

DESIGN, PERFORMANCE EVALUATION AND DETERMINATION OF
OPTIMUM IRRIGATION LEVELS FOR TEFF (*Eragrostis tef* L.) UNDER
DRAGLINE SPRINKLER IRRIGATION SYSTEM IN NORTH DODOTA

Demissew Tsega Nigussie



A Thesis Submitted to

Water Resources Engineering Program

School of Civil Engineering and Architecture

Adama Science and Technology University

Adama

February, 2018

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School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of

Masters in Irrigation Engineering

Office of Graduate Studies

Adama Science and Technology University

Adama

February, 2018

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DEDICATION

This thesis is dedicated to my late son, Yabets Demissew, who had impatient desire to see my Success but pass out accidentally before two years.

BIOGRAPHICAL SKETCH

The author, Demissew Tsega Nigussie was born on November 23/1973 G.C. in Munessa Woreda West Arsi Zone of Oromia National Regional State. He attended his primary education at Munessa Primary School, junior secondary school education at Kerssa Junior Secondary School, and Senior Secondary School at Adama Compressive Secondary School. Following the completion of his high school education, he joined Jimma Agricultural College, now it is called Jimma University, in 1991 to pursue tertiary education and graduated with the Diploma of General Agriculture in July, 1992. Since September 1993, to Oct 1994, he worked at Assebetefery Agri-Technical School and served as a teacher. In Oct 1995 he was employed in Wonji/Shoa sugar factory and served as field coordinator in sugarcane plantation sections. In July 2002, he joined Hawassa University and graduated in the year 2007 with the Bachelor of Science Degree in Plant Production and Dry Land Farming. Since September, 2005, he has been working in junior, middle and higher management levels in the same employee. In the year 2010, he joined at Adama University and attended Civil Engineering course for two years. In campaign 2013/2014 he joined the School of Graduate Studies at Adama Science and Technology University to study for the degree of Master of Science in Irrigation Engineering.

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LIST OF ABBREVIATIONS

A	Wetted Area (m^2), area of irrigation (ha), area of pipe (i.e. πr^2)
AE	Application Efficiency
ARC	Agricultural Research Council
ASAE	American Society of Agricultural Engineering
ATA	Agricultural Transformation Agency
ASAE	American Society of Agricultural Engineers
ASTU	Adama Science and Technology University
CWD	Crop Water Deficit
CWP	Crop Water Productivity
CU	Christiansen's Uniformity Coefficient
DU	Distribution Uniformity
DU_{lq}	Distribution Uniformity of Lower Quarter
EIAR	Ethiopian Institute for Agricultural Research
ELWL	Lower excised leaf water loss
ERD	Effective Rooting Depth
ET _c	Crop Evapotranspiration
ET/ET _p	Potential Evapotranspiration
ET _o	Reference Evapotranspiration
EWP	Economic Water Productivity
GPE	Gross production economic
GRP	Glass fiber reinforced polyester pipe,
Ha	Hectare
IWMI	International water management institute
L1	Lateral nearest to the pump house
L2	Lateral furthest to the pump house
m	Meter
mm	Millimeter
MAD	Management Allowed Deficiency

MARC	Melkassa Agricultural Research Center
MOFED	Ministry of finance and economic development of Ethiopia
MOARD	Ministry of agriculture and rural development of Ethiopia
NFPA 13	Standards for the Installation of Sprinkler Systems
PVC	Polyvinyl Chloride
RASM	Readily available soil moisture
TGR	Total gross return
UNDP	United Nations Department of Economic and Social Affairs Population Division
USDA	United State Department of Agriculture
WP	Water productivity
WSSE	Wonji/Shoa Sugar Estate
WUE	Water use efficiency
WUI	Crop Water Use Index/ Irrigation Water Use Index
WWDSE	Water Works Design and Supervision Enterprise

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ABSTRACT

The economic basis and food source of fast growing Ethiopia's population is rain fed agriculture. But, the rainfall is unreliable, scanty and no enough water for most farmers to produce more than one crop per year and hence food insecurity and poverty are observed in the country due to low agricultural production and water productivity which necessitates the development of irrigated cereal food production. Among the cereal food crops, teff is the most well-known and widely consumed grain in Ethiopia and produced once in a year by rain fed agriculture and the

supply is by far less than the demand. In this study, dragline sprinkler irrigation system was designed, installed at Dodota Farm Land and the sprinkler system performance was evaluated by determining key performance parameters (Christiansen's uniformity coefficient, distribution uniformity of the lower quarter and application efficiency). And also, a field experiments was conducted and irrigation level that maximized grain and straw yield, crop water and economic water productivity were determined. For the purpose, four varying irrigation water application levels were used as irrigation treatments in a Randomized Complete Block Design (RCBD) with three replications. The varying irrigation levels were: irrigating at 100% ETo (T1)), 85% ETo (T2)), 70% ETo (T3), and irrigating at 55% ETo (T4). Accordingly, the average Christiansen's uniformity coefficient (CU) values ranged from 82.3% for afternoon test time to 87.8% for morning test time and the average distribution uniformity of lower quarter (DULq) values ranged from 76.5% for afternoon test time to 80.71 % for morning test time. A maximum teff grain yield of 3084.2Kg/ha was obtained when teff was irrigated at 70% ETo (T3) which was equal to 382 mm of applied depth of irrigation water. And also, the higher total income 72971.5Birr/ha for (3084.2 Kg/ha grain plus 6450 Kg/ha straw yield) of teff was obtained in 70% ETo(T3), irrigation water application level. But, there was no significant variation in total income between T2, T3 and also there was no significant variation observed in total income between T1 and T2. However, the highest water productivity (2.79 kg/m³) and the highest economic water productivity (20.96 Birr/m³) were obtained in 55% ETo (T4), irrigation water application level (294 mm).

Key Words: Economic water productivity, Irrigation level, Reference evapotranspiration, Teff, Water productivity, yield, yield component.

1. INTRODUCTION

1.1. Background and Justification

The coming challenge for the arid and semi-arid areas of the world could be food crop production due to limited availability of water. The problem is more pronounced in arid and semi-arid areas of undeveloped countries in which Ethiopia is one of them. Ethiopia is the second most populous country in Africa. The economic basis of Ethiopia is rain fed agriculture and agriculture produces the food to feed the country's population and it directly supports 85 percent of the population's livelihoods (CIA, 2009), 43 percent of gross domestic product

(MOFED, 2006), over 80 percent of export value (MOARD and US Department of State, 2010), and 80% of total employment (Belete et al., 2011).

Ethiopia has vast areas of fertile and irrigable land, diverse climate and large labor pool for agricultural development. Despite this potential, however, Ethiopian agriculture has remained underdeveloped. Irrespective of Ethiopia's endowment with potentially huge irrigable land, formally accounted overall irrigation development is estimated at some 5 – 6 percent of the developable potential of 3.7 million ha (Awulachew *et al.*, 2007), showing that water resources have made little contribution towards the development of the irrigated agriculture sector. On the contrary, a number of studies made in the field confirm that if the country's water resources are developed to provide water supply for irrigation, it would be possible to attain enough agricultural surpluses both for domestic consumption as well as for exports. Thus, the development and adoption of irrigated agriculture could secure food production, self-sufficiency; improve livelihoods and increase food resilience and security (Hussain and Hanjra, 2004, Awulachew *et al.*, 2007). Therefore, achieving greater efficiency of water use in the country will be a major challenge in the near future and will include the employment of techniques and practices that deliver a more accurate supply of water to crops.

Teff (*Eragrostis tef* L.) is one of the major cereal food crops cultivated in the country and it accounts for about a quarter of total cereal production in Ethiopia (Gabremadhin and Eleni, 2001) and it is a staple food for about 85% of the 90 million inhabitants of Ethiopia, and is currently only cultivated under rain fed agriculture with very low (1 ton/ha) yield. Large area of land for teff cultivation is found in the moisture deficit zone of the country and the rainfall is highly variable and insufficient for teff production in these areas. Therefore, it is imperative to bring large areas of the arid, semi- arid and sub-humid regions with uneven rainfall distribution under irrigated teff cultivation. As teff contributes a large proportion of cereals crop production in the country, solving the major problem of teff production is unquestionably one way of realizing food security of the country. Solving the major problem of teff production is possible by developing and adopting irrigated teff cultivation. By using irrigation teff can be produced 2-3 times per year. This in turn reduces poverty of the poor farmers whose livelihood's depends on rain fed teff production as well as food security of the country to be realized. Before adopting irrigated teff cultivation, the irrigation method that is suitable for the area and for the crop must

be selected, designed and evaluated. The predominant features of teff producing lands in Ethiopia as well as in the study area include a relatively steep slope, undulating topography, very susceptible terrain to gulling and soil erosion, thus, sprinkler irrigation is advantageous as it does not require precision land leveling, it can apply water effectively without risking soil erosion and it can provide variable yet precise water applications, requires low labor input than furrow irrigation. Therefore, using the factors listed above, in this study, dragline sprinkler irrigation system was selected, designed, installed at Dodota farm land which is one of water scarce areas in Oromia region. As water is one of the most valuable resources that must be used or utilized in efficient manner, water application depths must be evaluated experimentally in the field before adopting it for small scale as well as large scale crop production. In this study, varying levels of irrigation water application depths were experimentally evaluated in order to select the best performing one in water use water productivity and irrigation efficiency, increasing yield per unit of water applied.

1.2. Problem Statement

The economic basis and food source of fast growing Ethiopia's population is rain fed agriculture; the rainfall is, however, unreliable, scanty, erratic and inadequate for crop production and drought has been the main climatic related risk in Ethiopia. Due to large spatial and temporal variations in rainfall, there is not enough water for most farmers to produce more than one crop per year. Thus food insecurity has remained the major problem that is a great concern to the country. Moreover, frequent dry spells and droughts exacerbate the incidence of crop failure and the intensity of recurrent droughts resulted in food insecurity and poverty and affects the livelihoods of agricultural communities and the whole economy due to low agricultural

production and water productivity. The need to meet the growing demand for food will require increased crop production from less water (Ali and Talukder, 2008). And thus, increasing productivity of water in agriculture by producing more output under more efficient use of water is a key strategy for addressing water scarcity. As water supplies are limited, and as there is a reasonable increase in the price of agricultural production, great attention is required to increase water productivity (WP) and the farmer's goal should be to maximize net income per unit of water used. In Ethiopia, teff is produced using rainfall once in a year; the supply didn't much with its demand which resulted in continuous increase for unit price of teff from year to year due to low crop productivity, land productivity, water productivity, land degradation (soil erosion) and due to low and unsustainable rain fall. However, the use of sprinkler irrigation system for irrigated teff production can increase crop, land and water productivity. On the other hand, Ethiopia has vast areas of fertile and irrigable land, diverse climate and large labor pool for agricultural development in general and for irrigated teff production in particular. Most of the fertile lands and manpower in teff producing areas of Ethiopia are idle for long periods out of the major rainy season due to lack of developing, designing and adopting modern irrigation systems such as sprinkler irrigation system for cereal food crops production particularly teff production. Despite of the importance, teff as a food crop in Ethiopia, there has been only limited research and studies were conducted on the performance of irrigated teff and few of the studies were done and were limited at research stations and no sprinkler irrigation system has been designed and tested on farmer's field for irrigated teff production. Therefore, to this effect, in this study, dragline sprinkler irrigation system was designed, installed and tested on farmer's field for irrigated teff production in dry periods at Dodota Farm Land.

1.3. Objectives

1.3.1. General Objective

The general objective of this study was to increase Teff yield, optimize agricultural water productivity and land productivity of the study area using sprinkler irrigation system.

1.3.2. Specific Objectives

The specific objectives of the study were:

- To design,
- To evaluate the performance of sprinkler irrigation system,

- To evaluate effect of different irrigation levels on the agronomic and water use performance, and
- To determine effect of different irrigation depths on economic performance of teff irrigated under sprinkler irrigation system.

1.4. Research Questions

- What design norms used to ensure efficient and effective dragline sprinkler irrigation system for teff?
- What is the efficiency of the designed sprinkler irrigation system in water application and distribution uniformity?
- What is the agronomic, water use and economic performance of teff irrigated using sprinkler system? and
- What is the level of irrigation depth that maximizes crop yield, crop water and economic water productivity?

2. LITERATURE REVIEW

2.1. Sprinkler Irrigation System

In the sprinkler method of irrigation, water is applied above the ground surface as a spray somewhat resembling rainfall and the spray is developed by the flow of water under pressure through small orifices or nozzles (Reddi and Reddy, 1995). The pressure is usually obtained by pumping, although it may be by gravity if the water source is high enough above the area to be irrigated. Sprinkler irrigation is adaptable to most crops, soils and topographical circumstances and it is suited for most row, field and tree crops and water can be sprayed over or under the crop canopy. It is also adaptable to any farmable slop, whether uniform or undulating (Brouwer *et al.*, 2001 and Hill et al., 2008). Even though sprinklers are adaptable to most soils, they are best

suited to sandy soils with high infiltration rates. However, for an economical system and even water distribution over the total land surface, careful judgment of the design criteria is required.

2.2. Design Norms for Sprinkler Irrigation

Design norms are important to ensure an efficient and effective sprinkler irrigation system. The nozzle, pressure, spray angle, wetted area overlap, wind speed and direction are the major factors among others can influence the operation of a sprinkler irrigation system (Burger *et al.*, 2003).

2.2.1. Nozzle

A sprinkler can have one main and secondary nozzle. The main nozzle determines the reach, while the secondary nozzle determine the distribution uniformity (Burger *et al.*, 2003). The nozzles are one of the least expensive components, yet are often neglected. Nozzle wear does occur with times, which result in an enlargement of the orifice. According to (Jansen, 1981, Withers and Vipond, 1980, Keller and Bliesner, 1990), a 10% enlargement of the orifice will result in an increase of about 20% in delivery rate and a 20% increase in power consumption. The nozzle determines the flow breaks up the water into droplets and disperses them in a specified pattern and size for desired effect – two-nozzle sprinklers have higher flexibility for adjustment.

2.2.2. Pressure

The discharge of a sprinkler is a function of the nozzle diameter and pressure. The optimum pressure at which a sprinkler must operate can be calculated using the following rule of thumb: operating pressure of the sprinkler (m) is 6 to 7 times the nozzle diameter in mm (Burger *et al.*, 2003). Sprinkler effectiveness is reduced by operation at either excessively high or low pressures. Pressures that are too high produce fogging and irregular turning. Fogging produces too many small droplets that fall too close to the sprinkler. Pressures that are too low cause improper jet breakup, producing a doughnut-shaped spray pattern. Under either condition, water is not uniformly distributed (Smajstrla *et al.*, 2005). Each type of sprinkler has certain pattern characteristics that change as nozzle size and operating pressure change. Each has an optimum range of operating pressure for each nozzle size. At the lower side of the specified pressure range for any nozzle, the water is broken up into larger drops. When pressure falls too low, the water from the nozzle falls in a circle a distance away from the sprinkler, thus, giving a poor

distribution pattern. On the high side of the pressure range, the water from the nozzle break up into finer drops and settles around the sprinkler (Keller and Bliesner, 1990).

2.2.3. Spray Angle and Sprinkler Rotation

The sprinkler spray angle influences how high the water is projected into the air. The higher the water is projected, the wider the reach of the sprinkler. However, this subjects the spray to higher wind speeds and larger pattern distortion than water is ejected closer to the ground surface (Keller and Bliesner, 1990), as cited in (Burger *et al.*, 2003). According to Keller and Bliesner (1990), the best angle for sprinkler jet under ideal conditions is 320° above the horizontal. The required discharge of an individual sprinkler is a function of the water application rate and the two-way spacing of sprinklers. Uniform distribution is achieved by overlapping on the lateral and between the laterals; the overlapping depends on the required application rate mm/h, the discharge of the sprinkler m^3/h and the general wind speed km/h (Burger *et al.*, 2003).

Sprinkler rotation is one of the factors that influence water distribution of the sprinkler system. A constant sprinkler rotation speed will give a good distribution. An average of 2 rotations per minute or an optimum speed between 2.1 to 2.5 m/s on the outer circumference is recommended (Burger *et al.*, 2003).

2.3. Water Distribution Pattern of Sprinkler Irrigation System

When irrigation is applied by sprinkler method, water is distributed over the irrigated area by spraying it through the air. High uniformity of water application is achieved by overlapping the spray patterns from adjacent sprinklers. This generally means that the water sprayed from one head reaches the adjacent spray heads (Smajstrla and Zazueta, 2003). During sprinkler operation, a stream of water is discharged into the air at high velocity. Friction between the air and the water stream causes the stream to break apart into water droplets that fall to the surface, similar to rainfall. A sprinkler water distribution pattern depends on: the sprinkler spacing, operating pressure, nozzle diameters, the management, wind speed and direction (Keller and Bliesner, 1990, Topake *et al.*, 2005, Liu, 2009). When there is no wind, the size of droplets and their distribution patterns primarily depend on the nozzle design and any associated stream break up mechanisms, the sprinklers operating pressure, and the height of the sprinkler above the ground surface (Brouwer *et al.*, 2001, Smajstrla and Zazueta, 2003). Under windy condition, wind speed and direction also affect droplet sizes and distribution patterns. The climatic factors which affect

water distribution are wind speed and direction. These factors have less effect on the distribution pattern of continuously moving lateral system than one set systems. Consistent high velocity winds can in fact rule out the effective use of sprinkler irrigation or limit operations to times of relatively low winds such as night. Under high wind conditions the application pattern is tremendously skewed. This results in highly non-uniform application of water (Cuenca, 1989). Several authors (Dechmi, 2002, Moazed *et al.*, 2010) have reported the wind to be the main environmental variable affecting sprinkler performance; it is the most important uncontrollable factor (Abo-ghobar, 1994, Topak *et al.*, 2005). Wind causes the break up and distribution processes to change in two ways (1) it affects the breakup of the water due to air resistance and (2) it blows all the resulting drops around (Solomon, 1990).

2.3.1. Wetted Diameter and Wetted Area Overlap

Wetted diameter is defined as the distance across a water application pattern from dry soil in front of the system to dry soil behind the system. The wetted area is a circular area that is wetted by a single sprinkler device and by a series of overlapping sprinkler devices. In addition to the sprinkler device selected, operating pressure of the irrigation system and height of operation are factors in determining wetted diameter. Wetted diameter decreases most significantly with lower operating pressure (Yonts *et al.*, 2007). Keller and Bliesner, (1990), indicated that, the required discharge of an individual sprinkler is a function of the water application rate and the two-way spacing of the sprinklers and Uniform distribution is achieved by overlapping on the lateral and between laterals. The overlapping depends on the required application rate [mm/h], the discharge of the sprinkler [m^3/h] and the general wind speed [km/h]. There are three types of sprinkler spacing's: square, rectangular and triangular. Each type has certain advantages, but under average conditions best results in terms of distribution uniformity are usually obtained from a square spacing (Keller and Bliesner, 1990).

2.3.2. Discharge and Gross Application Rate

The discharge rate of a sprinkler head is determined by the size of the sprinkler nozzle and the operating pressure. Reducing the operating pressure of the sprinklers reduces the sprinkler discharge rate. For a particular nozzle size, the discharge rate is not significantly changed by small changes in operating pressure. Reducing the sprinkler nozzle size may be an alternative for reducing the application rate (Schwankl *et al.*, 2007). The average rate at which the water is

theoretically applied by the sprinkler to the wetted area is known as the gross application rate. Each soil has a known ability to soak up water, which is generally known as the infiltration rate of a soil. An application rate higher than infiltration rate will result in runoff and inadequate moisture replacement. Generally sprinklers give an application rate of between 6 to 9 mm/h which most soils can handle and give the highest distribution efficiency (Burger *et al.*, 2003).

