

**EFFECT OF DEFICIT IRRIGATION AND ROW SPACING ON
GROWTH, YIELD AND WATER PRODUCTIVITY OF TEF
(*Eragrostis tef*) IN CENTRAL RIFT VALLY OF ETHIOPIA**

ADDIS GEBREIGIZAHABER



**A THESIS SUBMITTED TO
DEPARTMENT OF WATER RESOURCES ENGINEERING
SCHOOL OF CIVIL ENGINEERING AND ARCHITECTURE**

**PRESENTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE DEGREE OF MASTER'S IN WATER
RESOURCE ENGINEERING
(SPECIALIZATION IN IRRIGATION ENGINEERING)**

**OFFICE OF GRADUATE STUDIES
ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY**

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JULY 2019**

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ABBREVIATIONS AND ACRONYMS

BI	Border Irrigation
CV	Coefficient of Variation
DP	Deep Percolation
Ea	Field Application Efficiency
Ec	Electrical Conductivity
Etc	Crop Evapotranspiration
Eto	Reference Evapotranspiration
FC	Field Capacity
Ig	Gross Irrigation Depth
In	Net Irrigation Depth
Kc	Crop Coefficient
Ky	Yield Response Factor
LSD	Least Significant Difference
MC	Volumetric Moisture Content
MoE	Ministry of Education
MoWR	Ministry of Water Resources
Msl	Meters Above Sea Level
Ms	Weight of Oven Dry Soil
PWP	Permanent Wilting Point
RAW	Readily Available Water
SMC	Soil Moisture Content
SMD	Soil Moisture Depletion
TAW	Total Available Water
U2	Wind speed at 2 m Height
Y	Yield
Ya	Actual Harvested Yield
Ym	Maximu[m Harvested Yield

ABSTRACT

*Irrigation development in arid and semi-arid regions of Ethiopia is seriously constrained due to the increasing competition for irrigation water as a result of recurrent drought become common problem. Novel irrigation technologies need to be developed that water saving and water productivity per unit of land can be increased. Hence, the objective of this study was to determine effect of deficit irrigation application and row spacing of tef (*Eragrostis tef*) production and water use efficiency under water limited situation. Field experiment was carried out at Melkassa Agricultural Research Center, Ethiopia during growing season of 2018 with border irrigation system and sixteen irrigation treatments replicated three times in a split plot design. The treatments included three levels of deficit irrigation (55% ET_c , 70% ET_c , 85% ET_c) and control (100% ET_c) as main plot and four row spacing's are 10, 15, 20 and 25 cm as subplot. The analysis of variance indicated highly significant differences in yield, yield components and CWP ($P < 0.01$). The highest tef grain yield of 3076.5 Kg/ha was obtained from the control with 25 cm row spacing which was not significantly different for the 85% ET_c with 20 cm ($P < 0.01$). In terms of irrigation and CWP, 55% ET_c deficit irrigation application with 25 cm row spacing gave the highest CWP which was highly significant different from all other treatment combinations ($P < 0.01$). The minimum (0.2) and maximum (0.93) yield response factor was obtained at 85% ET_c with 25 cm row spacing and 70 ET_c , respectively. This revealed, yield response factor (K_y) for tef was showed that there is yield reduction as crop stressed and row spacing minimize. The study suggests that, in water scarce area, farming community can adopt border irrigation with 85% ET_c under 25 cm row spacing without significant grain yield reduction. However, if there is enough amount of water, one can use with full irrigation under 25 cm row spacing.*

Key Words: *Border irrigation, Crop water productivity, Deficit irrigation, Tef, Row Spacing and grain yield.*

1. INTRODUCTION

1.1. Background

Water is the lifeblood of the planet, and the state of this resource affects all natural, social and economic systems. The ever-increasing world population and the demand for additional water supply by industrial, municipal, and agricultural sectors exert a lot of pressure on renewable water resources (Andarzian *et al.*, 2011; Valipour, 2014). Growing competition for water from domestic and industrial sectors is likely to reduce its availability for irrigation.

The coming challenge for the arid and semi-arid areas of the world could be food crop production due to limited availability of water resources. 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 and the population of Ethiopia has increased from 24 million in 1970 to 85 million in 2012 with population growth rate of 3.2% and an expected population of 145 million by 2050 (Awulachew *et al.*, 2010 and UNDP, 2011) and currently the population is estimated to be more than 90 million.

The economic basis of Ethiopia is rainfed agriculture. Agriculture produces the food to feed the country's population and it is the leading sector of Ethiopia's economy. Agriculture 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 labour pool for agricultural development. Despite this potential, 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 develop potential of 3.7 million hectares.(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 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 primary challenge in the near future and will include the employment of techniques and practices that deliver a more accurate supply of water to crops.

Tef (*Eragrotis tef*) 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 rainfed agriculture with very low (1 ton/ha) yield (CSA, 2011). Large area of land for tef cultivation is found in the moisture deficit zone of the country and the rainfall is highly variable and insufficient for tef 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 tef cultivation. As tef contributes a large proportion of cereal crop production in the country, solving the major problem of tef production is unquestionably one way of realizing food security of the country and solving the major problem of tef production is possible by developing and adopting irrigated tef cultivation. By using irrigation tef can be produced 2- 3 times per year and this in turn reduces poverty of the poor farmers whose livelihood's depends on rainfed tef production as well as food security of the country to be realized.

Low productivity of tef in Ethiopia is mainly attributed to lack of improved agronomic practices. Such as reduced seeding rate, transplanting in a row instead of broadcasting, and the use of complex fertilizers that contain essential macro- and micro-nutrients such as zinc and copper. Row planting one way should be in place to increase the productivity of the crop.

Deficit irrigation has been suggested as an alternative strategy for making better use of irrigation water. Deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield.

The study focused on the efficient utilization of the scarce water resource during the dry period to produce tef under irrigation using an appropriate water saving system. Specific deficit irrigation system was chosen in this study as a deficit irrigation (DI) strategy, since DI maximizes irrigation water productivity and optimizes crop yields (Geerts and Raes, 2009; Savic *et al.*, 2011; Nigus, 2013; David *et al.*, 2016)

1.2. Statement of the Problem

The economic basis and food source of fast growing Ethiopia's population is rain fed agriculture; however the rainfall is, 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 situation 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, tef 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 tef from year to year due to low crop 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 tef production in particular. Most of the fertile lands and manpower in tef producing areas of Ethiopia are idle for long periods out of the major rainy season due to lack of adopting irrigation systems such as border irrigation system for cereal food crops production particularly tef production.

Despite of the importance tef as a food crop in Ethiopia, there has been only limited research and studies were conducted on the performance of irrigated tef.

1.3. Objectives

General objective

The overall objective of the study was to evaluate the effect of deficit irrigation and row spacing on productivity of tef.

Specific objectives

- To evaluate the effects of deficit irrigation on growth, yield and water productivity of tef.
- To evaluate the effects of row spacing on growth, yield and water productivity of tef.
- To evaluate the interaction effect of row spacing and deficit irrigation on growth, yield and water productivity of tef.

