoff is prevented (Evett et al., 2009). Most of the time this rim height is 5 or 10 cm. Height less than 5 cm is impracticable for keeping the lysimeter separate from the soil and water of the adjacent land surface (Khan et al., 1993).

Surface area (expressed in terms of diameter or length and width, based on shape) is the other parameter in designing a lysimeter, which is based on the expected plant to be studied. The surface area should be representative of the crop planting geometry (Ritchie & Burnett, 1968). The planting geometry determines the number of crops within a given area. A dimension exactly representing a section of a few lines and a number of plants cannot be made common to all crops; rather, plant density should be made the same inside and outside with little modification of geometry, which would perhaps not affect crop growth (Khan et al., 1993).

In determining the surface area of the outer tank, the gap between the outer and inner tanks should have to be considered. As an observation of Khan et al. (1993) for weighing lysimeters, the area between the outer and inner tank (annulus) ranging from 4% to 65% of the lysimeter soil area was used. Martin et al. (2001) and Sanches et al. (2017) respectively reported a gap between the outer and inner tank of 9.5 mm and 8 cm. As a general guide, this gap should be as narrow as practical to limit wall heating; however, sufficient clearance should be provided to avoid any wall contact during weighing (Howell et al., 1991).

2. Drainage system and pipe

The drainage system is used to remove excess water that accumulates at the bottom of the inner tank. Different mechanisms can be used, such as vacuum drains and gravity drains (gated, PVC mounted at the bottom of the inner tank to transport the water accumulated to the drainage reservoir at the chamber). Different types have been reported on (Zupanc et al., 2012; Schmidt et al., 2013; Mariano et al., 2015; Jayaram et al., 2018; Fenner et al., 2019).

The drainage pipe that transports drained water from the inner tank to the drained water collector having a smooth gradient with a diameter of 2 cm and 5 cm has been reported by Lorite et al. (2012) and Silva et al. (2020), respectively.

3. Weighing mechanism

The main part of a lysimeter facility is its weighing mechanism. In a weighing system, scaling a large mass of several tons to measure a change in a small mass is the great challenge (Nolz, 2016). As a review of Howell et al. (1991), a variety of weighing mechanisms are reported such as:

1. Mechanical scales (permit large counter-weights to offset lysimeter mass) with an accuracy of 0.05 mm to 0.02 mm,
2. Floating lysimeter using the principle of buoyancy with an accuracy of 0.025 mm,
3. Hydraulic weighing that has accuracies of 0.05 to 0.1 mm and
4. Electronic scales or strain-gage load cells (measure the total lysimeter mass); load cells are more accurate than 0.01%.

This weighing system can be built above or underground (Gifford et al., 1982). Martin et al. (2001) designed an aboveground lifting and weighing system composed of an electrical winch (to lift the lysimeters) and a strain gage with a digital weigh meter (directly to weigh the lysimeters). While designing this system, the author considered three points: 1) it can be easily moved from one lysimeter to the next; 2) it can be easily removed from the field so as not to interfere with field operations; and 3) it has sufficient ground clearance to allow the lysimeter to be lifted completely out of the retaining shell as design criteria.

The required ET accuracy influences many weighing lysimeter design parameters, especially the type of scale. In using electronic scales as a weighing mechanism, the resolution of the lysimeter depends on the resolution of the scale (load cell) and the data logger (for those who have a data logger) (Payero & Irmak, 2008). Three descriptions of lysimeter accuracy (resolution, precision, and accuracy) are often used and sometimes confused. Resolution is the last significant definable increment of the measurement; precision is the stated level of the measurement (variability among numerous measurements), and accuracy is the definable verification of the stated measurement compared to a "true" value (Fritschen & Gay, 1979). Lysimeter resolution is determined by the ratio of the resolution of the scale to the surface area of the lysimeter. A resolution of 0.056 mm (for 0.5 kg scale resolution and 9 m^2 lysimeter surface area) and 0.17 mm (for 1.5 kg scale resolution) by Lorite et al. (2012), 0.1 mm by Nolz (2016), 0.15 mm by Mariano et al. (2015), and 1 mm as mentioned by Lorite et al. (2012) have been reported.

2.5.3. Installation of lysimeters

As described above, lysimeters can be classified as monolithic or reconstructed. The installation of the reconstructed type of lysimeter follows a different procedure based on the drainage system it has. However, in common as reported by Fisher (2004), Schmidt et al. (2013), and Sanches et al. (2017), the following activities have been undertaken while installing the lysimeters. 1) A pit sufficiently larger and deeper than the lysimeter outer tank was dug; the soil is removed in a 10 cm layer and placed in a separate pile. 2) The bottom of the pit was leveled; the outer tank was placed, and soil was backfilled around. 3) The inner tank was placed at the centre of the outer tank. 4) The drainage system was installed, and finally the inner tank was backfilled.

During backfilling, the soil was backfilled with the original soil material in the reverse order in which it was removed. However, before the soil is backfilled, to facilitate drainage, different materials such as gravel (pebbles having 1-2 cm diameter), sand, and geotextile or mesh were placed at the bottom of the inner tank. Even if the combination and order of the placement of those materials differ from author to author. For instance, the following materials and orders were used: gravel-sand-soil (Schmidt et al., 2013; Ghamarnia et al., 2014) and gravel-geotextile-soil (Lorite et al., 2012). While backfill gentle compaction with watering was made (Ghamarnia et al., 2014). After backfilling the lysimeter with soil, it was subjected to wetting-drying cycles to promote the settling of soil particles (Corwin & LeMert, 1994).

2.5.4. Calibration and testing

Following installation and before using the lysimeters, a test should be undertaken, especially of the weighing mechanisms (Fisher, 2012; Silva et al., 2020). Testing is required to ensure the reliability of the weighing system and specifications provided by the manufacturer. According to Martin et al. (2001), performance tests can be achieved through evaluating linearity, repeatability, and creep; the combined effects of the individual errors were addressed through the measurement uncertainty. Morse and Baer (2003) reported that testing involves four components: reproducibility, linearity, calibration, and corner load.

i. Calibration

Calibration refers to a comparison of the weight reading of a given mass standard and the actual value of that standard (Morse & Baer, 2004). According to Gifford et al. (1982), calibration of the lysimeter was performed by loading and unloading known weights (weights that are standardized by weighing on an electronic scale having high resolution) and recording the outputs. Of course, recording while unloading provides a check on hysteresis; however, hysteresis is checked if the lysimeters are weighing continuously, not necessarily if the lysimeters are weighing intermittently (Martin et al., 2001). Different loading cycles were used by different authors; for instance, Martin et al. (2001) used one, while Silva et al. (2020) used five.

Known weights can be prepared from packed sand, gravel, bricks, or using other materials. These weights are weighted on the lysimeter to produce calibration points for analysis. The calibration points are pairs of data (true value and lysimeter reading of the standard mass) subjected to linear regression analysis (Sanches et al., 2017), and then a calibration curve is produced. This curve (regression line or best-fit equation) shows the relationship between the measurement values and a known reference and is often referred to as the transfer function. Different authors, Ünlü et al. (2010), Schmidt et al. (2013), Fenner et al. (2019), and Silva et al.

(2020) have described similar procedures to calibrate load cell-based weighing lysimeters of varying shapes and sizes.

ii. Linearity

Linearity is the characteristic that measures the accuracy of the instrumental intermediate readings throughout the weighing range of the instrument (Morse & Baer, 2004). The relationship between the input (true value of the load) and the output (the reading of the scale) is called its characteristic curve; ideally, it is a straight line. The deviation of the characteristic curve from this straight line going through the weighing range is called non-linearity. This deviation is systematic in nature for a given balance unit, although generally different from balance to balance (Morse & Baer, 2004). During the linearity test, measurements should be made at about ten equal steps across the range of the balance (Davidson & Perkin, 2004).

The data collected from the calibration procedure is used to analyse the linearity of the system. For each measured value, the difference (deviation) between the measured value and the best-fit equation was evaluated. The maximum deviation is the linearity error; it is compared with the manufacturer's specifications (Martin et al., 2001).

iii. Repeatability

Repeatability is the capability of a device to produce the same output reading when the same load is applied several times in sequence on the platform using the same procedure. Walendziuk and Idzkowski (2017) pointed out the test is undertaken with a test load of about 50% of the calibration range, and one repeatability test consists of 10 repeated measurements of the same mass.

As described by Martin et al. (2001), repeatability is analysed by lifting the standard weight 10 times and calculating the residual of each lift. The residual is the difference between the measured weight and the average weight. The repeatability was taken as the average spread of these residuals. In more elaboration, repeatability is expressed as a standard deviation (Morse & Baer, 2003; Walendziuk & Idzkowski, 2017).

The largest standard deviation is the repeatability error, compared with the standard deviation at the specification (NATA, 2018). As an observation of Davidson and Perkin (2004), for a repeatability assessment, the maximum difference between consecutive weighing, the maximum difference between any weighing, the standard deviation of the series $\sigma(n-1)$ and the standard deviation of the series accounting for drift should be calculated. The average measured mass difference can also be compared with the certified mass difference.

While the repeatability test, the test is performed with at least one test load, LT, which should be selected in a reasonable relation to Max (maximum) and the resolution of the instrument, to allow an appraisal of the instrument performance. For instruments with a constant scale interval d, a load of about 0.5Max ≤ LT ≤ Max is quite common; this is often reduced for instruments where LT would amount to several 1000 kg (Euramet, 2015). After selecting the test load Morse and Baer (2003) stated the repeatability test procedure as follows with data recording format, Table 2.1.

1. Tare the instrument to read all zeros.
2. Place the test weight on the scale. Record the reading in the column labelled "full scale"
3. Remove the weight (don't rezero), and record the reading under "zero"
4. Repeat steps 2 and 3 until lines 1 to 11 are all filled in.
5. Transcribe the two columns of numbers into a spread sheet program.
6. Use the program to calculate the standard deviation of both columns of numbers.
7. Compare the standard deviation calculated with the instrument specification.

Table 2-1. Repeatability test data collection chart

line	Zero	Full scale
1	x	
2		
:		
11		
Standard deviation (SD)		x

iv. Measurement uncertainty

As described by Martin et al. (2001) above, after the performance test of the system is evaluated using linearity, repeatability, and creep, individual error for each parameter is obtained. The combined effect of the individual errors is called measurement uncertainty.

The author found uncertainty of the weights measured varied with the number of lifts, and for five lifts performed, then the measurement uncertainty would be ±0.4 kg over the area of the lysimeters (0.929 m^2), this represents a water depth of 0.43 mm, which is acceptable for periods of a day or more.

2.5.5. Validation

To confirm the validity of the measurements obtained from a newly developed weighing lysimeter, the result from the newly developed lysimeter was compared with the result of other studies for the same crop (Soler-Méndez et al., 2021). In addition, the authors made a comparison between the results obtained with the FAO-56 PM data of the crop in kc base. The comparison results in both cases showed similarities, and the authors confirmed that the measurements of the standard weighing lysimeter are valid for the main function for which it was designed, which is the control of the water balance of vegetable and herbaceous crops.

3. OVERALL METHODOLOGICAL APPROACHES OF THE STUDY

3.1. Description of the Study Area

3.1.1. Location

The study was conducted within the year 2022-2025 at Melkasa Agricultural Research Centre (MARC) which is found in the South East Shoa Zone of Oromia regional state, central rift valley of Ethiopia. Geographically the area is located at 8^o 24'-8^o 26'N, 39^o 18'-39^o 22'E, and 1550 m.a.s.l. latitude, longitude, and altitude respectively.

3.1.2. Climate

The climatic condition of Melkasa is characterized as hot throughout the year with a low amount of annual rainfall. It has an annual average rainfall of 845.5 mm with minimum and maximum temperatures of 14^oC and 29^oC respectively. The evaporative demand becomes highest during the months of March, April, and May. During these months, the average maximum temperature is around 30^oC while the average relative humidity drops to 51%. During the main crop growing season (June to September), average maximum temperature and average relative humidity are approximately 27^oC and 64%, respectively (Yenesew M. 2015). According to the agro-ecological zones classification of the Ethiopia Ministry of Agriculture, Melkasa falls in the semi-arid agro-ecological zone.

3.1.3. Soil

The soil of Melkasa is classified as a Hypo Calcic Regosol (World Reference Based Classification). The dominant soil type is Andosol of volcanic origin with loam and clay loam texture. Such soils are considered to have high water-holding capacity.

3.1.4. Farming system

Melkasa Agricultural Research Centre practices different farming systems; including dairy, poultry, and crop farm. A variety of crops are grown on the crop farm. During the main growing season, crops such as teff, sorghum, maize, haricot beans, and soya beans are grown. Whereas onion, tomato, banana, papaya, and sugarcane are grown in the off season. During the off-season, crops are grown using irrigation from the Awash River as a water source. The location map of the study area is given in Figure 3-1.

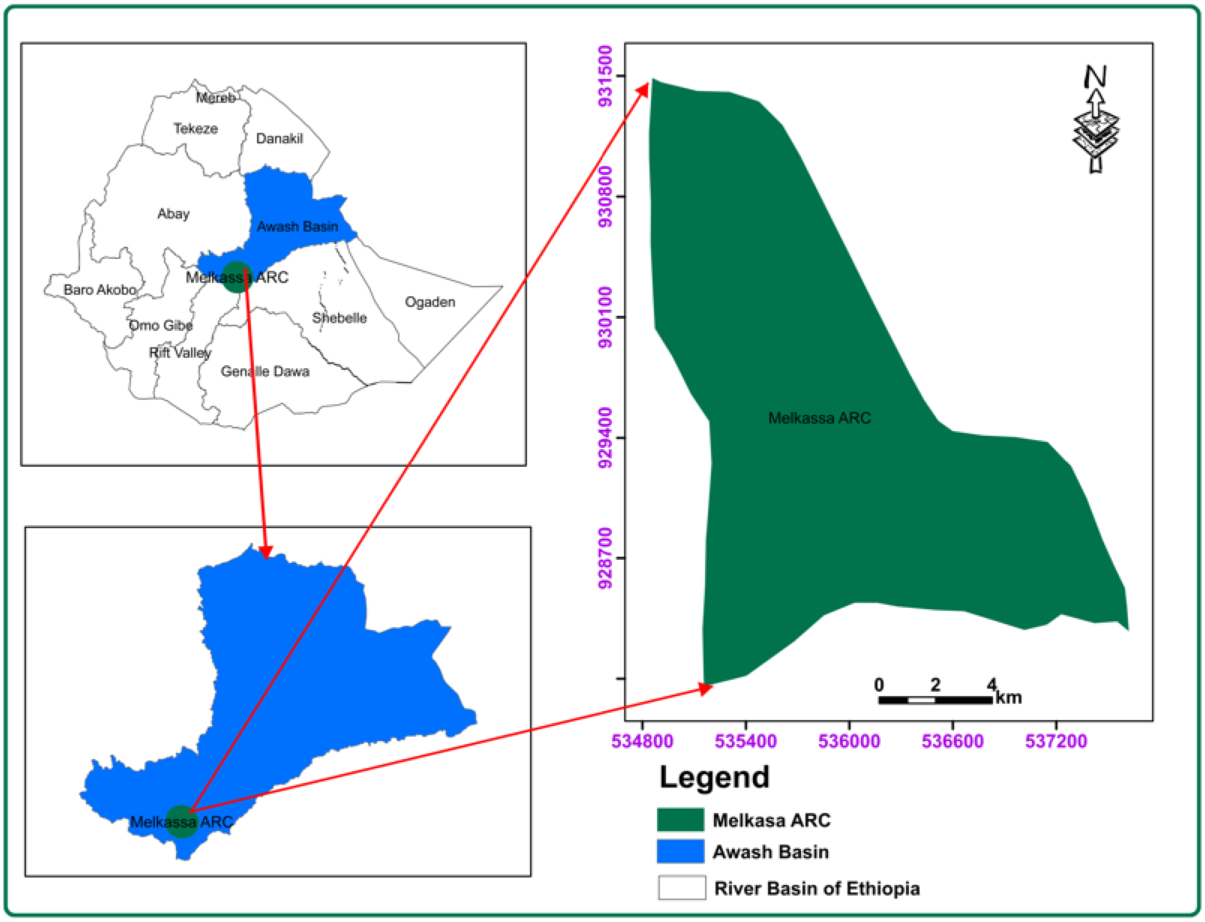

Figure 3-1. Location map of the study area

3.2. Overall Research Method and Design

This section outlines the research method and design used to accomplish the study. An experimental design approach was employed, which involved data collection and analysis. In addition to the data gathered from a lysimeter experiment to measure the water requirement of onion, climatic data were obtained from the Melkassa Agricultural Research Center weather station. The collected data were then processed to meet the requirements of the selected models used in the Kc-approach. The reference evapotranspiration (ETo) was determined, and the water requirement of onion was computed as the product of ETo and the crop coefficient (Kc) values, as recommended in the FAO-56 guidelines.

The research was conducted in the following steps: First, a simple weighable lysimeter was developed and tested. Next, the water requirement of onion was determined, and the crop coefficient was developed. Finally, the selected ETo models used in the Kc-approach were evaluated and calibrated based on measured onion evapotranspiration as shown in Figure 3-2. These models were designed for use in semi-arid climatic regions of Ethiopia, where data are often scarce.

Each component of the study, including the background, materials and methods, data collection and analysis procedures, results and discussion, as well as conclusions and recommendations, is presented in separate chapters.