2.4. Evaporation and Wind Drift Losses in Sprinkler Irrigation System

Evaporation, wind drift, and deep percolation are chief causes of water loss (Hill *et al.* 2008). Evaporation and drift losses are typically from 5% to 10% but can be higher when the air is dry and if there is a lot of wind, the water droplets are small (Merkley and Allen, 2004). At higher wind speeds, larger droplets can be transported by the wind, and droplets can be transported greater distances (Smajstrla and Zazueta, 2003). Such losses can be fairly significant if the sprinkler nozzles are located high above the crop canopy where they are subjected to higher wind velocities than those that occur close to the canopy (Cuenca, 1989; Abo-Ghobar, 1994). Evaporation losses from sprinklers are dependent upon both climatic factors and operating Conditions. Evaporation loss from a sprinkler irrigation system can be reduced by changing the sprinkler operating conditions to increase the sizes of water droplets or by irrigating when climate demands are low (Smajstrla and Zazueta, 2003). Nozzle size, operating pressure and wind speed are the predominant factors that affect losses from sprinkler system (Abo-Ghobar, 1993). And the evaporation and wind drift losses can be calculated using Trimmer (1987) equation as:

$$E = \left[1.98 (D)^{-0.72} + 0.22 (es - ea)^{0.63} + 3.6 \times 10^{-4} (h)^{1.16} + 0.14 (u)^{0.7} \right]^{4.2} \quad (2.1)$$

Where: E = Evaporation and wind drift, percent

D = Nozzle diameter, mm

h = Nozzle operating pressure, KPa

U = Wind velocity, m/s

es – ea = Vapor pressure deficit, Kpa

The vapor pressure deficit is given by:

$$e_s - e_a = 0.61 \exp \left[17.27 \frac{T}{T + 237.3} \right] (1 - RH) \quad (2.2)$$

Where: T = Air temperature, oC

RH = Relative humidity, fraction,

2.5. Performance Evaluation of Sprinkler Irrigation System

The manufacturer reported precipitation rates and design distribution uniformity may not be accurate and the fact that the system has low distribution uniformity may be a function of design, installation, and maintenance. Characterization of the system's performance is useful to indicate areas of needed improvements and in order to make appropriate corrections/modifications. Therefore, irrigation performance evaluation mostly conducted after installation and every two weeks to determine, precipitation rate, and identify necessary system adjustments by utilizing Catch-container tests. Moreover, an irrigation audit can reveal inefficiencies such as: quantity of water exceeding the plant needs, non-uniformity of water application, precipitation rate exceeding soil infiltration rate, incorrect heads/nozzles, improper application pressure, and malfunctioning and/or misdirected sprinklers.

The major objectives of an evaluation are to determine how much water reached the crop, how uniformly it is distributed, and how much is lost during the application process. The end result is water savings that is achieving efficient and effective application of water. By using this approach, the amount of water made available for use by the crop could be calculated (Magwenzi, 2000, Thomas, 2003). Irrigation evaluations are used in the field to establish irrigation performance, which in sprinkler irrigation is primarily represented by irrigation uniformity and efficiency. During the evaluation process, quantitative levels of uniformity are established. Sprinkler irrigation systems require a minimum value of uniformity in order to be considered acceptable (Dechmi, *et al.*, 2003b). Evaluations involve measuring conditions at one or more points in a field selected to be typical or representative. Value judgments or additional measurements must be made to correlate these data to an overall fields, farms, or project efficiency (Merriam *et al.*, 1983). Irrigation systems require a number of resources such as labor, water, power and time so optimizing an irrigation system by combining the correct type, design and operation of the system allows the use of these resources to be minimized (Wigginton and Raine, 2001). Therefore, performance assessment has to be made in order to be able to optimize an irrigation system (Julaia, 2009).

2.5.1. Performance Parameters of the Irrigation System

The most commonly used performance parameters to measure the sprinkler irrigation system performance are: precipitation rate and application efficiency, distribution uniformity and uniformity coefficient (Merriam *et al.*, 1983 and Burt *et al.*, 1997). The different efficiencies have different purposes and should be carefully differentiated. Some of these indicators such as uniformity of water distribution within a field are more properly expressed as ratios (Burt *et al.*, 1997).

Application Efficiency

Water application efficiency is an irrigation concept that is very important in both system design and irrigation management. It can be divided into two components, water losses and uniformity of application. When either the water losses are large, or uniformity is poor, efficiency will be low. Although both components of efficiency are influenced by system design and management, losses are predominantly affected by management, while uniformity is predominantly affected by system design (Solomon 1988b, Topak *et al.*, 2005). Application efficiency is also a measure of how efficiently water has been applied to the root zone of the crop. This parameter relates the total volume of water applied by the irrigation system to the volume of water that has been added to the root zone and is available for use by the crop. For in-field evaluation where the depth of water applied is less than the root zone moisture deficit prior to irrigation and run-off is not evident, the irrigation water available to the crop can be assumed to be equal to the average depth of water applied as measured at the soil surface (i.e. with catch cans). Evaluating application efficiency has the same spatial and temporal boundary constraints as all other parts of the irrigation system. The methods for evaluation range from measuring the inflow and outflow from a single event, to estimating the inputs and outputs over an irrigation season or a number of seasons. There are many water indices that can be applied to evaluate the system, but important step within the Barrett, Purcell & Associates Framework is to clearly define the units used in the index. These crop water use indices are a measure of the agronomic performance of the crop (yield and economic return) in relation to the irrigation water applied (Helen *et al.*, 1999).

The concepts of potential and actual application efficiency are also useful for measuring irrigation system performance. Potential application efficiency, PAE, is useful in measuring the performance of a system for a single irrigation event. PAE is based on the concept that the

application could be terminated at such time that the target would be just met by the average of the lowest values in the irrigation infiltration distribution (Burt *et al.*, 1997). Potential application of low quarter (PELQ) indicates how efficiently the tested sprinkler system can apply water if the system is run the correct length of time (under optimum management neglecting pre-nozzle losses) to just satisfy the management allowable deficiency (MAD). Actual application efficiency of low quarter (AELQ) is the ratio of the average low-quarter (LQ) depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied and calculated from nozzle discharge (Merriam *et al.*, 1983) using distribution data. The purpose is to determine the losses of water as a result of wind and evaporation and can be analyzed using formula (Merriam *et al.*, 1983) as:

$$AE = \frac{x_{av}}{GAR} * 100 \quad (2.3)$$

Where, AE = application efficiency (%)

x_{av} = average depth irrigation water applied [mm]

GAR = gross sprinkler application rate [mm]

Irrigation Uniformity

The ability of a sprinkler irrigation system to apply water uniformly throughout the irrigated area is a major factor influencing whether or not crop growth can be maintained. Ideally, an irrigation system would apply water in a completely uniform manner so that each part of the irrigated area receives the same amount of water (Solomon, 1988a). Unfortunately, there seems to be no way to achieve this. Even natural rainfall is not completely uniform. So the phrase “irrigation uniformity” actually refers to the variation, or non-uniformity, in the amounts of water applied to locations within the irrigated area (Solomon, 1990). Uniformity of irrigation is a measure of the evenness of the application. As higher uniformity of application is achieved, variation in depths applied at different points in the field differ less from the average depth. An irrigation system with good uniformity of application saves water, because it allows avoiding over irrigating parts of the field while concentrating on putting adequate water on dry or other problem areas (Thomas, 2003), Keller and Bliesner (1990) classified the irrigation uniformity in solid set system as “low” when CU was below 84% and distribution uniformity is below 75% for high value crops.

Distribution Uniformity (DU)

Distribution uniformity (DU) is a measure of how evenly water is applied during an irrigation event. This uniformity of application can have a big effect on crop yield and optimum water application. There are several interpretations of DU in the literature, but a common measure applied to sprinkler irrigation, is the Christiansen's Uniformity Coefficient (CU), which is essentially a ratio of the sum of the variation of depths from the average depth to the sum of all the depths. Uniformity of sprinkler irrigation is often evaluated by measuring the application depths using catch cans. Distribution uniformity is expressed as a percentage (between 0 and 100%). Common values for existing sprinkler systems range between 60 and 80% and for furrow irrigated fields, 50 and 60% or less. The uniform application of water in a field is important, but it has to be considered together with the efficiency of the application. The distribution uniformity represents the spatial evenness of the applied water across a field or a farm as well as within a field or a farm (Wigginton and Raine, 2001, Howell, 2003). Another similar uniformity coefficient is Distribution Uniformity of the Lower Half (DU_{50}). It is the ratio of the average applied depth of the lower half to the grand mean of applied depth. It reflects the relationship between the drier half and the whole field (Liu, 2009). The water distribution uniformity is a measure of the uniformity of distribution in lowest quarter (DU_{Lq}) which can be estimated using the catch can test method and determined by measuring the applied water and calculating the ratio between the average of the lowest 25% of the measurements and the average of all the measurements in the testing area. The DU calculated by using formula (Burt *et al.*, 1997) as:

$$DU = \frac{AveLq}{AveT} * 100 \quad (2.4)$$

Where, DU = Distribution uniformity, %

$AveLq$ = Average of the lowest quarter of the catch can reading (mm)

$AveT$ = Average of all catch can readings (mm)

Uniformity Coefficient (CU)

The uniformity coefficient most often used is the Christiansen's uniformity coefficient which was developed to describe how evenly a single sprinkler distributes water. This method

compares the absolute variation of the wettest and driest areas with the average (Solomon 1988a). CU treats the over application and under application the same and reflects the overall average uniformity. Both over-and under-irrigation occurring in the same system could cancel each other out, which would result in a relatively high CU value (Solomon 1988a, Liu, 2009). According to (Pair *et al*, 1983), a minimum of 70% uniformity is required for agricultural sprinklers. And the CU-value calculated and analyzed by means of the following formula (Christiansen, 1942):

$$CU = 100 \times \left(1 - \frac{\sum |xi - xav|}{nxav} \right) \quad (2.5)$$

Where, CU = Christiansen's uniformity coefficient [%]

$$xav = \text{average application [mm]} = \frac{\sum xi}{n}$$

n = number of measuring points or catch cans

Xi = application depth at point i [mm]

2.6. Irrigated Teff (*Eragrostis tef* L.) Production

Teff (*Eragrostis tef* L.), Williams love grass, warm-season grass, is a cereal crop grown primarily in Ethiopia (Lewis, 2013), and it was one of the earliest plants domesticated (Murphy, Denis J., University Press, 2007). Ethiopia is the center of origin and diversity of teff. Teff is adapted to environments ranging from drought stress to waterlogged soil conditions. It is well adapted to a variety of soil conditions ranging from drought- stressed to water logging soils and it usually grows about 60 to 90 cm (Norberg *et al.*, 2009), and has a shallow fibrous root system with mostly erect stems. The effective root system distributed in soil layer from surface to 5 cm below and the maximum natural rooting depth in the soil layer from surface is 80 cm (Ayumi *et al.*, 2012). Two methods of tef planting are practiced in Ethiopia. The traditional planting method broadcasting, or scattering seeds by hand and the improved method - row planting are the major methods for planting of teff (Berhe, 2012). Irrigation is normally required frequently following seeding and until the roots are established at two to three weeks. After planting of teff, light and frequent irrigations are needed for optimum stand establishment. Emergence is rapid (3 to 7 days). After emergence, tef is irrigated similar to any other grass crop (Creech *et al.*, 2012). And

once established, teff is typically irrigated in the same way as other grass crops. It is recommended to irrigate often after planting especially if planting into a dry seedbed. The shallow placement and small size of teff seed necessitates light, frequent irrigations for establishment. Once roots are established, (Norberg *et al.*, 2009), recommended to irrigate teff according to 100-percent estimated crop water use for pasture (Agrimet, [http:// www.Usbr.gov/pn/ agrimet/](http://www.Usbr.gov/pn/agrimet/)) or 70 percent of the reference evapotranspiration. Investigations carried out so far on teff indicated that, both its agronomic and physiological traits are affected if the crop is subjected to different levels of water stress. And also, in study conducted to investigate the influence of various soil moisture regimes on physiological processes of teff, it was found that severe water stress (75% of water withhold) has caused 92.8% and 60% reduction in net assimilation and respiration, respectively (Dejene, 2009). While teff is reported to be drought tolerant. Recent studies also indicate that, adequate irrigation is necessary for optimum production. In its native country (i.e. in Ethiopia), it has been reported that, teff needs at least 17 inches of rainfall for grain production (Rosenberg *et al.*, 2006, cited in Jay *et al.*, 2011). According to (Jay *et al.*, 2011), teff appears to be most productive in regions having at least 24 inches of rainfall, or supplemental irrigation and it is estimates that, teff requires approximately 50 to 70% as much water as alfalfa to produce an economic crop. Due to the short growing season, teff uses less irrigation water than any other crops. The primary water savings possible with Teff production is related to the relatively short growing season as compared to alfalfa and less irrigation. However, determining the appropriate level of irrigation for teff is vital to the productivity and the conservation of water. Research results in Nevada and California in USA recommended a minimum of 609.6 mm of water per season (Davison *et al.*, 2010).

2.7. Reference Evapotranspiration (ET_o)

The evapotranspiration rate from a reference surface, not shortage of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ET_o. The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m⁻¹ and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m⁻¹ implies a moderately dry soil surface resulting from about a weekly irrigation frequency (Allen *et al.*, 1998). The concept of the reference evapotranspiration was introduced to study the evaporative

demand of the atmosphere independently of crop type, crop development and management practices. As water is abundantly available at the reference evapotranspiration surface, soil factors do not affect ET. Relating ET to a specific surface provides a reference to which ET from other surfaces can be related. It obviates the need to define a separate ET level for each crop and stage of growth. ETo values measured or calculated at different locations or in different seasons are comparable as they refer to the ET from the same reference surface. The only factors affecting ETo are climatic parameters. Consequently, ETo is a climatic parameter and can be computed from weather data. ETo expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. As a result of an Expert Consultation held in May 1990, the FAO 56 Penman-Monteith method is now recommended as the sole standard method for the definition and computation of the reference evapotranspiration (Allen *et al.*, 1998). The method has been selected because it closely approximates grass ETo at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters (Allen *et al.*, 1998).

2.8. Crop Evapotranspiration

Crop evapotranspiration is one of the basic parameters in water use and productivity performance indicators. The single crop coefficient approach suggested by (Allen *et al.*, 1998) is one of the methods used to determine the actual crop evapotranspiration. In the crop coefficient approach, differences in the crop canopy and aerodynamic resistance relative to the hypothetical reference crop are accounted for within the crop coefficient. The Kc factor serves as an aggregation of the physical and physiological differences between crops and the reference definition. In the single crop coefficient approach, the effect of crop transpiration and soil evaporation are combined into a single Kc coefficient. The coefficient integrates differences in the soil evaporation and crop transpiration rate between the crop and the grass reference surface. As soil evaporation may fluctuate daily as a result of rainfall or irrigation, the single crop coefficient expresses only the time- averaged (multi-day) effects of crop evapotranspiration (Allen *et al.*, 1998). The crop coefficient approach can be used to compute ETc for the growth periods. This method requires, determination of and reference crop evapotranspiration [mm d⁻¹], crop coefficients at the initial (Kc ini), mid-season (Kc mid) and crop coefficient at the late-season stages (Kc late), (Allen *et al.*, 1998).

2.9. Crop Coefficients and Crop Water Requirement of Irrigated Teff

The value of K_C varies with crop, development stage of the crop and to some extent with wind speed and humidity and for most crops it increases from a low value at time of emergence to a maximum value during full development period and declines as the crop matures” (Doorenbos and Kassam, 1979). Depending on the time interval between wetting events, the magnitude of the wetting event, and the evaporation power of the atmosphere, K_c can vary between 0.1 and 1.15 (Allen, 1998). According to Allen, “the effect of the difference in aerodynamic properties between the grass reference surface and agricultural crops is not only crop specific but also varies with the climatic conditions and crop height” Different research has sought to identify appropriate K_c for warm-season grass species. By summarizing the results from a series of applied water studies, Mayer and Gibeault (1987) and Snyder and Pruitt (1985) using a modified penman equation, suggested a K_c of 0.6 for irrigation of warm-season grasses. This became a widely accepted value for irrigation of warm-season grasses, however, more recent studies have indicated higher K_c values may more accurately reflect warm-season grass water use. Allen *et al.*, (1998) recommended a K_c value of 0.80 to 0.85 for irrigating warm-season grasses. According to (Yihun, 2015), the overall average Teff K_c values for the initial, development, mid-season and late-season growth stages are found to be 0.6, 0.8, 1.2 and 0.8 respectively. Yihun also reported that, Teff crop evapotranspiration (ET_c) for whole growth period found to be in the range of 299 to 342 mm and the overall average is 319 mm. This average value is significantly different from the 375 mm ET_c value obtained for Barley (Araya *et al.*, 2011), but is comparable to that of Millet, which is 330 mm (Grema and Hess, 1994).

2.10. Crop Water Use and Irrigation Water Use Indices

According to [Barrett Purcell & Associates, 1999 and Skewes 1997), crop water use indices and irrigation water use indices are the most common water use indices (WUI) relating to the application of water to a crop. Improving water use efficiency or crop water use index will require the amount of water a crop transpired to be maximized and the losses that occur as the water moves to the plant to be minimized. A crop water use index or efficiency compares the yield or economic return from the crop to the amount of water the crop transpires. According to Stirzaker (1999), when irrigation application is below optimum, there is generally a positive response in yield for each unit of irrigation water applied. Beyond this optimum point there is, on well drained soils, no further increase in yield for each extra input of irrigation water.

According to (Helen *et al.*, 1999), the current understanding is applying the dual compartment toolbox approach that is central to the Barrett, Purcell & Associates framework (1999), provides clear distinction between irrigation and agronomic (crop) water use efficiencies and indices. This distinction is important in terms of reporting a measure of performance. Generally, improving water use efficiency or a crop water use index will require the amount of water a crop transpires to be maximized and the losses that occur as the water moves to the plant to be minimized. In some cases it may be desirable to limit the amount of water a crop transpires, (deficit irrigation), and in this case maximizing transpiration is not the objective of irrigation. A water use economic index would be needed to measure the improved performance when transpiration is intentionally restricted. Crop water use efficiency compares an output from the system, such as yield or economic return, to crop evapotranspiration (Solomon, 1984). In contrast an irrigation index or efficiency often compares an output, such as yield, economic return or amount of water retained in the root zone to an input, such as some measures of water applied. Water use indices generally are a ratio of an agronomic or economic variable to a volumetric or depth measure of the water applied to the root zone, transpired by the crop or available to the crop. Therefore, the water use index approach generally measures the productivity or profitability of an irrigation enterprise as opposed to the water balance (Barrett Purcell & Associates, 1999 and Skewes, 1997). The time period considered when calculating an agronomic or economic based water use index is generally over a season or year.

The water productivity concept is based on 'more crop per drop' or producing more food from the same water resources' or producing the same amount of food from less water resources. In broad sense, productivity of water is related to the value derived from the use of water. Definitions of water productivity are not uniform and change with the background of the researcher or stakeholder involved. For example at field scale if we concentrate on the productivity then we can express this as total dry matter production or as actual yield as harvestable product. At basin scale, economists wish to maximize the economic value from water used.(Kijne *et al.*,2003b), provided several strategies for enhancement of agricultural water productivity by integrating varietal improvement and better resource management at plant level, field level and agro-climatic level. Water productivity is also sometimes measures specifically for crops (crop water productivity).

2.10.1 Crop Water Productivity (CWP)

Crop water productivity (CWP) is defined by different definitions of various researchers. Water productivity is a ratio, which relates the crop yield with the volume of irrigation water supplied (Bos, 2002). Bos also indicated that, Crop yield over irrigation supply and crop yield over water consumed are the most water productivity indicators. Bessembinder *et al.*, (2005), defined CWP as the amount or the value of product over volume or value of water depleted or diverted. And also, Molden *et al.*, (2007), defined Crop water productivity (CWP) as the amount or the value of product over volume of water depleted or diverted.

2.10.2. Economic Water Productivity (EWP)

Gross value of production over cropped area, gross value of production over irrigation supply and gross value of production over water consumed are economic water productivity indicators. Economic water productivity (EWP) is expressed in gross income in Birr or US\$ per gross water supplied in m³. By considering the size of irrigable area, the price of water applied, and the income gained from the sale of grain (main product) and the straw (by-product) considering the average seasonal local market price Birr or (US\$), the economic water productivity of irrigated crop can be determined. The gross income is the product of the average price of the crop per kg for the season and the average grain yield per given irrigable area plus the product of the price of the crop straw per kg of the season and the average straw yields per given irrigable area. Local market prices have to be considered, because almost all the products are consumed locally under the present conditions. Increase in crop production per unit of water doesn't necessarily result into an increase in the farmer's income because of the non-linearity of crop yield with the price.

3. MATERIALS AND METHODS

3.1. Description of the Study Area

This study was carried out in Wonji Shoa Sugar Estate at Dodota farm land which is located in the Central Rift Valley of Ethiopia and lies downstream of Koka Dam, 125 km southeast of Addis Ababa and 18 km south of Adama town. It is situated in the Awash Basin at an elevation of 1555 meters above mean sea level at 8.31°N latitude and 39.12°E longitudes. The main irrigated land lies south west of Awash River, found at about 500 meters in the north-western side of the Wonji Shoa Sugar Factory (Figure 1). The area experiences a bimodal rainfall distribution pattern, receiving the Kiremt rains during July to September and Belg rains during

March to June. The long term average of annual rainfall was recorded as 891 mm. The mean maximum and the mean minimum air temperature reported as 29.9 °C and 14.9 °C respectively. The long-term average relative humidity, reference evapotranspiration (ET_o) and sunshine hours were reported as 50.9%, 4.95 mm/day, 8.4 hours/day, respectively (Appendix Table 4).