1.4. Research questions

This study attempted to address the following scientific research questions:

- What is the optimum irrigation application level and Row spacing for tef?
- How surface irrigation is determined for the suitability of growing tef?
- What is the optimal row spacing in growing tef?

1.5. Significance of the study

The outcome of this study may serve as a source of additional information for farmers, policy makers and planners in design and implementation of good agronomic practices for better crop production and productivity. It will be provide as a base line for the researchers who want to conduct further study on the problem.

2. LITERATURE REVIEW

2.1. Water Resources Potential

Though water covers about two-thirds of the Earth's surface, it is a scarce resource as most of it is unavailable and too salty for use. Only 2.5% of the world's water is not salty, and two-thirds of that is locked up in the icecaps and glaciers. About 20% of the fresh water is not accessible, and much of it arrives at the wrong time and place, as monsoons and floods. Currently, less than 0.08% of all the Earth's water is available for human use. Nevertheless, of this small proportion of available water more than two-third is used for agriculture (FAO, 2000).

The growing world population and developing industries are today involved in a competitive struggle with the agriculture sector, the major water consumer compared to industries and municipalities (IWMI, 2000; Rijsberman, 2006). The ongoing process of global warming is thought to contribute to the destabilization of the world's weather systems, affecting people in drought prone regions and in areas susceptible to inundation (Vorosmarty et al., 2000). Contamination not only compromises the water quality and threatens the ecology and biodiversity of the ecosystem; it also lowers the available amount of water (Meinzen-Dick and Rosegrant, 2001).

Ethiopia has 12 river basins that provide an estimated annual run-off of 125 billion m³, with the Abay basins accounting for 45 percent of this amount. While much of this run-off could be used for irrigation or other purposes, Ethiopia has limited water infrastructure to use this surface water. The country has also, barely exploited its groundwater resources, especially for agriculture (Awulachew *et al.*, 2010). The preliminary estimated amount of yearly groundwater recharge of the country is about 28 billion m³ (MoWIE, 2014).

2.1.1. Water Scarcity

Increasingly water is a contested resource even in areas of the world that are relatively well endowed with water. The common perception is that water shortage (i.e. an absolute shortage of water supply in a specified domain) is the main reason for this state of affairs. However, the reality is that water scarcity, (i.e. an excess of water demand over available water supply) is by far the more important global challenge (FAO, 2012a).

Changing climate patterns will have important implications for water availability in Africa. According to the IPCC (2014), by 2030 an additional of 75 to 250 million people in Africa

are projected to be exposed to an increased water stress due to climate change. The most important pressure on renewable water resources is linked to the agricultural sector in which irrigation represent the maximum demands (Valipour, 2014).

Based on projections of the population growth and the increase in the standard of living, there are various views on the speed of increase in food production required to cope with the rapidly increasing mouths to be fed. The sector vision of Water for Food and Rural Development indicates the need for doubling the food production over the coming 25 years whereas the International Food Policy Research Institute suggests duplication in food production would be required in the forthcoming 50 years (Schultz, *et al.*, 2005). The food production principally depends on availability of water and an increase in production necessarily requires more water to be set aside for the agriculture sector. However, it is estimated that between 2000 and 2025, the global average annual water availability per capital will fall from 6,600 m³ to 4,800 m³. Besides, due to uneven distribution of water resources some 3 billion people will live in countries wholly or partially arid to semi-arid having less than 1,700 m³ per capita per year water availability. Countries or regions are broadly considered water stressed when the annual per capita availability is between 1,000 and 2,000 m³. With availability below 1,700 m³ per capita per year, a country is deemed 'water scarce'; with less than 1,000 m³ per capita per year, it becomes 'severe' (ICID, 2002). This fact about the availability of water could be among the reasons for the general consensus that exists among scholars that the major part of the increase in production (about 90%) would have to come from already cultivated land, among others, by water saving, improved irrigation and drainage practices, and increase in storages. The remaining 10% of the increase in food production would have to come from new land reclamations, either in the High lands or in the Lowlands (Van Hofwegen and Svendsen, 2000 and Schultz, *et al.*, 2005).

Ethiopia receives an average annual rainfall of 744 mm apparently adequate for food crop production, and pasture growth for livestock. However, the distribution of rain varies from region to region. Much of the eastern parts and countries like Somalia and Djibouti receive very little rainfall, less than 100 mm/year, while the Southwest highlands receive 2400 mm/year. In the Southern and Eastern highlands, there is a bimodal rainfall distribution, with the first and generally smaller rains peaking in April, and the second in September. The main dry season extends from October to February, being longer and drier in the North. Hence, production of sustainable and reliable food crops is almost impossible due

to temporal and spatial imbalance in the distribution of rainfall and the consequential non-availability of water in the required period. Intense rainfall sometimes causes flooding, particularly along the Awash River and in the Lower Baro Akobo and Wabe Shebelle river basins, causing damage to standing crops (Welderufael, 2006). Sometimes, even the Western highlands of the country suffer from food shortage owing to the discrepancies in the rainfall distribution (MoWIE, 2001).

2.1.2. Irrigated Agriculture

Agricultural production is the major user of the Earth's water resources and the water demand for this sector is increasing steadily with its root on population growth. These days about 70% of the available water we have on Earth is used for agriculture and by 2020 additional 17% more water is needed than is available now if we are to feed the world (Sleper *et al.*, 2007).

Although irrigation has an important role to play in contributing to food security and poverty alleviation, it covers only 17% of the world cultivated area and provides 40 to 45% of the world food and fiber supply (Evans and Sadler, 2008). The volume of water withdrawn for irrigation, globally, will increase from 2.6 billion km³ in 2005 - 2007 to an estimated 2.9 billion km³ in 2050 with most of the net increase occurring in lower income countries (Bruinsma, 2011). In Ethiopia, irrigation contributed approximately 5.7% to agricultural Gross Domestic Product (GDP) and 2.5% to the overall GDP during the 2005/2006 cropping season (Hagos *et al.*, 2009).

The efficiency of water use in most agricultural productions is low with poor management and improper designs of water application systems. Only part of agricultural water withdrawals is effectively used in the production of food or other agricultural commodities. According to FAO (1996), the crop effectively uses only 40 to 60% of the total applied water. The remainder of the water is lost in the system, and in the field, either through evaporation, runoff to the drainage system or by percolation into the groundwater. Perhaps that part of water lost can be recovered, but additional costs are needed to be incurred. As a step towards achieving the objective of more crops per drop of water, there is a need for irrigators to begin to adopt the use of techniques and practices that save irrigation water and minimize needless waste.

The use of efficient irrigated farming practices with the most economical exploitation of the water resources is an issue as far as irrigation water saving is concerned. Based on the

actual crop need, the irrigation management has to be improved so that the water supply to the crop can be reduced while still achieving a high yield (Pereira *et al.*, 2002).