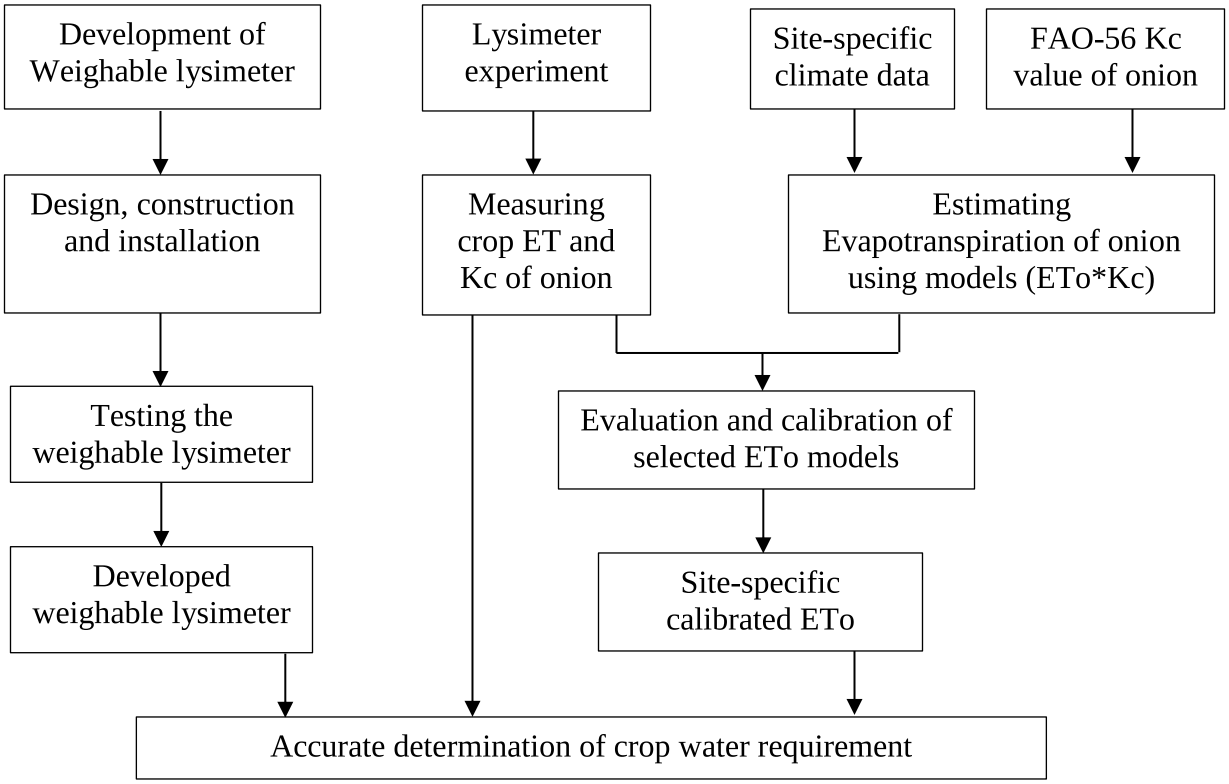

Figure 3-2. Conceptual framework of the study

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4. DEEVELOPMENT AND TESTING OF A SIMPLE WEIGHABLE LYSIMETER

Abstract

A simple weighable lysimeter was designed, constructed, and calibrated for measuring the water requirements and crop coefficients of shallow-rooted crops. It has a portable weighing mechanism to quantify changes in soil moisture content. The weighing mechanism consists of a horizontal steel bar, a hydraulic car jack, both ends hooked vertical steel bars, a stand, and a digital weighing balance. As the lysimeter's inner tank, a plastic drum with a 55 cm diameter that yields 0.24 m^2 *of internal area was used. A performance test was conducted, and a rating curve was developed at the beginning of the growing seasons in 2023 and 2024 to evaluate the sensitivity of the weighing mechanism in determining crop water use. Linearity, repeatability, and measurement uncertainty tests were conducted. The linearity error was ± 0.04 kg and ± 0.03 kg for the years 2023 and 2024, respectively, which is within the allowable limit. The weighing system repeats the measurement perfectly with no error (repeatability error was zero). The combined uncertainty of the measurements was 0.023 kg, representing the cumulative effect of individual errors. The lysimeter weighing system is capable of detecting variations in depth of water as small as 0.2 mm of moisture content. Therefore, the developed lysimeter can be used to determine water requirements and crop coefficients of shallow-rooted crops for the design and management of irrigation in data-scarce areas of Ethiopia.*

Key words: *Lysimeter, Weighing, Portable, Water use, shallow-rooted crops.*

Published article

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4.1. Background of the Study

Lysimeters are soil-filled tanks or containers where plants are grown and applied to monitor how much water is consumed by a vegetated surface in evapotranspiration. It is also used in determining the chemical mobility in the soil profile in water quality investigations (Martin et al., 2001). Lysimeters used in evapotranspiration research are often categorized by gravity or vacuum drainage, weighing or non-weighing, and monolithic or rebuilt soil profiles (Kohnke & Dreibelbis, 1940). Different lysimeter types have been reported (Gifford et al., 1982; Khan et al., 1993; Martin et al., 2001; Payero & Irmak, 2008; Parisi et al., 2009; Lorite et al., 2012; Fisher, 2012; Nicolás-Cuevas et al., 2020; Soler-Méndez et al., 2021). Basically, common lysimeters are of two kinds: non-weighing and weighing (Parisi et al., 2009).

Weighing lysimeters are standard tools (Ünlü et al., 2010), the most accurate technique to measure crop evapotranspiration (Johnson et al., 2005), and used to verify or calibrate weather-based reference evapotranspiration estimation models (Fenner et al., 2019). These are true, provided that they are appropriately designed, built, installed, and operated (Bryla et al., 2010; Sanches et al., 2017). The lysimeter weight difference before and after a certain period (Δt) yields data on the average change in soil water content (ΔS) (Nicolás-Cuevas et al., 2020). This gives the crop's average evapotranspiration rate, together with other elements of the soil water balance (irrigation, precipitation, and drainage).

Weighing lysimeters are classified as either continuous or intermittent (weighable lysimeters), depending on how long it takes between two successive weight measurements (Howell et al., 1991). The former are not commonly utilized because of their high installation costs and need for specialized workers, even if they are accurate and precise (Howell et al., 1985).
With this kind of lysimeter, successive measurements are collected in a one-minute time interval, and both the lysimeter and the weighing mechanism are permanently installed (Zupanc et al., 2012). In weighable lysimeters, successive measurements are gathered over a day or longer time interval, and the weighing facility moves to the lysimeter each time to take readings since it is movable.

Lysimeters' main objective in evapotranspiration determination is to create a controlled environment enabling the monitoring of water entering and leaving the system. This needs matching the soil-plant system within the lysimeter with respect to soil water content (Shenkut et al., 2013), plant density, soil or nutrient availability (Khan et al., 1993), and other factors with the surrounding environment. However, it is challenging to match the water and soil conditions both inside and outside the lysimeter. For instance, more moisture is available at the bottom of the soil profile of a lysimeter relative to the surrounding area of the same depth, unless an efficient drainage system drains the surplus water (Tanner, 2015). To minimize this problem, great concern is required at every stage of the design, building, installation, and field management of the lysimeters.

Lack of site and crop-specific data is hindering efficient and effective design and management of irrigation in Ethiopia. Lysimeters are the old and still useful tools to directly measure water requirements and crop coefficients, which are important for efficient irrigation management. In Ethiopia, a limited number of lysimeters are available (at Melkasa, Werer, and Bishoftu Agricultural Research Centers). In all sites, the type of lysimeter is a non-weighing type; soil moisture change is monitored using a neutron probe, which is expensive. From this perspective, this study was aimed to design, construct, and calibrate a simple weighable lysimeter to measure water requirements and crop coefficients of irrigated shallow-rooted crops.

4.2. Material and Methods

4.2.1. Design and construction of lysimeter

In designing the weighable lysimeter for measuring crop evapotranspiration, the following three points were considered as a design criterion, which are very important. First, the lysimeters needed to be big enough to replicate field circumstances; second, they needed to be small enough to avoid requiring pricey lifting and weighing equipment, as stated by Martin et al. (Martin et al., 2001); and third, the weighing scale needed to be readily available on the local market. Based on the aforementioned requirements, a system for crops with shallow roots was designed (onion was taken as a test crop).

In November 2022, the development of the lysimeters started with excavation work for two lysimeters, a drainage system, and an access chamber. It was completed by constructing and installing the lysimeters, drainage system, lifting, and weighing mechanism for the growing seasons of 2023 and 2024. In all the two years, the same lifting and weighing mechanism was used. In these two consecutive growing seasons, the lysimeters were utilized to study onion water requirements.

As a component, each lysimeter contained a circular inner and outer tank. As the inner tank, a plastic drum with a 55 cm internal diameter, 0.5 cm thickness, and 65 cm depth, which yields 0.24 m^2 of internal surface area, was used (Figure 4-1a). This plastic drum was placed into the drum holder built from a steel bar that had two eye bolts placed face-to-face with each other to support the plastic drum during lift. This component was built from a steel bar of 10 mm in diameter (Figure 4-1b). A concrete pipe was used as an outer tank to avoid contact between the inner tank and the surrounding soil. It was sized to a 5 cm gap all around the drum holder to avoid wall contact as well as to allow up and downward movement of the inner tank during weighing (Figure 4-1c). To allow the drainage of any water that could fall between the inner and outer tanks into the ground, the bottom of the concrete pipe was left open.

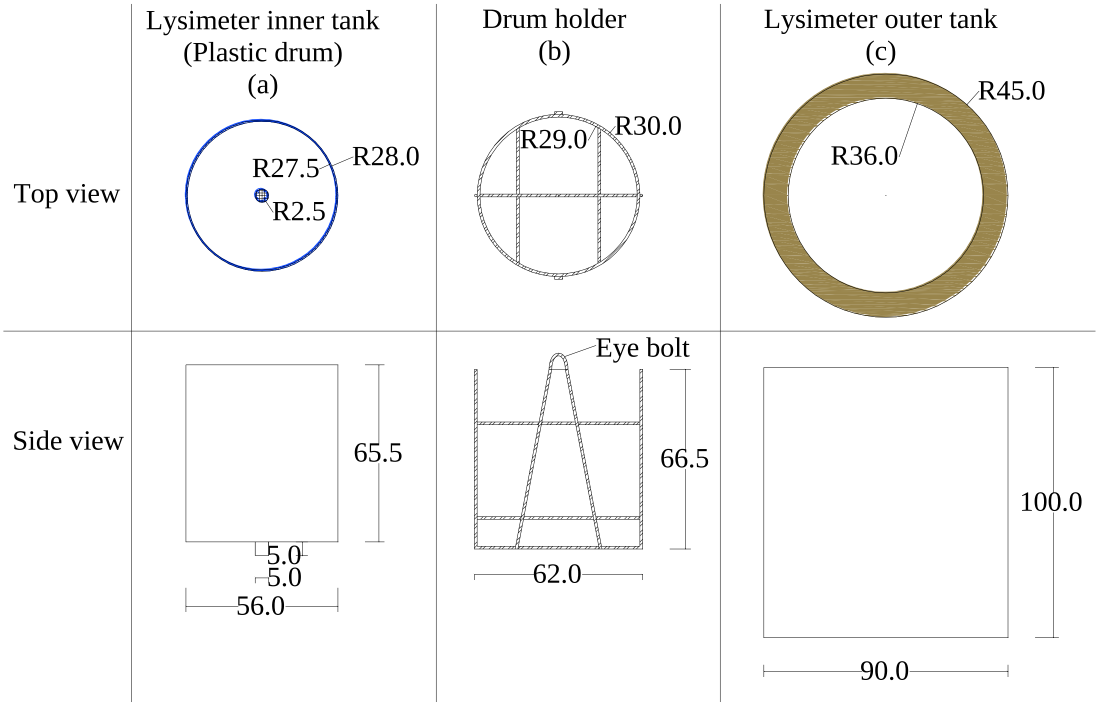

Figure 4-1. Top and side views of the design drawings for the inner tank (a), drum holder (b), and outer tank (c); all the dimensions are in centimeter

The gravity drain type of drainage system was designed for the lysimeters to maintain the same soil moisture profiles within and out of the lysimeter (Figure 4-2). To facilitate drainage at the bottom of the inner tank, 5 cm thickness of gravel (pebbles having 1-2 cm diameter) and 2 cm thickness of sand were provided. Moreover, to remove the excess water, a 50-mm-diameter hole (outlet) at the base of the inner tank was provided, which was centered and mounted with a 2 inch shower drain having a 50 mm depth. Further, the drainage system had two components: the drainage pipe and the drained water collector.

The drainage pipe used was a pipe system that was used to transport drained water from the outlet of the inner tank to the drained water collector, located at the access chamber. It was composed of a receiving vessel and 50-mm-diameter PVC aligned horizontally to the access chamber with a smooth gradient. The receiving vessel comprises a funnel made of an iron sheet that had a 23 cm diameter and 110 mm diameter PVC, which was reduced to 50 mm diameter using a reducer. This receiving vessel had a 28 cm height and was buried vertically at the center of the outer tank, 7 cm below the bottom of the inner tank. The drained water was collected at the drain collector, which had a 10-liter capacity, dimensions of 27 cm in height, and a 28 cm top diameter. The drained water between two irrigation intervals was measured at the access chamber, which had a 1.2 m width, 1.5 m length, and 1.4 m depth.

The drainage system has three components: the drainage system in the lysimeter, the drainage pipe, and the drained water collector. The drainage pipe and the drained water collector work together to transport and collect the drained water from the lysimeter, respectively. The drainage system within the lysimeter is crucial for maintaining consistent soil moisture conditions both inside and outside the lysimeter. This is achieved through:

- Matching the characteristics of the soil inside the lysimeter with the surrounding. This was achieved through backfilling the soil in the natural order where it was removed and careful compacting during backfilling. This creates similarities in water retention and movement properties.
- Providing a drainage material and outlet at the bottom to remove the excess water drained to prevent excess moisture within the lysimeter.

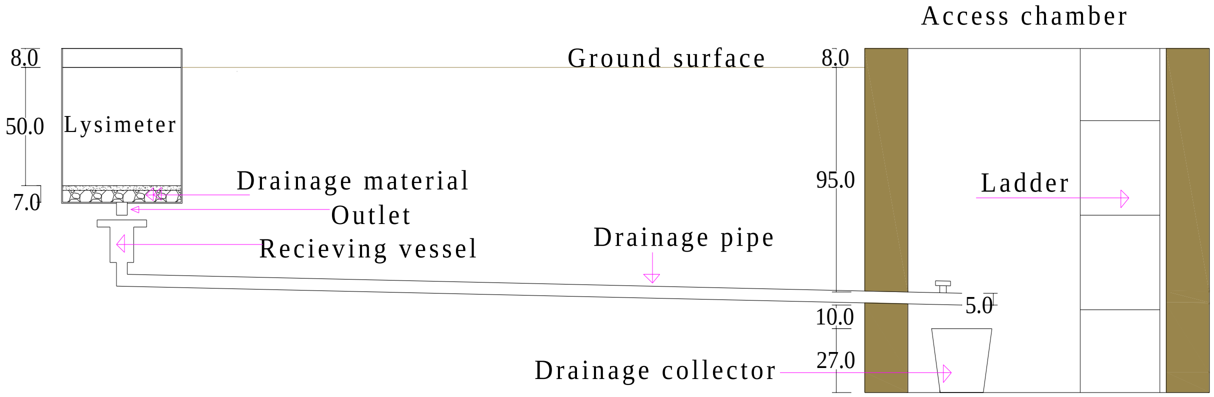

Figure 4-2. A design drawing of the drainage system showing the drainage facility within the lysimeter, the drainage pipe, and the drained water collector at the access chamber

4.2.2. Lifting and weighing system

The lifting and weighing system's design requirements were to: 1) make it simple to transfer among lysimeters; 2) make it simple to remove from the site so as not to obstruct field activities; and 3) have enough strength to support the loads, as adopted from Martin et al. (Martin et al., 2001).

The lifting system was constructed from four different components (Figure 4-3). The first component is a horizontal steel bar, which is placed at the top of the hydraulic car jack and used to suspend the lysimeter during the lift for weighing. The steel bar having the capacity to hold the load caused by the mass suspended on it without bending was selected. For this case, a steel bar with a diameter of 24 mm and a length of 80 cm was used. The second component is the hydraulic car jack, which is used to lift all the loads suspended on the steel bar by bushing up. So, a hydraulic car jack with a lifting capacity of 10 tons was selected in respect of stability during lift, even if the required lifting capacity was 262 kg. The third component is the stand, a table-like structure measuring 110 cm above the ground used to place the weighing platform. The fourth component is two steel bars, 12 mm in diameter and 130 cm in length, hooked on both ends with removable links that were used to connect the eye bolts on the drum holder and the horizontal steel bar for lifting the lysimeter. This bar could withstand a tension load caused by the total mass within the lysimeter.

The weighing system used was a digital scale weighing platform floor scale, Model No. TESA33001, with a 300 kg and 1.5 kg maximum and minimum capacity, respectively, with a division of 50 grams. It has a display function and measures the weight directly. This weighing system was selected based on its suitability for the designed system, availability in the market, and relatively low cost (Figure 4-3).

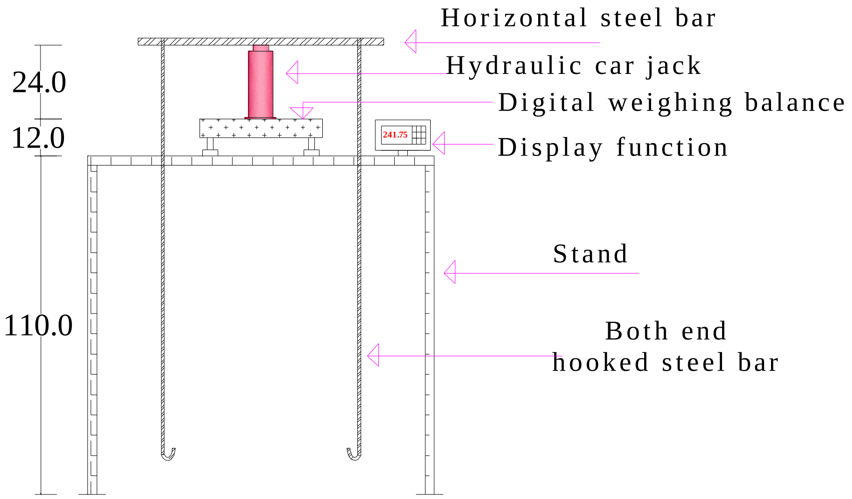

Figure 4-3. Side view design drawing of a lifting and weighing system, which is moved to the lysimeter position and placed at the ground surface to lift the lysimeter for measurement

4.2.3. Lysimeter installation

The lysimeters were installed at Melkasa Agricultural Research Center (MARC), which is found in the Southeast Shoa Zone of Oromia regional state of Ethiopia. The lysimeters were installed at a non-weighing type lysimeter experiment site at the research center. The assembled and installed lysimeter drawing with all its components is shown in Figure 4-4.

At each lysimeter location, a circular pit that is slightly deeper and larger than the outer tank was dug, and at the access chamber location, a rectangular pit considering the working space was dug. For the drainage pipes, a canal that connects the center of each lysimeter location with the access chamber, having a depth less than the height of the drainage collector from the depth of the access chamber, was dug. During excavation of the circular pit and canal, the soil was removed in a 10 cm layer and placed in a separate pile for backfill.

The drainage pipes were then installed carefully. The bottom of the lysimeter pit was leveled, lean concrete was placed, leaving a 40 cm diameter circular area at the center, and the outer tank was lowered into the pits. The opening surrounding the outer tank was backfilled with soil, and 30 cm thick concrete was placed inside the outer tank, leaving a 40 cm diameter circular area at the center. Then, the annular area between the receiving vessel and this 40 cm diameter circular area was filled with gravel to facilitate the drainage of water that might enter between the inner and outer tanks.

The drum holder was lowered into the outer tank, and the inner tank was placed inside the drum holder by aligning the outlet on the inner tank with the receiving vessel. In each inner tank, a drainage material, a 5 cm layer of gravel (pebbles having 1-2 cm diameter), and 2 cm of sand were provided. The rest of the inner tank, leaving the rim and the canal for the drainage pipe, were filled back using the initial soil in the opposite order that it was removed. Finally, four footings at the outer side of the corners of a square, which inscribe the outer tank, had a 20 cm by 20 cm dimension at surface level for the stand using concrete, and the access chamber using hollow blocks were constructed. The drained water collectors were placed in the access chamber at the outlet position of the drainage pipes.