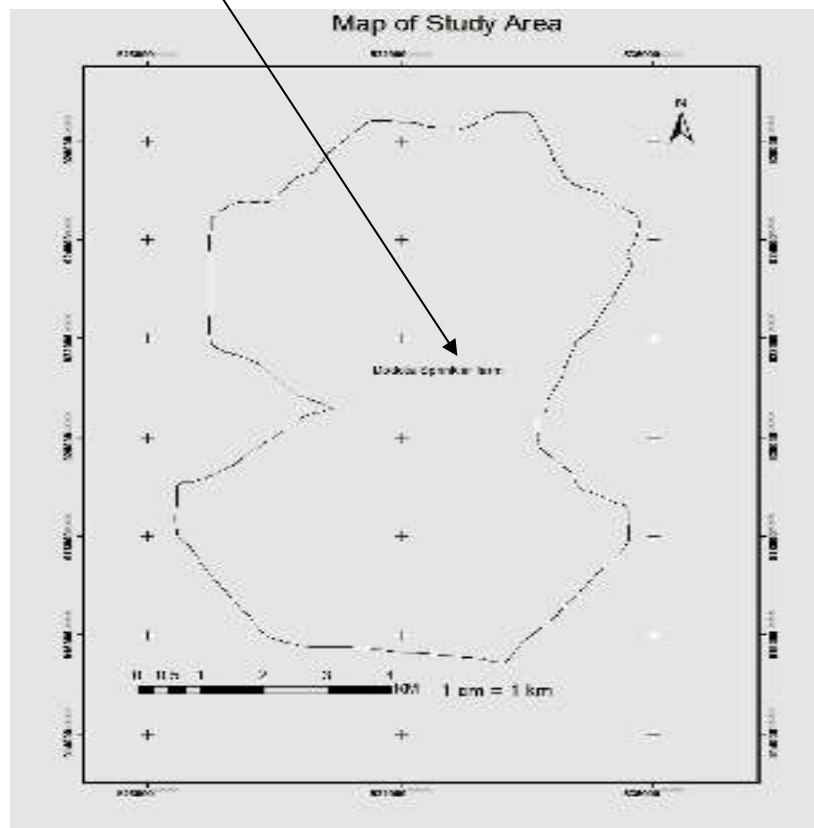
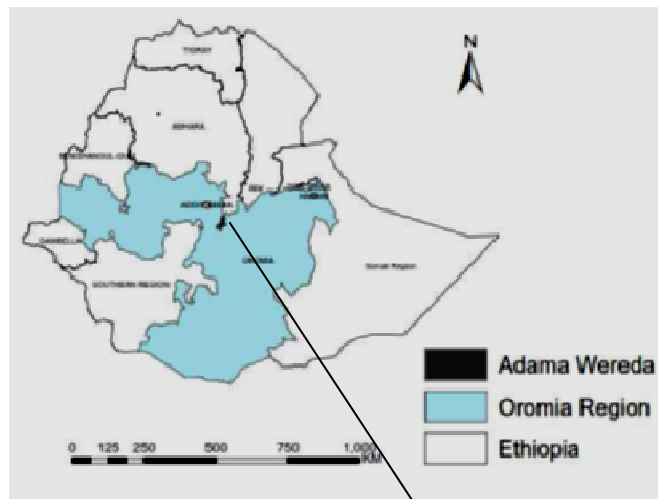


Figure 3.1: Location Map of the Study Area

3.2. Designing of Sprinkler System for Irrigated Teff Production

In designing of the sprinkler system, the design methodologies followed include:

- Collection of basic design input data,
- Determination and analysis of basic design parameters,
- Performing hydraulic calculations, and
- Selection of sprinkler type and material of sprinkler

Were done following the methodology and procedures outlined in ARC-Institute for Agricultural Engineering “*Irrigation Design Manual*” (Lategan ,1995, Koegelenberg *et al.*,1996 and Burger *et al.*, 2003), “Irrigation Guide Part 652 (210-vi-NEH, 1997) section 652.0605” (Keller, 1997), “Sprinkler and Trickle Irrigation” (Keller and Bliesner, 1990), and “Norms for the design of Irrigation systems” by (Koegelenberg, 2002).

3.2.1. Collection of Basic Design Input Data

Soil Infiltration Measurements

Soil infiltration rate was measured using standard double ring Infiltrometer technique and infiltration rate measurement was taken from three sampling sites in the study field. A standardized approach was applied at each of the sampling sites according to the method described in (USDA, 1999). Based on the volume of the rings water was measured out in a measuring cylinder and poured over the rings. The amount of time it takes for the water in the inner ring to infiltrate into the soil was noted and the infiltration rate was then computed as (Franzluebbers, 2002).

$$\text{Infiltration rate } \left(\frac{\text{cm}}{\text{hr}} \right) = \frac{V}{A * T} \quad (3.1)$$

Where, V = Volume of water (cm³)

A= the area of the inner infiltration ring (cm²)

T = the time recorded (hour).

Soil Bulk Density, Moisture Content Measurement and Soil Texture Determination

The soil samples were taken from the experimental field for determination of the soil physical properties (bulk density, moisture content and soil texture). Soil samples for bulk density

estimation were taken by making use of a core sampler and core rings of known volume. Considering the maximum effective root depth of teff to being 30 cm, soil samples were collected from two depths (0-15 cm and 15- 30 cm) at two positions of the experimental field for laboratory analysis. The samples were weighed and oven dried at a temperature of 105⁰c for 24 hours and weighed again and again until a constant weight is recorded. Soil water content in the cores, was determined gravimetrically and bulk density was used to calculate moisture content by volume of the soil samples (FAO, 1989).

$$\text{Bulk density (BD)} = \frac{\text{Weight of oven dry soil (gm)}}{\text{Volume of same soil (cm}^3\text{)}} \quad (3.2)$$

Meteorological Data

Long year climate data (1977-2016) and real-time meteorological data, which included minimum and maximum air temperature, relative humidity, sunshine hours, evaporation, wind speed and rainfall were collected from Ethiopian Agricultural Research Organization, Melkassa Research Center which is located at long 39⁰ 21'E Lat 8⁰ 24'N. The reference evapotranspiration (ET_o) and effective rainfall were determined using CROPWAT 8.0 software.

3.2.2. Determination and Analysis of Basic Design Parameters

Crop Evapotranspiration

This is the loss of water through transpiration of the growing plant plus evaporation from the soil surface. The peak ET_o value 5.99 mm/day (Appendix Table 4) and weighted average K_c of 0.85 (Yihun, 2015) were used and crop evapotranspiration was calculated using formula (Allen *et al.*, 1998).

$$ET_c = ET_o K_c \quad (3.3)$$

Where, **ET_c** = crop evapotranspiration

ET_o = reference peak evaporation rate (mm/day)

K_c = crop coefficient

$$ET_c = 5.99 \text{ mm / day} * 0.85 = 5.09 \text{ mm / day}$$

Readily Available Water

Taking in to account, silty clay soil of the study field (Appendix Table 2), effective root depth of 0.3 m, water holding capacity 220.97 mm/m (Appendix Table 3), climatic condition of the

study site (Appendix Table 4) and considering the percentage allowable water depletion of (50%), the readily available water was calculated using the formula (Burger *et al.*, 2003).

$$RAW = WHC * ERD * \partial / 100 \quad (3.4)$$

Where, RAW = readily available water (mm)

WHC = water holding capacity (mm/m)

ERD = effective rooting depth (m)

∂ = percentage allowable water depletion (50%)

$$RAW = 220.97 * 0.3 * 50 / 100 = 33.15 \text{ mm}$$

Net Irrigation Requirement

This is the depth of irrigation water necessary to meet evapotranspiration of the crop during a certain period and in a specific growing phase of the crop. In order to determine the net irrigation requirement, effective rainfall was assumed to be zero as the study was planned in dry period and the calculated value of peak evapotranspiration 5.99 mm/day (Appendix Table 4) was used and net irrigation requirement was calculated using formula (Keller and Bliesner, 1990) as follow:

$$NIR = ET - Re \quad (3.5)$$

Where, NIR = net irrigation requirement mm/day

ET = evapotranspiration mm/day

Re = effective rainfall mm/day

$$NIR = 5.09 - 0 = 5.09 \text{ mm/day}$$

Gross Irrigation Requirement

It is the net irrigation requirement of a given crop plus operational losses of the system. The gross irrigation requirement was determined by considering the application efficiency of the selected sprinkler $\geq 75\%$ (Table 3.1). As it was used in most sprinkler irrigation system design and the gross irrigation requirement was computed as: (Keller and Bliesner, 1990 as cited in Burger *et al.*, 2003).

$$GIR = \frac{100NIR}{\eta_s} \quad (3.6)$$

Where, GIR = gross irrigation requirement (mm/day)

NIR = net irrigation requirement (5.09 mm/day)

η_s = system efficiency (75%)

$$GIR = \frac{100 * 5.09}{75} = 6.79 \text{ mm/day}$$

Irrigation Interval

This is the actual laps between the commencements of two successive applications for specific irrigation set. The soil is a reservoir that stores water for the plant. The plant uses the water each day out of the reservoir at a certain rate, thus at maximum use would only be available for so many days. The cycle length was therefore, determined using the RAW and NIR values mentioned earlier and the irrigation interval was computed as follows (Burger *et al.*, 2003).

$$II = \frac{RAW}{NIR} \quad (3.7)$$

Where, II = Irrigation interval (days)

RAW = readily available water (mm/m)

NIR = net irrigation requirement (mm/day)

$$II = \frac{33.15 \text{ mm}}{5.09 \text{ mm/day}} = 6 \text{ days}$$

Area Covered Per Sprinkler

According to Burger *et al.*, (2003), one would use a sprinkler spacing of 18 x18 m in area where the average maximum wind velocity is < 13km/h. long years average wind speed in the study area was 2.41 m/s i. e. 8.67 Km/h (Appendix Table 4) which is < 13km/h, therefore, in this study a sprinkler spacing of 18 x18 m, a square pattern with 50% overlapping was designed. And area covered per sprinkler was calculated using the formula (Keller and Bliesner, 1990, cited in Burger *et al.*, 2003).

$$A = LeLd \quad (3.8)$$

Where, A = wetted area (m²)

L_e = lateral spacing (m)

L_d = sprinkler spacing (m)

$$A = 18\text{ m} * 18\text{ m} = 324\text{ m}^2$$

Choice of Sprinkler

Sprinklers with an application rate of between 6 to 9 mm/h which most soils can handle and give the highest distribution efficiency (Burger *et al.*, 2003). A double nozzle size 4.76 mm x 2.38 mm brass body sprinkler was chosen that was able to apply the required gross application rate of 5.54mm/h at 3 bars (Table 3.1) and is available in the sprinkler equipment dealers in the country. And the sprinkler discharge was calculated using the following formula (Keller and Bliesner, 1990 as cited in Burger *et al.*, 2003).

$$qe = GAR * A \quad (3.9)$$

Where, qe = sprinkler discharge (L/hr.)

GAR = gross application rate (mm/hr.)

A = wetted area (m^2)

$$qe = 5.54\text{ mm/h} * 324\text{ m}^2 = 1.79\text{ m}^3/\text{h}$$

$$GAR = \frac{qe}{A} \quad (3.10)$$

$$GAR = \frac{1.79\text{ m}^3/\text{h}}{324\text{ m}^2} = 5.54\text{ mm/h}$$

Net Application Rate

The rate at which water is applied to the soil surface by the sprinkler is net application rate. After taking into account the application efficiency of the system 75% (Table 3.1), the net application rate was calculated using formula (Burger *et al.*, 2003).

$$NAR = GAR * \eta_a \quad (3.11)$$

Where, NAR = net application rate (mm/hr.)

GAR = gross application rate (mm/hr.)

η_a = application efficiency (%)

$$NAR = 5.54 \text{ mm/h} * 0.75 = 4.16 \text{ mm/h}$$

Standing Time

Standing time is the calculated period of time for which a system has to irrigate to apply the design application. The design application is in the maximum application for which the system was designed and it was calculated using the following formula (Burger *et al.*, 2003).

$$ts = \frac{RAW}{NAR} \quad (3.12)$$

Where, ts = stand time (hr.)

RAW = readily available water (mm)

NAR = net application rate (mm/hr.)

$$ts = \frac{33.15 \text{ mm}}{4.16 \text{ mm/h}} = 7.97 \text{ h} = 8 \text{ hours}$$

Gross Application per Cycle

The gross application per cycle was calculated according to the daily crop requirement and the cycle length using the formula (Keller and Bliesner, 1990) as follows:

$$GA = GIR \text{ } tc \quad (3.13)$$

Where, GA = gross application rate per cycle (mm)

GIR = gross irrigation requirement (mm/day)

tc = cycle length (days)

$$GA = 6.79 \text{ mm/day} * 6 \text{ days} = 280.73 \text{ mm}$$

Numbers of Sets per Day

Based on the application rate and stand time and topography of the land and infiltration rate of the soil the farmers in the area can work 7 days in a week and can irrigate 21 hours in a day and therefore, for this study, the assumed sets per day sequence was obtained using equation (3.14) below as it would fit in to the number of operating hours per day. And thus, working hours per day was calculated using formula (Burger et al., 2003):

$$th = tsn \quad (3.14)$$

Where, th = working hours per day (hr.)

ts = stand time (hr.)

n = sets per day

$$n = \frac{th}{ts} = \frac{21}{8} = 2.63 = 2 \text{ sets / day}$$

Number of Sets per Cycle

The number of positions to which a sprinkler is moved during an irrigation cycle is dependent upon the number of working days in a cycle and the number of stands per day (Burger et al., 2003).

$$nc = ntc \quad (3.15)$$

Where, nc = number of sets per cycle

tc = cycle length

n = sets per day

$$nc = 2 * 6 = 12 \text{ sets per cycle}$$

Number of Sprinklers Operating Simultaneously

The number of sprinklers operating simultaneously was determined as: (Adopted from Burger et al., 2003).

$$Ne \geq \frac{A10000}{nc \cdot LsLd} \quad (3.16)$$

Where, Ne = number of sprinklers

A= area of irrigation (ha)

nc = sets per cycle

Ld = laterals spacing (M)

Le = sprinkler spacing (M)

$$Ne \geq = \frac{2.18 * 10000}{12 * 324} = 6 \text{ sprinklers}$$

3.2.3. Hydraulic Calculations

Determination of Hydrant Inlet Pressure

The components of the manifold and lateral operating head required at the splitting point (Hm) i.e. the hydrant inlet pressure includes: (Sprinkler operating head (Ha), friction head loss through the lateral and manifold pipeline including flexible HDPE dragline hose (Hf), head required by the riser (Hr), elevation loss as a result of the lateral being laid uphill respectively (He) and head loss through the head control valve/hydrant (Hvc) and thus, the hydrant operating head (Hm) is defined by the summation of the above components as follows:

$$Hm = Ha + Hf + Hr \pm He + Hvc \quad (3.17)$$

And the average head for designed sprinkler lateral line was expressed approximately by the formula (ASAE, 1978).

$$Ha = Ho + 0.25\Delta H + 0.4He \quad (3.18)$$

Where, Ha = average head for designed sprinkler lateral line (m),

Ho = nozzle pressure at the farthest end of lateral line (m),

ΔH = friction head loss in the lateral (m) and

He = maximum difference in elevation between the junction with the main and the farthest sprinkler on the lateral (m). He is positive for uphill and negative for downhill

Determination of Friction Loss in Laterals, Sub-Main pipes and Fittings (***H_f***)

The determined values of friction head losses in pipes and fittings were determined using formulas (3.19 and 3.20) and are presented in (Appendix Table 7).

Friction head loss in lateral and sub-main pipes (***H_f***) and head losses in fittings due to friction were estimated using Hazen William's equation as:

$$\frac{hf}{L/100} = K \left(\frac{Q}{C} \right)^{1.852} D^{-4.87}$$
$$hf = \frac{KL}{100} \left(\frac{Q}{C} \right)^{1.852} D^{-4.871} \quad (3.19)$$

Where, L = pipe length (m)

V = pipe velocity (m/s)

K = Conversion constant, equal to 1.212×10^{10} for metric units

C = Hazen Williams coefficient, 120 (for PVC)

D = internal pipe diameter (m)

$$\text{Head loss in fittings } hf \text{ (m)} = \frac{Kv^2}{2g} \quad (3.20)$$

Where, K = friction coefficient

V = flow velocity (m/s)

g = gravity acceleration (9.81 m/s^2)

Capacity of the sprinkler system

Considering the rate of application and spacing of sprinkler, required sprinkler capacity of the sprinkler system was computed using formula (ASAE, 1978) as:

$$Q = q \times N_s \quad (3.21)$$

Where, Q = discharge of all sprinklers, lit/sec

q = discharge of each sprinkler, lit/sec

N_s = total number of sprinklers operating at a time

$$Q = 0.497 (l/s) \times 6 = 2.98 l/s$$

Sprinkler Design Discharge

The discharge of each sprinkler depends upon sprinkler spacing and the water application rate and was calculated using the formula (Reddi and Reddy, 1995) as:

$$q = \frac{S_1 \times S_2}{3600} \times I \quad (3.22)$$

Where, q = sprinkler discharge, l/s

S₁ = spacing of sprinklers along laterals, m

S₂ = lateral spacing along sub-main line, m

I = optimum application rate, mm/h

$$q = \frac{18 \text{ m} \times 18 \text{ m}}{3600} \times 5.54 \text{ mm/h} = 0.5 l/s$$

3.2.4. Selection of Type of Sprinkler System and Material of Sprinkler

The existing dragline sprinkler system of the Wonji Shoa Sugar estate was selected and used due to its record of good performance, labor availability and relative low investment (WWDSE, 2010 & 2013). And, based on the sprinkler design discharge and pressure, revolving type double nozzle (4.76 mm x 2.38 mm) sprinkler with intermediate pressure having medium wetted

diameter (22 m – 30 m) and very good moisture distribution features (SCS of USDA, 1968), brass sprinkler was selected from catalogue and is presented in Table 3.1 below as follows:

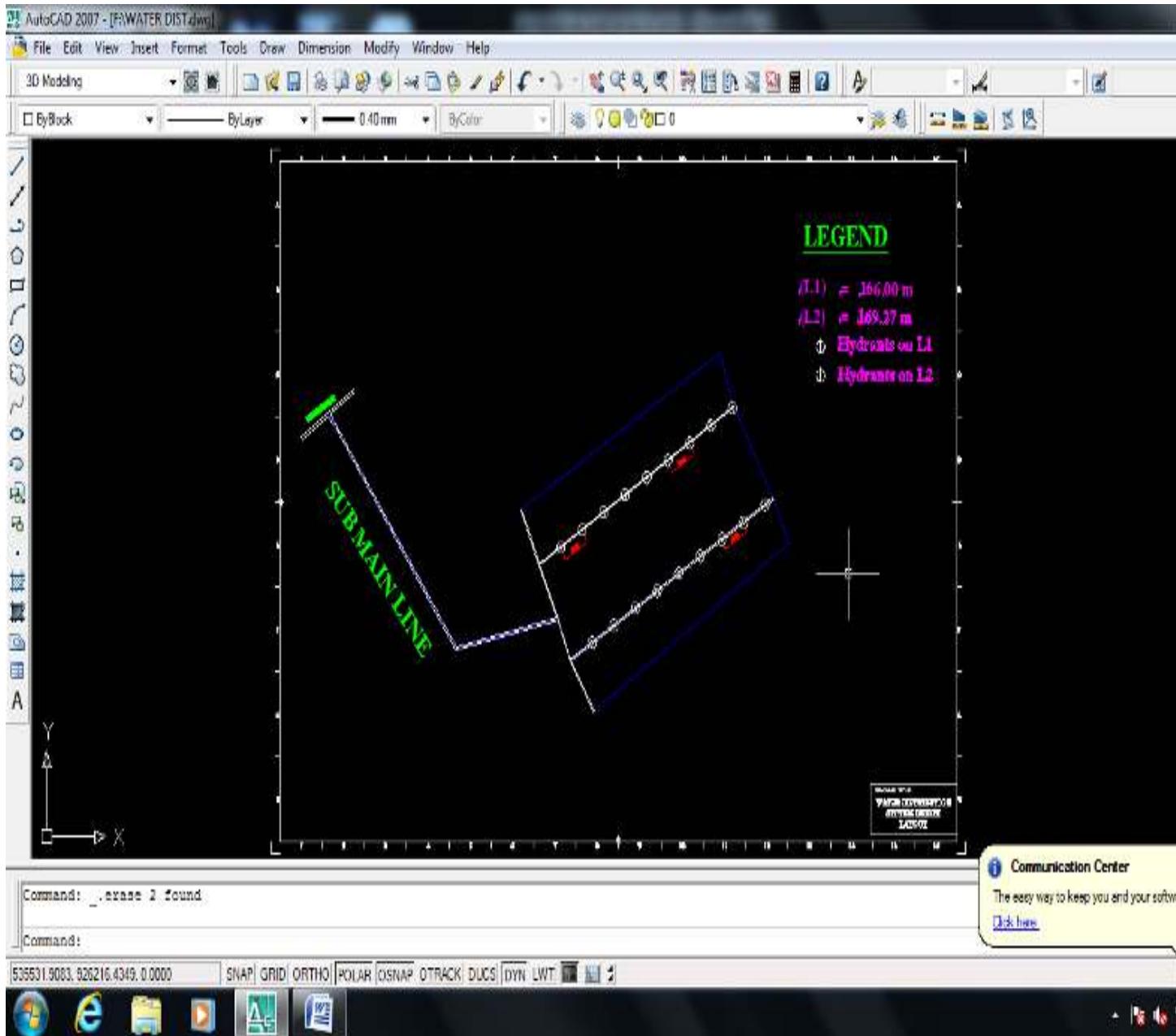
Table 3.1: Property of selected sprinkler

