EVALUATION AND IMPROVEMENT OF SUGARCANE IRRIGATION WATER MANAGEMENT IN WONJI SHOA SUGAR ESTATE, ETHIOPIA

BELAY YADETA NEGERA

A DISSERTATION SUBMITTED TO:

DEPARTMENT OF WATER RESOURCES ENGINEERING

SCHOOL OF CIVIL ENGINEERING AND ARCHITECTURE

PRESENTED IN FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN WATER RESOURCE ENGINEERING (SPECIALIZATION IN IRRIGATION ENGINEERING)

OFFICE OF GRADUATE STUDIES

ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

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STUDENT'S DECLARATION

I hereby declare that this Dissertation entitled *"**Evaluation and Improvement of Sugarcane Irrigation Water Management in Wonji Shoa Sugar Estate, Ethiopia**"* 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.

Belay Yadeta Negera	______________________	_______________
Name of Student	Signature	Date

APPROVAL BY SUPERVISORS

We, the supervisors of this dissertation hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the dissertation entitled *"**Evaluation and Improvement of Sugarcane Irrigation Water Management in Wonji Shoa Sugar Estate, Ethiopia**"* by Mr. Belay Yadeta.

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APPROVAL BY BOARD EXAMINERS

We, the undersigned, members of the Board of Examiners of the dissertation open defense by **Mr. Belay Yadeta Negera** have read and evaluated the dissertation entitled *"**Evaluation and Improvement of Sugarcane Irrigation Water Management in Wonji Shoa Sugar Estate, Ethiopia**"* and examined the candidate during open defense. This is, therefore, to certify that the dissertation is accepted for partial fulfillment of the requirement of the degree of Doctor of Philosophy in Irrigation Engineering.

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BIOGRAPHICAL SKETCH

The author, **Mr. Belay Yadeta Negera** was born on 25th of May 1986 from his father Yadeta Negera and his mother Gete Yermo in Gobe Kura, Mida Kegn District, West Shew Zone of Oromia Regional State, Ethiopia. He attended his primary school at Haro Alunko, junior school at Gaba Kamisa and High school at Gedo Secondary Schools in West Shewa Zone. In December 2005, he joined Hawassa University and graduated with BSc. Degree in July 10, 2008. He was joined School of Graduate Studies at Haramaya University in February, 2009 to pursue his MSc studies and graduated with MSc. degree in Irrigation Agronomy in 2011.

After his graduation he served as a lecturer at Ambo University, Department of Water Resource and Irrigation Management until 2017. Then, in 2017/2018 he joined Adama Science and Technology University, department of Water Resource Engineering to pursue his Ph. D studies in Water Resource Engineering specialization in Irrigation Engineering which he successfully defended on 26th of May 2022.

DEDICATION

This dissertation work is dedicated to all my families, who have supported me throughout my journey starting from the beginning of my education up to the realization of my dream in education, obtaining a PhD degree.

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LIST OF ACRONYMS AND ABBREVATIONS

AE	Application Efficiency
AGB	Above ground biomass
ANOVA	Analysis of variance
Asi	Apparent specific gravity of soil
BMC	Billion Meter Cube
CSA	Central Statistical Agency
CWR	Crop water requirement
Da	Depth of application
Di	Root depth
DP	Deep Percolation
Ds	Depth of stored water
DU	Distribution Uniformity
E	Coefficient of efficiency factor
ETc	Crop Evapotranspiration
ETo	Reference Evapotranspiration
FAO	Food And Agriculture Organization
FC	Soil moisture content at field capacity
FL	Furrow length
FQ	Furrow discharge
FS	Furrow slope
HDM	Hydrodynamic Model
HI	Harvest index
IA	Index of Agreement
ISO	International Sugar Organizations
IWR	Irrigation water requirement
Kc	Crop Coefficient
MC	Present moisture content
KWM	Kinematic Wave Model

MARC	Melkassa Agricultural Research Center
MBE	Mean Bias Error
Mha	Million Hectares
OP	Optimized performance
P_{eff}	Effective rain fall
PM	Penman Monteith
PWP	Soil moisture at permanent wilting point
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
SASTA	South Africa sugar technology association
SW	Soil Water
TAW	Total available water
Tco	Time of cutoff
VBM	Volume Balance Model
Wd	Weight of dry soil
WP	Water Productivity
WSSE	Wonji Shoa Sugar Estate
WUE	Water Use Efficiency
Ww	Weight of wet soil
ZIM	Zero Inertia Model
Zreq	Required depth of irrigation

GENERAL ABSTRACT

Since the last two decades, irrigation development and expansion are rapidly increasing all over the country. With the increasing expansion and development of irrigation, the poor performance of the existing irrigation systems is becoming areas of concern. Improper management of irrigation has led to poor performances of schemes with many undesirable consequences like salinity, water-logging and overall sustainability problems of irrigation. In line with this the current study was undertaken on evaluation and improvement of irrigation water management practices at Wonji Shoa Sugar Estate. The general objective of the study was to evaluate irrigation water management practices for sugarcane under Wonji Shoa Sugarcane farm with the view to improve on-farm irrigation water management. Performance of current furrow irrigation practices was evaluated from ten selected fields with three commonly used furrow lengths (32, 48 and 64m). The performances of irrigation evaluated in term of application efficiency, distribution uniformity and deep percolation from field measurement were simulated using WinSRFR model. Sugarcane crop evapotranspiration and crop coefficient were determined and developed using lysimeter experiment at Melkassa Agricultural Research Center. The sugarcane NCO-$_{334}$ was planted in the established lysimeter. Soil moisture was monitored using gravimetric method and calibrated neutron probe throughout the growing period of sugarcane. Reference evapotranspiration in the study area was determined using CropWat 8.0 model. Field experiment was conducted to analyze the effect of furrow irrigation design parameters on sugarcane growth, yield and quality parameters as well as on water productivity. The field experiment was laid out using split-split plot design with three factors as main factor (furrow slope, 0.05, 0.08 and 0.11), sub-factor (furrow length, 30, 50 and 70m) and sub-sub factors (furrow inflow rate, 4, 5 and 6l/s) replicated three times with three levels of each factor. All growth, yield and quality parameters were analyzed using SAS 9.4 software and mean separation was tested at 5% significance level for all parameters. For the three rates of water application, sugarcane water productivity parameters were determined from the field and simulated using AquaCrop model. The performances of current furrow irrigation current practices were in the rage of poor in terms all performance indicators used. Since the performance of current furrow irrigation was poor, an improvement options were developed by varying inflows rate (reducing) and cutoff time (increasing) decision variables. As a result, the overall performance of furrow irrigation was improved for all furrow lengths. More specifically, application efficiency and distribution uniformity were significantly improved. From these results it can be recommended that furrow irrigation decision variable should be redecided to achieve more efficient irrigation water management. The sugarcane evapotranspiration was measured throughout the growing period using lysimeter experiment. The result obtained indicated that crop evapotranspiration ranges from 1.63 to 7.13mm/day during the early and peak growth stages, respectively. The crop coefficients were found to be 0.42, 0.93, 1.26 and 1.05 at emergence, tillering, grand formation and ripening growth stages respectively. Hence, these results were obtained from a one season experiment, they can be useful as field measurement-based data are lacking in the area and other regions of Ethiopia. Additionally, performance different reference evapotranspiration models were evaluated as compared to *Penman-Monteith method and Blaney-Criddle model was performed better under the current climatic. The effect of furrow slope showed statistically significance variation at 5% significance on growth parameters but non significant variation on yield components of* *sugarcane. But the effect of furrow length showed statistically significant variation on almost all growth and yield parameters of sugarcane at 5% significance level. Finally, the effect of furrow discharge rate on all growth and yield parameters considered has shown statistically significant variation at 5% significance level. In general, from the three furrow discharge rates, 4l/s resulted in a better sugarcane growth and yield parameters. The effect of furrow slope, furrow length and furrow inflow rate on all sugarcane quality parameters showed statistically non significant variation. The sugarcane water productivity as simulated using AquaCrop model showed higher values than for the three-irrigation application rate. Generally, it can be recommended that, while improving the current irrigation water management practices requires selection of the right combination of operational decision variables, the furrow irrigation design parameters and decision variables should be reconsidered for the new setup of furrow system. Although under data scarcity condition, the sugarcane crop water requirement and coefficient determined in this study can be useful, it must be noted that the information generated are based on a one-time experiment.*

Keywords: *Crop coefficient, Crop evapotranspiration, Furrow irrigation design, Lysimeter, Performance evaluation, Sugarcane growth, Sugarcane quality, sugarcane yield, Water Productivity*

1. GENERAL INTRODUCTION

1.1. Background

Water is a renewable natural resource that is critical for agricultural activities. Irrigation is part of agricultural activity that involves the application of water to soil artificially with the aim of maintaining soil moisture status favorable for plant growth. Humans perform this activity to apply water to crops while taking into account the agroecology of the irrigated area in order to improve the quality of life of the rural population (Tesfaw, 2018). Irrigation is needed when the rainfall is not adequate to fulfill the water requirement of the crop considered. This may be due to the variation in intensity and distribution of rainfall throughout the crop season. Therefore, irrigation is very essential in producing the potential yield of the crop and multiple crops during on and off rainfall season. In such cases, irrigation helps to alleviate global poverty by boosting productivity, creating more job opportunities and stabilizing income and nutrient consumption for rapidly growing populations (Haile and Kassa, 2015).

Irrigation has been practiced since ancient times with unspecified beginning period traditionally practiced in Ethiopia. But, modern irrigation was started in the early 1950's by the bilateral agreement between the government of Ethiopia and the Dutch company jointly known as Hender Verneering Amsterdam (H.V.A) in Ethiopia for the production of commercial crops such as sugarcane and cotton plantation (Haile and Kassa, 2015). Even if irrigation plays a vital role in Ethiopian economy, there are some constraints regarding its development. From these factors, inadequate awareness of irrigation water management aspects, inadequate skills and knowledge on improved and diversified irrigation agronomic practices and shortage of basic technical knowledge on modern irrigation development and managements are the most widely observed at different scale irrigation system (Kassie, 2020).

Irrigation development is expected to continue and major component in the national development plans of Ethiopia. Ethiopia is one of the countries endowed with abundant water resources. The country has 12 river basins with an annual runoff volume of 124 billion meter cube (BMC) of surface water and estimated 2.6 to 30 BMC ground water potentials. The irrigation potential is also estimated an average of 5.3 Mha from 16.5Mha of total cultivated area (Tesfaw, 2018). For long term sustainability of an irrigation system, improvements in the performance of current water application and on-farm water management practices seem to be more necessary than any other practice. This improvement requires consideration of factors influencing the hydraulic processes, water infiltration and uniformity of water application to the entire field (Assefa, 2017).

In Ethiopia, increased urbanization and improved life standards have reinforced the competition for water resource. On the other hand, poor irrigation water management leads to the supply of more or less amount of crop water requirements during the crop growth periods. Therefore, irrigation water management strategies that fully satisfy crop water requirements during the crop growth stages is considered as one solution to overcome the negative effects of irrigation (Adeyemi *et al.*, 2017). Reliable and suitable irrigation water supplies result in vast improvements in agricultural production and assure the economic development in Ethiopia. Sustainability of irrigated agriculture depends primarily on efficient management of irrigation water hence it is vital to raise the performance of less productive irrigation systems while sustaining the efficient irrigation (Mamo and Wolde, 2015).

While crop production to supply food to the increasing population has been given priority, crops that serve as raw materials to industries are also given attention. Sugarcane is amongst industrial crops widely planted in the country. It is an industrial cash crop mainly cultivated for sugar production in tropical and subtropical climatic conditions all over the world including Ethiopia. A reliable and suitable irrigation water supply can result in vast improvements in agricultural production and assure the economic vitality. Sugarcane is one of the crops which relatively higher water consuming throughout its growing stages compared to other irrigated crops (Carvalho *et al.,* 2019). The demand for the sugar production is extremely increasing in Ethiopia and the expansion of the sugar factories also increased from time to time similarly. However, the rate of expansion does not keep pace with demand which requires critical evaluation of the factors which hinders its production (Erifo, 2016). From the factors that influence the production of sugarcane, irrigation water management which is the most important in sugarcane production which mostly cultivated by surface irrigation. From the sugarcane plantation in Ethiopia, Wonji Shoa Sugar Estate is one of the largest sugar factories in the country. But, currently due to the mismanagement of irrigation, different adverse effect of irrigation is emerging from time to time and the sugarcane production and productivity is extremely decreasing which requires critical considerations (Dinka *et al*., 2014)

1.2. Statement of the Problems

With increasing demands for sugar and needs for import substitution, Ethiopia is aggressively expanding irrigated sugarcane production. Nevertheless, less emphasis has been given to the importance of sustaining and improving the performance of existing irrigation schemes. As a result, the development of salinity and waterlogging in irrigated areas is widespread in many farms.

Despite its important contributions to the national sugar production, Wonji Shoa Sugar Estate did not experience significant rehabilitation and upgrading since its establishment in 1954. Surface irrigation has been the dominant irrigation methods used by the Estate over such long years of production. Combined with low skilled irrigators, surface irrigation practices have been leading to many undesirable consequences of irrigation. Thus, the need for efficient management of irrigation water in surface irrigation is increasingly needed to use water efficiently and ensure sustainability. The performance of large scale surface irrigation like sugarcane plantation in Ethiopia is not well evaluated and understood (Tadesse and Guchie, 2017).

Proper irrigation scheduling and water management of sugarcane requires knowledge about its water requirement that in turn depend on crop coefficient. However, limited research on sugarcane water requirement and crop coefficient were conducted in other countries like Brazil (Gabriel *et al.,* 2015), Austrialia (Win *et al.,* 2014), different regions of India (Yadav, 2018) and South African (Singels *et al.,* 2013). In Ethiopia, the few research has been conducted on sugarcane water requirement using the crop coefficints given in FAO guidelines (Abera *et al.*, 2016; Chala , 2019) due to lack of field based measueremens of crop coefficent in Ethiopia. While Ethiopia is increasingly embarking on expansion of irrigated suagrcane production, there is a need to generate information about the water requirements and crop coeffecint of sugarcane and optimizing the irrigation practices.

The amount of water applied can be reduced through, precise land leveling, proper layout of the field, use of appropriate irrigation methods and proper irrigation scheduling (Qureshi and Ashraf, 2019). The common furrow irrigation design parameters that affect the crop water consumption are furrow slope, furrow length and furrow spacing in addition to the decision variables like discharge rate and irrigation time.

In Wonji Shoa sugarcane plantation, irrigation has been practiced by unskilled irrigators with no systematically developed irrigation scheduling and hence, problems of groundwater rise (water-logging), widespread development salinity and are visible in many farm units (Dinka and Ndambuki, 2014; (Dinka *et al.*, 2014). Due to these adverse effects of irrigation mismanagement in the area, it is urgently important to improve the overall irrigation management practices of the farms to enhance sugarcane productivity and ensure sustainability of the resources use.

1.4. Objectives of the Study

1.4.1. General objective

The general objective of the study was to evaluate irrigation water management practices for sugarcane under Wonji Shoa Sugarcane estate with the view to improve on farm irrigation water management Practices.

1.4.2. Specific objectives

The specific objectives of the study were:

- To evaluate the performance of current furrow irrigation water management practices and develop improvement options.
- To measure and analyze sugarcane crop water requirement and develop its crop coefficient.

- To analysis the impacts furrow irrigation design parameters on sugarcane growth, yield and quality parameters, and water productivity.

1.5. Research Questions

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

- What is the current performance level of furrow irrigation water management practices at Wonji Shoa sugarcane plantation?
- What is the optimum level of sugarcane water requirement corresponding its crop coefficient at each growth stages under Wonji Shoa climatic condition?
- What are the impacts of furrow irrigation design parameters on growth, yield, quality, and water productivity under Wonji Shoa sugarcane Estate?

1.6. Significance of the Study

Evaluation of the irrigation water management practiced of irrigated sugarcane production became necessary because many resources (land, water and capital) are increasingly committed for production of sugar in the country. For efficient irrigation water management, determination of accurate sugarcane water requirements is very important since the scarcity of fresh water is becoming emerging problem. Knowing the performance of current status of irrigation water management practices helps to develop improvement options of irrigation management. Improvement options can be achieved through determining appropriate sugarcane water requirement and locally developing its crop coefficient; identifying optimum furrow irrigation design parameters and decision variables; and analyzing the effect of design parameters and decision variables on the growth, yield and quality parameters of sugarcane under the current study area. Therefore, this study will help the sugarcane producers to attain sustainable sugarcane production by applying efficient irrigation water management practices, saving water and reducing adverse effect of irrigation (salinity, water logging etc.) by proper irrigation water management.

1.7. Scope of the Study

Established in 1954, Wonji Shoa Sugar Estate is the pioneers of the large-scale irrigation project in the country. This large-scale irrigation project has been producing sugarcane by using most commonly used furrow irrigation system. Over such long years of operation, the scheme has neither experienced significant rehabilitation nor upgrading of management practices. In line with this, the current study was undertaken to evaluate its performance and develop improvement options. The current study was conducted for two consecutive years (2018/19 – 2020/21) at Melkassa Agricultural Research Center using lysimeter experiment to determine sugarcane water requirement and develop its crop coefficient. In Parallel on field experiment was conducted at Wonji Shoa sugarcane farm to evaluate the performance of the current irrigation water management practices and developing improvement options. The third experiment focused on analyzing the impacts of furrow irrigation design parameters on the growth, yield and quality of sugarcane under Wonji Shoa conditions. Appropriate surface irrigation models were also employed for the analysis of the effects of the current and suggested improved practices on overall performances of the system.

1.8. Organization of the Dissertation

This dissertation is organized into seven chapters as follows:

Chapter 1 This chapter presents the general introduction about irrigation water resources, performance evaluation of furrow irrigation under sugarcane production, determination of sugarcane water requirement and its crop coefficient, analyzing the impact of furrow irrigation design parameters on the field and quality of sugarcane and scheduling sugarcane. This part generally includes introduction, reason why this study was conducted, purpose of the study, the scope of the study and use of the study for the sugarcane producers.

Chapter 2: This chapter is devoted for literature review to summarize the results and critical conclusions of the past studies on similar subject and lay down foundation for this study. It includes botanical description of the study crop, its production and productivity, previous research works on the specific topics of the study.

Chapter 3: In this chapter, the general description of the study area, locations, farming systems, climatic conditions, methodology including general description of the specific objectives of the study and research design for all observational and experimental parts of the data collections are outlined.

Chapter 4: This part contains list of references used and cited in the above sections.

The following chapters (5-7) are devoted for presentation and descriptions of the results of the specific objectives of the study which are also published in peer reviewed journals. For each of the articles: the background of the study, problem statement, research objectives and questions, methodology, results, discussions, conclusions and recommendations followed by list of used references are provided.

Chapter 5: This chapter presents the results of the specific objective entitled "*Performance Evaluation of Furrow Irrigation Water Management Practices and Developing Improvement Options". ***Article published under this paper**

Performance evaluation of furrow irrigation water management practice under Wonji Shoa Sugar Estate condition, in Central Ethiopia; ***2022) 69(21), 1-23. Springer Open Access Journal of Engineering and Applied Science. https://doi.org/10.1186/s44147-022-00071***

Chapter 6: This chapter communicates the results of the second specific objective entitled *"Measuring and Analyzing of Sugarcane Water Requirement and Developing Its Crop Coefficient Under Wonji Shoa Climatic Condition". **Articles published under this paper:***

Determination of Water Requirement and Crop Coefficient for Sugarcane Using Lysimeter Experiment under Semiarid Climatic Conditions of Ethiopia; **2021, 147(11).** ***Journal of Irrigation and Drainage Engineering, ASCE. doi: 10.1061/(ASCE)IR.1943-4774.0001615***

Comparison Of Measured and Estimated Sugarcane Water Requirement under Arid and Semiarid Climatic Condition of Ethiopia: The Case of Wonji Shoa Sugar Estate; **2021, 8(2) 269-283.** ***Journal of Emerging Technologies and Innovative Research*** **www.jetir.org.**

Chapter 7: In this chapter the results of the third specific objective entitled *"Analyzing the effects of Furrow Irrigation Design Parameters on Sugarcane Growth, Quality and Water Productivity Under Wonji Shoa Climatic Condition"*

2. LITERATURE REVIEW

2.1. Botanical Description of Sugarcane

Genetically, sugarcane (*Saccharum hybrid spp*.) originates from New Guinea and belongs to the grass family. The most common important species of genus *Saccharum* are *Saccharum officinarum, Saccharum Sinense, Saccharum barberi, Saccharum robustum, Saccharum spontanuem and Saccharum edule* (Wu and Altpeter, 2015). The first three species are the cultivated species and the last three are wild species. Sugarcane is C4 plant with a high rate of photosynthesis (150-200%) which is more as compare to other plants. It is a perennial crop with high self-tolerance. The plant tillers 4-12 stems, depending on the variety and site conditions which can grow up to 3 to 5 meters (Tena *et al.,* 2016). The main parts of the sugarcane plant are the Root, Stalk and Leaf System. The sugar content in sugarcane plant fluctuates between 11 to 16%. In Ethiopia, sugarcane is used for the production of sugar and few other byproducts. Ethiopia has suitable agroecological zones for the production of sugarcane that is the primary input in the production of sugar. The country's conditions is most suitable for water intensive crops like sugarcane production and productivity among the highest sugarcane producers in sub Saharan African countries (Bayrau *et al.,* 2014).

2.2. Sugarcane Production in the World

Sugarcane is the world largest crop by production in quantity and produced in over 120 countries. Global production now exceeds 1.65 billion tons a year. Approximately 80% of sugar is produced from sugarcane, which is largely grown in tropical countries. The remaining 20% is produced from sugar beet, which is grown mostly in the temperate zones of the northern hemisphere, 70 countries produce sugar from sugarcane, 40 from sugar beet and 10 from both (Zulu *et al.,* 2019). The ten (10) largest sugar producing nations represent roughly 75% of world sugar production. The ten largest sugarcane producing countries were Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Philippines, USA and Indonesia (Fernando *et al.,* 2016).

In terms of production, Brazil stands on the top with 33% of global sugarcane production followed by India 23%, China 7% and Pakistan 4%. Worldwide sugarcane occupies area coverage of 20.42 Mha with a total production of over 1.65 billion tons per year. In

Brazil, sugarcane currently covers 9.5 Mha, or 1% of the country's total area. Brazil uses sugarcane to produce sugar and ethanol for gasoline ethanol blends (gasohol) a locally popular transportation fuel. In India, sugarcane is used to produce sugar, jaggery and alcoholic beverages. In the USA, sugarcane is mostly grown commercially in Florida, Hawaii, Louisiana and Texas for sugar production and many biproducts (Shrivastava *et al.,* 2011).

As many researchers indicated, the leading sugarcane producer over the world is Brazil that cover more irrigated land of the country. The productivity of sugarcane in most Sub Sahara African countries was extremely varying and only accounts about 5% of the world sugarcane production. South Africa is the leading country in sugarcane production in Sub Sahara Africa followed by Sudan and Mauritius countries. In case of Ethiopia, current sugarcane production provides only 60% of the annual demand of the country for domestic consumption. The annual per capita consumption of sugar in Ethiopia was very low (5.1kg) even as compared to the African standards (16.3kg) (ISO, 2010).

In Ethiopia, the area coverage of sugarcane is 31,236.81ha with the total production of 1,411,903.81.2 tons/year with the productivity of 45.2 tons/ha (CSA, 2018). The main factors that affect the production and productivity of sugarcane were water shortage at different growth stages, land preparation and topographic situation (if surface irrigation was used), shortages of fertilizer, chemicals, weeds and pest managements. Moisture stress at different growth stage highly influences the yield of sugarcane (Girei and Giroh, 2017).

2.3. Irrigation Methods in Sugarcane Production

Surface, overhead and drip irrigation methods are most commonly used irrigation in sugarcane crops depending on physical characteristics, economic, social and other considerations. Furrow irrigation is widely used because of its low cost and energy requirement. The pressurized irrigation systems (sprinkler and drip irrigation) are usually more efficient than the furrow irrigation. But furrow irrigation system is designed in such a way to ensure an adequate and uniform water application over the fields and to minimize the potential water losses. Many researchers in this field have engaged in optimizing the design of furrow irrigation system to improve irrigation performance. However furrow irrigation performance is affected by several factors including inflow discharge, soil infiltration characteristics, field length, required application volume, cutoff time, surface roughness and field slope (Nie *et al.,* 2014).

The furrow length and field slope are commonly considered design factors that are not easily modified and often specified by farmers. Similarly, the surface roughness and soil infiltration characteristic are essentially fixed factors over which the irrigator has limited, if any control. However, inflow discharge and cutoff time are generally considered as management factors which can be varied between events by the irrigator and hence used to improve irrigation performance. Many optimization models were used to optimize the furrow irrigation systems to evaluate performance of surface irrigation. The modeling included factors such as irrigation application efficiency, distribution uniformity and storage efficiency for design of furrow irrigation (Nie *et al.,* 2014).

2.4. Performance Evaluation of Furrow Irrigation in Sugarcane Production

The performance of irrigation systems directly affects crop growth status, water use efficiency (WUE), cost of production and profitability of the producers. The same irrigation method and the same amount of water can produce significant differences in yield with different patterns of water application (Srivastava, 2012). Therefore, more uniform irrigation application needs to be targeted through design, continuous evaluation and maintenance practices. Traditionally, most sugarcane farming systems used surface irrigation (specifically furrow irrigation) because of its simplicity and low cost. But the increasing cost of energy, labor and the increasing demand for scarce water resources has led to greater adoption of overhead or drip irrigation methods which leads to more application efficiency and uniformity of irrigation water applied. However, furrow irrigation is still the major method used worldwide. The major drawbacks of furrow irrigation in the sugarcane farmers are the high labor requirement, high losses of water through percolation, evaporation and tail water losses finally resulted in less water use efficiency (WUE) (Gunarathna *et al.,* 2018).

Irrigation system performance describes the effectiveness of the physical system and operating decisions to deliver irrigation water from a water source to the crop. Irrigation efficiency is generally defined from three viewpoints as irrigation system performance, uniformity of water application and response of the crop to irrigation. There are different irrigation efficiency indicators in which all of them strongly dependent on soil type, slope, crop growth stage, water delivery system capacity and many other management factors (Teshome *et al.*, 2018). As those authors concluded, the same irrigation method values have different efficiency values that vary substantially from one field or location to another. Proper irrigation management can increase the application efficiency in which poor irrigation management can result in inefficient use of water that results in low application efficiency. Improper timing and inadequate irrigation applications that do not meet the crop water requirement may impose stress to the crop and reduce yield and yield quality. Generally, performance evaluations of surface irrigation relay on application efficiency, distribution uniformity and in some parts on the deep percolation (Raza *et al.*, 2012).

The study conducted by Akbar *et al.* (2017) on surface irrigation systems were evaluated the performance of surface irrigation using the WinSRFR 4.1.3. As those authors stated, WinSRFR model was used for integration of irrigation system evaluation, irrigation system design and operational analysis. This model was extensively used for evaluation and optimization of surface irrigation performance throughout the world. The result obtained by those authors revealed that irrigation performance including application efficiency, potential application efficiency, adequacy and distribution uniformity of 17 irrigation events were evaluated and further potential for improvement by optimizing field sizes were identified using surface irrigation evaluation model WinSRFR 4.1.3. According to the findings of those authors, irrigation efficiencies obtained were poor with application efficiency (41% to 82%), potential application efficiency (43% to 95%), adequacy (1.16 to 2.29) and distribution uniformity (80% to 99%) on irrigated field.

The study findings by Mazarei *et al. (*2020) on optimization of furrow irrigation performance of sugarcane fields using WinSRFR model indicated that different combination of furrow irrigation decision variables gives different efficiency parameters in the study area. Those authors used three performance parameters in their study including application efficiency (AE), distribution uniformity (DU) and deep percolation (DP). To evaluate selected performance parameters, they considered three irrigation events in the selected seven sugarcane fields. The result obtained revealed that AE and DU performances were improved during the second irrigation events. The minimum DP performance was obtained during the third irrigation events.

2.5. Optimization Models of Surface Irrigation Systems

In Surface irrigation, mathematical models are important for the evaluation and design purposes. Those models are classified into four main groups as full hydrodynamic models, zero-inertia models, kinematic wave models and volume balance models. The fully hydrodynamic model is the most complex and the most accurate. It is based on the complete Saint Venant equations for the conservation of mass and momentum. The zero inertia models are slightly simplified version of the complete Saint Venant equations that leaves out the acceleration or inertia terms in the momentum equation. The kinematic wave model uses further simplifications and uniform flow assumptions. The simplest model that involves the largest number of assumptions is the volume balance model. It is based on the analytical or numerical solution of the temporally and spatially lumped mass conservation commonly referred to as the volume balance approach. Mathematical models for the design, operation and evaluation of various surface irrigation methods have been used in user friendly computer programs such as the WinSRFR (Bautista *et al.,* 2016), SURDEV and SIRMOD (Mehanna *et al.,* 2009).

The mathematical models are based on the equations that describe the processes governing the over land flow and infiltration in surface irrigation. The hydrodynamic equations used in the mathematical models for describing the overland flow in surface irrigation are the equations of mass and momentum conservation known as the Saint-Venant equations after the modification include infiltration (Valipour, 2012a). The detail equation for those different models to simulate surface irrigation events including full hydrodynamic (HDM), zero inertia (ZIM), kinematic wave (KWM) and volume balance (VBM) described as follow.

2.5.1. Fully Hydrodynamic Model

Hydrodynamic models use the most general form of the Saint-Venant equations, that are nonlinear partial differential functions that characterize unsteady, gradually varied flow of water in a furrow. Full Hydrodynamic models are used for calibration and evaluation of simpler models due to their accuracy. However, they are the most complex and the most expensive in their requirements for data acquisition and execution, which is given by the following equation (Ebrahimian and Liaghat, 2011).

$$\frac{\delta A}{\delta t}+\frac{\delta Q}{\delta x}+\frac{\delta Z}{\delta \tau}=0 \qquad 2.1$$

$$\frac{1}{Ag}\frac{\delta Q}{\delta t}+\frac{2Q}{A^2 g}\frac{\delta Q}{\delta x}+\left(1-\frac{Q^2 T}{A^3 g}\right)\frac{\delta y}{\delta x}-S_o+S_f=0 \qquad 2.2$$

Where: y = depth of flow (m), t = time from the beginning of irrigation (s), τ = intake opportunity time (s), Q = discharge (m^3/s), x = distance along the field length (m), Z = infiltration rate (m/s), g = acceleration due to gravity (m/s^2), S_0 = longitudinal slope of field (m/m), S_f = Slope of energy grade line (friction slope) (m/m), A = cross-sectional area (m^2), T = top width of flow (m)

2.5.2. Zero Inertial Model

Zero inertia models are based on the understanding that flow velocities encountered in surface irrigation is very small and changes in velocity with respect to time and space are virtually nonexistent. Under most surface irrigation conditions, inertial terms in the Saint-Venant equations are negligible when compared to the force terms (heat and friction). The zero inertia models are a simplified form of the full hydrodynamic model without the acceleration and inertia terms which is given by the following equation (Aricò and Nasello, 2018).

$$\frac{\delta y}{\delta x}=S_o-S_f \qquad 2.3$$

The parameters are described in the above section

2.5.3. Kinematic Wave Model

Kinematic wave model assumed that flow in the irrigation channel is all at a fixed depth. The momentum equation is reduced to the well-known steady flow identity between bottom and friction slope. In the Kinematic wave model, the depth gradient of the flow (δy/δx) and inertial terms of the momentum equation (Equation 2.2) are often small in comparison with those of the bottom and friction slopes. Therefore, Equation 2.2 can be further simplified by assuming that the depth gradient and inertial terms are negligible and thus becomes to equation 2.4 (Ebrahimian and Liaghat, 2011).

$$S_o = S_f \qquad 2.4$$

2.5.4. Volume Balance Model

In volume balance model is applied primarily onto the advance phase and the momentum equation was completely neglected. The models based on this simplification were called volume balance models and based on the principle of mass conservation with the assumption of normal flow depth at the upstream end. Water front advance can be predicted by the volume balance approach in border and furrow using the following equation 2.5 (Ebrahimian and Liaghat, 2011).

$$Q_o t_x = \int_0^x A(x,t)dx + \int_0^x Z(x,t)dx \qquad 2.5$$

Where: Q_0 = flow rate at the inlet boundary

t_x = time of cutoff

A (x, t) = cross sectional area of the surface flow, variable with distance (x) and time (t)

Z (x, t) = Volume of infiltrated water, variable with distance and time

However, both kinematic wave and volume balance approaches are limited to sloping and free draining systems.

2.6. Evapotranspiration

Evapotranspiration is combined loss of water from soil as well as plants which is a very crucial component of hydrologic cycle. Evapotranspiration maybe varied based on crop growing environment, crop growth stage, degree of land surface coverage and evaporation from the soil surface. There are number of methods used to estimate the reference evapotranspiration (ETo) which is the basic detrimental factors in evapotranspiration. However, the methods present different results due to their various hypotheses and input data requirements in different climatic regions (Length, 2019).

Reference evapotranspiration is expressed as the evaporative demand of the atmosphere at a specific location and time of the year that does not consider crop and soil factors. The existing empirical equations to estimate ETo with limited data were categorized as temperature based, radiation based, evaporation based and material conversion based and mixed type Reference evapotranspiration was determined by many models for different climatic conditions. But, FAO Penman Monteith (PM) equation is widely accepted and standardized all over the world. Even though this method (PM) is most accurate not always easy to use mostly in developing countries as it requires almost all climatic parameters (Djaman *et al.,* 2016).

The study findings by Awal *et al.* (2020) revealed that the ETo determined by Hargreaves showed under estimation as compared to FAO penman monteith method. The performance of ETo determined by statistical measures indicated that the substantial reduction in RMSE, MBE and substantial increarement in R^2 and IA as compared to the FAO-PM equation. The other study result by Djaman *et al.* (2017) indicated the ETo determined by Irmak and Tabari underestimated ETo as compared to the FAO-PM equation. The statistical indices considered indicated lower performance which resulted in lower irrigation application that cause water stress to the crop and final yield losses. The study findings by Subedi and Chavez (2015) indicated the ETo determined by Thornthwaite method performed better in terms of low RMSE (1.77) values and high Index of agreement (0.93) as compared by FAO-PM equation. The same study result indicated that the ETo determined by Blaney Criddle model was lower in MBE (0.01), medium in R^2 (0.74) and IA (0.76). Finally, those study findings concluded that Blaney Criddle model perform better from 8 models considered as compared to the FAO-PM equation.

2.7. Sugarcane Water Requirement (ETc)

Crop water requirement is an important practical consideration for improved agricultural water use efficiency. It varies during the growing period, mainly due to variation in crop growth and climatic conditions. The total water consumption for the whole sugarcane growing season in the study area was found to be 1460.4 mm which was higher than the result obtained by lysimeter experiment (Win *et al.*, 2014).

The research conducted on calculation of crop evapotranspiration by Nazir *et al.* (2013) on calculation of crop evapotranspiration using four widely used methods were tested to identify the best method that suites to Pakistan’s diverse climate. Numerous researchers analyzed the performance of various methods for different locations. The results of such analyses are commonly influenced by site or measurement conditions or by errors in weather data collection. Hence, it became evident that the proposed methods do not behave the same way in different locations in diverse climatic regimes. Deviations from computed values as compared to observed values were often found to exceed acceptable ranges as indicated by FAO (1998). For a maximum yield of sugarcane, 1425mm crop evapotranspiration was recorded in tropical regions of India. The maximum amount of water consumed by sugarcane is at grand growth period and accounts to about 54% of the total crop water requirements (Win *et al.,* 2014).

2.8. Sugarcane Crop Coefficient

The crop coefficient function *(*Kc) which accounts for physical and agronomic differences between the crop and the reference surface was basically determined based on the FAO parameters. The research result conducted by Gabriel *et al.* (2015) in the lysimeter to determine the sugarcane crop coefficient indicated that there were agreements of the Kc value at initial and development growth stages with FAO-56 Penman Monteith values but there was a variation at late growth stages. According to the findings of those study, crop coefficient is the connection of the effects of the three characteristics distinguishing ETc from ETo. These are crop height, surface resistance and reflection coefficient or albedo of the crop soil surface. The variation of the crop coefficient (Kc) of sugarcane was determined by the relationship between ETc and ETo throughout the crop growing season. Those authors also reported that variations in Kc rates at short time intervals were caused by microclimate variations, differential growth of the plants, measurement mistakes due to hysteresis and by the loss of irrigation water by evaporation, expansion and contraction caused by temperature variations during the day.

The research findings by Marina *et al.* (2018) showed that as there were a variation in sugarcane crop cofficient at different growth stages that determined by experiment as compared to the Kc rates proposed by Allen e*t al*. (1998) employing the parameter suggested by FAO-56. The result obtained by Marina *et al.*, (2018) was indicated that the sugarcane crop coefficient for the first two stages (emergency and tillering phases) was higher than the FAO-56 recommendation but the latter two stages (grand growth formation and ripening phases) showed lower than the FAO-56 values. Based on their results, those authors recommended that every researcher should determine the sugarcane crop coefficient based on the climatic condition where the crop is grown rather than using the general literature values.

2.9. Factors Affecting Sugarcane Irrigation Water Requirement

There are many factors which affect the crop water requirements. The crop water requirement is highly dependent on growth parameters and transpiration. Those factors are related to environmental factors such as climate, soil fertility (mineral nutrition) and soil moisture conditions. Climatic parameters especially temperature and rainfall have a significant impact on the sugarcane water requirement. The findings of Farooq and Gheewala (2018) revealed that temperature has a direct significant impact on the sugarcane water requirements but the water requirement is inversely proportional to the rainfall specially, in the hotter climatic areas.

Under the climate change impact, water scarcity become emerging problems that is very difficult to fulfil the crop water requirement particularly for the water intensive crops like sugarcane. The sugarcane requires optimum rainfall during the vegetative growth as it encourages rapid cane growth, cane elongation and internodes formation. During ripening period, the water application from any source should be less in order to have good quality juice, less vegetative growth as well as reduction in the tissue moisture. An average of 1200 mm evenly distributed rainfall in the range of 1100-1500 mm is optimum for higher yield (Srivastava, 2012).

Sugarcane is strongly influenced by the impacts of long-term climatic change as well as local weather and seasonal variations. Climate parameters affects the growth and development of plants and significantly affect the sugarcane yield and quality (Srivastava, 2012). Since sugarcane is perennial crop and water intensive, to overcome the impact of climate on yield and quality, conserving water resources and efficiently utilizing it is recommended either by using more efficient irrigation systems or by improving the field management practices.

Sugarcane can be produced in all types of soils, however, well drained loamy soil with a pH of 6.5-7.5 and adequate nutrients is considered to be the ideal condition. A continuous monitoring of physical, chemical and biological conditions of the soil is required to ensure good cane growth, high yield and better quality sugarcane. In sugarcane production, irrigation water always required to be applied in accordance with the crop growth stages, soil types, moisture status and climatic consideration since the crop is highly affected by both over and under water application. To maintain good crop performance, growth, yield and quality of sugarcane production, the soil moisture was required to constantly kept at field capacity (McCray and Baucum, 2015).

2.10. Furrow Irrigation Design Parameters

Furrow irrigation is the most commonly used surface irrigation method in irrigated sugarcane production. The irrigation strategy adopted by management can also have a major effect on an irrigation system design and performance. The designers target a uniform distribution of water and acceptable efficiency. Thus, the designers select appropriate combinations of parameters like inflow rate, application time, length and depth of irrigation under the natural settings of infiltration characteristics of the soil, field slope and roughness. Other data required for surface irrigation design include topography of land surface (slope) and surface drainage points, physical and chemical characteristics of soil and finally economic condition in the area as well as the availability of labor. According to Assefa *et al.* (2017), in furrow irrigation system, the effect of furrow slope, furrow length and inflow rate have a significant impact on the yield of sugarcane.

According to Ghobadi *et al.* (2020) furrow irrigation design parameters highly affect the yield of the sugarcane. The authors concluded that rather than single design parameters the interaction of the parameters was found to highly affect the yield of sugarcane crop. The other study findings by Kannan *et al.* (2014) also indicated as the design of the furrow irrigation should always considers the soil types, topography, size and shape of the irrigation area inline to the furrow design parameters listed by many authors.

According to the study done by Zerihun *et al.* (2001) the time of cutoff, discharge rate and furrow length are the main three furrow irrigation design parameters that substantially influence the efficiency of irrigation. As those authors concluded in their study, for a set of field parameters in furrow irrigation design, it is a function of discharge rate applied and furrow length in which the water run.

The other similar study by Holzapfel *et al.* (2010) revealed that furrow irrigation design variables which highly influence the irrigation performance and crop production were inflow discharge, furrow length and time of cutoff. The findings of those study concluded that, even if the correct furrow irrigation design parameters considered, over irrigation resulted from shorter furrow length, larger inflow discharge and longer irrigation cutoff time which determinately affect the performance of irrigation, crop production and soil productivity.