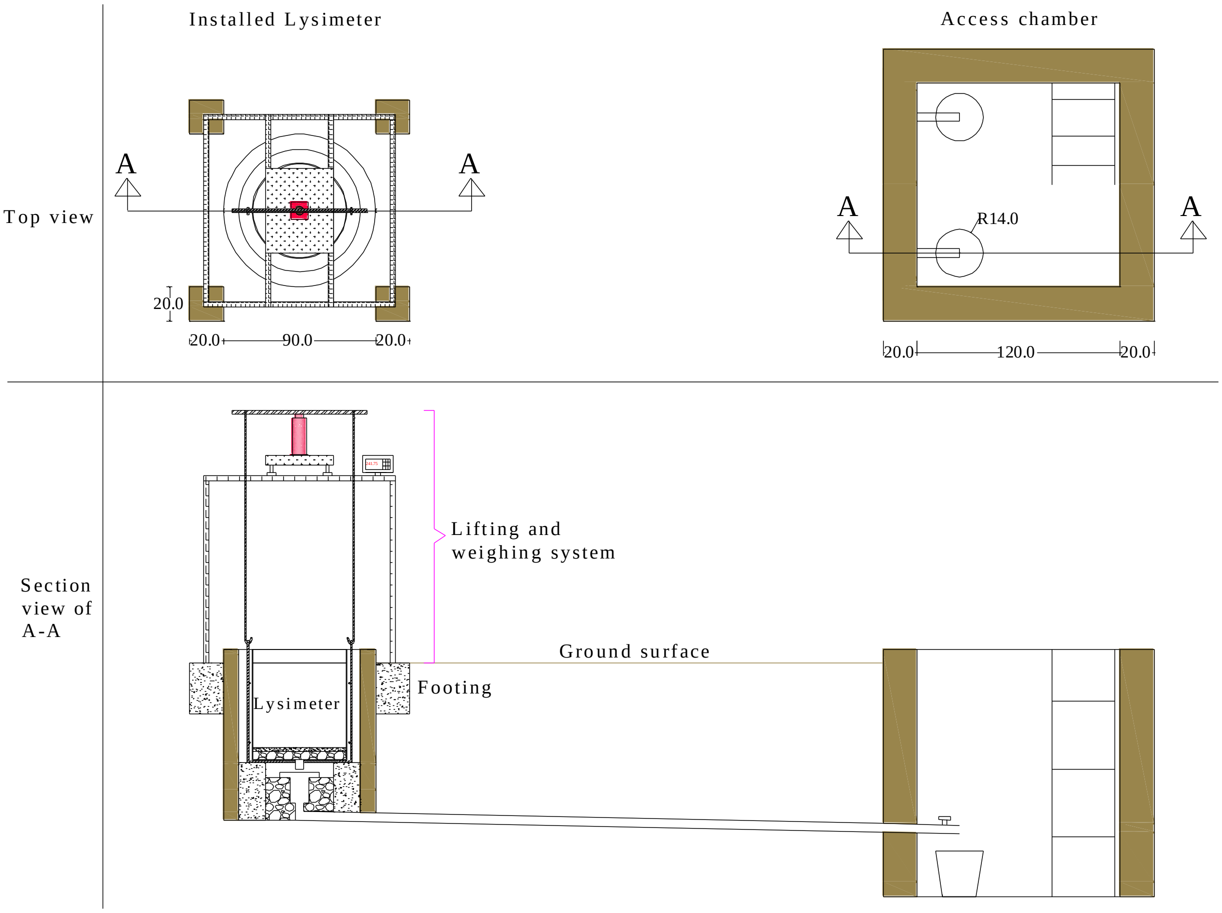

Figure 4-4. A design drawing of the installed lysimeter at Melkasa Agricultural Research Center; showing the system components: the lysimeter, drainage system, lifting, and weighing system

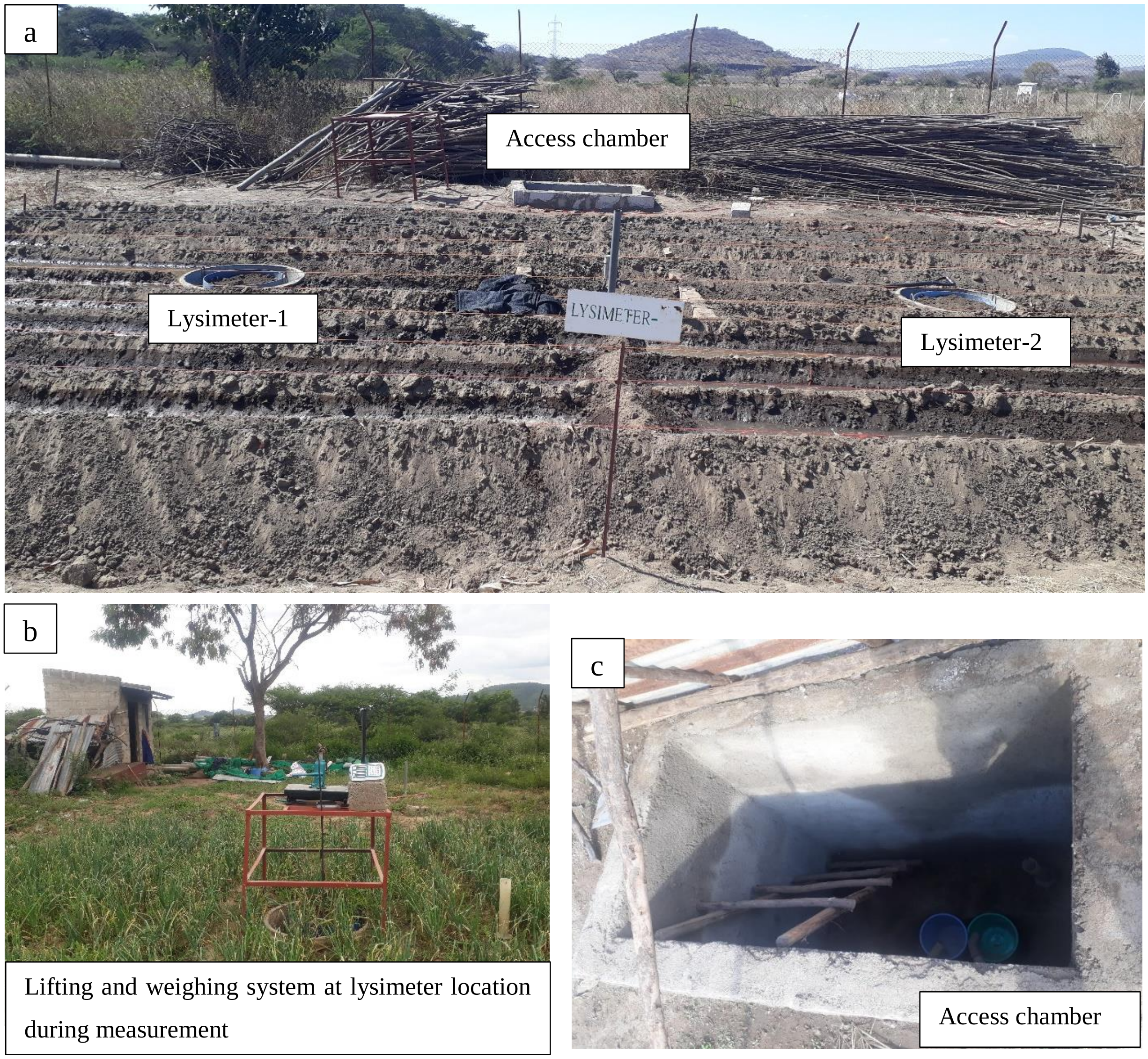

Figure 4-5. Lysimeters with access chamber (a), lifting and weighing systems (b), and inside of the access chamber (c)

4.2.4. Operational principle

The stand was positioned on the footings, and the weighing platform was placed on the stand with the hydraulic car jack on top of it. On the top of the hydraulic car jack, the horizontal steel bar was placed, and this bar was connected to the eyebolts on the drum holder using vertical removable steel bars hooked at both ends. A section view of the installed lysimeter in Figure 4-4 and the real-life image in Figure 5-5 show the arrangement.

When the hydraulic car jack operated (raised), the horizontal steel bar was pushed up, and since this bar was connected to the eyebolts on the drum holder, the lysimeter started to be lifted. As the lysimeter gets lifted, the weight is displayed on the display function. After taking the reading, the lysimeter is then moved down until it reaches the floor by reducing the height of the hydraulic car jack. Then, the weighing and lifting systems were moved to the other lysimeter.

4.2.5. Calibration and performance testing

A performance test was undertaken to ensure the reliability of the weighing system and adherence to the manufacturer's specifications. A weighing system evaluation was conducted at the start of the 2023 and 2024 growing seasons.

4.2.5.1. Calibration

Calibration is the process of comparing a mass standard’s weight reading with its actual value (Morse & Baer, 2004). Daniel et al. (2013) described that calibration of the lysimeter is performed by loading and unloading known weights (weights that are standardized by weighing on an electronic scale with high resolution). However, in this case, calibration was done by loading known weights within the calibration range; since the weighing system is intermittent, there is no need for a hysteresis check.

The calibration range considered was the mass between 70% of total available water depleted and field capacity (10.5 kg). The calibration range, known as the operating range, is the portion of the instrument's measurement range across which it is calibrated to provide accurate and reliable measurements. In this study, the operating range (commonly used measurement range) considered was the mass of readily available soil water (RAW) in the root zone. This readily available soil water is the average portion (p) of total available soil water (TAW) that can be used up before moisture stress (a decrease in ET) occurs. The value of p varies among crops, and it goes to 0.7, which implies readily available water is 70% of TAW (Allen et al., 1998). Even if the test crop was an onion with a p value of 0.3, the study considered crops with a maximum p value of (0.7) to widen the operating range for different crops.

So, this weight, i.e., the mass between 70% of total available water depleted and field capacity, was divided into six different known weights (considering the division of the weighing scale) to produce calibration points. Known weights were prepared from packed bricks in plastic bags using a scale with a 0.01 gram resolution. These masses were applied continuously in increasing steps on the constant load of the lysimeter, 236.6 kg, taken as the standard weight to be weighted on the lysimeter.

At each calibration point, pairs of data (the true value and the lysimeter reading of the standard mass) were collected. These data were subjected to a linear regression analysis as explained by Sanches et al. (2017), and then a calibration curve was produced. This curve (regression line or best-fit equation), often called the transfer function, shows how the measurement values are related to a recognized reference.

4.2.5.2. Performance test

The performance test of the weighable lysimeter was analyzed by evaluating linearity, repeatability, and measurement uncertainty parameters adopted from Martin et al. (2001).

Linearity is the characteristic that measures the accuracy of the instrumental intermediate readings across the instrument’s weighing range (Morse & Baer, 2004). The relationship between the true value of the load and the reading of the scale is called its characteristic curve; ideally, it is a straight line. As described by Morse & Baer (2004), the deviation of the characteristic curve from this straight line going through the weighing range is called non-linearity.

The data collected from the calibration procedure was used to analyze the system’s linearity. The deviation or difference between each measured value and the best-fit equation was evaluated for each measured value. The linearity error, or maximum deviation, is compared to the manufacturer's specifications (Martin et al., 2001).

Repeatability refers to the capability of a device to yield the same result when an identical load is applied several times in sequence to the weighing system using the same procedure. As described by Walendziuk & Idzkowski (2017), the test is undertaken with a test load of about 50% of the calibration range, and one repeatability test consists of 10 repeated measurements of the same mass. It is expressed as a standard deviation (Morse & Baer, 2004; Walendziuk & Idzkowski, 2017) and calculated using Equation 4-1.

$$s(m) = \sqrt{\sum_{j=1}^{N} \frac{(m_j - \bar{m})^2}{N-1}} \qquad \text{Equation 4-1}$$

Where, s(m) = standard deviation, m_j = value j of measured mass, and $\bar{m}$ = mean mass and N = number of samples

The maximum standard deviation is the repeatability error; it is compared with the manufacturer's specifications (NATA, 2018).

For this study, three test loads from the calibration range were taken; each test load was measured 10 times, and the standard deviations were computed using Equation 4-1.

The tests in this study were undertaken in a relatively closed environment using a standard load instead of using the lysimeter in the field to reduce environmental effects such as the wind effect.

Measurement uncertainty describes the doubt that exists around the outcome of any measurement. The steps taken to compute the uncertainty of a measurement were identifying the sources of uncertainty, quantifying the uncertainties, and combining the uncertainties to provide an overall figure.

The standard uncertainty of linearity and repeatability error for linearity and repeatability measurements were computed using Equations 4-2 and 4-3, respectively.

$$u_{Le} = \frac{a}{\sqrt{3}} \qquad \text{Equation 4-2}$$

Where, u_{Le} = standard uncertainty of linearity error and a = half range of the error

$$u_{Re} = \frac{s}{\sqrt{n}} \qquad \text{Equation 4-3}$$

Where, u_{Re} = standard uncertainty of repeatability error and, s = standard deviation and n = number of measurements

The combined standard uncertainty of the measurements was computed using Equation 4-4.

$$u_c = \sqrt{u_{Le}^2 + u_{Re}^2} \qquad \text{Equation 4-4}$$

Where, u_c = combined standard uncertaininity, u_{Le} = standard uncertainty of linearity error and u_{Re} = standard uncertainty of repeatability error

4.2.6. Validation

To confirm the validity of the developed lysimeter, the stage-based crop coefficient of the developed lysimeter for the test crop was compared with the FAO-56 value as described by Soler-Méndez et al. (2021). The crop coefficient of the test crop for the developed lysimeter was determined as a ratio of crop evapotranspiration (measured using the lysimeter) and reference crop evapotranspiration (computed using CROPWAT version 8.0).

4.3. Results and Discussions

4.3.1. Calibration

The calibration curve produced for the weighing lysimeter follows the calibration points perfectly. The linear regression coefficient for both years and the plot of lysimeter weight (measured weight) versus true weight for the year 2023 are presented in Table 4-1 and Figure 4-6, respectively.

Table 4-1. Linear regression coefficient for the weighing system calibration curve

Year	Test range (kg)	Equation coefficient[*]		R^2
		b	c	
2023	10.41	1.0001	-0.0337	0.999
2024	10.53	1.0010	-0.2380	0.999

[*] y=bx+c where y - dependent variable, presents lysimeter weight (kg) and
x - independent variable, presents the true weight (kg)

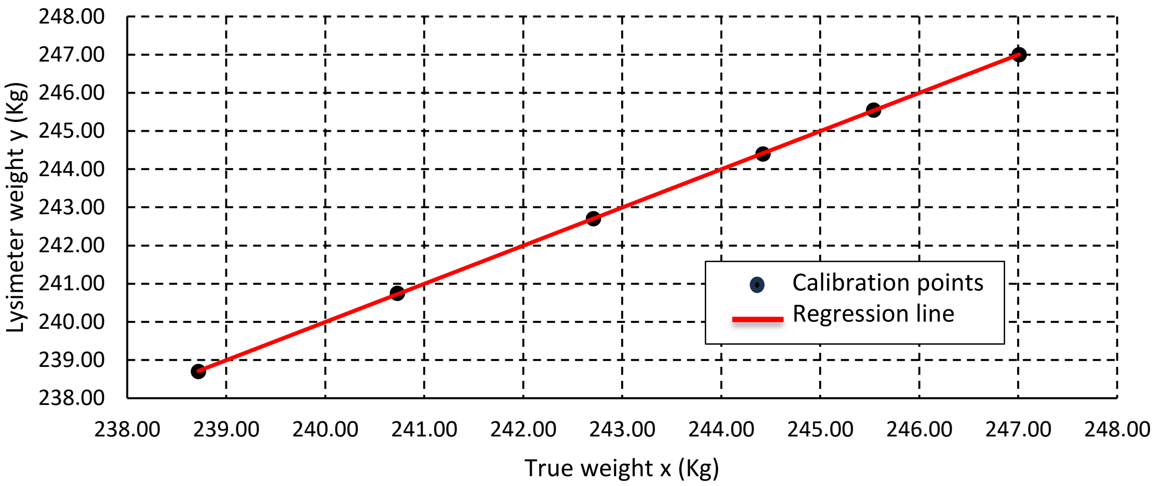

Figure 4-6. Calibration curve for the year 2023

4.3.2. Linearity test

The data collected from the calibration procedure was used to analyze the system’s linearity. The deviation or difference between each measured value (lysimeter reading) and the best-fit equation (m-y) was evaluated for each measured value. The linearity error, or maximum deviation, is compared to the manufacturer's specifications. The linearity error was ± 0.04 kg and ± 0.03 kg for the tested range of 10.41 kg and 10.53 kg for the years 2023 and 2024, respectively. The linearity error for the test year 2023 was presented in Figure 4-7. Per the standards provided by the manufacturer, the non-linearity ought to be ± 0.05 kg. Thus, the system’s linearity meets the manufacturer’s specifications.

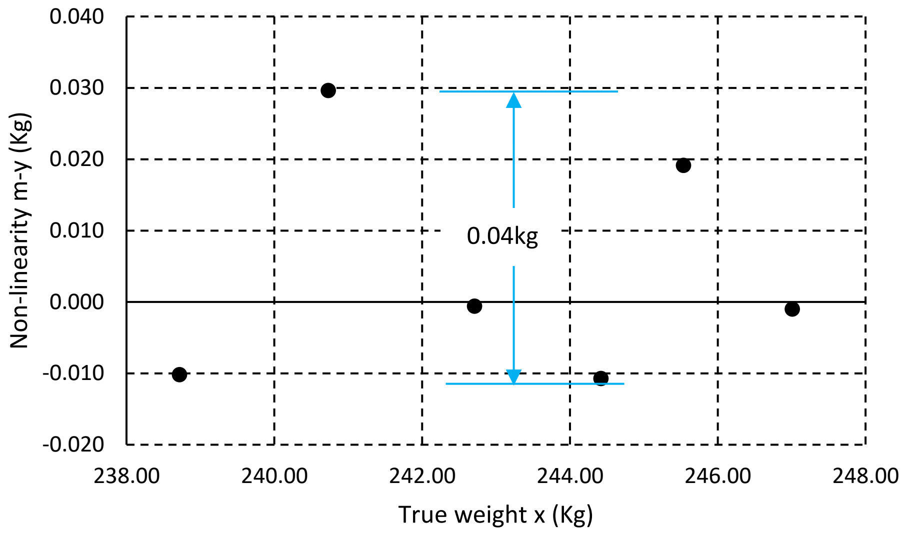

Figure 4-7. Residuals from the weighing lysimeter calibration test for the year 2023

4.3.3. Repeatability test

Data for the repeatability test was collected by loading three test loads as a trial with different weights on a standard load of 236.6 kg and 237.05 kg for the years 2023 and 2024, respectively. The repeatability error was measured using the residual average spread, or the average spread of the difference among the average and measured weight for each lift, described as a standard deviation. For all three trial loads in both years, the analysis showed a zero-standard deviation, which means the weighing system repeats the measurement perfectly with no error. The reason for the claim of zero repeatability error is due to the characteristic of the weighing system. The weighing system used has a division of 50 grams; this means it cannot detect small changes within this range. This made the measurement repeatable without error. Figure 4-8 displays the trial's residual in relation to the number of lifts.

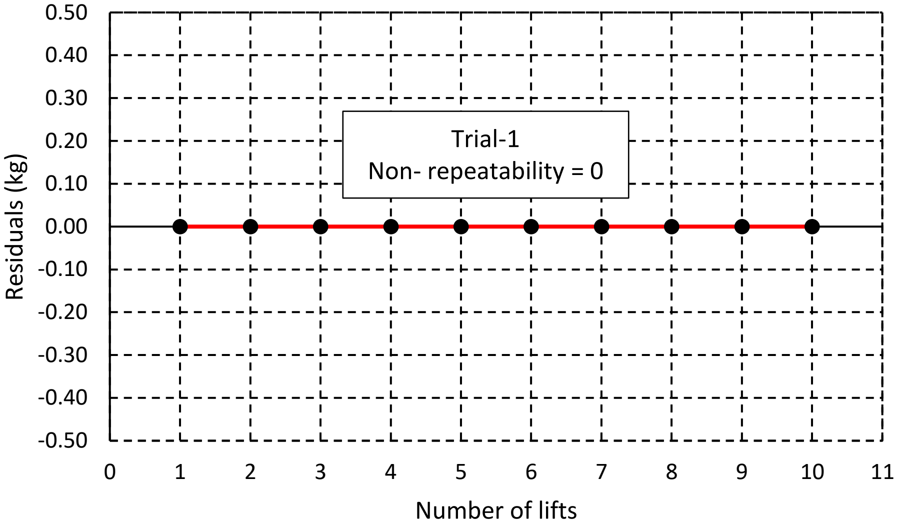

Figure 4-8. Repeatability error of the weighing system for trial-1 of 10 lifts

4.3.4. Measurement uncertainty

After the errors for linearity and repeatability measurements were quantified, the standard uncertainty of measurement for each error and for the combined effect was computed. The result showed that for the linearity and repeatability error of ± 0.04 kg and 0 (zero), the standard uncertainty of measurements was found to be 0.023 kg and 0 (zero), respectively. The combined standard uncertainty of the measurements was 0.023 kg. This analysis shows repeatability error makes no contribution to the total uncertainty, whereas linearity error was the main cause.