Characteristics	Value	Remark
Type	Brass	
Double nozzle size	4.76 mm x 2.38mm	3/16" x 3/32"
Average discharge (m ³ /hr.)	1.79	
Net application per irrigation (mm/hr.)	4.16	
Gross application per irrigation (mm/hr.)	5.54	With $\geq 75\%$ efficiency
Average working pressure (bar)	3	
Average radius (m)	15	

3.2.5. Distribution (Pipeline) System Design and Layout

A dragline sprinkler irrigation system was designed and installed to irrigate 108 m x 185.64 m (2.00 ha) a rectangular land. Conveyed water from Awash River via the main canal is the source of irrigation water for the sprinkler system. The water from the main canal was pumped to 1200 mm diameter GRP main-pipeline in which its main purpose was to irrigate sugar cane farm at North Dodota. The water for this study was tapered off from the main pipe line at a distance of 884.60 meters from the pump station to the sub-main1, 200 mm diameter Upvc pipe size which has 6 meters length and then it was reduced to sub-main2, 90 mm diameter which has 225.51 meters length that runs in the south east direction from the mainline. The sub mainline was designed assuming that, it can convey the required quantity of water at desired pressure to the two lateral lines. As the diameter of sub mainline would depend on system capacity, it was decided by the total number of laterals (two laterals) and by the total number of sprinklers (six sprinklers) respectively operated at a time. According to (SCS, 1968 and Rain Bird, 1971), for

semi portable rotation type sprinkler system like dragline of this study, the amount of water that required and supplied should be the sum of the capacity of all sprinklers to be operated at same time in a day. It is the product of the maximum number of sprinkler and the design sprinkler discharge (10.74 m^3). Thus, the maximum design discharge calculated ($1.79 \text{ m}^3/\text{h}$) times the maximum number of operating sprinklers (6 sprinklers) in the laterals was used for designing of the sub-main pipe network. One manifold pipeline has 75 mm diameter and 55 meters long was installed in the north-south direction. Two lateral pipelines each with 63 mm diameter were laid out in the west-eastern direction. The length of the first lateral line (L1) was 166.00 m and the second lateral line (L2) was 169.27 m. These water distribution systems brought water from the source point in the area irrigated and to the individual sprinkler nozzles. A total of 18 hydrants were connected to rise water from the laterals and then to the sprinklers by using a $\frac{3}{4}$ inch diameter flexible plastic hose. The design and layout of the distribution system is presented in figure 3.2 below.



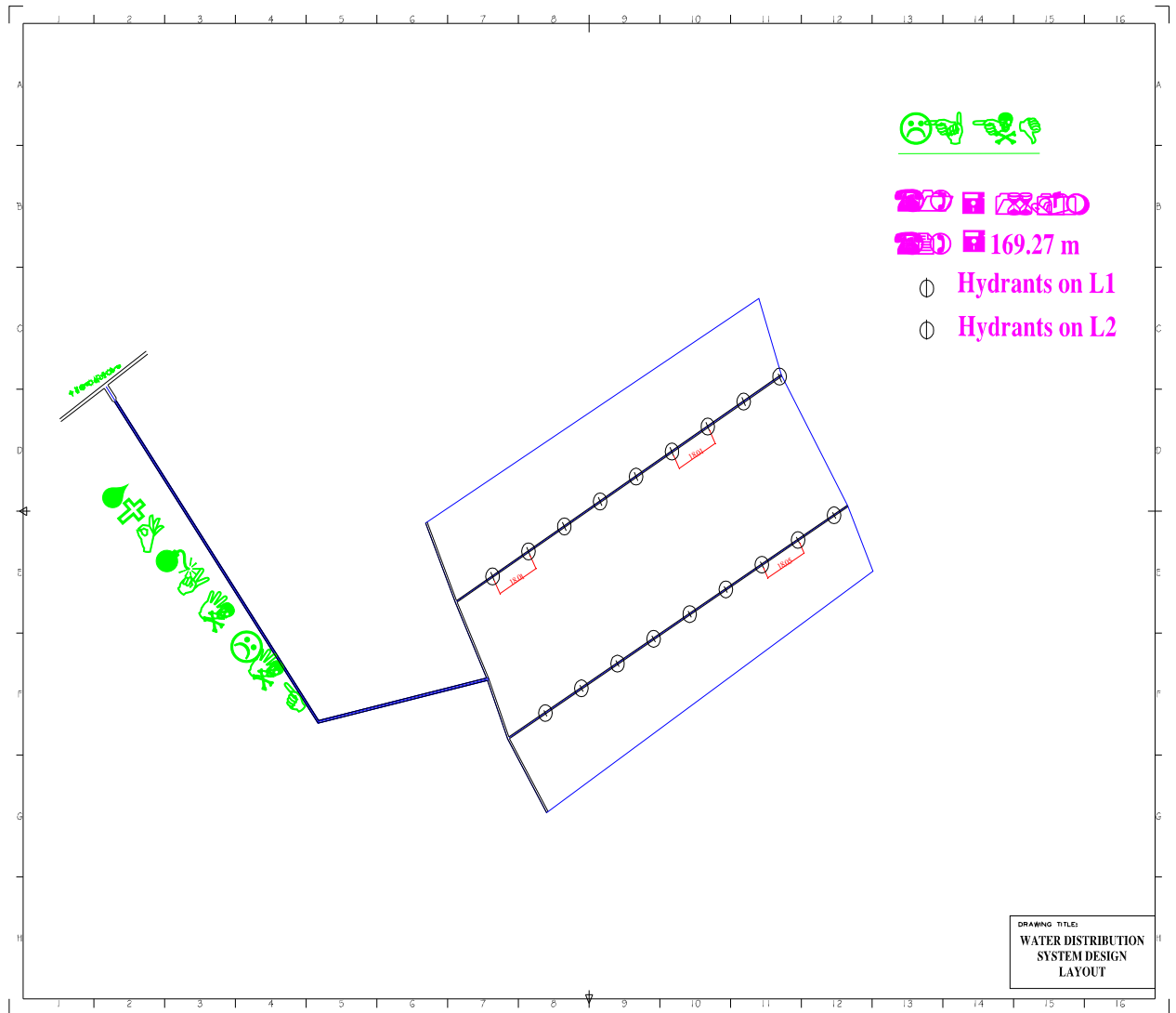


Figure 3.2: The Sprinkler System Design Layout

3.3. Performance Evaluation of the Irrigation System

Application efficiency (AE), distribution uniformity (DU) and Christiansen's uniformity coefficient (CU) are performance parameters selected and used to evaluate the performance of the irrigation system. These parameters were analyzed using formulae (2.3 – 2.5).

3.3.1. Data Collection and Analysis

Sprinkler Operating Pressure Measurement

The pressures at the sprinklers were measured using pressure gauge (0 -500KPa), fitted with a pitot tube. According to ARC (2006) as cited in Beer and Bhembe (2008), the numbers of

measuring points should be representative of the test site. Accordingly, sprinkler pressure measurements were taken at hydrant 1, hydrant 3, hydrant 5, hydrant 7 and hydrant 9, on both L1 and L2. Therefore, 10 measuring points in total (Figure 3.3). Assuming that, maximum growth height of teff (1.4 m) plus 0.6, therefore, the designed riser height was 2.0 meters above the ground surface and pressures of the sprinklers was measured at height of one meter above the ground, then 1 m (or 10 KPa) was subtracted from the pressure registered on the pressure gauge, in order to determine the sprinkler pressure at normal operating height of the riser. And Pressure variation was calculated and analyzed using the following equation (Beer and Bhembe, 2008):

$$\Delta P = \frac{P_{\max} - P_{\min}}{P_{ave}} \quad (3.23)$$

Where, ΔP = Pressure variation, %

$P_{\max}$ = Maximum operating pressure (KPa)

$P_{\min}$ = Minimum operating pressure (KPa)

P_{ave} = Average operating pressure (KPa)

Sprinkler Discharge Measurement

The discharge of the sprinklers was also measured at the same points where pressure measurements were done in a container with a hose pipe connected to the sprinkler nozzle (Appendix picture 1). The size of the container was 60 liters and a stopwatch was used to record the time it takes to fill the container. By taking the time it took to fill the container, the discharge was determined.

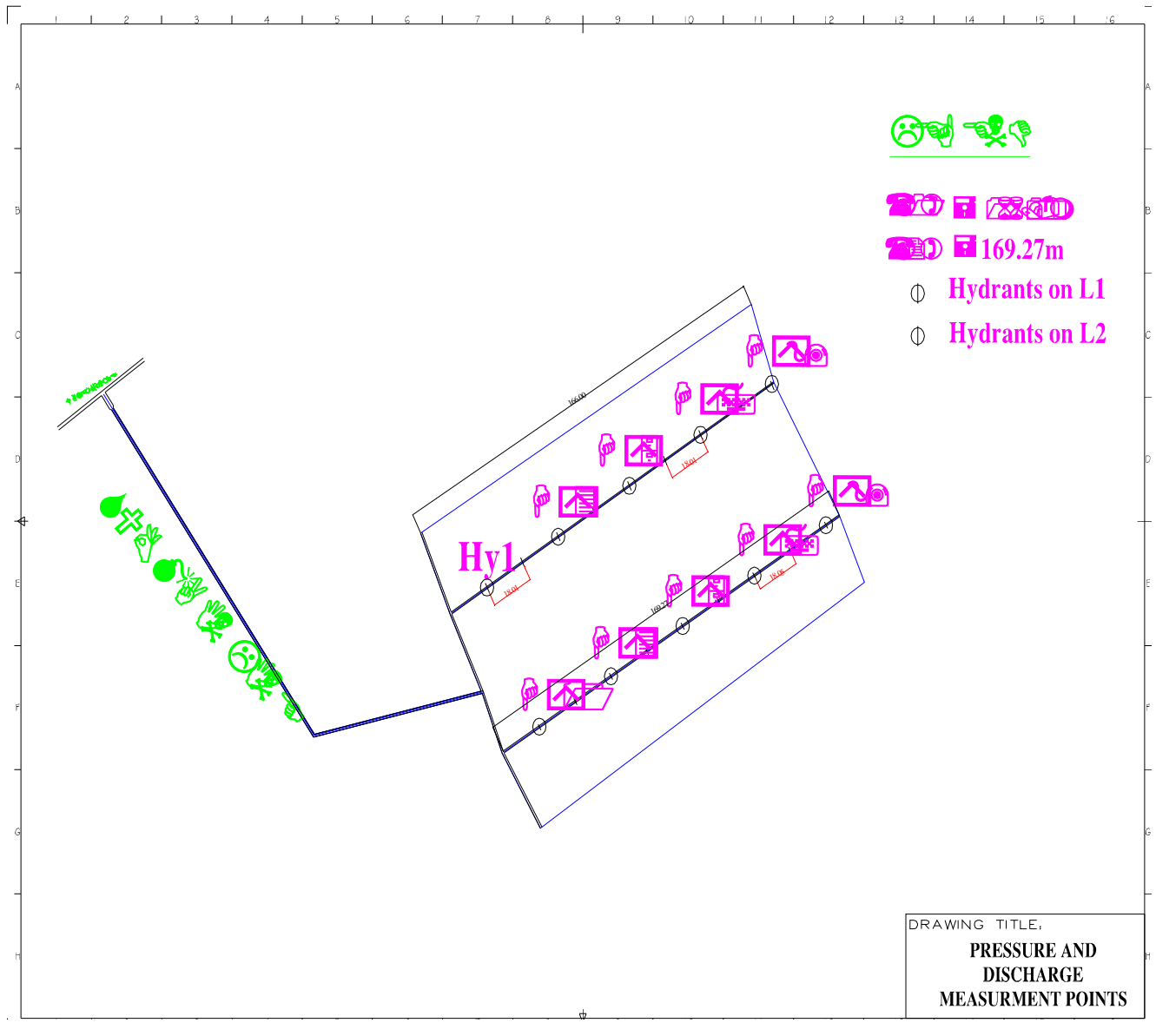


Figure 3.3: Position of testing points on laterals for sprinkler pressure and discharge tests

Where, L1 is Lateral nearest to the pump house and L2 is Lateral furthest to the pump house

Sprinklers Throw Distance Measurement

The wetted diameter was determined by footprint measurement and the boundary between the wetted area and un-wetted areas was observed, boundaries were made and the distance was measured in meter.

Distribution Uniformity and Precipitation Rate Measurements

In this study, four sprinkler test methods were used for uniformity measurement, that is, 2 hour test: 2 sprinklers, moved from position after one hour. The test involved setting out catch cans (containers) used to capture the water as it falls to the ground by running the system. This allows the determination of both the depth of water applied at any position as well as the variation in water applied across the field. Cuenca (1989) recommended a minimum of 24 collectors for four sprinklers uniformity test. Accordingly, uniformity measurement with four sprinklers was determined by placing 36 identical catch cans on a grid between two adjacent lines (laterals) and four sprinklers. For the analysis of performance parameters, the sprinkler spacing was taken as 18 m x 18 m as designed. According to (Merkley and Allen, 2004), the catch-can spacing used should be 2 m or 3 m). As per this recommendation, the catch-can spacing (center to center) used for this study was 3 m x 3 m, and was placed 1.5 m from the boundary lines of the block (Figure 3). The catch can opening diameter was 6.5 cm and 13 cm height and each can were placed on pegs of height 30 cm above the ground surface. The test run time was 2 hours. The volume of water collected within a catch can was measured in milliliters (ml) by pouring the water collected into a graduated cylinder. In order to observe the effect of wind on the performance of the irrigation system, the tests were carried out under different wind conditions, during morning (from 8 a.m. to 10 a.m.), afternoon (from 3 p.m. to 5 p.m.) and night time (9 p.m. to 11 p.m.). For each test time 3 observations in different plots were done in which the total number of observations were being 9. Net precipitation rate (PR_{net}) is the rate that sprinklers apply water to a given area per unit time. using distribution data, the net precipitation rate (PR_{net}) was calculated as follows (Miller *et.al*, 2005) :

$$PR_{net} = \frac{V_{avg} \times 60}{TR \times CDA} \quad (3.24)$$

Where, PR_{net} = Net Precipitation Rate, (cm h⁻¹),

V_{avg} = Average catch can volume (ml),

TR = Testing run time (min) and
CDA = Catch can open surface area (cm²).

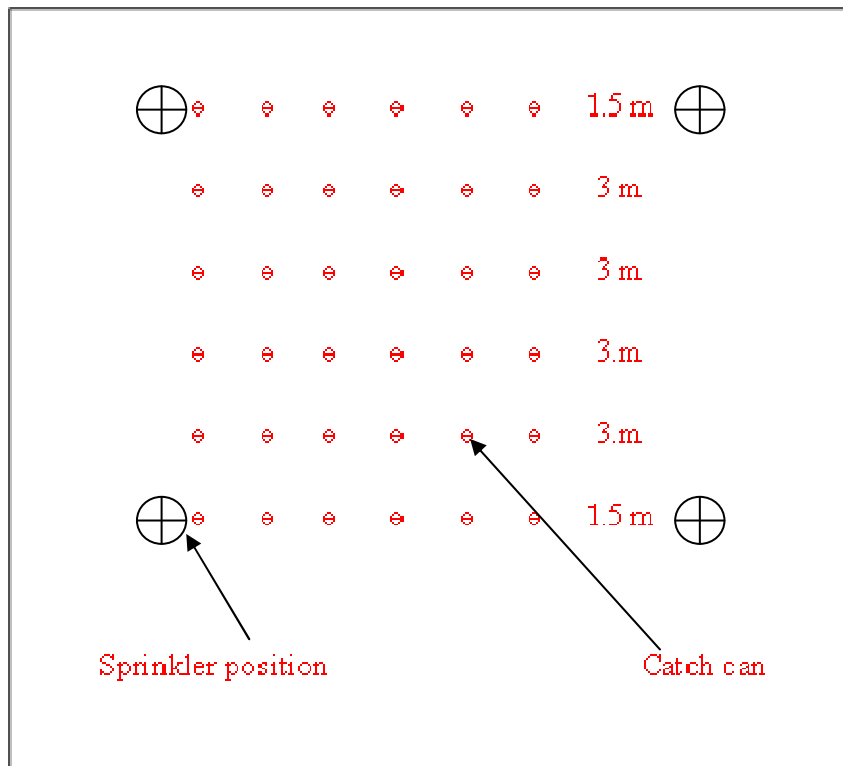


Figure 3.4: Catch can set-up to measure the distribution pattern of four sprinklers

3.4. Irrigation Level Treatments

A field experiment was conducted at North Dodota during dry period (13 December, 2016 to 10 April, 2017), in order to evaluate, agronomic performance, water use and water productivity of teff.

3.4.1. Experimental Design and Treatments

The experiment was laid out in Randomized Complete Block Design (RCBD) with three replications. There were a total of four treatments based on different levels of irrigation water throughout the growing season. The four irrigation levels used were: 100% ETo (T1), 85% ETo (T2), 70% ETo (T3) and 55% ETo (T4). The experimental plots were irrigated at depths equal to

100% ETo, 85% ETo, 70% ETo and 55% ETo levels regardless of crop and soil parameters based on the computed daily reference evapotranspiration (ETo) with the aid of CROPWAT program. Each replication was 4 plots making a total of 12 experimental plots. In accordance with specifications of the design, each treatment was assigned randomly to experimental units within a block (Figure 3.5).

Irrigation Trials: Irrigation Levels

- T1= 100% ETo = 552 mm,
- T2= 85% ETo = 469 mm,
- T3= 70% ETo = 382 mm,
- T4= 55% ETo = 294 mm.

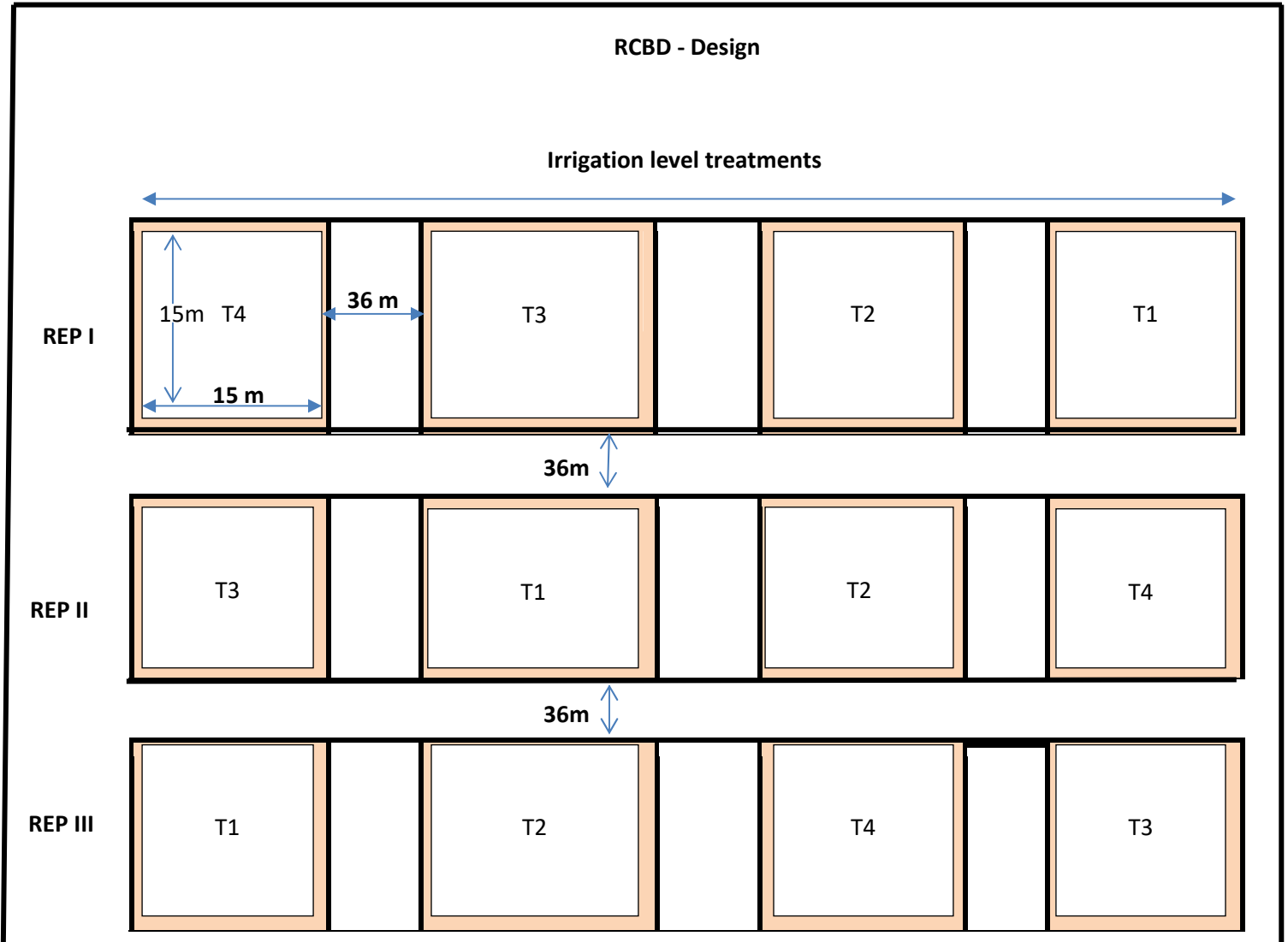


Figure 3.5: Randomly assigned irrigation levels treatment within a block

Where, REP I, REP II and REP III are number of replications within a block.