2.1.3. Water Productivity

Concept of water productivity in agricultural production systems is focused on ‘producing more food with the same water resources’ or ‘producing the same amount of food with less water resources’. Water productivity (WP) mainly refers to the ratio between output derived from water use and the water input (volume or value of water depleted or diverted) (Clement *et al.*, 2011). The more commonly used concept of ‘water productivity’ and its measurement at various scales is a robust measure of the ability of agricultural systems to convert water into food. Increasing water productivity is particularly important where water is scarce compared with other resources involved in production (Drechsel *et al.*, 2015).

In crop production system, water productivity is used to define the relationship between crops produced and the amount of water involved in crop production, expressed as crop production per unit volume of water (Kassam and Smith, 2001). Usually, water productivity is defined as a mass (kg), monetary (\$) or energy (calorific) value of produce per unit of water evapotranspiration (Molden *et al.*, 2010), and, as such, it is a measure of the ability of agricultural systems to convert water into food.

According to Dang *et al.* (2001), the water productivity is defined in three different ways. The water productivity per unit of evapotranspiration (WPET) is the mass of crop production divided by the total mass of water transpired by the crop and lost from the soil. The water productivity per unit of irrigation (WPI) is the crop production divided by irrigation flow. The water productivity per unit of gross inflow (WPG) is the crop production divided by the rain plus irrigation flow. Water productivity with reference to evapotranspiration WPET takes into accounts only water evaporated or transpired and is therefore focused on plant behavior whereas WPI and WPG include not only ET but also water used in other ways for crop products and water that is wasted.

Increasingly water productivity is being flagged as an important issue in relation to global and regional food security (Molden *et al.*, 2010). A consequence is that attention formerly given to irrigation efficiency is being transferred to water productivity (Pereira *et al.*, 2012). Increasing the WP of irrigated and rainfed agriculture is thereby seen as the critical element in increasing agricultural production without major increases in fresh water

diversion to agriculture particularly in regions facing increasing water scarcity (FAO, 2012a).

2.1.4. Deficit Irrigation

The traditional irrigation development paradigm is based on providing sufficient water to avoid water deficits at all times, in order to achieve maximum yields (Doorenbos and Pruitt, 1992). Because of water supply constraints, this paradigm is changing nowadays (Bouman, 2007). Hence, the challenge for the coming decades will be the task of increasing food production with less water, particularly in countries with limited water, land resources and inefficient water use (FAO, 2002). Therefore, developments of new irrigation scheduling techniques, which are not necessarily based on full crop water requirement, are important.

Deficit (DI) is one of such strategies maximizing water use efficiency (WUE) for higher yields per unit of irrigation water applied. In this method, the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season with the expectation that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops (English and Raja, 1996).

According to Kirda (2002), deficit irrigation practices differ from traditional water supplying practices. The irrigation managers need to know the level of transpiration deficiency allowable without significant reduction in crop yield. The main objective of deficit irrigation is to increase the water productivity of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

In DI, the irrigation water requirement is not completely fulfilled, allowing the soil water to be depleted to a threshold, such that the crop experiences mild water stress. The crop response, which may or may not include a reduction in the rate of water use and/or yield reductions, depends on the degree of soil drying, the crop characteristics and the timing of the water deficit. It is generally thought that withholding water during the vegetative period, as opposed to the flowering or yield forming stages, has less impact on final yields (Loveys *et al.*, 2004).

The potential benefits of deficit irrigation are derived from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water (English *et al.*, 1990). The water saved by DI can be used to irrigate more land on the same farm or in the water user's community, which, given the high opportunity cost of water, and may largely compensate for the economic loss due to yield reduction (Kipkorir *et al.*, 2001; Ali *et al.*, 2007). In other words, DI aims at stabilizing yields and at obtaining maximum WP rather than maximum yields (Kazemeini and Edalat, 2011).

The main advantage of deficit irrigation is that it maximizes the productivity of water. Although a certain reduction in yield is observed, the quality of the yield (e.g. sugar content, grain size) tends to be equal or even superior to rain-fed or full irrigation (Cui *et al.*, 2008). An additional advantage is that DI creates a less humid environment around the crop than full irrigation, decreasing the risk of fungal diseases (Cicogna *et al.*, 2005). Related to the issues of individual and communal benefits, farmers might consider communal advantages of allowing sub-optimal yields on their individual yields, by practicing DI, so that the water saved might be used to irrigate additional land in the community (Kipkorir *et al.*, 2001). Compared to full irrigation, DI treatment saved 60% of water and increased irrigation water use efficiency (WUE) without tomato yield reduction (Savic *et al.*, 2011).

Many investigations have been conducted to gain experiences in irrigation of crops to maximize performances, efficiency and profitability. However, investigations in water-saving irrigation still are continued (Sleper *et al.*, 2007). In no water limited or even in water-limited areas farmers use full irrigation. In this method, crops receive full evapotranspiration requirements to result the maximum yield. Nowadays, full irrigation is considered a luxury use of water that can be reduced with minor or no effect on profitable yield (Kang and Zhang, 2004). However, the amount of irrigation reduction is crop-dependent and generally accompanied by no or minor yield loss that increases the water productivity (Ahmadi *et al.*, 2010). Deficit irrigation strategies would require an accurate assessment of growth stage-specific stress tolerances for crops (Upchurch *et al.*, 2005) and optimal water management supported by advanced irrigation systems; i.e., able to promptly cope with crop water requirements at sensitive phenological stages (Evans and Sadler, 2008). The proper application of deficit irrigation practices can generate significant savings in irrigation water allocation and full water requirement during the first two stages

of maize is not advisable if water shortage cannot be avoided during the remaining of the season especially during the mid-season stage (Yenesew and Ketema, 2009).

2.2. Crop Water Productivity under Deficit Irrigation

Water Productivity (WP) is generally defined in agronomy as the ratio of crop yield (usually economic yield) to water used to produce the yield. WP is a measure of the productivity of the water consumed by the crop. In areas with limited water resources, where water is the greatest limitation to production, WP is the main criterion for evaluating the performance of production systems (FAO, 2002).

One of the field-level methods for increasing water productivity is deficit irrigation, where deliberately less water is applied than that required to meet the full crop water demand. The prescribed water deficit should result in a small yield reduction that is less than the concomitant reduction in transpiration. Therefore, it causes a gain in water productivity per unit of water transpired. For deficit irrigations to be successful, farmers need to know the deficit that can be allowed at each of the growth stages and the level of water stress that already exist in the root-zone. When water is scarce, farmers could reduce the irrigation as appropriate to maximize returns to water if they have control over the timing and amount of irrigations (FAO, 2003).

Deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield (Mermoud *et al.* (2005). In this method, the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. The expectation is that any yield reduction (especially in water-limiting situations) will be compensated by increased production from the additional irrigated area with the water saved by deficit irrigation (Ali *et al.*, 2007).