4.3.5. Resolution

The lysimeter weighing system is capable of detecting variations in mass as small as 50 grams, or 0.2 mm of water head.

4.3.6. Validation

Stage-based crop coefficients of the developed lysimeter for the test crop (Onion) were found to be 0.68, 1.03, and 0.86 for the initial, mid-season, and late-season stages, respectively. In comparison, the FAO-56 (Allen et al., 1998) suggested crop coefficient values of 0.7, 1.05, and 0.75 for these stages. The close similarity between these values confirms that the measurements from the developed lysimeter are acceptable and validates its design for the intended function.

4.3.7. Limitations and future work

The developed lysimeter was designed for shallow-rooted crops, but to be applicable for a wider range of crops, the designed lysimeter has two limitations. First, the lysimeter's depth is small, with an overall depth of 65 cm and a net soil depth of 50 cm. To accommodate deep-rooted crops, the -soil profile in the lysimeter must be deeper to match the root depth of the crop. Increasing the depth while maintaining the same surface area results in a greater volume and, consequently, a higher mass, which necessitates a larger lifting and weighing system. Second, the capacity of the current lifting and weighing system is limited, with a maximum weighing capacity of 300 kg. This limitation in the stand height of the lifting system and the weighing system's capacity restricts the use of the lysimeter for deep-rooted crops.

4.4. Conclusion

The weighable lysimeter detailed in this study was utilized in the 2023 and 2024 growing seasons at Melkasa Agricultural Research Center. The system did not encounter significant operational problems, and the developed weighing, lifting, and drainage system was successful. Data were gathered on the water use of onions.

Because of the weighing system's portability, issues with spatial variability in field research can be resolved by distributing numerous lysimeters randomly over an experimental plot. The weighing system generated acceptably accurate data that could be used for determining crop water requirements and crop coefficients for several crops grown in Ethiopia.

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5. DETERMINATION OF WATER REQUIREMENT AND CROP COEFFICIENT OF ONION (*Allium cepa* L.) USING A WEIGHING LYSIMETER

Abstract

In response to the growing challenge of water scarcity in agriculture, efficient irrigation planning and management have become increasingly essential. A critical component of this is determining the precise water requirements of crops. This study was conducted at Melkasa Agricultural Research Centre in Ethiopia during February to May in 2023 and 2024 and focused on quantifying the water requirement and crop coefficient of onion (Allium cepa L.), Nafis variety. Using weighable lysimeters, the study measured field-level water balance components, with crop evapotranspiration calculated through the water balance equation. The CROPWAT model and meteorological data from a station located nearby were used to estimate reference evapotranspiration. The results indicated that the pooled seasonal crop evapotranspiration was 460.27 mm, while the reference evapotranspiration for the same period was 509.18 mm. The average crop coefficient values were determined to be 0.68, 0.89, 1.03, and 0.86 for the initial, developmental, mid-, and late-season stages, respectively. Additionally, a third-order polynomial equation was established to predict the values of the crop coefficient based on the number of days after transplanting. These findings offer valuable insights for improving water resource use efficiency and optimizing irrigation scheduling for the production of onion, particularly in regions like Melkasa, where neither field-based measured data nor site-specific validated estimation methods are lacking.

Key words: *Evapotranspiration, Crop coefficient, Semi-arid, weighable lysimeter, Onion*

Published article

The following article was published from this chapter.

Quantification of onion (Allium cepa L.) evapotranspiration and crop coefficient via weighable lysimeter under semi-arid climate of Melkasa, Ethiopia. *Heliyon*, *11*(4), e42566. https://doi.org/10.1016/j.heliyon.2025.e42566

5.1. Background of the Study

In many regions, especially in developing countries, the water available for irrigation is decreasing continuously. One key factor is the growing competition for water among various sectors, including domestic and industrial uses (Dingre & Gorantiwar, 2020). On the other hand, the development of new water resources is constrained by several technical and economic factors, including high costs, a lack of suitable reservoir locations, complexities in water delivery, and environmental concerns (Pereira, 2005). Additional challenges like desertification and the overexploitation of existing water resources (Bachour, 2013) further exacerbate the situation. Moreover, climate change impacts on the availability of water resources for agriculture are already visible in many regions, especially arid and semi-arid areas (Halasuru Jayaram, 2018). Furthermore, low efficiencies in irrigated agriculture contribute to increased water demand for irrigation (Yadeta et al., 2021b), further exacerbating water scarcity.

Thus, under water scarcity conditions for agriculture, proper use and management of available water for irrigation is crucial. In line with this, effective planning and management of irrigation and improving irrigation efficiency are vital. For this purpose, accurate determination of crop water requirements is needed (Holzapfel et al., 2010; Wickramaarachchi et al., 2011).

Although measurement of crop evapotranspiration using a weighable lysimeter is costly and time-consuming, it is still useful for calibration of empirical equations. Allen et al. (1998) describe a generally accepted procedure for estimating the water requirements of crops for irrigation scheduling. Using lysimeters to measure water balance components is an old approach and yet a helpful method to quantify water requirements of crops directly and drive crop coefficients, which are critical for effective management of irrigation (Kebede et al., 2024). It uses cropped lysimeters to measure the amount of lost water as a result of transpiration, drainage, and evaporation. These data are then used to calibrate the crop coefficient values (Gee et al., 2009) and develop area-specific crop coefficients to predict the evapotranspiration of crops from reference evapotranspiration (Bayisa et al., 2024).

It is crucial to develop site-specific crop coefficients for accurate determination of crop water requirements under particular climatic conditions. This is because crop water requirements and, hence, crop coefficients vary from location to location depending on factors like local climate, soil types, irrigation regime, management practices, and other environmental factors for the same crop (Allen et al., 1998; Abedinpour, 2015). However, such measurements using lysimeters are rarely undertaken due to the requirement of high cost and lack of equipment and laboratory facilities in many areas (Yadeta et al., 2021a).

When direct measurement is not possible, the indirect method, which uses the Kc approach, in which crop water requirement is estimated as a product of crop coefficient and reference evapotranspiration, is used. In this approach, the accuracy of the water requirement determined depends on the method used to estimate the reference evapotranspiration.

Onion is among the most widely cultivated vegetable crops in Ethiopia, particularly in the study area. The study area has historically been known for its limited water resources and inefficient irrigation water management. Currently, the area is facing significant water stress due to demand for water exceeding supply (Edossa et al., 2010), underscoring the crucial need for precise irrigation management practices. Despite the importance of onion crops, their crop coefficient and water requirements remain insufficiently studied.

Several studies have been conducted to estimate ETc and Kc for onion in various regions with semi-arid climate conditions worldwide (López-Urrea et al., 2009; Halasuru Jayaram, 2018; Hend et al., 2019; Matsunaga et al., 2022). However, some studies have been conducted to determine the water use of onion in Ethiopia. Bossie et al. (2009), Dirirsa et al. (2015), and Abebe et al. (2021) were among those who offered insights into crop coefficients and crop water requirements for the Red Bombay onion variety. Another improved onion variety that is widely grown in the area is the Nafis onion variety. This variety of onion is preferred by most farmers due to its early maturing nature, shorter production time, and hence lower production costs. However, the crop coefficient and water requirement are not yet studied.

In light of this, this region has historically been known for its limited water resources and inefficient irrigation water management. The aim of this study was to determine the crop coefficient and water requirement of onion using a weighable lysimeter in order to optimize irrigation water use and enhance water use efficiency for onion production in semi-arid regions of Melkasa, Ethiopia.

5.2. Materials and Methods

5.2.1. Study area description

The experimental study was conducted for two consecutive years (2023 and 2024) at Melkasa Agricultural Research Centre (MARC). The center is located at 8^{o} 24' latitude and 39^{o} 21' longitude, with an altitude of 1550 meters above sea level. Agro-ecologically, the area is classified as a semi-arid zone, in which the climatic condition is characterized as hot throughout the year with an annual average rainfall of 845.5 mm, 14^{o}C minimum and 29^{o}C maximum temperatures. The study area location map is illustrated in Figure 5-1.

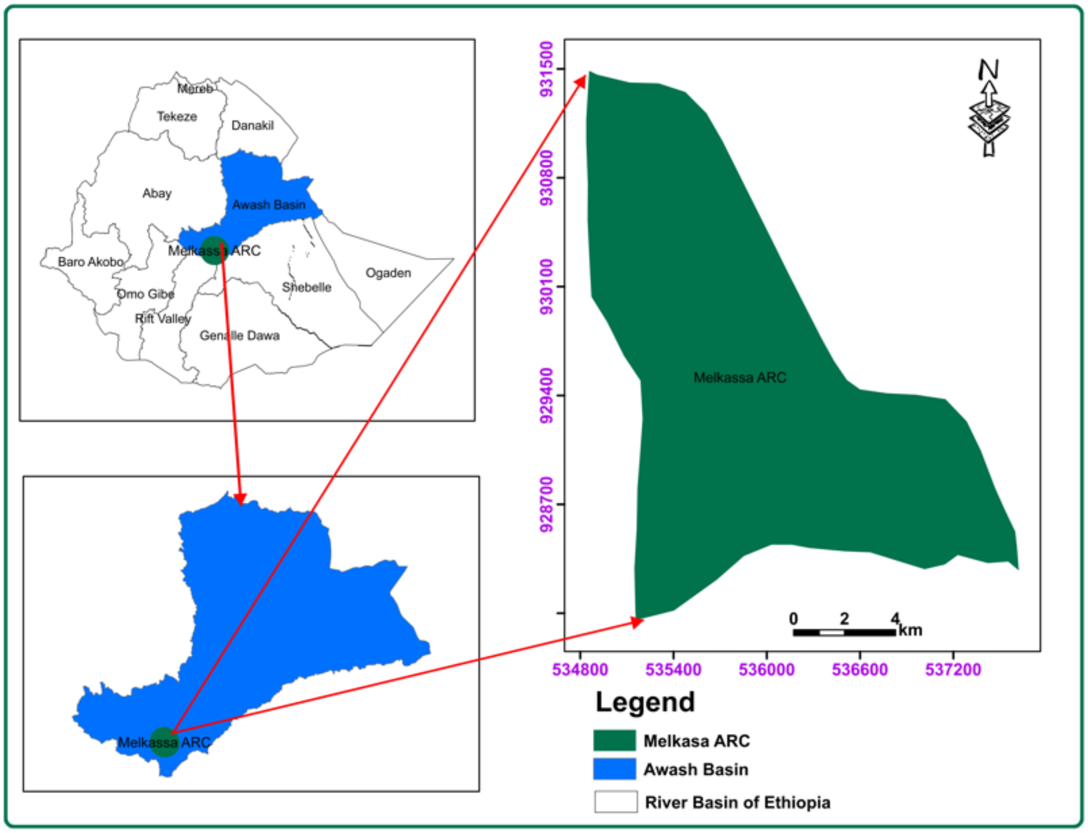
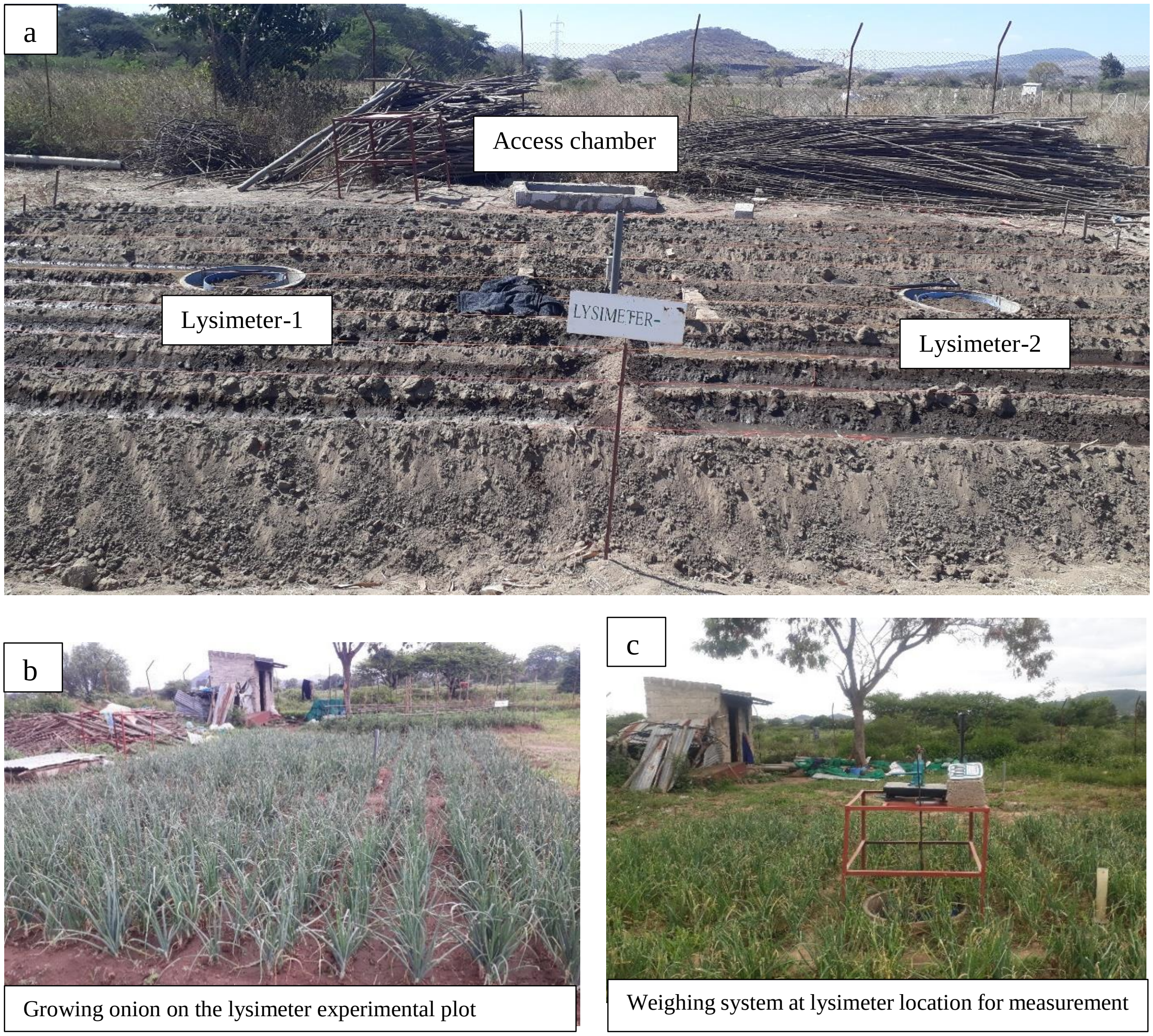


Figure 5-1. Map of the study area

5.2.2. Experimental setup

For determining the crop coefficient, Kc and water requirement, ETc of onion, a weighable type of lysimeter designed, constructed, and tested by Kebede et al. (2024) was used. The lysimeters are circular-shaped, 65 cm in depth (including the depth of the rim and drainage material, 15 cm), and 55 cm in diameter (yielding 0.24 m^2 of internal surface area) each, but for buffering conditions, onion was planted on a 10 m by 6 m area outside of the lysimeters. The two lysimeters are located four meters apart from each other within the buffer zone. An access chamber with 1.5, 1.2, and 1.4 meters of length, width, and depth, respectively, supported with a ladder located at a side of the lysimeters, was constructed, enabling the measurement of drained water from each lysimeter, which was directed via drainage pipes towards the drained water collector. The arrangement of the lysimeter experimental plot is shown in Figure 5-2a, while Figures 5-2b and 5-2c depict the field conditions, specifically the growing onion and the weighing system at the lysimeter location for measurement, respectively. A detailed description of the weighable lysimeter is available in Kebede et al. (2024).

The onion variety considered in this study was Nafis, an improved variety widely cultivated in the region. Moreover, this variety is highly preferred by most farmers due to its early maturity, which allows for faster harvesting, a shorter production cycle, and reduced production costs. However, despite its popularity and the economic advantages it offers, essential parameters useful for irrigation management, such as its crop coefficient and water requirements, are insufficiently studied, highlighting the need for further research.



Growing onion on the lysimeter experimental plot

Weighing system at lysimeter location for measurement

Figure 5-2. The experimental lysimeter's layout (a) and field condition pictures (b and c)

The characteristics of the experimental field soil were analysed in Melkasa Agricultural Research Center soil laboratory. The parameters analysed include bulk density, soil texture, moisture content at wilting point, and field capacity by taking soil samples at intervals of 15 cm. The result revealed that the texture of clay loam with 1.2 g cm^{-3} bulk density and volume-based soil moisture content of 26.25% and 38.88% at the permanent wilting point (PWP) and field capacity (FC), respectively.

5.2.3. Crop agronomy

Seedlings of onion, Nafis variety, were prepared according to the way the farmers actually practice to supply as planting material. The experimental plot was prepared with 60 cm-spaced ridges by aligning one ridge to be at the center of the lysimeters. On February 1, in both years, 2023 and 2024, of the growing seasons, the seedlings were transplanted in a single row on each ridgeside spaced 20 cm apart, providing 10 cm of space between plants. All recommended agronomic practices adopted were the same for both the buffer area as well as in the lysimeters. Fertilizers with 100 kg and 200 kg per hectare rates of Urea and DAP, respectively, were used as nutrient sources in order to improve the development and productivity of onion crops. It was harvested on May 21 during the growing season of 2023 and May 20 during the growing season of 2024. The total growth season was 110 days, which is the sum of 15, 30, 40, and 25 days, respectively, for the growth stages: initial, developmental, mid-, and late-season stages.

5.2.4. Soil moisture monitoring and application of irrigation

The change in soil moisture content was measured directly from the mass change of the lysimeter between two time intervals (Payero & Irmak, 2008; Clothier et al., 2022). At the beginning, the moisture of the soil was placed at its field capacity, then the change in moisture content between irrigation intervals was monitored as a difference in mass of the lysimeter at the current and previous time before irrigation and computed using Equation 5-1.

$$\Delta SM = WL_t - WL_{t-1} \qquad \text{Equation 5-1}$$

Where, ΔSM = Change in soil moisture content (kg), WL_t = Weight of lysimeter at current time (kg), WL_{t-1} = Weight of lysimeter at previous time (kg)

Irrigation water was applied at or before the depletion factor (p) reached 0.3, as suggested by Allen et al. (1998), to establish an optimal soil moisture condition. This was achieved through continuous soil moisture analysis, which was undertaken at 2- to 3-days intervals to ensure the availability of optimum soil moisture content in the root zone. The quantity of water required to revert the soil to field capacity was computed using Equation 5-2 and applied using a calibrated watering can.

$$SMD = WL_{FC} - WL_i \qquad \text{Equation 5-2}$$

Where, SMD = Soil Moisture Depleted (kg), WL_{FC} = Weight of lysimeter at field capacity (kg), WL_i = Weight of lysimeter at urrent condition (kg)

5.2.5. Evapotranspiration determination

The determination of evapotranspiration using the weighable lysimeters involved the measurement of the soil water balance components. Weather data, including rainfall (P), was obtained from Melkassa Agricultural Research Center weather station, which is situated around 50 m away from the lysimeter plot. Applied irrigation water (I) and change in soil moisture content (ΔSM) were quantified, respectively, using Equations 5-2 and 5-1. While the drainage water (Dp) was collected at the access chamber and measured.