The experimental field was ploughed before planting and a 15m x 15 m (225 m²) gross plot size was used as experimental unit. A 36 m wide-open strip separated the blocks and the plots

within a block were also 36 m apart from each other. The teff variety Dz-Cr-387-RIR-355 (Kuncho) was sown at seed rate of 20 kg/ha. Irrigation, as per treatment, was applied in (4 days) interval. A uniform dose of 100 kg Di-ammonium phosphate (DAP) ha⁻¹ was applied at planting to all plots and 100 Kg urea (46% N) ha⁻¹ was applied at 30 DAS to all plots. All the required agronomic practices were followed uniformly in all plots throughout the growing period. Harvesting was done by cutting near the ground when the teff was fully matured 119 days after sowing (DAS). The harvested teff was sun dried for ten days before threshing.

3.4.2. Irrigation Schedule and Water Control Mechanism

Irrigation scheduling criteria were set based on the depth interval of irrigation and percentage of reference evapotranspiration criteria and irrigation was fixed to four days interval, but the irrigation water application depth was variable. The required irrigation schedule calculations were made and the system was run at the determined length of time and irrigation water was applied on treatment plots at depths, amounts equal to (T1, T2, T3 and T4). Rainfall was measured by rain gauge which is installed just at the study site during the study period and effective rainfall was determined by using CROPWAT 8. 0. Software. Considering the effective rainfall, irrigation interval was prolonged until it particularly suited to the irrigation levels based on depth and the set interval. The depth of water application to each plot was controlled by running the system based on the determined sprinkler runs time and then just stops the run when the calculated run time was reached using pressure regulation valve installed at operation point.

3.4.3. Sprinkler Runs Time Determination

In order to apply irrigation water to each experimental plots sprinkler run time need to be determined. The individual sprinkler run times was determined from irrigation level treatments (% ET_O), irrigation interval and the system PR using a hand-held calculator. The sprinkler runs time was calculated by using formula (Shaw and Pittenger, 2009) as:

$$\text{Run Time (minutes) per irrigation event} = \frac{\%ET_o \times II \times 60}{PR} \quad (3.25)$$

Where, II = irrigation interval (4 days),

PR = average sprinkler precipitation rate, 4.01 mm/h (Table 8),

60 = conversion factor hours to minutes and minutes to hours and

$ET_O \%$ = depth of the amount of irrigation water applied which is equal to 100, 85, 70 and 55% of the average reference evapotranspiration during water application period for (T1), (T2), (T3) and (T4) respectively.

After the sprinkler runs time for each irrigation level treatments determined by formula (3.25), then practically a period of time was waited (until irrigation interval days reached), and the system was run until the calculated run time per treatment reached.

3.5. Data Collection and Analysis

3.5.1. Crop Growth Data

The plant height (cm) was measured from the ground level to the panicle tip of the plant at three randomly selected plants from each plot at 70, 80, 90, 100, 110 and 119 days after sowing (DAS) respectively.

3.5.2. Grain and Straw Yield Data

A net plot size of 100 m^2 (10 m x 10 m) was harvested manually after physiological maturity and used for the determination of grain yield, straw yield and total biological yield and was expressed as Kg ha^{-1} . And straw yield was recorded by subtracting grain yield from above ground biomass. At both ends of the plots, 5 m was left as a border. Computation of a simple linear regression equation between grain yield and applied water level from the irrigation level experiment in teff was performed in order to estimate the linear relationship between mean yield and level of irrigation water applied.

3.5.3. Water Supply Data

The depth of irrigation water applied (mm) at each irrigation event per treatment as well as water supply from rain fall was recorded and is presented in Appendix Table 10A -10D and it was converted to total irrigation water applied in m^3 and to total water applied in m^3 (irrigation plus effective rainfall) in the growing period.

3.5.4. Grain and Straw Price Data

The grain and straw unit price of teff was collected from local market by interview of teff producers', teff traders and teff consumers. Accordingly the mean prices of teff grain and straw were found to be 20 and 1.75 Birr/Kg respectively (Personal communication, 2017).

3.5.5. Water use and Water Productivity

Irrigation WUI, gross production economic WUI and economic water productivity (EWP) are performance indicators used to evaluate water use and water productivity of the different irrigation levels and were determined using formulas 3.26 – 3.29 (Barrett Purcell & Associates, 1999 and Skewes, 1997) as follow:

$$\text{Irrigation WUI} = \frac{\text{Yield (Kg)}}{\text{Irrigation water applied (m}^3\text{)}} \quad (3.26)$$

$$\text{Gross production economic WUI} = \frac{\text{Gross return (Birr)}}{\text{Total irrigation water applied (m}^3\text{)}} \quad (3.27)$$

$$\text{EWP} = \frac{\text{Gross income (Birr)}}{\text{Applied irrigation water (m}^3\text{)}} \quad (3.28)$$

$$\text{GI} = (\text{PTG} \times \text{YLDg}) + (\text{PTS} \times \text{YLDs}) \quad (3.29)$$

Where, EWP = economic water productivity in (Birr/m³)

GI = gross income in Birr

PTG = price of Teff grain per Kg of the season in (Birr/Kg)

YLDg = average grain yield per given irrigable area (Kg/ha)

PTS = price of Teff straw per Kg of the season in (Birr/Kg)

YLDs = average straw yield per given irrigable area (Kg/ha)

3.6. Statistical Analysis

- Comparisons of crop growth, grain and straw yield as well as water use and water productivity among treatments were performed by analysis of variance (ANOVA) using statistical analysis systems (SAS Version 9.2). Whenever significant differences were detected in the F- test, the means were compared using the LSD test at 5% levels of significance.
- Regression analysis was used to test treatment effects using simple linear regression equation. R^2 values were computed and compared to the tabular r value for 5% level of significance and 1% level.

4. RESULTS AND DISCUSSION

4.1. Irrigation System Design Analysis

4.1.1. Design Pressure Network

Buried laterals takeoff from one side of manifold pipe at an interval of 54 meter. Laterals have risers at an interval of 18 meter to supply water to the sprinkler head via a flexible HDPE dragline hose. The flexible hose irrigates, not only along the lateral, but also along grid lines located 18 m left and right. Pressure regulation valve was installed at a point where a 200 mm diameter and 6 meter long PVC pipe and 90 mm diameter 225.51 meters long sub-main2 connected. The required hydrant inlet pressure (Hm) was calculated using equation (3.17) and found as 35 m (Table 4.1). Considering the allowable pressure difference over the lateral/dragline $\leq 20\%$ (Jensen, 1983), the sprinkler can operate at hydrant inlet pressure (Hm) of 28 m.

Table 4.1: Design_hydrant_inlet_pressure_component_analysis

Description	Design
Sprinkler operating head (Ha)	28 m
Head required by stand pipe and riser (H_r)	2.7 m
Elevation loss of laid laterals (He)	0.62 m
Friction head loss in pipes and fittings (H_f)	3.68 m
Required hydrant inlet pressure (H_m)	35 m

4.1.2. Design Discharge Network

The maximum calculated design discharge of individual sprinklers was $1.79\text{m}^3/\text{h}$ and the designed numbers of sprinklers operating simultaneously were 6, therefore, the total discharge required for the field was $10.74\text{m}^3/\text{h}$. Based on design discharge, 75 mm diameter one manifold pipeline which has a length of 55 meters was installed at hydraulically appropriate position at the corner center of the field in the north-south direction. Two lateral pipelines were laid across prominent slopes to minimize the variation of pressure along the lateral. The laterals run parallel to the contours so as to restrict height differences as much as possible. Nine hydrants on each

laterals were installed and each to operate on 27 sprinkler positions. The total number of hydrants was 18 and thus there are 54 sprinkler positions. These hydrants were connected to raise water from the laterals with sprinklers mounted on quick-coupling tripods at one end which is connected by flexible hose attached on quick coupling hydrant ball valves on the riser at the other end. Irrigation water was applied by moving the sprinkler and tripod from one position to the next or from valve to valve in a predetermined grid pattern within the irrigation period. Based on hydraulic calculations carried out, the determined diameters and length of sub-main, manifold, lateral, dragline hose and stand pipes is presented in Table 4.2 below,

Table 4.2: Summary of the installed pipes length and diameter

Description	Length (m)	Diameter nominal DN (mm)	PN
Sub-mainline-1	6	200	16
Sub-mainline-2	219.00	90	10
Manifold pipeline	55.00	75	10
First lateral (L1)	166.00	63	10
Second lateral (L2)	169.27	63	10
Stand pipe	2.0	25	10
Dragline hose	20	25	10
Riser proper buried above lateral pipe	1.0	32	10

4.1.3. Dragline Module

During the peak season, each sprinkler designed to operate for 21 hours per day, 8 hours standing time and 2 sets per day within 6 days irrigation interval in a dragline module which has one sprinkler, one roll of hose, tripod and ball valves coupled in riser connected to the buried lateral at a maximum depth of 70 cm. It is the sprinkler head mounted on a tripod that is set, not the lateral which is buried and therefore fixed. The assembly per module besides one tripod

comprise 20 meters roll of 25 mm diameter flexible hose, one quick coupler to the sprinkler side and one ball valve coupler to the inlet at the buried riser.

Table 4.3: Summary of dragline module parameters

Description	value
Peak net daily irrigation water demand (mm)	5.09
Peak gross daily irrigation water demand at plot head (mm)	6.79
Irrigation time	21 hrs.
Sprinkler mesh spacing	18m x 18m
Distance between laterals	18 m
Sprinkler design discharge (l/s)	0.5
Design head of sprinkler (bar)	3
Area of 1 module = 54 m x 72 m	0.3888 ha
Days per sprinkler rotation	6

4.1.4. Water Application Rate

Considering the manufacturer provision and property of the selected sprinkler capacity, water application rate calculated and selected as optimum and recommended for practical purpose of this study was 5.54 mm/hour and it was not limited by infiltration rate of the soil as the soil infiltration rate of the study field was 23 mm/h (Appendix Table 1).

4.2. Sprinkler System Performance Analysis

4.2.1. Sprinkler Operating Pressure

As indicated in (Table 4.4), the measured sprinkler operating pressure ranged from a minimum of 289KPa to maximum of 350KPa respectively and the average was 319.5KPa. Koegelenberg (2002), as well as Beer and Bhembé (2008), recommended that, “pressure difference between sprinklers on the same line must deviate $\leq 20\%$ of the average pressure”. Accordingly, pressure

variations calculated from field measurements found as 19.09% (Table 4.4) is acceptable as it agreed to within the recommended range of (Beer and Bhembé, 2008 and Koegelenberg, 2002). And also, it was found in practice that, the average operating pressure of the sprinkler was 319.5 KPa which is between 60 and 70 times the nozzle diameter (mm) and agreed to the suggestion given by Koegelenberg (2002).

Table 4.4 Measured sprinkler operating pressure as compared to designed pressure specification

Description	Nozzle size	Measured at normal operating height	Design
Minimum operating sprinkler pressure (KPa)	4.76 x 2.38 mm	289	288
Maximum operating sprinkler pressure (KPa)	4.76 x 2.38 mm	350	336
Mean operating sprinkler pressure (KPa)	4.76 x 2.38 mm	319.5	312
Percentage pressure difference between measuring points		19.09%	15.38%

4.2.2. Sprinkler Discharge

As indicated in (Table 4.5), sprinkler discharge rate measured ranged from 1.64 to 1.75 m³/h. And the mean discharge rate measured was 1.68 m³/h which was almost similar to the designed discharge rate of 1.79m³/h. The percentage difference in discharge rate measured between the tests points obtained was 6.55% which was not varied by more than 10% from the average discharge at the specified test points and satisfied the norm recommended by Koegelenberg *et al.*, (1996).

Table 4.5: Comparison between the designed and actually measured sprinklers discharge rate at five different test points

Test points Laterals	Hy ₁	Hy ₃	Hy ₅	Hy ₇	Hy ₉	Sum of Lateral	Sprinkler designed discharge rate (m ³ /h)
L1	1.75	1.66	1.68	1.67	1.64	8.4	1.79
L2	1.73	1.65	1.66	1.68	1.67	8.39	1.79
					$\sum x$	16.79	
					Mean	.68m ³ /h	
Percentage difference in discharge rate between the test points						6.55%	10%

Where, L1 is Lateral nearest to the pump house and L2 is Lateral Fareast from the pump house

Hy₁ = sprinkler discharge rate measured just at hydrant 1, on both L1 & L2,

Hy₃ = sprinkler discharge rate measured at a distance of 41 meters from hydrant 1 in which the sprinkler connected to hydrant 3, on both L1 & L2,

Hy₅ = sprinkler discharge rate measured at a distance of 82 meters from hydrant 1 in which the sprinkler connected to hydrant 5, on both L1 & L2,

Hy₇ = sprinkler discharge rate measured at a distance of 123 meters from hydrant 1 in which the sprinkler connected to hydrant 7 on both L1 & L2 and

Hy₉ = sprinkler discharge rate measured at a distance of 164 from hydrant 1 in which the sprinkler connected to hydrant 9, on both L1 & L2.

4.2.3. Gross Application Rate (GAR)

The gross application rate (mm/h) was obtained by dividing the discharge rate which was practically applied by the sprinkler to the wetted area by using formula (3.10). As can be seen from (Table 4.6), the measured and calculated gross application rate ranged from a minimum of 5.06 mm/h to a maximum of 5.4 mm/h and the mean gross application rate was 5.18 mm/h which varied by about 6.5% from designed application rate of 5.54 mm/h. However, it satisfied the

design norm of $\geq 5\text{ mm/h}$, recommended by Koegelenberg *et al.*, (1996). According to Lategan, (1995), “the present norm of minimum gross application rate of $\geq 3\text{ mm/h}$ on the wetted area remains unchanged”, and thus, the minimum gross application rate of 5.06 mm/h obtained (Table 4.6), also satisfied the requirement suggested by Lategan (1995). As the infiltration rate of the soil in the study site was 23 mm/h (Appendix Table 1), and the mean gross application rate of 5.18 mm/h (Table 4.6) was not higher than the infiltration rate of the soil and was not resulted in runoff and inadequate water replacement and therefore is acceptable. The calculated coefficient of variation in application rate uniformity of this irrigation system was 2.73% , implying that, statistical uniformity of sprinklers application rate of 97.27% which is very good result and is acceptable.

Table 4.6: Calculated gross application rate (mm/h)

Test points Laterals	Hy ₁	Hy ₃	Hy ₅	Hy ₇	Hy ₉	Sum of Lateral
L1	5.4	5.12	5.19	5.15	5.06	25.92
L2	5.34	5.09	5.12	5.19	5.15	25.89
					Σx	51.81
					Mean	5.18 mm/h
					CV	= 2.73 %

4.2.4. Net Sprinkler Precipitation Rate and Sprinklers Throw Distance

Net Sprinkler Precipitation Rate

As can be seen from (Table 4.7), average of the morning, afternoon and night period's net sprinkler precipitation rate on L1 and L2 were 4.04 mm/h and 3.99 mm/h respectively. Overall average net sprinkler precipitation rate of the system, at the operating sprinkler pressure of 3.0 bars and nozzle size of $4.76\text{ mm} \times 2.38\text{ mm}$ was 4.01 mm/h which is more than minimum gross application rate requirement of 3 mm/h suggested by Lategan (1995). Considering the actual average application efficiency of 77.67% (Table 4.9), multiplied by the mean measured gross application rate of 5.18 mm/h , the overall precipitation rate of the system found as 4.02 mm/h ,

which is similar to the actual average calculated net precipitation rate of 4.01mm/h (Table 4.7) . Therefore, the sprinkler system could perform without the occurrence of runoff.

Sprinklers Throw Distance

As can be seen from (Table 4.7), the average sprinkler throw distance measured at the designed riser height of 2.0 meter, operating pressure 3.0 bars and nozzle diameter 4.76 mm x 2.38 mm have ranged from 26.03 meters in the afternoon test to 28.52 meters in the night test time. The wetted diameter increased as wind speed decreased and decreased as wind speed increased. Shauq (2003) also reported that the wetted diameter increased as the operating pressure and nozzle size increased and decreased as wind speed increased which is agreed to this study. Design sprinkler spacing involves an overlap of 50% of the sprinkler throw distance. The average measured sprinkler throw distance of the system at the designed nozzle size, riser height and pressure in the designed sprinkler spacing of (18 m x 18 m), during morning, afternoon and night time tests were 27.92, 26.03 and 28.52 meters respectively and satisfied 50% overlapping.

Table 4.7: Average net sprinkler precipitation rate calculated from catch can data (mm/h) and measured sprinkler throw distance at different periods of the day,

Measurement period	Net precipitation rate (mm/h)				Sprinkler throw	Wind speed
					distance (m)	(m/s)
	L1		L2			
Morning	4.19	4.0	4.15	3.95	27.92	2.98
Afternoon	3.98	3.98	3.89	3.93	26.03	3.96
Night	4.03	4.03	4	4.02	28.52	2.68
Average	4.04		3.99		27.49	3.21
Mean	4.01 mm/h					

4.2.5. Water Distribution Pattern of the Sprinkler System

The Christensen's coefficient of uniformity (CU) and distribution uniformity of lower quarter (DU_{lq}) are performance parameters used to evaluate water distribution pattern of the sprinkler system. As it can be seen from (Table 4.8), the average CU values at morning, afternoon and

night test periods were 87.8, 82.3 and 87.59 % respectively and the average was 85.9%. According to Koegelenberg *et al.*, (1996) CU- values of greater than 84% is acceptable and CU values $\geq 85\%$ are applicable for wind still conditions (Keller, 1990). As per these recommendations, the CU values obtained in both the morning and night test times indicted that, the uniformity of water distribution of the installed irrigation system was good and is acceptable. The average distribution uniformity of lower quarter (DU_{lq}) values ranged from 76.5% for afternoon test time to 80.71 % for morning test time. And the DU_{lq} value during the night test time was 80.86% which is almost the same as the morning test time result. A DU_{lq} value of less than 60% is unacceptable and value of more than 75% is recommended (Keller and Bliesner, 1990). As per this recommendation, the DU_{lq} values obtained in both the morning, afternoon and night test time are acceptable. Highest values of CU and DU_{lq} were obtained during the morning and night periods at low wind speed. Generally, afternoon period test results were lower than morning and night period tests because of high wind speed occurred at this time.

Table 4.8: Average values of CU and DU_{lq} during the morning, afternoon and night test periods

Test periods	CU %	$DU_{lq}\%$
Morning	87.8	80.71
Afternoon	82.3	76.5
Night	87.59	80.86
Average	85.9	79.36

4.2.6. Application Efficiency (AE) and the Losses as a Result of Evaporation and Wind

As it can be seen from (Table 4.9), the average AE values in the morning, afternoon and night test periods were 79, 74.4 and 79.62% respectively and the average found as 77.67%. The losses between the water that is pumped through the system and that lost before the water reaches the root zone in the morning, afternoon and night test periods computed using formula (2.1) and were 3.38, 4.16 and 2.71% respectively and the average loss was 3.42%. These values mentioned are important when used to change the net irrigation requirement to system capacity

(gross irrigation requirement). Although there are numerous figures in the literature, there is a lack of reliable figures for Ethiopian conditions. However, AE-values of greater than 75% are recommended by Burt (1994). As per this recommendation, the AE values obtained in both the morning and night test times indicated that, the application efficiency of the installed irrigation system was good and is acceptable. But AE in the afternoon period test time were lower than morning and night period tests and the losses at afternoon period test time were higher because of high wind speed occurred at this time. The results indicated that, evaporation and drift losses increased as wind speed and air increased. Similar results were also reported by (Abo-Ghobar, 1993 and Dereje Bishaw, 2012), which agreed with the result of this study. Because of this reason, the experimental plots were irrigated in the morning and night periods of the day at each irrigation events.