2.11. Sugarcane Growth, Yield and Quality Parameters

2.11.1. Sugarcane growth and yield parameters

In sugarcane, the stack height of the plant is an important factor in its development and final yield of the crop. The main sugarcane growth and yield parameters that are affected by different internal and external factors are cane height, girth (cane diameter), number of internodes, population stack and cane yield. As the study findings of Rajan *et al.* (2021), indicated that cane stack height, cane grith, number of internode per stack and stack population were significantly affected by the level of irrigation applied. The findings of Raza *et al.* (2012) revealed that irrigation level and interval of irrigation application highly influenced the growth and yield of sugarcane. As per those authors, the sugarcane growth parameters like cane height, cane diameter, numbers of internodes per cane stack and millable cane stack population significantly affected the sugarcane yield as well as sugar yield. The other study findings by Hase (2019) indicated that the cane height, number of internode, stack population and cane stack weight highly influenced the cane yield and sugar yield. The recommended standards for growth parameters of sugarcane are length of millable cane stack 237 cm, number of cane internodes per cane stack 13.50 and cane weight per stack 1.58 kg (Silva *et al.*, 2008).

2.11.2. Sugarcane Quality parameters

Sugarcane is a genetically complex crop that is extensively influenced by environmental factors resulting in diversity in cane yield and quality features among genotypes/varieties. The findings of Kumar (2016) indicated that the variation of sugarcane quality parameters highly affected by varietal differences than irrigation level. In sugarcane crop, the most common quality parameters considered are brix, polarization, purity, estimated reduced sugar yield (recovery percentage) and estimated sugar yield are the most common in quality analysis. The sugarcane quality parameters are mostly affected by availability of water, time of harvesting (age of the crop at harvest) and time of withholding irrigation before harvesting (Olivier *et al.*, 2006). According to the study made by Rajan *et al.* (2021), even if irrigation level showed variation in quality parameters, the variation was not statistically significant. The quality standards of sugarcane as recommended by South Africa sugar technology association (SASTA, 2009) cited by Babeker *et al.* (2020) are brix of cane ranges from 18-23%, polarization 14-21%, purity 77-93.5%, fiber 15-20% and moisture percentage 55-65%.

2.12. Sugarcane Irrigation Scheduling

The aim of irrigation scheduling was to maintain available soil water (SW) of the entire field within a predetermined target range. The irrigation scheduling methods basically based on crop water requirements, soil water storage capacity, and meteorological circumstances. In general, irrigation scheduling strategies can be classified as plant, soil, and climate based or a combination of the of the three factors. To decide when and how much irrigation water should be applied, the most prevalent approaches are to use daily crop evapotranspiration (ETc) estimates as crop water usage, assessments of soil moisture status, or a combination of these two methods (Kebede *et al.*, 2014).

Water balance approach is the most commonly used irrigation scheduling in many parties of the world. But irrigation scheduling systems in many parts of the United States employed different approaches of the water balancing in which crop specific ETc values are computed from daily air temperatures provided by the producer or online using data from nearby meteorological stations. Scheduling irrigation using evapotranspiration or maintaining equilibrium of soil moisture depletion, particularly useful in situations where soils with low water holding capacity that challenges for irrigation management. A good understanding of the soil water balance is essential for irrigation scheduling and evaluating seasonal management of irrigation performance as a one means of irrigation improvement (Henggeler, 2004).

The general assumption of irrigation scheduling for furrow irrigation practices is that the soil moisture content reaches at field capacity and the soil moisture deficit drops to zero after irrigation application events. According to the findings of Puttavenkategowda and Nagaraja, (2019), almost all sugarcane growth and yield parameters indicated the significance variation based on the frequency of irrigation application but the quality parameters were not much affected by the frequency of irrigation application. The other reports by Gillies *et al.* (2017) indicated that the proper irrigation scheduling according to the sugarcane water requirements increased the cane yield 19 to 22 ton/ha. According to the findings of Okuku and Onyando (2018) revealed that irrigation scheduling by CropWat model showed that even the amount of water applied to crops reduced, the yield of crops increased since irrigation applied at right time of the crop water requirement.

2.13. Sugarcane Water Productivity

The concept of water productivity in sugarcane production system is based on more crop per drop of water and it is key tool useful when comparing the productivity of water in different crop types or when comparing the productivity of water in agriculture with other competing sectors (Leal *et al.,* 2017). As the findings of those authors indicated the effect of different rate of irrigation water application showed a significant variation on sugarcane water productivity. the sugarcane water productivity obtained ranges 1.68 to 2.22 kg m^3 for full and 30% deficit irrigation respectively. From their findings they concluded that, the water productivity of sugarcane was higher for the deficit irrigation. Water productivity is affected by several factors, such as crop cultivar, water availability, climate, soil characteristics and management practices (Prabhakar *et al.,* 2018).

The water productivity values of various crops are determined and published in FAO drainage paper (Jonna and Peter, 2021). The other study result by Raes *et al.* (2018) have published water productivity values of various crops in FAO drainage paper 66 based on the field experimental measurements allover many regions. These authors reported that the recent water productivity values of most crops are higher than those of 1970th published by (Doornbos and Kassam, 1979) as result of development of improved crop varieties that are able to produce higher yields, drought and pest/disease resistant crops, improved soil fertility and land water management practices.

The need for crop growth and yield modelling has received tremendous attention in recent times due to global climate change and food security problem emerging from high population growth (Vanuytrecht *et al.,* 2014). One of the main purposes of crop growth models is to simulate yield production as a function of weather parameters, soil conditions, and land and water management practices (Naroua *et al.,* 2014). The crop models that require a greater number of input parameters which is difficult to generate from field experiments and crop growth are not water driven and input data under variable water supply situations is not easily accessible. To overcome those limitations, a crop water productivity model AquaCrop was developed by the Land and Water Division of FAO and released for use (Raes *et al.,* 2009). According to these authors, AquaCrop is water driven crop model to simulate yield response crops to water. It is designed to balance simplicity, accuracy and robustness and is particularly suited to address conditions where water is a key limiting factor in crop production.

3. OVERALL METHODOLOGICAL APPROACHES OF THE STUDY

3.1. Description of the Study Area

3.1.1. Location

The study was undertaken at Wonji Shoa Sugar Estate (WSSE) and Melkassa Agricultural Research Center (MARC). Both study areas are located in the South East Shoa Zone of Oromia regional state, central rift valley of Ethiopia. Geographically, both study areas are found in the same location under similar latitude and longitudinal conditions. Melkassa Agricultural Research center is situated at a latitude 8^{0}24’-8^{0}26’N and longitude 39^{0}18’-39^{0}22’ E while Wonji Shoa Sugar Estate at 8^{0}21’- 8^{0}29’ N and 39^{0}12’- 39^{0}18’E in which both locations located at an altitude of 1550 m.a.s.l. Thus, the study areas are located just close to each other. One experiment was conducted at Melkassa Agricultural Research center due to the availability of lysimeter arrangement and the other experiments were conducted on the farms of Wonji Shoa sugar Estate.

3.1.2. Climate

The climatic condition of both Melkassa Agricultural Research center and Wonji Shoa Sugar Estate are characterized as hot throughout the year with low amount of annual rainfall. The mean maximum and minimum temperatures of MARC are 28.4 and 14^{0}C respectively while at Wonji Shoa Sugar Estate, it is 27 and 15^{0}C respectively with the mean annual rainfall of 810.3 and 831mm respectively at both locations.

3.1.3. Soil

The soil of Wonji Shao Sugar Estate is greatly varied from place to place. But the overall soil of the Estate is characterized by heavy soil with high water holding capacity in which 70, 26 and 4% of Estate farm covered by vertisol, heavy clay soil and loamy sand soils respectively. According to the WSSE, the soil types of the Estate classified into five Soil Cycle Classes, A1, A2, BA2, B1.4 and C1 for purposes of easily management with pH of the soil ranges from 7.6 to 8.2 According to the report of MARC (2018), the dominant soil type of MARC is Andosol of volcanic origin with pH ranging from 7 to 8.2.

3.1.4. Farming system

At Melkassa Agricultural research center, multiple farming systems are undertaken. This includes dairy farm, poultry farm and crop farm. The cropping system during the main growing season includes cereals mainly teff, maize, sorghum, haricot bean and soybean while tomato, onion, papaya, banana and sugarcane are the main crops grown during the off-season using irrigation from Awash River water source. Wonji Shoa is characterized by very gentle and regular topography making it most suitable for irrigation. At Wonji Shoa sugar Estate, only Sugarcane crop is grown in the area mostly as monoculture but recently, different types of beans and wheat are started during the fallowing periods of the land as restoration period for sugarcane crop. Similar to Melkassa Agricultural Research center, the source of water for irrigation at Wonji Shoa Sugar Estate is Awash River. Location maps of the study sites are depicted in Figure 3.1.

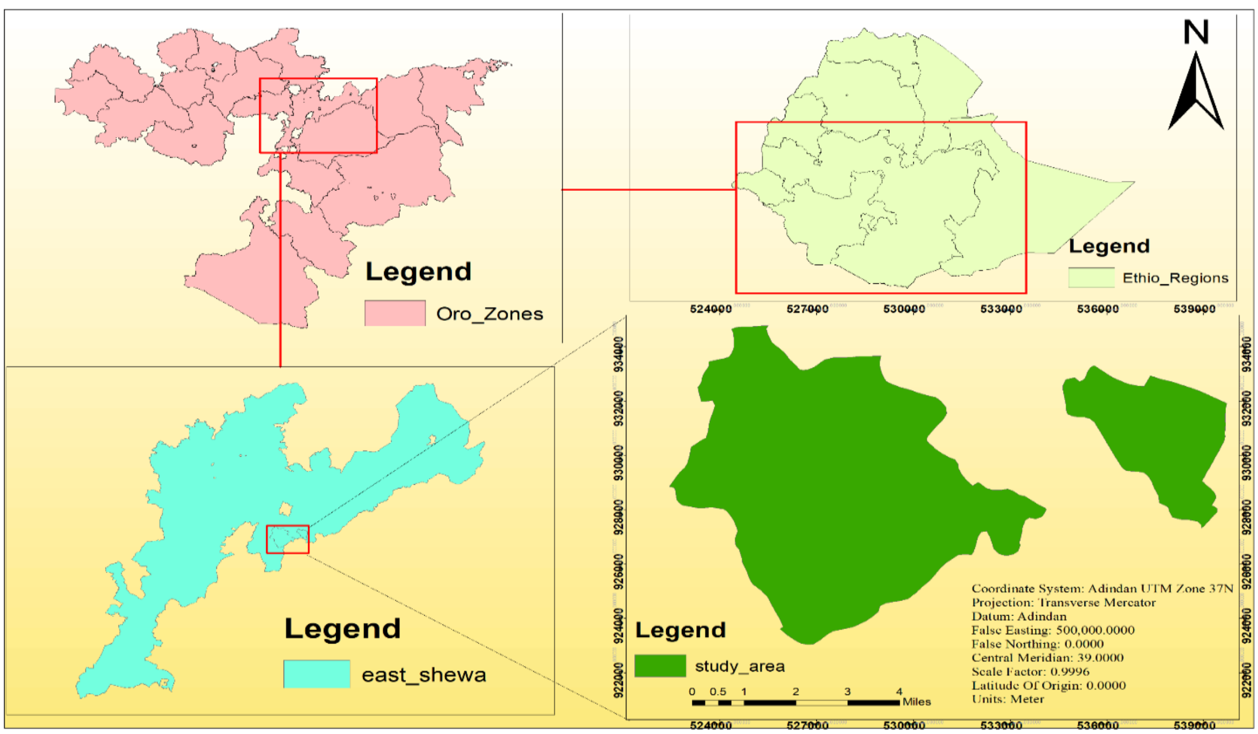

Figure 3.1. General location map of the study sites

3.2. Overall Research Methods and Design

All data required for the accomplishment of the research, types of data required, methods of data collection and methods used for data analysis are clearly described under this section. The design of this study was classified as experimental and extensive field observational research types. The general framework followed for the study is presented in Figure 3.2. The experimental research types were: sugarcane water requirement was determined and its crop coefficient was developed using lysimeter. The impact of furrow irrigation design parameters on the growth, yield and quality of sugarcane production, and water productivity were analyzed. The non experimental or observational research types used in this study was performance of existing furrow irrigation water management practices was evaluated and based on the result, the improvement options were under taken for Wonji Shoa Sugar Estate condition.

The background of the study, justification and objectives of the study, materials and methods used for each component, data collection procedures, data analysis, result and discussion, conclusion and recommendation for each component were described under each separate chapter.

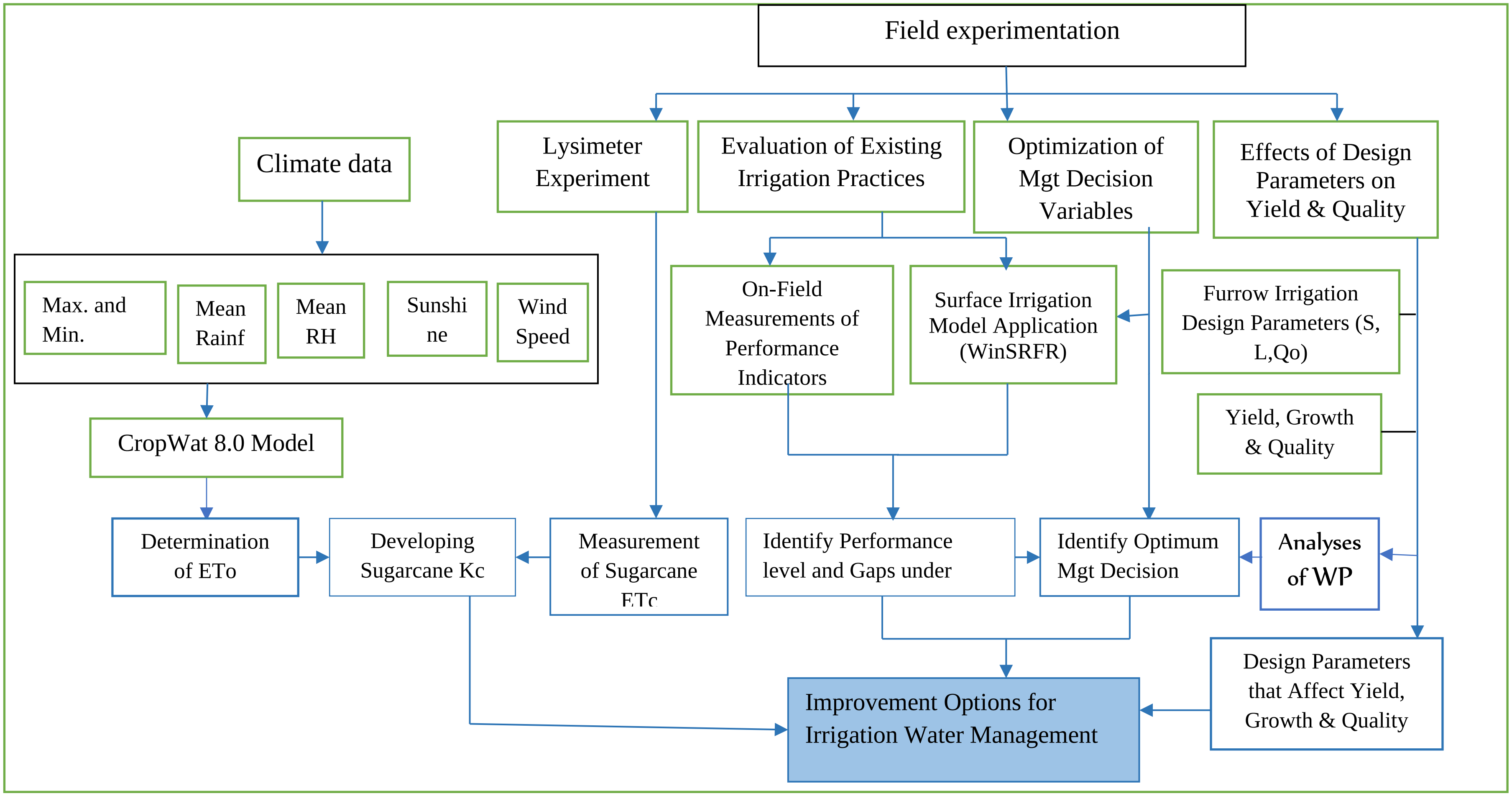

Figure 3.2. Conceptual frame work of the study

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5. PERFORMANCE EVALUATION OF FURROW IRRIGATION WATER MANAGEMENT PRACTICES AND DEVELOPING IMPROVEMENT OPTIONS[1]

ABSTRACT

Wonji Shoa Sugar Estate (WSSE) is one of the large-scale irrigation schemes in Ethiopia which was established in 1954. The WSSE was established for the production of sugarcane as a mono crop for long periods of time. In WSSE, furrow irrigation is the most dominant irrigation practices which require a critical evaluation of its performance for effective utilization of the available water resource. In line with this, the main purpose of the current study was to evaluate the performance of current furrow irrigation water management practices and develop improvement options. Performance evaluation of the current furrow irrigation was done based on field measurements and using simulation models like WinSRFR. For this purpose, ten fields were selected from commonly used furrow lengths (32, 48 and 64m). Performance indicators considered were application efficiency, distribution uniformity and deep percolation. The result obtained indicated that the application efficiency was found to be 46, 52 and 48% for furrow length 32, 48 and 64m respectively. The distribution uniformity values are 87, 81 and 90% for these lengths considered respectively. Whereas, the deep percolation was found to be 54, 48 and 52% for furrow lengths of 32, 48 and 64m respectively. Based on achievable performance levels under similar practices, the results found here can be categorized as poor. As an improvement options, decision variables (inflow rate and cutoff time) were varied to achieve better performance improvement. Advance and recession time for all furrow length were recorded and simulated using WinSRFR model. The result obtained showed that, there is a big difference between the cutoff times currently used to irrigate all furrow lengths and the cutoff times determined following standard procedures. As an improvement option both inflow rate and cutoff time were varied until better performance improvement was achieved. Thus, by changing inflow rate from existing, 4.7 l/s to 3.5l/s and cutoff time from 9 to 11 minutes for furrow length 32m, the application efficiency and deep percolation were improved by 32.7% and 38% respectively. Other furrow lengths have also shown significant improvement in terms of the same performance indicators. But distribution uniformity did not show significant variations for all furrow lengths. From practical point of view, it can be concluded that the inflow rate and cutoff time suggested can be used to improve the current poor on-farm irrigation water management practices. At the onset of irrigation, it is important that the optimum decision variables be determined based on field measurements that results in an improvement of overall irrigation efficiency.

Keywords: *Cutoff time, Furrow irrigation, decision variables, Furrow design parameters, Performance evaluation, Statistical indices*

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[1] *From this research components, one article was in published in* ***journal of Engineering and Applied Science*** *[Springer open access journal]*

5.1. Background of the Study

Irrigation is an artificial application of water to crops by using gravity or pressure to convey water from source to the field that required by the crop to fulfill soil moisture deficit in the crop root zone. There are three major categories of irrigation (surface, subsurface and pressurized) systems. From these, surface (gravity) irrigation system is one of the major categories of irrigation systems (Taddesse *et al.*, 2019). On a global basis, 69% of all water withdrawn for human use currently consumed by agriculture, mostly in the form of irrigation with very low water use efficiency. Surface irrigation is the dominant irrigation method with very low efficiency (<70%). Surface irrigation system refers to application of water which is applied and conveyed over the field surface by gravitational force. Surface irrigation includes furrow, border and basin irrigation systems which has most common configurations of surface irrigation. Surface irrigation methods having relatively lower water use efficiency when compared to the pressurized systems are responsible for the low performance of irrigation. Surface irrigation is widely practiced throughout the world, more than 95% irrigated area is covered by this methods especially in the developing countries (Akbar *et al.*, 2016).

Surface irrigation method, specifically furrow irrigation is the most widely used method of irrigation in the world despite its low efficiency due to the complexity of the interactions between field design, soil infiltration characteristics and irrigation water management practice. In many developing countries like Ethiopia, furrow irrigation is widely used because of its low cost and energy requirement as compared to pressurized irrigation systems (sprinkler and drip irrigation systems) which are usually more efficient than the furrow irrigation (Koech and Langat, 2018).

Furrow irrigation is designed on the basis of soil, crop, topography, size and shape of the irrigated area. A furrow irrigation systems performance is influenced by various design elements. Many studies have demonstrated that improving irrigation management and field design can greatly enhance irrigation performance (Ali, 2011).

There were few attempts done to enhance furrow irrigation performance with improved irrigation water management in considering all furrow irrigation design parameters (Mazarei *et al.,* 2020). Performance evaluation is the systematic analysis of an irrigation system or management based on measurements taken under field conditions and practices normally used and comparing the same with an ideal one. Traditionally, irrigation assessment is conducted to evaluate the performance of existing irrigation systems. A full irrigation evaluation involves an assessment of the water source characteristics, pumping, distribution system, storage system and field application systems. However, assessments are also conducted on several components on farm irrigation system. The performance of an irrigation system at field scale depends on several design variables, management variables and system variables. In general, a set of indicators are used for evaluating the performance of an irrigation scheme. The irrigation performance indicators are classified as engineering, field water use, crop and water productivity and socio economic indicators (Adane *et al.,* 2020).

The performance of furrow irrigation system is very low as compared to pressurized systems. Performance of surface irrigation systems can be assessed by their performance indices, such as advance and recession time (Mazarei and Mohammadi, 2019). There are three approaches for modeling the advance and recession phases in surface irrigation system. These are fully hydrodynamic models, volume balance models and empirical models (Valipour, 2012). Furrow irrigation system should be designed in such a way to ensure an adequate and uniform water application over the fields and to minimize the potential water losses. Many researchers in this field have engaged in optimizing the design of furrow irrigation systems to improve its performance (Mamuye and Mekonen, 2015; Akbar *et al.,* 2016).

Water use efficiency and water productivity indicators are used to evaluate the irrigation performance and its variability between irrigation systems and crops. Improving irrigation efficiency has been the most common approach by engineers to save water but higher irrigation efficiency can lead to increase area under irrigation due water saving which in turn result in an increased consumptive water use (Zhuo and Hoekstra, 2017). Improved efficiency in irrigation system design can help to reduce the amount of irrigation water applied and hence, reducing water logging and salinity problems while at the same time satisfying crop water requirement. Efficient application and uniform distribution of water by furrow irrigation is dependent on furrow parameters such as inflow, field slope, soil infiltration rate, roughness coefficient, field shape and irrigation water management (Assefa, 2017).

In principle, irrigation is required when rainfall is insufficient to compensate the amount of water lost by crop evapotranspiration. To accurately apply the amount of water required without excess or stress, irrigation scheduling one of the most methods of irrigation management. Hence, proper irrigation scheduling based on timely measurements or estimations of soil moisture content and crop water needs believed as the most important practices for irrigation management. Irrigation scheduling plays an important role for improving water use efficiency, water productivity, growth and quality of sugarcane production (Singh *et al.*, 2020). Irrigation scheduling makes sure that water is consistently available to the plant and that is applied according to crop requirements. This indicates irrigation scheduling involves deciding when and how much irrigation water to be applied to the field. Good irrigation scheduling will apply water at the right time and in the right quantity in order to optimize production and minimize its adverse environmental impacts. A number of devices, techniques and computer methods are available to assist producers in determining when water is needed and how much is required (Gu *et al.*, 2017).

Irrigation scheduling requires local real time data because irrigation system design considers a historical record to evaluate the expected maximum capacity for water supply and delivery systems. On farm irrigation water requirements is very important for proper irrigation scheduling that used for water management strategies to prevent over application of water while minimizing yield loss due to water shortage or drought stress. Modern irrigation scheduling is based on the soil water balance for one or more points in the field (Ghaffar *et al.*, 2013). By estimating the future soil water content, irrigation can be applied before crop experience water stress. Hence performance evaluation of the existing irrigation practices is very important, because it helps to know whether any improvement options are required or not, to sustain the irrigation system and maintain the productivity of the crop. This is the main reasons why irrigation scheduling parameters depends on soil water holding capacity, irrigation method and crop water requirements. Irrigation scheduling is extremely important management practices for irrigators and helps to optimize irrigation water uses.

5.2. Statement of the Problems

Surface irrigation is the most widely used irrigation methods in sugarcane production in developing country. From the surface irrigation method, furrow irrigation is the most dominant method and which requires critical evaluation on large scale mechanization farms like Wonji Shoa Sugar Estate. Maintaining efficient and effective utilization of irrigation water in large scale irrigation schemes at an acceptable level is the major challenges. The main problems in such irrigation schemes are less consideration for uniformity of application and volume of irrigation water required at the time of irrigation based on crop water requirements, crop growth stages, soil type and climatic condition of the area. But efficient and adequate amount of irrigation water application may result in attaining potential crop yield and improve the water use efficiency of the crop. On the other hand, furrow irrigation is associated to many problems which resulted in low efficiency and less uniformity. The main causes of those problems in surface irrigation system are largely due to absence of careful design, inappropriate irrigation water management and maintenance practices specially, canal after the first season production and before the next season production (Eslamian *et al.,* 2017).

The major problems for the occurrence of poor performance of furrow irrigation system resulted from incorrect dimensioning of furrow and poor design including irrigation application (El-Hazek, 2016). As this author concluded, performance evaluation of irrigation water managements is generally useful to achieve the required efficiency before it leads to adverse effect of irrigation. Evaluation of existing irrigation system performance and improvements of existing irrigation system status can be conducted by different performance indicators. Performance indicators should be such that they can be empirically quantified, statistically tested (Akbar *et al.*, 2017). As the findings of many researchers concluded, performance of furrow irrigation is affected by a range of factors including the inflow discharge, soil infiltration characteristic, field length, required application depth, cutoff time, surface roughness and field slope. The main purpose of furrow irrigation performance evaluation is to achieve an efficient and effective use of irrigation water applied to the fields. Because, poor design and lack of suitable criteria for irrigation systems are generally responsible for uneven irrigation application leading to wastage of water, waterlogging and salinity problems specially in surface irrigation system (Eslamian *et al.*, 2017).

There are several conditions imposed the researchers to carry out performance evaluation of irrigation scheme and some of these are:

- When something is wrongly undertaken but the factors which cause it is not clearly known, which requires finding to know what are the causes for this
- When it required to know whether the existing situation is at good conditions or requires some improvement.
- When a researcher seeks to understand the detailed workings of an irrigation in order to draw generalized inferences about the performance of the irrigation scheme.

In Wonji Shoa Sugar Estate, the problem of water logging condition is the common problems that physically observed at the field condition even during the off-rainfall time. This condition definitely affects the performance of the furrow irrigation that dominantly used for sugarcane production under Wonji Shoa Sugar Estate climatic condition. Therefore, the current study was undertaken to know whether the performance of furrow irrigation as it at good or not under the current study area. In line with this, the current study was conducted on performance evaluation of existing furrow Irrigation water management practices at field condition and develop improvement option on the dominant furrow irrigation decision variables.

5.3. Objective of the Study

The general objective of this study was to evaluate the performance of current furrow irrigation water management practices and developing an improvement option

The specific objectives were:

- To evaluate the performance of current furrow irrigation water management practices under the current study area climatic condition.
- To identify the major problems that affect the performance of current furrow irrigation water management practices under study area.

5.4. Research Questions

To address the objective of the study, the following research questions are formulated:

- What is the performance of existing furrow irrigation water management practices at Wonji Shoa Sugar Estate?
- What are the major factors that affect furrow irrigation water management practices in the study area?

5.5. Significance of the Study

Appropriate irrigation water management and sustainability of the irrigation structure has been major challenge in irrigation schemes, especially under large scale basis. The management of irrigation water at large scale is not uniformly managed due to the difference in the knowledge of the irrigators in relation to crop water requirement and soil types. Efficient and adequate amount of irrigation water advances for crop production and elevate water use efficiency for future purposes. The aim of Irrigation water management is to keep the water level in the root zone within a range where crop yield and quality are not damaged due to either inadequate or excess water. Evaluation of the irrigation water management practiced at Wonji Shoa sugarcane production is very important because Wonji Shoa sugar Estate is one of the major sugar producers in the country. So, evaluating the performance of furrow irrigation water management is used to maintain the irrigation system and reduce the adverse effect of irrigation for future production in the area. Based on the outcome of this study with the standards, the irrigation scheduling can be continued or rescheduled for the future.

5.6. Material and Methods

5.6.1. Description of the study area

Wonji Shoa Sugar Estate (WSSE) is located in the South East Shoa Zone of Oromia Regional State, at a distance of 110 km from Addis Ababa, the capital city of Ethiopia. Geographically, it is situated at $8^{0}21$'- $8^{0}29$' N and $39^{0}12$'- $39^{0}18$'E and altitude of 1223 to 1550 m above MSL (Figure 5.1). The area is characterized by gentle and regular topography making it most suitable for irrigation. Sugarcane is grown in the area, mostly as a monoculture. The climate of the area is characterized as semi-arid with the main rainy season during the months of June to September. The rainfall of the area is erratic both in quantity and distribution. The area receives mean annual rainfall of 831mm with mean annual maximum and minimum temperature of 27 and 15^{o}C respectively. The soil of the area varies from sandy loam to heavy clay types.

The Estate is the first commercial large scale irrigation scheme in Ethiopia and was established in 1951 at Wonji by Netherland's Hender Verneering Amsterdam (H.V.A.) Company private investors and the Ethiopian government. When the factory started production in 1954 its initial production was 140 tons/day (WSSF, 2018). The two factories are known by the name Wonji and Shoa, Sugar Factory altogether had the capacity of producing 75,000 tons of sugar per year till recent time (prior to the completion of the new Wonji Shoa Sugar Factory at Dodota site far apart in the old factories). After serving for more than half a century and getting obsolete, the two factories viz., Wonji and Shoa sugar factories were closed in 2011 and 2012 respectively. Replacing these pioneer factories, the new and modern factory had started production in 2013 with higher production capacity. Currently, the WSSE sugarcane plantation covers and irrigated area of 12,000 ha of which 5,000 ha is managed by the Estate itself and 7,000 ha is managed by out-growers that dominantly produced using sprinkler irrigation systems. The irrigation water source is Awash River. The Wonji Shoa sugar Estate location map is presented in Figure 5.1.

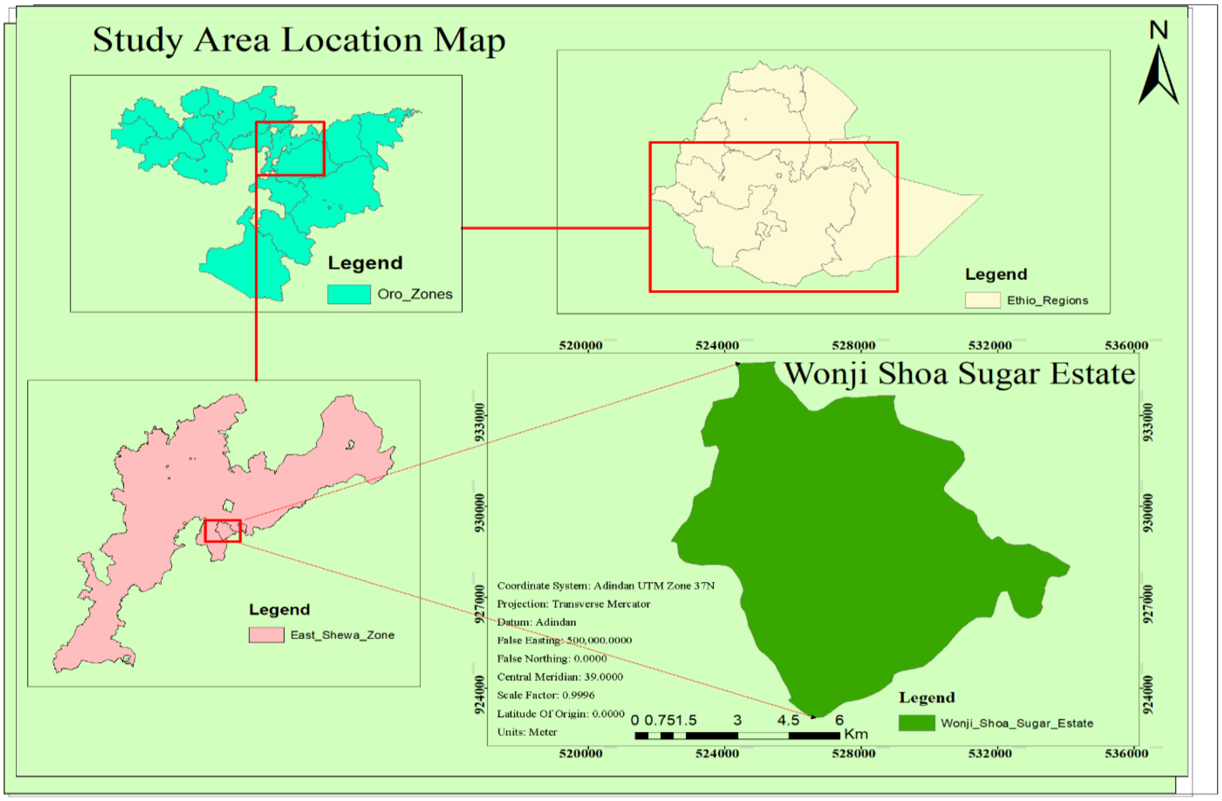

Figure 5.1. Location map of the study area

5.6.2. Experimentation

5.6.2.1. Field selection

To collect the required data, ten fields were selected with three different furrow lengths commonly used in the area (32, 48 and 64 meters). The furrow width is commonly 1.45 m for all furrow length. Those fields were selected purposefully based on their location difference in all directions by considering the soil type and furrow lengths. Even if those furrow lengths are commonly used in the study area, currently furrow length of 32 m is more dominantly used in all types of soils. Furrow length 48 m rarely used and 64m is obsoleted in the plantation fields but used only in ratoon fields during the study period (2019 to 2020). By considering these conditions, ten fields were purposively selected. Accordingly, five fields with 32 m furrow length, three fields with 48m furrow length and two fields with 64 m furrow length were selected in which data were taken from five furrow for all selected fields.

5.6.2.2. Water application methods

Irrigation water was applied to the field by furrow irrigation system. During the irrigation application, the water was diverted to the field ditches using controlled gates at the outlets of the secondary channel. The inflow rate applied to each furrow lengths (32, 48 and 64m) was 4.7 l/s under the conventional furrow irrigation currently practiced. After practically measured, the cutoff time for each furrow length were 9, 15 and 25 minutes respectively. This inflow rate was applied to each field during the three irrigation events and the performance of the irrigation evaluated before the implementation of the improvement options.

5.6.2.3. Data collection methods

Primary and secondary data were collected to evaluate the performance of the existing furrow irrigation practices in the study area. The primary data collected from the field during irrigation events include furrow geometry, furrow length, furrow width (top and bottom width), maximum flow depths and irrigation time were measured at field condition using meter tape and a ruler. Advance, recession and cutoff time were recorded using a stop watch at 16 m intervals for all fields and furrow lengths. The selected fields, furrow lengths, soil texture and cane types are given in Table 5.1.

Table 5.1. Selected fields for the performance evaluations

S/No	Field number	Furrow length (m)	Soil type	Cane type
1	15	32	clay	1st Ratoon
2		48	clay	1st Ratoon
3		64	clay	2st Ratoon
4	16	48	clay	Plantation
5	42	32	Silty	Plantation
6	80	32	Silty	Plantation
7		48	Silty	Plantation
8	102	32	Silty	2nd Ratoon
9	264	64	Silty	3rd Ratoon
10	279	32	clay	Plantation

5.6.4. Soil sample collection and analyses

Soil samples were collected at two soil depths (0-30 and 30 – 60 cm) of representative fields to determine soil bulk density, soil textures and soil moisture content. Soil sample was analyzed in the laboratory at Wonji Shoa Sugar Research and Development Center. The soil moisture content at field capacity and permanent wilting point of the selected fields were taken from the center because it was done very recently by Sugar Research and Development at Wonji center in 2017. The soil parameters were analyzed following standard laboratory procedures and manual (Bashour and Sayegh, 2007).

The soil sample was taken at 16m intervals along the furrow for all fields from the specified depths of sampling and soil moisture was determined using gravimetric methods. The soil samples were taken from inside furrow before and after irrigation water application from two to three days based on the soil types. The soil samples were taken by soil core sampler and then the soil wet weight was weighted using movable sensitive balance immediately after the sample taken. The samples were then oven-dried at 105°C for 24 hours. The dried weight of the soil sample was again weighted to calculate the volumetric moisture content using (Equation 5.1) (Bashour and Sayegh, 2007).

$$\theta_v = \left[\left(\frac{W_w - W_d}{W_d}\right) \times \text{Di} \times 100\right] \times \text{As} \qquad 5.1$$

Where: θv = volumetric soil moisture content (% volume bases), Ww = wet weight of the soil (g), Wed = dry weight of the soil (g), Di = Sampling depth (cm), As = apparent specific gravity (-)

The water holding capacity of the soil was analyzed by computing the total available water and readily available water using (Equation 5.2 and 5.3) (FAO, 2020).

$$TAW = 1000(\theta_{FC} - \theta_{PWP}) \times D_i \qquad 5.2$$

$$RAW = \rho \times TAW \qquad 5.3$$

Where: TAW = the total available soil water in the root zone (mm), θ_{FC} = the soil water content at field capacity (m^3/m^3), θ_{PWP} = the soil, water content at wilting point (m^3/m^3), Di = the rooting depth (m), ρ = soil moisture depletion fraction (%).

The required depth of irrigation (Zreq), depth of water stored in the soil profile of the root zone (Ds) and the total depth of water applied to the field (Da) were calculated using (Equation 5.4 –5.6).

$$Z_{req} = \sum_{i=1}^{n} 10(\theta_{FC} - \theta_{mi}) \times AS_i \times D_i \qquad 5.4$$

Where: Z_{req} = Amount of water required to fill the root zone to field capacity (mm), θ_{FC} = Soil moisture content at field capacity (%), θ_{mi} = Present soil moisture content (%), AS_i = apparent specific gravity of the soil (unit less), D_i = effective root depth (m), n = number of sampling depth in the root zones

$$D_s = \sum_{i=1}^{n} \frac{(M_{ai} - M_{bi})}{100} \times AS_i \times D_i \qquad 5.5$$

$$D_a = \frac{\bar{Q} \times \Delta t}{A} \qquad 5.6$$

Where: Mai = Moisture content of i^{th} layer of the soil after irrigation on a dry weight basis (%), Mbi = Moisture content of i^{th} layer of soil before irrigation on dry weight basis (%), $\bar{Q}$ = average discharge to furrow during the irrigation (m^3/s), Δt = duration of the irrigation (s), A= furrow irrigated area (m^2)

The depth of water percolating below the root zone is the amount of water infiltrated minus the water extracted by the plant roots to meet its evaporation demands. Or this means deep percolation is the difference in amount of water applied to satisfy the crop water requirement and amount of water excess applied or lost before the crop conception. This is computed using the soil water balance analysis. This depth of water can be computed experimentally in different methods like lysimeter but for the current study it was computed from the soil moisture analysis (Equation 5.7)

$$D_p = \theta_i + I_d + R_d - \theta_{FC} - ET \qquad 5.7$$

Where: Dp = depth of water deep percolated (mm/day), θ_i = initial soil moisture content (mm/m), Id = depth of irrigation applied (mm), Rd = depth of available rainfall (mm), θ_{FC} = soil moisture content at field capacity and ET = evapotranspiration (mm/day)

The soil infiltration function is one of the most important parameters in the surface irrigation system performance evaluation. There are different infiltration functions developed so far that can be used based on some preferences of the users according to available input data and required outputs. The infiltration function is empirically determined to yield the relationship between the infiltrated water and the opportunity time (the time during which the water contact the soil). One of the empirical infiltration models which is widely used for surface irrigation design and operation is Kostiakov's infiltration model (Kostiakov, 1932) which was later modified as Kostiakov-Lewis's equation. The power type Kostiakov function is the most widely accepted to describe the infiltration characteristics (Equation 5.8).

$$Z = Kt^{a} \qquad 5.8$$

Where: Z = is the infiltrated water (m^3/m), k is infiltration constant ($m^3/min/m$), a is empirical parameters (-) t is intake opportunity time (min).

To overcome the shortage of kostiakov equation, the constant term added to the original equation of kostiakov equation. The modified kostiakov equation known as Kostiakov-Lewis equation adds a parameter fo to account for the basic infiltration rate in more permeable soils where infiltration does not tend to zero over time given by equation 5.9

$$Z = Kt^{a} + f_{o}t \qquad 5.9$$

Where: *fo* is basic (constant) infiltration rate ($m^3/m/min$) and others are as defined in Eq 5.8.