The evapotranspiration of onion crops for each growth stage or time interval, expressed as unit mass or volume per unit area, or by equivalent water height (Rana & Katerji, 2007), was computed using Equation 5-3, the general water balance equation.

$$ET_c = I + P - D_p - \Delta SM \qquad \text{Equation 5-3}$$

Where, ETc = crop evapotranspiration (mm), I = applied irrigation water (mm), P=rain fall (mm), Dp = deep percolation (drained water) (mm), ΔSM = change in soil moisture content(mm)

5.2.6. Reference evapotranspiration determination

Reference evapotranspiration was computed using the version 8.0 CROPWAT model that employs the Penman-Monteith equation (Allen et al., 1998). Input climatic data for the model includes temperature (maximum and minimum), relative humidity, wind speed, and sunshine hours, which were collected from the weather station of the research center. The weather station is situated around 50 meters from the lysimeter plot and measures various parameters, including temperature with a mercury-in-glass thermometer, relative humidity with psychrometers, wind speed with cup anemometers, sunshine hours with a Campbell-Stokes sunshine recorder, and precipitation with a manual rain gauge.

5.2.7. Crop coefficient determination

The ratio of measured evapotranspiration of crop, ETc to ETo, reference evapotranspiration from version 8.0 of the CROPWAT model, was used to calculate the crop coefficient, or Kc (Equation 5-4).

$$K_c = \frac{ET_c}{ET_o} \qquad \text{Equation 5-4}$$

Where, Kc = Crop coefficient, ETc = Crop evapotranspiration (mm), and ETo = Reference evapotranspiration (mm)

5.3. Results and Discussions

5.3.1. Reference evapotranspiration, ETo

The daily computed ETo throughout the growing period is presented in Figures 5-3 and 5-4. Table 5-1 presents the average decadal weather input data for the CROPWAT model and computed reference evapotranspiration (ETo) using the model. During the 2023 growing season, the reference evapotranspiration value fluctuated between 2.49 and 6.00 mm day^{-1} with a 4.50 mm day^{-1} average value, while during the 2024 growing season it fluctuated from 2.36 to 6.07 mm day^{-1} with a 4.22 mm day^{-1} average value. The pooled reference evapotranspiration value for the growth stages: initial, developmental, mid- and late-season was found to be 4.62, 4.74, 4.65, and 4.48 mm day^{-1}, respectively (Table 5-2). The average reference evapotranspiration value for the whole growth season was found to be 509.18 mm.

Table 5-1. Average decadal weather data and computed reference evapotranspiration

DAT	2023 growing period						2024 growing period					
	Tmin	Tmax	RH	U_2	Sunshine	ETo	Tmin	Tmax	RH	U_2	Sunshine	ETo
	°C	°C	%	m s^{-1}	hr	mm day^{-1}	°C	°C	%	m s^{-1}	hr	mm day^{-1}
1-10	8.3	29.9	84.5	2.7	10.1	4.68	13.8	29.9	65.4	2.8	9.1	5.13
11-20	9.4	29.3	83.4	3.0	10.1	4.74	14.5	29.9	67.1	1.7	6.1	4.14
21-30	11.2	30.7	83.3	2.1	8.1	4.47	11.5	32.1	58.5	2.0	9.6	5.39
31-40	13.9	30.3	81.2	2.6	7.3	4.48	14.5	30.9	67.3	1.6	8.0	4.74
41-50	14.4	27.3	73.5	1.7	3.9	3.54	13.5	32.3	58.2	2.1	10.1	5.81
51-60	14.2	28.0	71.0	1.8	5.7	4.06	14.6	28.9	71.9	1.6	4.7	3.87
61-70	14.3	29.8	66.6	1.8	8.8	5.03	14.9	29.1	71.2	1.6	6.8	4.37
71-80	14.1	30.9	61.3	2.0	10.5	5.67	14.4	31.2	68.1	1.8	8.3	5.02
81-90	14.6	27.0	76.2	1.2	6.0	3.81	15.6	28.9	73.0	1.3	5.7	3.96
91-100	14.3	28.7	71.7	1.5	7.8	4.46	15.4	29.0	72.7	1.3	7.2	4.26
101-110	14.7	30.6	71.8	2.0	8.7	4.94	15.2	31.7	63.9	1.8	9.3	5.26

DAT - days after transplanting, Tmax - maximum temperature, Tmin - minimum temperature, U_2 - wind speed at 2 m height, RH - relative humidity, and ETo - reference evapotranspiration.

Table 5-2. Stage-based and seasonal reference evapotranspiration

Growing season	Initial (mm day^{-1})	Developmental (mm day^{-1})	Mid-season (mm day^{-1})	Late season (mm day^{-1})	Seasonal (mm)
2023	4.70	4.32	4.70	4.43	498.78
2024	4.54	5.16	4.59	4.52	519.58
Average	4.62	4.74	4.65	4.48	509.18

5.3.2. Crop evapotranspiration (ETc) of onion

The daily fluctuation in water requirement of onion throughout the growing season is presented in Figures 5-3 and 5-4. Tables 5-3 and 5-4 present the average decadal and stage-based evapotranspiration of onion, as quantified from the water balance of the lysimeter. It shows that the evapotranspiration of onion was lower during the initial stage, raised at the development stage, peaked at the mid-season stage, and slowly declined at the late-season stage. The average water requirements of onion for the growth stages: initial, developmental, mid-, and late-season are presented in Table 5-4. The averaged values varied from 3.12 mm day^{-1} to 4.81 mm day^{-1} at the initial and mid-season growth stages of onion, respectively. The seasonal water requirement for onion was found to be 460.27 mm on average. The low crop evapotranspiration of onion at the late season stage following the initial stage was mainly due to limited canopy cover in the early stage and termination of leaf growth in the late stage (Allen et al., 1998; Dirirsa et al., 2015; Abebe et al., 2021). However, high water requirements were observed at the mid-season stage due to fully developed canopies and processes like flowering, tuber formation, and filling (Abebe et al., 2021).

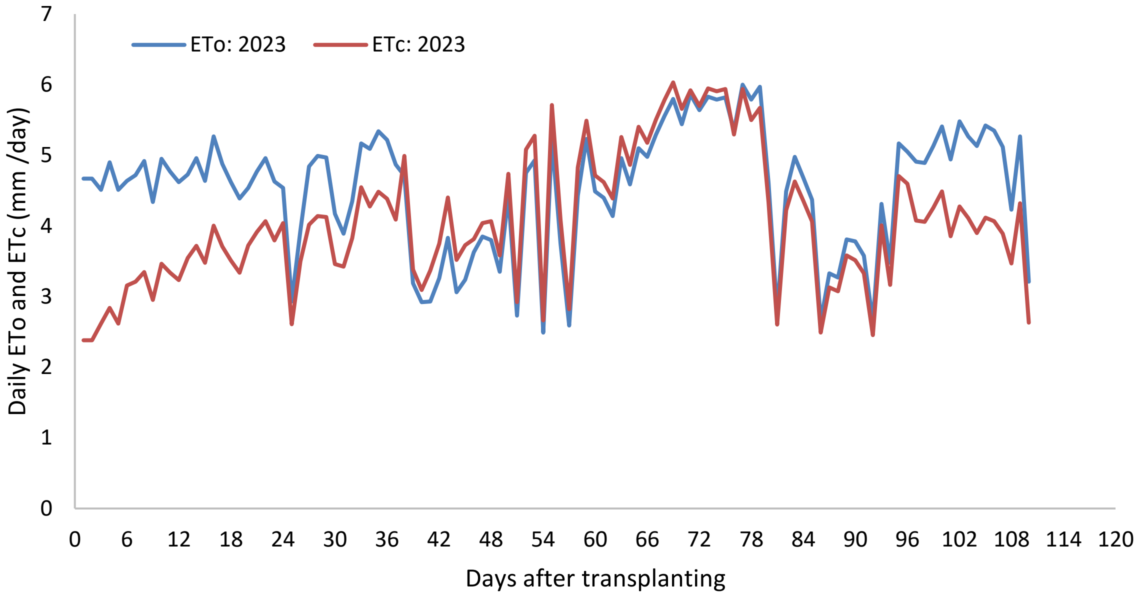


Figure 5-3. Reference evapotranspiration and onion evapotranspiration during the growing season

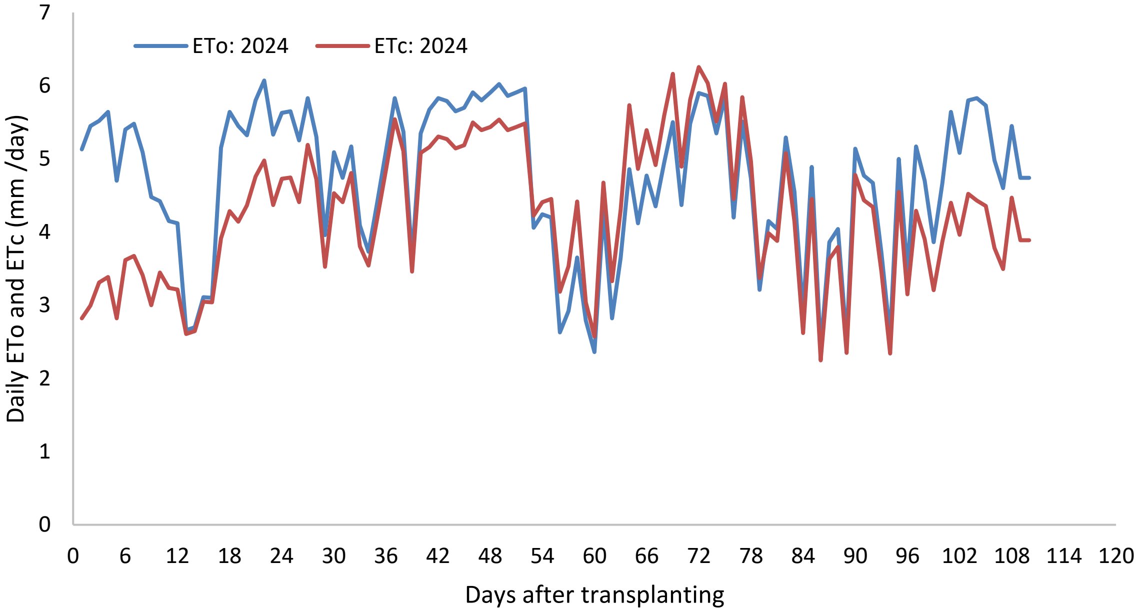


Figure 5-4. Reference evapotranspiration and onion evapotranspiration during the growing season

Table 5-3. Decadal measurements of water balance components and evapotranspiration of onion

DAT	2023 growing season					2024 growing season				
	I mm	P mm	Dp mm	ΔS mm	Average ETc mm	I mm	P mm	Dp mm	ΔS mm	Average ETc mm
1-10	25.52	0.00	0.00	-3.33	2.89	29.06	0.00	0.00	-3.31	3.24
11-20	35.21	0.00	0.00	-0.55	3.58	22.40	20.60	10.08	-1.33	3.42
21-30	25.63	7.29	0.00	-4.56	3.75	32.50	17.00	4.50	-0.78	4.58
31-40	37.40	55.50	32.80	19.69	4.04	20.31	123.50	76.25	22.71	4.49
41-50	0.00	67.92	47.50	-17.72	3.81	28.85	0.00	9.23	-33.70	5.33
51-60	23.54	35.00	17.50	-3.21	4.43	21.88	41.29	10.21	9.52	4.34
61-70	38.13	17.50	4.33	-1.78	5.31	32.92	29.71	6.69	7.41	4.85
71-80	52.40	63.50	33.73	26.59	5.56	34.06	15.00	1.27	-4.81	5.26
81-90	15.00	71.58	64.90	-14.40	3.61	20.83	25.46	7.63	2.08	3.66
91-100	2.19	47.79	25.48	-14.79	3.93	0.00	109.54	83.79	-14.77	4.05
101-110	0.00	5.42	0.00	-33.33	3.88	0.00	0.00	0.00	-40.63	4.06

DAT - days after transplanting, I - irrigation, P - rainfall, Dp - deep percolation, ΔS - change in soil moisture content, and ETc - crop evapotranspiration.

Table 5-4. Growth stage-based and seasonal evapotranspiration of onion (Nafis variety)

Growing season	Initial (mm day^{-1})	Developmental (mm day^{-1})	Mid-season (mm day^{-1})	Late season (mm day^{-1})	Seasonal (mm)
2023	3.08	3.83	4.82	3.75	447.66
2024	3.15	4.54	4.79	3.92	472.88
Average	3.12	4.19	4.81	3.84	460.27

5.3.3. Crop coefficient of onion

Decadal and observed values of crop coefficients were established and presented in Table 5-5 and Figures 5-5a and 5-5b, respectively. It can be seen that the crop coefficient consistently raised from 0.62 to 1.11 during 10-60 days after transplanting. During 60 to 80 days, the value was decreased slightly from 1.11 to 1.08 and then to 1.01. During the late season, 80 to 110 days after transplanting, it further declined to 0.78. Table 5-6 presents the average growth stage-based crop coefficient. The value increased from 0.68 at the initial to 1.03 at mid-season and then declined to 0.86 at the late-season growing stage. The crop coefficient value reached its maximum at the critical time, approximately covering from 40 to 85 days after transplanting. During the growth stages of development and mid-season, the increased crop coefficient value is a result of rapid crop development (Bayisa et al., 2024). The crop's development and covering of the ground to attain full size with growing root depth and plant height resulted in a rise in water abstraction and an increase in crop evapotranspiration (Allen et al., 1998; Srinivas & Tiwari, 2018). The gradual decline in crop coefficient value during the late-stage season was due to decreased water requirement as a result of termination of leaf growth (Allen et al., 1998; Abebe et al., 2021).

Table 5-5. Decadal values of crop coefficient

DAT	2023 growing season			2024 growing season			Average Kc
	ETc mm	ETo mm	Kc	ETc mm	ETo mm	Kc	
1-10	2.89	4.68	0.62	3.24	5.13	0.63	0.62
11-20	3.58	4.74	0.75	3.42	4.14	0.83	0.79
21-30	3.75	4.47	0.84	4.58	5.39	0.85	0.84
31-40	4.04	4.48	0.90	4.49	4.74	0.95	0.92
41-50	3.81	3.54	1.08	5.33	5.81	0.92	1.00
51-60	4.43	4.06	1.09	4.34	3.87	1.13	1.11
61-70	5.31	5.03	1.06	4.85	4.37	1.11	1.08
71-80	5.56	5.67	0.98	5.26	5.02	1.05	1.01
81-90	3.61	3.81	0.95	3.66	3.96	0.92	0.94
91-100	3.93	4.46	0.88	4.05	4.26	0.95	0.92
101-110	3.88	4.94	0.78	4.06	5.26	0.77	0.78

Table 5-6. Growth stage-based values of crop coefficient

Growing season	Growth stage			
	Initial	Developmental	Mid-season	Late season
2023	0.66	0.89	1.03	0.85
2024	0.69	0.89	1.04	0.87
Average	0.68	0.89	1.03	0.86

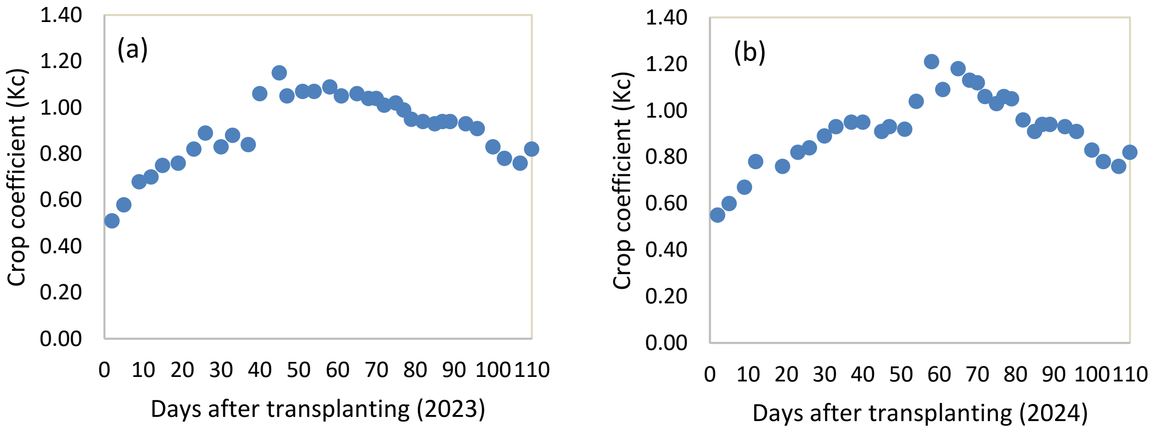


Figure 5-5. Observed values of onion crop coefficients for the growing seasons of 2023 (a) and 2024 (b)

The average growth stage-based values of crop coefficient found in the current study were 0.68, 0.89, 1.03, and 0.86, respectively, for the growth stages: initial, developmental, mid-, and late-season. Table 5-7 illustrates crop coefficient values found in the literature and this study. The values obtained in this study were aligned well with the values reported by Abebe et al. (2021), Dirirsa et al. (2015), and López-Urrea et al. (2009), even if the result of Abebe et al. (2021) has a slightly lower value at the initial stage. The report of Hend et al. (2019) agrees with this study except for the initial and developmental stages. The crop coefficient value reported by Martín De Santa Olalla et al. (2004) comports with the values of the current study, except for the initial and late season stages. The finding of Bossie et al. (2009) shows lower values for all growth stages.

Table 5-7. Stage-based onion crop coefficient values determined by different authors compared to the current study

Author	Growth stage			
	Initial	Developmental	Mid-season	Late season
Abebe et al. (2021)	0.49	0.90	1.01	0.79
Hend et al. (2019)	0.40	0.41	1.10	0.87
Dirirsa et al. (2015)	0.61	0.86	1.02	0.80
Bossie et al. (2009)	0.47	-	0.99	0.46
López-Urrea et al. (2009)	0.65	-	1.20	0.75
Martín De Santa Olalla et al. (2004)	0.50	-	1.00	0.70
Current study	0.68	0.89	1.03	0.86

Furthermore, a comparison was made between the crop coefficient values developed using the lysimeter and FAO-56 suggested Kc for onion. The crop coefficient curve derived in this study (Figure 5-6) has the same trend as the FAO-56 estimated curve. In comparison, the values were almost similar during the initial, developmental, and mid-season growth stages. However, the crop coefficient value developed using the lysimeter was slightly higher in the late season.

According to Allen et al. (1998), it is believed that local differences in environmental factors lead to variance in crop developmental stage and variety selection, which impacts crop coefficient. Key environmental factors include temperature, which affects the rate of plant growth and development; wind speed, which affects evapotranspiration rates; humidity, which influences transpiration and water loss; and solar radiation, which drives photosynthesis and energy absorption. Soil characteristics, such as texture, structure, and moisture-holding capacity, further contribute to these variations by determining how water and nutrients are absorbed by the crops. These factors vary significantly across different geographic regions, creating distinct growing conditions that directly influence the water requirements of crops and their overall performance. These variations clearly demonstrate the challenges associated with employing crop coefficients to estimate agricultural water requirements in a given year with varying crop development patterns, as well as the difficulties in extrapolating crop coefficients to different locations (Abedinpour, 2015).