Samson and Ketema (2007) indicated that deficit irrigation increased the water use efficiency of onion from 6% by stressing the crop during the initial stage to 13% by partially stressing the crop at 75% of crop evapotranspiration compare to the optimum application throughout the growing season. WP decreased with increasing water application level from 50 to 100% ET_c (David *et al.*, 2016). Similarly, Shock *et al.* (1998) and Kebede (2003) reported that irrigation water use efficiency was higher at the irrigation treatment of 50% available soil moisture than at 25% or 75% available soil moisture. On the contrary, high water use efficiencies were observed with increasing level of irrigation, or no irrigation in the vegetative period (Kadayifci *et al.*, 2005). Genetic variation among

genotypes within the same plant species has been documented, suggesting that WP is under genetic control (Yoo *et al.*, 2009).

Deficit irrigation has been widely investigated as a valuable and sustainable production strategy in dry areas. By limiting water applications to drought-tolerant growth stages or throughout the growth period, this practice aims to maximize water productivity and to stabilize rather than maximize yields. Research results confirm that deficit irrigation is successful in increasing water productivity for various crops without causing severe yield reductions. Nevertheless, a certain minimum amount of seasonal moisture must be guaranteed (Geerts and Raes, 2009).

2.3. Crop Yield Response Factors (Ky) under Deficit Irrigation

The yield response factor (Ky) defined as the decrease in yield with respect to the deficit in water consumptive use (ET). Drought tolerance varies considerably by genotype and phenological stage, so it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season (Kirda and Kanber, 1999). When water deficit occurs during a specific crop development period, the yield response can vary depending on crop sensitivity at that growth stage. Therefore, timing the water deficit appropriately is a tool for scheduling irrigation where a limited supply of water is available (FAO, 2002).

Doorenbos and Kassam (1999) formulated the relationship between the relative yield decreases produced by relative evapotranspiration deficit in a given irrigation scheduling protocol. The formulation relates four parameters (Ya, Ym, ETa and ETm) to a fifth: Ky, the yield response factor.

$$1 - \frac{Y_a}{Y_m} = K_y \left[1 - \frac{ET_a}{ET_m} \right] \quad (2.1)$$

Where: Ky is yield response factor, Ya is the actual yield (t/ha), Ym is the maximum yield (t/ha), ETa is actual crop water consumptive use (mm), ETm is the maximum crop water consumptive use (mm), $(1 - \frac{Y_a}{Y_m})$ is the decrease in relative yield and $(1 - \frac{ET_a}{ET_m})$ is the decrease in relative crop water consumptive.

FAO and International Atomic Energy Agency (IAEA) research coordinated group studied yield responses of major field crops to deficit irrigation, including cotton, maize, potato, sugar cane, soybean and wheat (FAO, 2002). The Ky values obtained from FAO data sets

and from an IAEA coordinated research project (CRP) showed a wide range of variation for this parameter $0.20 < k_y < 1.15$ (FAO, 2002), and $0.08 < k_y < 1.75$ (IAEA). However, for many other crops FAO recommendation of K_y values are more reliable and practical. Accordingly, they reported yield response factor (K_y) value of 1.1 for onion under deficit irrigation during the whole growing season (Doorenbos and Kassam, 1999).

Crop yields obtained under various levels of reduced evapotranspiration were fitted to the linear crop yield response function and showed that cotton, maize, wheat, sunflower, sugar beet and potato are well suited to deficit irrigation practices, with reduced evapotranspiration imposed throughout the growing season. This list may also include common bean, groundnut, soybean and sugar cane where reduced evapotranspiration is limited to a certain growth stage(s). With a 25 percent deficit, WUE was 1.2 times that achieved under normal irrigation practices (Kirda, 2002).

Crop yield response factor varies depending on species, variety, irrigation method and management, and growth stage when deficit evapotranspiration is imposed. The crop yield response factor gives an indication of whether the crop is tolerant of water stress. A response factor greater than unity indicates that the expected relative yield decrease for a given evapotranspiration deficit is proportionately greater than the relative decrease in evapotranspiration (Kirda *et al.*, 1999).

2.4. Irrigated Agronomy of Tef

Tef (*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 tef. Tef 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 tef (Berhe, 2012). Irrigation is normally required frequently following seeding and until the roots are established at two to three weeks. 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, Tef 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 tef seed necessitates light, frequent irrigations for establishment. Once roots are established, (Norberg *et al.*, 2009), recommended to irrigate tef 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 tef 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 tef, 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 tef 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, tef 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), Tef appears to be most productive in regions having at least 24 inches of rainfall, or supplemental irrigation and it is estimates that, Tef requires approximately 50 to 70% as much water as alfalfa to produce an economic crop. Due to the short growing season, tef uses less irrigation water than any other crops. The primary water savings possible with tef production is related to the relatively short growing season as compared to alfalfa and less irrigation. However, determining the appropriate level of irrigation for tef 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).

2.4.1. Tef planting

It has been argued recently that low tef productivity is partly caused by the way farmers sow tef seed. Traditionally, farmers broadcast the seed using a rate of 25–50 kg per hectare (ATA 2013a). This practice reduces yields because of the uneven distribution of the seeds, higher competition between plants for inputs (water, light and nutrients), and difficult weeding once the plants have matured (Fufa *et al.* 2011). As a solution, it has been proposed to reduce seed rates and to plant seed in rows. Reducing the seed rate to between 5 and 10 kg per hectare allows for reduced competition between seedlings and optimal

tillering of the Tef plants. By row planting, land management and especially weeding can also be done more readily and the incidence of lodging is reduced (Berhe et al. 2011, Chanyalew and Assefa 2013).

Row planting over broadcasting because it increased the number of plant tillers, produced stronger and fertile tiller culms, and the number of seeds per panicle increased (Berhe et al. 2011). Since, Tef improved seed, reduced seed rate and row planting (*TIRR*) package (ATA, 2014) is a new breakthrough in the country and also there is a blanket recommendation of row spacing (20 cm) by Ministry of Agriculture for all tef varieties that have different growing habit and characteristics for different agro ecologies and soil types, the agronomic components like row spacing and seed rate for different varieties should be optimized. The blanket row spacing has limitation on the productivity of tef which is influenced by the fertility status of the soil, climate and yield potential of specific variety. Different research findings recommended different row spacing of tef Variety. Tareke & Nigusse (2008) and Alemat *et al.* (2016) recommended a row spacing of 20 cm, while Fekeremariam *et al.* (2014) concluded that the row spacing of 15 cm, on the other hand the row spacing of 15-30 cm for transplanting and drilling of growing Tef to enhance its productivity (Amare and Adane, 2015). Moreover, there is a trend by farmers use broadcasting and there is not clear recommendation of row spacing to tef seed for different varieties and climate. However, limited research has been done to evaluate appropriate row spacing of tef in the study area. Therefore, this study was initiated with the following objectives: To evaluate the effect of row spacing on yield and to determine the appropriate row spacing for maximum productivity of tef.