Zero inertia model is based on the understanding that flow velocities encountered in surface irrigation is very small and changes in velocity with respect to time and space are virtually non-existent. Under most surface irrigation conditions, inertia terms in the Saint-Venant equations are negligible when compared to the force terms (heat and friction). The zero inertia models are a simplified form of the full hydrodynamic model without the acceleration and inertia terms which is given by Equation 5.10 (Zayton, 2015).

$$\frac{\delta y}{\delta x} = S_{o} - S_{f} \qquad 5.10$$

Where: y = depth of flow (m), x = distance along the field length (m), S_0 = longitudinal slope of the field (m/m), S_f = Slope of energy grade line (friction slope) (m/m)

5.6.5. Performance evaluation of furrow irrigation

The irrigation performance evaluation provides an overview of the extent to which the irrigation meets the water requirements and the applied water is distributed uniformly throughout the field. The most common performance evaluation criterion is application efficiency, deep percolation ratio, tailwater ratio, distribution uniformity, and water requirement efficiency. But for the performance evaluation of close ended furrow irrigation conditions, application efficiency, deep percolation, and distribution uniformity are commonly used. In general, to improve irrigation performance, mathematical models of the surface irrigation processes have been developed in the last decades. Developed models consider several variables, including field geometries, slope, hydraulic roughness, furrow discharges and irrigation time. The interaction among these variables determines the advance times, recession times and infiltrated water depth, which in turn influence performance indicators such as application efficiency and uniformity of water distribution along the furrow. These selected parameters were evaluated by measuring the required data from the field and simulated using the WinSRFR model. The performance of furrow irrigation is evaluated interms of application efficiency, distribution uniformity and deep percolation parameters mathematically determined using Equation 5.11 – 5.13 (Mazarei *et al.,* 2020).

$$AE = \frac{D_S}{D_a} \times 100 \qquad 5.11$$

$$DU = \frac{D_{min}}{D_a} \times 100 \qquad 5.12$$

$$DP = \frac{D_p}{D_{aver}} \times 100 \qquad 5.13$$

Where: Ds = depth of soil moisture stored in the root zone (mm), D_a = total depth applied to the furrow (mm), D_{min} = minimum depth of water infiltrated in the field (mm), D_{aver}. = mean of depths infiltrated over the furrow length (mm)

To improve the performance of the furrow irrigation, two decision variables considered were cutoff time and in flow rate. The procedures adopted are as follows:

Step one: all decision variables under current practices were used to evaluate the performance

Step two: inflow rate was reduced while the cutoff time were kept constant

Step three: cutoff time was increased while the inflow rate were kept current practices

Step four: cutoff time was decreased while the inflow rate were kept current practices

Step five: combination of improved decision variables (reduced inflow rate and increased cutoff time) from the current practices

Based on the weighted factors of the performance indicators of furrow irrigation which was computed using (Equation 5.13) and the maximum values used as the decision variables to improve the performance of the irrigation (Mazarei *et al.*, 2020).

$$OP = (\alpha \times AE) + (\beta \times DU) - (\gamma \times DP) \qquad 5.13$$

Where: Correction factors for the parameters $\alpha = \beta = \gamma = 0.33$, this indicates the weighted factor ($\alpha + \beta + \gamma = 1$)

5.6.6. Input data for WinSRFR model

The functionality and organization of WinSRFR were defined based on the analytical process typically followed in assessing and improving the hydraulic performance of surface irrigation systems. WinSRFR model was one of the performance evaluation models used to assess the performance of irrigation to know whether the irrigation was at good conditions or requires improvement. All required data for the WinSRFR model was collected from the field with close ended furrow irrigation system. These data were required depth of irrigation, furrow geometry, advance, cutoff and recession time of irrigation. These data were collected from the selected fields. The soil samples were taken from the field and analyzed to determine the required depth of irrigation. The furrow geometry was measured at constant intervals along the furrow. The advance, cutoff and recession time were recorded during the three irrigation events. There are several efficiency terms which are used to evaluate irrigation system performance. But for this study, application efficiency, distribution uniformity and deep percolation were used. The major input parameters for the simulation are presented in Table 5.2.

Table 5.2. Input parameters for the WinSRFR simulation model

Furrow geometry	Input depending on furrow lengths		
Furrow length (m)	32	48	64
Furrow spacing (m)		1.45	
Average Furrow bottom width (m)	0.31	0.32	0.32
Irrigation system	Surface (Furrow irrigation)		
Down steam condition		Closed ended	
Furrow slope (m/m)		0.05	
Manning roughness n values based on the crop growth nature		0.15	
Types of simulation model		Zero inertia	
Flow parameters (in the existing situation)			
Furrow inflow rate (l/s)		4.7	
Cutoff time depending on the furrow length (min)	9	15	25
Infiltration function	Modified Kostiakov equation		
Changed decision variables (Improvement options)			
Furrow inflow rate (L/s)		3.5	
Cutoff time (min.)	11	18	31

5.6.7. Statistical indices used to measure model performance

Measured and simulated performance indicators were evaluated using the statistical indices. To test the goodness of fit between measured and simulated values different statistical indices were used (Mazarei *et al.,* 2020).

5.6.7.1. Coefficient of determination (R^2)

The coefficient of determination is used to measure the model goodness of fit. In WinSRFR model, R^2 is an indicator of the efficiency of the model in comparing the measured values with the simulated values. The values of coefficient of determination ranges $0 \leq R^2 \leq 1$ and the model can be accepted if the value is greater than 0.6. It explains the amount of variance explained by the model in comparison to the measured values (Equation 5.14).

$$R^2 = \left[\frac{[\sum_{i=1}^{n}(M_i - \bar{M})(S_i - \bar{S})]}{\sum_{i=1}^{n}(M_i - \bar{M})^2 x \sum_{i=1}^{n}(S_i - S)]^2}\right]^2 \qquad 5.14$$

Where: n = number of observations, M_i = in^t value of the measurement, S_i = ith value of the simulated, $\bar{M}$ = mean of the measured values, $\bar{S}$ = mean of values simulated

5.6.7.2. Root mean square error (RMSE)

Root mean square error is a measure of the overall deviation between measured and simulated values. The root mean square error has a minimum value of 0 and the values closer to 0 indicate the better model performance (Equation 5.15)

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M)^2}{n}} \qquad 5.15$$

5.6.7.3. Index of agreement (IA)

Index of agreement is another statistical index used to measure the model efficiency. The value of IA varies from -∞ to +1. The closer the value to +1 indicates the simulated values better than the measured values (Equation 5.16) (Davis *et al.*, 1985).

$$\mathrm{IA} = 1 - \left[\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{(\sum_{i=1}^{n}|S_i - \bar{S}| + |M_i - M|)^2}\right] \qquad 5.16$$

5.7. Results and Discussions

5.7.1. Soil physical properties

The soil samples taken from each field were analyzed at Wonji Shoa sugar research and development center. The results obtained indicated that the average soil bulk density of the fields ranged from 1.49 to 1.60 for the upper depth (0-30 cm) and 1.59 to 1.70 g/cm^3 for lower depth (30-60 cm) but the recommended soil bulk density of the Wonji Shoa ranges from 1.5 to

1.7 g/cm^3 from 0-30 and 30-60 cm depth respectively. The detail physical properties of the fields considered are given in Table 5.3.

Table 5.3. Analysis of selected soil parameters for the selected fields

Field No	Furrow length (m)	ρ_b (g/cm^3)		Soil texture	θ_{FC} (%)		θ_{PWP} (%)		θi (%)	
		0-30	30-60		0-30	30-60	0-30	30-60	0-30	30-60
15	32	1.53	1.64	Clay	48.50	51.90	21.60	22.4.	40.29	41.82
42		1.55	1.64	Silt	49.10	49.70	28.60	27.20	41.18	42.87
80		1.54	1.62	Silt	48.50	51.90	21.60	22.40	41.15	42.12
102		1.51	1.60	Silt	49.10	49.70	28.60	27.20	40.03	41.09
279		1.55	1.66	Clay	49.10	49.70	28.60	27.20	40.72	44.25
15	48	1.60	1.70	Clay	48.50	51.90	21.60	22.40	42.77	43.30
16		1.50	1.62	Clay	50.50	54.90	24.20	24.40	44.30	45.02
80		1.55	1.60	Silt	48.50	51.90	22.40	21.73	40.59	43.93
15	64	1.50	1.59	Clay	48.88	51.16	21.98	22.28	40.41	42.59
264		1.49	1.61	Silt	48.88	51.16	21.98	22.28	41.36	42.68

ρ_b = bulk density, θ_{FC} = soil moisture content at field capacity, θ_{PWP} = moisture content at the permanent wilting point, θi = present soil moisture content

The result obtained from the selected soil parameters revealed that the soil parameters analyzed were within the range of the analysis obtained in the previous study by the center. But the bulk density in upper depth indicated a little variation which is greater than the previous study by the center and this may be due to the compaction of the soil by agronomic operation and repeated irrigation.

5.7.2. Advance and recession time

For each furrow length considered, the advanced and recession time was measured during the three irrigation events. The measured advanced and recession time was simulated using the WinSRFR model. Whether the time allotted for irrigation is greater than or less than the required time for each furrow length during three irrigation events were evaluated. The results of the measured and simulated irrigation time are presented in Table 5.4.

Table 5.4. Measured and simulated irrigation time under current irrigation practices

IEs	FL (m)	Q (l/s)	Tco (min)	Advance time (min)		Recession time (min)	
				Measured	Simulated	Measured	Simulated
1	32	4.7	9	10	8	37	33
	48	4.7	15	17	14	58	39
	64	4.7	25	28	23	68	47
2	32	4.7	9	16	15	54	39
	48	4.7	15	19	17	60	42
	64	4.7	25	28	26	57	41
3	32	4.7	9	10	7	38	37
	48	4.7	15	17	12	58	43
	64	4.7	25	29	28	61	47

IEs = irrigation events, FL = furrow length, Tco = cutoff time

The results in the Table 5.4 show that cutoff time is slightly shorter than advance time which seems to be against the practice, i.e., cutoff time is the sum of advance time and ponding time. However, the current on-farm practices fail to follow this principle. The reason could be that the irrigators consider such a high inflow rate on a clayey soil could meet the ponding required at the end of the furrow even if the inflow is cutoff before reaching the end. They might have also observed the risk of overtopping of the furrows due to massive tailwater reaching the end of furrows if early cutoff is not practiced. Such exercises are credited to the field irrigators which sounds to be acceptable.

There was less variation between the measured advanced time for furrow length 32 and 64m during second and third irrigation events. But there was significant variation in furrow length 48 and 64m during all irrigation events. The variation between measured and simulated advance time was high in furrow length 48 and 64 m but less in furrow length 32m during the overall irrigation events. This indicates when the variation is very high the time allocated for irrigation is not an accurate and less variance indicated that the allocated time for irrigation was more accurate. In case of recession time, in all furrow lengths, the simulated recession time was lower than the measured recession time, which indicates irrigation water applied stagnated on the surface of the land for a long period (Table 5.4). The variation was significantly high in furrow length 64 m followed by 48m and relatively less in 32m. The current study was similar to the study conducted by Mazarei *et al.,* (2020) which indicates the better agreement between measured and simulated for advance time than the recession time. Similarly, the study conducted by Ali and Mohammed (2015) indicates similar result with the current study. Also, the other study conducted by Pascual *et al.* (2013) indicated low variation in advance and recession time between measured and simulated values.

5.7.3. Performance evaluation of furrow irrigation

Performance evaluation of furrow irrigation was done based on the measurement undertaken on selected furrows as described in the methodology section. WinSRFR model was used to simulate the measured data whether they were best fitted or not. The results are presented in Table 5.5 with detail results for each field and furrow lengths in appendix table 5.1. The measured and simulated application efficiency, distribution uniformity and deep percolation were compared across the furrow length considered and compared to the standard ranges of recommendation for furrow irrigation (Irmak *et al.,* 2011). The overall average values of measured and simulated application efficiency and deep percolation performance of the current furrow irrigation practices showed poor but distribution uniformity of the irrigation was relatively good for all furrow lengths.

Table 5.5. Measured and simulated performance indicators under current furrow irrigation

IEs	FL (m)	Q(l/s)	T_{co} (min)	AE (%)		DU (%)		DP (%)	
				Meas.	Sim.	Meas.	Sim	Meas.	Sim.
1	32	4.7	9	48.4	43.2	85.8	83.2	51.6	56.8
	48	4.7	15	52.0	43.7	79.3	73.0	48.0	56.3
	64	4.7	25	45.0	55.5	90.5	70.0	55.0	44.0
2	32	4.7	9	44.2	46.6	87.2	80.6	55.8	53.4
	48	4.7	15	49.7	48.0	82.7	64.7	50.3	52.0
	64	4.7	25	49.0	49.0	91.0	62.5	51.0	51.0
3	32	4.7	9	46.0	53.2	89.0	77.2	54.0	46.8
	48	4.7	15	54.0	53.7	81.7	67.7	46.0	46.3
	64	4.7	25	41.5	41.5	88.0	69.5	48.5	58.5

IE = Irrigation events, FL = Furrow length, Q = Inflow rate, Tco = cutoff time, Meas. = Measured, Sim = simulated, AE = Application efficiency, DU = Distribution Uniformity, DP = Deep percolation

The average application efficiency obtained from three irrigation events were 46, 52 and 48% for furrow length 32, 48 and 64m respectively. The performance of furrow irrigation under the current irrigation practices showed poor.

Application efficiency for furrow length 32 and 64 m was less than the recommendation during all irrigation events. But relatively, furrow length 48m was within the recommendation ranges for all irrigation events. However, the distribution uniformity for furrow length 48m was less than the furrow length 32 and 64m in all irrigation events. In term of irrigation distribution uniformity, furrow length 64m was very good followed by furrow length 32 and 48m respectively. On the other hand, the deep percolation was greater than the recommendation ranges for furrow length 32 and 64m but for furrow length 48m during all irrigation events showed within the recommendation ranges (Table 5.6). High deep percolation implies that more amount of irrigation water was lost before the crop conception.

To improve the performance of furrow irrigation, decreasing the inflow rate and increasing the cut off time or vice-versa is the main options. In line with this, for the first alternatives to improve the performance of the irrigation, the irrigation water applied was reduced by 25% from the normal irrigation water inflow rate used (28 l/s for six sets of furrows at one time) in the current irrigation practices. After this reduction of inflow rate, the furrow irrigation performance was computed for all furrow lengths during all irrigation events. The measured and simulated performance indicators of the furrow irrigation after the inflow rate reduced were improved (Table 5.6, appendix table 5.2).

Table 5.6. Measured and simulated performance by reducing inflow rate from 4.7→3.5 l/s

IEs	FL (m)	Varying Q (l/s)	T_{co} (min)	AE (%)		DU (%)		DP (%)	
				Meas.	Sim.	Meas.	Sim	Meas.	Sim.
1	32	3.5	9	61.0	44.0	85.8	81.4	39.0	56.0
	48	3.5	15	59.0	57.7	79.3	63.7	41.0	42.3
	64	3.5	25	60.0	59.5	90.5	51.5	40.0	40.5
2	32	3.5	9	61.0	62.0	85.8	74.2	41.0	38.0
	48	3.5	15	60.0	57.3	89.7	57.7	40.7	42.7
	64	3.5	25	65.5	64.0	91.0	49.5	34.5	36.0
3	32	3.5	9	56.8	62.6	83.0	71.2	43.2	37.4
	48	3.5	15	68.3	69.3	81.7	56.7	31.7	30.7
	64	3.5	25	56.0	56.0	88.0	59.5	44.0	44.0

As can be seen from the results, decreasing the inflow rate of 4.7 l/s (current irrigation practices) to 3.5 l/s showed an improvement of furrow irrigation performances. From the furrow irrigation performance indicators considered, application efficiency (AE) was improved by 29.0, 20.2 and 33.8% for furrow length 32, 48 and 64 m respectively. Similarly, deep percolation (DP) was reduced by 23.6, 21.4 and 23.3% for the same furrow lengths. The result showed that by only reducing the inflow rate, AE and DP were significantly improved by but distribution uniformity did not show significant changes.

In the second alternative, irrigation cutoff time was changed by keeping the other variables as constant as same to the existing practices. In this scenario, the cutoff time was decreased by 2, 4 and 6 minutes for furrow length 32, 48 and 64m respectively from currently practiced. The performance of the furrow irrigation was improved as compared to the current furrow irrigation performance. As can be seen from Table 5.7, irrigation performance of the furrow lengths considered were improved (Appendix table 5.3).

Table 5.7. Measured and simulated performance indicators by varying (reducing) cutoff time

IEs	FL (m)	Q (l/s)	Varying T_{co} (min)	AE (%)		DU (%)		DP (%)	
				Meas.	Sim.	Meas.	Sim	Meas.	Sim.
1	32	4.7	7	66.0	67.6	85.8	68.0	34.0	32.4
	48	4.7	12	68.3	69.3	81.7	56.7	31.7	30.7
	64	4.7	19	56.0	56.0	88.0	59.5	44.0	44.0
2	32	4.7	7	61.0	65.2	87.2	68.8	33.0	36.8
	48	4.7	12	68.3	68.7	82.7	51.3	31.7	31.3
	64	4.7	19	69.5	71.5	91.0	41.5	30.5	28.5
3	32	4.7	7	63.0	66.4	89.0	67.2	39.0	33.6
	48	4.7	12	71.0	70.7	81.7	50.7	29.0	29.3
	64	4.7	19	64.5	63.5	88.0	53.5	35.5	36.5

The results presented in Table 5.7 revealed that, the performance of furrow irrigation was improved by changing only cutoff time by keeping the other parameters constant. By reducing cutoff time from the current practices, application efficiency was improved by 37.0, 33.3 and 40.0% from the current practices for furrow length 32, 48 and 64 m respectively. Also, deep percolation was significantly improved by 34.4, 35.9 and 28.7% for the same furrow lengths but distribution uniformity was only slightly changed during all irrigation events. But, the performance of furrow irrigation was not significantly improved by increasing cutoff time under the current furrow inflow rate condition.

Finally, the performance of furrow irrigation was evaluated by varying both inflow rate and cutoff time from the current irrigation practices. In furrow irrigation, performance can be improved by reducing the discharge rate and increasing the cutoff time or vice-versa. But in relation to irrigation water resource concern, reducing discharge rate and increasing cutoff time is more preferable. In the current study, the discharge rate was reduced from 4.7 to 3.5 l/s and cutoff time increased by from 9 to 11, 15 to 19 and 25 to 31minutes for furrow length 32, 48 and 64m respectively. By combining those two decision variables, the performance of furrow irrigation in all furrow lengths during the three irrigation events were improved. The measured maximum and minimum optimized values were 47.69 and 41.30% recorded from furrow length 64 and 32m during the first and second irrigation events respectively. The overall mean optimized values obtained by changing discharge rate and cutoff time were 32.7, 34.9 and 32.6% for furrow length 32, 48 and 64m respectively during the three irrigation events (Table 5.8, Appendix table 5.4)).

Table 5.8. Measured and simulated performance under varied inflow rate and cutoff time

IEs	FL (m)	Q (l/s)	T_{co} (min)	AE (%)		DU (%)		DP (%)		OP (%)	
				Meas	Sim	Meas	Sim	Meas	Sim	Meas	Sim
1	32	3.5	11	68.2	67.6	85.8	68.4	31.8	32.4	46.9	40.8
	48	3.5	19	77.0	77.7	81.0	49.7	23.0	22.3	44.6	34.7
	64	3.5	31	77.0	76.5	90.5	34.5	23.0	23.5	47.7	28.9
2	32	3.5	11	68.4	68.6	87.2	69.8	31.6	32.4	41.3	35.4
	48	3.5	19	76.3	78.0	82.7	42.7	23.7	22.0	44.7	32.6
	64	3.5	31	74.5	76.5	91.0	35.5	30.5	23.5	44.6	29.1
3	32	3.5	11	63.4	62.2	89.0	67.8	36.6	37.8	44.8	37.0
	48	3.5	19	77.7	74.7	81.7	54.0	22.3	25.3	45.2	34.1
	64	3.5	31	76.5	78.5	88.0	38.0	23.5	21.5	46.5	31.4

OP = optimized values of performance indicators

As can be seen from the results given in Table 5.8, the performance indicators of furrow irrigation were improved by reducing inflow rate and increasing cutoff time from the current practices. In doing so, AE was improved by 32.7, 34.9 and 32.6% for furrow length 32, 48 and 64 m respectively. Similarly, DP was improved by 38.1, 30.8 and 25.8% for the same furrow lengths but DU was not significantly improved. The trends in of application efficiency, distribution uniformity and deep percolation depicted in the following subsections.

5.7.3.1. Application efficiency

For well designed and managed furrow irrigation, the standard ranges of furrow irrigation application efficiency recommended is 50-70% but can be more based on soil types and management practices (Griffiths, 2007). The performance evaluation of three furrow lengths for the three irrigation events were evaluated based on the current irrigation practices that showed poor performance. As an improvement options, by varying the decision variables separately and combining together, application efficiency was improved under each scenario. When the average measured application efficiencies of the three furrow lengths in the overall three irrigation events at the current practices compared, a furrow length of 48 m was performing better than 32 and 64 m. From the current study findings, it can be concluded that based on the average measured values, only furrow length 48 m slightly fulfil the recommendation for furrow irrigation application efficiency. This indicated that the performance of the current furrow irrigation practices based on application efficiency showed poor performance.

Based on the current furrow irrigation application performance, when the decision variable varied separately and combining the best performing decision variables, application efficiency of furrow irrigation was significantly improved. But the improvement of furrow irrigation application efficiency was high when the reduced inflow rate and increased cutoff time are combined than the separated decision variables.

The measured data was simulated using WinSRFR model similarly showed as the combined decision variables significantly improves the furrow irrigation application efficiency then the separated decision variables. When the three furrow lengths compared in terms of application efficiency, furrow length 48 m performed better than 32 and 64 m. The application efficiency was compared in all scenarios for all furrow lengths during the three irrigation events were presented in Figure 5.2.

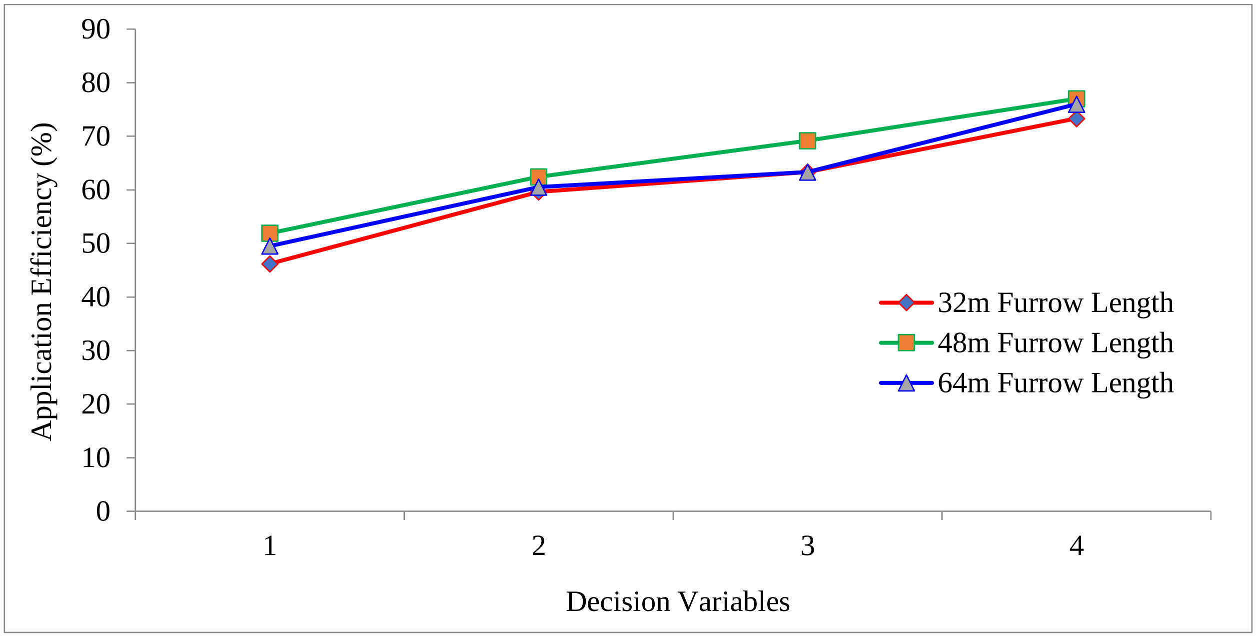

Figure 5.2: Average Application efficiency of furrow irrigation under varied decision variables

Keys:

1: Current practice (inflow rate = 4.7/s, cutoff time 9, 15 and 25 minutes for furrow lengths 32, 48 and 64 m respectively)

2: Reduced inflow rate (Q = 3.5l/s), cutoff time 9, 15 and 25 minutes for furrow lengths 32, 48 and 64 m respectively)

3 = Current inflow rate (4.7 l/s) and reduced cutoff time 7, 12 and 19 minutes for furrow lengths 32, 48 and 64 m respectively)

3 = Combination of reduced inflow rate (3.5 l/s) and increased cutoff time 11, 19 and 31 minutes for furrow lengths 32, 48 and 64 m respectively)

The current study findings are similar to the finding of Shumye and Singh (2018) which revealed that the application efficiency of furrow irrigation highly dependent on the decision variables, specially discharge applied in relation to the cutoff time. Similar to the current study, the other study findings by Mamo and Wolde (2015) indicated that the application efficiency of furrow irrigation significantly improved as the discharge applied varied but less when cutoff time changed. The findings by Taddesse *et al.* (2019) also showed the application efficiency of furrow irrigation obtained by changing the decision variable was higher than the current study findings as well as other related findings. From the field observation during the current experiment, the main reasons which resulted in lower application efficiency were mismanagement of irrigation water, which includes the loss of irrigation water after enter to the field ditches due lateral flow to the side furrows, time of irrigation application and lack of soil consideration for irrigation since all soil types irrigated similarly with same rate of irrigation application.

5.7.3.2. Distribution Uniformity

The achievable distribution uniformity for furrow irrigation was poor if it is less than 70%, good from 70-85%, very good 85-90 and excellent if greater than 90% (Irmak *et al.,* 2011). The distribution uniformity performance of furrow irrigation for all furrow lengths considered under the three irrigation events were presented in Figure 5.3. The distribution uniformity is considered as poor and the irrigation water applied was unevenly distributed if it is ≤ 60% and good if ≥ 80%. Based on these criteria, the values of distribution uniformity in all furrow lengths were found to be within the acceptable range. The result obtained by varying the decision variables showed no significant change in distribution uniformity of furrow irrigation as compared to the current practices. Similarly, the simulated values using WinSRFR model showed similar results with the measured values. When the average distribution uniformity from the three furrow lengths during all irrigation events are compared, better distribution uniformity was obtained from furrow length 64m and less distribution uniformity obtained from furrow length 48m (Figure 5.3).

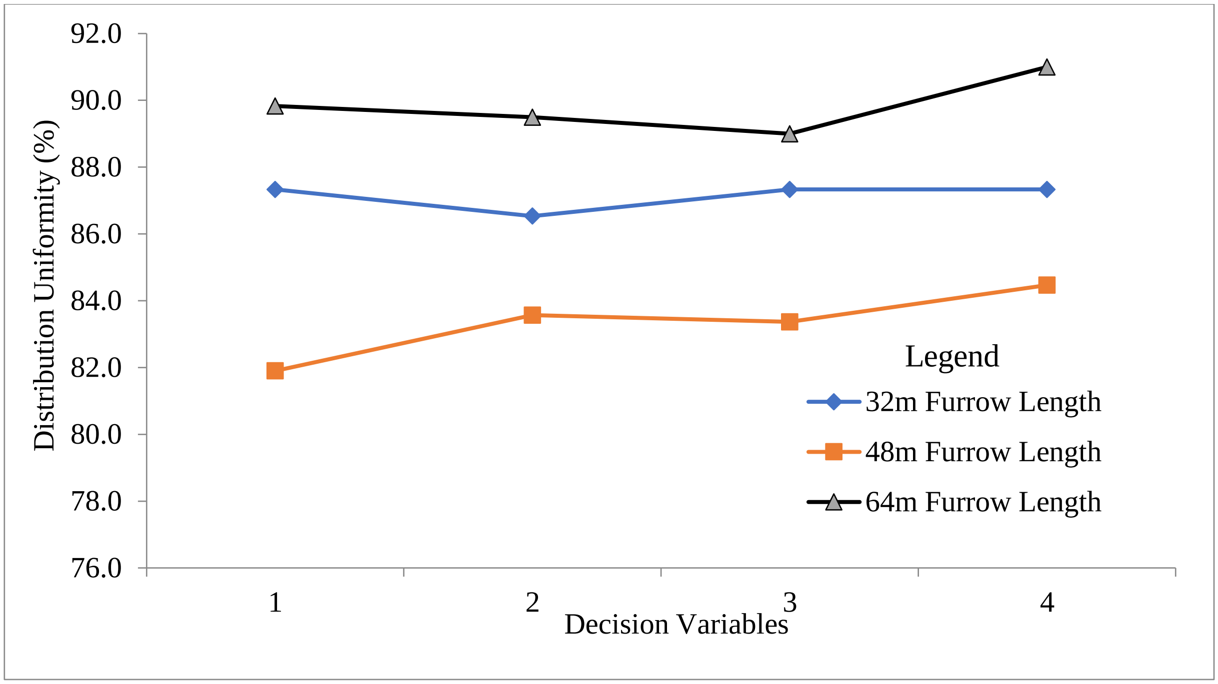

Figure 5.3: Average Distribution Uniformity under varied decision variables

Keys:

1: Current practice (inflow rate = 4.7/s, cutoff time 9, 15 and 25 minutes for furrow lengths 32, 48 and 64 m respectively)

2: Reduced inflow rate (Q = 3.5l/s), cutoff time 9, 15 and 25 minutes for furrow lengths 32, 48 and 64 m respectively)

3 = Current inflow rate (4.7 l/s) and reduced cutoff time 7, 12 and 19 minutes for furrow lengths 32, 48 and 64 m respectively)

3 = Combination of reduced inflow rate (3.5 l/s) and increased cutoff time 11, 19 and 31 minutes for furrow lengths 32, 48 and 64 m respectively)

The study findings by Pascual *et al.* (2013) indicates that the distribution uniformity of furrow irrigation was improved by changing inflow rate and cut off time but the improvement was not significant as that of application efficiency similar to the current study results. The other study findings conducted by Mazarei *et al.* (2020) indicated that the minimum distribution uniformity was obtained during low volume of irrigation applied to longer furrow length, but the distribution uniformity increased as the irrigation event increased but in the current study result indicated as the irrigation events increased the distribution uniformity was not linearly increased.

5.7.3.3. Deep percolation

For properly designed and managed furrow irrigation, a deep percolation value ranges from 30 to 50%, but as the values of deep percolation increased, it is not recommended since more of irrigation water applied is lost (Griffiths, 2007). From the existing irrigation practices, the maximum and minimum measured deep percolation was 58.5 and 46.0% from furrow length of 64 and 48m during the second and third irrigation event. From the simulated values using WinSRFR model, the maximum and minimum deep percolation obtained were 58.5 and 44.0% from furrow length 64m during third and first irrigation events.

In case of deep percolation, as the furrow irrigation decision variable varied, deep percolation of furrow irrigation was significantly improved similar to application efficiency. When the decision variables separately varied, the deep percolation was significantly reduced for all furrow lengths. But, more improvement of deep percolation was obtained when the reduced inflow rate and increased cutoff time combined together similar to that of application efficiency.

Also, when the measured data simulated using WinSRFR model, deep percolation was showed similar results. The deep percolation performance of furrow irrigation for all furrow lengths considered under the three irrigation events were presented in Figure 5.4.

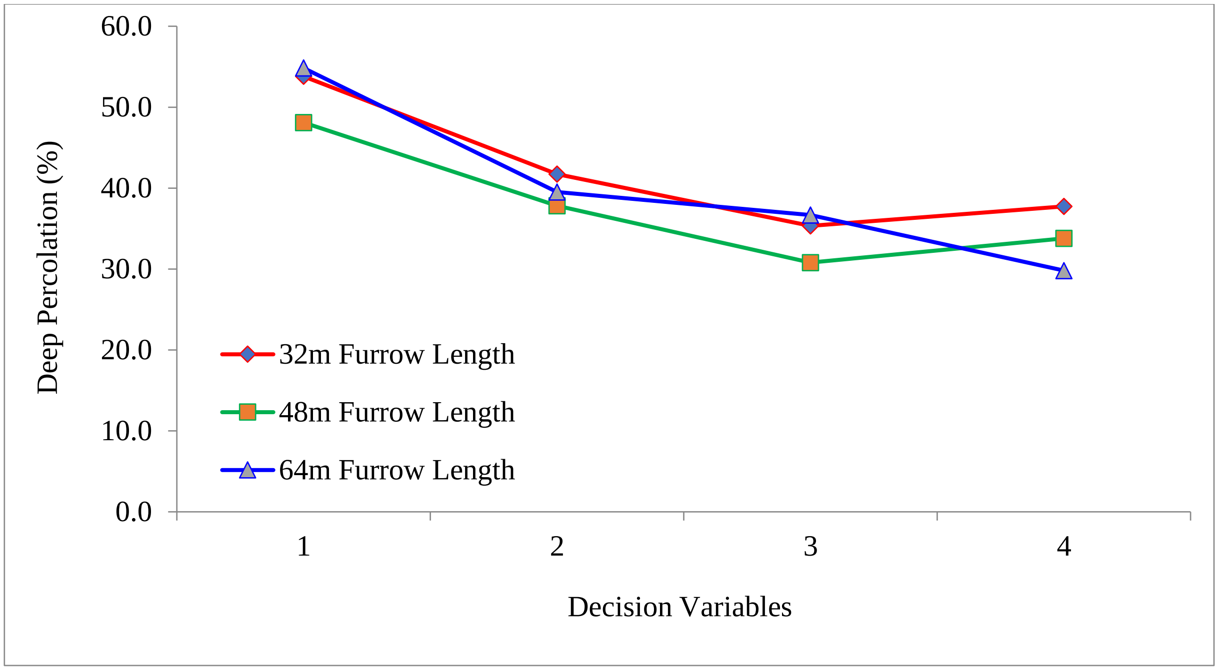

Figure 5.4. Deep Percolation performance under varied decision variables

Keys:

1: Current practice (inflow rate = 4.7/s, cutoff time 9, 15 and 25 minutes for furrow lengths 32, 48 and 64 m respectively)

2: Reduced inflow rate (Q = 3.5l/s), cutoff time 9, 15 and 25 minutes for furrow lengths 32, 48 and 64 m respectively)

3 = Current inflow rate (4.7 l/s) and reduced cutoff time 7, 12 and 19 minutes for furrow lengths 32, 48 and 64 m respectively)

3 = Combination of reduced inflow rate (3.5 l/s) and increased cutoff time 11, 19 and 31 minutes for furrow lengths 32, 48 and 64 m respectively)

The study findings by Mazarei *et al.* (2020) indicated that the deep percolation was improved by changing the decision variables and the values were within the range of recommendation for furrow irrigation. But in current study, the deep percolation was out of the recommendation ranges from the existing irrigation practices. However, similar to this study findings, the current study also showed an improvement by changing the decision variables. The other study findings conducted by Mamo and Wolde (2015) indicated that deep percolation was also within the acceptable range of all furrow lengths considered under the sugarcane field. Similar to this study, the current study result indicated that the computed values of deep percolation were within the acceptable range of all furrow lengths after the decision variables changed.

Generally, from this study, it can be concluded that there was a high loss of irrigation water applied in the form of deep percolation for all furrow lengths based on the existing irrigation practices in the study area.

5.7.4. Statistical analysis of advance and recession time

Advance and recession times were measured and simulated under different furrow lengths (32m, 48m, and 64m) and uniform furrow slopes (0.05%) for determining the possibility of using WinSRFR as a prediction tool of the furrow irrigation performance evaluation under Wonji Shoa climatic condition.

Based on the values of indices obtained from advance time, in terms of R^2 measured values were better than the model for furrow length 32m in all irrigation events. But for furrow length 48 and 64m model predicted values were better than the measured values for all irrigation events. In terms of RMSE, the model predicted values were better than the measured values in all furrow lengths during all irrigation events (Table 5.9).

Table 5.9. Statistical Indices of advance and recession time

IEs	FL (m)	Q (l/s)	Tco (min)	Advanced			Recession		
				Statistical Indices					
				R^2	RMSE	IA	R^2	RMSE	IA
1	32	4.7	9	0.01	0.00	0.83	0.80	0.02	0.99
	48	4.7	15	0.97	0.06	0.32	0.75	0.30	0.99
	64	4.7	25	0.99	0.00	0.99	0.99	0.32	-0.88
2	32	4.7	9	0.01	0.00	0.79	0.81	0.00	0.99
	48	4.7	15	0.97	0.06	0.68	0.96	0.17	0.99
	64	4.7	25	0.99	0.00	0.99	0.98	0.17	0.51
3	32	4.7	10	0.01	0.00	0.41	0.89	0.00	0.99
	48	4.7	15	0.99	0.06	0.10	0.84	0.21	0.99
	64	4.7	25	0.99	0.00	0.99	0.99	0.16	0.19

R^2 = Coefficient of determination, RMSE = Root mean square error, IA = index of agreement

As it can be seen from Table 5.9, generally for all statistical indices considered for advance time, the model prediction was better than the measured values. This indicated that the time allocated for irrigation was not accurate as required for almost all furrow lengths during all irrigation events. From the current study result, it can be concluded that, the applied discharge and cut off time should be reduced alternatively from the existing situation or increasing one decision variable and decreasing the other decision variable for all furrow lengths to obtain good performance efficiency of furrow irrigation.

5.7.5. Statistical analysis of furrow irrigation performance

The performance of current furrow irrigation was evaluated using selected statistical indices. Those statistical indices were used to evaluate whether the measured performance of the furrow irrigation was in a good agreement with the simulated values or not. To obtain the improved performance of furrow irrigation, the decision variables (discharge and cut off time) were changed alternatively from the existing irrigation practices. The computed performance from actually measured data during three irrigation events for all furrow length considered (32, 48 and 64m) were simulated using the WinSRFR model. There was a good agreement between measured and simulated values of furrow irrigation performance for almost all irrigation events for furrow length 32 and 64m but there was relatively a better agreement for furrow length 48m in terms of all statistical indices the agreement between the computed and simulated values of those irrigation performance considered were analyzed using statistical indices (Table 5.10).

Table 5.10: Statistical indices of current furrow irrigation performances

IEs	FL (m)	AE			DU			DP		
		Statistical Indices								
		R^2	RMSE	IA	R^2	RMSE	IA	R^2	RMSE	IA
1	32	0.72	0.62	0.62	0.26	0.86	0.41	0.15	0.80	0.89
	48	0.99	1.41	0.05	0.97	0.99	0.71	0.09	3.66	0.92
	64	0.98	0.00	0.00	0.99	0.98	0.99	0.09	8.23	0.92
2	32	0.31	0.18	0.18	0.56	0.95	0.41	0.15	0.80	0.89
	48	0.99	2.57	0.09	0.98	0.69	0.83	0.47	31.55	0.98
	64	0.97	0.00	0.00	0.99	1.00	0.99	0.38	28.56	0.80
3	32	0.30	0.79	0.49	0.98	0.83	0.11	0.25	5.23	0.76
	48	0.99	0.61	0.02	0.99	0.97	0.74	0.18	15.51	1.00
	64	0.98	0.00	0.00	0.99	0.98	0.97	0.23	19.30	0.90

In case of all the furrow irrigation performances considered, the model prediction was better than the computed values for all furrow lengths in all irrigation events. This indicated that more of irrigation water applied was lost before the crop uses, irrigation water applied was not uniformly distributed throughout the furrow lengths in all irrigation events for all furrow lengths considered in which more of the irrigation water losses due to deep percolation since the furrow condition close ended. But, after the decision variables was changed, the performance of furrow irrigation was significantly improved. All the statistical indices used to evaluate the goodness of fit between the measured and simulated values also showed good agreements in all furrow lengths during all irrigation events (Table 5.11).

Table 5.11. Statistical indices of improved furrow irrigation performances

IEs	FL	AE			DU			DP		
		Statistical Indices								
		R^2	RMSE	IA	R^2	RMSE	IA	R^2	RMSE	IA
1	32	0.72	0.62	0.62	0.26	0.86	0.41	0.80	0.15	0.89
	48	0.99	0.41	0.05	0.97	0.99	0.71	0.66	2.09	0.92
	64	0.98	0.00	0.00	0.99	0.00	1.00	0.23	4.19	0.92
2	32	0.31	0.18	0.18	0.56	0.95	0.41	0.80	0.15	0.89
	48	0.99	0.57	0.09	0.98	0.69	0.83	0.55	0.47	0.99
	64	0.99	0.00	0.00	0.99	0.00	0.99	0.56	0.38	0.80
3	32	0.30	0.79	0.49	0.98	0.83	0.11	0.23	0.25	0.76
	48	0.99	0.61	0.02	0.99	0.97	0.74	0.51	1.18	0.99
	64	0.99	0.00	0.98	0.99	0.00	0.98	0.30	2.23	0.90

The study findings by Dewedar *et al.* (2019) revealed that the indices used to evaluate performance of furrow irrigation with different furrow length resulted, the model predictions were better than the computed value similar to the current study based on the existing irrigation practices. The other study findings by Taddesse *et al.* (2019) indicated that the performance of furrow irrigation predicted by model was better than the computed values which showed the goodness of fit between computed and predicted was not good similar to the current study under the existing situations.