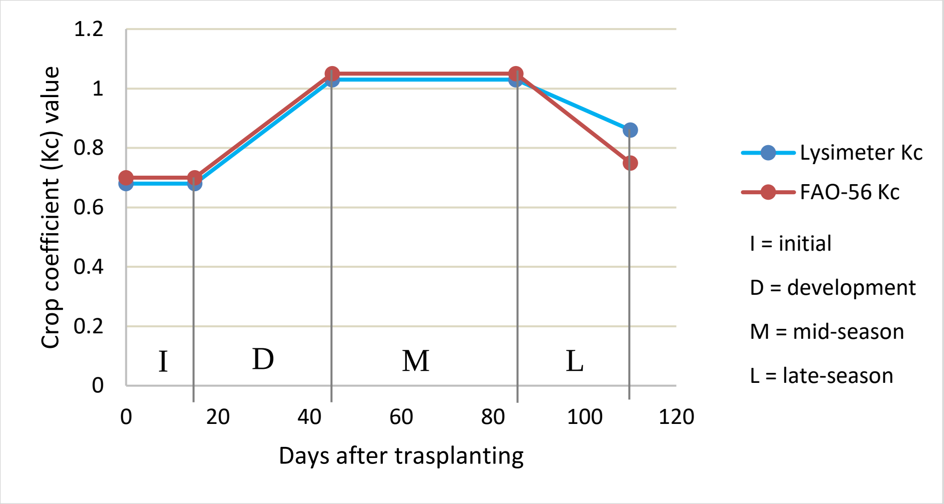


Figure 5-6. Crop coefficient determined using lysimeter and FAO-56 recommended for onion

A third-order polynomial equation was fitted to measured data with R^2 equal to 0.87, as shown in Figure 5-7. Different studies proposed a similar third-order polynomial function to predict the variation in the crop coefficient of onion (Bossie et al., 2009; Zheng et al., 2016).

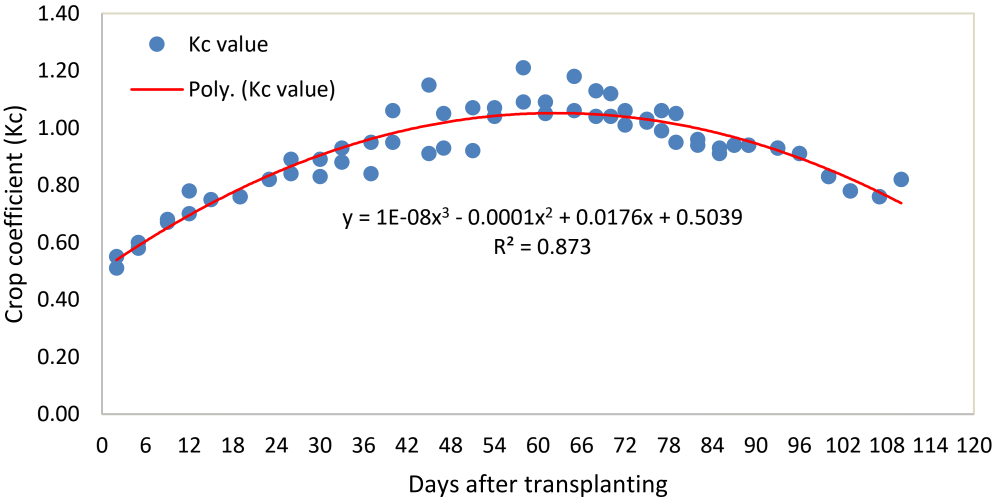


Figure 5-7. Crop coefficient of onion as a function of number of days after transplanting

5.4. Conclusion

The water requirements and crop coefficient of the Nafis onion variety were determined through field measurements conducted over two consecutive years in the semi-arid climate of Melkasa, Ethiopia. The daily average evapotranspiration of the onion crop ranged from 3.12 mm at the initial to 4.81 mm at mid-season growth stages. The total seasonal water requirement of the crop was calculated to be 460.27 mm. Crop coefficient values for initial, developmental, mid-, and late-season stages were determined as 0.68, 0.89, 1.03, and 0.86, respectively, aligning well with the standard literature values, including the FAO guidelines. Furthermore, a third-order polynomial equation was presented to predict the values of the crop coefficient. These findings offer a reliable basis for improving irrigation water use efficiency and optimizing irrigation scheduling for the production of onion, particularly in semi-arid regions like Melkasa, where neither field-based measured data nor site-specific validated estimation methods are lacking.

5.5. Recommendation and Future Work

The lysimeters used in this study were specifically developed for shallow-rooted crops, limiting their applicability for measuring ETc and Kc for deep-rooted crops (Kebede et al., 2024). Scaling up the size and capacity of lysimeters to accommodate a wider range of crops is a critical consideration, particularly in regions like Ethiopia, where weighing types of lysimeters are not available. Additionally, integrating lysimeter data with remote sensing techniques could significantly enhance the spatial and temporal assessment of ETc and Kc values. This approach could also support the development of ETo maps, providing valuable tools for improved water resource management.

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6. EVALUATION AND CALIBRATION OF SELECTED CROP EVAPOTRANSPIRATION ESTIMATION MODELS

Abstract

In light of increasing water scarcity in agriculture, efficient irrigation planning has become essential, with accurate estimation of crop water requirements playing a critical role. Although lysimeter experiments provide precise measurements, their use is often constrained by high costs, time demands, and limited access to equipment and facilities. As a result, crop water needs are frequently estimated through the Kc-approach using weather-based models. However, the transferability of these weather-based models to other environments result in over- or underestimation, which affects the estimation of ETc. Thus, this study evaluated the performance of ten ETo models and calibrated the Hargreaves and Blaney-Criddle equations using lysimeter-measured crop evapotranspiration (ETc). Hargreaves, Droogers and Allen, Irmak, Trajovic, Tabari and Talaee, Tabari, Dorji, Blaney-Criddle, Thornthwaite, and FAO-56 Penman-Monteith were the models that were assessed; they all required limited and easily accessible climate input data except the FAO-56 Penman-Monteith. ETo values were computed using each model and multiplied by FAO-56 crop coefficients to estimate onion water requirements. Model performance was evaluated using statistical indicators including MBE, RMSE, R^2, and IA. A ranking approach, based on the indices, was used to identify the best-performing model. Results revealed that the FAO-56 PM model outperformed all other models. From the other nine models, the Blaney-Criddle model was the most accurate model. Calibration significantly enhanced the accuracy of both the Hargreaves and Blaney-Criddle equations, with the Hargreaves coefficient increasing by 48% (from 0.0023 to 0.0034) and the Blaney-Criddle coefficient decreasing by 9% (from 1 to 0.9135). These findings suggest that the calibrated models are suitable alternatives for estimating onion water requirements using the Kc-approach, especially in regions lacking direct measurement data. Additionally, they serve as effective substitutes for the FAO-56 PM model in areas with similar climatic conditions and limited meteorological data.

Key words: *Water requirement, Onion, Lysimeter, Kc-approach, ETo-models, Performance evaluation, Calibration*

Published article

A manuscript entitled “Enhancing crop evapotranspiration estimation in semi-arid Ethiopia: evaluating and calibrating selected ETo models using lysimeter data”, is currently submitted to a journal for consideration.

6.1. Background of the Study

In many places, especially in developing nations, the amount of water available for irrigation is gradually decreasing. One significant concern is the growing competition for water resources among various sectors, including residential and commercial applications (Dingre & Gorantiwar, 2020). However, the development of additional water resources is limited by a number of technical and financial obstacles, including high costs, a lack of suitable reservoir sites, challenges in distributing water, and environmental concerns (Pereira, 2005). The situation is made worse by other issues like desertification and over usage of the available water supplies (Bachour, 2013). Furthermore, in many countries, particularly those that are dry and semi-arid, climate change is already having an impact on the availability of water resources for agriculture (Halasuru Jayaram, 2018).

Thus, effective water management is essential for sustainable agriculture, particularly in semi-arid regions where water scarcity poses significant challenges. In Ethiopia, optimizing crop water use is crucial for improving agricultural productivity. One of the key factors in effective water management is accurately estimating crop water requirements (ETc), which plays a vital role in irrigation planning and scheduling (Holzapfel et al., 2010; Wickramaarachchi et al., 2011).

Crop water requirement determination is more accurate with direct measurement using lysimeters. However, because of the high cost requirements and lack of laboratory equipment and infrastructure, such investigations are rarely conducted (Yadeta et al., 2021). When direct measurement is not possible, an indirect method that uses the Kc-approach is used, where crop water need is determined as a product of ETo and Kc (Doorenbos & Pruitt, 1977; Allen et al., 1998). In this case, the accuracy of the water requirement depends on the method used to estimate the ETo (Muhammad et al., 2019).

For estimating ETo, reference crop evapotranspiration, from meteorological data, numerous models have been developed (Hargreaves & Samani, 1985; Allen et al., 1998; Droogers & Allen, 2002; Irmak et al., 2003; Trajkovic, 2007; Tabari & Talaee, 2011; Tabari et al., 2013; Berti et al., 2014; Heydari & Heydari, 2014; Dorji et al., 2016; Ahooghalandari et al., 2016; Mendoza

& Peña, 2021). Certain techniques are only valid in particular climatic and agronomic circumstances, and their application needs to be validated locally.

Among the available models, the FAO-56 Penman-Monteith approach is a standard equation for estimating ETo for various global climatic circumstances. However, data required in the Penman-Monteith method are not always available, especially in developing countries (Hunduma et al., 2020), in general, and specifically in Ethiopia. Therefore, given the extensive data requirements of the FAO-56 Penman-Monteith method or the unavailability of measured ETo, it is essential to identify the best-performing alternative models that require limited input data (Song et al., 2019) or to calibrate them accordingly to be used in a specific area of interest. Because the transferring of these ETo models to other environments result in over- or underestimation, which affects the estimation of ETc.

In this regard, to enhance ETo model accuracy, researchers have extensively studied calibration, adjusting model parameters to account for local climatic circumstances. One of the most popular methods in model calibration is adjusting the empirical coefficients of temperature-based models like Blaney-Criddle, Hargreaves-Samani, and Priestaley-Taylor (Heydari et al., 2015; Metcalfe et al., 2019).

A study on the calibration of the Hargreaves-Samani model by Tabari & Talaee (2011), Djaman et al. (2015), Cobaner et al. (2017), Majeed et al. (2017), and Ogunrinde et al. (2022) showed that calibration enhanced the model’s performance across different climatic sub-regions. A study on the Blaney-Criddle model’s calibration improved its applicability across diverse environments. Locally modified coefficients greatly increased the model's accuracy in calculating ET_0, according to a study conducted in Turkey by Gharehbaghi & Kaya (2022). Additionally, a study conducted in Iran (Fooladmand & Ahmadi, 2009) and in Jordan (Mohawesh, 2010) emphasized the significance of spatial calibration in arid and semi-arid regions to minimize estimation errors.

Overall, regional calibration significantly boosts the reliability of these models, making them suitable for data-limited areas. From these perspectives, the aim of this study was to evaluate and calibrate ETo models for accurate evapotranspiration estimation using lysimeter data to optimize crop water use in the semi-arid climatic conditions of Melkasa, Ethiopia.

6.2. Materials and Methods

6.2.1. Description of the study area

The study was conducted in the years 2023 and 2024 for two growing seasons at Melkasa Agricultural Research Centre (MARC), in the central rift valley of Ethiopia. Geographically, the area is located at $8^0$24'- $8^0$26 latitude, $39^0$18'- $39^0$22' longitude, and 1550 m.a.s.l. altitude. Agro-ecologically, the region falls within a semi-arid zone, characterized by a hot climate year-round, with an average annual rainfall of 845.5 mm and temperatures ranging from a minimum of 14°C to a maximum of 29°C. In the area dominated with loam and clay loam textured soil, a variety of crops are grown. During the main growing season, crops such as teff, sorghum, maize, haricot beans, and soybeans are grown. Whereas onion, tomato, banana, papaya, and sugarcane are grown in the off-season. During the off-season, crops are grown using irrigation from the Awash River as a water source.

6.2.2. Data collection

A weighable lysimeter, developed and tested by Kebede et al. (2024), was utilized to measure the crop water requirement (ETc) of onion.

Soil moisture monitoring and irrigation application

Soil moisture variation was directly measured by tracking the change in mass of the lysimeter over specific time intervals (Payero & Irmak, 2008). Initially, the soil moisture was set to field capacity. The moisture content change between irrigation periods was determined by calculating the difference in lysimeter mass before irrigation (Kebede et al., 2025) and was computed using Equation 6-1.

$$\Delta SM = WL_t - WL_{t-1} \qquad \text{Equation 6-1}$$

Where, ΔSM = Change in soil Moisture content (kg), WL_t = Weight of lysimeter at current time (kg), WL_{t-1} = Weight of lysimeter at previous time (kg)

Irrigation water was supplied when the depletion factor (p) approached or reached 0.3, following the recommendation of Allen et al. (1998), to maintain optimal soil moisture conditions. This was made possible by routinely checking the soil's moisture content every two to three days, which allowed for consistent water availability in the root zone. Equation 6-2 was used to determine how much water was required to replenish the soil to its field capacity, and a calibrated watering can was used to apply it.

$$SMD = WL_{FC} - WL_i \qquad \text{Equation 6-2}$$

Where, SMD = Soil Moisture Depleted (kg), WL_{FC} = Weight of lysimeter at field capacity (kg), WL_i = Weight of lysimeter at urrent condition (kg)

Weighable lysimeters were used to measure the components of the soil water balance in order to determine evapotranspiration. Meteorological data, including rainfall (P), was obtained from the weather station at the Melkassa Agricultural Research Center, which is located about 50 meters from the lysimeter area. The amount of irrigation water applied (I) and the change in soil moisture content (ΔSM) were calculated using Equations 6-2 and 6-1, respectively. In the access chamber, drainage water (Dp) was collected and then measured.

Equation 6-3, which is based on the general water balance equation, was used to compute the evapotranspiration of onion at each time period, presented as volume per unit area, unit mass, or an equivalent water height (Rana & Katerji, 2007).

$$ETc_L = I + P - D_p - \Delta SM \qquad \text{Equation 6-3}$$

Where, ETc = crop evapotranspiration (mm), I = applied irrigation water (mm), P=rain fall (mm), Dp = deep percolation (drained water) (mm), ΔSM = change in soil moisture content(mm)

For the purpose of comparison and evaluation of the different models, the water requirement of onion was estimated using selected Kc-approach-based models. The climatic data collected from the Melkassa Agricultural Research Center weather station was prepared according to the requirements of the selected models, and the reference evapotranspiration was determined.

6.2.3. Description of selected models used in the Kc-approach

The models used in the Kc approach were selected based on the availability of input data requirements (Al-Ghobari, 2000). The models considered in this study were Hargreaves and Samani, Droogers and Allen, Irmak, Trajovic, Tabari and Talaee, Tabari, Dorji, Blaney Criddle, and Thornthwaite. These models are radiation- and temperature-based models where the required input climatic data are relatively low and accessible. In addition to these models the FAO-56 PM model was checked its performance in the study climate condition.

6.2.3.1. Hargreaves model

With the aim of developing a simple and practical method to estimate crop water requirements with minimum climatological data, Hargreaves and Samani made an improvement on the original Hargreaves (1975, 1982) equation (Hargreaves & Samani, 1985). To develop the model, the authors used measured lysimeter evapotranspiration of cool season grass as an index of reference crop evapotranspiration. The equation estimates the reference evapotranspiration from values of maximum and minimum temperature and is given by Equation 6-4.

$$ETo = 0.0023 * R_A * TD^{0.5}(T_{mean} + 17.8) \qquad \text{Equation 6-4}$$

6.2.3.2. Droogers and Allen model

Droogers and Allen (2002) proposed an ETo estimation model based on the Hargreaves and Samani (1985) equation (Droogers & Allen, 2002). The authors proposed the following form of the Hargreaves equation, Equation 6-5, on a global scale using a high-resolution monthly climate data set to estimate ETo of arid climate.

$$ETo = 0.0030 * 0.408R_A(T_{mean} + 20) * TD^{0.4} \qquad \text{Equation 6-5}$$

6.2.3.3. Irmak model

According to Irmak et al. (2003), simplified or empirical temperature- or radiation-based equations with fewer parameters can be used when the climate data needed to estimate ETo using one of the combination methods, such as the FAO-56 PM method, are unavailable or unreliable for a local region. Using the FAO 56-PM technique as an index, the authors created a radiation-based equation (Equation 6-6) to estimate reference evapotranspiration (ETo) in order to minimize the need for input parameters and computation (Irmak et al., 2003).

$$ETo = -0.611 + 0.149R_s + 0.079T_{mean} \qquad \text{Equation 6-6}$$

6.2.3.4. Trajovic model

Where there is a lack of data required to use the FAO-56 PM method, a simple empirical Hargreaves equation is often used (Trajkovic, 2007). However, this equation generally overestimates ETo at humid locations. Therefore, the author made an adjustment to Hargreaves and Samani's (1985) equation and proposed a value of 0.424 instead of the original 0.5 exponent for the equation (Equation 6-7).

$$ETo = 0.0023 * R_A * (T_{max} - T_{min})^{0.424} \left(\frac{T_{max}+T_{min}}{2} + 17.8\right) \qquad \text{Equation 6-7}$$

6.2.3.5. Tabari and Talaee model

Tabari and Talaee developed a model to estimate ETo as a function of mean solar radiation and air temperature to be used in arid climates (Equation 6-8).

$$ETo = 0.0031 * R_A(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} \qquad \text{Equation 6-8}$$

6.2.3.6. Tabari model

Tabari and his colleagues developed a radiation-based method (Equation 6-9) for estimating ETo using solar radiation and air temperature data based on the FAO-56 PM model as a reference (Tabari et al., 2013).

$$ETo = -0.642 + 0.174R_s + 0.0353T_{mean} \qquad \text{Equation 6-9}$$

6.2.3.7. Dorji model

Absence of the required range of meteorological variables to calculate ETo using the standard FAO-56 PM in terms of quantity and quality in developing countries; Dorji and his colleagues enforced the selection and calibration of a method that only requires information on temperature that is more generally available from climate stations (Dorji et al., 2016). Based on this, the authors developed Equation 6-10, taking FAO-56 PM as a reference.

$$ETo = 0.002 * R_A(T_{mean} + 33.9) * TD^{0.296} \qquad \text{Equation 6-10}$$

For all models, ETo = reference evapotranspiration (mm), TD = T_{max} - T_{min} and T_{mean} = (T_{max} + T_{min})/2. Temperature is measured in ^{o}C, while ETo and R_A are both in equivalent water evaporation units. For models that require incoming solar radiation, Rs is given by Equation 6-11.

$$R_s = K_{RS}(T_{max} - T_{min})^{0.5} * R_A$$ Equation 6-11

Where K_{RS} = 0.16 (adjusted coefficient)

6.2.3.8. Blaney-Criddle model

According to Mendoza and Peña (2021), the Blaney-Criddle FAO approach was derived by multiplying the monthly average temperature by the monthly percentage of annual hours of sunlight and then relating the monthly evapotranspiration values to the result. FAO changed this, using local climate adaptations (Mendoza & Peña, 2021). Equation 6-12 provides an appropriate computation.

$$ETo = p(0.457T_{mean} + 8.13)$$ Equation 6-12

Where ETo = reference evapotranspiration (mm day^{-1}), T_{mean} = mean daily air temperature (^{o}C) and, P = mean daily percentage of annual day hours of sunlight.