Table 1: AE values and losses in the morning, afternoon and night test periods

Description	Application efficiency %	Air temperature (0C)	Relative humidity (%)	Wind speed (m/s)	Evaporation & wind drift losses%
Morning	79	26.0	59	2.98	3.38
Afternoon	74.4	27.0	56	3.96	4.16
Night	79.62	15.7	58	2.68	2.71
Average	77.67	26.5	57	3.21	3.42

4.3. Effect of Different Irrigation Levels on the Agronomic Performance of Teff

4.3.1. Crop Growth

As can be seen from (Table 4.10), the plots (T1) where 552 mm of irrigation water was applied in the growing season produced the maximum of teff height (120 cm) and the lowest teff height (96 cm) was obtained in T4 where 294 mm of irrigation water was applied and the mean teff

height was 109.5 cm. The growth height of teff was significantly influenced by different irrigation levels (Table 4.11). However, statistically there was no significant variation observed between T1 and T2 in crop height (Table 4.16). The plant height at (T1) was greater by 4.17, 10.83 and 20% over T2, T3 and T4 respectively; showing that, the height of the crop increased to some limit with increased depths of applied irrigation water and was relatively lower at lower depth of applied irrigation water (Figure 4.1). A similar finding has been reported by (Kidist Hilemichael and Tena Alamirew,2017), who concluded that a 50% (Etc) resulted in 54.6 cm height of teff whereas, a 60,70, 80, 90 and 100% (ETc) resulted in 58.2, 62.1, 69.4, 72.2 and 81.7 cm height, respectively. This result was also supported by Aklilu (2009) who concluded that a 50% (Etc) resulted in 43.5 cm height of pepper whereas, a 75 and 100% (ETc) resulted in 56.8 and 60.7cm height, respectively.

Table 4.10: RCBD Crop growth height (cm)

Treatment	Irrigation level (mm)	REP -1	REP -2	REP -3	Treatment total	Treatment mean
T1	552	119.5	116.3	124.2	480	120
T2	469	117.5	113.5	114	460	115
T3	382	105.2	109.6	106.2	428	107
T4	294	95.2	98.9	93.9	384	96
	REP Total	437.4	438.3	438.3	1752	438
				REP Grand mean		109.5

Where, T1, T2, T3 and T4 are 100, 85, 70 and 55% ETo levels respectively.

Table 4.11: ANOVA for teff growth height

Source of variation	DF	Sum of squares	Mean square	F value
REP	2	0.1350	0.0675 ^{ns}	0.01
Treatment	3	987.0	329.0**	30.35
Error	6	65.05	10.84**	
Total	11	1052.18		
C.V			3.01	

**, * = Significant at 1 and 5% levels, ns = non- significant; DF= degree of freedom

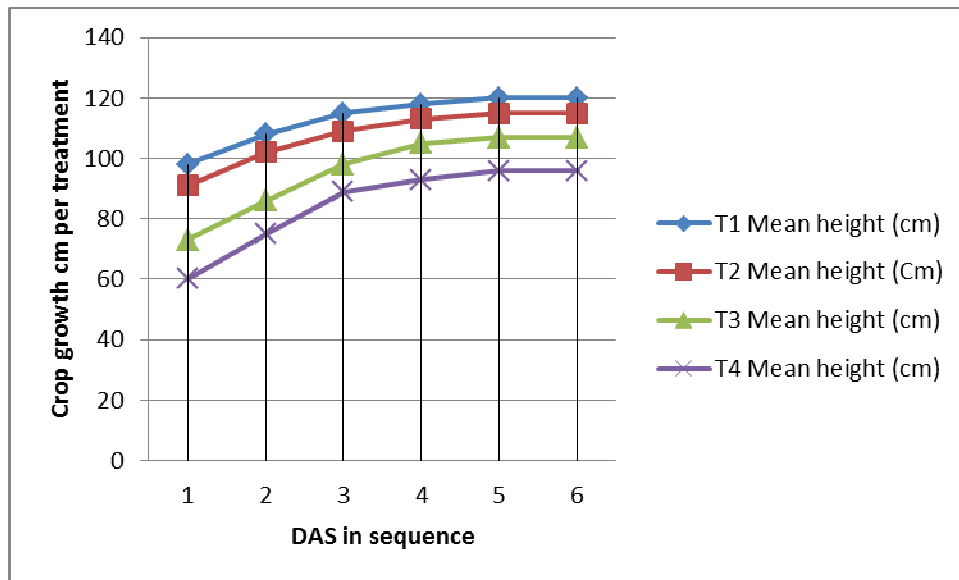


Figure 4.1: Growth height of teff measured in days after sowing per irrigation level treatments

Where, sequence 1, 2, 3, 4, 5 and 6 are 70, 80, 90, 100, 110 and 119 crop measurement days after sowing (DAS) respectively.

4.3.2. Grain Yield

As can be seen in (Table 4.12), in (T3), 382 mm of irrigation water was applied for the growing season and produced mean maximum teff grain yield of (2980 kg/ha) and the lowest mean grain yield (2510 Kg/ha) was obtained in (T1), 552 mm of applied irrigation water. Grain yield of teff was significantly influenced by different irrigation levels (Table 4.13), but, statistically there was no significant difference between T1, T2 and T4 in grain yield (Table 4.16). This result is in line

with the work of (Yihun , 2015) who reported that, for the seeding rate of 25 kg/ha and 10 kg/ha of teff, maximum yield of 3120 and 2910 Kg/ha respectively found from the treatment which received 380 mm of water. The mean grain yield obtained (T3) was greater by 15.77, 9.13 and 12.75% over T1, T2 and T4 respectively. The reduction in grain yield in T1 and T2 with applied depth 552 and 469 mm of water respectively could be due to crop lodging (Appendix picture 4), which in turn was due to high water application beyond the optimum crop water requirement. Lodging could decrease the potential grain yield that could have been gained from the improved vegetative growth. The decrease in grain yield of teff due the increase in lodging may be attributed to the reduction in net assimilate rate from reduced interception of light and absorption of nutrient and water (Acquaah, 2005). In addition, apical dominance may be destroyed due to lodging, leading to increased tillering and branching, which could be wasteful if it does not contribute to harvestable yield (Acquaah, 2005).

From the present investigation it was observed that the highest grain: straw ratio (46.43%) was recorded from application of 294 mm of irrigation water while the lowest grain: straw` ratio (27.289%) was obtained from 552 mm. It is known that under very high water application, grain: straw ratio decreases, but moderate water application increases grain: straw ratio as it was evidenced by the highest straw yield at the highest dose of water application. In addition, the highest grain: straw ratio at the depth of 294 mm was probably because of the lower crop height which resulted in a relatively lower straw yield per hectare.

Table 4.12: RCBD teff grain yield (Kg/ha)

Treatment	Irrigation level (mm)	REP -1	REP -2	REP -3	Treatment total	Treatment mean
T1	552	2430	2590	2510	7530	2510.00
T2	469	2610	2787.8	2726.2	8124	2708.00
T3	382	3084.2	2857.8	2998	8940	2980.00
T4	294	2698.6	2601.4	2500	7800	2600.00
	REP Total	10822.8	10837	10734.2	32394	10798.00
				REP Grand mean		2699.5

Table 4.13: ANOVA Table of grain yield

Source	DF	Sum of squares	Mean square	F value
REP	2	1551.62	775.81 ^{ns}	0.06
Treatment	3	373689.00	124563**	10.18
Error	6	73390.06	12231.68*	
Total	11	448630.7		
C.V			4.09	

**, * = Significant at 1 and 5% levels, ns = non- significant; DF= degree of freedom

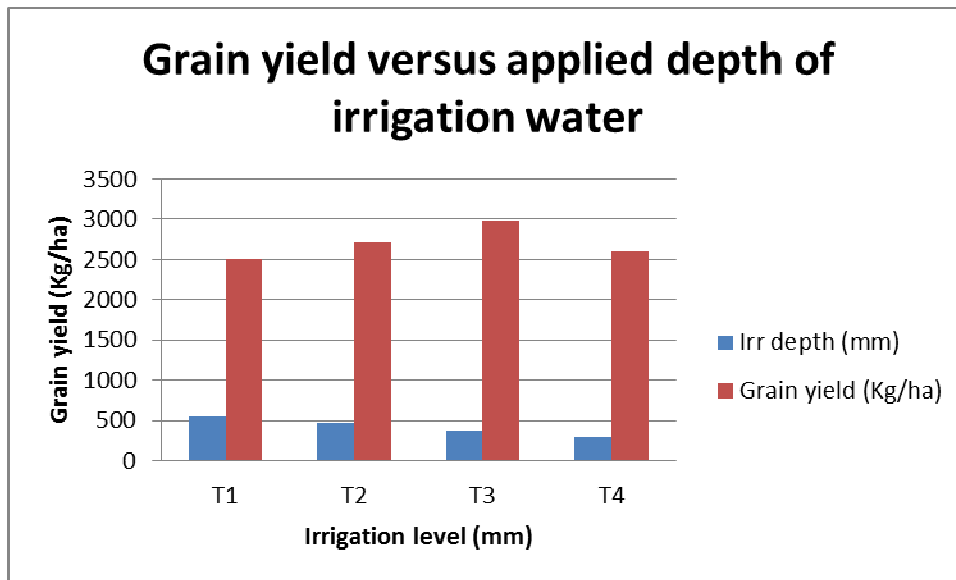


Figure 4.2: Mean grain yield of teff per hectare per applied depth of irrigation water

Where, T1, T2, T3 and T4 are 552, 469, 382 and 294 mm respectively.

4.3.3. Straw Yield

The highest mean straw yield (9200 Kg/ha) was obtained from (T1), irrigation depth of 552 mm and the lowest mean straw yield (5600 Kg/ha) was obtained from (T4), irrigation depth of 294 mm per growing season (Table 4.14). The straw yield obtained in T1 was significantly different from T2, T3 and T4 and there was a consistent increase in straw yield of teff from the minimum applied depth of 294 mm up to the maximum depth of 552 mm per the growth season (Table 4.14). This was due to the fact that excess water application favored vigorous vegetative growth

as evidenced by the lowest grain yield at the highest depth of applied water. As can be seen from (Table 4.15), the straw yield of teff was significantly influenced by different irrigation levels. At higher depth of applied water, the straw yield was also higher (Figure 4.3). The higher straw yield with increasing irrigation levels can be attributed to the most important contribution of sufficient water, in enhancing the vegetative growth and higher crop height. Kidist H. and Tena A. (2017) reported that, the increase in the dry biomass with increasing soil water application level could also be attributed to the increase in vegetative growth as plant height, leaf area, and lateral shoot number. Therefore, it could be concluded that, higher straw yield of 9200 kg/ha was obtained in T1 as a result of the relatively higher vigorous vegetative growth and crop height which was due to the higher depth of water (552 mm).

Table 4.14: RCBD Straw yield (Kg/ha)

Treatment	Irrigation level (mm)	REP -1	REP -2	REP -3	Treatment total	Treatment mean
T1	552	8582	9243	9775	27600	9200
T2	469	7690	8310	8000	24000	8000
T3	382	6450	6998	7372	20820	6940
T4	294	5000	5600	6200	16800	5600
	REP Total	27722	30151	31347	89220	29740
				REP Grand mean		7435

Table 4.15: ANOVA for Straw yield (Kg/ha)

Source of variation	DF	Sum of squares	Mean square	F value
REP	2	1705923.50	852961.75*	14.59
Treatment	3	21140100.00	7046700.0***	120.54
Error	6	350762.50	58460.42**	
Total	11	23196786.00		
C.V			3.25	

**, * = Significant at 1 and 5% levels, ns = non- significant; DF= degree of freedom

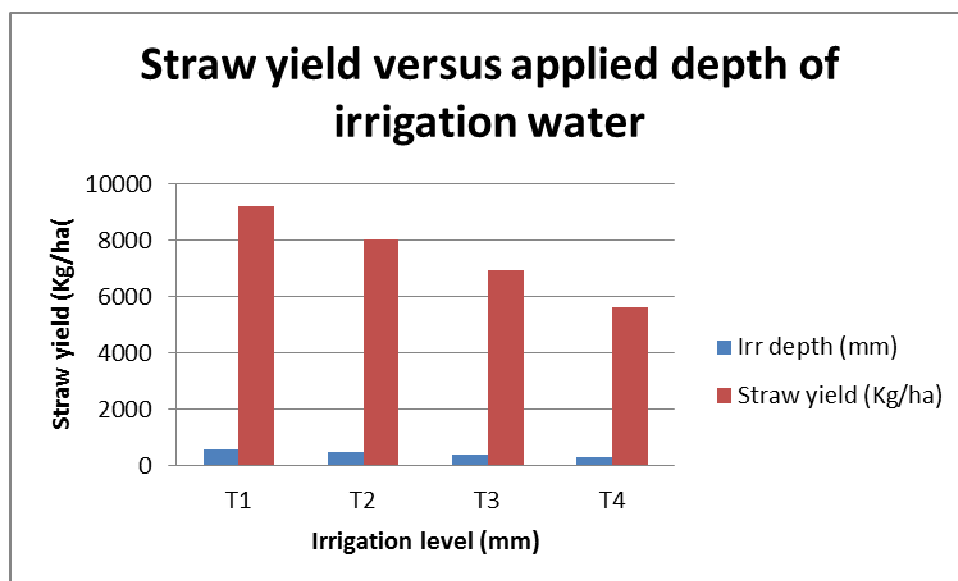


Figure 4.3: Mean straw yield of teff per hectare per applied depth of irrigation water

Table 4.16: Mean comparison of crop height, grain and straw yield of teff as affected by different irrigation levels

Irrigation level treatment (mm)	Grain yield (kg/ha)	Straw Yield (kg/ha)	Crop Height (cm)
552 (T1)	2510.0b	9200.0a*	120.0a*
469 (T2)	2708.0b	8000.0b	115.0a
382 (T3)	2980.0a**	6940.0c	107.0c
294 (T4)	2600.0b	5600.0d	96.0d
LSD 5%	220.96	483.06	6.57
CV (%)	4.09	3.25	3.0

Values followed by the same letter(s) within a column for each parameter are not significantly different at $P < 0.05$. NS: not significantly different at 5%.

4.3.4. Regression Correlation Analysis

For the grain yield, comparing the absolute value of the computed, r , value to the tabular r value with $(t-1) = 3$ degree of freedom, which are .878 at the 5% level of significance and .959 at the 1% level (Appendix Table 12). The computed, r , value is smaller than the tabular, r , for both 5% level of significance and 1% level. Therefore, the simple linear correlation coefficient is declared not significant at both 5% level of significance and 1% level. However, the computed, r , value of 0.73 (Table 4.17), indicates that, 53% of the variations in the grain mean yield is accounted for by the linear function of the level of irrigation water applied.

For the straw yield, comparing the absolute value of the computed, r , value to the tabular r value with $(t-1) = 3$ degree of freedom, which are .878 at the 5% level of significance and .959 at the 1% level (Appendix Table 12). The computed, r , value is greater than the tabular, r , value at the

5% level and at the 1% level. . Therefore, the simple linear correlation coefficient is declared significant at both 5% level of significance and 1% level. The computed, r, value of 0.99 (Table 4.18), indicates that, 98% of the variations in the mean straw yield are accounted for by the linear function of the level of irrigation water applied. The relatively higher, r, value obtained is also indicative of the closeness between the estimated regression line and the observed points as shown in Figure 4. 10 within the range of 2940 to 5520 m³/ha of water, the linear relationship between mean yield and level of irrigation water applied seems to fit the data adequately.

Table 4.17: Computation of a simple linear regression equation between grain yield and water level from the irrigation level experiment in teff

Treatment	Water level m ³ /ha	Grain yield Kg/ha	Deviation from mean		Square of deviate		Product of deviate
	X	Y	X	Y	X ²	Y ²	(X * Y)
T1	5520	2510	1277.5	-189.5	1632006	35910.25	242086.3
T2	4690	2708	447.5	8.5	200256.3	72.25	3803.75
T3	3820	2980	-422.5	280.5	178506.3	78680.25	118511.3
T4	2940	2600	-1302.5	-99.5	1696506	9900.25	129598.8
	16970	10798	0	0	3707275	124563	494000
	4242.5	2699.5					
Computed, r, value = 0.73*							

Table 4.18: Computation of a simple linear regression equation between straw yield and water level from the irrigation level experiment in teff

Treatment	Water level m ³ /ha	Straw yield Kg/ha	Deviation from mean		Square of deviate		Product of deviate
	X	Y	X	Y	X ²	Y ²	(X * Y)
T1	5520	9200	1277.5	1765	1632006	3115225	2254788
T2	4690	8000	447.5	565	200256.3	319225	252837.5
T3	3820	6940	-422.5	-495	178506.3	245025	209137.5
T4	2940	5600	-1302.5	-1835	1696506	3367225	2390088
	16970	29740	0	0	3707275	7046700	5106850
	4242.5	7435					

Computed, r, value = 0.99**

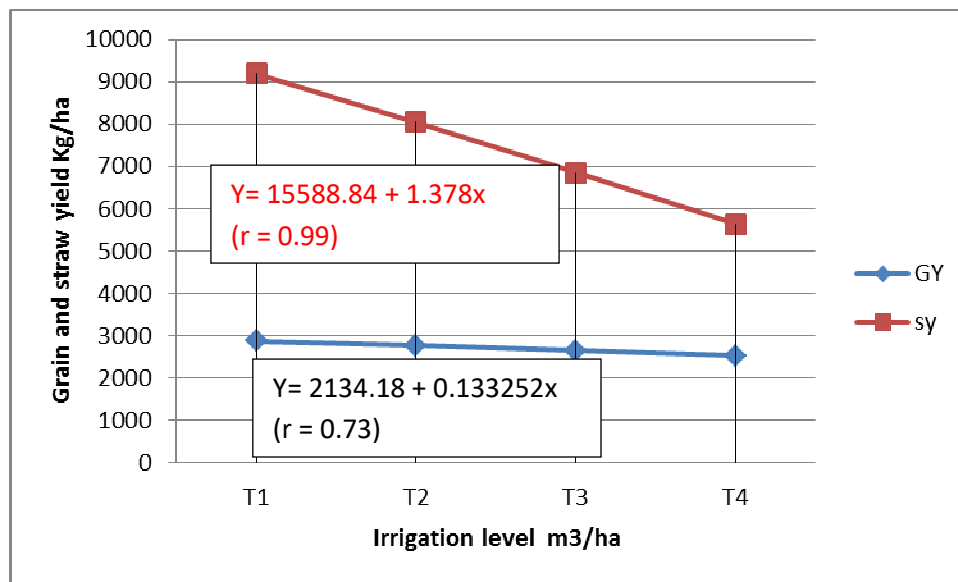


Figure 4.4: Relationship between irrigation levels (independent variables) and the grain and straw yields (dependent variables)

Where, T1, T2, T3 and T4 are irrigation levels equal to 5520, 4690, 3820 and 2940 m³/ha respectively. GY and SY are grain and straw yields of teff respectively.

4.3.5. Analysis of Opportunity Cost of the Different Irrigation levels

Opportunity cost is the potential benefit that is given up when one alternative is selected over another. In this study, the teff crop was irrigated in four alternative irrigation levels: (100% ETo, 85% ETo, 70% ETo and 55% ETo). Accordingly, teff irrigated at 100% ETo (T1) was assumed as full irrigation which is equal to the atmospheric demand regardless of soil and crop factors and was considered as the standard (control) irrigation level. Whereas teff irrigated at 85% ETo (T2), 70% ETo (T3) and 55% ETo (T4) level were considered as in-deficit of the atmospheric demand by 15%, 30% and 45% respectively, regardless of soil and crop factors. As can be seen from (Table 4.19), 830, 1700, and 2580 m³ of water per hectare was saved from T2, T3 and T4 respectively instead of irrigating teff at (T1). The opportunity cost of forgone water in (T1) is the additional 0.18, 0.45 and 0.88 ha of land (Table 4.19), that could have been cultivated by irrigating teff at T2, T3 and T4 respectively instead of (T1). And also, the opportunity cost of lost time in (T1) is the saved 20.79, 42.53 and 64.54 labor working hours in T2, T3 and T4 respectively (Table 4.19), that could have been used for execution of other important activities.