5.8. Conclusions and Recommendations

5.8.1. Conclusions

Performance evaluation of furrow irrigation under the Wonji Shoa sugarcane plantation showed poor performance in term of application efficiency, distribution uniformity and deep percolation under current irrigation water management practices. Due to the poor performance of furrow irrigation under the existing irrigation management practices, in the current study improvement options were implemented by altering the furrow decision variables. During this study ten sugarcane field were selected from commonly used furrow lengths, 32, 48 and 64m. In the performance evaluation activities, three irrigation events for all furrow lengths were considered. Furrow inflow rate and cutoff time was varied alternatively to evaluate the performance of current irrigation water management practices. When inflow rate and cutoff time was varied from the existing irrigation practices, the performance of furrow irrigation has improved. Further improvement was achieved by combining both decision variables (inflow rate and cutoff time) that resulted in a better performance of furrow irrigation especially in the case of application efficiency and deep percolation performance indicators. For all scenarios including the current irrigation practices, WinSRFR model was employed to simulate these performance indicators. Similar to the measured values, simulated values showed better improvement was obtained from furrow length 48m in terms of application efficiency and deep percolation but distribution uniformity did not indicate Significant improvement. After the decision variables varied from the current practices, the agreement between measured and simulated performance indicators were good.

Generally, from the current study findings, it can be concluded that to improve the performance of furrow irrigation under Wonji Shoa Sugar Estate, furrow inflow rate should be reduced from 4.7 l/s (current inflow rate) to 3.5 l/s (improved inflow rate). The cutoff time should be increased from current cutoff time (9, 15 and 25 minutes) to 11, 19 and 31 minutes for furrow length 32, 48 and 64 m respectively to attain better performance of furrow irrigation. This indicates that, for improvement of furrow irrigation performance appropriate combination of decision variables are very important that must be experimentally improved to adopt and use for practical management practices.

5.8.2. Recommendations

For very demanded crops like sugarcane that produced with surface irrigation under large scale irrigation, performance evaluation is very important for better productivity and sustainability of the irrigation system. Performance evaluation helps to undertake correction measures based on the performance status of irrigation at current situation. By considering these, the current study was undertaken on performance evaluation of furrow irrigation water management practices and developing improvement options. Based on the findings of the study that significantly improve the performance of the furrow irrigation, the following recommendations are forwarded for a better irrigation water management in the study area.

- The performance of the current furrow irrigation was found to be poor in terms of evaluated performance indicators. For a better performance of the furrow irrigation, like the current findings, appropriate decision variables (reduced to 3.5 l/s and increased by 2, 4 and 6 min.) shall be used for effective irrigation water management practices and overcome the adverse effect of irrigation.
- Since better improvement is obtained from the longer furrow length, to improve the performance of furrow irrigation from the point of proper irrigation water management practices, longer furrows should be used than the shorter furrow length dominantly used in the current study area.
- Finally, it is recommended as further investigation should be undertaken on the dominant soil types of the area with longer furrow length that additionally save the land unexploited between the field ditches.

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6. MEASURING AND ANALYSING OF SUGARCANE WATER REQUIREMENT AND DEVELOPING ITS CROP COEFFICIENT UNDER WONJI SHOA CLIMATIC CONDITION[2] [3]

ABSTRACT

Sugarcane is one of the most important industrial crops grown throughout tropical areas. Its production is significantly expanding in developing countries like Ethiopia, due to increasing demand for sugar. However, sugarcane is characterized by a long growing period and high crop water requirement. Effective irrigation water management of sugarcane requires accurate determination of its water requirements throughout the growing period. The aim of this study was to determine sugarcane water requirements and establish its crop coefficient as well as selecting ETo model that best fits with penman monteith in case of data scarcity for the local climatic condition. Sugarcane was grown on non-weighable lysimeters to quantify the field water balance components from which actual crop evapotranspiration was calculated. A neutron probe was calibrated and used to monitor the moisture content per unit of time. The soil moisture in the lysimeters was managed in way that optimum conditions were maintained to ensure unrestricted crop evapotranspiration. Reference evapotranspiration was estimated using climate data from a nearby station by CropWat 8.0 model. Six ETo models were selected and their performance was evaluated as compared to the CropWat model that may use in case of weather data scarcity for CropWat model in the local climatic condition. The performance of these models was evaluated using selected statistical indices. The result obtained showed that, the sugarcane evapotranspiration ranged from 1.63 to 7.13 mm/day during the early and peak growth stages, respectively. The sugarcane crop coefficients developed were 0.42, 0.93, 1.26, and 1.05 during emergence, tillering, grand formation, and ripening stages respectively. Hence, these results were obtained from a one season experiment, they can be useful as field measurement-based data are lacking in the area and other regions of Ethiopia. Penman-Monteith method is universally used model in determination of reference evapotranspiration but it requires intensive weather data requirement. But, under such conditions like the current study area, Blaney-*Criddle model is a better model to determine ETo. From the current study, it can be recommended that, the experimentally determined sugarcane water requirement and locally developed Kc values should be used in the study area for effective sugarcane irrigation water management as well as any other area until the current result experimentally disproved.*

Keywords: *Crop Coefficient, Evapotranspiration, Lysimeter, Neutron probe, Reference Evapotranspiration Model, performance evaluation, sugarcane*

[2] First article of this paper is published in ***journal Irrigation and Drainage Engineering*** *[ASCE]*

[3] Second article of this paper is published in **Journal of Emerging Technologies and Innovative Research**

6.1. Background of the Study

Sugarcane is a perennial water intensive crop and highly demanded. However, water is becoming increasingly scarce resource due to high competition for water resources from different sectors to fully satisfy sugarcane crop water requirement. In the global context, around 80% of sugarcane is grown in the regions that have a history of water scarcity in rift valley of the country (Adeba *et al.*, 2015). On average 3000 - 4000 mm of water is applied to sugarcane depending on the method of irrigation while water requirement based on evapotranspiration is less than 2000 mm (Liu *et al.*, 2015). On the other hand, some other study indicated the water requirement of sugarcane varies from 1200 to 3500 mm depending on soil types, crop growing duration and the climatic conditions of the area (Shrivastava *et al.*, 2011). Scarcity and growing competition for fresh water resource reduce water availability specially for surface irrigation. To increase the efficiency of irrigation, especially for surface irrigation, an accurate estimation of crop water requirements in irrigated agriculture is essential for effective planning and management of scarce water resources (Holzapfel and Leiva, 2014).

The basic problem concerning efficient use of water for sugarcane is to apply the required amount of irrigation water uniformly with minimum loss throughout the growth period to obtain the maximum yield of the crop (Carr, 2011). A variety of approaches are available for estimating crop evapotranspiration. The most widely accepted two step approaches are through quantification of atmospheric evaporative demand (ETo) and surface characteristics called crop coefficient (Kc) (Silva *et al.*, 2012).

In determination of crop water requirement, Lysimeter is one of the most accurate methods. Once crop evapotranspiration is determined, the crop coefficient can be determined as the ratio of the crop evapotranspiration to the reference evapotranspiration determined by many methods. After the required whether variables are collected or taken from the meteorological station near the study area, CropWat model can be used to determine ETo. CropWat 8.0 model is the most accurate method in determining the reference evapotranspiration (Osaeid *et al.*, 2013). Accurate prediction of ET is essential for the estimation of the water budget and the management of water related environmental systems (Khoshravesh *et al.*, 2017).

Crop water use is generally estimated by multiplying the reference evapotranspiration by pre-determined crop specific coefficient (Djaman *et al.*, 2015). Many authors in the related field of study attempted to develop a standard, precise and globally acceptable method of estimating reference evapotranspiration for accurate computation of crop water requirement (Adeboye *et al.,* 2009).

There were many models developed to estimate reference evapotranspiration (ETo) in environments that lack direct ETo measurements. A major complication in ETo estimation using these models is due to their less meteorological data requirement that influence the accuracy. However, obtaining all the required whether variables may not be easy often times. This restriction at time prohibits the use of more accurate models and necessitates the use of models that have less demanding meteorological data requirements. An international scientific community has accepted the FAO-56 Penman Monteith (FAO-56PM) model as the most precise one for its good results when compared with other models in various regions of the world. Estimation of ETo by globally accepted FAO56-PM requires many weather parameters like maximum and minimum temperature, solar radiation, sunshine hours, wind speed and relative humidity. In the case of some whether variables are not fully available to use the most accurate and recommended methods, selecting the model that is more accurate as compare to this very important.

Irrigation water sources are one of the most limiting factors in crop production in arid and semi-arid regions specially for perennial crops like sugarcane since the annual rainfall is low and erratic in time and space. Once sugarcane water requirement is determined and its crop coefficient is developed, the irrigation water required for a given command area can be computed based on the availability of water resource which highly influences the sustainability of irrigated area. Most of the time, surface irrigation systems design depends on irrigation canals without considering water requirement of the crop which resulted in over or under irrigation practices that resulted in reduction of the crop yield (El-Hazek, 2016).

6.2. Statement of the Problems

Sugarcane is one of the most industrial crops produced almost all over the worlds. The production and productivity of this important crop is not much attractive especially in developing countries like Ethiopia. Commercial sugarcane production system in Ethiopia and elsewhere in the world is to increase cane and sugar production per unit area. But, the availability of water resources restricts increasing the amount of sugarcane establishment and growth in many regions throughout the world because sugarcane requires substantial amounts of water during growth stages (Nelmicio *et al.,* 2016; Verma and Singh, 2019). In order to attain potential production of the crop, implementation of standard cultural practices is imperative. In Ethiopia, specifically at Wonji Shoa Sugar Estate, there is no advanced technology used in sugarcane production, especially in relation to the factors involved in the growth of sugarcane subjected to different water availability (Teixeira *et al.,* 2016).

Determination of sugarcane water requirements and developing its crop coefficient is not well developed as per other crops. Limited researches were conducted on determination of sugarcane water requirements and its crop coefficient. However, a limited research concerning the sugarcane water requirement and crop coefficient was conducted in Brazil (Gabriel *et al.,* 2015), Austrialia (Win *et al.,* 2014), different regions of India Yadav and Yadav (2018) and South African (Singels *et al.,* 2013). In case of Ethiopia, there were limited research conducted on sugarcane water requirement due to many factors like consuming time, requires more finance, tedious and large data requirement but no research was conducted on sugarcane crop coefficient. The few research conducted on sugarcane were focused on crop water requirement at different growth stages based on the FAO recommendation of the crop coefficient (Abera *et al.*, 2016).

The main reason why this research focused on the development of sugarcane crop coefficient was even if the sugarcane production in the country is expanding, no research was conducted on the development of sugarcane crop coefficient which resulted in the mismangement of irrigation water application. Additionally, ETo is not determined by the most accurate and recommended methods using full available weather data. When all required data are not available, selecting the best model in the current climetic condition helps to over come the mismanagement of irrigation. Because, both extreme irrigation application (over or under) resulted in significant on sugarcane production and productivity. Therefore, the main purpose of thi study was to measure and analyze sugarcane water requirement and crop coefficient under Wonji Shoa climatic condition.

6.3. Objectives of the Study

The general objective of this study was to measure and analyze sugarcane crop water requirement and developing its crop coefficient

The specific objectives were:

- To determine sugarcane water requirement under optimum growth condition using lysimeter experiment.
- To develop crop coefficient for sugarcane using lysimeter experiment.

6.4. Research Questions

- What is the extent of sugarcane water requirement during its growing season?
- What are the optimum values of sugarcane crop coefficient over the growing period?

6.5. Significance of the Study

Determination of the accurate crop water requirement and crop coefficient is very important in irrigated agriculture in view of proper water resources. Since, scarcity of fresh water is the emerging problem, especially in agricultural sectors due to its high consumption of available water, this requires accurate determination of crop water requirement based on atmospheric demand of the area, crop growth stages and the soil conditions. In line with this, the current study was focused on experimentally determining the sugarcane water requirements and developing its crop coefficient based on the local climatic condition of the study area. In this study, lysimeter experiment is the most accurate methods of determining crop water requirement was used. The optimum irrigation water management was monitored using calibrated neutron probe. The reference evapotranspiration was determined from local weather parameters using CropWat 8.0 model and other selected ETo models. The sugarcane crop coefficient was developed at each growth stage from crop water requirement determined using lysimeter experiment and reference evapotranspiration is determined from the local climatic conditions. The finding of this study is very important for Wonji Shoa sugarcane plantation in which the experiment was conducted under this specific location, as well as other regions in with similar conditions where the crop produced for proper irrigation water management practices. In addition, the result of this study was used to overcome the problem of mismanagement of irrigation water application which resulted in sugarcane yield reduction, water logging and salinity problems. The current study also identified the better model in determining reference evapotranspiration that may be used when all weather parameters are not fully available to use the penman monteith under current climatic condition or area which have similar climatic conditions. Generally, the findings of this study used for proper sugarcane irrigation water management practices.

6.6. Materials and Methods

This study was conducted to determine sugarcane water requirement and develop its crop coefficient using lysimeter experiment. The study was also used to identify a good performing model in estimating reference evapotranspiration model as compared to Penman Monteith (CropWat 8.0 model). Penman Monteith is the most accurate and recommended model in determining the reference evapotranspiration in which is application limited due the scarcity of weather parameters in many regions in the world.

6.6.1. Description of the study area

The experiment was conducted at Melkassa Agricultural Research Center (MARC) which is located in the south east of Adama town Oromia Regional State, Ethiopia. Melkassa Agricultural Research Center was established in 1969 as a National Horticulture research Center with staff members of five personnel and land area not exceeding five hectares. Over the years, other important research programs and commodities have been included in the research program that contributed to improved rain fed and irrigated agricultural development with a main focus on dry and lowland areas of moisture stress and irrigable areas of the country.

MARC located at rift valley of Ethiopia at latitude 8^{0}24’ -8^{0}26’N and longitude 39^{0}18’-39^{0}22’ E With a distance of 117km from capital city of the country, Addis Ababa with altitude of 1550 m.a.s.l. It is located in the low land area in which the climatic condition is hot throughout the year with low amount of annual rainfall.

The maximum and minimum temperatures of MARC are 28.4 and 14^{0}C respectively with the mean annual rainfall of 810.3mm. The climatic condition of the area categorized under arid to semi-arid agroecological zone. The dominant soil type of MARC is Andosol of volcanic origin with pH ranging from 7 to 8.2. The cropping system during the main growing season includes cereals mainly teff, maize, sorghum, haricot bean and soybean while tomato, onion, papaya, banana and paper are the main crops grown during the off-season using irrigation from Awash River water source (MARC, 2018). The location map of the study area (MARC) was presented in the (Figure 6.1).

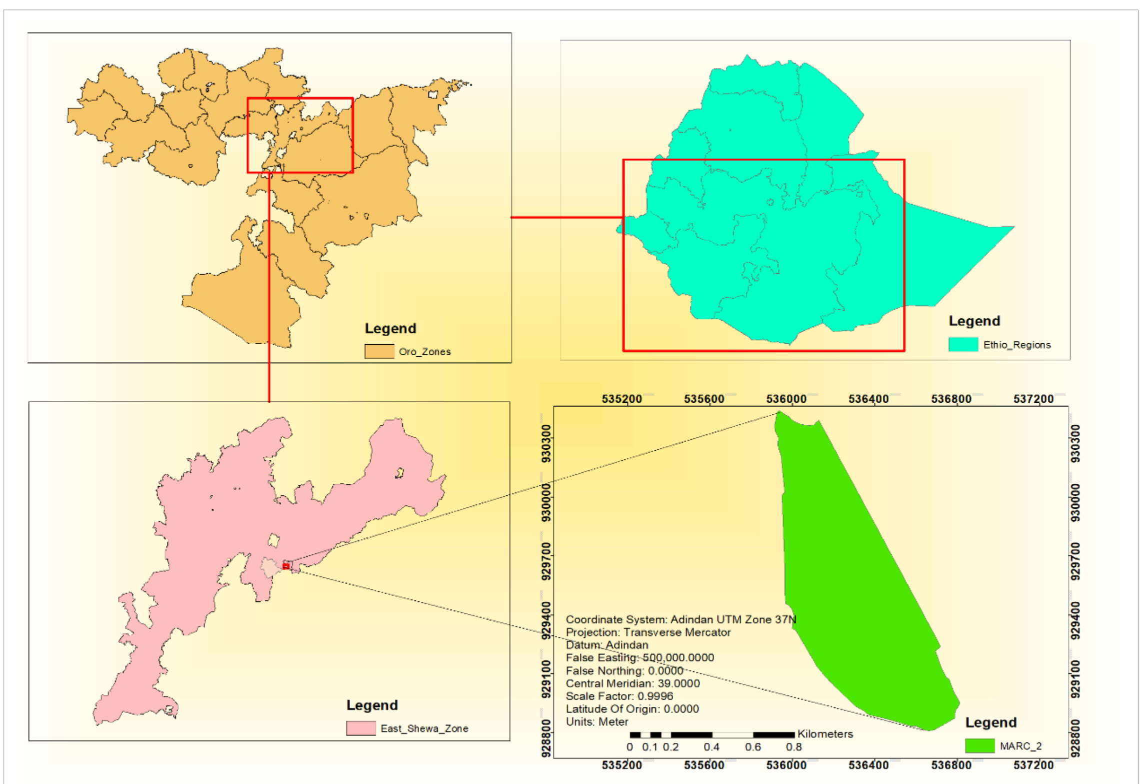

Figure 6.1. Location Map of the Study area

6.6.2. Materials used and experimental set up

The experimental materials used during this experiment were meter tape, rope, spade, auger, moisture can, sensitive balance, water can, cane setts, neutron probe and measuring cylinder. The experiment was conducted on the drainage type lysimeter which found near the meteorological station of the institution (MARC).

6.6.2.1. Lysimeter experiment

Lysimeters are commonly used to quantify water balance components of a soil monolith isolated from its surrounding. The lysimeter was constructed by excavating a rectangular area of 1m wide and 2m length with 3m depth. After the profile was opened, the necessary reinforced concrete foundation and plastering of walls for water proofing was incorporated. Following the construction of the tank, gravel layer of 40cm was placed at the bottom of tank to facilitate drainage which was overlayed by refilling of sand and soil layer by layer respectively.

Lysimeter experiment at the research site (MARC) has long years of experience. The sugarcane setts were planted on the area of the rectangular shaped concrete boxes of size 1 meter width and 2 meters length (2 square meter area) but for buffering condition outside the lysimeter sugarcane planted on 6 * 6 m (36m^2). A manhole of 3m depth and 3m wide supported by ladder is set for the lysimeters to enable the measurement of drainage water which comes out from the bottom of lysimeter and guided through drainage pipes to collector bucket. For this experiment two lysimeters were used which are located very closely to large sugarcane plantation field. Some soil physical properties of the experimental soil were analyzed at research center soil laboratory includes bulk density, soil texture and continuous soil moisture analysis but the soil moisture content at field capacity and permanent wilting point was used from the result of analysis done by the research center very recently (2018/19).

The sugarcane (*Saccharum officinarum*) variety used for the experiment was taken from the Wonji Shoa Sugar Estate. Among many sugarcane varieties currently cultivated at the Wonji Shoa Sugar Estate, NCO-334 variety was selected because of its short maturity and largely cultivated in the Estate. In the lysimeter including the boundary area, furrow layout was prepared. The two bud sugarcane setts of selected variety were planted in rows in the lysimeter as well as the boundary area. Parts of the lysimeter on which the experiment conducted was presented in Figure 6.2.

Figure 6.2: Partial view of lysimeter experiment and measuring drained water from drainage manhole

6.6.2.2. Soil moisture monitoring

The soil moisture content of the soil monoliths was monitored regularly using calibrated neutron probe. The neutron probe was calibrated ahead of the experimental measurement. As measurement of soil moisture using neutron probes in the shallow depths is not advisable due to sensitivity of neutron to moisture within 30cm diameter, the soil moisture up to 30cm depth was monitored using gravimetric method. The probe was used for depths beyond 30cm (30-60 and 60-90cm).

To calculate the depth of equivalent moisture, the slope and intercept were calculated from the data collected from wet (inside the lysimeter) and dry (from access tube) installed near the lysimeter using the equations (6.1 and 6.2) (Kohl, 1971).

$$\text{Slope (A)} = \frac{(\text{MH}-\text{ML})}{(\text{RH}-\text{RL})} \qquad 6.1$$

$$\text{Intercept (B)} = \text{ML} - \text{A} \times \text{RL} \qquad 6.2$$

Where: MH = high moisture value (from a wet access tube), ML = low moisture value (from dry access tube), RH = Probe count ratio at high moisture value and RL = Probe count ratio at low moisture value.

The result obtained was used to develop a linear relationship between the two variables as given in Equation 6.3 (Kohl, 1971).

$$\text{M} = \text{A(r)} + \text{B} \qquad 6.3$$

Where: M is moisture content (CPC) and r is count ratio (count/ standard count)

Therefore, the coefficients A and B were obtained from the paired measurements of count ratio and equivalent depth of water using linear correlation method. The values of the coefficients were stored in the neutron probe. Then, the daily soil moisture reading was taken in unit of centimeter per centimeter (CPC) and converted to mm/m which helps to know the daily change in soil moisture content.

Hence, the calibrated neutron probe was used to monitor soil moisture in the lysimeter throughout the growing period of the sugarcane. The coefficients were determined from the moisture data collected from wet (inside the lysimeter) and dry (outside near the lysimeter) access tubes and computed using Equation 6.3 and inserted into the neutron probe that saved with separate code to monitor the soil moisture continuously (Figure 6.3).

Figure 6.3: Neutron Calibration and soil moisture monitoring in the Lysimeter

The soil samples collected were weighed and oven dried that used to determine the soil moisture content for the particular irrigation intervals. Equivalent depth of water was calculated using equation 6.4 (Dingre and Gorantiwar, 2020).

$$D_{eq} = \left(\frac{W_w - W_d}{W_d}\right) \times Z_r \times A_s \qquad 6.4$$

Where: D_{eq} = equivalent depth of water (cm/cm), W_w = Wet weight of soil sample (gm), W_d = oven dried weight of soil sample (gm), Zr = depth of soil sample (cm) and A_s = apparent specific gravity of soil.

The irrigation water was applied based on the results for regular soil moisture analysis. The soil moisture content in the lysimeter from 0-30cm was measured by gravimetric while beyond this depth (30-60 and 60-90cm) by using a neutron probe as clearly described earlier. The soil moisture depletion level to be applied at any time during growing period was computed using Equation 6.5.

$$\mathrm{SMD} = (\theta_{fc} - \theta_{i}) \qquad 6.5$$

Where: SMD = soil moisture depleted, θ_{fc} = soil moisture content at field capacity, θ_{i} = soil moisture content at the present time.

Irrigation water was applied when 40% of the total available soil moisture was depleted from the crop root zone. This level of soil moisture is believed to provide optimum condition for unrestricted crop evapotranspiration. The volume of irrigation water applied was computed using Equation 6.6.

$$\mathrm{V} = \mathrm{A} \times \mathrm{D}_{req} \qquad 6.6$$

Where: V = volume of irrigation water applied (m^3), A = surface area of the lysimeter (m^2), D_{req} = irrigation depth (mm)

The sugarcane evapotranspiration over the season was computed from the general water balance of the lysimeter using Equation 6.7.

$$\mathrm{ETc} = (\mathrm{P_{eff}} + \mathrm{I}) - \mathrm{Dp} \pm \Delta\mathrm{SM} \qquad 6.7$$

Where: ET_c = Crop evapotranspiration (mm/day), I = applied irrigation water, Peff = effective rain falls (mm) during the period, Dp = Deep percolation (drainage) (mm), ΔSM = change in soil moisture content (mm).

The irrigation water applied based on the soil moisture content in the root zone of the sugarcane. The interval ranged from five to eight days depending on growth stages and amount of water applied. Always irrigation was applied before the soil moisture in the crop root zone reach the set depletion level of 40% throughout the crop growth periods. The effective rainfall was determined from total available rainfall during the growing periods of the crop. The reference evapotranspiration was computed using the widely accepted accurate methods (FAO Penman Monteith method). The volume of drained water from the lysimeter was continuously collected and measured at each irrigation interval. The change in soil moisture content was computed from soil moisture content measured before and after irrigation. After all the water balance components were quantified, the total crop evapotranspiration per unit of time was computed using Equation 6.8 (Tellen, 2017).

$$\mathrm{ETc} = \left(\sum_{i=1}^{N} (\mathrm{I} + \mathrm{Peff}) - \sum_{i=1}^{N} \mathrm{Dp} \pm \sum_{i=1}^{N} \Delta \mathrm{SM} \right) \qquad 6.8$$

Where: I = Irrigation water applied (mm), P_{eff} = available effective rainfall (mm), DP = Deep percolation (mm), $\Delta SM = \text{change is soil moisture}$

The decadal weather parameters used to determine reference evapotranspiration during the sugarcane growth periods were present in Appendix Table 6.1. Following the determination of crop evapotranspiration (ETc) and reference evapotranspiration (ETo), growth stage based crop coefficient for sugarcane was developed using Equation 6.9 (Dingre and Gorantiwar, 2020).

$$\mathrm{Kc_i} = {}^{\mathrm{ETc_i}}/_{\mathrm{ETo_i}} \qquad 6.9$$

Where: Kci = crop coefficient during ith growth stage, ETc_i = crop evapotranspiration during ith growth stage, ETo_i = reference evapotranspiration during ith growth stage.

6.7. Description of Selected Models

6.7.1. Blaney Criddle model

Blaney and Morin (1942) first developed an empirical relationship between ET and mean air temperature, average relative humidity and mean percentage of day time hours. Blaney and Criddle (1962) later modified this relationship by excluding humidity term. The basic assumption was that evapotranspiration varies directly with the sum of the products of mean monthly air temperature and monthly percentage of annual day time hours for an actively growing crop with adequate soil moisture (Teixeira *et al.*, 2008). Those authors described by citing Doorenbos and Pruitt (1977), the most fundamental revision of Blaney Criddle model by FAO-24 and estimate a grass related reference crop for determination of evapotranspiration. The model equation is given by Equation 6.10

$$\mathrm{ETo} = \mathrm{p}(0.46\mathrm{T}_{\mathrm{mean}} + 8.13) \qquad 6.10$$

Where: T_{mean} = mean temperature, P = Mean monthly percentage of total annual day time hours,

6.7.2. Drooger and Allen Model

This model was developed to estimate the daily or monthly reference evapotranspiration as a function of air temperature and solar radiation (Droogers and Allen , 2002). ETo computed Drooger and Allen using Equation 6.11.

$$\mathrm{ET_o} = 0.003(\mathrm{Tmean} + 20)(\mathrm{Tmax} - \mathrm{Tmin})^{0.4} \times \mathrm{Ra} \qquad 6.11$$

Where: T_{max} = summation of all maximum temperature of the month divides by number of days of the months, T_{min} = summation of all minimum temperature of the month divides by number of days of the months, Ra = Terrestrial radiations

6.7.3. Hargreaves model

Hargreaves and Samani (1985) proposed several improvements for the Hargreaves (1975) equation for estimating grass related reference ET. Because solar radiation (Rs) data are often not available, Hargreaves and Samani (1985) recommended estimating Rs from extra-terrestrial radiation (Ra) and the difference between mean monthly maximum and minimum temperatures (Tabari *et al.*, 2013). The equation to determine ETo given as (Equation 6.12).

$$\mathrm{ETo} = 0.0023 \times \mathrm{Ra}(\mathrm{Tmean} + 17.8) \times (\mathrm{Tmax} - \mathrm{Tmin})^{0.5} \qquad 6.12$$

6.7.4. Irmak model

This model was also used to compute the daily or monthly reference evapotranspiration as a function of air temperature and solar radiation (Irmak *et al.*, 2003). This is computed using Equation 6.13 as

$$\mathrm{ET_0} = 0.611 + 0.149\mathrm{Rs} + 0.079 \times \mathrm{Tmean} \qquad 6.13$$

6.7.5. Thornthwaite model

Thornthwaite model has been widely criticized for its empirical nature but is widely used. Because Thornthwaite model estimating ETo can be computed using only temperature, it has been one of the most misused empirical equations in arid and semi-arid irrigated areas where the requirement has not been maintained. The ETo according to Thornthwaite model is given as (Equation 6.14).

$$\mathrm{ETo} = \mathrm{ET}' \times \left(\frac{\mathrm{d}}{12}\right) \times \left(\frac{\mathrm{N}}{30}\right) \qquad 6.14$$

To compute this, the following should be first computed

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

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

Where: i = monthly heat index for the month j, (0 when mean monthly temperature is 0°C or less), I = annual heat index, Ta = mean monthly air temperature (0°C), j = number of months (1 - 12), ET' = adjusted ET depending on the number of days N in a month($1 \leq N \leq 31$), d = duration of average monthly day light (hr) and N = number of days in a given month (1 - 31 days).

6.7.6. Tabari model

Finally, this model was used to compute the daily or monthly reference evapotranspiration as a function of mean air temperature and solar radiation (HosseinTabari *et al.*, 2013). This is computed using Equation 6.15.

$$\mathrm{ET_o} = -0.642 + 0.174\mathrm{Rs} + 0.0353 \times \mathrm{Tmean} \qquad 6.15$$

For all models requires solar radiation was computed using Equation 6.16.

$$\mathrm{Rs} = \mathrm{K_{RS}}(\mathrm{Tmax} - \mathrm{Tmin})^{0.5} \times \mathrm{Ra} \qquad 6.16$$

Where: K_{RS} = adjusted coefficient = 0.16

6.8. Performance Evaluation of the Models

The output of a model depends on the principle of the model itself and the accuracy of the input data. The performance of the models was evaluated using statistical indices. A model is a good representation of reality only if it predicts an observable phenomenon with acceptable accuracy and precision. In the current study, reference evapotranspiration determined by each selected models were compared with the reference evapotranspiration computed using most accurate and recommended model, Penman Monteith using CropWat 8.0 model. The performance of the models were evaluated using different statistical indices adopted from Douglas *et al.* (2009) as compared to the Penman Monteith model. The statistical indices used to evaluate the performance of the selected models were:

6.8.1. Root mean square error (RMSE)

Root mean square error index was used to measure the tendency of error occurred in the models in determining the reference evapotranspiration (ETo) as compared to CropWat 8.0 model. RMSE was rated as excellent if RMSE<10%, good if RMSE 10-20%, fair if RMSE 20-30% and poor > 30% which computed by Equation 6.17

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{1=1}^{N}(\mathrm{ETo_m} - \mathrm{ETo_{CW}})^2}{N}} \qquad 6.17$$

6.8.2. Mean bias error (MBE)

The mean bias error indicates whether the selected models overestimated or under estimated the ETo. Mean bias error positive value indicates over estimation ($ETo_m > ETo_{CW}$) and negative value indicates ($ETo_m < ETo_{CW}$) underestimation but the optimal value for MBE is zero computed by equation (6.18).

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(ETo_m - ETo_{CW}) \qquad 6.18$$

6.8.3. T-test

The models were assessed based on RMSE and MBE alone may be misleading in the absence of t-test. The t-test statistics should be used in conjunction with MBE and RMSE error to better evaluate model performance. Finally, t-test statistics indicator can be viewed as supplement of MBE and RMSE error in supporting models to determine whether or not model estimate are statistically significant at particular confidence level. The optimal value of t-test is zero or very small which is computed by equation (6.19) as:

$$t = \left[\frac{(n-1) \times MBE^2}{RMSE^2 - MBE^2}\right] \qquad 6.19$$

6.8.4. Coefficient of determination (R^2)

The coefficient of determination is one of the commonly used statistical indices which indicates the variation between the variables considered. The coefficient of determination ranges from 0 to 1 which indicates the strength of linear association between ETo computed by models and Penman Monteith model. The model can be accepted if the value is greater than 0.6 which computed using Equation 6.20 (Hafeez and Khan, 2018)

$$R^2 = \left[\frac{\sum_{i=1}^{N}(ETo_m - \overline{ETo}_m) \times (ETo_{CW} - \overline{ETo}_{CW})}{\sqrt{\sum_{i=1}^{N}(ETo_m - \overline{ETo}_m)^2 \times \sum_{i=1}^{N}(ETo_{CW} - \overline{ETo}_{CW})^2}}\right]^2 \qquad 6.20$$

6.8.5. Index of agreement (IA)

Index of agreement was used to measure the tendency of agreement between ETo computed by Penman Monteith model and the selected models. The performance of the model is good if the value of IA ≥ 0.95 but if the value is 1, there was a perfect agreement between the two which was computed using Equation 6.21.

$$IA = 1 - \left[\frac{\sum_{i=1}^{N}(ETc_{mod} - ETc_{CW})^2}{\sum_{i=1}^{N}[(ETc_{mod} - \overline{ETc}_{CW}) + (c - \overline{ETc}_{CW})]^2}\right] \qquad 6.21$$

Finally, the variation in sugarcane crop coefficient developed by lysimeter experiment and FAO recommendation ploted on the graphical representation.

6.8. Result and Discussion

6.8.1. Soil physical properties

A few of soil physical properties were analyzed by taking the soil samples from the lysimeter. The soil samples taken at three depths and analyzed in the Melkassa Agricultural Research center soil laboratory were presented in (Table 6.1).

Table 6.1. Soil physical properties

Depth	Percentage of soil particles (%)				ρb	FC	PWP
(cm)	Sand	Silt	Clay	Soil Texture	(g/cm^3)	(%, vol)	(%, vol)
0-30	43.80	38.60	17.60	Loam	1.01	24.5	9.39
30-60	47.00	37.00	16.00	Loam	1.06	25.7	13.36
60-90	45.70	37.00	17.30	Loam	1.15	25.00	13.23

ρb = Soil bulk density, FC = soil moisture content at field capacity, PWP = soil moisture content at permanent wilting point

The result presented in Table 6.1, showed that the soil texture in the lysimeter was loam which indicates moderate to low water holding capacity. But, the bulk density of the soil indicated that as the soil is heavy soil with mostly clay nature. This mis much properties of the soil may be due to the repeatedly use of the lysimeter that create a soil compaction.

6.9.2. Neutron calibration

The neutron probe was calibrated and used to monitor soil moisture in the lysimeter throughout the growing period of the sugarcane. The coefficients were determined from the moisture data collected from wet (inside the lysimeter) and dry (outside near the lysimeter) access tubes which computed using Equation 6.3. The result of the analysis and the linear equation developed from neutron probe calibration was presented in Figure 6.4.

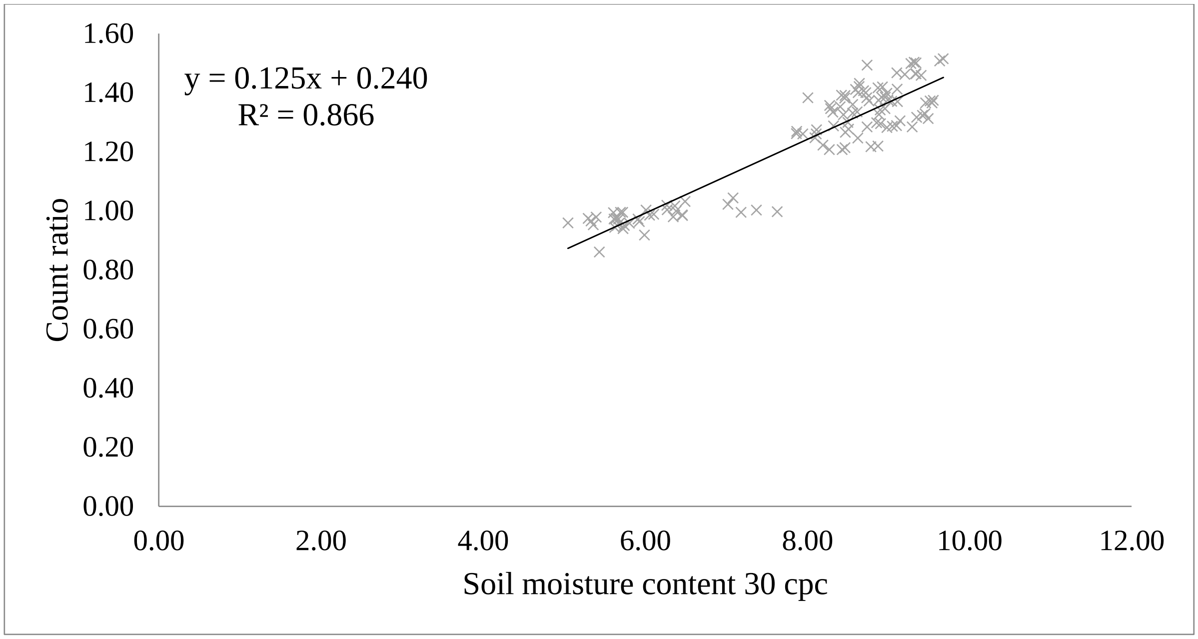

Figure 6.4: Neutron probe calibration curve

6.9.3. Soil moisture regime during the growing period

While measuring crop evapotranspiration, it is important that the soil water content be kept at an optimum level throughout the measurement period. In this study, the soil moisture content was determined throughout the growing period at three depths intervals (0-30, 30-60 and 60-90cm). The result obtained indicated that the soil moisture relatively more in the lower depth (Figure 6.5) and some amount of those may be lost in the form of drainage beyond the crop root zone which was measured from the lysimeter drainage manhole as deep percolation.

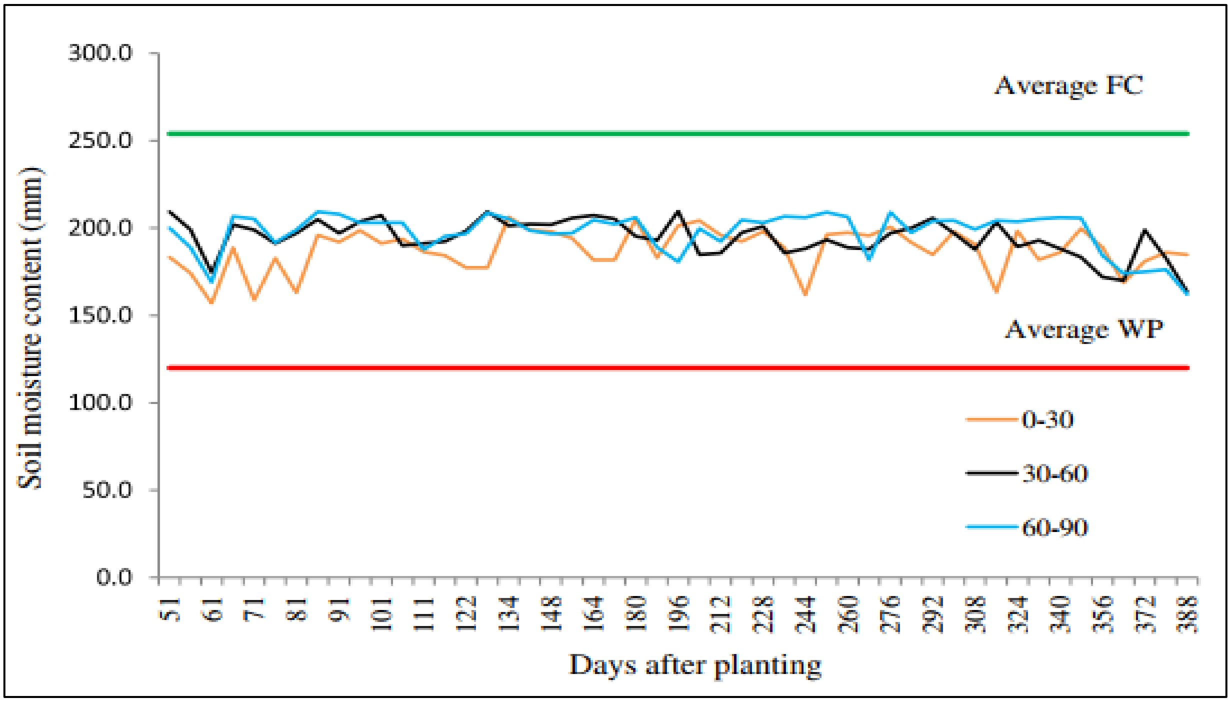

Figure 6.5: Soil moisture regime at different depths during the crop growing period

As can be observed from Figure 6.5, the soil moisture content at different depths shows only slight variation throughout the growing period. However, with increasing growth of the crop the soil moisture depletion increases that in turn necessitates application of more amounts of water. As depicted in the same Figure, at early growth stages of the crop, even if less amount of irrigation water was applied, more of the irrigation water applied was lost in the form of evapotranspiration and drainage.

The volume of water deep percolated was more in the early growth stages of the crop because at this growth stages the crop root zone was shallower and soil water stored in the deeper soil depth was lost in the form of drained water beyond the crop root zone that was measured as deep drainage (Figure 6.6).