2.5. Soil Moisture Measurement

The growth and yield of any crop is mostly related to the amount of water used. The variable amount of water contained in a soil and its energy state are important factors affecting growth of plants (Hillel, 2004). Moreover, according to Hansen, *et al.* (1979) in irrigated regions the capacity of the soil to store available water for use of growing crops is of special importance and interest, because the depth of water to apply in each irrigation and the interval between irrigation are both influenced by storage capacity of the soil. Therefore, it is possible to assess the soil moisture status in the field through taking samples of the soil at different depths in the root zone. In good irrigation practice the soil moisture content over the root depth is checked before irrigation and then again after irrigation to determine if the water has penetrated the full depth of the root zone but not

deeper. Checking the soil moisture status before and after irrigation provides the farmer with valuable information on the amount of water to apply for each irrigation and helps to reduce wastage through over-irrigation. To check the depth of penetration the soil samples at different depths should be taken 1 to 3 days after irrigation, as the water takes time to percolate through the soil horizon (Burton, 2010).

Soil water content can be measured directly or indirectly. In the first case, the amount of the water is directly measured, for instance, by measuring its weight as a fraction of the total soil weight (gravimetric method).

Gravimetric measurement is a direct method; and it is the reference method for soil water content (SWC) measurement. It is based on the weight measurement of a wet sample before and after oven drying at 105°C for 24 hour (Evelt *et al.*, 2008). The difference in weight is expressed as fraction of the soil solid weight, called gravimetric water content. This quantity can be expressed as volume fraction, by multiplying the gravimetric water content by the bulk density of the sample and dividing by the density of liquid water. When the gravimetric measurement is performed for calibration of other SWC sensors, it is important to measure the sample bulk density for conversion into the volumetric form.

However, this measurement method usually is destructive since the soil sample is removed from the field to be analyzed in the laboratory. Moreover, it is a time-consuming way of measuring soil water content. Because of these limitations, varieties of indirect measurements have been developed (Bittelli, 2011).

An indirect method measures another variable that is affected by the amount of soil water, and then it relates the changes of this variable to the changes in soil water content, through physically based or empirical relationships called calibration curves. For instance, the dielectric sensors exploit the changes in soil dielectric properties as function of soil water content; the neutron scattering technique is based on the loss of high-energy neutrons as they collide with other atoms, in particular hydrogen contained in the water molecules. Although the direct gravimetric method is the reference method for SWC measurement and commonly used for indirect methods calibration, the majority of the commercial sensors are based on indirect methods (tensiometer, resistivity measurement, neutron scattering, measurement of thermal properties, time domain reflectometry (TDR) and others) (Bittelli, 2011).

2.6. Crop Water Requirement and Irrigation Scheduling

With increasing scarcity and growing competition for water, judicious use of water in agricultural sector will be necessary. This means that exact or correct amount and correct timing of application should be adopted. In addition, it will need more widespread adoption of deficit irrigation, especially in arid and semi-arid regions (Ali, 2010).

2.6.1. Crop water requirement

The total crop water requirement is the maximum amount of water that a crop can use productively when the soil water content is not limiting (Brouwer and Heibloem, 1986). Crops mainly need water for cooling purposes; most of the root's water uptake is released back to the atmosphere through transpiration, and only a negligible fraction is retained for crop growth. In field experiments, partitioning transpiration from soil water evaporation is difficult. Therefore, in practice, evapotranspiration (ET) is measured or calculated. Evapotranspiration is the combination of two separate processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration (Allen *et al.*, 1998). Therefore, "crop evapotranspiration" and "crop water requirement" are terms used interchangeably (Schneekloth and Andales, 2009).

Crop water requirement (CWR) is defined as the amount of water required to compensate the evapotranspiration loss from a cropped field. In cases where all the water needed for optimal growth of the crop is provided by rainfall, irrigation is not required and the Irrigation Water Requirement (IWR) is equal to zero. In cases where all water has to be supplied by irrigation the IWR is equal to the CWR. However, when part of the CWR is supplied by rainfall and the remaining part by irrigation, the IWR is equal to the difference between the crop evapotranspiration (ET_c) and the Effective Precipitation (P_{eff}) (Allen *et al.*, 1998).

The water requirements are different from one crop to another. Although growing crops are continuously using water, the rate of water use depends on (1) the kind of crop, (2) the degree of maturity and (3) atmospheric condition, such as radiation, temperature, wind, and humidity. The rate of growth at different soil water contents varies with different soils and crops. During early stages of growth, the water needs are generally low, but they increase rapidly during the maximum growing period to the fruiting stage. During the later stages of maturity, water use decreases as the crops ripen (Schwab *et al.*, 1995).

2.6.2. Crop Coefficients and Crop Water Requirement of Irrigated Tef

The value of KC 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, Kc ini 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 Kc 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 Kc of 0.6 for irrigation of warm-season grasses. This become a widely accepted value for irrigation of warm-season grasses, however, more recent studies have indicated higher Kc values may more accurately reflect warm-season grass water use. Allen et al., (1998) recommended a Kc value of 0.80 to 0.85 for irrigating warm-season grasses. According to (Yihun, 2015), the overall average tef Kc 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, Tef crop evapotranspiration (ETc) 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 ETc value obtained for Barley (Araya et al., 2011), but is comparable to that of Millet, which is 330 mm (Grema and Hess, 1999).

Tef (Eragrostic Tef) crop coefficient for effective irrigation planning and management.

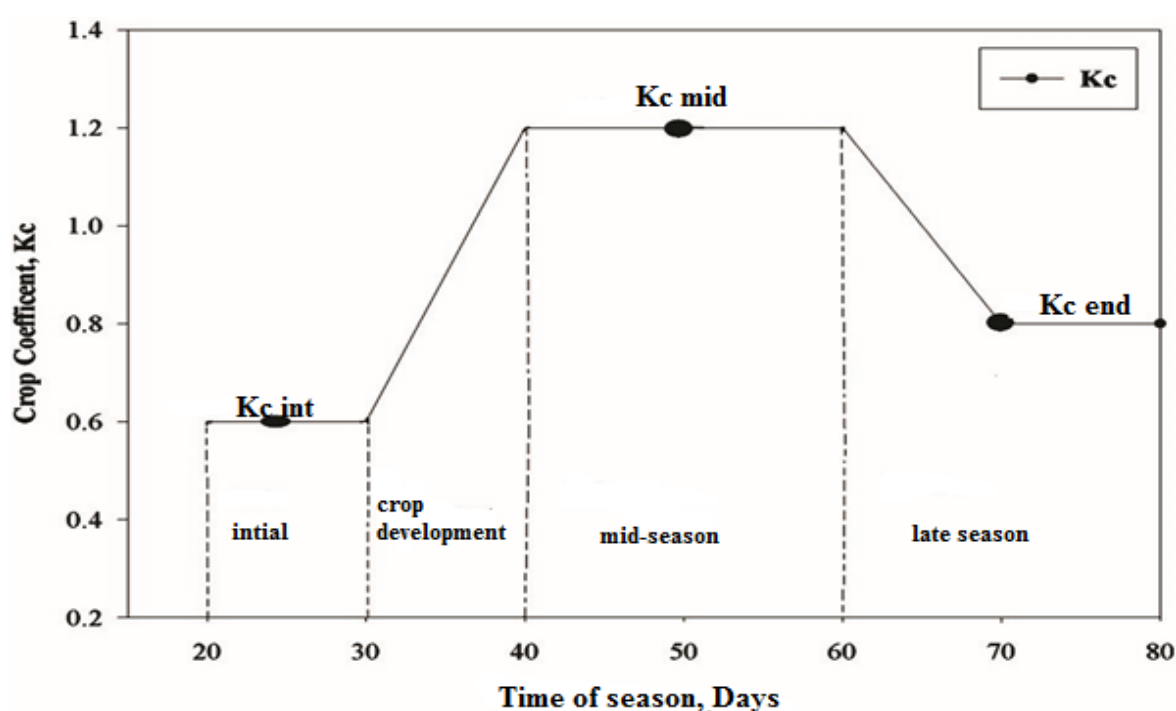


Figure 2.1. Average Kc values

Table 2.1. Crop coefficient (Kc) values of Barley, Millet and Teff grown under irrigation