Table 4.19: Summary of opportunity cost values per treatment

Treatment	Applied depth of irrigation water (m ³ /Ha)	Water saved (m ³)	Additional land could have been cultivated (Ha)	Total sprinkler run hours per treatment	Time saved (hours)
T1	5520	-	-	137.9	-
T2	4690	830	0.176972	117.11	20.79
T3	3820	1700	0.445026	95.37	42.53
T4	2940	2580	0.877551	73.36	64.54

4.4. Effect of Different Irrigation Depths on Water Use Performance of Teff

4.4.1. Crop Water Productivity (CWP)

As can be seen from (Table 4.20), the highest water productivity (2.79 kg/m^3) of yield was obtained under 55% ETo irrigation water application level (294 mm) whereas the lowest water productivity (2.12 Kg/m^3) of teff yield was obtained in 100% ETo level under irrigation depth of 552 mm. Crop water productivity was significantly influenced by different irrigation levels (Table 21). And also, Figure 4.5 below shows, crop water productivity as a function of the amount of applied irrigation water which implies that, crop water productivity decreased with increasing irrigation depth and increased with decreasing irrigation depth. This may be due to the fact that, the occurrence of non-beneficial evapotranspiration under higher water application beyond crop water requirement. On the other hand crop water productivity was relatively higher with lower irrigation depth. This was also due to effective water consumption under the lower depth of water application. The trend of CWP in this study is in agreement with the findings of (Yuan *et al.*, 2004, Kidist and Tena 2017) and the authors reported that, the trends for both the WP for plant biomass and WP for the production of total fresh berry yields. The authors concluded that the lower the amount of irrigation water received, the higher the water productivity obtained for the drier plant biomass and berry yields. According to (Zwart and Bastiaanssen, 2004, as cited in Kidist and Tena, 2017); globally measured average WP values per unit water depletion are 1.09, 1.09, 0.65 and 1.80 kg/m^3 for wheat, rice, cotton, and maize respectively. Similarly, Yihun, (2015) reported that higher water productivity of 1.16 and 1.08 kg/m^3 was obtained from treatments which received 25% and 50% deficit irrigation respectively, throughout the whole growth season. Moa *et al.*, 2003 reported that highest WP of cucumber yield was obtained in treatment groups with minimal irrigation levels. Similarly, Sezen *et al.*, (2005) reported that higher WP was obtained with lowest irrigation level in field grown beans; however, lower irrigation level resulted in lower total yield which is in agreement with the findings of this study. This implies that, the amount of water applied had an inverse relationship with the biomass water productivity and water productivity probably will become more important as access to water become more limited (Shdeed, 2001). Therefore, by growing more with less water, more water will be available to irrigate arable land and produce teff 2-3 times a year in water prone areas of Ethiopia.

Table 4.20: RCBD Crop water productivity (Kg/m^3)

Treatment	Irrigation level (mm)	REP -1	REP -2	REP -3	Treatment total	Treatment mean
T1	552	1.99	2.14	2.22	6.35	2.12
T2	469	2.20	2.37	2.29	6.86	2.29
T3	382	2.48	2.58	2.71	7.77	2.59
T4	294	2.61	2.78	2.92	8.31	2.77
	REP Total	9.28	9.87	10.14	29.29	9.77
				REP Grand mean		2.44

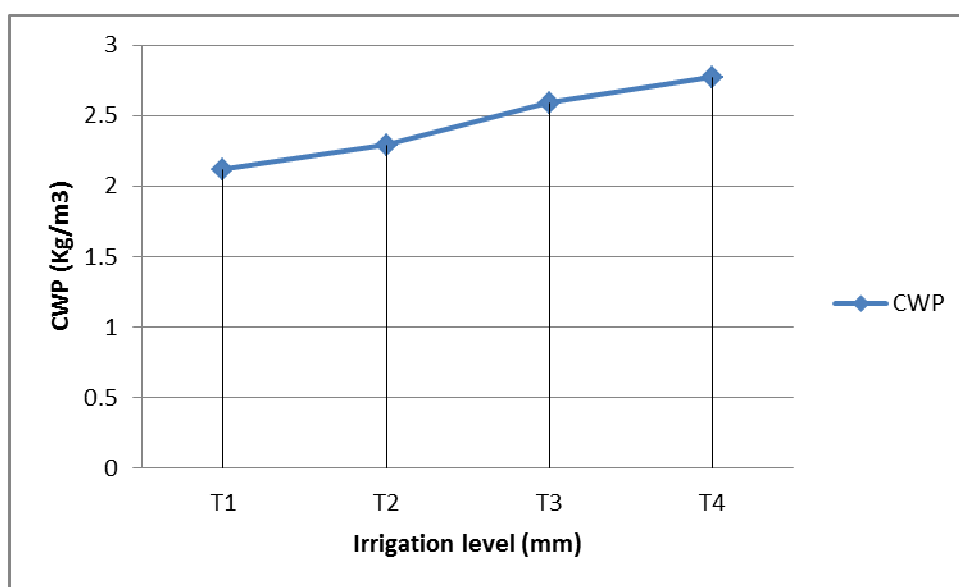


Figure 4.5: Crop water productivity (CWP) per irrigation levels treatments
Where, T1, T2, T3 and T4 are 552, 469, 382 and 294 mm respectively.

Table 4.21: ANOVA for Crop water productivity (Kg/m³)

Source of variation	DF	Sum of squares	Mean square	F value
REP	2	0.09671667	0.04835833*	14.64
Treatment	3	0.77835833	0.25945278***	78.56
Error	6	0.01981667	0.00330278***	
Total	11	0.89489167		
	C.V		2.36	

**, * = Significant at 1 and 5% levels, ns = non- significant; DF= degree of freedom

4.4.2. Economic Water Productivity (EWP)

As can be seen from (Table 4.22), the highest economic water productivity (20.63 Birr/m³) was obtained in (T4), irrigation depth of 294 mm while the lowest economic water productivity (12.00 Birr/m³) was obtained in (T1), irrigation depth of 552 mm and irrigation economic WUI (Birr/m³) was higher for teff irrigated at 55% of ETo and lower for teff irrigated at 100% ETo, indicating that, higher value of EWP was gained at a lower depth of irrigation water. This implies that, the possibility of producing teff with less depth of irrigation water and water saving is possible without affecting crop yield by applying irrigation water at the required depth. As can be seen from (Table 23), economic water productivity was significantly affected by different irrigation depths. As the depth of irrigation water exceeds the required amount, it resulted in loss of gross production mainly due to crop lodging and irrigation water loss that could have been used for additional production. Implying that, as water is readily available, crop evapotranspiration continues and maximizes up to a certain point and as water is relatively lower the crop evapotranspiration is restricted. As it can be seen from (Figure 4.6), water productivity decreased with increased irrigation depth and increased with lower irrigation depth. This may be due to the fact that effective water consumption and maximized evapotranspiration at lower applied depth of irrigation water.

Table 4.22: RCBD Economic water productivity (EWP)

Treatment	Irrigation level (mm)	REP -1 (Birr/m ³)	REP -2 (Birr/m ³)	REP -3 (Birr/m ³)	Treatment total	Treatment mean
T1	552	11.51	12.30	12.18	35.99	12.00
T2	469	13.99	14.98	14.60	43.57	14.52
T3	382	19.08	18.15	19.05	56.28	18.76
T4	294	21.27	20.97	20.63	62.87	20.96
REP Total		65.85	66.4	66.46	198.71	
REP Grand mean						16.56

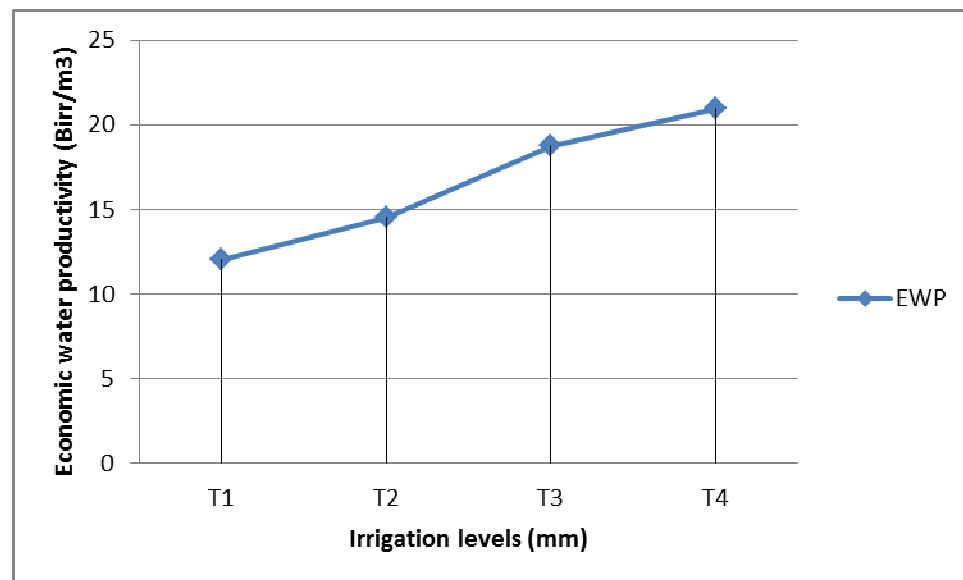


Figure 4.6: Economic water productivity (EWP) per irrigation level treatments

Where, T1, T2, T3 and T4 are 552, 469, 382 and 294 mm respectively

Table 4.23: ANOVA for Economic water productivity (Birr/m³)

Source of variation	DF	Sum of squares	Mean square	F value
REP	2	0.0565167	0.0282583 ^{ns}	0.11
Treatment	3	147.4280917	49.1426972***	187.99
Error	6	1.5684833	0.2614139**	
Total	11	149.0530917		
C.V			3.09	

**, * = Significant at 1 and 5% levels, ns = non- significant; DF= degree of freedom

4.5. Effect of Different Irrigation Depths on Economic Performance of Teff

4.5.1. Total Gross Return

As can be seen from (Table 4.24), the higher total mean gross income (71745 Birr/ha) was obtained in (T3), irrigation depth of 382 mm and the lower total mean gross return (61800.00 Birr/ha) was obtained in (T4), irrigation depth of 294 mm applied for the whole growth period. As can be seen from (Table 4.25), total gross return was significantly affected by different irrigation depths. However, there was no significant variation in total income between T2 and T3 and also there was no significant variation observed in total income between T1 and T2 (Table 26). As can be seen from figure 4.7, the total gross return was lower in T1 and the increased in T2 and become higher in T3 and then declined in T4. The total gross return obtained per hectare in irrigation level treatment T3 is higher by about 7.59, 4.99 and 13.86 % than T1, T2 and T4 respectively. On the other hand, T3 saved about 30.79 and 18.55% of irrigation water more than T1 and T2 respectively. But, in T4 water was saved by more than 23.04% as compared to T3. From the above findings, Teff crop irrigation requirement under sprinkler system in the study area for whole growth period found to be in the range of 294 to 382 mm and the overall average being 338 mm. This average value is significantly different from the 375 mm ETc value obtained for Barley (Araya et al., 2011), but is comparable to that of teff irrigated by watering can which is 319 mm (Yihun, 2015) and Millet, which is 330 mm (Grema and Hess, 1994). Therefore, in this study teff irrigated at (T3) 70% ETo performed better in grain yield and total gross return than teff irrigated at T1, T2 and T4. A similar finding has been reported by

(Norberg *et al.*, 2009) who reported that, irrigating teff at 70 percent of the reference evapotranspiration enables to get economic yield.

Table 4.24: RCBD Total gross return (TGR)

Treatment	Irrigation level (mm)	REP -1 (Birr/ha)	REP -2 (Birr/ha)	REP -3 (Birr/ha)	Treatment total	Treatment mean
T1	552	63618.50	67975.25	67306.25	198900	66300
T2	469	65657.50	70298.50	68524.00	204480	68160
T3	382	72971.50	69402.50	72861.00	215235	71745
T4	294	62722.00	61828.00	60850.00	185400	61800
REP Total		264969.5	269504.3	269541.3	804015	
REP Grand mean						67001.25

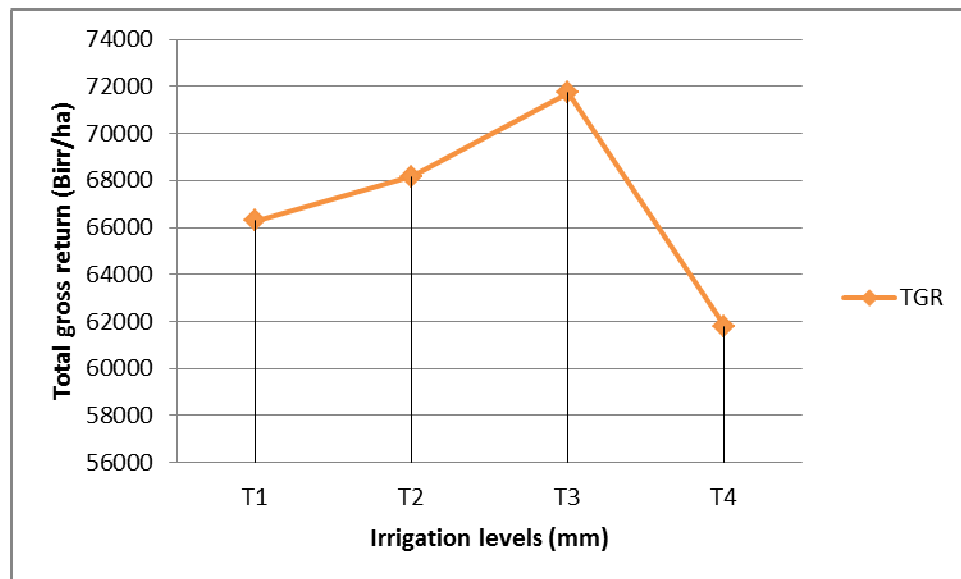


Figure 4.7: Total gross return/gross income/ per irrigation level treatments

Where, T1, T2, T3 and T4 are 552, 469, 382 and 294 mm respectively

Table 4.25: ANOVA for Total gross return (Birr/ha)

Source of variation	DF	Sum of squares	Mean square	F value
REP	2	3455518.7	1727759.4 ^{ns}	0.36
Treatment	3	154171856.3	51390618.8**	10.81
Error	6	28512542.2	4752090.4*	
Total	11	186139917.1		
C.V			3.25	

**, * = Significant at 1 and 5% levels, ns = non- significant; DF= degree of freedom

Table 4.26: Mean comparison of, crop water productivity (CWP), economic water productivity (EWP) and total gross return (TGR) of teff crop as affected by different irrigation levels

Treatment	Applied water (m ³)	TGR (Birr/ha)	CWP (kg/m ³)	EWP (Birr/m ³)
100% ETo (T1)	5520	66300b	2.12d	12.00d
85% ETo (T2)	4690	68160.0ab	2.28c	14.52c
70% ETo (T3)	3820	71745.0a	2.59b	18.76b
55% ETo (T4)	2940	61800.0c	2.79a	20.96a
LSD 5%		4355.3	0.1148	1.02
CV (%)		3.25	2.35	3.08

Values followed by the same letter(s) within a column for each parameter are not significantly different at P< 0.05. NS: not significantly different at 5%.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Among the cereal food crops, teff is the most well-known and widely consumed grain in Ethiopia, but it was only produced once in a year by rain fed agriculture and thus, the supply is by far less than the demand. In order to alleviate this problem, this study was initiated to design and evaluate the performance of sprinkler irrigation system for Teff (*Eragrostic tef L.*) production in the study areas. Four irrigation levels were used to evaluate the response of different irrigation level on agronomic parameters (i.e., yield and yield components and crop water and economic water productivity of teff. Accordingly, the following major conclusions are drawn:

- The mean sprinkler operating pressure, discharge, gross application rate of the sprinkler system were found as 319.5KPa, 1.68 m³/h, 5.18 mm/h respectively.
- Higher average CU value 87.8% was obtained at morning test period and lower CU value of 82.3% was obtained at afternoon test period.
- Higher average distribution uniformity of lower quarter (DU_{lq}) value of 80.71 % was obtained at morning test time and lower average distribution uniformity of lower quarter (DU_{lq}) value of 76.5% was obtained for afternoon test time.
- The higher average AE value of 79.62% at night test period and lower average AE value of 74.4% was obtained for the afternoon test period.
- The mean net sprinkler precipitation rate was 4.01mm/h and system could perform without the occurrence of runoff since it was less than the average soil infiltration rate of the study field.
- The calculated coefficient of variation in application rate uniformity of this irrigation system was 2.73% indicating that, statistical uniformity of sprinklers application rate of 97.27%.
- A mean maximum teff grain yield of 2980 Kg/ha was obtained when teff was irrigated at 70% of the reference evapotranspiration (T₁), 382 mm applied depth of irrigation water. This is three fold the yield farmers currently harvest from rain fed agriculture. The mean grain yield (2980 Kg/ha) obtained in (T₃) was significantly higher than T₁, T₂ and T₄ but, statistically there was no significant variation observed in grain yield (Kg/ha)

between T1, T2 and T4 for the 552, 469 and 294 mm applied depth of irrigation water respectively.

The opportunity cost of forgone water in alternative (T1) is the saved water (2580 m³), that could have been used to cultivate additional 0.88 ha in alternative (T4) instead of T1 and the opportunity cost of lost time in alternative (T1) is the saved labor working time (64.54 hours) that could have been used for execution of other important activities.

- The highest water productivity (2.79 kg/m³) and the highest economic water productivity (20.96 Birr/m³) respectively were obtained in (T4), irrigation depth of (294 mm).
- The higher mean total income (71745 Birr/ha) was obtained in (T3), irrigation depth of 382 mm and the lower mean total gross return (61800.00 Birr/ha) was obtained in (T4), irrigation depth of 294 mm, but, there was no significant variation in total income between T2 and T3 and also there was no significant variation observed in total income between T1 and T2.
- Therefore, it could be concluded that, the optimum irrigation level of teff irrigated under sprinkler system in the month of December to end March for the study area found as in the range of 294 mm to 382 mm and the average being 338 mm.

5.2. Recommendations

Scenarios:

1. Grain yield strategy → agricultural production.
2. Animal feed strategy → straw yield → animal production.
3. Water shortage strategy → water productivity.

- In water scarce areas, teff producing farmers are recommended to avail irrigation water from rain water harvesting as well as from dug well or bore well and adopt sprinkler irrigated teff production in dry periods as well as supplemental irrigation when rainfall is not sufficient in the normal teff growing seasons,
- For grain yield strategy, the aim is to increase the productivity of teff. Therefore it is recommended to irrigate teff at 70% ETo level (382 mm), since higher mean yield of teff (2980 Kg/ha) was obtained in this irrigation level,

- For water scarce areas and water shortage situations, the strategy is to increase water productivity, therefore, it is recommended to irrigate teff at 55% ETo level (294 mm), since it has found the highest crop water productivity and economic water productivity under this water level,
- In animal feed strategy, the aim is to increase straw yield, since teff's straw is preferred for its feed value for animal production, therefore, it is recommended to irrigate teff at 100% ETo level (552) for forage purpose,
- Based on the findings of this study, it is recommended to produce teff from less water by using dragline sprinkler system and therefore, the implementation of sprinkler irrigated teff production shall be carried out in teff producing areas of the country in order to enhance main potential benefits which include employment opportunities, improving economic growth, improving living standards of the farmers and community and in order to address the current high demand of teff, by producing surplus teff which enables to alleviate poverty and realize food security of the country,
- As one of the predicament of graduate research, the experiment is a one season one site experiment. Hence, further investigation is recommended using different varieties of teff, sowing methods, irrigation interval and different climatic conditions under sprinkler irrigation system.