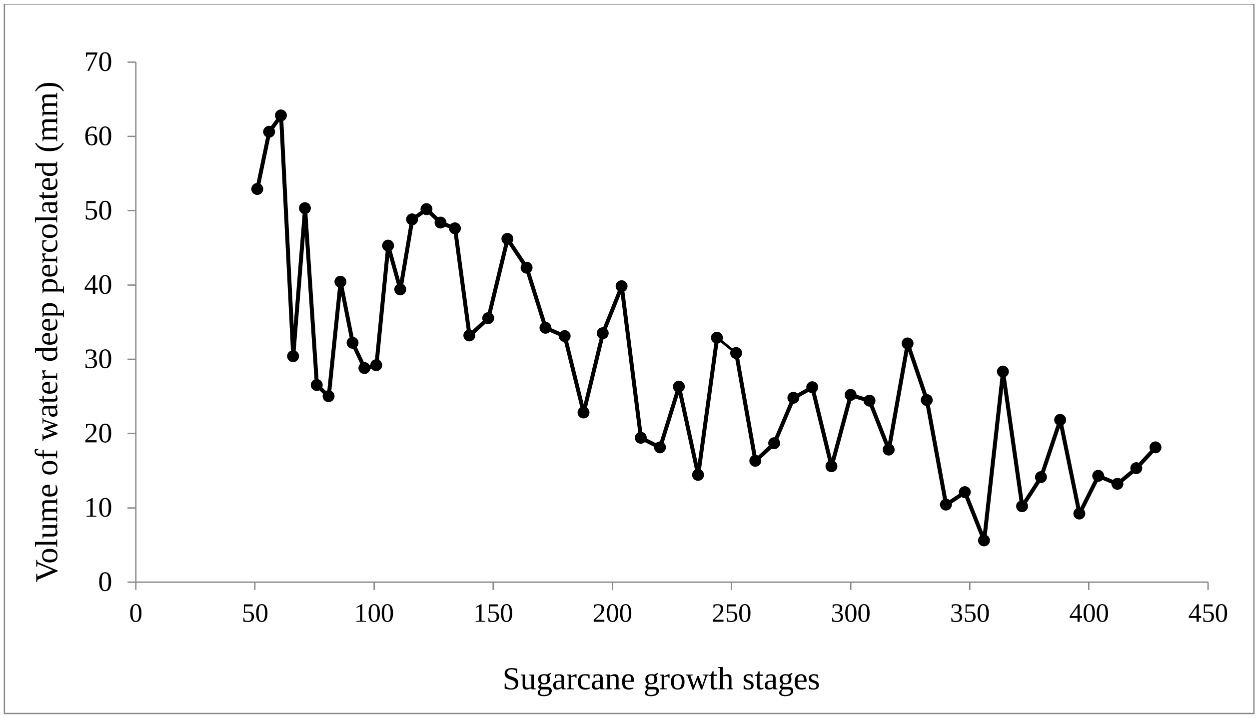

Figure 6.6: Volume of water lost as deep percolation beyond the crop root zone from drainage manhole

6.9.4. Reference evapotranspiration

The weather parameters required for determination of reference evapotranspiration were maximum and minimum air temperature, wind speed, solar radiation and relative humidity. These weather parameters were collected during the growing season of the sugarcane. Sugarcane was best grown where the temperature ranges from 20 to 35^{o}C. In current study area, the mean minimum and maximum temperature ranges from 17.40 to 33.30^{o}C which indicated slightly lower than the recommended ranges but the data considered was for the crop growing season only. The mean monthly minimum, mean and maximum temperature of the study area was presented in the (Figure 6.7).

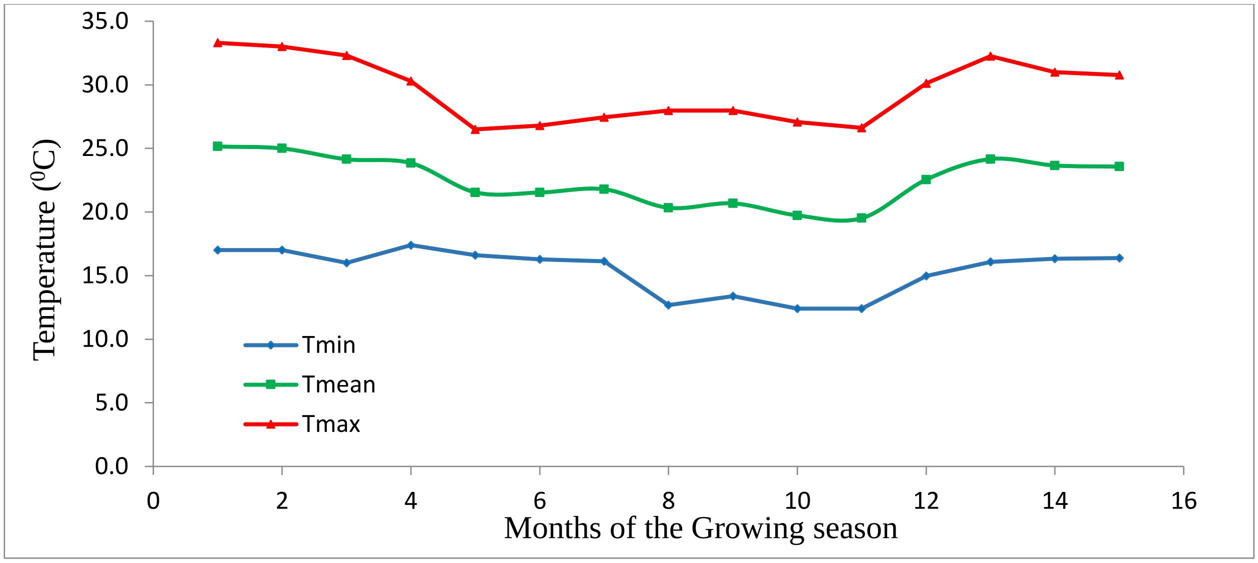

Figure 6.7: Mean monthly temperature of the study area

High humidity favors rapid cane elongation during the grand growth period. The humidity favors or retards the growth of sugarcane but the minimum and maximum humidity for sugarcane growth range 27 to 92% but the moderately relative humidity of 45– 65% coupled with limited water supply is favorable. The mean monthly minimum and maximum relative humidity in the current study area was 46.81 and 71.42% respectively as presented in Figure 6.8.

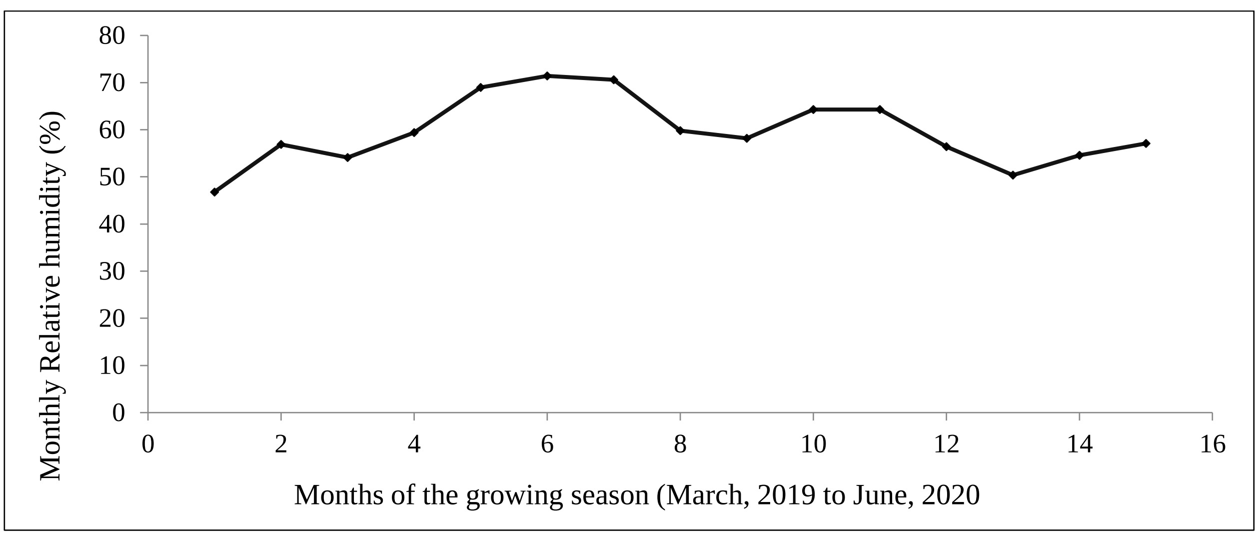

Figure 6.8. Mean monthly relative humidity of the study area

Sugarcane growth requires long duration of daylight and mostly cane effectively grown when the average daylight above 10 hours and wind speed of less than 5m/s. But in reality, many study indicated the mean monthly sunshine hours were ranges from 8.10 to 12.66 hours and wind speed of 2.66 to 4.74 m/s for effective sugarcane growth (Irmak and Irmak, 2003). In the current study area, the monthly average daylight were 6.06 to 9.71 hours and wind speed of 1.43 to 2.96m/s in which both weather parameters were lower than the crop requirement that affect the effective growth of sugarcane. The mean monthly sunshine hours and wind speed of the study area was presented in the Figure 6.9.

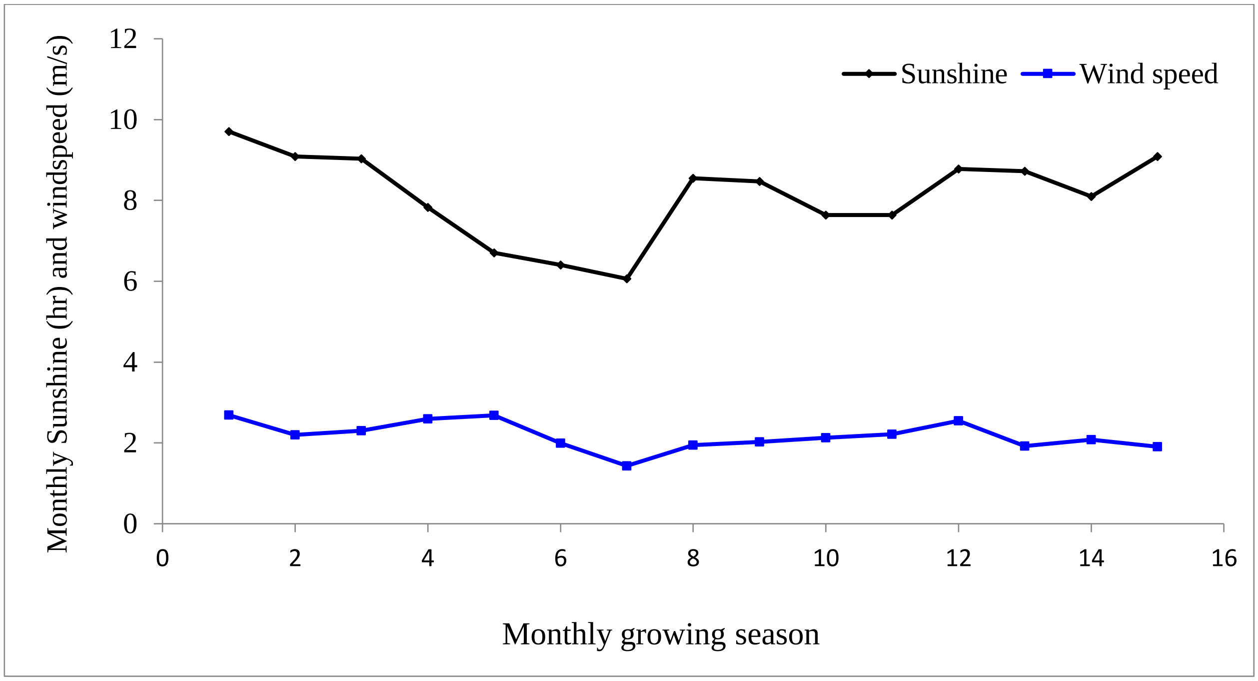

Figure 6.9: Mean monthly Sunshine hours and wind speed during growing seasons

The reference evapotranspiration was determined from those weather parameters using Penman Monteith (PM) model. The daily reference evapotranspiration was determined starting from the planting month of sugarcane in the lysimeter (March, 2019/20) to the maturity of the sugarcane (May 2020/21). The daily reference evapotranspiration determined using Penman Monteith (PM) model was presented in the (Figure 6.10).

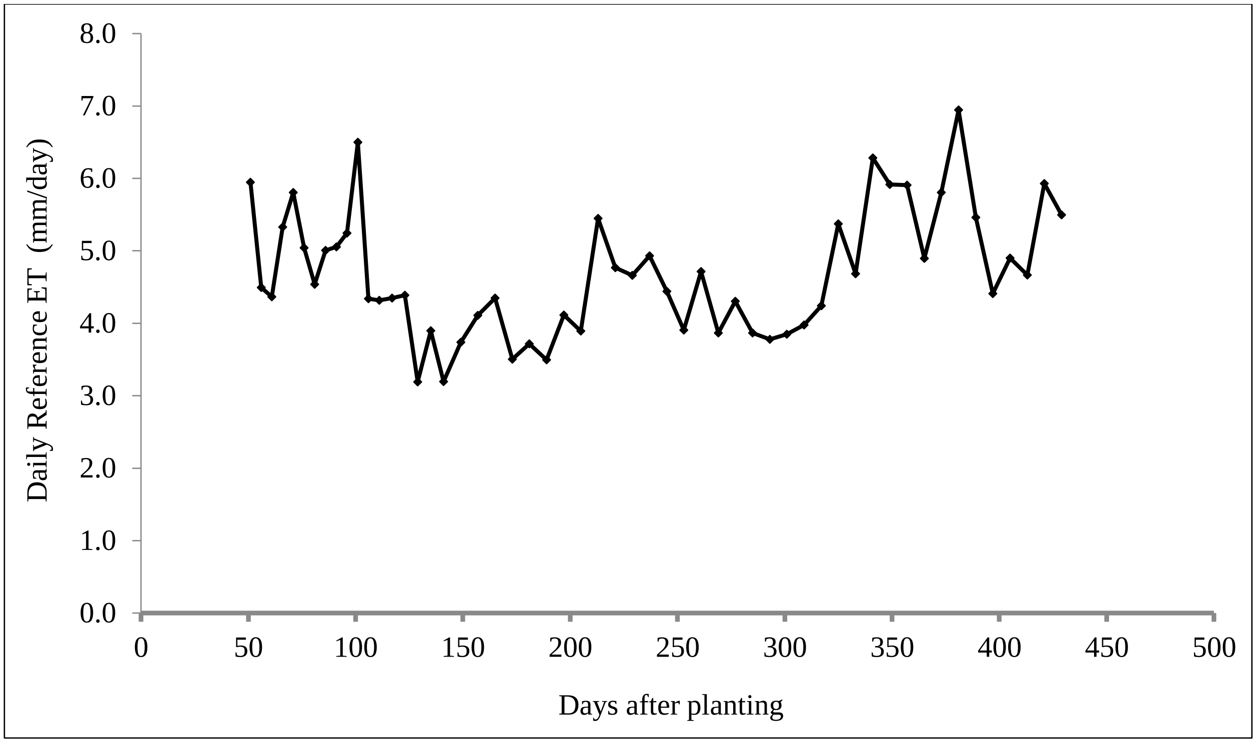

Figure 6.10: Daily reference evapotranspiration (ETo) during the growing period of sugarcane

The values of computed reference evapotranspiration (ETo) were used to develop sugarcane crop coefficient with the sugarcane evapotranspiration directly measured from the lysimeter experiment throughout the growing season of sugarcane.

6.9.5. Sugarcane evapotranspiration (ETc)

The daily evapotranspiration of Sugarcane was determined from the lysimeter water balance was presented in Figure 6.11. The result indicates that the daily evapotranspiration rate varied from 1.6 – 3.1 mm/day during emergence, 2.8 – 5.2 mm/day during tillering, 4.0 – 6.3 at grand formation stage and 4.5–7.5 mm/day during ripening growth stages (Appendix Table 6.1). The crop demonstrates high evapotranspiration rates during the late growth stages. However, irrigation was purposely reduced during the end of ripening stage to enhance the accumulation of sucrose.

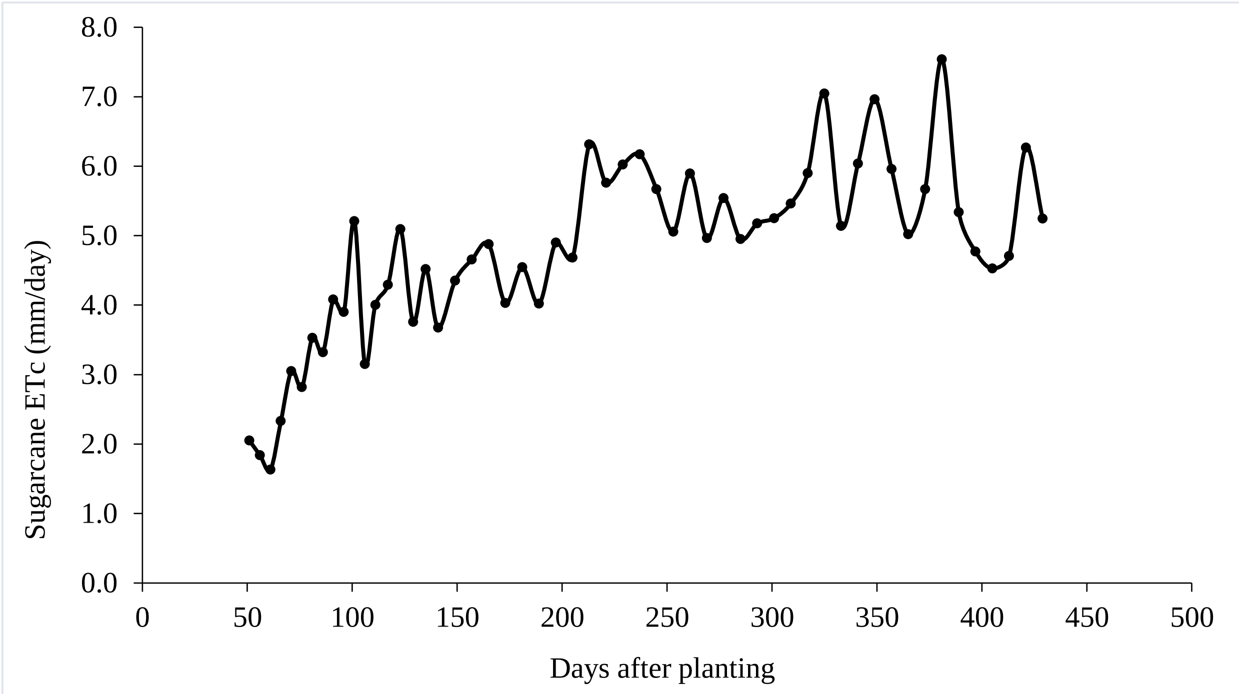

Figure 6.11. Daily evapotranspiration of sugarcane measured from Lysimeter from 2019 to 2020

The study conducted by Win *et al.* (2014) also relatively complies with the the results of this study except at emegergence and development growth stage. Except slight variations at distinct growth stages, the studies conducted by many authors agree with the results of this study (Silva *et al.*, 2012; Karuppanan, 2018). The variations in sugarcane evapotranspiration were expected due to site specific climate and management differences. The total sugarcane evapotranspiration for each growth stages are presented in Table 6.2.

Table 6.2: Sugarcane Evapotranspiration based lysimeter water balance at each growth stages

Growth stages (GS)	GP (days)	Inputs (mm)	Losses (mm)	ETc (mm/GS)
Initial	70	181.7	127.2	54.50
Tillering	86	690.05	339.9	350.10
Grand formation	160	1156.3	314.9	841.40
Ripening	112	758.85	117.15	641.70
Total	428	2,786.9	899.15	1,887.7

GP = Growing period of each growth stages, ETc = crop evapotranspiration

6.9.6. Development of crop coefficient (Kc) for sugarcane

Crop coefficient is the ratio of crop evapotranspiration and reference evapotranspiration (Equation 6.8). The daily reference evapotranspiration as estimated from local weather data by CropWat model was presented in Figure 6.9. The atmospheric water demand in the area is relatively low during the main rainy season which lasts commonly from June to August and high during the dry months of the year (December – April). From the current study the sugarcane crop coefficient developed at each growth stages were presented in the Table 6.3.

Table 6.3: Developed sugarcane crop coefficient at each growth stages

Growth stages (GS)	Growing period (days)	ETc (mm/GS)	ETo (mm/GS)	Kc
Initial	70	54.50	129.72	0.42
Tillering	86	350.10	377.12	0.93
Grand formation	160	841.40	670.69	1.26
Ripening	112	641.70	613.44	1.05
Total	428	1,887.7	1,791.1	

ETo = reference evapotranspiration, Kc = crop coefficient

Finally, the sugarcane crop coefficient was developed from locally determined reference evapotranspiration and experimentally determined sugarcane evapotranspiration by Lysimeter. The sugarcane crop coefficient (Kc) developed based on daily values of ETc and ETo as a function of growing period was presented in Figure 6.12 (Appendix table 6.1).

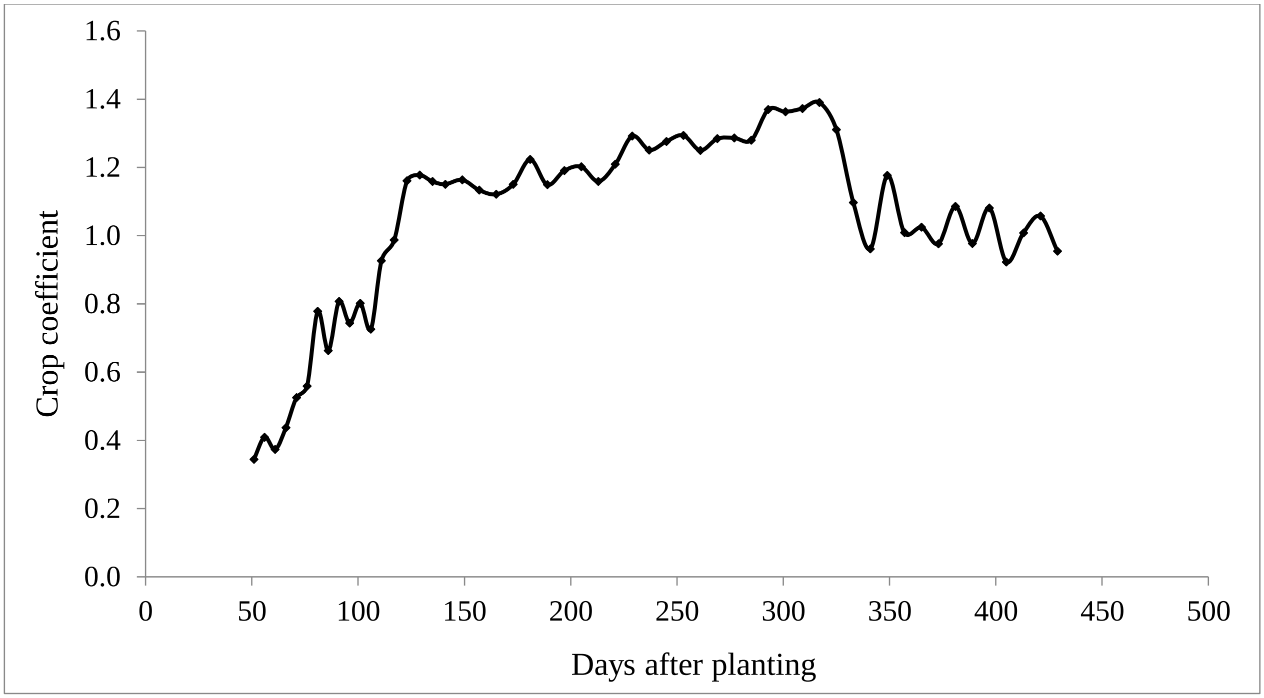

Figure 6.12. Sugarcane crop coefficient (Kc) values determined from lysimeter experiment

Sugarcane crop coefficient based on water balance at each growth stage was given in Table 6.4. While ETc on short time interval like on daily basis is important for irrigation management of crops for the purpose of determining generalized crop coefficient of the crop at each growth stage. The sugarcane crop evapotranspiration and crop coefficient were developed at each irrigation intervals during the crop growing season.

The average Kc values obtained at each growth stage were 0.42, 0.93, 1.26 and 1.05 at emergence and germination, tillering, grand formation and ripening growth stages respectively. The Kc values obtained from the current study and that found in literatures was presented in Table 6.4. There is slight variation between the values of Kc developed by different authors influenced by site specific factors. However, the results are in slightly in good agreement with a FAO-56 guideline on sugarcane crop coefficient and good with many of the earlier studies findings in the literature.

Table 6.4. Sugarcane Kc determined by different researchers at each growth stages as compared to current study

Authors	Kc –values per growth stage			
	Germination and emergence	Tillering	Grand formation	Ripening
Current study (2021)	0.42	0.93	1.26	1.05
Da Silva *et al.* (2013)	0.18	0.74	1.06	0.76
Win *et al. (* 2014)	0.53	0.81	1.25	1.27
Gabriel *et al.* (2015)	0.31	1.15	1.25	0.90
Dinger and Gorantiwar (2020)	0.43	1.03	1.29	0.56
Osaeid *et al.* (2013)	1.07	1.33	1.45	1.14
FAO 56 (1998)	0.40	1.02	1.25	0.75

The Kc values of sugarcane determined by Dingre and Gorantiwar (2020) was in good agreement with the results of current study with slight deviation at ripening growth stage. The findings of Win *et al*. (2014) showed relatively similar variation in all growth stages with the current results except at ripenning growth stage. The other findings by DaSilva *et al.* (2013) showed a great differences at all growth stages as compared to the current study result as well as the FAO-56 recommendation and other related literatures. In opposite to the current study, the findings by Osaeid *et al.* (2013) indicated higher Kc values at all growth stages. Compared to FAO-56 values, the sugarcane Kc values obtained were greater at emergence and germination and ripening growth satges, lower at tillering growth stages and similar at grand formation growth stages. The little variation in sugarcane crop coefficient at some growth stages may be due to the experimental management, location specificity and accuracy in data collection during the growth stgaes of the crop. There is a good agreemnt between the results of the current study and the FAO recommendation and some other literatures on sugarcane Kc values. The result shows that the Kc values from the current study is justifiable and can be used in the future studies.

6.9.7. Reference evapotranspiration by selected models

There are different models used to determine reference evapotranspiration but the selection of the models depends on availability of the weather parameters required by the models at specific location of the area and accuracy of the models. The following models were selected to determine the reference evapotranspiration for the current study area.

6.8.7.1. Blaney Criddle model

Determination of the reference evapotranspiration by this model required only temperature and sunshine hour data. Based on those required weather data collected from the study area, the reference evapotranspiration was determined (Figure 6.13) and the result obtained from this model compared with that of PM model.

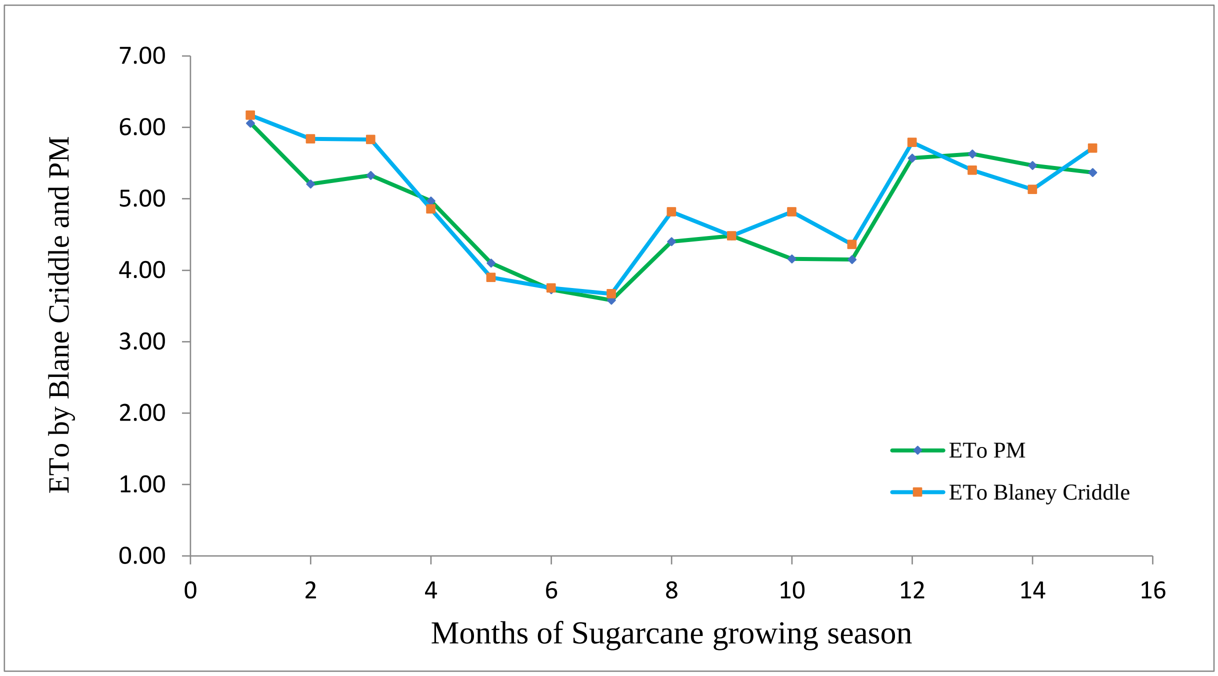

Figure 6.13. ETo determined by Blaney Criddle model as compared to FAO PM model

As the result obtained indicated, the variation of ETo determined by the Blaney Criddle model and PM model was less during the most growing periods of the crop. Therefore, this model can be used under scarcity of weather parameters that are required for PM. If water requirement of the sugarcane determined by using this model and crop coefficient developed for the specific location, this may not cause any adverse effect of irrigation due to over or under water application on growth and yield. The result obtained by Gotardo *et al. (*2016), revealed that the reference evapotranspiration obtained by Blaney Criddle model was more closer to the FAO-penman monteith model than all the other models. Similar to the current study, the study by Hafeez and Khan (2018) revealed that the reference evapotranspiration determined Blaney Criddle model was better agreement with the FAO Penman Monteith model than the other models considered.

6.9.7.2. Hargreaves model

Determination of the reference evapotranspiration by Hargreaves model required only temperature and solar radiation data. Based on the required weather data collected from the study area, the reference evapotranspiration determined by this model was presented in Figure 6.14 and the result obtained was compared with the PM model.

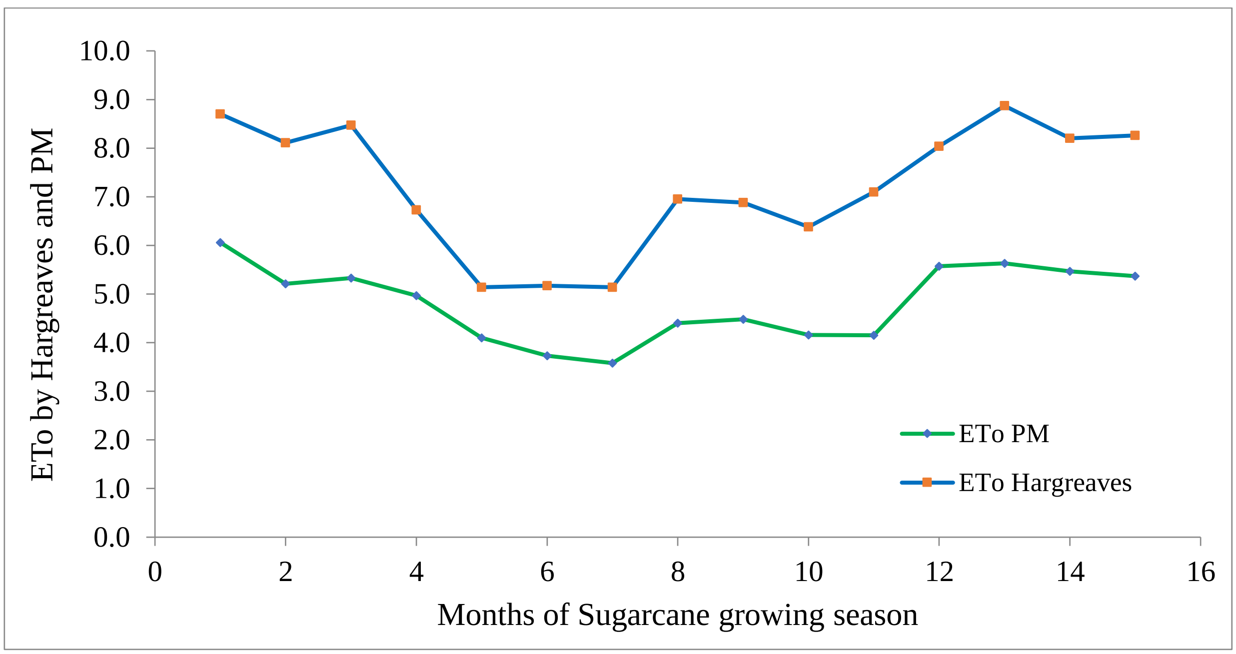

Figure 6.14. ETo determined by Hargreaves model as compared to FAO PM model

The reference evapotranspiration determined by this model indicated a very much variation from the PM model throughout the growing season of the crop. As a result, if the crop water requirement determined by using this model, it can cause an over irrigation and since the sugarcane is sensitive to both irrigation extremes, it can affect the crop growth as well as the yield of the crop significantly. The result of this findings is similar to the findings by Lima *et al.* (2013) in which the ETo determined by the Hargreaves model was greater than the FAO Penman Monteith model thoughout the growing periods. The result of the present study is also in agreement with that of Adeboye *et al.* (2009) who revealed that the ETo determined by this model was greater than that of the FAO PM throughout the growing season of the crop.

6.8.7.3. Thornthwaite model

Determination of the reference evapotranspiration by this model required only temperature data. Based on the data collected from the study area, the reference evapotranspiration was determined by this model is shown in (Figure 6.15) and the result obtained was compared with the PM model.

Figure 6.15: ETo determined by Thornthwaite model as compared to FAO PM model

As the result indicated, ETo determined by this model was greater than that of PM model only during early growth stages of the crop and lower than the ETo determined by PM model at except at initial of crop growth stages. If crop water requirement was determined based on this model after the establishment, the crop faces water stress throughout the crowing periods and as a result the crop growth as well as the yield of the crop might be adversely affected. The result obtained by Khedkar *et al.* (2015), indicated that the reference evapotranspiration determined by Thornthwaite model showed lower than that of FAO Penman Monteith model similar to the current findings. The other study findings by Hossein *et al.* (2013) showed that ETo determined by Thornthwaite model was lower than the Penman Monteith model throughout the study periods similar to the current study.

6.8.7.4. Drooger and Allen model

The reference evapotranspiration was determined by this model from temperature and solar radiation only. Based on the required data collected from the study area, the determined reference evapotranspiration was compared with the PM model (Figure 6.16).

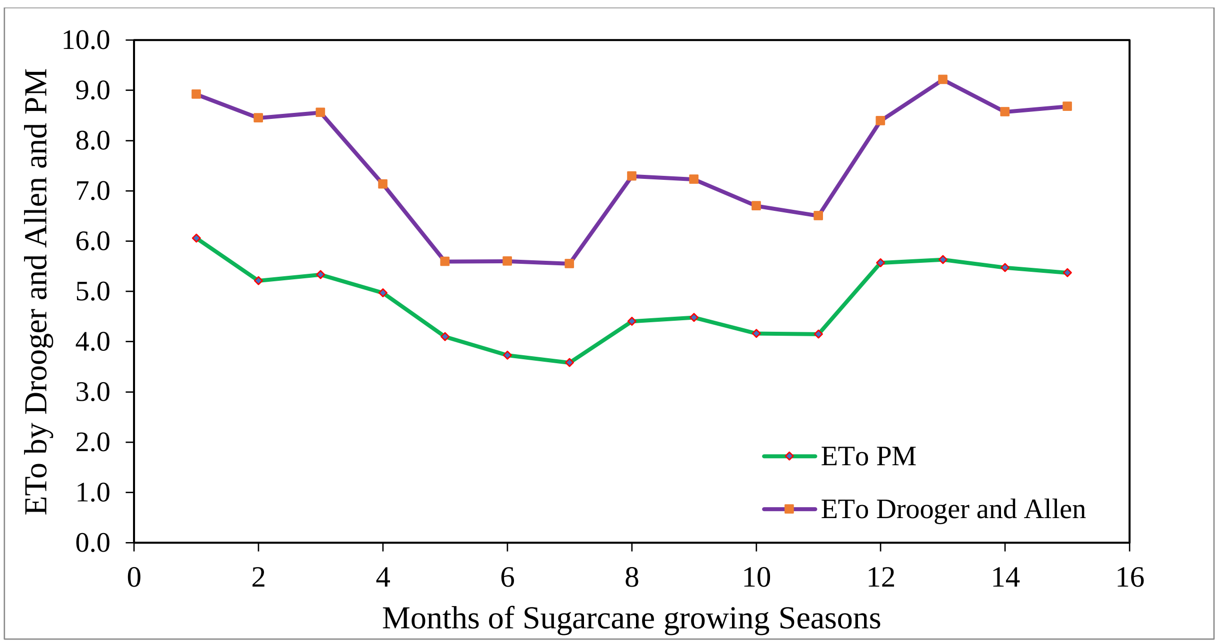

Figure 6.16: ETo determined by Drooger and Allen as compared to FAO PM model

The reference evapotranspiration determined by this model was much greater than the PM model throughout the growing season of the crop. As it can be observed from Figure 6.16, ETo determined by this model was very much greater at early and late growth period of the crop. If the crop water requirement was determined based on this model, more water may be applied throughout the growing periods of the crop that can adversely affect the growth and yield of the crop. The study findings by Peng and Feng (2017) showed that the ETo determined by this model was by far lower than the Penman Monteith model similar to the current study finding. The other study findings by Droogers and Allen (2002) showed higher estimation of reference evapotranspiration similar to the current study findings.

6.8.7.5. Irmak model

The reference evapotranspiration was determined by Irmak model used temperature and solar radiation data collected from the study area. The reference evapotranspiration determined by this model was compared with PM model (Figure 6.17).

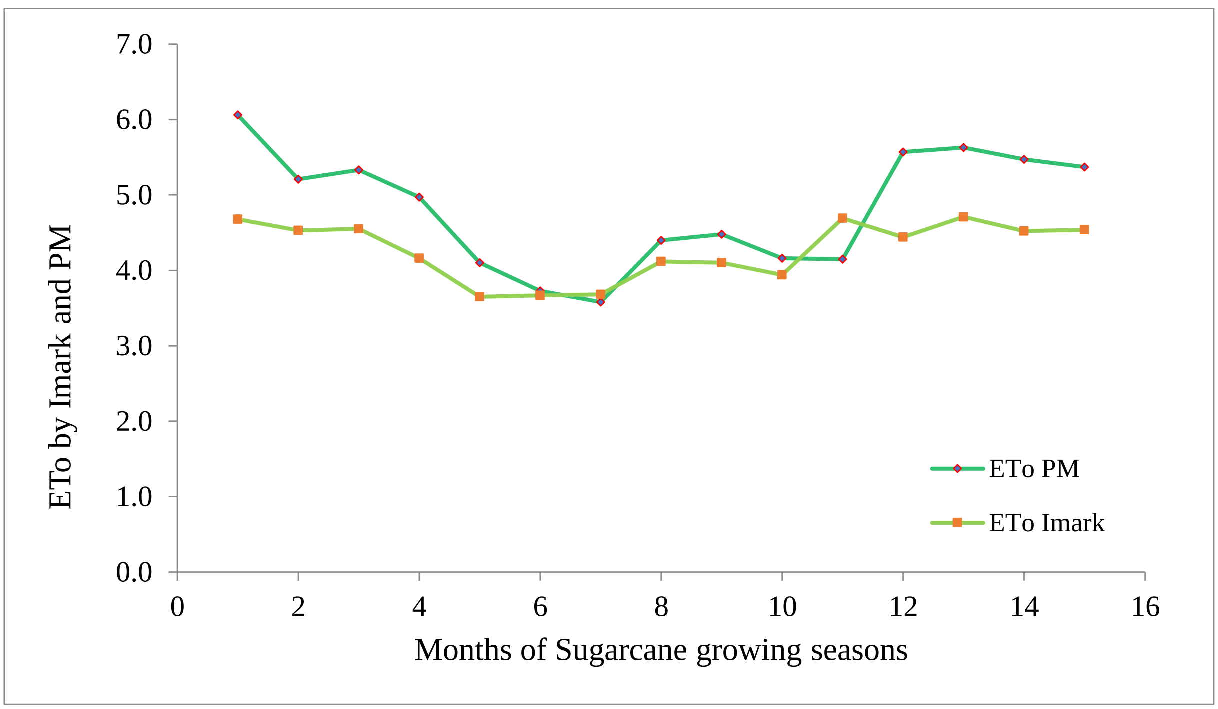

Figure 6.17: ETo determined by Irmak model as compared to FAO PM model

The reference evapotranspiration determined by this model indicated relatively lower than that of PM model during early and late growth stages. But a little bit similar during development and mid-season growth stages with PM model. If the crop water requirement applied based on this model, its effect on the crop growth and yield will be relatively less compared to the previous models.

6.8.7.6. Tabari model

The reference evapotranspiration was determined by this model in which the model required only temperature and solar radiation data collected from the study area that compared with the PM model (Figure 6.18).