6.2.3.9. Thornthwaite model

The Thornthwaite equation, Equation 6-13, is a simple and widely used method for estimating reference evapotranspiration (ETo). Despite its popularity, it has faced criticism for its empirical nature. Since the Thornthwaite model calculates ETo using only temperature, it is often misapplied, particularly in semi-arid and arid regions where its requirements have not been maintained.

$$ETo = ET' * \left(\frac{d}{12}\right)\left(\frac{N}{30}\right)$$ Equation 6-13

To determine ETo, the following calculations must first be performed:

1. $i = \left(\frac{T_{mean}}{5}\right)^{1.51}$ 2. $I = \sum_{j=1}^{12} j_i$ 3. $ET' = C\left(\frac{10T_{mean}}{I}\right)^{a}$

C = 16 (constant), and $a = 67.5 * 10^{-8}I^3 - 77.1 * 10^{-6}I^2 + 0.0179I + 0.492$

Where: i = monthly heat index for the month j (zero when the Tmean is 0°C or lower). I = yearly heat index. Tmean = monthly average air temperature (°C), j = month number it is 1 - 12. ET' =

unadjusted potential evapotranspiration (monthly), is calculated using a normal month of 30 days with 12 hours of sunshine per day. ET' is then adjusted using the actual number of days in the specified month (N), ($1 \leq N \leq 31$) and d is the mean monthly daylight length (hours).

Once the ETo was estimated using all ten models, the water requirement of onion was computed by the Kc-approach using Equation 6-14. The crop coefficient was adopted from the FAO paper suggested for the crop (Allen et al., 1998).

$$ETc_M = ETo_M * Kc_{FAO} \qquad \text{Equation 6-14}$$

Where, ET_{CM} = Onion water requirement computed from model, ET_{OM} = Reference evapotranspiration determined by model, Kc_{FAO} = Onion crop coefficient, FAO recommended

6.2.3.10. FAO-56 PM (Penman-Monteith) model

To calculate the reference evapotranspiration (ETo) using this model, version 8 of the CropWat model was employed. This computer-based decision-support tool, developed by the FAO, uses a set of equations to estimate reference evapotranspiration, crop water requirements, irrigation schedules, and irrigation water demand, all of which are based on rainfall, soil, crop, and climate data (Ewaid et al., 2019). The model calculates daily ETo using the FAO Penman-Monteith equation. This method is particularly advantageous compared to other techniques due to its foundation in physical principles and its validation through several lysimeter tests. The data needed by the CropWat 8.0 model to compute daily ETo include minimum and maximum temperatures, sunshine hours, wind speed, and relative humidity (Abebe et al., 2021).

6.2.4. Evaluation of model performance

In light of the unavailability of lysimeter-based measurements and the lack of sufficient data needed for the FAO-56 PM method, various alternative models were formulated to estimate reference evapotranspiration (ETo). Based on the description of Song et al. (2019) from the models developed, nine of them, with a limited input data requirement, were selected for evaluation to select the best performing model in the climatic condition of the study area. Furthermore, the FAO-56 PM model was evaluated.

6.2.4.1. Evaluation procedure

Initially, the crop evapotranspiration (ETc) for onion was calculated using the crop coefficient (Kc) approach, where ETc was obtained by multiplying reference evapotranspiration (ETo) estimated through the selected ETo models with crop coefficients recommended by the FAO. The ETc values derived from each model were then compared to lysimeter-measured ETc using various statistical indicators. Finally, to identify the best-performing model, a ranking system was applied.

6.2.4.2. Statistical indices used for model performance evaluation

Different statistical indices taken from Yadeta et al. (2021a) were utilized to evaluate the performance of the Kc-approach-based ETo models used to estimate the water requirement of onion under the climatic conditions of the study area with regard to the measured value from the lysimeter experiment.

Root Mean Square Error (RMSE)

The actual differences between lysimeter results and values predicted by a model are measured by the root mean square error, or RMSE. This difference represents the model's estimation error for onion evapotranspiration. Equation 6-15 is used to calculate the RMSE, and the lower the RMSE, the better the model performance (Jacovides & Kontoyiannis, 1995). Zero is the optimal value.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(ETc_M - ETc_L)^2}{N}} \qquad \text{Equation 6-15}$$

Mean Bias Error (MBE)

The value of this metric provides information on whether the model is overestimating or underestimating onion evapotranspiration. The tested model is overestimating when the numbers are positive and underestimating when they are negative. Zero is the optimal value; the smaller the MBE, the better the model performance, which is computed using Equation 6-16 (Jacovides & Kontoyiannis, 1995).

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(ETc_M - ETc_L) \qquad \text{Equation 6-16}$$

Coefficient of determination (R^2)

Since it indicates the proportion of one variable's variation (fluctuation) that can be predicted from the other, the coefficient of determination is helpful. It's a measure that enables figuring out how confident one can be in predictions derived from a particular model. The model is acceptable if the coefficient of determination, which shows the degree of linear relationship between evapotranspiration estimated by the model and measured by the lysimeter, is greater than 0.6. The coefficient of determination runs from $0 \leq R^2 \leq 1$. The condition that has the highest (R^2) is the best and is computed using Equation 6-17.

$$R^2 = \left[\frac{\sum_{i=1}^{N}(ETc_M - \overline{ETc}_M) * (ETc_L - \overline{ETc}_L)}{\sqrt{\sum_{i=1}^{N}(ETc_M - \overline{ETc}_M)^2 * \sum_{i=1}^{N}(ETc_L - \overline{ETc}_L)^2}}\right]^2 \qquad \text{Equation 6-17}$$

Index of agreement (IA)

Measures the relative error that enables model cross-comparison, which is provided by the index of agreement. It's employed for measuring the degree of agreement between lysimeter-measured and model-estimated evapotranspiration. It has a range of 0 to 1, with 1 denoting full agreement between the model's predictions and observations and values nearer 0 denoting poorer agreement (Willmott, 1984) and computed using Equation 6-18.

$$IA = 1 - \left[\frac{\sum_{i=1}^{N}(ETc_M - ETc_L)^2}{\sum_{i=1}^{N}(\,|ETc_M - \overline{ETc}_L| + |ETc_L - \overline{ETc}_L|\,)^2}\right] \qquad \text{Equation 6-18}$$

6.2.4.3. Model ranking

A model with greater R^2 and IA values and lower MBE and RMSE, which are zero or very near to zero, is the best performing model. To identify the best performing model, a ranking system similar to that used by Ilesanmi et al. (2014) and Ratshiedana et al. (2025) was applied. Each model was ranked based on individual statistical metric values, and the overall performance was evaluated by comparing the average of these ranks; a smaller average rank indicates a better performance (Ratshiedana et al., 2025).

6.2.5. Calibration of Hargreaves and Blaney-Criddle models

Based on the lack of direct measurement using a lysimeter and the unavailability of required data to use the standard FAO-56 PM method to estimate reference evapotranspiration (ETo), different models were developed. But these models require local calibration to validate their usage in specific climate conditions. In the current study, the Hargreaves and Blaney-Criddle models were selected for calibration, which requires low and available data (Rácz et al., 2013).

Hargreaves equation

In the absence of direct measurement and data to use the FAO-56 PM method, the Hargreaves equation is recognized by FAO and is often used (Berti et al., 2014). Moreover, as described by Berti et al. (2014), this model (Equation 6-19) was selected for calibration because of its limited data requirement (minimum and maximum air temperature and extra-terrestrial radiation), simplicity, and potentiality to calibrate its parameters to improve the estimations. In addition, from the models selected for evaluation in this study, seven of them (Hargreaves and Samani, Droogers and Allen, Irmak, Trajovic, Tabari and Talaee, Tabari, and Dorji models) were derived from the Hargreaves model and have similar variables.

$$ETo_{HG} = 0.0023 * R_A * TD^{0.5}(T_{mean} + 17.8) \qquad \text{Equation 6-19}$$

Blaney-Criddle equation

This model (Equation 6-20), like the Hargreaves equation, is frequently selected for calibration because of its ease of use, low data requirements, and efficiency in predicting reference evapotranspiration (ET_0). It is appropriate for areas with little meteorological data because it simply needs temperature and daylight hours, unlike more complex models like Penman-Monteith. Studies indicate that local calibration improves its accuracy, and it has been widely used in semi-arid and dry regions where water management is essential (Allen et al., 1998). Furthermore, it is a popular option, particularly in developing countries, because of its usefulness in irrigation planning and water resource management (Doorenbos & Pruitt, 1977).

$$ETo = p(0.457T_{mean} + 8.13) \qquad \text{Equation 6-20}$$

6.2.5.1. Calibration procedure

One of the most common approaches in model calibration is modifying the empirical coefficients of the models (Heydari et al., 2015; Metcalfe et al., 2019). A similar calibration procedure was used to calibrate the two models considered in this study, and the method of calibration was adopted from Tabari & Talaee (2011) and Gharehbaghi & Kaya (2022) which used a similar method.

Initially, the ETo was estimated using the model, and then the water requirement of onion was computed by the Kc-approach using Equation 6-21. The crop coefficient was adopted from the FAO paper suggested for the crop (Allen et al., 1998).

$$ETc_{HG} = ETo_{HG} * Kc_{FAO} \qquad \text{Equation 6-21}$$

Where, ET_{CM} = Onion water requirement computed from model, ET_{OM} = Reference evapotranspiration determined by model, Kc_{FAO} = Onion crop coefficient, FAO recommended

Then, to calibrate the model based on the measured crop water requirement of onion for the study area as well as for areas with similar climatic conditions, the ratios of the water requirement of onion measured using the lysimeter, ETc_L (Equation 6-3), to the estimated using the model, ETc_M (Equation 6-21), values were computed for each decade using Equation 6-22.

$$C_{MC} = ETc_L/ETc_M \qquad \text{Equation 6-22}$$

Where, C_{MC} = Calibrated model coefficient,ETc_L = Onion water requirement measured using lysimeter,ETc_M = Onion water requirement computed from the model

This value, $C_{MC,}$ is the modified coefficient for the Blaney-Criddle model, but the modified coefficient of the Hargreaves equation was determined by multiplying the value, $C_{MC,}$ by the original empirical coefficient of the equation (0.0023). The calibrated equation of the ETo model is given as Equation 6-23.

$$ET_{O_{Calibrated\ Model}} = C_{MC} * ET_{O_M} \qquad \text{Equation 6-23}$$

6.3. Result and Discussion

6.3.1. Lysimeter-based crop evapotranspiration (ETc) of onion

Table 6-1 presents the decadal values of measured water balance variables and evapotranspiration for onion, averaged over the two growing seasons. The crop water requirement ranged from 30.61 mm to 54.09 mm per decade with a total seasonal crop water requirement of 460.27 mm. The result of the current study agrees, in relative terms, with the results of other studies conducted at different places with similar climatic conditions by different researchers. The finding of Abebe et al. (2021) showed a seasonal evapotranspiration of onion was found to be 465.57 mm. As reported by Dirirsa et al. (2015), the evapotranspiration of onion throughout the growing season was 469 mm. While the study conducted by Bossie et al. (2009) resulted in a 390.5 mm water requirement for onion, which was relatively lower than the current study.

Table 6-1. Decadal values of measured water balance components and onion ETc

Decades	I (mm)	P (mm)	Dp (mm)	ΔS (mm)	ETc (mm)
1	27.29	0.00	0.00	-3.32	30.61
2	28.80	10.30	5.04	-0.94	35.00
3	29.06	12.15	2.25	-2.67	41.63
4	28.85	89.50	54.52	21.20	42.63
5	14.43	33.96	28.36	-25.71	45.73
6	22.71	38.15	13.85	3.15	43.85
7	35.52	23.60	5.51	2.82	50.80
8	43.23	39.25	17.50	10.89	54.09
9	17.92	48.52	36.26	-6.16	36.34
10	1.09	78.67	54.64	-14.78	39.91
11	0.00	2.71	0.00	-36.98	39.69

I = irrigation, P = Precipitation, Dp = deep percolation, and ΔS = change in soil moisture.

6.3.2. Kc-approach-based crop evapotranspiration (ETc) of onion

The crop evapotranspiration of onion from the Kc-approach was determined as a product of ETo, estimated using selected ETo models and crop coefficients taken from FAO suggestions. The ETo models selected to estimate the reference evapotranspiration were Hargreaves and Samani, Droogers and Allen, Irmak, Trajovic, Tabari and Talaee, Tabari, Dorji, Blaney Criddle, Thornthwaite, and FAO-56 PM. The decadal values of reference evapotranspiration computed using the ETo models, averaged over the two growing seasons, are presented in Table 6-2.

Table 6-2. Decadal reference evapotranspiration estimated using selected ETo-models

Decades	Hargreaves and Samani	Droogers and Allen	Irmak	Trajovic	Tabari and Talaee	Tabari	Dorji	Blaney Criddle	Thornthwaite	FAO-56 PM
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
1	35.15	36.16	33.48	28.12	47.38	28.16	23.89	47.22	25.64	49.07
2	31.79	32.87	31.40	25.54	42.85	25.56	21.81	47.55	26.51	44.41
3	36.98	37.75	34.74	29.45	49.84	29.12	24.62	48.29	28.20	49.32
4	32.06	33.33	31.84	25.91	43.21	25.14	22.06	49.57	31.36	46.10
5	30.57	31.77	30.58	24.70	41.21	23.97	21.04	48.93	30.10	46.76
6	24.16	25.55	26.47	19.77	32.56	19.42	17.29	48.39	28.94	39.68
7	31.06	32.64	31.10	25.30	41.87	24.50	21.87	50.93	30.83	46.97
8	37.28	38.68	35.20	30.09	50.25	28.94	25.51	51.71	32.87	53.45
9	24.32	25.95	26.60	20.03	32.78	19.53	17.71	50.28	29.71	38.86
10	28.85	30.51	29.64	23.61	38.88	22.89	20.60	50.71	30.82	43.57
11	35.10	36.52	33.92	28.40	47.31	27.20	24.10	52.26	34.76	51.01

The FAO crop coefficient values suggested for onion were 0.70, 1.05, and 0.75 at initial, mid-, and late-season growth stages, respectively. Based on the suggested Kc values and ETo estimated by each model, the evapotranspiration of onion was computed and compared with lysimeter-based measured onion evapotranspiration in Figure 6-1.

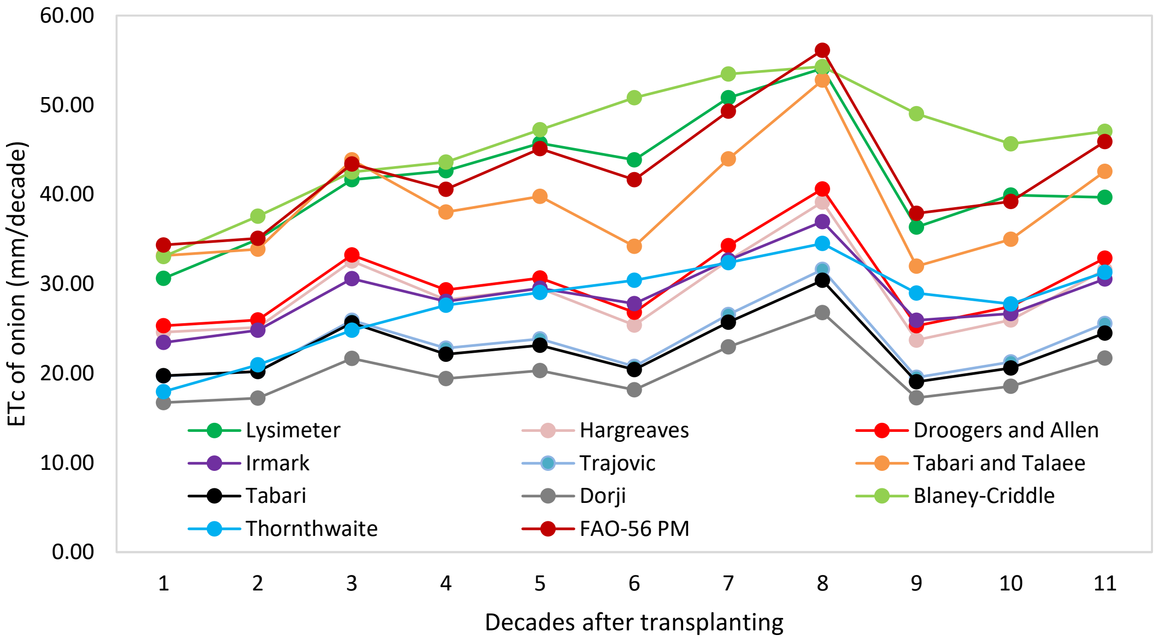

Figure 6-1. Evapotranspiration of onion measured (using lysimeter) and estimated (Kc-approach-based)

Hargreaves model

The evapotranspiration of onion estimated by this model was consistently lower than the lysimeter-measured values throughout the entire crop-growing season (Figure 6-1). The total crop water requirement of onion estimated using this model was found to be 318.38 mm, while 460.27 mm was measured using the lysimeter. This shows that the model underestimates the water requirement of onion over the crop-growing season by 30.83%.

This model has been evaluated in a variety of climate ranges, as explained by Ahooghalandari et al. (2016); nonetheless, it typically underestimates ETo values in semiarid and arid regions, which is consistent with the current study. Heydari et al. (2014) also reported this model underestimates the ETo in arid climatic conditions, which agrees with the current study. Given that the crop is susceptible to both irrigation extremes, using irrigation according to this model would have reduced the crop's potential yield because of a water deficit.

Droogers and Allen model

The estimated evapotranspiration of onion using this model was lower than the lysimeter-based measured value across the crop growing season (Figure 6-1). The total crop water requirement of onion estimated using this model was found to be 331.84 mm, while 460.27 mm was measured using the lysimeter. This shows that the model is 27.9% underestimating the amount of water that onions need to use during the crop-growing season.

As reported by Heydari et al. (2014) and Tabari & Talaee (2011), this model has been tested under arid climate conditions, and it underestimates ETo, which agrees with the current study. In contrast to the current study, the other investigation by Yadeta et al. (2021a) found that this model overestimates ETo in semi-arid and arid climates. Since the crop is vulnerable to over- and under-irrigation extremes, applying irrigation in accordance with this model would have resulted in a water deficit, which would have decreased the crop's potential yield.

Irmak model

Over the course of the growing season, the onion evapotranspiration determined by this model was continuously less than the values obtained by lysimeters (Figure 6-1). This model computed an onion ETc of 316.88 mm, but the measured lysimeter was 460.27 mm. This indicates that the amount of water required by onions during the crop-growing season is 31.15% underestimated by the model.

As reported by Heydari et al. (2014) and Ahooghalandari et al. (2016), this model underestimates ETo when evaluated in arid climates, which agrees with this study. The results of the study by Yadeta et al. (2021a), which estimated sugarcane ETc in semi-arid and dry climates, showed that this model underperforms at the initial and late growing phases but performs well at the mid-stage. Using this model to apply irrigation water possibly caused water deficit, which would have decreased the crop's potential yield.

Trajovic model

This model's estimation of onion evapotranspiration was much less than the lysimeter's measured value over the entire duration of the crop-growing season (Figure 6-1). Using this model, the total crop water need for onion was calculated to be 257.67 mm, and the lysimeter-measured value was 460.27 mm. This demonstrates that the water requirement of onion during the crop-growing season was underestimated by the model by 44.02%.

According to the findings of Celestin et al. (2020), on the study conducted in evaluation of ETo model performance in comparison with the FAO Penman-Monteith model, this model underestimates ETo values, which agrees with the current study. Using irrigation water in accordance with this model would have decreased the crop's potential yield due to a water shortage because the crop is vulnerable to both irrigation extremes.