Crop	Initial	Developmental	Late season	Midseason	Source
Barley	0.3	0.75	1.05-1.2	0.25-0.4	Doorenbos and kassam, 1979Allen et al., 1998;
Millet	0.3	0.75	1.05-1.2	0.3-0.4	Doorenbos et al., 1994; Allen et al., 1998
Teff	0.6	0.8	1.1	0.8	Yihun, 2015

2.6.3. Irrigation scheduling

The goal of irrigation scheduling is to determine how to supply crops with the correct amount of water at the appropriate time. Irrigation scheduling involves preventing the soil water deficit from falling below some threshold level for a particular crop and soil condition. This may involve estimating the earliest date to permit efficient irrigation or the latest date to avoid the detrimental effects of water stress on the crop (Ritchie and Johnson, 1990). Scheduling water application is very critical to make the most efficient use of irrigation system, as excessive irrigation reduces yield, while inadequate irrigation causes water stress and reduces production. Establishing irrigation scheduling requires knowledge about availability of water supply, crop water use or evapotranspiration (ET), irrigation and effective rainfall, soil water-holding capacity and current available soil moisture

content. This information is the main factor to decide when to apply water and how much water to apply. This often results in lower energy and water use and optimum crop yield, and increases irrigation efficiency. The amount of water applied is determined by using a criterion to determine irrigation need and a strategy to prescribe how much water to apply in any situation. The most common irrigation criteria are soil moisture content and soil moisture tension. The critical soil water content can be found at different level. For many crops irrigation should start when soil water content drops below 50 % of the total available soil moisture (Hoffman *et al.*, 1990).

Irrigation scheduling techniques can be based on soil water measurement, meteorological data or monitoring plant stress. Conventional scheduling methods are to measure soil water content or to calculate or measure evapotranspiration rates. The water content way may be more practical and easy to use (Hanson *et al.*, 2000). The successful irrigation scheduling requires good understanding to the knowledge of soil water holding capacity, crop water use, and crop sensitivity to moisture stress at different growth stages. This requires consideration about the effective rainfall, and availability of irrigation water (Waskom, 1994).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

The study was conducted at Melkassa Agricultural Research Center experimental site during 2018 dry season. The area is situated in the Central Rift Valley of Ethiopia. It is geographically located between latitude of 8°24' to 8°26' N, longitude of 39°19' to 39°21' E and the mean altitude of the area is 1550 m.a.s.l (Figure 3.1). It is located about 107 km to the East of Addis Ababa, capital city of Ethiopia and 17 km Southeast of Adama. Loam and clay loam soil textures are the dominant soils of the area, which is classified as Lithosols with pH of 7.

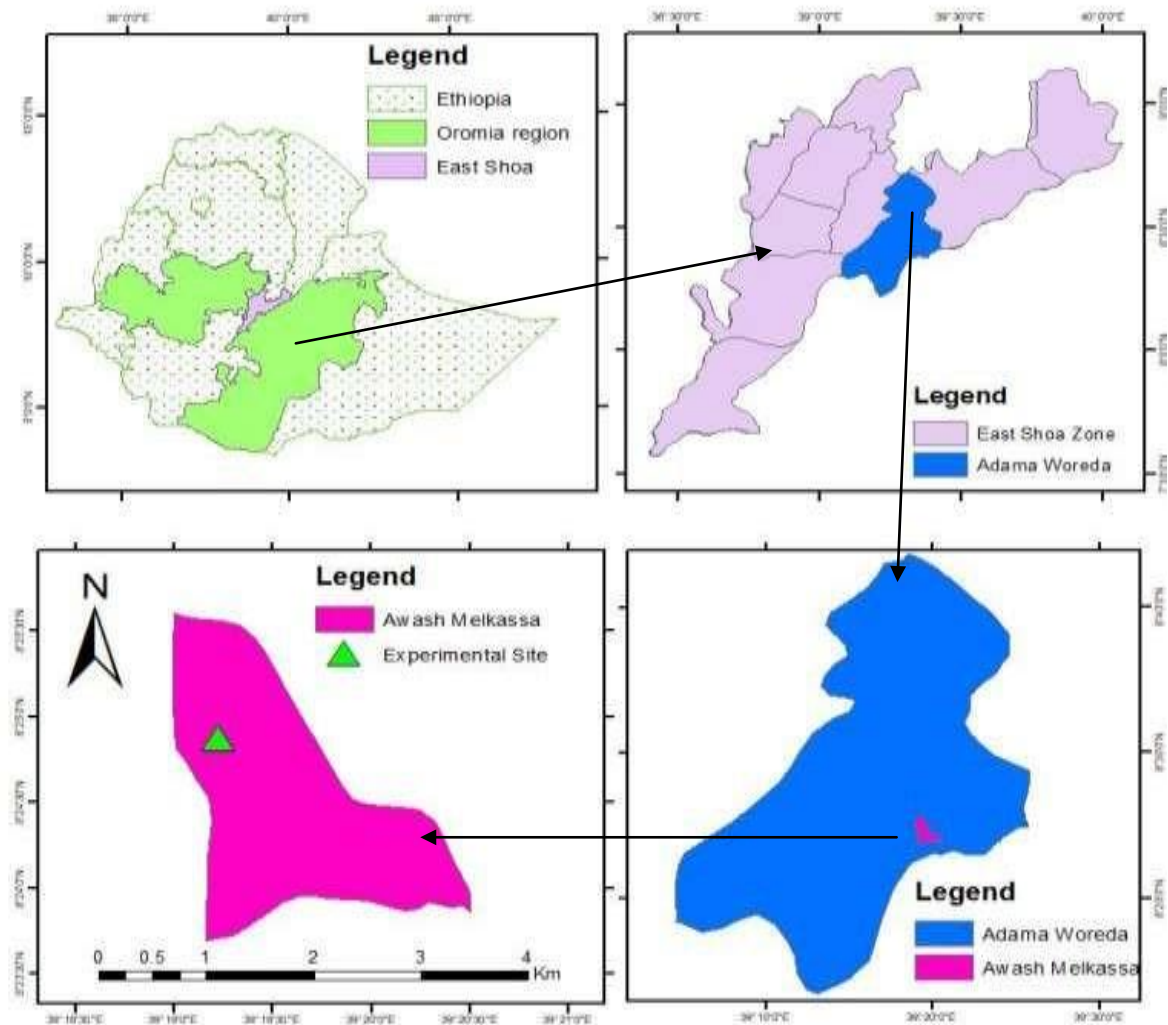


Figure 3.1: Map of the study area

3.1.1. Climate

Long-term (1977 – 2017) climatic record of Melkassa agro-meteorological observatory station, average annual rainfall in the area is 824.9 mm. The climate of the area is characterized as semi-arid with low and erratic rainfall pattern. Kiremt season have got more rainfall about 67.4% of the total rainfall of the area occurs from June to September, with peak month of July and August. The mean maximum and minimum monthly rainfall is 204.2 mm and 9.6 mm occurs in the month of August and November, respectively. The mean maximum temperature varies from 26.3 °C to 31.0 °C while the minimum temperature varies from 10.4 °C to 16.4 °C, with the average of 21.3 °C.