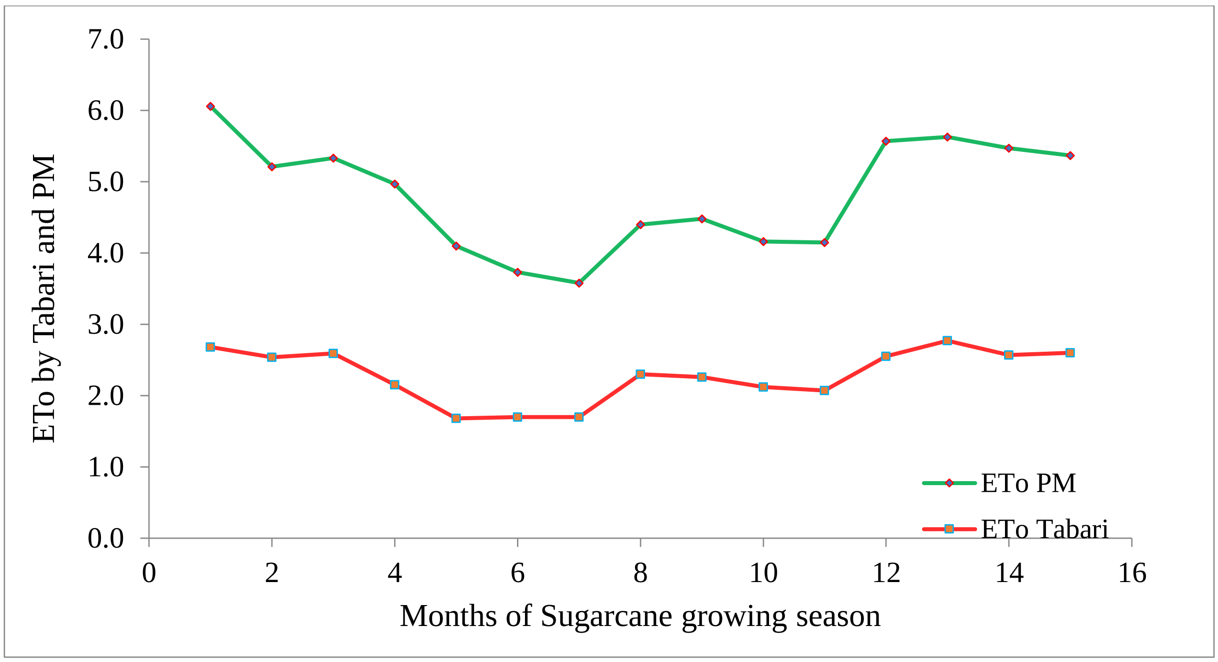

Figure 6.18: ETo determined by Tabari as compared to FAO PM model

The reference evapotranspiration determined by this model was very much lower than the PM model throughout the growing periods of the crop. Hence, if the crop water requirement of the crop determined based on this model, throughout the growing periods the crop faces water stress which may result in lower crop growth performance and finally the yield of the crop will be adversely affected.

6.9.8. Performance evaluation of the models

In the current study, different statistical indices were used to evaluate the performance of the selected reference evapotranspiration models as compared to the CropWat model. The performance evaluation was used to select the best models that best fit with the reference evapotranspiration determined by recommended model (PM model). From many statistical indices used to evaluate the performance of selected models, the most frequently used were root mean square error (RMSE), mean bias error (MBE), t-test, coefficient of determination (R^2) and Index of agreement (IA). The values of the indices for each selected models were worked out and are presented in Table 6.5.

Table 6.5. Statistical indices used to evaluate the performance of the selected model

Models	RMSE	MBE	t-test	R^2	IA
Blaney-Criddle	5.71	0.13	0.01	0.67	0.86
Drooger and Allen	13.86	2.3	0.34	0.90	0.29
Hargreaves	12.57	1.87	0.29	0.01	0.41
Irmak	6.21	0.62	0.13	0.62	0.85
Tabari	14.83	-2.49	0.38	0.85	-1.36
Thornthwaite	10.35	-1.54	0.29	0.00	0.03

From the selected reference evapotranspiration models, the selection criteria were based on lower RMSE and MBE and higher R^2 and IA with lower t-test value. Based on the RMSE values Blaney-Criddle model (5.71) performed better followed by Irmak model (6.21) as compared to the PM model in the current study area. The current study result is similar with the study conducted by Shwetha and Nagesh Kumar (2018) on Comparitive evaluation of different potential evapotranspiration estimation approaches in which Blaney-Criddle model performed better than all other selected models. Tabari and Thornthwaite models under estimated reference evapotranspiration but Droogen and Allen, and Hargreaves models were over estimated the reference evapotranspiration in the current study climatic condition. The Blaney-Criddle and Irmak models relatively similar to that of the PM model. In general, based on the result obtained on the performance evaluation of selected reference evapotranspiration models in the current study area climatic condition, Blaney-Criddle models was observed to be the best model as compared to the PM model compare to the other models. Next to the Blaney-Criddle, Irmak model was better model as compared to the PM model than the other models. This indicated that, in case where all required climatic variables for the PM models are not available to determine ETo, Blaney-Criddle model can be used to determine the reference evapotranspiration under the current climatic condition.

6.10. Conclusions and Recommendations

6.10.1. Conclusions

Sugarcane production in Ethiopia increased from time to time to meet the increasing demand for sugar. On other hand, sugarcane is a perennial water-intensive crop which requires critical irrigation water management through the growing seasons of the crop. But furrow irrigation method is the most dominantly used irrigation methods under sugarcane production on the large-scale basis like Wonji Shoa Sugar Estate. The efficiency of furrow irrigation is affected among other by the level of knowledge the crop coefficient which is required to determine crop and irrigation water demand. The sugarcane irrigation planning and management has been threated due to lack of these measured parameters. The crop water requirement and crop coefficient for sugarcane were successfully determined based on a one season lysimeter experiment and Melkassa Agricultural Research Center. The results indicated that average sugarcane water requirements obtained were 2.18, 4.02, 5.26 and 5.73 mm/day during emergence and germination, tillering, grand formation, and ripening growth stages respectively. The sugarcane crop coefficients obtained from the current study at these growth stages were 0.42, 0.93, 1.26, and 1.05, respectively. As ETc and ETo are influenced by site specific climate conditions, it is quite normal that ETc and Kc varies for the same crop across regions. Therefore, from the current study it can be concluded that, although the experiment was undertaken for one season, for data scarce conditions like in Ethiopia, the values determined in this study can be helpful for irrigation water management of intensively produced sugarcane. Also, based on the performance of the ETo model evaluated as compared to FAO Penman Monteith, Blaney-

Criddle model can be used when there is unavailability of required data for PM in determining the reference evapotranspiration in the study area.

6.10.2. Recommendations

Irrigated sugarcane farms are rapidly expanding in Ethiopia to satisfy sugar demands and substitute imports. With increasing expansion, it is also important to improve its productivity and sustaining the production. Form the results of this study, the following recommendation are put forward:

- Site specific information about crop, climate, soil and management condition are required for effective planning and efficient management of irrigation
- So far measured data related to water requirement and crop coefficient of sugarcane are lacking. The results of this study, although based on a single season experiment, can be useful for planning and management of irrigated sugarcane.
- Under Wonji Shoa condition, the sugarcane exhibits increasing water requirement toward grand formation and ripening stages. The later stage is also the growth stages when sucrose accumulation is taking place and irrigation is purposely reduced.
- Irrigated sugarcane farms are expanding throughout the country. Hence, it important that the crop water demands and crop coefficient of this important industrial crop be determined through conduction adequate experiments.
- For determination of reference evapotranspiration, Penman-Monteith is universally used. However, as the model is data intensive, its application is limited in some areas where the data required are scarce. Hence, under such conditions, Blaney-Creddle may be used.

6.10. References

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7. ANALYZING THE EFFECTS OF FURROW IRRIGATION DESIGN PARAMETERS ON SUGARCANE GROWTH, QUALITY AND WATER PRODUCTIVITY UNDER WONJI SHOA CLIMATIC CONDITION"

ABSTRACT

Sugarcane is one of the essential industrial crops produced all over the tropical areas. Sugarcane production is highly expanding in developing countries like Ethiopia. However, due to its long growing season, it is characterized by very high crop water requirements. In Wonji Shoa, sugarcane is primarily produced using furrow irrigation. Proper and sustainable management of furrow irrigation system requires identification of optimum combination of design parameters and decision variables. A field experiment was conducted at Wonji Shoa Sugar Estate to evaluate the effects of furrow irrigation design parameters and decision variables on growth and yield parameters and water productivity. The factorial experiment was undertaken using furrow slope (0.05, 0.08, 011), furrow length (30, 50, 70 m) and furrow inflow rate (4, 5, and 6 l/s) as main factor, sub factor and sub-sub factor with three levels of each factor that laid out using split-split plot design replicated three times. All required data on growth and yield of sugarcane parameters were collected and analyzed using SAS 9.4 version statistical software. Sugarcane water productivity was analyzed from the experiment and simulated using AquaCrop model for the three irrigation inflow rates (4, 5 and 6l/s). The effect of furrow slope showed statistically significant variation at 5% significance level on growth parameters (cane height, cane weight, cane diameter and number of cane internode per stalk), but non significant variation on yield components of sugarcane (moisture percent, dry substance, number of millable cane stalk and sugarcane yield). But the effect of furrow length showed statistically significant variation on almost all growth and yield parameters at 5% significance level except sugarcane yield. Finally, the effect of furrow inflow rate on all growth and yield parameters showed statistically significant variation at 5% significance level except number of millable cane stalk. The interaction effects between the three factors showed significant variation on cane yield. In general, the highest sugarcane yield was obtained from furrow slope three (0.11 %), furrow length three (70 m) and furrow discharge rate one (4 l/s). The effect of furrow slope, furrow length and discharge rate on almost all sugarcane quality parameters showed statistically non significant variation. This result indicates that the effect of furrow irrigation design parameters has no direct relation with the quality parameters of sugarcane. The sugarcane water productivity was found to be 15.2, 12.0 and 9.6 kg/m^3 for inflow rate of 4, 5 and 6 l/s respectively. Appropriate furrow irrigation designs and decision variables resulted in better sugarcane water productivity. This revealed that when proper consideration is given to irrigation design and decision variables, it leads to reduces the adverse effects irrigation on sugarcane productivity and sustainable production in addition to saving natural resources. Therefore, from the current result it can be concluded that, appropriate furrow irrigation design and decision variables are the key factor for sugarcane productivity, production and sustainability that also improve the sugarcane water productivity.

Keywords: *AquaCrop***,** design parameters, *decision variables, Sugarcane, growth, quality, Yield, Water productivity*

7.1. Background of the Study

Irrigation water sources are among the most limiting factors in crop production in arid and semi-arid regions, mainly for perennial crops like sugarcane. The annual rainfall is low and erratic in time and space. Even if its efficiency is low, surface irrigation is one of the most commonly used irrigation methods in the developing countries. The furrow irrigation methods are largely covered from farm households to large mechanized farm. In most cases, especially in developing countries like Ethiopia, surface irrigation system depends primarily on irrigation canals without considering the water requirement, which results in over or under irrigation practices that reduce crop yield (El-Hazek, 2016).

Around 75% of the available water resource is used for irrigation, primarily for surface irrigation with low water use efficiency, which requires better irrigation water management to reduce the water losses since the water demand is increasing from time to time. Many countries in the world are facing irrigation water shortage which requires critical consideration of surface irrigation water management improvement like furrow irrigation to overcome the water shortage (Zayton, 2015).

The main factors that affect furrow irrigation efficiency can be categorised as design parameters, soil characteristics and water management practices. Design variables include the field longitudinal slope, which affects both the rate of advance and recession, and length of furrow, which determines the flow rate required for the uniformity of infiltration over the water run (Sengera and Mpala, 2017). This indicates that, the design procedure determines the main decision variables that highly influence irrigation efficiency. In designing furrow irrigation, the proper design consideration focused on furrow geometry, advance time, and required depth of application to minimize the furrow channels' erosion problem (Ahmed *et al.*, 2005).

Furrow irrigation is most common type of surface irrigation. The most common furrow geometry considered during design are furrow length, width, bottom width and slope. Furrow discharge largely dependent on soil type, crop water requirement, and advance time depending on the required irrigation depth. Still, its irrigation efficiency is very low due to design problems, especially in arid and semiarid regions that favor more water losses from an open surface (Leal *et al.,* 2017). Designing effective irrigation systems at the farm level is an important element to boost the sustainability of irrigated agriculture. Not only designing new irrigation system but also improving the performance of existing system by redesigning the most important decision variables that affect the water application and on farm water management methods appear to be more important than any other activity for the long term sustainability of an irrigation system (Sengera and Mpala, 2017).

Improving the irrigation system's design and improving water use efficiency or water productivity is one of the critical responses to growing water scarcity, primarily for low efficiency irrigation system. Increasing water productivity is particularly appropriate where water is scarce, and one needs to realize the full benefits of other production inputs. The performance improvement of most surface irrigation systems through the implementation of optimal management practices such as using gated pipes, different precision land levelling, and selection of correct inflow rates based on the soil and crop water requirement is significant at field conditions (El-Sanat, 2018)

Sugarcane can be irrigated by furrow, overhead, and drip irrigation systems all over the world. Even if those irrigation methods are used for sugarcane production, furrow irrigation is the most dominant. But, compared to pressurized systems, furrow irrigation's efficiency is very low, not exceeding 60-70% with an average of 50-55%. The furrow irrigation efficiency is mainly affected by geometric parameters (length, slope and cross section), flow rate, plant age, and soil characteristics. Even if the efficacy of furrow irrigation is low, it is still the major method used worldwide. The major drawbacks of furrow irrigation and the main reasons for its unpopularity among sugarcane farmers are the high labour requirement and low WUE stemming from percolation and tail-water losses (Gunarathna *et al.,* 2018). The primary means of improving irrigation efficiency of furrow irrigation is through proper irrigation design with appropriate combination of decision variables (Dayer *et al.,* 2018). In Wonji Shoa Sugar Estate, furrow irrigation is the only irrigation type used for sugarcane production. However, there is limited studies were undertaken on the furrow irrigation design variables.

Generally, most of irrigation structures constructed in Ethiopia are not working with their intended capacity due to design problems and poor water management including the large scale irrigation like Wonji Shoa Sugar Estate. The expansion of irrigation from small to large scale has increased from time to time throughout the country but without proper consideration of irrigation water management, which may not be a guarantee to fulfill its intended objectives. To achieve the planned objectives at any level, special consideration should be taken into account on structural and improvement of irrigation water management to enhance irrigation efficiency and water productivity (Tesfaye *et al.,* 2016).

7.2. Statement of the Problems

Sugarcane is one of Ethiopia's most important industrial crops, primarily produced using furrow irrigation methods. The production and productivity of this critical crop are not much attractive in Ethiopia, like Wonji Shoa Sugar Estate, one of the country's most prominent pioneer in the sugar industry. The Commercial sugarcane production system in Ethiopia and elsewhere is to increases sugar production per unit area. The production and productivity of sugarcane are affected by improper irrigation water management, irrigation scheduling, agronomic management, and environmental factors. Hence, appropriate irrigation design with suitable decision variables is one of the critical factors for improving the sugarcane production and productivity. In sugarcane production, improving the irrigation water use efficecny is very importnant since water is one of the main limiting factors and sugarcane requires more irrigation water for long periods to be harvested. The amount of water applied can be reduced through precise land levelling, proper field layout, appropriate irrigation methods and proper irrigation scheduling (Qureshi and Ashraf, 2019). An adequate amount of water is needed at the right time to get higher sugarcane yield and that should be applied to the field. The application of right amount of irrigation water at a right time improves the sugarcane water consumption that improves water productivity.

If the furrows irrigation designs are not constructed with suitable slope in relation to soil type and furrow length, the system could not work properly even by applying proper decision variables. This may result in wasting of precious water resources and induces soil erosion which influence the efficiency of irrigation. Furrow irrigation systems can attain good level of efficiency when all design parameters are well designed and appropriately implemented. On the other hand, limited water resources restrict expansion of sugarcane establishment and growth in many regions of Ethiopia. Improving water productivity is very important particularly for water intesnive crops like sugarcane since water scarcity is the major problem of crop production. In irrigated lands, water productivity is critical to mitigating water shortage problems specially in arid and semiarid regions. Aquacrop model is one of the most commonly used to analyze the water production under water stress condtions.

The efficeiny of furrow irrigation is highly dependent on the design parameters and decision variables (Sengera and Mpala, 2017). Since, sugarcane requires substantial amounts of water throughout the growing season, its water requirements at different growth stages needed to plan, design and implement appropriate irrigation water management practices. In line with this, selection of proper furrow irrigation, the decision variable combination helps to increase the irrigation efficiency by delivering the required amount at the required time properly. Due to this, selections of appropriate furrow irrigation design parameters are essential especially in large scale irrigation like Wonji Shoa sugarcane plantation to overcome the adverse effect of the mismanagement of irrigation water. As the result obtained under section 5 of this study, the performance of current furrow irrigation water management practices is poor, improvement options were developed based on the selecting appropriate decision variables. This result should be used as an input for this field experiment but due to both researches conducted parallelly, the decision variables for this experiment was based on currently under use. By considering this, the field experiment was undertaken to identify the appropriate furrow irrigation design parameters and its effect on growth and yield of sugarcane under Wonji Shoa sugarcane plantation.

7.4. Objectives of the Study

General objective of the study was to analyze the effect of furrow irrigation design parameters on sugarcane growth, yield and quality parameters, and its water productivity under Wonji Shoa climatic condition.

The specific objectives were:

- ✓ To determine the optimum furrow irrigation design parameters (furrow slope, length and discharge rate)
- ✓ To analyze the impact of different furrow irrigation design parameters on growth, yield and quality parameters of sugarcane.
- ✓ To analyze the impact of different furrow irrigation design parameters on sugarcane water productivity.

7.5. Research Questions

- What is the optimum furrow irrigation design parameters under Wonji Shoa condition?
- What is the impact of furrow irrigation design parameters on sugarcane growth, yield and quality parameters?
- What is the impact of furrow irrigation design parameters on sugarcane water productivity?

7.5. Significance of the Study

Furrow irrigation is the commonly used irrigation method at Wonji Shoa Sugar Estate. Since, sugarcane is the perennial crop, the problems of furrow irrigation design and decision variables highly affects irrigation efficiency, sugarcane production and soil productivity for the future. The findings of this study could help the institution to redesign the furrow irrigation with an appropriate combination of the decision variables. This may use to reduce irrigation water losses and improves furrow irrigation efficiency. Specifically, the current study is helpful for irrigation and plantation section of the Estate, to appropriately design the irrigation water diverted from the water source and required at the field according to sugarcane water requirements. This study results will also help all field experts to understand the adverse effect of irrigation water mismanagement on crop production and future soil productivity. Because, during the study periods, most of the irrigators in the field said that more irrigation application is resulted in more sugarcane yield. Since the study focused on the design of furrow irrigation, the result of this study can be used in any area where sugarcane produced using furrow irrigation methods. But further research on the design of furrow irrigation based on the combination of appropriate decision variables is very important to validate the current study findings for effective and improved sugarcane irrigation water management that improve the crop productivity.

7.6. Materials and Methods

7.6.1. Description of the study area

The Wonji Shoa Sugar Estate (WSSE) is located in the South East Shoa Zone of Oromia Regional State, at a distance of 110 km from Addis Ababa, the capital city of Ethiopia. Geographically, it is situated at $8^0$21’- $8^0$29’ N and $39^0$12’- $39^0$18’E and altitude of 1223 to 1550m above MSL. The soil of the area varies from sandy loam to heavy clay types. The area is characterized by gentle and regular topography, making it most suitable for irrigation. Sugarcane is grown in the area, mainly as a monoculture. The site’s climate is semiarid, with main rainy season from June to September. The rainfall of the area is erratic both in quantity and distribution. The site receives mean annual rainfall of 831mm with mean yearly maximum and minimum temperature of 27 and 15^0C respectively.

The Estate is the first commercial large scale irrigation scheme in Ethiopia and was established in 1954 at Wonji by Netherland’s Hender Verneering Amsterdam (H.V.A.) Company private investors and the Ethiopian government. When the factory started production in 1954 its initial production was 1,400 quantal/day (WSSF, 2018). Wonji and Shoa know the two factories. Sugar Factory altogether had the capacity of producing 750,000 quantal/year till recent time (before the completion of the new Wonji Shoa Sugar Factory at Dodota site far apart from the old factories). After serving for more than half a century and getting obsolete, the two factories

Wonji and Shoa sugar factories were closed in 2011 and 2012, respectively. Replacing these pioneer factories, the new and modern factory started production in 2013 with higher production capacity. Currently, the WSSE sugarcane plantation covers and irrigated area of 12,000 ha of which 5,000 ha is managed by the Estate itself and 7,000 ha is managed by an out-growers. The irrigation water source is Awash River. The Wonji Shoa sugar Estate location map is presented in (Figure 5.1).

7.6.2. Materials and treatment combinations

For this experiment, different materials were used from the field preparation to data collection. Measuring tape, spade, rake and pitchfork were used for field preparations and layout. Planting materials and inputs used were sugarcane variety NCO_{334}, with two buds, fertilizers and chemicals. The soil sample was collection using auger, shovel, soil moisture can and sensitive weight balance. Depth wise soil moisture analyzed using oven dry and sensitive balance. The irrigation water is managed using Parshall flume, ruler, stop watch were used. Finally, for sugarcane yield and quality parameters analysis, cane cutter (machete), weight balance, length measuring meter and caliper were used in addition to different laboratory materials

For this experiment, three different factors (furrow slope, length and discharge rate) with three levels for each factor were used. Based on the numbers of factors included in the factorial experiment, split-split plot design was selected. The required depth of application and cutoff time for each furrow length and inflow rate computed and the treatment combinations are given in Table 7.1.

Table 7.1. Treatment combination of factors including all levels of factors (Zreq.= 78.6 mm)

Furrow slope (%)	Furrow length (m)	Inflow rate (l/s)	Tco (min)
0.05	30	4	24
		5	19
		6	16
	50	4	40
		5	32
		6	26
	70	4	55
		5	44
		6	37
0.08	30	4	24
		5	19
		6	16
	50	4	40
		5	32
		6	26
	70	4	55
		5	44
		6	37
0.11	30	4	24
		5	19
		6	16
	50	4	40
		5	32
		6	26
	70	4	55
		5	44
		6	37

7.6.3. Experimental design and layout

The treatments were laid out in a split-split plot design with three factors arranged as the main plot, subplot and sub-subplot with three replications in which all factors have three levels. The factors were arranged as per the experimental design as main factor plot, furrow slope (FS), subplot factor, furrow length (FL) and sub-subplot factor, furrow discharge rate (FQ) which applied to all furrow slope and furrow lengths (Figure 7.1).

Figure 7.1:Layout of the experimental design

The experimental factors given in Figure 7.2 are defined as F1, F2, F3 are furrow length of 30, 50, 70m and Q1, Q2, Q3 are inflow rates of 4, 5, 6 l/s r and slope 1, 2 and 3 are 0.05, 0.08 and 011 respectively.

7.6.4. Soil moisture analysis

In the determination of the soil moisture content of the field experiment, the soil sample was taken from the field in the Z fashion across the whole field at two depths (0-30 and 30-60cm) to determine the required depth of irrigation of the field. To determine the soil moisture content, the wet weight of soil sample was taken from the field at each depth and weighted at the field using sensitive balance and then taken to oven dry at 105^0C for 24hrs. The oven dried soil sample was weighted to obtain dried weight and the gravimetric moisture content of the soil was determined using (Equation 7.1)

$$\theta_g = \left[\left(\frac{W_{wet} - W_{dry}}{W_{dry}}\right) \times Di\right] \times 100 \qquad 7.1$$

Where: W_{wet} = Wet weight of soil (g), W_{dry} = Dry weight of soil (g), Di = depth of sampling (cm)

The volumetric soil moisture content was determined using (Equation 7.2) and the change in soil moisture content (ΔSM) before irrigation (SM_{BI}) and after irrigation (SM_{AI}) was computed using (Equation 7.3) before the next irrigation application.

$$\theta_v = \theta_g \times {}^{\rho b}/_{\rho w} \qquad 7.2$$

$$\Delta SM = SM_{AI} - SM_{BI} \qquad 7.3$$

The total available water (TAW) for plant use can be determined from the soil water content at field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}). The total available water within the given soil depth is determine using (Equation 7.4).

$$\mathrm{TAW} = (\theta_{FC} - \theta_{PWP}) \qquad 7.4$$

Where: TAW = total available water (mm/m), $\theta_{FC,}$ θ_{PWP} = soil moisture content at field capacity and permanent wilting point

7.6.5. Irrigation application and management

Irrigation water was applied as full or supplemental irrigation based on the available soil moisture and effective rain fall throughout the crop growth periods. After the selected sugarcane variety with two bud sets were planted, irrigation was applied uniformly until the crop was established well. The irrigation treatments were started after the crop established and irrigation water applied was managed with Parshall flume always installed at 5m far from the experimental field inlet. The time of cut-off was calculated for all furrow lengths and discharge rate for the management of irrigation water applied according to each treatment. Before irrigation water was applied, the available soil moisture was always determined by taking the soil sample from the field from each treatment and available effective rainfall was computed and used for irrigation water balance. The net depth of irrigation water requirement was computed using Equation 7.5.

$$d_{net} = TAW \times \rho \times Zr \qquad 7.5$$

Where: dnet = net depth of irrigation water applied (mm), TAW = total available soil moisture, p = depletion fraction for the crop, Zr = required depth of application (mm)

The required depth of application computed from the furrow geometry and inflow of water (discharge) using (Equation 7.6)

$$Z_r = \frac{Q_i \times 3600}{L \times W} \qquad 7.6$$

Where: Q = Inflow rate of water to the furrow (L/s), L and W = Furrow length and width (m),

After the required depth of application was known, the cut off time for each furrow length was computed from the general irrigators' equation (Equation 7.7)

$$T_{co} = \frac{A \times Zr}{Q \times 60 \times Ea} \qquad 7.7$$

Where: Tco = cutoff time (min), A = area for the furrow (m^2), Zr = required depth of application (m), Q = inflow rate to the furrow (l/s)

7.6.6. Data collection

This study was conducted from March 2019/20 to August 2021 at Wonji Shoa Sugar Estate. From the beginning of the experiment, different data were collected. The major data collected were soil data, weather data, irrigation data, sugarcane growth parameters, analysis of sugarcane quality parameters with some observational data records throughout the crop growth periods.

7.6.6.1. Data on sugarcane growth and yield parameters

For sugarcane's growth and yield component analysis, millable cane stalks were taken from all the treatments. The millable cane stalks were considered for each treatment in all replications for different analyses. The following parameters were collected for analysis of the sugarcane growth and yield parameters.

i). Cane height (CH)

The data on cane height was recorded from randomly selected five sugarcane stalk samples taken from each treatment from all replications. The cane height was measured, and then the average cane height was worked by following Sweet and Patel (1985) using equation 7.8.

$$\text{Average cane height (cm)} = \frac{(\sum 5 \text{ cane stalk height})}{5} \qquad 7.8$$

ii). Cane weight (CW)

The data on cane weight was recorded from randomly selected five sugarcane stalk samples taken from each treatment for all replications. The weight of five millable cane stalk was measured by simple balance at field level. Then, the average cane weight was worked by following Sweet and Patel (1985) using equation 7.9.

$$\text{Average cane weight (kg)} = \frac{(\sum 5 \text{ cane stalk weight})}{5} \qquad 7.9$$

iii). Cane diameter (CD)

The data on cane diameter was recorded from randomly selected five sugarcane stalk samples taken from each treatment for all replications. The cane diameter was measured by caliber and then the average cane diameter was worked by following Sweet and Patel (1985) (Equation 7.10)

$$\text{Average cane diameter (cm)} = \frac{(\sum 5 \text{ cane stalk diameter})}{5} \qquad 7.10$$

iv). Number of cane internodes (NCI)

The data on the number of internodes per stalks was recorded from randomly selected five sugarcane stalk samples taken from each treatment for all replications. Then, the average number of internodes per stalks was worked out by following Sweet and Patel (1985) (Equation 7.11)

$$\text{Average NIC per stalk } = \frac{(\sum 5 \text{ cane stalk NI})}{5} \qquad 7.11$$

v). Moisture percent (MP)

The weight of the clean empty container used for drying cane sample in the oven was recorded as mass (M1). Then about 100 gm of the shredded cane sample was placed in empty container and weighed to record the mass of the container plus cane (M2). Then, the container with sample of cane was placed in the drying oven and moisture teller for drying samples at 110^0c temperatures. When the temperature was stabilized, the drying time was set for about 45 minutes. Finally, the hot container with dried cane sample was weighed to record mass, (M3). The moisture percent in cane was determined from the difference of the wet and dry sample according to the recommendation by (Hundito, 2010) using equation 7.12.

$$\text{Moisture \% cane} = \left(\frac{M_2 - M_3}{M_2 - M_1}\right) \times 100 \qquad 7.12$$

Where: M1 = weight of empty container, M2 = weight of empty container plus cane sample

M3 = weight of empty container plus dried cane sample

vi). Dry substance (DS)

The dry substance was determined for all treatments from the moisture % cane determined using equation 7.13

$$\text{Dry substance \% cane} = 100 - \text{moisture \% cane} \quad 7.13$$

vii). Number of millable cane stalk (NMCS)

The total number of millable cane was counted at 10m intervals for all treatments and converted to furrow length to know the total cane stack population that have greater than 1.0m in length and visible internodes. The total sugarcane stalk per furrow area for each treatment were converted to hectare.

viii). Cane yield (CY)

The sugarcane yield was estimated from the average weight of 20 randomly sampled millable canes (Appendix Figure 7.2) multiplied by the total number of millable cane in each treatment from all replications following (Sweet and Patel, 1985) using equation 7.14.

$$\text{Cane yield} \left({}^{\text{ton}}/_{\text{ha}}\right) = \frac{\text{Weight of 20 MC}}{20} \times \frac{\frac{\text{TNMC}}{\text{FL}} \times 1000}{\text{sampling area FL } (\text{m}^2)} \quad 7.14$$

Where: MC = millable cane stalk, FL = Furrow length, TNMC = total number of millable cane stalks per furrow length

7.6.6.2. Quality parameters of sugarcane

a). Brick percent juice (Bx, %)

The bricks percent juice (Total dissolved Solids) was determined from 5 randomly selected cane stalk samples from each treatment for all replications. The stalk samples were cut from the ground in the morning. After removing sugarcane growing tops and stripping of leaves from the cane stalks, the cane stalk was carried for juice extraction. Cane samples were weighed and fed in to Jeffcott cutter shredder crusher. The cane juice extracted blended in 1000 ml water and 10 ml of a 5 percent solution of Sodium carbonate for 10 minutes.

From this extract, 100 ml portions of an extract of the clarified juice samples were prepared. The sample was passed immediately through the Brixometer devices to 0.2 gm of filter-aid was added. The 100 ml portions of extracting sample stirred and filtered through Whatman No-6. Then, the funnel was covered with a watch glass. The first 10 ml of running filtrates were discarded and the Brix % was determined from extract with the precision of refractometer (Be) (Figure 7.2). After that, the Brix % per unit of extract and fiber % in cane, the Brix % of canes was calculated as suggested by Hundito (2010) using equation 7.15.

$$\text{Brix \% cane (Bx)} = \text{Be}(4 - 0.0125 \times \text{FP}) \qquad 7.15$$

Where: Bx = Brix % per unit clarified, Be = Brix % per unit extracted, FP = Fiber percent

Figure 7.2: Brix refractometer

b). Polarization percent of cane (PL, %)

PL percent juice was determined from 5 randomly selected cane stalk samples from each treatment. The stalk samples were cut from the ground in the morning. After removing sugar cane growing tops and stripping of leaves from the cane stalks, it was taken for juice extraction. Cane samples were weighed and fed into the Jeffcocutter shredder crusher.

The extracted cane juice was blended in 1,000 ml of water and 10 ml of a 5 percent solution of Sodium carbonate for 10 minutes at 8,000 rpm. 100 ml extracted sample was taken and clarified with minimum amount of dry basic lead acetate (0.5 gm.), then added some filter. The 100 ml portions of extracting sample were shaken and allowed to stand until flocculation was completed and filtered by Whatman No-91 (Figure 7.3). Then, the funnel covered with a watch glass. The first 25 ml of running filtrates was discarded and the rest filtrates were polarized in 200 mm Pol tube recorded. From the Pol reading and Pol % per unit extract (Pe) was taken from the Schmidt table. Then from Pol % per unit extract (Pe) and fiber % cane, the Pol % cane (PL) was calculated as suggested by (Hudito, 2010) using equation 7.16.

$$PL\ \%\ cane\ (Pc) = Pe(4 - 0.0125 \times FP) \qquad 7.16$$

Where: Pc = Pol % per unit clarified, Pe = Pol % per unit extracted, FP = Fiber percent

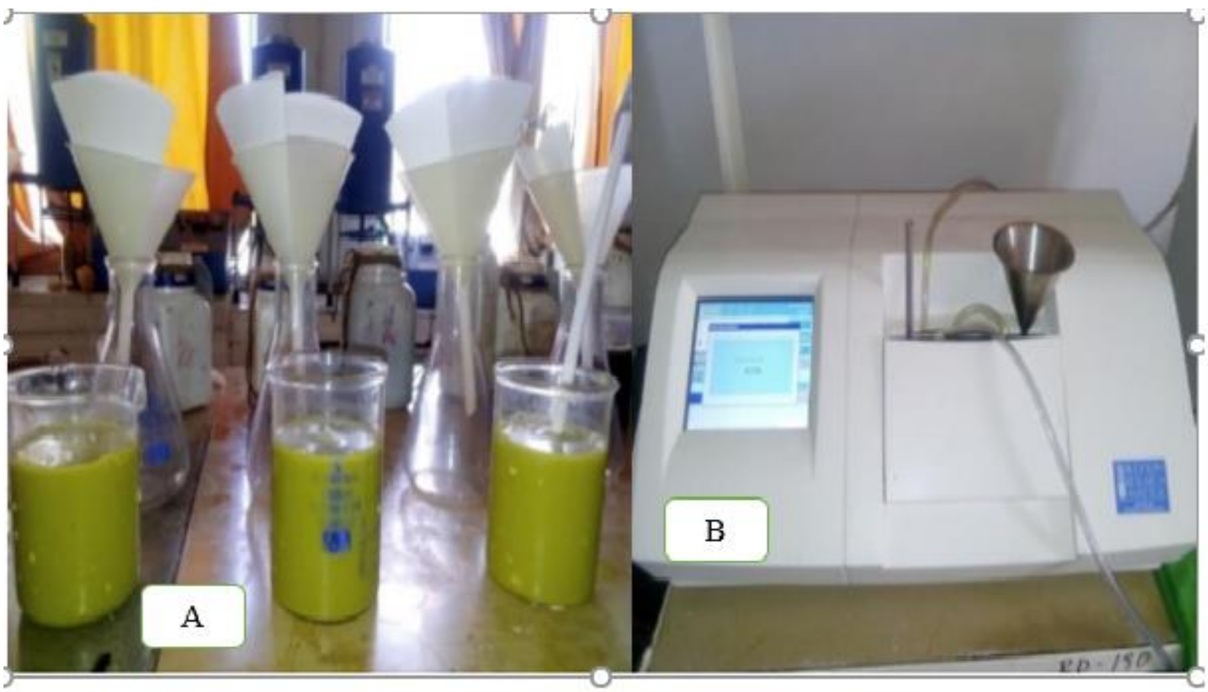

Figure 7.3: Juice preparation for pol reading A) Clarified juice and B) Polarimeter

c). Fiber percent (FP, %)

The fiber percent of sugarcane was calculated by using the analytical data of dry substance percent cane and Brix percent per unit of extract by following the recommendation by (Hundito, 2010) using equation 7.17.

$$\text{Fiber \% cane} = \frac{\text{DS}-4\text{Be}}{1-0.0125\text{Be}} \qquad 7.17$$

Where: DS = dry substance and Be = Brix % per unit of extract

d). Purity percent (PT, %)

Purity percent of juice was determined from the proportion of Pol percent per unit of extract to the Brix percent per unit of extract or from the proportion of Pol percent cane with the Brix percent cane for each treatment. Purity percent of cane should be analyzed 60 days before harvest. Then, purity % was calculated as suggested by (Hundito, 2010) using equation 7.18.

$$\text{Purity \% cane} = \frac{\text{Pe}}{\text{Be}} \times 100 \text{ or } \frac{\text{Pc}}{\text{Bc}} \times 100 \qquad 7.18$$

Where: Bc = Brix per unit of clarified and Be = Brix per unit of extract, PC = Pol per unit of clarified and Pe = Pol per unit of extract

e). Estimated recoverable sugar (ERS, %)

The recoverable sugar percent was calculated by using the Winter Carp indirect method of cane juice analysis (James and Chou, 1993) using equation 7.19.

$$\text{ERS (\%)} = [\text{pol \%} - (\text{Brix \%} - \text{Pol\%}) \times \text{NFS}] - \text{CF} \qquad 7.19$$

Where: ERS = estimated recoverable sugar, NSF = non sugar factor (0.7), CF = cane factor (0.57 for NCO-334)

f). Estimated sugar yield (ESY, ton/ha)

Sugar yield per hectare was calculated from the product of cane yield ton per hectare with estimated recoverable sugar for each treatment (Sweet and Patel (1985). ESY was computed using Equation 7.20.

$$\mathrm{ESY}\left(\frac{\mathrm{ton}}{\mathrm{ha}}\right) = \mathrm{CY}\left(\frac{\mathrm{ton}}{\mathrm{ha}}\right) \times \mathrm{ERS}(\%) \qquad 7.20$$

Where: ESY = estimated sugar yield, ERS = estimated recoverable sucrose (%), CY = cane yield per hectare, PA = plot area of the treatment (converted to the hectare)

7.6.6.3. Data analysis

All the data collected for growth, yield and quality parameters of sugarcane were subjected to analysis using SAS 9.4 version. The least significance between the treatments were test at 5% significance level.

7.6.7. Analyzing sugarcane water productivity using AquaCrop model

7.6.7.1. Description of AquaCrop model

AquaCrop is a crop simulation model which describes the interactions between the plant and the soil (extraction of water and nutrients by root from root zone) and management (soil status and irrigation management practices). The described system is linked to the atmosphere through the upper boundary which determines the evaporative demand (ETo) and supplies CO2 and energy for crop growth. Water drains from the system to the subsoil and the ground water table through the lower boundary. AquaCrop can be used as a planning tool or assist management decisions for irrigated and rainfed agriculture. AquaCrop is particularly useful for understanding the crop response to environmental changes and comparing attainable and actual yields. Identifying the constraints limiting crop production and water productivity, developing strategies under water deficit conditions to maximize water productivity, and evaluating the effect of climate change on crop production. AquaCrop uses a relatively small number of explicit parameters and essentially sensitive input variables. The variables and parameters are either widely available or required just simple methods for their determination. The system interaction as described by FAO is given in Figure 7.4.

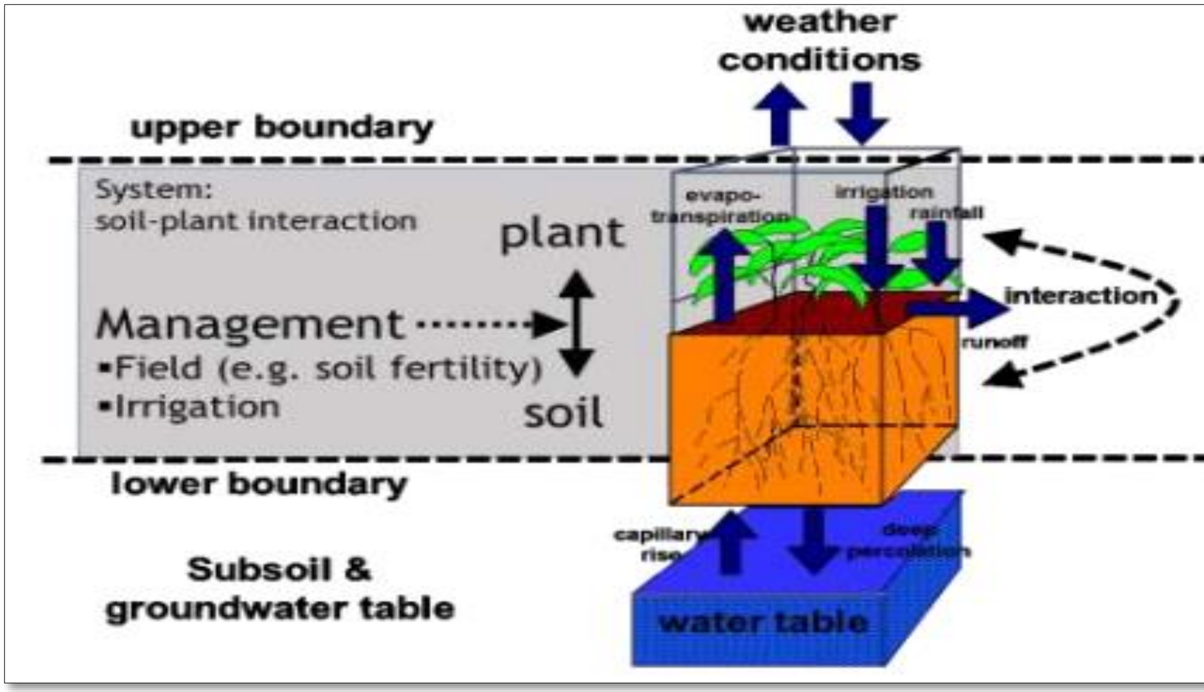

Figure 7.4: The system interactions described by AquaCrop model (FAO, 2017).