Tabari and Talaee model

The evapotranspiration of onion estimated using this model has close similarity with the lysimeter's measured value over the entire duration of the crop-growing season except at mid-season, which was underestimated (Figure 6-1). Using this model, the total ETc for onion was calculated to be 429.12 mm, and the lysimeter-measured value was 460.27 mm. This demonstrates that, in relative terms, this model estimates the water requirement of onion close similarly to the lysimeter-measured value, though it is lower by 6.77%.

The current study's findings are in line with the results of a study that compared the ETo model's performance with that of the FAO Penman-Monteith model, which found that the model performed well in computing ETo (Celestin et al., 2020). Given the current study's findings in relation to the lysimeter experiment, this model can possibly be used to estimate onion evapotranspiration in the study's current environment, where costly and time-intensive lysimeter experiments are not available.

Tabari model

During the whole crop-growing season, the onion evapotranspiration calculated by this model was continuously less than the lysimeter-measured values (Figure 6-1). Onion's total ETc, as calculated by this model, was 251.41 mm, whereas the lysimeter measured 460.27 mm. This indicates that the model is 45.38% underestimating the amount of water that onions need to use during the crop-growing season.

Yadeta et al. (2021a) evaluated this model in dry and arid region to estimate sugarcane ETc, and the result revealed that the model underestimates, which is consistent with this work. Using irrigation in accordance with this model would have decreased the crop's potential yield due to a water deficit because the crop is vulnerable to both irrigation extremes.

Dorji model

In a similar way to the Dorji model, this model estimated the onion evapotranspiration significantly lower than the lysimeter-measured value throughout the growing season (Figure 6-1). The total Onion ETc estimated was 220.73 mm, while the lysimeter measured value was 460.27 mm, which is 52.04% higher.

The study conducted by Celestin et al. (2020) on evaluation of model performance found that this model understates ETo values, which is in line with the current study. Using irrigation according to this model would have decreased the crop's potential yield due to a water deficit because the crop is vulnerable to both irrigation extremes.

Blaney Criddle model

With the exception of the late season, when it was overestimated (Figure 6-1), the onion evapotranspiration calculated with this model closely matched the lysimeter's measured value throughout the crop-growing season. With this model, the total ETc for onion was estimated at 504.23 mm, whereas the measured lysimeter value was 460.27 mm. In relative terms, this shows that the model's estimation of the onion's water requirement closely matches the lysimeter's measured value, though it is higher by 9.55%.

As reported by Mohawesh (2010) and Yadeta et al. (2021a), this model has been tested under arid and semi-arid climate conditions, and it performed well in estimating ETo. A similar report was presented by Heydari et al. (2014), a study that compared the ETo model's performance with that of the FAO Penman-Monteith model. The findings of all those authors are in line with the current study. Considering the results of the current study in comparison to the lysimeter experiment, this model can be applied to estimate onion evapotranspiration under the study's current climate conditions, where costly and time-intensive lysimeter experiments are not available.

Thornthwaite model

The model's estimated evapotranspiration for onion was consistently lower than the lysimeter-measured values throughout the entire crop-growing season (Figure 6-1). The total crop water requirement calculated using this model was 305.60 mm, whereas lysimeter measurements indicated a requirement of 460.27 mm. This discrepancy suggests that the model underestimates the water needs of onion over the growing season by 33.6%.

The study conducted by Heydari et al. (2014) in arid regions and Hafeez et al. (2020) in semi-arid regions revealed that this model underestimates ETo. Similarly, Yadeta et al. (2021) reported that estimating sugarcane evapotranspiration using this model in the Kc-approach in semi-arid and dry circumstances resulted underestimation throughout the growing season. So, applying irrigation water based on this model may result in a water deficit and poorer crop productivity.

FAO-56 PM (Penman-Monteith)

The evapotranspiration of onion computed using this model was very closely agreed with the lysimeter-measured value across the crop-growing season (Figure 6-1) with only 1.81% overestimation. The ETc for onion was estimated to be 468.62 mm, whereas the lysimeter-measured value was 460.27 mm.

Allen et al. (1998) reported that this model provides more accurate and consistent ETo estimation compared to other empirical methods. Numerous studies have validated the model's robustness across various geographical regions. For instance, the FAO-56 PM model has shown high accuracy in humid, semi-arid, and arid climates when quality weather data are available (Djaman et al. 2015; Hadria et al., 2021). The other study by Ratshiedana et al. (2025) reported this model outperformed out of 30 models tested in estimating ETc. All the findings are in line with the current study. Considering the results of the current study in comparison to the lysimeter experiment, this model can be applied to estimate onion evapotranspiration under the study's current climate conditions, where costly and time-intensive lysimeter experiments are not available.

6.3.3. Models performance evaluation

Different statistical indices were utilized to evaluate how well the Kc-approach-based ETo models, which were used to estimate the water requirement for onion, performed in relation to the lysimeter-measured value under the research area's climate. After analyzing those models, the ones that most closely matched the lysimeter data in determining the onion evapotranspiration were selected. The coefficient of determination (R^2), mean bias error (MBE), root mean square error (RMSE), and index of agreement (IA), the most frequently used statistical indices, were used to evaluate the performance of specific models (Yadeta et al., 2021). The results of the computation for the indices for each of ten models are shown in Table 6-3.

Table 6-3. Models performance based on statistical indices

Model	RMSE	MBE	R^2	IA
Hargreaves and Samani	1.35	-1.29	0.64	0.48
Droogers and Allen	1.23	-1.17	0.69	0.51
Irmak	1.35	-1.30	0.83	0.48
Trajovic	1.89	-1.84	0.68	0.38
Tabari and Talaee	0.49	-0.28	0.64	0.85
Tabari	1.95	-1.90	0.65	0.36
Dorji	2.22	-2.18	0.73	0.33
Blaney Criddle	0.54	0.40	0.70	0.84
Thornthwaite	1.45	-1.41	0.69	0.48
FAO-56 PM	0.26	0.08	0.85	0.96

The result revealed that RMSE varied from 0.26 to 2.22 for the models considered. According to the RMSE values, in comparison to the lysimeter-measured value, the FAO-56 PM model outperformed all other models with a value of 0.26. From those nine models, Tabari and Talaee (0.49) and Blaney-Criddle (0.54) models performed better in the current research area (Table 6-3). A study conducted by Yadeta et al. (2021a) on the comparison of measured and estimated water requirements reported that the Blaney-Criddle model performed better than other models considered in the study, which agrees with the result of the current study.

In terms of MBE, the Hargreaves and Samani, Droogers and Allen, Irmak, Trajovic, Tabari and Talaee, Tabari, Dorji, and Thornthwaite models were underestimated when compared to lysimeter-measured value, while the Blaney-Criddle and FAO-56 PM models were overestimated. In this performance evaluation indices (MBE), the FAO-56 PM model outperformed all other models with a value of 0.08. However, from those nine models, the Tabari and Talaee model (-0.28) performed better, followed by the Blaney-Criddle model (0.40).

Based on the IA performance evaluation indices among the ETo models used in the Kc-approach in this study, the FAO-56 PM model demonstrated the highest degree of agreement with the lysimeter measured value (0.96). However, from those nine models, the Tabari and Talaee model (0.85) showed a better degree of agreement with lysimeter-measured evapotranspiration of onion, followed by the Blaney-Criddle model (0.84). In contrast, the Tabari model was the model that showed the lowest agreement with measured using a lysimeter followed by Dorji.

Models ranking

Figure 6-2 illustrates the performance rankings of various models used to estimate crop evapotranspiration (ETc), as compared to ETc values measured using a lysimeter. The analysis showed the models ranked from most to least accurate as follows: FAO-56 PM, Blaney-Criddle, Tabari and Talaee, Droogers and Allen, Irmak, Hargreaves and Samani, Thornthwaite, Trajovic, Dorji, and finally, Tabari. Among all models, the FAO-56 PM showed the highest accuracy, almost similar to the measured value. However, from those nine models, the Blaney-Criddle model demonstrated the highest accuracy, with its estimates closely matching the lysimeter measurements. The Tabari and Talaee model followed as the next most reliable. In contrast, the Dorji and Tabari models were the least accurate, with the Tabari model producing the greatest deviation from actual values.

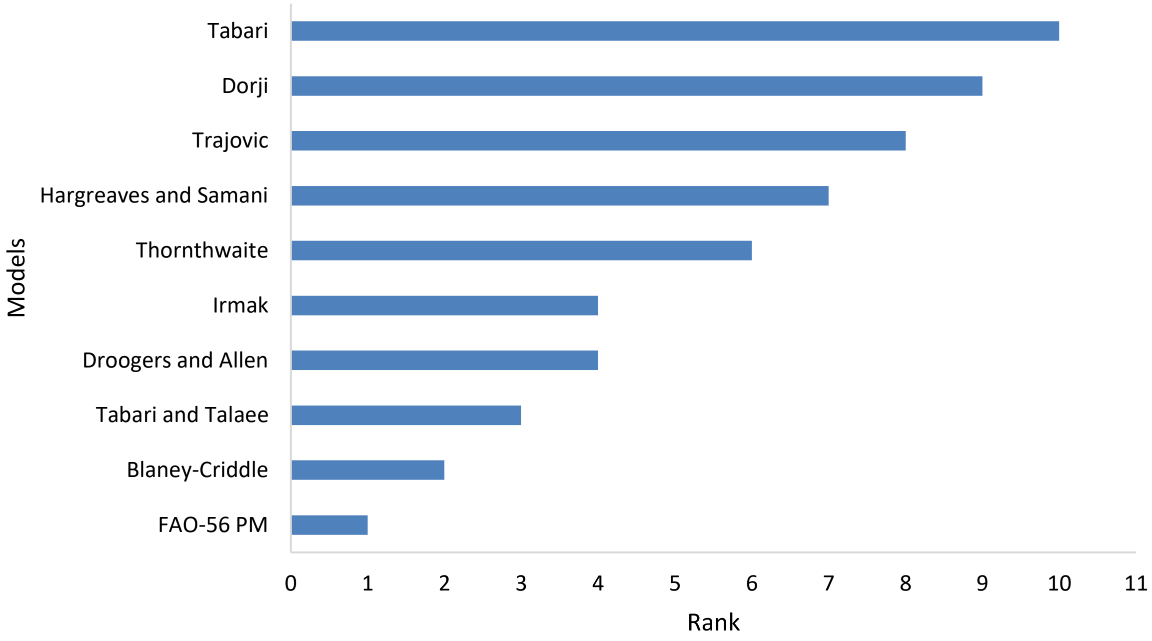

Figure 6-2. Model ranking

6.3.4. Calibration of Models

6.3.4.1. Calibration of Hargreaves equation

Table 6-4 shows the decadal values of the modified coefficient for the Hargreaves equation throughout the onion growing season. The findings indicated that the pooled value of the new coefficient is 0.0034, approximately 48% higher than the original value of 0.0023. This value is also higher than 0.0030 reported by Drooger and Allen (2002), which was proposed to be used on a global scale. This implies that the original Hargreaves model underestimates reference evapotranspiration (ETo) in the study area. Therefore, it is suggested to use the adjusted coefficient of 0.0034 rather than the original value for this region and other areas with similar climatic conditions. Equation 6-24 provides the modified Hargreaves equation for estimating ETo.

$$ETo = 0.0034 * R_A * TD^{0.5}(T_{mean} + 17.8) \qquad \text{Equation 6-24}$$

Table 6-4. Adjusted coefficients of the Hargreaves equation for each decade

Year	1	2	3	4	5	6	7	8	9	10	11	Average
2023	0.0025	0.0028	0.0029	0.0034	0.0046	0.0039	0.0034	0.0031	0.0036	0.0034	0.0029	0.0033
2024	0.0032	0.0038	0.0030	0.0035	0.0031	0.0041	0.0038	0.0033	0.0035	0.0037	0.0028	0.0034
Average	0.0029	0.0033	0.0029	0.0035	0.0038	0.0040	0.0036	0.0032	0.0035	0.0035	0.0029	0.0034

6.3.4.2. Calibration of Blaney-Criddle equation

Table 6-5 presents the decadal values of the new coefficient of the Blaney-Criddle equation during the growing season of onion. The finding revealed that the averaged value of the new coefficient was 0.9135, which is about 9% less than the original value of 1. This shows the original Blaney-Criddle model overestimates the ETo in the study area. Therefore, it was proposed to use the new coefficient, 0.9135, instead of the original coefficient in the study area and areas with similar climatic conditions. The adjusted Blaney-Criddle equation for the estimation of ETo is given by Equation 6-25.

$$ETo = 0.9135 * p(0.457T_{mean} + 8.13) \qquad \text{Equation 6-25}$$

Table 6-5. Adjusted coefficients of the Blaney-Criddle equation for each decade

Year	1	2	3	4	5	6	7	8	9	10	11	Average
2023	0.9056	0.9883	0.8914	0.9336	0.8294	0.8783	0.9921	1.0273	0.7501	0.8684	0.8320	0.8997
2024	0.9455	0.8789	1.0657	1.0202	1.1006	0.8480	0.9077	0.9652	0.7328	0.8804	0.8554	0.9273
Average	0.9255	0.9336	0.9786	0.9769	0.9650	0.8631	0.9499	0.9962	0.7414	0.8744	0.8437	0.9135

6.3.5. Validation of calibrated models

To verify the accuracy of the calibrated models, Hargreaves and Blaney-Criddle, the reference evapotranspiration (ETo) values obtained from the models were compared with that calculated using the FAO-56 Penman-Monteith method, implemented via the CROPWAT 8.0 model, throughout the onion growing season, as used by Soler-Méndez et al. (2021) and recommended by Ratshiedana et al. (2025). Moreover, the evaluation of models in this study showed that the FAO-56 Penman-Monteith method outperformed all other models and very closely agreed with the lysimeter-measured value.

The below figure, Figure 6-3 presents a comparison of the pooled decadal ETo values estimated using the original and calibrated Hargreaves and Blaney-Criddle equations with the FAO-56 PM method.

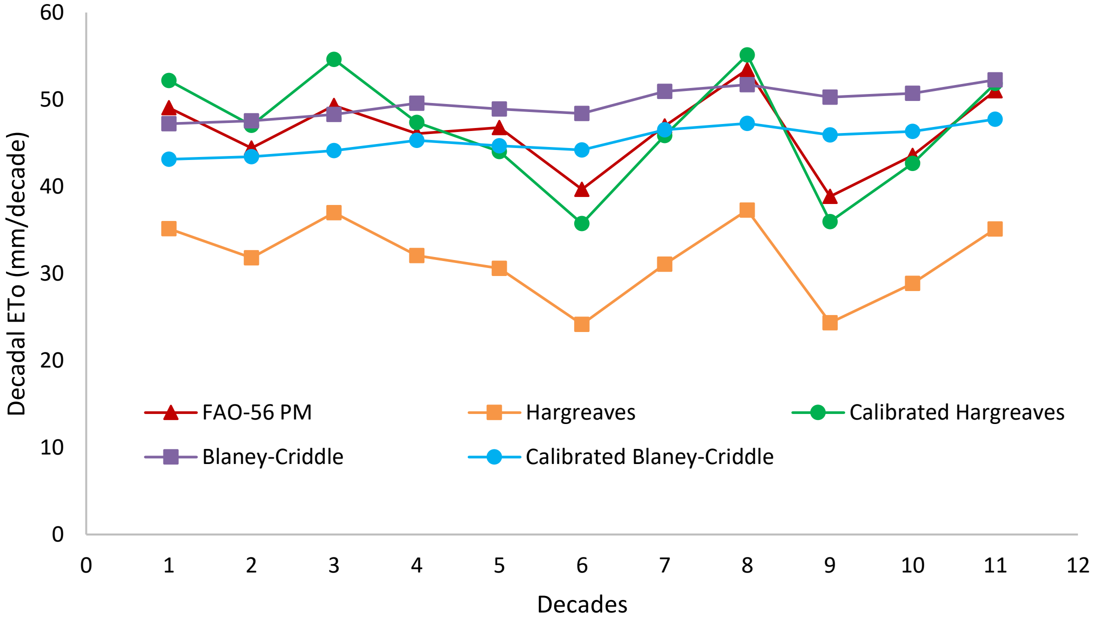

Figure 6-3. Comparisons of decadal ETo computed using the calibrated models with the FAO-Penman-Monteith model

6.3.5.1. Validation of Hargreaves equation

As observed in Figure 6-3, during the onion growing season, the reference evapotranspiration calculated using the calibrated Hargreaves method was 512.41 mm, while the FAO PM approach (via version 8 of the CropWat model) yielded 509.18 mm. The close agreement between these results supports the accuracy and reliability of the calibrated Hargreaves equation.

6.3.5.2. Validation of Blaney-Criddle equation

As presented in Figure 6-3, during the onion growing season, the reference evapotranspiration calculated using the calibrated Blaney-Criddle model was 498.63 mm, while the FAO PM method, applied through the CropWat 8 model, produced a value of 509.18 mm. The minimal difference between these values indicates the reliability and applicability of the calibrated Blaney-Criddle equation.

6.4. Conclusion

This study evaluated ten ETo models and calibrated the Hargreaves and Blaney-Criddle equations using lysimeter-measured crop evapotranspiration (ETc) for onion in the semi-arid climate of Melkasa, Ethiopia. Among the evaluated models, the FAO-56 PM model outperformed all the other models. From the other nine models, the Blaney-Criddle model demonstrated the highest reliability. Calibration significantly improved the performance of both the Hargreaves and Blaney-Criddle equations. The Hargreaves coefficient increased by approximately 48%, from 0.0023 to 0.0034, while the Blaney-Criddle coefficient decreased by about 9%, from 1 to 0.9135, resulting in enhanced accuracy. These findings suggest that the calibrated Hargreaves and Blaney-Criddle models are effective alternatives for estimating onion water requirements using the Kc-approach, particularly in the absence of lysimeter data. Furthermore, they offer practical substitutes for the FAO-56 PM method in regions with similar climatic conditions and limited meteorological data. Implementing these models can support improved irrigation planning and optimize water use efficiency. Future research should focus on refining the Hargreaves and Blaney-Criddle equations for broader applicability across diverse climates.

7. GENERAL CONCLUSION AND RECOMMENDATION

7.1. General Conclusion

This study successfully developed and deployed a portable weighable lysimeter system at the Melkasa Agricultural Research Center during the 2023 and 2024 growing seasons, enabling accurate and reliable measurement of crop water use for short rooted crops. The system demonstrated effective performance with no significant operational issues, providing essential data on the water requirements and crop coefficients of the Nafis onion variety. Field-based measurements revealed total seasonal water use of 460.27 mm and crop coefficient values that align with FAO guidelines, offering a strong foundation for improving irrigation scheduling and water use efficiency. Additionally, evaluation and calibration of ten ETo estimation models highlighted the superior performance of the FAO-56 Penman-Monteith method, while calibrated Hargreaves and Blaney-Criddle models emerged as practical alternatives in data-scarce regions. Collectively, these findings contribute valuable insights for optimizing irrigation management in semi-arid regions and emphasize the importance of integrating field-based measurements with calibrated models to enhance agricultural water use efficiency.

7.2. General Recommendation

To enhance the versatility and applicability of the developed lysimeter for a broader range of crops, including deep-rooted varieties, future improvements should address two key limitations. First, the current soil profile depth is insufficient for deep-rooted crops; thus, increasing the lysimeter's depth is essential to accurately reflect their root zones. Second, any increase in depth will also require upgrading the lifting and weighing mechanisms to handle the resulting larger mass. Enhancing the system's structural and mechanical capacity will enable its use across diverse crop types and improve its overall utility in agricultural research and irrigation planning.

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