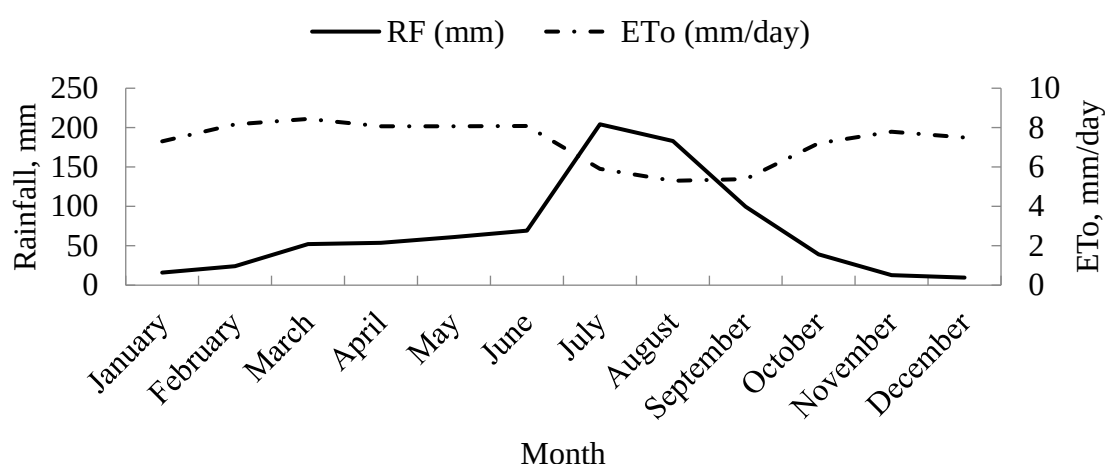


Figure 3.2: Long-term monthly climatic water balance data of the study area

3.1.2. Agronomic practice

Farmers in the area grow crops three times a year of which two using traditional furrow irrigation during cool (September to January) and hot (February to May) seasons and the other during wet/ the rainy season (June–September) using irrigation during cool and hot season and rainfall with supplemental irrigation during wet season. The crops grown include pepper, tomato, onion, potato, haricot beans, sweet potato, papaya, wheat, maize and tef. Most of the time, vegetable crops grow during dry season and cereal crops during rainy season (Scholten, 2007). The source of irrigation water in the study area is Awash River that serves 27% of the total irrigated agriculture of the country (Zemedu, 2011). The dominant soil group of the study area is Andosol, which is made up volcanic rocks called deposit pumice. The textural classification mainly varies from clay to clay loam (Ham, 2008).

3.2. Soil Physical and Chemical Characteristics

3.2.1. Soil sampling

Composite soil samples were collected from three location of the experimental field at 15 cm soil depth interval up to 60 cm (0 – 15 cm, 15 – 30 cm, 30 – 45 cm and 45-60 cm) for soil physico-chemical property analysis.

Undisturbed soil samples were also collected for bulk density determination using core sampler having a volume capacity of 98.125 cm³ for every 15 cm soil depth up to 60 cm.

3.2.2. Soil physical characteristics

Soil texture

The hydrometric method was used to identify the particle size distribution of sand, silt and clay content from soil sample collected. The textural class of the soil was determined using USDA textural triangle (USDA, 1975).

Bulk density

For the determination of bulk density, undisturbed soil samples were collected and oven dried for 24 hours at a temperature of 105⁰C. It was then computed using the following equation as stated by Michael (1978).

$$\rho_b = \frac{W_d}{V_s} \quad (3.1)$$

where, ρ_b is the bulk density of the soil in g/cm³, W_d is the weight of oven dry soil in gram and V_s is the volume of same soil sample in cm³.

Field capacity (FC) and permanent wilting point (PWP)

The FC and PWP were determined using pressure plate and pressure membrane apparatus, respectively. Soil samples were saturated for one day (24 hours) and a pressure of 1/3 bar and 15 bar were exerted, respectively for FC and PWP, until no water droplets detected.

Soil infiltration rate

The infiltration rate of the soil in the experimental field was determined using double ring infiltrometer before the experimental work was started. The field test was set up at three locations. Drop in water level in the inner ring was recorded from the measuring ruler attached to inner ring. The level of water was brought back to approximately the original level maintaining the water level outside the ring similar to the inside whenever the level

of water drops to a level that may not guaranty for next reading. Readings were taken frequently at the beginning of the test, but with extended interval between readings as the time goes on until the drop in water level over equal time interval remains the same.

3.2.3. Soil chemical characteristics

The soil pH was determined by measuring soil solution of 1:2.5 ratios (soil to water) with a pH meter using combination glass electrode as described by Jackson (1958). The percentage of organic carbon (OC) was determined following the wet digestion method as described by Walkley and Black (1934). OM content was then determined by multiplying OC by 1.724 (Nelson and Sommers, 1996). Electrical conductivity of the irrigation water and the soil was determined using electrical conductivity meter (EC meter).

3.3. Treatments and Experimental Design

The treatments include four row spacing's and four irrigation levels. The four strip spacing's are 10 cm, 15 cm, 20 cm and 25 cm and the four irrigation levels are 100% ET_c, 85% ET_c, 70% ET_c and 55% ET_c of the requirement. The experimental deign was split plot in RCBD with three replications (Figure 3.1), in which the four Row spacing were used as main-plot and the four irrigation applications were used as sub plot.

The experiment was having twelve treatment combinations with 48 plots. Each experimental plot was having 5 m length, 3 m width (3.0 m x 5.0 m) with 1 m free space between plots, 1.5 m between blocks. The individual fields were separated from each other by means of soil bunds.