Since the AquaCrop model considers many factors, to see the agreements of all parameters determined by the AquaCrop model, above ground biomass, harvest index, yield and water productivity parameters were measured from the field experiment. For this purpose, from the field experiment conducted using three furrow inflow rates (4, 5 and 6 l/s), the considered parameters were collected in the following procedures.

The above-ground biomass was determined by taking all parties of the sugarcane crop above ground from one meter at three different sections along the furrow length. The sample was taken for the furrow length in each furrow discharge rate and averaged out the weighted sample from one meter. After the average weight from one meter obtained, it was converted to the area under each treatment and finally presented per hectare yield (Equation 7.21).

$$AGB\ (Kg) = \sum[(\frac{CSW1\ + CSW2 + CSW3}{3}) + \sum(\frac{SW1\ + SW2 + SW3}{3})] \times A \qquad 7.21$$

Where: AGB = Above ground biomass CSW = cane stalk weight, SW= sheath weight,

A = area of sample

Cane yield (CY): To obtain the cane yield, after the sheath removed from the cane stack similarly weighted from the sampled area and the average weight from three section across the furrow length was converted to the area (Equation 7.22).

$$Cane\ stalk_{weight}(Kg) = \sum(\frac{CSW1\ + CSW2 + CSW3}{3}) \times A \qquad 7.22$$

From the two above yields computed (above ground biomass and cane stalk yield), the sugarcane harvest index was computed using equation 7.23

$$HI\ (\%) = \frac{Cane\ yield}{Above\ ground\ biomass} \times 100 \qquad 7.23$$

To determine the sugarcane biomass water productivity and evapotranspiration water productivity, the total sugarcane evapotranspiration was determined from reference evapotranspiration and crop coefficient. The reference evapotranspiration was determined from the local weather parameters using the model and crop coefficient was determined from the lysimeter experiment. After these parameters were computed, above ground biomass water productivity (WP_{AGB}) and crop evapotranspiration water productivity (WP_{ET}) were determined using equation 7.24 and 7.25.

$$WP_{AGB} = \frac{Sugarcane\ Biomass\ produced}{Sugarcane\ evapotranspiration} \qquad 7.24$$

$$WP_{ET} = \frac{Sugarcane\ yield\ produced}{Sugarcane\ evapotranspiration} \qquad 7.25$$

7.6.7.2. Input data and outputs of AquaCrop model

The input data required for the AquaCrop model were weather, crop, soil characteristics and management practices. The input-output interaction system process in AquaCrop is described in Figure 7.5.

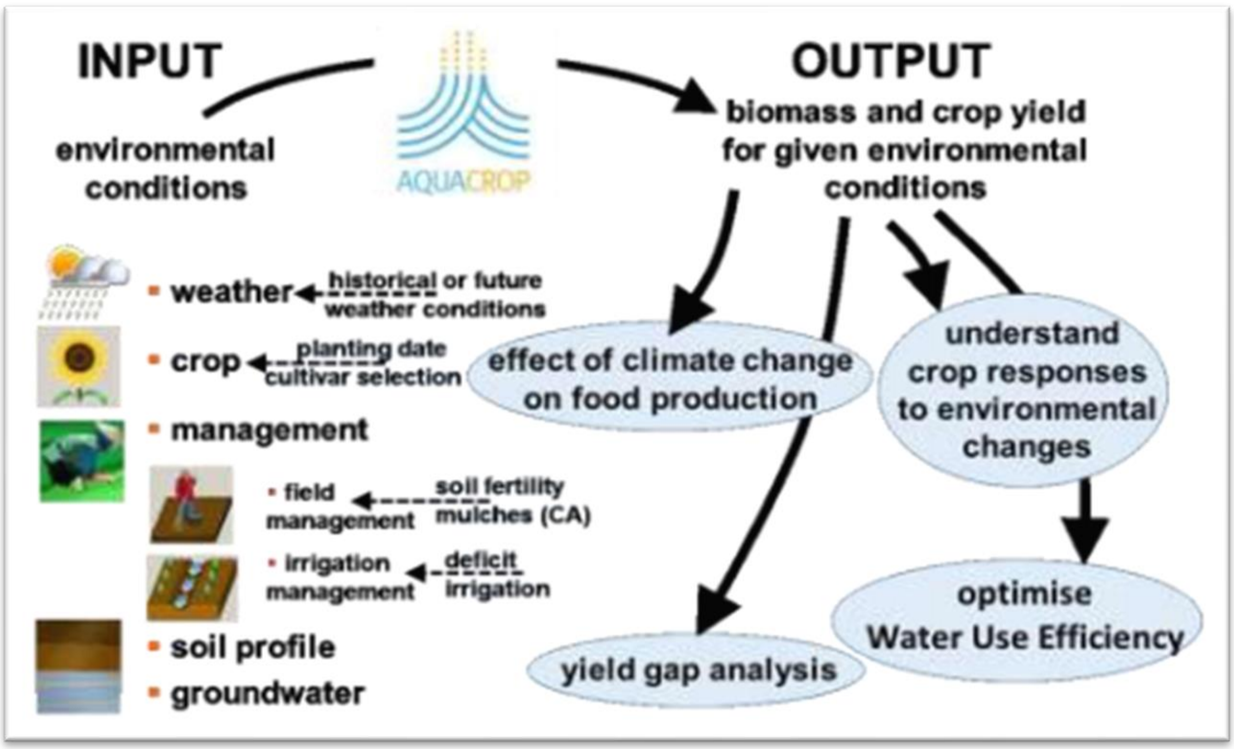

Figure 7.5: The inputs and out puts of AquaCrop model (FAO, 2017).

AquaCrop simulates final crop yield in four steps that are easy to understand and which makes the modelling approach transparent. The four steps consist in the simulation of AquaCrop were development of green canopy cover (CC), crop transpiration (Tr), above ground biomass and crop yield which discussed below.

Development of green canopy cover (CC): In AquaCrop foliage development is expressed through green canopy cover (CC) and not via Leaf Area Index (LAI). The green canopy covers (CC) is the fraction of the soil surface covered by the canopy. It ranges from zero at planting

(0% of the soil surface covered by the canopy) to a maximum value at mid-season which can be one when a full canopy cover is reached (100% of the soil surface covered by the canopy). The CC was estimated based on the method employed by (Farahani *et al.*, 2009) using Equation 7.26.

$$\mathrm{CC} = 1 - \exp^{(-0.65\mathrm{LAI})} \tag{7.26}$$

Crop transpiration (Tr): is the amount of water lost from the crop system through opening stomata. Crop transpiration is calculated by multiplying the reference evapotranspiration (ETo) with the crop transpiration coefficient (Kc_{Tr}) and by considering a water stress (Ks) which is one when there is no stress. The crop coefficient is proportional to CC and hence varies throughout the life cycle of the crop in correspondence with the simulated canopy cover. Water stress does not only affect canopy development but also induce stomata closure and hence affect directly crop transpiration is given by Equation 7.27.

$$Tr = ETo \times Kc_{Tr} \tag{7.27}$$

Above ground biomass (AGB**):** The above ground biomass produced is proportional to the cumulative amount of crop transpiration (ΣTr). The proportional factor is the biomass water productivity (WP). In AquaCrop WP is normalized for the effect of the climatic conditions which makes the normalized biomass water productivity (WP*) valid for diverse locations, seasons and CO_2 concentrations. By separating ET into crop transpiration (Tr) and soil evaporation (E), AquaCrop avoids the confounding effect of the non-productive consumption of water (E). The conceptual equation at the core of the AquaCrop, states that biomass production (B) is proportional to the cumulative amount of water transpired (ΣTr) which computed using Equation 7.28.

$$B = WP \times \sum \left(\frac{Tr_i}{ETo_i} \right) \tag{7.28}$$

The simulated above ground biomass integrates all photosynthetic products assimilated by the crop during the season. Harvest Index (HI) is the fraction of AGB to that of harvestable product (crop yield, Y). Temperature and water stresses directly affect one or both of the above products. AquaCrop considers also the effect of weed infestation, soil fertility and soil salinity stress on canopy development, crop transpiration and biomass production (Equation 7.29).

$$HI = \frac{Y}{AGB} \tag{7.29}$$

The steps in AquaCrop simulation represented from the crop development to the yield formation of the crop (Figure 7.6).

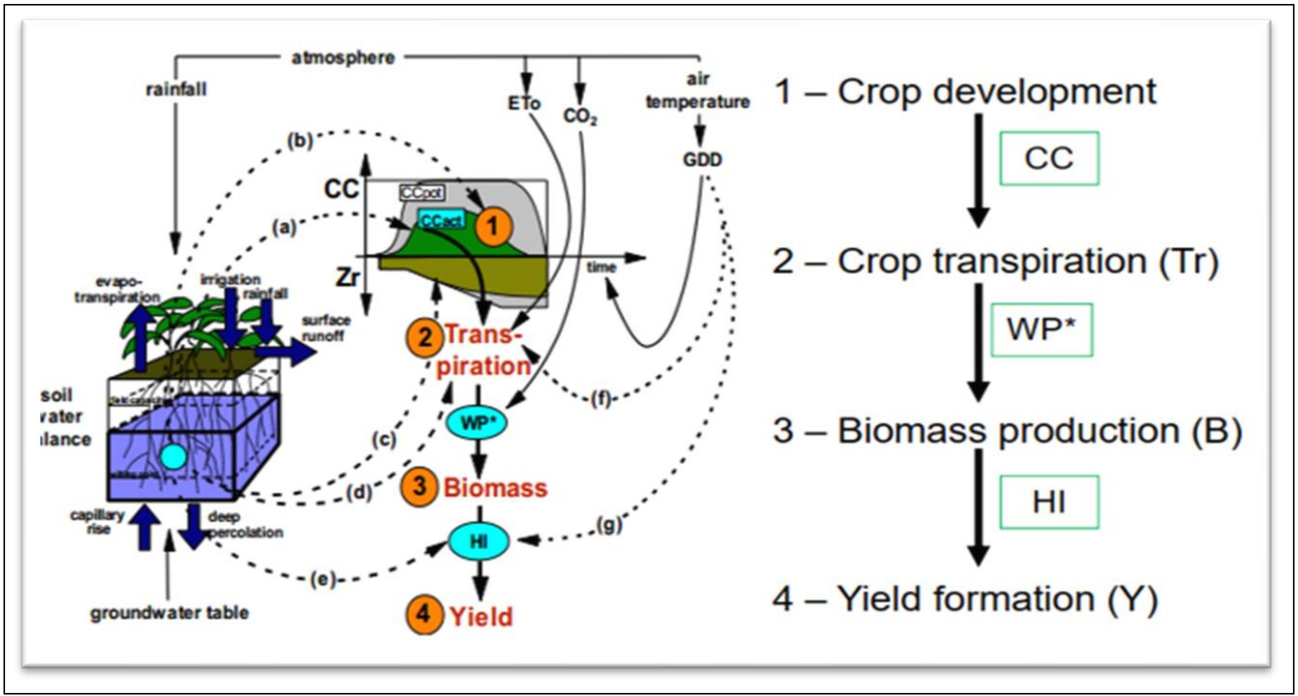

Figure 7.6. Simulation steps in AquaCrop model (FAO, 2017).

7.6.7.3. Water productivity

In AquaCrop model, distinction is made between biomass water productivity (WP_{AGB}) and evapotranspiration water productivity (WP_{ET}) or also called water use efficiency (WUE). The above ground biomass water productivity (WP) expressed as kg of biomass per m^3 of water transpired by Equation 7.30.

$$WP_{AGB} = \left(\frac{Cane\ Biomass\ produced\ (kg)}{Water\ Evapotranspired\ (m^3)}\right) \tag{7.30}$$

Evapotranspiration water productivity (WP_{ET}) is the relationship between crop yield and evapotranspiration expressed as kg of yield produced per m^3 of water evapotranspired. WP_{ET} is typically used as an indicator to assess the performance of a system. AquaCrop uses WP_{ET} to identify the environments in which management strategies by which the yield per unit water (ET) can be maximized. This type of performance indicator is useful under conditions of scarcity of water resources. WP_{ET} is computed using Equation 7.31.

$$WP_{ET} = \left(\frac{Cane\ Yield\ produced\ (kg)}{Water\ Evapotranspired\ (m^3)}\right) \qquad 7.31$$

7.6.7.4. Performance evaluation of AquaCrop model

The model evaluation was performed based on the measured and simulated sugarcane growth, yield and water productivity parameters for the three irrigation treatments. The efficiency of the model must be emulated based on the statistical indicators for the goodness of fit between measured and simulated sugarcane growth, yield and water productivity parameters.

a). Coefficient of determination (R^2): In AquaCrop, R^2 is an efficiency indicator of the model by comparing the measured values of parameters with the predicted values. It explains the amount of the variance explained by the model in comparison to the measured values. The value of the coefficient of determination ranges from 0 to 1, with values close to 1 indicating a good agreement between measured and simulated values of parameters and typically values greater than 0.6 are considered as acceptable. This indicator determined using equation 7.32

$$R^2 = \left[\frac{\sum(O_i - \bar{O}_i)(P_i - \bar{P}_i)}{\sqrt{\sum(O_i - \bar{O}_i)^2(P_i - \bar{P}_i)^2}}\right]^2 \qquad 7.32$$

Where: Oi = observed parameters, Pi = predicted parameters

b). Root Mean Square Error (RMSE): This is another statistical indicator widely used and measures the average magnitudes of differences between measured and simulated values of parameters. The values of RMSE ranges from 0 to ∞ with 0 indicates good agreement and ∞

indicates poor agreements between the two values. This indicator determined using equation 7.33

$$RMSE = \sqrt{\frac{\sum(P_i - O_i)^2}{n}} \qquad 7.33$$

c). Coefficient of Efficiency factor (E) determines the relative magnitude of the simulated values as compared with the measured values. The values of coefficient of efficiency vary from -∞ to +1. The coefficient of efficiency value 1 indicates the perfect agreement between the measured and simulated values of the parameters. A coefficient of efficiency value 0 indicates the simulated values of parameters by model is better than the measured values of the parameters. A coefficient of efficiency value negative indicates measured values of the parameters are better than the simulated values of the parameters. This model efficiency indicator is computed by equation 7.34

$$E = 1 - \left(\frac{\sum(P_i - O_i)^2}{\sum(O_i - \bar{O}_i)^2}\right) \qquad 7.34$$

d). Index of Agreement (IA): Index of agreement is another statistical index used to measure the AquaCrop model efficiency. This index is used to measure the degree to which the measured values of parameters are approached to the simulated values of parameters. The value of d varies from 0 to 1. The value of 1 indicates the perfect agreement between measured and simulated value of parameters while 0 indicates complete disagreement. This index is computed using equation 7.35.

$$IA = 1 - \left(\frac{\sum(P_i - O_i)^2}{\sum(|P_i - \bar{O}_i| + |O_i - \bar{O}_i|)^2}\right) \qquad 7.35$$

7.7. Result and Discussions

The effect of furrow irrigation design parameters (furrow slope, length and discharge rate) was analyzed on sugarcane growth, yield and quality parameters. Also, the effect of different rate of irrigation water applied on sugarcane water productivity was analyzed.

7.7.1. Effect of furrow irrigation design parameters on sugarcane growth and yield parameters

7.7.1.1. Effect of furrow slope on sugarcane growth and yield parameters

The water flow in the furrow, water retention and infiltration are highly influenced by slope of the furrow along the furrow length that reduces the contact time of water with soil. The effect of furrow slope on sugarcane growth parameters were evaluated on different growth and yield components of the crop. To evaluate the effect of furrow slope on sugarcane growth and yield parameters, cane height, cane weight, cane diameter, number of cane internodes, cane moisture percent, dry substance, number of millable cane stalk and cane yield were analyzed.

The minimum and maximum values of those parameters were cane height (228.60 and 235.93cm), cane weight (6.44 and 7.39kg per 5 cane stalk), number of cane internode (23.93 and 27.69), cane diameter (2.61 and 2.80cm), moisture percentage (50.22 and 65.91%), dry substance (34.09 and 49.78%), number millable cane stalk (290.82 and 1175.67 000/ha), and cane yield (115.24 and 200.00 ton/ha) respectively. The effect of furrow slope on cane height, cane weight, cane diameter and number of cane internodes showed statistically significant variation at 5% significance level (Table 7.2). This may be due to furrow slope affects the water retention in the crop root zone across the furrow length, since the irrigation water applied flow across the furrow by gravity force. On the other hand, since the sugarcane crop is sensitive to both shortage and excess water stress, the variation of furrow slope may cause water logging at some part and water shortage at other part of the furrow in which both conditions affect the sugarcane growth and yield. The effect of furrow slope showed statistically non significant variation for moisture percentage dry substance, number of millable cane stack and cane yield at 5% significance level. Specially, the number of millable cane stack is affected if there is water logging or water stress at tillering growth stages in which newly emerged stalk are unable to survive in both water stress conditions. Finally, all the cane yield attributes were directly corresponding to the final cane yield. Hence, even if the effect of furrow slope showed significant variation on some parameters, the final and most important parameters, number of millable cane stalk and cane yield showed statistically non significant variation (Table 7.2). This indicated that furrow slope has no direct effect on the yield of sugarcane crop (Appendix table 7.1).

Table 7.2. Effect of furrow slope on growth and yield of sugarcane

Furrow slope (%)	Growth and Yield Parameters of Sugarcane							
	CH (cm)	CW (kg)	CD (cm)	NCI (/stk)	MP (%)	DS (%)	NMCS (000/ha)	CY (ton/ha)
0.05	235.89[a]	8.63[a]	2.94[a]	29.62[a]	64.15[a]	45.41[a]	673.11[a]	166.75[a]
0.08	231.62[b]	6.91[b]	2.62[b]	25.79[b]	61.55[ab]	38.45[b]	657.53[a]	172.91[a]
0.11	227.16[c]	5.81[c]	2.42[c]	22.42[bc]	57.30[c]	35.64[bc]	733.15[a]	181.31[a]
Mean	231.56	7.12	2.66	25.94	61.00	39.83	687.93	173.66
LSD (at 5%)	3.56	0.95	0.11	3.24	4.24	6.48	94.52	19.38
CV	1.44	6.02	1.77	7.3	6.18	9.47	6.06	4.92
SIGN	0.024*	0.018*	0.007**	0.022*	0.24ns	0.24ns	0.33ns	0.39ns

CH = cane stalk height, CW = cane weight, CD = cane diameter, NCI = number of cane internode, DS = Dry substance, NMCS= number of millable cane stalk, CY = sugarcane yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significance at $P < 0.001$, high significant at $P < 0.01$, significance at $P < 0.05$ and non significance at $P > 0.05$ respectively.

Similar to the current study, the other study findings by Assefa *et al.* (2017) indicated that the effect of furrow slope showed non significant variation on cane yield. As Assefa *et al.* (2017) concluded, the cane yield is directly related to its height and diameters that substantially contributes towards final cane yield and sugar yield. In similar to the current study result, the study findings by Sengera and Mpala (2017) revealed that the effect of furrow slope showed non significant variation on the sugarcane number of millable cane stalk and cane yield.

7.7.1.2. Effect of furrow length on sugarcane growth and yield parameters

Similar to furrow slope, the effect of furrow length on sugarcane growth and yield parameters were analyzed. The sugarcane growth and yield parameters evaluated were cane height, cane weight, cane diameter, number of cane internodes, cane moisture percent, dry substance, number of millable cane stalk and cane yield. The effect of furrow length on cane height, cane weight, cane diameter, number of cane internodes, moisture percentage, dry substance and number of millable cane stalk were statistically showed significant variation at 5% significance level (Table 7.3). Due to the effect of furrow length on the water runs, in the longer furrow length the amount of irrigation water distributed is not uniform because in the inlet direction the water has more opportunity time for water infiltration as compared to the furrow length at end. On the other hand, since the furrow condition was closed ended, more water stored at the end of the shorter furrows which causes water logging problems. In line with those conditions almost all sugarcane growth and yield parameters showed significant variation between different furrow lengths considered.

The effect of furrow length showed statistically non significant variation on cane yield at 5% significance level. The moisture and fiber percentage are inversely proportional as one increased, the other decreased. Specially, the cane yield is highly affected if there is water logging or water stress occurred because the sugarcane crop by its nature. Sugarcane crop is sensitive to extreme water conditions. Finally, even if there is a variation in cane yield, the effect furrow length was nonsignificant and the cane yield resulted in increasing as furrow length increased in the current experiment. As indicated in Table 7.3, except cane yield, the effect of furrow length showed significant variation on at the specified significance level.

Table 7.3: Effect of furrow length on the growth and yield of sugarcane

Furrow Length (m)	Growth and Yield Parameters of Sugarcane							
	CH (cm)	CW (kg)	CD (cm)	NCI (/stk)	MP (%)	DS (%)	NMCS (000/ha)	CY (ton/ha)
30	237.49[a]	7.95[a]	2.92[a]	26.81[a]	69.78[a]	43.22[a]	399.49[c]	168.99[a]
50	228.03[b]	6.93[b]	2.70[b]	25.57[ab]	62.90[b]	39.10[b]	684.72[b]	172.49[a]
70	222.57[bc]	6.05[bc]	2.60[c]	24.71[bc]	58.94[c]	38.06[bc]	979.59[a]	179.49[a]
Mean	229.36	6.98	2.74	25.70	63.87	40.13	687.93	173.66
LSD (at 5%)	5.84	0.91	0.07	1.34	3.98	3.98	90.50	17.72
CV	1.11	5.74	1.19	2.30	2.89	4.49	27.28	4.38
SIGN	0.023*	0.006**	0.047*	0.068*	0.044*	0.047*	0.0005***	0.47[ns]

CH = cane stalk height, CW = cane weight, CD = cane diameter, NCI = number of cane internode, DS = Dry substance, NMCS= number of millable cane stalk, CY = sugarcane yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significance at $P < 0.001$, high significant at $P < 0.01$, significance at $P < 0.05$ and non significance at $P > 0.05$ respectively.

The study findings by Sengera and Mpala (2017) revealed that the effect of furrow length showed non significant variation on the sugarcane yield similar to the current findings number of millable cane stalk and cane yield. But in opposite to the current study, all growth and yield of sugarcane showed statistically significant variation at 5 % significance level (Sengera and Mpala, 2017). Similar to the current study findings, the other study findings by Assefa *et al.* (2017) also indicated that the effect of furrow length showed statistically non significant variation on cane yield. Hence, furrow length has no effect on the sugarcane yield.

7.7.1.3. Effect of furrow inflow rate on sugarcane growth and yield parameters

Similar to furrow length, the effect of furrow discharge on sugarcane growth and yield parameters were analyzed. The sugarcane growth and yield parameters were evaluated as the same in the case of furrow slope and furrow lengths. The effect of furrow discharge rate on all growth and yield parameters considered (cane height, cane weight, cane diameter, number of cane internodes, moisture percentage, dry substance and cane yield) showed significant variation at 5% significance level (Table 7.4). But the effect of discharge rate showed non significance variation on the number of millable cane stalk. This indicates that the effect of furrow discharge rate has an effect on the growth and yield parameters of sugarcane. As it is already stated, sugarcane crop is highly sensitive to water logging as well as water stress, the growth and yield parameters affected by both irrigation conditions.

Based on the result obtained, in general furrow discharge rate 1 (4lit/sec) resulted in good performance of the sugarcane growth parameters and more yield as compared to the other two discharge rates. As the furrow discharge rate increased from 4 to 5 and 5 to 6lit/sec the growth and yield parameters of sugarcane decreased (Table 7.4). This indicates that as the furrow discharge rate increased beyond the crop requirement, the growth and yield parameters of the sugarcane starts to decline. From current study, it can be concluded that furrow discharge rate 4l/s is optimum rate of furrow discharge to harvest more yield of sugarcane crop under the Wonji Shoa conditions.

Table 7.4: Effect of discharge rate on the growth and yield of sugarcane

Inflow rate (L/s)	Growth and Yield Parameters of Sugarcane							
	CH (cm)	CW (kg)	CD (cm)	NCI (/stk)	MP (%)	DS (%)	NMCS (000/ha)	CY (ton/ha)
4	237.74[a]	7.54[a]	3.17[a]	27.54[a]	63.01[a]	39.99[a]	688.89[a]	176.18[a]
5	225.45[b]	6.83[b]	2.97[b]	25.72[b]	61.07[b]	37.93[b]	696.31[a]	173.59[b]
6	213.92[c]	5.93[c]	2.72[c]	25.08[bc]	58.43[c]	36.37[c]	678.61[a]	171.20[c]
Means	225.70	6.77	2.95	26.11	60.84	38.10	687.94	173.66
LSD (at 5%)	2.91	0.54	0.07	1.02	1.43	1.43	24.00	1.28
CV	0.55	3.46	1.06	1.75	1.05	1.60	42.07	3.19
SIGN	0.002**	0.045*	0.043*	0.044*	0.001**	0.001**	0.38[ns]	0.005**

CH = cane stalk height, CW = cane weight, CD = cane diameter, NCI = number of cane internode, DS = Dry substance, NMCS= number of millable cane stalk, CY = sugarcane yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significance at $P < 0.001$, high significant at $P < 0.01$, significance at $P < 0.05$ and non significance at $P > 0.05$ respectively.

Similar to the current study findings, the study findings by Bhebhe (2020) revealed that irrigation rate has a significant influence on the growth and yield parameters of sugarcane. The amount of irrigation water applied throughout the sugarcane crop highly affected the yield and growth parameters, specially, the moisture percentage and dry substance of sugarcane was affected by the amount of irrigation applied which indirectly affect the other parameters. The study findings by Sengera and Mpala (2017) indicated that the irrigation rate applied to the sugarcane crop significantly affects the growth and yield parameters.

The study findings by Raza *et al.* (2012) showed that different rate of irrigation has showed a statistically significant effect on growth and yield parameters of sugarcane. The other study findings by Ashagre and Khan (2020) showed that the effect of irrigation withholding significantly affects the sugarcane growth parameters and yield. From all parameters, moisture percentage of cane at harvest showed very high significant variation with the same cane variety of the current study. Similarly, the other findings by Wawire, (2006) revealed that the effect of irrigation on sugar yield showed highly significant variation in opposite to the current findings.

The interaction effect between furrow slope and length, slope and discharge rate, furrow length and discharge rate as well as the between three factors showed statistically non significant variation at 0.05% significant variation almost all growth parameters of the sugarcane except cane yield. The interaction effect between the three factors showed statistically significant variation (Table 7.5).

Table 7.5. Interaction effect of the factors on the growth and yield of sugarcane

Treatments Interactions	Growth and Yield Parameters of Sugarcane							
	CH (cm)	CW (kg)	CD (cm)	NCI (/stk)	MP (%)	DS (%)	NMC (000/ha)	CY (ton/ha)
Slope*Length	230.34[a]	7.03[a]	2.7[a]	25.61[a]	60.12[a]	39.88[a]	147.55[a]	199.07[a]
Slope*Inflow	232.15[a]	7.10[a]	2.7[a]	25.76[a]	60.12[a]	39.88[a]	174.73[a]	200.00[a]
Length*Inflow	232.19[a]	7.04[a]	2.69[a]	25.79[a]	59.93[a]	40.07[a]	174.40[a]	199.07[a]
Slope*Length*Inflow	232.01[a]	7.05[a]	2.7[a]	25.76[a]	59.86[a]	40.17[a]	176.26[a]	196.97[b]
Mean	232.22	7.08	2.69	25.78	60.03	39.97	174.87	198.78
LSD (at 5%)	9.66	0.61	0.1	2.17	7.7	7.7	13.37	0.91
CV	3.87	9.62	4.38	9.61	17.39	26.12	6.87	41.94
SIGN	2.97[ns]	1.18[ns]	0.57[ns]	0.87[ns]	0.35[ns]	0.35[ns]	1.96[ns]	0.09[*]

FS = Furrow slope, FL = Furrow length, FQ = Furrow discharge, CH = cane stalk height, CW = cane weight, CD = cane diameter, NCI = number of cane internode, DS = Dry substance, NMCS= number of millable cane stalk, CY = sugarcane yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significance at $P < 0.001$, high significant at $P < 0.01$, significance at $P < 0.05$ and non significance at $P > 0.05$ respectively.

Similar to the current study, the study findings by Sengera and Mpala (2017) revealed that the interaction effect of furrow slope, length and discharge rate showed statistically significant variation on the sugarcane yield at 5 % significance level. Those authors concluded from their findings, medium furrow slope (0.08), longer furrow length and higher discharge rate (3l/s) resulted in better sugarcane yield. In the current study, the interaction effect of more slope (0.11) and less discharge resulted in better sugarcane yield. Similar to the current study findings, the other study by Assefa *et al.*, (2017) also indicated that the interaction effect of furrow slope, length and discharge rate showed statistically significant variation on cane yield.

7.7.2. Effect of furrow irrigation design parameters on sugarcane quality parameters

7.7.2.1. Effect of furrow slope on sugarcane quality parameters

The effect of furrow slope was analyzed on the selected sugarcane quality parameters. The minimum and maximum values of the sugarcane quality parameters analyzed were brix percent juice (17.28 and 20.42%), pol percent (16.25 and 19.19%), purity percent (88.72 and 98.69%), fiber percentage (24.67 and 66.66%), estimated reduced sugar (11.88 and 14.32) and estimated sugar yield (16.10 and 28.10 ton/ha) respectively. The effect of furrow slope on almost all sugarcane quality parameters showed statistically non significant variation at 5% significant level. However, from the sugarcane quality parameters considered, the effect of slope showed statistically significant variation only on PL and ESY at 5% significant level (Table 7.6). From this result even if the effect of furrow slope showed statistically nonsignificant variation on most quality parameters, this showed statistically significant variation on the most important parameter (estimated sugar yield) (Appendix table 7.2).

Table 7.6. Effect furrow slope on sugarcane quality parameters

Furrow slope (%)	Quality Parameters of Sugarcane					
	BX (%)	PL (%)	PT (%)	FP (%)	ERS	ESY (ton/ha)
0.05	18.89[a]	18.01[a]	95.34[a]	44.75[a]	13.35[a]	23.98[a]
0.08	18.78[a]	17.89[ba]	95.34[a]	37.79[ab]	13.25[a]	22.93[ba]
0.11	18.74[a]	17.85[b]	95.25[a]	33.97[bc]	13.23[a]	22.23[b]
Mean	18.80	17.92	95.31	38.84	13.28	23.05
LSD (at 5%)	0.388	0.394	1.233	8.5	0.311	1.3
CV (%)	3.806	4.049	2.386	9.66	4.334	10.402
SIGN.	0.73[ns]	0.004*	0.988[ns]	0.241[ns]	0.728[ns]	0.031*

BX = brix juice percent, PL = pol percent, PT = purity percent, fiber percent, estimated reduced sugar, ESY = estimated sugar yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significance at $P < 0.001$, high significant at $P < 0.01$, significance at $P < 0.05$ and non significance at $P > 0.05$ respectively.

In opposite to the current study findings, the findings of Assefa *et al.* (2017) also revealed that the effect of furrow slope on estimated sugar yield showed statistically non significant variation. However, the interaction effect of furrow slope, furrow length and flow rate showed significant variation. The other findings by Sengera and Mpala (2017) revealed that the effect of furrow slope on estimated sugar yield showed statistically non significant variation in opposite to the current study findings.

7.7.2.2. Effect of furrow length on sugarcane quality parameters

The effect of furrow length on sugarcane quality parameters were analyzed and the minimum and maximum values of all those parameters were similar as that described under the effect furrow slope. The effect of furrow length on all sugarcane quality parameters showed statistically non significant variation at 5% significant level (Table 7.7).

Table 7.7. Effect of furrow length on sugarcane quality parameters

Furrow Length	Quality Parameters of Sugarcane					
(m)	BX (%)	PL (%)	PT (%)	FP (%)	ERS	ESY (ton/ha)
30	18.81[a]	17.92[a]	95.29[a]	39.57[a]	13.28[a]	23.5[a]
50	18.71[a]	17.79[a]	94.98[a]	37.42[a]	13.16[a]	22.83[a]
70	18.89[a]	18.06[a]	95.64[a]	36.40[a]	13.4[a]	22.81[a]
Mean	18.80	17.92	95.30	37.80	13.28	23.05
LSD (at 5%)	0.388	0.394	1.233	4.00	0.311	1.300
CV	3.806	4.049	2.386	4.59	4.334	10.402
SIGN	0.656[ns]	0.333[ns]	0.575[ns]	0.144[ns]	0.307[ns]	0.485[ns]

BX = brix juice percent, PL = pol percent, PT = purity percent, fiber percent, estimated reduced sugar, ESY = estimated sugar yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column are indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significant at $P < 0.001$, high significant at $P < 0.01$, significant at $P < 0.05$ and nonsignificant at $P > 0.05$ respectively.

Similar to the furrow slope, the effect of furrow length on estimated sugar yield showed statistically non significant variation similar to the findings of Assefa *et al.* (2017). However, the interaction effect of furrow slope, furrow length and flow rate showed significant variation. Similar to the effect of furrow slope, the effect of furrow length on estimated sugar yield showed statistically non significant variation in opposite to the current study findings (Sengera and Mpala, 2017).

7.7.2.3. Effect of furrow discharge rate on sugarcane quality parameters

Similar to the furrow slope and length, the effect of furrow discharge rate on sugarcane quality parameters were analyzed, and the minimum and maximum values of all those parameters were similar as indicated under furrow slope. The effect of discharge rate on the sugarcane quality parameters showed almost non-significant variation at 5% significance level. As the current study findings revealed, the effect of furrow discharge rate on the pol, estimated reduced sugar and estimated sugarcane yield showed non significance variation. But the effect of furrow discharge on brix and purity showed statistically significant variation at 5% significance level (Table 7.8).

In general, the most important part of the sugarcane yield is the final yield (sugar yield) which indicated statistically non-significant variation between the irrigation treatments. Even if the effect of irrigation treatments statistically showed non significant variation, there is yield variation in which maximum sugarcane yield obtained from the irrigation treatment one (4l/s) followed by irrigation three (6l/s) and two (5l/s) respectively.

Table 7.8. Effect of furrow discharge rate on sugarcane quality parameters

Furrow Discharge	Quality Parameters of Sugarcane					
(L/s)	BX (%)	PL (%)	PT (%)	FP (%)	ERS	ESY (ton/ha)
4	18.61[a]	17.92[a]	96.27[a]	39.93[a]	13.31[a]	23.45[a]
5	18.78[ba]	17.84[a]	94.99[b]	38.28[b]	13.21[a]	22.59[a]
6	19.02[b]	18.00a	94.65[b]	36.91[c]	13.21[a]	23.10[a]
Mean	18.80	17.92	95.30	38.37	13.24	23.05
LSD (at 5%)	0.388	0.394	1.233	1.44	0.311	1.300
CV	3.806	4.049	2.386	1.63	4.334	10.402
SIGN	0.012*	0.729[ns]	0.027*	0.001**	0.749[ns]	0.416[ns]

BX = brix juice percent, PL = pol percent, PT = purity percent, FP = fiber percent, estimated reduced sugar, ESY = estimated sugar yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column are indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significant at $P < 0.001$, high significant at $P < 0.01$, significant at $P < 0.05$ and nonsignificant at $P > 0.05$ respectively.

Similar to the current study findings, the study findings by Rajan *et al.* (2021) on irrigation treatment in addition to soil nutrient improvement showed non significant variation on all sugarcane quality parameters considered including the final sugarcane yield. The study findings by Singh *et al.* (2018) revealed that the effect of irrigation rate showed statistically non significant variation on brix, pol and purity parameters of sugarcane but the current study findings showed statistically significant variation on brix and purity in opposite to this study but similar in pol. However, the purity percent in sugarcane of the current study was higher than the previous studies. In opposite to the current study, the study findings by Sengera and Mpala (2017) revealed that the effect of irrigation rates on sugarcane and sugar yield showed statistically significance variation.

The interaction effect between furrow slope and length, slope and discharge rate, furrow length and discharge rate as well as the between three factors showed statistically non significant variation at 5% significant variation on all quality parameters of the sugarcane (Table 7.9).

Table 7.9. Interaction effect of the factors on the sugarcane quality parameters

Treatment Interactions	Quality Parameters of Sugarcane					
	BX (%)	PL (%)	PT (%)	FP (%)	ERS	ESY (ton/ha)
FS*FL	18.8[a]	17.79[a]	95.3[a]	67.59[a]	38.84[a]	13.28[a]
FS*FQ	18.8[a]	17.79[a]	95.3[a]	67.6[a]	38.84[a]	13.28[a]
FL*FQ	18.8[a]	17.92[a]	95.3[a]	67.08[a]	38.84[a]	13.28[a]
FLS*FL*FQ	18.8[a]	17.92[a]	95.3[a]	66.5[a]	38.84[a]	13.28[a]
Mean	18.8	17.86	95.3	67.61	38.84	13.28
LSD (at 5%)	0.67	0.66	1.92	24.72	7.29	0.52
CV (%)	3.95	4.19	2.18	4.11	21.68	4.45
SIGN.	0.72[ns]	0.64[ns]	1.32[ns]	0.09ns	0.62[ns]	0.69[ns]

FS = Furrow slope, FL = Furrow length, FQ = Furrow discharge, BX = brix percent, PL = pol percent, PT = purity percent, fiber percent, estimated reduced sugar, ESY = estimated sugar yield

Note: Means for sugarcane growth parameters within a column followed by the same letter are not significantly different from each other at $p < 0.05$. However, mean values of different letters within a column are indicate significant differences by a > b > c

Keys: ***, **, * and ns indicate very high significant at $P < 0.001$, high significant at $P < 0.01$, significant at $P < 0.05$ and nonsignificant at $P > 0.05$ respectively.

7.7.3. Analysis of sugarcane water productivity

The sugarcane water productivity parameters were measured (computed) from the field and simulated using AquaCrop model from three rates of irrigation application (4, 5 and 6l/s). These parameters were above ground biomass, cane yield, harvest index, biomass water productivity and evapotranspiration water productivity. The sugarcane irrigation water required for the full growing period was 1802.6 mm. The sugarcane irrigation water requirement was determined from local weather parameters, soil condition and crop growth parameters including the crop factors developed from the lysimeters experiment. However, there was a high rain fall availability during this experiment and the effective rain fall was computed using CropWat model was 1048.4 mm during the growing season of the crop.

7.7.3.1. Sugarcane biomass and yield

The measured above ground biomass of sugarcane was greater than the simulated for all irrigation treatments. When the measured and simulated above ground sugarcane biomass compared, there was a great variation for the three irrigation treatments. Higher above ground biomass was obtained from furrow irrigated by inflow rate of 4l/s followed by 5 and 6l/s. But from the simulated values, the highest above ground biomass was obtained from5l/s followed by 4 and last 6l/s (Figure 7.8).

The measured sugarcane yield was greater than the simulated values for all irrigation treatments. There was no significant variation in sugarcane yield from measured values for all irrigation treatments but from the simulated values the highest sugar yield was obtained from 5 l/s and there was no variation between 4 and 6 l/s inflow rates. Similarly, the measured values of harvest index were greater than the simulated values in all irrigation treatments but the variation between measured and simulated values for each inflow rates were not significant (Figure 7.8).