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7. APPENDICES

Appendix Table 1: Soil infiltration rate test results

Time reading	Time difference (min)	Cumulative time (min)	Gauge reading (cm)
5:18	0	0	24
5:27	9	9	23
5:40	13	22	22
6:00	20	42	21
6:25	25	67	20
6:52	27	94	19
7:20	28	122	18
7:49	29	151	17
8:18	31	182	16
8:51	33	215	15
9:24	33	248	14
9:57	33	281	13
10:30	33	314	12
Infiltration rate = 23 mm/h			

Appendix Table 2: Soil samples result of soil texture of the study area

Number of observation	Easting L	Northing L	Soil depth	Sand%	Silt%	Clay%	Type of soil texture
1	0533470	0926236	0-45	23	38	39	Silt clay
2	0533576	0926233	0-45	25	37	38	Silt clay

Appendix Table 3: Soil samples result on bulk density, moisture content and water holding capacity

Number of observations	Location		Soil depth (cm)	Core sampler no	Wt. Of moist soil sample (gm)	Wt. of dry soil sample (gm)	Moisture content %	Water holding capacity (mm/m) formula	Bulk density (g/cm ³)
	Easting	Northing							
1	0533470	0926236	0 -15	013	145.9	123.67	18	198	1.1
2	0533470	0926236	15 -30	031	164.42	132.8	23.8	285.6	1.2
3	0533470	0926236	30 -45	093	148.41	120.94	22.7	249.7	1.1
4	0533576	0926233	0 -15	009	162.42	138.49	17.3	207.6	1.2
5	0533576	0926233	15 -30	138	154.97	129.59	19.6	215.6	1.1
6	0533576	0926233	30 -45	152	167.51	143.15	17	204	1.2
7	0533549	0926281	0 -15	03	172.26	147.66	16.6	215.8	1.3
8	0533549	0926281	15 -30	22	160.61	120.47	18.6	223.2	1.2
9	0533549	0926281	30 -45	030	143.34	122.26	17.2	189.2	1.1
							18.98	220.97	1.2

Appendix Table 4: Long years mean monthly climatic data in the study area collected from Melkassa Agricultural Research Centre (1977-2016)

Month	Rainfall (mm)	Min T (oC)	Max T (oC)	RH (%)	Sunshine (h)	Wind speed (m/s)	Calculated average ETo (mm/day)
January	19.2	11.69	27.9	50.65	8.98	2.34	4.76
February	33.3	13.37	29.14	48.8	9.0	2.53	5.41
March	59.7	15.2	30.4	44	8.5	2.94	5.34
April	62.1	16.3	32.2	48.6	8.8	2.22	5.99
May	56.9	17.2	33.1	46.7	8.4	2.02	5.27
June	68.3	16.8	32.4	49.9	6.8	2.51	5.30
July	215.7	16.9	31.6	58.56	6.9	2.56	4.99
August	223.5	16.5	30.4	60.9	7.3	2.31	4.45
September	98.1	16.3	28.3	58.2	8.7	1.97	4.36
October	34.2	13.3	27.9	47.8	9.3	2.23	4.67
November	11.0	12.8	27.5	45.5	9.1	2.83	4.55
December	8.7	12.8	27.6	46.4	9.1	2.43	4.34
Average		14.93	29.87	50.9	8.4	2.41	4.95
Total	890.7						1795.43

Appendix Table 5: Real-time monthly climatic data collected from Awash Melkassa weather station during the study period

Month	Rainfall (mm)	Min T (oC)	Max T (oC)	RH (%)	Sunshine (h)	Wind speed (m/s)	Rad (Mj/m ² /day)	Calculated average ETo (mm/day)
Dec	-	10.1	27.2	53	9.3	3.15	21.4	5.17
Jan	-	6.1	28.9	41	10.3	2.93	22.7	5.8
Feb	-	15.3	29.3	56	9.4	3.18	22.8	5.72
Mar	20	15.7	32.5	46	9.5	2.71	24	6.48
Average		11.8	29.48	49	9.6	2.99	22.7	5.79
Total	20							694.63

Appendix Table 6: Manifold and Lateral pipes/Dragline Equipment's

Type of Equipment	D Manifold/ D lateral			Clamp Saddle	Adapter nipple (PVC) Female solvent & Male	
Manifold Starter	90/75			90 * 2"	90 – 75 * 2"	
Manifold Reducer	D1/D2			Reducing bush Male x female solvent	Socket (Female solvent)	
	90/75			90/75	90	
Manifold End Plug				Pipe diameter	Cap PVC (Female solvent)	
				75	75	
Lateral/Dragline	Lateral pipe	Riser pipe	Clamp saddle	Adapter nipple		
Hydrant valve connection				Between saddle and riser Female solvent/socket and BSP Male	Between riser & valve Female solvent/socket & BSP Female	
				63	32	63 * 1'
End Plug	Lateral	Riser	90° Elbow	Reducer bush (Male x Female)	Adapter Female solvent socket x Male	Cap BSP female Threaded
	63	50	63	63 x 50	50 * 2'''	2'''
Reducer	Reducer		Reducer bush (Male x Female solvent)		Socket Female Solvent	
	75/63		75 x 63		75	
	63/50		63 x 50		63	

Source: WWDS, 2010. Wonji/Shoa Sugar Factory, North Dodota Irrigation and Drainage Design Final Report, Addis Ababa, Ethiopia.

Appendix Table 7: Irrigation Water Distribution pipes and Fittings Head Loss Analysis

Description	Unit	Quantity	Discharge (m ³ /s)	Diameter (m)	Velocity (m/s)	Roughness	Friction Coefficient	Formula	Dynamic Loss (m)
Reducer	Pc	1	0.00329	0.2	1.39		0.1	$K * V^2/2g$	0.009848
Reducer	Pc	1	0.00329	0.09	1.51		0.1	$K * V^2/2g$	0.011621
Reducer	Pc	2	0.00329	0.075	2.13		0.1	$K * V^2/2g$	0.046248
90° bend	Pc	1	0.00329	0.09	1.51		1.5	$K * V^2/2g$	0.17432
90° bend	Pc	2	0.00329	0.075	2.13		1.5	$K * V^2/2g$	0.346858
Check valve	Pc	1	0.00329	0.2	1.39		1.9	$K * V^2/2g$	0.187104
Sub-main pipe	m	36.59	0.0039	0.09	1.51	150	0.048371	$K * L$	1.769895
Manifold pipe	m	9.21	0.00329	0.075	2.13	150	0.03163	$K * L$	0.291312
Lateral pipe	m	55.66	0.00329	0.063	2.73	150	0.01156	$K * L$	0.64343
Stand pipe	m	0.33	0.00047	0.025	2.73		0.01156	$K * L$	0.003815
Riser pipe	m	0.12	0.00047	0.025	2.73		0.01156	$K * L$	0.001387
Hydrant valve	Pc	18	0.00047	0.025	2.73		0.4	$K * V^2/2g$	0.151945
Dragline hose	M	3.33	0.00047	0.025	2.73		0.01156	$K * L$	0.038495
Total									3.676278

Appendix Table 8: Sprinkler operating pressure measured at different test points

	Sprinkler operating pressure measured at five hydrants at specified distances on each of the laterals (KPa)					
	Hy ₁	Hy ₃	Hy ₅	Hy ₇	Hy ₉	Average
L1	325	300	289	320	330	312.8
L2	329	300	312	340	350	326.2
Mean						319.5

Where, L1 is Lateral nearest to the pump house and L2 is Lateral Fareast from the pump house and Hy₁, Hy₃, Hy₅, Hy₇, and Hy₉ are hydrant 1, 3, 5, 7 and 9 respectively on L1 & L2.

Appendix Table 9: Crop Height measured at mid- season and late- season of the teff crop growth stages

Crop growth stages	(DAS)	T1	T2	T3	T4
		Mean height (cm)	Mean height (Cm)	Mean height (cm)	Mean height (cm)
Mid-season	70	98	91	73	60
	80	108	102	86	75
Late- season	90	115	109	98	89
	100	118	113	105	93
	110	120	115	107	96
	119	120	115	107	96

Where, T1, T2, T3 and 4 are irrigation level treatments irrigated at 100, 85, 70 and 55% ET_O.

DAS is the length of Days after sowing in which height measurement was taken.

Appendix Table 10: Sprinkler run time, average depth of irrigation water applied per irrigation events, number of irrigation rounds and the total depth of applied irrigation water, per irrigation level treatments

Appendix Table 10A: Irrigation level treatment T1: (Teff irrigated at 100% ETo)

No of irrigation rounds	Teff growth stage	Date of irrigation	Sprinkler precipitation Rate (mm/hr.)	Ave. actual ETo (mm)	Sprinkler run time in hours	Average applied depth / irrigation event (mm)	Rainfall (mm)	Effective rainfall(mm)
1	initial	Dec-13-16	4.01	5.32	5.3	21.0		
2	initial	Dec-17-16	4.01	5.32	5.3	21.0		
3	initial	Dec-21-16	4.01	5.36	5.35	21.45		
4	initial	Dec-25-16	4.01	5.36	5.35	21.45		
5	initial	Dec-29-16	4.01	5.36	5.35	21.45		
6	initial	Jan-2-17	4.01	5.68	5.67	22.7		
7	initial	Jan-6-17	4.01	5.68	5.67	22.7		
8	initial	Jan-10-17	4.01	5.68	5.67	22.7		
9	initial	Jan-14-17	4.01	5.68	5.67	22.7		
10	Gr & dv	Jan-18-17	4.01	5.68	5.67	22.7		
11	Gr & dv	Jan-22-17	4.01	6.03	6.0	24.06		
12	Gr & dv	Jan-26-17	4.01	6.03	6.0	24.06		
13	Gr & dv	Jan-30-17	4.01	6.03	6.0	24.06		
14	Mid-sn	Feb-3-17	4.01	6.03	6.0	24.06		
15	Mid-sn	Feb-7-17	4.01	6.03	6.0	24.06		
16	Mid-sn	Feb-11-17	4.01	6.03	6.0	24.06		
17	Mid-sn	Feb-14-17	Rainfall	--	--	--	15	14.6
18	Mid-sn	Feb-17-17	4.01	5.3	5.3	21.25		
19	Mid-sn	Feb-18-17	Rainfall	--	--	--	5	5
20	Mid-sn	Feb-19-17	4.01	5.6	5.6	22.46		
21	Mid-sn	Feb-23-17	4.01	5.6	5.6	22.46		
22	Mid-sn	Feb-27-17	4.01	5.6	5.6	22.46		
23	Mid-sn	Mar-3-17	4.01	5.6	5.6	22.46		
24	Late-sn	Mar-7-17	4.01	5.6	5.6	22.46		
25	Late-sn	Mar-11-17	4.01	6.8	6.8	27.27		
26	Late-sn	Mar-15-17	4.01	6.8	6.8	27.27		
Irrigation End Date Mar-19-17				Total		552.3	20	19.6

Appendix Table 10B: Irrigation level treatment T2: (Teff irrigated at 85% ETo)

No of irrigation rounds	Teff growth stage	Date of irrigation	Sprinkler precipitation Rate (mm/hr.)	Average actual value of 100%ETo (mm/day)	85% ETO value mm mmm(mm/day)	Sprinkler run time in hours	Average applied depth per irrigation event (mm)	Rainfall(mm)	Effective rainfall(mm)
1	initial	Dec-13-16	4.01	5.32	4.52	4.5	18.0		
2	initial	Dec-17-16	4.01	5.32	4.52	4.5	18.0		
3	initial	Dec-21-16	4.01	5.36	4.56	4.55	18.25		
4	initial	Dec-25-16	4.01	5.36	4.56	4.55	18.25		
5	initial	Dec-29-16	4.01	5.36	4.56	4.55	18.25		
6	initial	Jan-2-17	4.01	5.68	4.83	4.81	19.25		
7	initial	Jan-6-17	4.01	5.68	4.83	4.81	19.25		
8	initial	Jan-10-17	4.01	5.68	4.83	4.81	19.25		
9	initial	Jan-14-17	4.01	5.68	4.83	4.81	19.25		
10	Gr & dv	Jan-18-17	4.01	5.68	4.83	4.81	19.25		
11	Gr & dv	Jan-22-17	4.01	6.03	5.13	5.1	20.45		
12	Gr & dv	Jan-26-17	4.01	6.03	5.13	5.1	20.45		
13	Gr & dv	Jan-30-17	4.01	6.03	5.13	5.1	20.45		
14	Mid-sn	Feb-3-17	4.01	6.03	5.13	5.1	20.45		
15	Mid-sn	Feb-7-17	4.01	6.03	5.13	5.1	20.45		
16	Mid-sn	Feb-11-17	4.01	6.03	5.13	5.1	20.45		
17	Mid-sn	Feb-14-17	Rainfall	--		--	--	15	14.6
18	Mid-sn	Feb-17-17	4.01	5.3	4.53	4.52	18.13		
19	Mid-sn	Feb-18-17	Rainfall	--		--	--	5	5
20	Mid-sn	Feb-19-17	4.01	5.6	4.76	4.75	19.05		
21	Mid-sn	Feb-23-17	4.01	5.6	4.76	4.75	19.05		
22	Mid-sn	Feb-27-17	4.01	5.6	4.76	4.75	19.05		
23	Mid-sn	Mar-3-17	4.01	5.6	4.76	4.75	19.05		
24	Late-sn	Mar-7-17	4.01	5.6	4.76	4.75	19.05		
25	Late-sn	Mar-11-17	4.01	6.8	5.78	5.77	23.14		
26	Late-sn	Mar-15-17	4.01	6.8	5.78	5.77	23.14		
Irrigation End Date Mar-19-17					Total		469.2	20	19.6

Appendix Table 10C: Irrigation level treatment T3: (Teff irrigated at 70% ETo)

No of irrigation rounds	Teff growth stage	Date of irrigation	Sprinkler precipitation Rate (mm/hr.)	Average actual value of 100%ETo (mm/day)	Calculated value of 70% ETo (mm/day)	Sprinkler run time in hours	Average applied depth per irrigation event (mm)	Rainfall (mm)	Effective rainfall (mm)
1	initial	Dec-13-16	4.01	5.32	3.72	3.7	14.84		
2	initial	Dec-17-16	4.01	5.32	3.72	3.7	14.84		
3	initial	Dec-21-16	4.01	5.36	3.75	3.74	15.0		
4	initial	Dec-25-16	4.01	5.36	3.75	3.74	15.0		
5	initial	Dec-29-16	4.01	5.36	3.75	3.74	15.0		
6	initial	Jan-2-17	4.01	5.68	3.98	3.97	15.92		
7	initial	Jan-6-17	4.01	5.68	3.98	3.97	15.92		
8	initial	Jan-10-17	4.01	5.68	3.98	3.97	15.92		
9	initial	Jan-14-17	4.01	5.68	3.98	3.97	15.92		
10	Gr& dv	Jan-18-17	4.01	5.68	3.98	3.97	15.92		
11	Gr& dv	Jan-22-17	4.01	6.03	4.22	4.2	16.84		
12	Gr& dv	Jan-26-17	4.01	6.03	4.22	4.2	16.84		
13	Gr& dv	Jan-30-17	4.01	6.03	4.22	4.2	16.84		
14	Mid-sn	Feb-3-17	4.01	6.03	4.22	4.2	16.84		
15	Mid-sn	Feb-7-17	4.01	6.03	4.22	4.2	16.84		
16	Mid-sn	Feb-11-17	4.01	6.03	4.22	4.2	16.84		
17	Mid-sn	Feb-14-17	Rainfall	--		--	--	15	14.6
18	Mid-sn	Feb-17-17	4.01	5.3	3.71	2.65	10.63		
19	Mid-sn	Feb-18-17	Rainfall	--		--	--	5	5
20	Mid-sn	Feb-19-17	4.01	5.6	3.92	3.91	15.68		
21	Mid-sn	Feb-23-17	4.01	5.6	3.92	3.91	15.68		
22	Mid-sn	Feb-27-17	4.01	5.6	3.92	3.91	15.68		
23	Mid-sn	Mar-3-17	4.01	5.6	3.92	3.91	15.68		
24	Late-sn	Mar-7-17	4.01	5.6	3.92	3.91	15.68		
25	Late-sn	Mar-11-17	4.01	6.8	4.76	4.75	19.04		
26	Late-sn	Mar-15-17	4.01	6.8	4.76	4.75	19.04		
Irrigation End Date Mar-19-17					Total		382.4	20	19.6

Appendix Table 10D: Irrigation level treatment T4: (Teff irrigated at 55% ETo)

No of irrigation rounds	Teff growth stage	Date of irrigation	Sprinkler precipitation Rate (mm/hr.)	Average actual value of 100%ETo (mm/day)	Calculated value of 55% ETo (mm/day)	Sprinkler run time in hours	Average applied depth per irrigation event (mm)	Rainfall (mm)	Effective rainfall (mm)
1	initial	Dec-13-16	4.01	5.32	2.93	2.93	11.72		
2	initial	Dec-17-16	4.01	5.32	2.93	2.93	11.72		
3	initial	Dec-21-16	4.01	5.36	2.95	2.95	11.8		
4	initial	Dec-25-16	4.01	5.36	2.95	2.95	11.8		
5	initial	Dec-29-16	4.01	5.36	2.95	2.95	11.8		
6	initial	Jan-2-17	4.01	5.68	3.12	3.11	12.47		
7	initial	Jan-6-17	4.01	5.68	3.12	3.11	12.47		
8	initial	Jan-10-17	4.01	5.68	3.12	3.11	12.47		
9	initial	Jan-14-17	4.01	5.68	3.12	3.11	12.47		
10	Gr& dv	Jan-18-17	4.01	5.68	3.12	3.11	12.47		
11	Gr& dv	Jan-22-17	4.01	6.03	3.32	3.31	13.27		
12	Gr& dv	Jan-26-17	4.01	6.03	3.32	3.31	13.27		
13	Gr& dv	Jan-30-17	4.01	6.03	3.32	3.31	13.27		
14	Mid-sn	Feb-3-17	4.01	6.03	3.32	3.31	13.27		
15	Mid-sn	Feb-7-17	4.01	6.03	3.32	3.31	13.27		
16	Mid-sn	Feb-11-17	4.01	6.03	3.32	3.31	13.27		
17	Mid-sn	Feb-14-17	Rainfall	--		--	--	15	14.6
18	Mid-sn	Feb-17-17	4.01	5.3	2.92	0.43	1.72		
19	Mid-sn	Feb-18-17	Rainfall	--		--	--	5	5
20	Mid-sn	Feb-19-17	4.01	5.6	3.08	3.07	12.31		
21	Mid-sn	Feb-23-17	4.01	5.6	3.08	3.07	12.31		
22	Mid-sn	Feb-27-17	4.01	5.6	3.08	3.07	12.31		
23	Mid-sn	Mar-3-17	4.01	5.6	3.08	3.07	12.31		
24	Late-sn	Mar-7-17	4.01	5.6	3.08	3.07	12.31		
25	Late-sn	Mar-11-17	4.01	6.8	3.74	3.73	14.96		
26	Late-sn	Mar-15-17	4.01	6.8	3.74	3.73	14.96		
Irrigation End Date Mar-19-17					Total		294.0	20	19.6

Appendix Table 11: Data on grain and straw yield (Kg/ha) and crop height (cm) of teff , subject to four irrigation level treatments in RCB design with three replications

Treatment	REP I			REP II			REP III			Mean grain :straw ratio
	Mean crop height (cm)	Grain yield Kg/ha	Straw yield Kg/ha	Mean Crop height (Cm)	Grain yield Kg/ha	Straw yield Kg/ha	Mean Crop height (cm)	Grain yield Kg/ha	Straw yield Kg/ha	
T1	119.5	2430	8582	116.3	2590	9243	124.2	2510	9775	27.38
T2	117.5	2610	7690	113.5	2787.8	8310	114	2726.2	8000	33.85
T3	105.2	3084.2	6450	109.6	2857.8	6998	106.2	2998	7372	42.94
T4	95.2	2698.6	5000	98.9	2601.4	5600	93.9	2500	6200	46.43

Where, T1, T2, T3 and T4 are 100, 85, 70 and 55% ET_0 irrigation levels respectively.

Appendix Table 12: Simple linear correlation coefficients, r, at the 5% and 1% levels of significance

Df	1	2	3	4	5	6	7	8	9
5%	0.997	0.950	0.878	0.871	0.754	0.707	0.666	0.632	0.602
1%	1.000	0.990	0.959	0.917	0.874	0.834	0.798	0.765	0.735

SOURCE: Statistical methods by George W. Sendecor and William G. Cochran. Sixth edition © 1967.



Appendix picture 1: Sprinkler discharge and water distribution measurements



Appendix picture 2: Growth and development stage of teff



Appendix picture 3: Mid-season growth stage of teff



Appendix picture 4: Lodged teff due to high water application



Appendix picture 5: Teff at seed filling stage

Appendix Form .1: Sprinkler Evaluation Data Sheet

Location.....Field No..... Field Area (ha).....Observer..... Date.....

Crop Type Growth Stage.....

Type of Sprinkler System.....Hydrant Pressure.....

Riser Height..... Lateral Pipe Diameter..... Nozzle Size

Test Data

Weather: Temperature..... Humidity.....

Wind Velocity: Begin..... Finish.....

Wind Direction: Begin.....Finish.....

Lateral Spacing..... Gauge Spacing x.....

Sprinkler Number on the Lateral.....

$$\text{Sprinkler Discharge} = \frac{\text{Volume caught}}{\text{Time minute}}$$

Time of Test: Begin..... Finish....., Duration, hr..... Min.....

Evaporation Gauge Depth: Begin..... Finish..... Loss..... Rate.....

Comments.....

Appendix Form 2: Catch Can Record Data Sheet for Evaluation of Sprinkler Irrigation System

Date-----

Test time in the day		Rain gauge readings (ML)					
		Row 1	Row 2	Row 3	Row 4	Row 5	Row 6
Morning	Row A						
	Row B						
	Row C						
	Row D						
	Row E						
	Row F						
Afternoon	Row A						
	Row B						
	Row C						
	Row D						
	Row E						
	Row F						
Night	Row A						
	Row B						
	Row C						
	Row D						
	Row E						
	Row F						

Appendix Form 3: Sprinkler Runs Time Record Sheet

Month & Date	Irrigation level treatment	Sprinkler pressure bar(changed)	Sprinkler run time minute	Sprinkler run time hours	Average applied depth mm