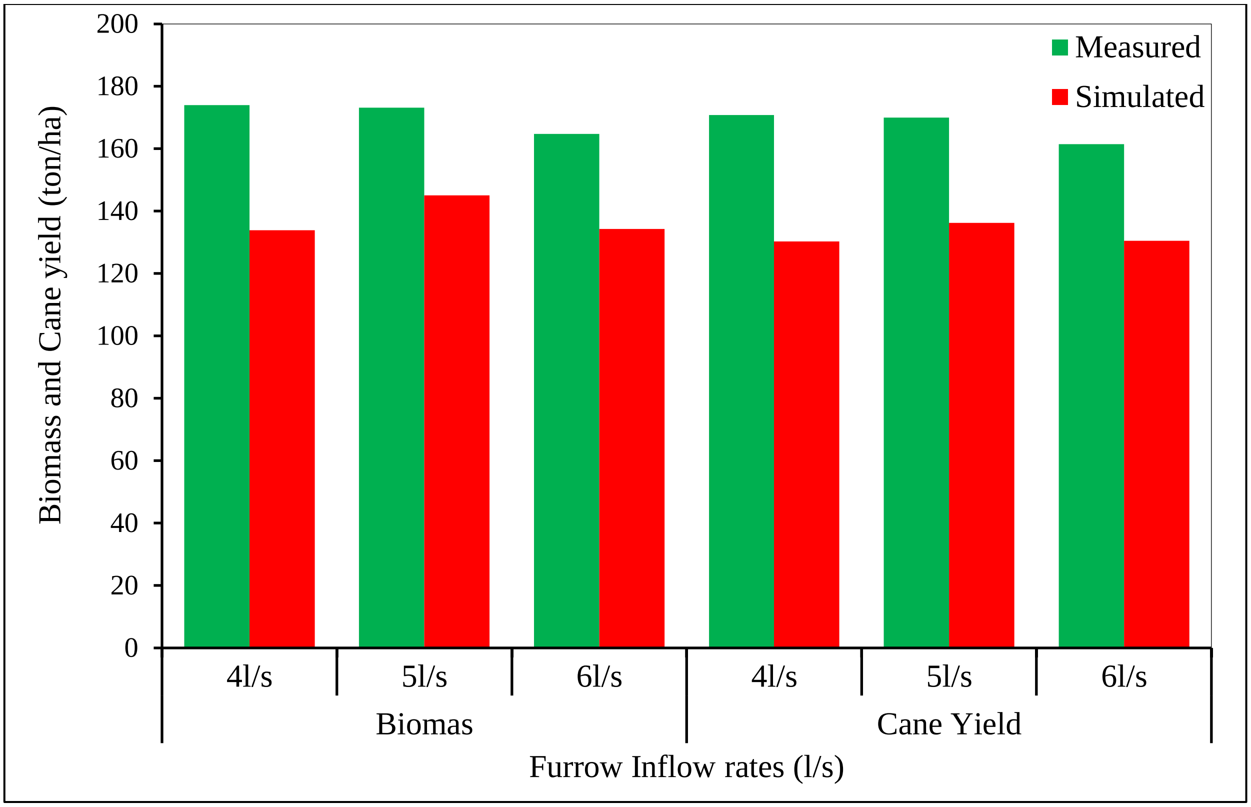

Figure 7.7. Measured and simulated sugarcane biomass and yield

The study findings by Leal *et al.*, (2017) indicated that the impact of irrigation rate on the sugarcane biomass was non-significant variation even if there was an increments. This study revealed that by decreasing irrigation by 30% the sugarcane biomass only decreased by 0.45 kg/m3 which indicates insignificant variation of biomass yield. Similar to this study, the current study showed less variation in sugarcane biomass between 4 and 5 l/s inflow rates but slight variation with that of 6 l/s. On other hand, the study by Herrera *et al.* (2017) showed that the sugarcane biomass was lower than the current study as well as others related studies (Gava *et al.*, 2011, Oliveira *et al.*, 2011).

But the cane yield showed significant variation with respect to the variation in inflow rates. As a result of the current study showed, inflow rate 4 l/s was resulted in higher yield of sugarcane which is in agreement with findings of Carvalho *et al.*, (2019) and Teixeira *et al.*, (2016). The other study by Singh and Ishwar (2018) showed that reducing irrigation water by 50% from full irrigation resulted in higher yield of sugarcane.

7.7.3.2. Sugarcane biomass and water productivity

The measured above ground biomass water productivity of sugarcane was showed high variation between the inflow rates with high values obtained from lower inflow rate (4l/s). this indicates that, inflow rate 4l/s is sufficient for sugarcane and beyond this inflow rate applied may be lost and cause other adverse effects of irrigation. When the measured and simulated above ground biomass water productivity of sugarcane are compared, there is less variation for inflow rates 4 and 6 l/s as compared to 5 l/s. From the measured above ground biomass, higher value obtained from 4 l/s but from the simulation it is from 5 l/s. Generally, the variation between measured and simulated above ground biomass for all inflow rates were not much significant (Figure 7.9).

The variation in sugarcane evapotranspiration water productivity between irrigation all inflow rates were showed high variation. The variation in sugarcane evapotranspiration water productivity showed decreased as the inflow rate increased. The highest values of WP_{ETc} was obtained from the lower inflow rate (4 l/s) and the lowest WP_{ETc} obtained from higher inflow rate (6 l/s). The result obtained from the simulated values also showed similar trends (Figure 7.9). There was no variation in harvest index from the simulated values but there was little variation from the computed values, the highest harvest index computed from irrigation treatment two followed by one and three respectively (Figure 7.9).

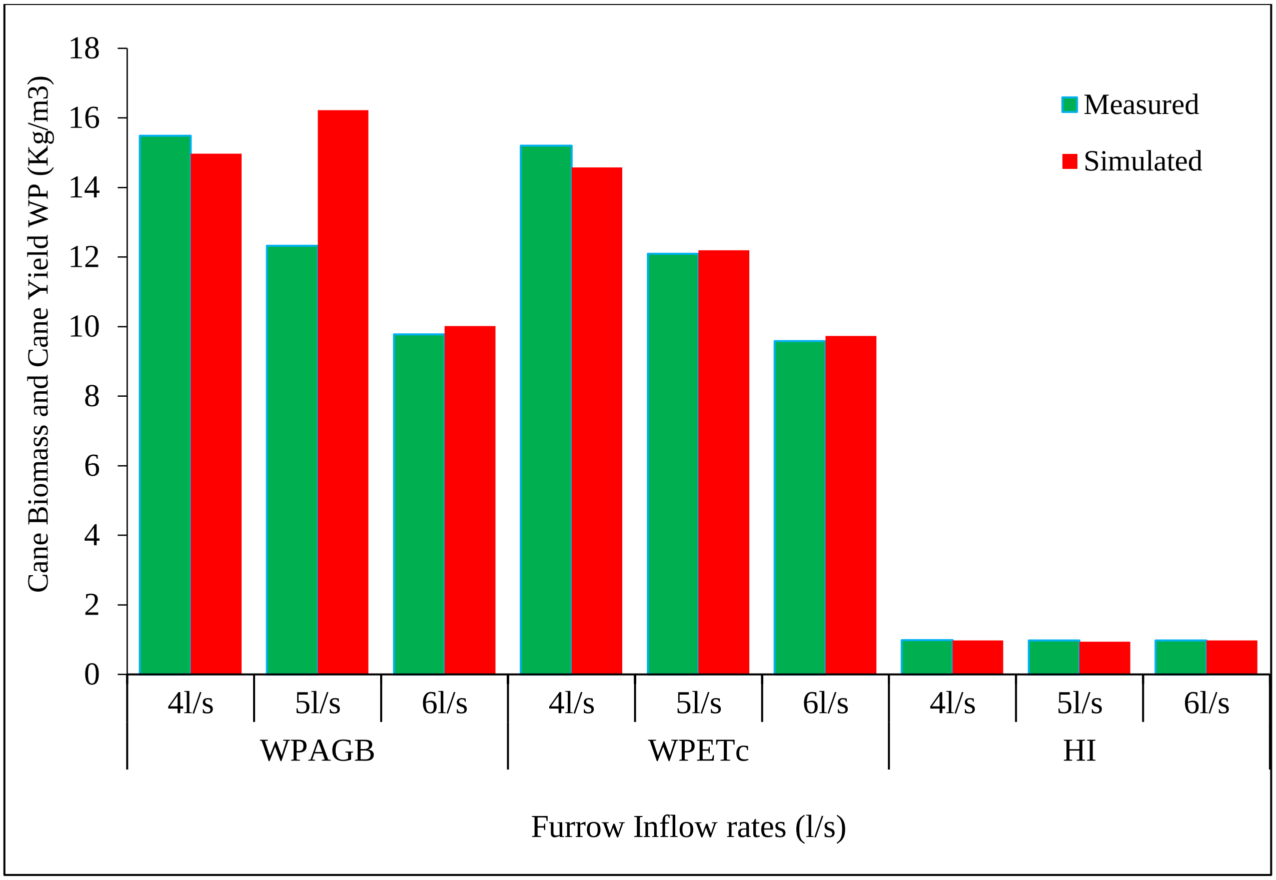

Figure 7.8. Measured and simulated sugarcane above ground biomass crop evapotranspiration water productivity and harvest index

Both biomass and evapotranspiration are the key in agricultural water management in irrigated agricultural regions specially for crops like sugarcane since it is perennial and very high water consuming crop. The current study is in agreement with the findings by Revathy and Balamurali (2019) in which different inflow rates were resulted in different WP_{AGB} and WP_{ETc} both from measured and simulated values with similar trends. In opposite to the current study, the study by Leal, *et al.* (2017) revealed that the sugarcane biomass and evapotranspiration water productivity of sugarcane slightly increased as the inflow rate increased.

7.7.3.3. Statistical analysis of sugarcane water productivity

Based on the statistical indicator of coefficient of determination, there was poor agreement between the measured and simulated values of all sugarcane parameter (above ground biomass, cane yield, harvest index, above ground biomass water productivity) except evapotranspiration water productivity. In terms of root mean square error, also parameters showed that poor agreement between the measured and simulated values of the parameters except harvest index. In terms of coefficient of efficiency, harvest index and above ground biomass water productivity showed a good agreement between measured and simulated values. Measured values are better for cane yield and evapotranspiration water productivity. However, in terms of index of agreement, all parameters showed better agreement between the measured and simulated values (Table 7.10).

Table 7.10. Statistical Analysis of Sugarcane Water Productivity

Parameters	Statistical Indices			
	R^2	RMSE	E	d
Above ground biomass (ton/ha)	0.44	5.80	0.01	0.75
Cane Yield (ton/ha)	0.11	6.17	-0.11	0.98
Harvest Index (%)	0.11	0.04	0.99	0.99
WP_{AGB} (Kg/m^3)	0.98	2.89	0.98	0.91
WP_{ET} (Kg/m^3)	0.30	1.26	-11.04	0.84

7.8. Conclusion and Recommendations

7.8.1. Conclusions

Sugarcane is perennial water intensive crop which is commonly produced using furrow irrigation in the current study area. Hence, the efficiency of furrow irrigation is relatively low and affected by many irrigations design and decision variables. To improve the efficiency of furrow irrigation, appropriate design parameters and decision variables should be implement based on the local condition of the area. In consideration of furrow irrigation design parameters, furrow slope and length should be designed according to the soil type, topographic situation of the land and climatic condition of the area. Also, the decision variables like inflow rate and cutoff time can be influenced by similar factors that requires a critical consideration for improving irrigation efficiency, increasing cane production and productivity in a sustainable way. The results of the current study showed that the effect of furrow slope and length showed statistically non significant variation on most growth and yield parameters. But the effect of furrow inflow rate showed a significant variation on these parameters and the lower inflow rate showed better yield of sugarcane. Similarly, the interaction effect between furrow slope, length and inflow rate showed significant variation on cane yield. When the interaction effects of those factors considered, furrow slope (0.11), furrow length (70m) and furrow inflow rate (4 l/s) resulted in a relatively better sugarcane yield. Hence, the water demand of the sugarcane is adequately met with this low inflow rate (4l/s). In terms of quality, the effect of design and decision variables considered showed non significant variation almost all sugarcane quality parameters. Additionally, the interaction effect between these three factors similarly showed non significant variation on all quality parameters considered. Relatively high water productivity was found to be registered under inflow rate of 4l/s compared to 5 and 6l/s. With increasing inflow rate the water productivity was found to decrease. The agreement between measured and simulated sugarcane water productivity showed relatively good agreements on more parameters. Therefore, relatively longer furrow 70m irrigated with the low inflow rate of 4l/s could produce better yield by at the same time saving water and hence, resulting in high water productivity.

7.8.2. Recommendations

Based on the overall results of this part of study, namely, effect of furrow irrigation design parameters on various growth, yield, quality and water productivity of sugarcane, the following recommendation can be made:

- The furrow irrigation design parameters, furrow length and furrow discharge rate should be redesigned to improve the sugarcane yield and to reduce the adverse effects of irrigation. Additionally, the topography of the area is very flat, which requires very serious considerations of furrow slope and furrow length configurations to overcome uneven distribution of water problems.

- From the furrow irrigation design parameters considered, relatively sloppy furrow (0.11%), longer furrow (70m) and low inflow rate (4l/s) could be used to achieve better yield and water productivity.
- Further researches that cover different dominant soils types of sugar farm is recommended to substantiate the results obtained in this research regarding the evaluation of the effect of furrow design parameters considered here on sugarcane growth, yield and quality parameters as well as its water productivity.

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8. OVER ALL CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusions

Sugarcane production is currently expanding in Ethiopia to respond to the increasing demand for sugar both for consumption and export substitution. Wonji Shoa is the oldest and one of the pioneers in sugarcane production in the country. The Estate has been using furrow irrigation for sugarcane production. Such method of irrigation has been used since the establishment of the farm in 1954. The common problem of furrow irrigation is its low efficiency as compared to the pressurized methods that in turn leads to groundwater rise and water-logging, salinity and other undesirable consequences. In addition to that, irrigation water is not applied by considering crop water requirement by considering soil, crop growth stages and climatic condition of the area due lack of irrigators' skill and knowledge about irrigation. For effectively applying the required amount of irrigation water to sugarcane, its crop evapotranspiration and crop coefficient is very crucial. These parameters are important not only for operation of irrigation system through proper irrigation scheduling but also for irrigation system design. All these operational procedures contribute to productivity enhancement and sustainability of irrigation system. to evaluate irrigation water management practices for irrigated sugarcane under Wonji Shoa Sugar Estate with a view to improve on-farm irrigation water management practices. To accomplish this objective, three distinct specific research objectives were formulated as follows: 1) to evaluate the performance of current furrow irrigation water management practices and develop improvement options; 2) to measure and analyze Sugarcane evapotranspiration and develop its crop coefficient using lysimeter experiment; and 3) to evaluate the effect of furrow irrigation design parameters on sugarcane growth, yield and quality parameters, and its water productivity. For the performance evaluation of the current furrow irrigation practices, ten fields were selected from the three commonly used furrow lengths (32, 48 and 64m). All the required data for the performance evaluation was collected from those fields. The performance of the furrow irrigation was evaluated in terms of application efficiency, distribution uniformity and deep percolation. With the view to improve the performance of the current practices WinSRFR model was used to simulate key performance indicators by varying furrow decision variables until maximum values of the selected indicators are obtained. For all selected fields, the required data were collected during three irrigation events. Sugarcane crop evapotranspiration and its crop coefficient were determined using lysimeter experiment at Melkassa Agricultural Research Center near Wonji Shoa Sugar Estate. The sugarcane variety NCO-334 was planted in the established lysimeter. The soil moisture was monitored using gravimetric method and calibrated neutron probe throughout the growing period of sugarcane. Reference evapotranspiration in the study area was determined using CropWat 8.0 model using the local weather parameters. In parallel field experiment was conducted at Wonji Shoa Sugar Estate to analyze the effect of furrow irrigation design parameters on sugarcane growth, yield and quality parameters as well as its water productivity at field condition. The furrow design parameters considered were furrow slope (0.05, 0.08 and 0.11), furrow length (30, 50 and 70 m) and inflow rate (4, 5 and 6 l/s). The field experiment was laid out using split-split plot design with three factors as main factor, subfactor and sub-sub factors with three replications. All the growth and yield parameters of the sugarcane were collected and analyzed using SAS 9.4 software. Similarly, the sugarcane quality parameters were determined in the laboratory at Wonji Shoa sugar research and development center and subjected to analysis using SAS 9.4 software. The mean separation was tested at 5% significance level for all growth, yield and quality parameters. For the three rate of inflow, sugarcane water productivity was determined and simulated using AquaCrop model.

The results indicate that the current irrigation water management practices showed poor performance in terms of application efficiency, distribution uniformity and deep percolation for the three furrow lengths. Since the performance of current furrow irrigation was evaluated as poor, alternative improvement options were developed tested. In principle, furrow irrigation application efficiency can be improved by reducing inflow rate (Q) or increasing the cutoff time (Tco) and also in vice-versa. In the current study, as an improvement options, both decision variables (Q and Tco) were varied from the current practices. The result obtained indicated that reduction of the current inflow rate by 25% and prolonging the cutoff time by 25% has improved performance of furrow irrigation under all furrow lengths. Accordingly, the application efficiency was improved by 32.7, 34.9 and 32.6% for 32, 48 and 64m furrow lengths respectively. But the distribution uniformity was not significantly improved. The deep percolation was reduced by 38.1, 30.8 and 25.8% for 32, 48 and 64m furrow lengths respectively. Hence, it is important that furrow irrigation decision variables are regularly checked for maximum performances. The sugarcane evapotranspiration was computed for the whole growing period using water balance approach after generating data using lysimeter experiment. The result indicated that sugarcane evapotranspiration obtained ranged from 1.63 to 7.5mm/ day. Moreover, the study found that sugarcane crop coefficients were 0.42, 0.93, 1.26 and 1.05 at emergence, tillering, grand formation and ripening growth stages respectively. Although a one season experiment, considering the data scarcity in relation to these parameters, the results presented in this study can be useful for design and operation of the growing irrigated sugarcane in the country.

The effect of furrow slope and furrow length showed statistically non significant variation at 5% significance on most of the growth and yield parameters of sugarcane. But the effect of furrow inflow rate on growth and yield parameters of sugarcane has shown statistically significant variation at the same significance level. In general, inflow rate 4l/s resulted in a better sugarcane growth and yield performance as compared to the 5 and 6 l/s. On the other hand, the effect of furrow design parameters on almost all sugarcane quality parameters has shown statistically non significant variation at 5% significance level.

The effect of inflow rate on Sugarcane water productivity has shown a variation in almost all water productivity parameters. When these inflow rates are compared, inflow rate 4 l/s showed a better sugarcane water productivity. Moreover, AquaCrop model was used to simulate the effects of inflow rate on water productivity of sugarcane. However, statistical analysis, showed poor agreement between measured and simulated parameters. Generally, from the current study results it can be concluded that, furrow inflow rate should be reduced and cutoff time increased from the existing irrigation practices to improve the performance of furrow irrigation. For effective irrigation water management, experimentally determined sugarcane ETc and locally developed sugarcane Kc should be used. Appropriate combination of furrow irrigation design parameters and decision variables should be implemented for better irrigation water management practices and improvement of the sugarcane production in the study area.

8.2. Recommendations

Based on the findings of the current study under taken at Wonji Shoa Sugar Estate the following recommendation were forwarded.

1. The performance of furrow irrigation under the existing situation at Wonji Shoa Sugar Estate was found to be poor. Reducing inflow rate per furrow by 25% and prolonging the cutoff time by 25% can improve the performances. It is also important to build the skills of irrigators in irrigation practices. It is important to regularly check and validate the decision variables to be used for irrigation practices.

2. In Ethiopia, even if the sugarcane is the most demanded commercial crop, its crop water requirement is not well studied and its crop coefficient is not experimentally developed. Therefore, to apply optimum irrigation, there is a need for knowledge about crop water requirement under Wonji Shoa climatic conditions. Although limited to a one season experiment, crop water requirement and coefficient results generated in this study can be used for design and operation of irrigated sugarcane.

3. Furrow design parameters and decision variables obviously affect sugarcane growth, yield and water productivity. The effect of these design parameters showed significantvariation on sugarcane yield and water productivity. Based on the result of the current findings, slightly slopy furrow (0.11%), longer furrow length (70 m) and less inflow rate (4l/s) showed relatively better performances. Similarly better sugarcane water productivity parameter was obtained from less inflow rate (4 l/s) that can be used as optimum amount of furrow inflow rate under the current study area. In principle, what matters is whether the required depth of water is timely applied to the root zone or not. Finally, the author believes that the results regenerated in this study, the discussions and conclusions drawn will have important contributions to improve the irrigation practices in general and agricultural water management in particular.

APPENDIX TABLES

Appendix Table 5.1. Measured performance of current irrigation practices

Irrigation events	Field No	Furrow length (m)	Performance Indicators		
			AE (%)	Du (%)	Dp (%)
One	15	32	32	96	68
	42		54	87	46
	80		58	90	42
	102		34	64	66
	279		64	92	36
	15	48	46	86	56
	16		55	89	45
	80		54	63	43
	15	64	49	90	49
	264		41	91	61
Two	15	32	33	96	67
	42		39	91	61
	80		58	92	42
	102		38	63	62
	279		53	94	47
	15	48	36	86	64
	16		42	90	58
	80		71	72	29
	15	64	55	92	45
	264		43	90	57
Three	15	32	48	96	52
	42		50	95	50
	80		58	93	42
	102		40	63	60
	279		34	98	66
	15	48	54	82	46
	16		45	85	55
	80		63	78	37
	15	64	43	92	57
	264		40	84	60

Appendix Table 5.2. Measured performance of furrow irrigation by varying the inflow rate from the current practices

Irrigation events	Field No	Furrow length (m)	Measured		
			AE (%)	DU (%)	DP (%)
One	15	32	59	96	36
	42		64	87	38
	80		63	90	40
	102		53	64	47
	279		66	92	34
	15	48	54	86	46
	16		58	89	41
	80		65	63	36
	15	64	62	90	39
	264		58	91	41
Two	15	32	59	89	42
	42		62	87	40
	80		60	88	38
	102		64	77	39
	279		59	88	44
	15	48	55	87	46
	16		53	93	48
	80		71	89	28
	15	64	59	92	41
	264		72	90	28
Three	15	32	49	87	52
	42		56	89	39
	80		58	88	42
	102		60	62	37
	279		55	89	46
	15	48	58	82	34
	16		69	85	33
	80		74	78	28
	15	64	53	92	46
	264		58	84	41

Appendix Table 5.3. Measured performance of furrow irrigation by varying cutoff time from the current practices

Irrigation events	Field No	Furrow length (m)	Measured		
			AE (%)	DU (%)	DP (%)
One	15	32	59	96	42
	42		65	87	33
	80		74	90	30
	102		58	64	41
	279		72	92	26
	15	48	65	86	34
	16		72	89	28
	80		68	70	33
	15	64	57	86	43
	264		55	90	44
Two	15	32	51	96	38
	42		64	91	31
	80		59	92	34
	102		62	63	32
	279		68	94	32
	15	48	62	86	34
	16		72	90	29
	80		71	72	32
	15	64	68	92	31
	264		71	90	29
Three	15	32	53	96	38
	42		57	95	39
	80		65	93	42
	102		68	63	38
	279		72	98	40
	15	48	68	82	28
	16		73	85	26
	80		73	78	32
	15	64	62	92	37
	264		67	84	34

Appendix Table 5.4. Measured performance of furrow irrigation by varying both inflow rate and cutoff time from the current practices

Irrigation events	Field No	Furrow length (m)	Measured		
			AE (%)	DU (%)	DP (%)
One	15	32	67	96	30
	42		69	87	29
	80		63	90	30
	102		72	64	34
	279		70	92	36
	15	48	78	86	20
	16		76	89	23
	80		77	68	25
	15	64	76	90	24
	264		77	91	22
Two	15	32	65	96	33
	42		66	91	34
	80		73	92	24
	102		68	63	30
	279		70	94	37
	15	48	77	86	20
	16		76	90	27
	80		76	72	24
	15	64	76	92	33
	264		73	90	28
Three	15	32	60	96	39
	42		68	95	34
	80		58	93	42
	102		66	63	37
	279		65	98	31
	15	48	75	82	24
	16		78	85	20
	80		80	78	22
	15	64	74	92	22
	264		79	84	25

Appendix Table 6.5. Sugarcane evapotranspiration measured from lysimeter experiment during the growing season at each irrigation intervals

Growth stage	Days	ETc (mm/day)	ETo (mm/day)	Kc
	51	2.05	5.95	0.34
	56	1.84	4.49	0.41
	61	1.63	4.37	0.37
Germination and	66	2.33	5.33	0.44
Emergence	71	3.05	5.81	0.53
	76	2.82	5.04	0.56
	81	3.53	4.54	0.78
	86	3.32	5.01	0.66
	91	4.08	5.06	0.81
	96	3.9	5.24	0.74
	101	5.21	6.5	0.8
	106	3.15	4.34	0.73
	111	4	4.32	0.93
	117	4.29	4.35	0.99
Tillering	123	5.09	4.39	1.16
	129	3.76	3.19	1.18
	135	4.52	3.9	1.16
	141	3.68	3.19	1.15
	149	4.35	3.74	1.16
	157	4.66	4.11	1.13
	165	4.88	4.35	1.12
	173	4.03	3.5	1.15
	181	4.54	3.72	1.22
	189	4.02	3.5	1.15
	197	4.9	4.12	1.19
Grand formation	205	4.68	3.9	1.2
	213	6.31	5.45	1.16

Appendix Table 6.1 cont.

	221	5.76	4.77	1.21
	229	6.03	4.66	1.29
	237	6.17	4.93	1.25
	245	5.67	4.44	1.28
	253	5.06	3.91	1.29
	261	5.89	4.72	1.25
	269	4.96	3.87	1.28
	277	5.54	4.31	1.29
	285	4.95	3.87	1.28
	293	5.18	3.78	1.37
	301	5.25	3.85	1.36
	309	5.46	3.98	1.37
	317	5.9	4.24	1.39
	325	7.04	5.37	1.31
	333	5.14	4.69	1.1
	341	6.04	6.28	0.96
	349	6.96	5.92	1.18
	357	5.96	5.91	1.01
	365	5.02	4.9	1.02
Ripening	373	5.67	5.81	0.98
	381	7.54	6.95	1.09
	389	5.34	5.46	0.98
	397	4.77	4.41	1.08
	405	4.53	4.9	0.92
	413	4.71	4.67	1.01
	421	6.27	5.93	1.06

Appendix Table 7.1. Data on Sugarcane Growth and Yield parameters

S/No	Rep	MF	SF	SSF	CH	CW	CIN	CD	MP	DS	NMCs 000/ha	CY (ton/PA)
1	1	1	1	1	238.00	6.00	29.60	2.57	57.35	42.65	329.41	164.71
2	1	1	1	2	216.80	6.00	24.80	2.68	50.00	50.00	375.76	150.31
3	1	1	1	3	234.80	8.00	26.20	2.70	53.85	46.15	383.53	159.80
4	1	1	2	1	247.00	8.00	27.20	2.59	53.45	46.55	496.83	140.60
5	1	1	2	2	227.80	7.50	24.40	2.73	57.58	42.42	624.83	153.08
6	1	1	2	3	223.20	8.00	24.80	2.79	62.07	37.93	686.90	171.72
7	1	1	3	1	245.80	7.00	28.60	2.63	66.13	33.87	844.33	158.01
8	1	1	3	2	236.00	7.50	27.60	2.61	69.35	30.65	976.65	115.24
9	1	1	3	3	254.00	8.50	27.60	2.69	74.60	25.40	900.10	163.30
10	1	2	1	1	223.80	5.50	24.20	2.46	66.67	33.33	456.94	195.72
11	1	2	1	2	242.80	6.00	23.60	2.68	65.28	34.72	437.65	188.19
12	1	2	1	3	245.40	6.50	25.00	2.82	63.93	36.07	409.18	163.67
13	1	2	2	1	238.80	7.00	24.60	2.63	51.02	48.98	625.10	161.28
14	1	2	2	2	225.20	7.00	25.40	2.66	67.65	32.35	636.00	168.54
15	1	2	2	3	247.00	7.00	28.00	2.50	63.49	36.51	557.24	137.64
16	1	2	3	1	235.60	7.00	27.40	2.73	67.80	32.20	1079.80	183.57
17	1	2	3	2	214.20	6.00	26.60	2.41	50.00	50.00	1075.67	185.17

Appendix Table 7.1. cont.

18	1	2	3	3	219.40	6.00	27.00	2.72	65.57	34.43	913.69	149.45
19	1	3	1	1	239.20	7.00	29.00	2.67	45.10	54.90	464.00	194.88
20	1	3	1	2	215.60	7.00	22.40	2.85	69.44	30.56	434.35	178.81
21	1	3	1	3	224.20	7.00	25.80	2.66	64.15	35.85	414.12	172.55
22	1	3	2	1	246.40	8.00	23.80	2.86	68.85	31.15	725.52	178.48
23	1	3	2	2	216.80	8.00	22.20	2.86	73.33	26.67	793.10	187.17
24	1	3	2	3	199.80	6.00	22.60	2.61	47.17	52.83	805.93	197.45
25	1	3	3	1	243.00	7.00	23.00	2.74	61.67	38.33	1065.42	184.93
26	1	3	3	2	234.40	6.00	24.20	2.55	51.11	48.89	1175.67	198.18
27	1	3	3	3	238.40	8.00	22.40	2.69	41.46	58.54	1037.64	176.40
28	2	1	1	1	248.00	7.50	24.40	2.76	66.67	33.33	380.71	162.43
29	2	1	1	2	235.00	7.00	22.80	2.71	63.08	36.92	328.00	155.25
30	2	1	1	3	243.00	8.00	22.80	2.84	66.07	33.93	358.59	148.22
31	2	1	2	1	234.60	6.50	29.00	2.72	65.57	34.43	706.34	181.53
32	2	1	2	2	210.80	7.00	22.60	2.85	69.01	30.99	779.31	156.64
33	2	1	2	3	221.20	7.00	25.80	2.73	72.06	27.94	695.17	180.05
34	2	1	3	1	242.60	7.50	24.60	2.91	59.32	40.68	1041.38	165.88
35	2	1	3	2	213.00	7.00	21.80	2.90	64.62	35.38	1068.97	187.83
36	2	1	3	3	209.20	6.50	22.20	2.75	59.26	40.74	1055.76	187.02

Appendix Table 7.1. cont.

37	2	2	1	1	235.60	8.00	29.40	2.69	56.25	43.75	352.00	160.16
38	2	2	1	2	235.40	7.50	28.60	2.76	67.61	32.39	428.24	191.99
39	2	2	1	3	258.60	8.50	30.00	2.57	66.13	33.87	371.76	159.24
40	2	2	2	1	229.40	6.70	29.80	2.60	63.01	36.99	700.69	190.59
41	2	2	2	2	216.40	5.50	24.00	2.75	62.69	37.31	561.79	168.54
42	2	2	2	3	224.40	7.00	26.00	2.75	63.08	36.92	562.62	144.59
43	2	2	3	1	252.20	8.50	28.80	2.69	62.90	37.10	1002.66	188.36
44	2	2	3	2	229.80	7.50	26.00	2.84	63.64	36.36	973.69	198.91
45	2	2	3	3	222.00	7.00	26.60	2.82	63.89	36.11	1030.15	189.11
46	2	3	1	1	234.00	6.50	28.40	2.77	72.06	27.94	435.06	182.72
47	2	3	1	2	215.60	7.00	25.80	2.60	59.68	40.32	408.00	155.72
48	2	3	1	3	210.60	6.00	25.60	2.83	63.79	36.21	438.12	177.44
49	2	3	2	1	223.20	6.00	27.00	2.53	66.10	33.90	788.97	198.82
50	2	3	2	2	245.60	7.00	25.00	2.69	64.52	35.48	712.83	181.77
51	2	3	2	3	225.20	6.50	25.80	2.80	63.93	36.07	723.86	186.03
52	2	3	3	1	236.80	6.50	25.20	2.66	67.80	32.20	978.13	179.56
53	2	3	3	2	224.80	7.00	25.60	2.68	71.64	28.36	997.24	173.09
54	2	3	3	3	248.40	7.00	27.60	2.56	63.64	36.36	1013.99	168.76
55	3	1	1	1	238.80	7.50	25.60	2.77	32.76	67.24	423.06	171.34

Appendix Table 7.1. Cont.

56	3	1	1	2	225.20	6.50	26.00	2.78	46.15	53.85	424.94	165.73
57	3	1	1	3	247.00	7.00	28.20	2.73	48.15	51.85	438.59	184.94
58	3	1	2	1	235.60	6.50	27.20	2.75	52.63	47.37	718.62	171.75
59	3	1	2	2	214.20	7.00	27.20	2.56	55.17	44.83	694.07	160.33
60	3	1	2	3	219.40	6.50	27.00	2.75	48.15	51.85	686.90	181.34
61	3	1	3	1	223.80	7.00	25.00	2.83	64.41	35.59	920.00	198.46
62	3	1	3	2	242.80	6.50	24.20	2.83	45.28	54.72	926.90	170.81
63	3	1	3	3	245.40	6.00	24.60	2.78	59.32	40.68	908.37	195.95
64	3	2	1	1	246.40	8.00	25.60	2.83	61.64	38.36	290.82	126.99
65	3	2	1	2	216.80	6.50	21.80	2.81	60.94	39.06	384.94	157.83
66	3	2	1	3	199.80	5.50	21.60	2.66	57.97	42.03	402.82	170.53
67	3	2	2	1	243.00	7.00	22.60	2.72	54.84	45.16	657.10	185.96
68	3	2	2	2	234.40	7.00	24.20	2.69	66.67	33.33	587.31	149.18
69	3	2	2	3	238.40	7.50	22.80	2.74	59.72	40.28	708.41	192.69
70	3	2	3	1	239.20	7.00	28.80	2.72	54.84	45.16	905.42	194.02
71	3	2	3	2	215.60	7.50	23.20	2.79	58.82	41.18	840.59	181.33
72	3	2	3	3	224.20	6.50	24.80	2.73	55.74	44.26	800.99	185.37
73	3	3	1	1	238.80	7.50	25.60	2.77	58.67	41.33	396.71	169.26
74	3	3	1	2	225.20	6.50	26.00	2.78	64.52	35.48	435.29	184.27

Appendix Table 7.1. cont.

75	3	3	1	3	247.00	7.00	28.20	2.73	66.18	33.82	383.53	170.03
76	3	3	2	1	235.60	6.50	27.20	2.75	61.76	38.24	822.07	183.32
77	3	3	2	2	214.20	7.00	27.20	2.56	57.58	42.42	711.17	172.10
78	3	3	2	3	219.40	6.50	27.00	2.75	53.33	46.67	718.76	176.10
79	3	3	3	1	223.80	7.00	25.00	2.83	61.11	38.89	992.32	183.58
80	3	3	3	2	242.80	6.50	24.20	2.83	53.42	46.58	1007.49	186.39
81	3	3	3	3	245.40	6.00	24.60	2.78	64.79	35.21	915.86	197.56

Key Main Factor Indicates Furrow Slope, Sub Factor Furrow Length, Sub-Sub Factor Furrow Inflow Rates and CH = Cane Height, CW = Cane Weight, NCI = Number of Cane Internode Per Stalk, MP = Moisture Percentage, DS = Dry Substances, NMC = Number Of Millable Cane Stalk, CY Cane Yield

Appendix Table 7.2. Data on sugarcane Quality parameters

S/No	Rep	MF	SF	SSF	BX (%)	PL (%)	PT (%)	FP (%)	ERS ton/ha	ESY ton/ha
1	1	1	1	1	18.63	17.69	94.93	42.00	13.09	21.56
2	1	1	1	2	18.75	18.04	96.22	49.37	13.40	20.15
3	1	1	1	3	19.47	18.63	95.71	45.49	13.82	22.09
4	1	1	2	1	19.59	18.57	94.77	45.88	13.74	19.32
5	1	1	2	2	19.50	17.77	91.13	41.75	13.02	19.92
6	1	1	2	3	20.29	18.61	91.73	37.21	13.66	23.45
7	1	1	3	1	19.66	18.93	96.30	33.17	14.07	22.23
8	1	1	3	2	19.44	18.79	96.64	29.94	13.97	16.10
9	1	1	3	3	19.79	18.79	94.95	24.67	13.91	22.72
10	1	2	1	1	18.42	17.83	96.77	32.67	13.26	25.95
11	1	2	1	2	18.36	17.07	92.98	34.07	12.57	23.65
12	1	2	1	3	19.51	17.58	90.10	35.37	12.84	21.01
13	1	2	2	1	18.42	17.75	96.36	48.35	13.19	21.27
14	1	2	2	2	19.23	17.91	93.12	31.66	13.19	22.23
15	1	2	2	3	18.45	17.12	92.78	35.85	12.60	17.34
16	1	2	3	1	18.27	17.99	98.45	31.54	13.44	24.67
17	1	2	3	2	19.13	18.88	98.68	49.35	14.11	26.13
18	1	2	3	3	18.28	17.56	96.04	33.77	13.04	19.48

Appendix Table 7.2. Cont.

19	1	3	1	1	17.46	17.17	98.33	54.32	12.82	24.99
20	1	3	1	2	20.16	18.43	91.44	29.82	13.51	24.17
21	1	3	1	3	18.32	18.01	98.29	35.20	13.45	23.20
22	1	3	2	1	18.35	17.76	96.80	30.48	13.21	23.59
23	1	3	2	2	18.23	17.25	94.65	26.00	12.76	23.89
24	1	3	2	3	19.41	19.06	98.20	52.18	14.23	28.10
25	1	3	3	1	18.42	17.93	97.34	37.68	13.36	24.70
26	1	3	3	2	17.28	16.70	96.62	48.30	12.42	24.60
27	1	3	3	3	18.36	17.10	93.15	57.94	12.60	22.22
28	2	1	2	1	17.45	16.54	94.79	32.71	12.24	19.88
29	2	1	2	2	18.43	17.45	94.68	36.27	12.91	20.04
30	2	1	2	3	19.12	18.42	96.35	33.24	13.69	20.29
31	2	1	3	1	19.32	18.83	97.45	33.73	14.03	25.47
32	2	1	3	2	18.18	17.41	95.74	30.33	12.91	20.23
33	2	1	3	3	17.92	16.25	90.66	27.29	11.88	21.39
34	2	1	1	1	18.16	17.19	94.68	40.04	12.72	21.10
35	2	1	1	2	18.45	17.60	95.41	34.73	13.05	24.51
36	2	1	1	3	19.25	18.82	97.77	40.07	14.04	26.25
37	2	2	2	1	18.34	17.07	93.07	43.12	12.57	20.13

Appendix Table 7.2. Cont.

38	2	2	2	2	18.38	17.93	97.54	31.73	13.36	25.66
39	2	2	2	3	18.11	17.13	94.58	33.22	12.67	20.17
40	2	2	3	1	19.00	17.93	94.37	36.31	13.25	25.26
41	2	2	3	2	19.47	18.52	95.13	36.62	13.72	23.12
42	2	2	3	3	19.55	19.19	98.14	36.23	14.32	20.71
43	2	2	1	1	19.43	18.70	96.27	36.41	13.90	26.18
44	2	2	1	2	18.77	17.45	92.95	35.70	12.85	25.55
45	2	2	1	3	19.22	18.96	98.64	35.43	14.17	26.80
46	2	3	2	1	18.24	17.73	97.23	27.27	13.21	24.14
47	2	3	2	2	18.34	18.10	98.69	39.68	13.53	21.07
48	2	3	2	3	18.26	17.54	96.08	35.56	13.03	23.12
49	2	3	3	1	19.53	18.54	94.96	33.20	13.73	27.30
50	2	3	3	2	19.51	18.81	96.42	34.79	13.98	25.42
51	2	3	3	3	20.42	18.32	89.73	35.34	13.36	24.86
52	2	3	1	1	17.29	16.63	96.18	31.58	12.35	22.18
53	2	3	1	2	19.42	18.67	96.12	27.65	13.86	24.00
54	2	3	1	3	18.38	17.80	96.85	35.71	13.25	22.35
55	3	1	3	1	18.24	17.86	97.94	66.66	13.33	22.84
56	3	1	3	2	19.17	18.30	95.49	53.21	13.57	22.49

Appendix Table 7.2. Cont.

57	3	1	3	3	18.67	18.02	96.53	51.22	13.40	24.78
58	3	1	1	1	18.88	18.43	97.59	46.72	13.74	23.59
59	3	1	1	2	19.75	18.91	95.73	44.15	14.03	22.49
60	3	1	1	3	18.37	17.72	96.47	51.23	13.17	23.89
61	3	1	2	1	18.54	18.25	98.42	34.93	13.63	27.05
62	3	1	2	2	18.44	17.28	93.71	54.10	12.75	21.78
63	3	1	2	3	18.56	17.17	92.50	40.03	12.62	24.74
64	3	2	3	1	18.46	18.04	97.71	37.70	13.45	17.08
65	3	2	3	2	18.39	17.25	93.78	38.42	12.73	20.09
66	3	2	3	3	18.72	18.23	97.41	41.38	13.59	23.17
67	3	2	1	1	19.13	18.66	97.54	44.50	13.91	25.87
68	3	2	1	2	17.98	17.32	96.33	32.69	12.87	19.20
69	3	2	1	3	20.12	17.85	88.72	39.57	12.98	25.01
70	3	2	2	1	18.34	17.21	93.81	44.53	12.70	24.64
71	3	2	2	2	18.17	17.50	96.29	40.54	13.00	23.57
72	3	2	2	3	19.51	18.38	94.21	43.59	13.58	25.17
73	3	3	3	1	18.84	18.08	95.98	40.68	13.43	22.72
74	3	3	3	2	18.18	16.70	91.89	34.84	12.26	22.59
75	3	3	3	3	19.83	18.78	94.69	33.11	13.89	23.62

Appendix Table 7.2. Cont.

76	3	3	1	1	19.59	18.58	94.86	37.54	13.76	25.22
77	3	3	1	2	17.79	16.46	92.51	41.81	12.10	20.82
78	3	3	1	3	18.84	17.60	93.44	46.02	12.98	22.85
79	3	3	2	1	18.52	17.83	96.30	38.24	13.25	24.33
80	3	3	2	2	20.16	19.16	95.04	45.88	14.19	26.45
81	3	3	2	3	18.82	17.27	91.74	34.54	12.67	25.03

Key Main factor indicates furrow slope, Sub factor furrow length, sub-sub factor furrow inflow rates and BX = Brix percentage, PL= Polarization percentage, PT = Purity percentage, FP = Purity percentage, ERS = Estimated reduced sugar, SSY = Estimated sugar yield