Table 3.1. Experimental treatment combinations

Sub plot (Irrigation level, I)	Main plot, (Row spacing, S, cm)			
	S ₁ (10 cm)	S ₂ (15 cm)	S ₃ (20 cm)	S ₄ (25cm)
I ₁ (100% ET _c)	T ₁	T ₅	T ₉	T ₁₃
I ₂ (85% ET _c)	T ₂	T ₆	T ₁₀	T ₁₄
I ₃ (70% ET _c)	T ₃	T ₇	T ₁₁	T ₁₅
I ₄ (55% ET _c)	T ₄	T ₈	T ₁₂	T ₁₆

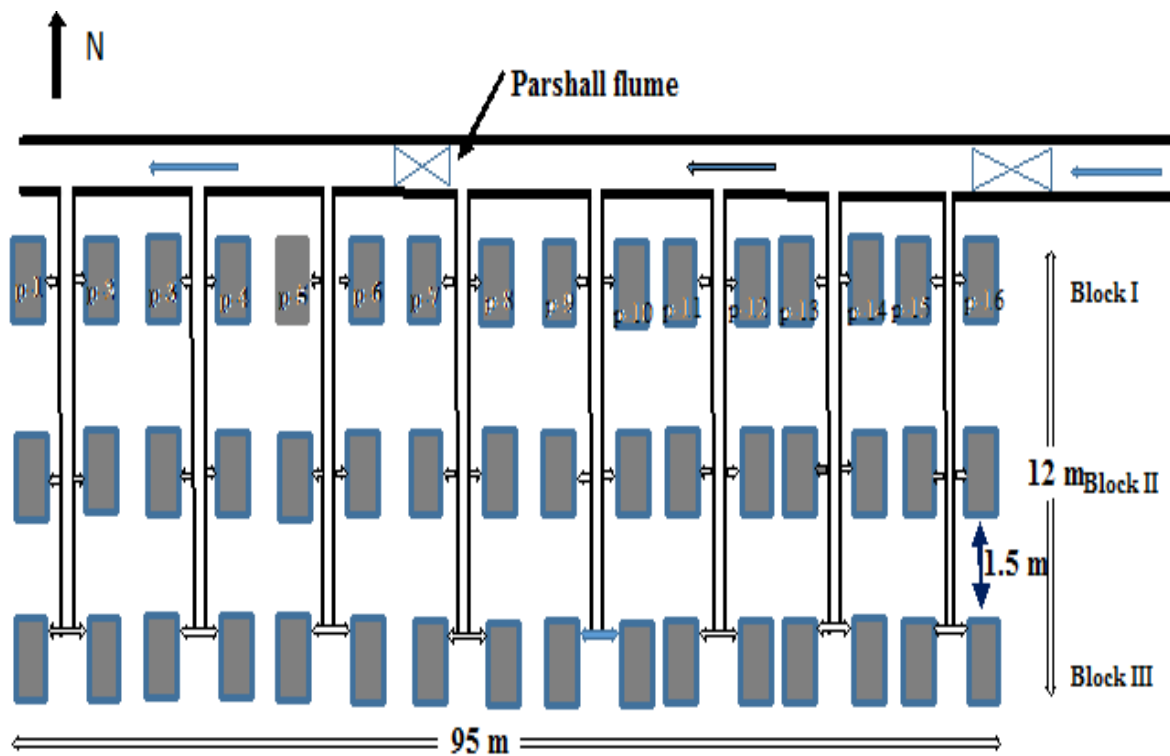


Figure 3.3. Experimental field layout

3.4. Crop Management Practices

The field experiment was carried out during cropping season of 2018 and land preparation were done using tractor driven disk plough and human labour forces for finishing and seedbed preparation. The experimental plots were pre-irrigated before three days to sowing. Tef variety Dz-Cr-409 (Boset) were seeded on well prepared experimental field plots. The variety selected was because of its acceptance by local farmers, high yield performance and disease resistance.

Two common irrigation was applied to all plots for the better plant establishment. Water applications for full irrigation treatments (100% ETc) was based on difference between the estimated crop water requirement and effective rainfall. The rest treatments received 85%, 70%, and 55% of the 100% ETc application. The 100% ETc depth of irrigation water was based on allowable soil moisture depletion/ depletion fraction (p) for cereal crops (Allen et al., 1998). Hence, the p-value for tef was assumed to be 0.55 of the total available soil water (FC – PWP) within the effective root depth of the crop. Each plot were irrigated using a measuring device Parshall flume.

The crop growing season of Tef (*Eragrostic tef*) were divided into four major growth periods: initial stage, development stage, mid-season stage and late season stage. The length of each crop growth stages were divided based on (Allen et al., 1998).

All cultural practices other than treatment variables were standard practices recommended for the area. Weeding and cultivation were performed by hand when deemed necessary. The recommended rate of 100 kg/ha DAP and 100 kg/ha urea was uniformly applied to the plots. DAP was applied at planting time only whilst urea was applied in split application, half at planting and another half during tillering stage (EIAR, 2007). Diseases and pests management were made as per the recommendation of agronomist at the research Centre.

3.5. Soil Moisture Measurement

The quantity of water contained in a soil called soil moisture which was measured gravimetrically for experimental plots before and after irrigation. The soil samples were collected at 15 cm interval for the first two soil depth and at 30 cm interval thereafter for the remaining effective root depth of the crop for gravimetric soil moisture analysis. The gravimetric water content of the soil expressed in weight basis is: (Cuenca, 1989).

$$\theta_w = \frac{w_w - w_d}{w_d} \quad (3.2)$$

Where, θ_w is the soil water content (g/g), w_w is the weight of wet soil sample (g) and w_d is the dry weight of the soil sample (g). The gravimetric soil water content expressed in volume bases (θ_v) is:

$$\theta_v = \theta_w * \frac{\rho_b}{\rho_w} \quad (3.3)$$

Where, θ_v is volumetric moisture content in (cm^3/cm^3); ρ_b is soil bulk density (g/cm^3), and ρ_w is water density (g/cm^3).

The volumetric moisture content was also converted to equivalent depth by multiplying with the root depth considered.

$$d \text{ (mm)} = \theta_v * \text{drt (mm)} \quad (3.4)$$

Where; d is equivalent depth (mm), drt is the root depth (mm), θ_v is volumetric moisture content (cm^3/cm^3).

3.6. Irrigation Water Management

The depth of water that can be extracted by plant roots is held in the soil in an ‘available’ form. The actual depth of water that can be obtained from the soil profile depends on the depth of the root system. Not all of the water found in the root zone will actually be taken up by roots. The total available water (TAW), stored in a unit volume of soil, was computed from the moisture content of field capacity and permanent wilting point and expressed as:

$$TAW = ((\theta_{Fc} - \theta_{Pwp}) * Dzr) * \frac{BD}{100} \quad (3.5)$$

Where, FC and PWP in % on weight basis; Dzr is the maximum effective root zone depth in mm and BD is the soil bulk density, (g/cm³).

For maximum crop production, the irrigation schedule was fixed based on readily available soil water (RAW). The RAW is the amount of water that crops can extract from the root zone without experiencing any water stress. The RAW was computed using the following equation:

$$RAW = P * TAW \quad (3.6)$$

where, RAW in mm, p is the depletion fraction no stress and TAW is total available water in mm.

The soil moisture depleted at any time was computed from the expression:

$$SMD = (\theta_{FC} - \theta_{SMC}) \times \frac{\rho_b}{\rho_w} \times D_z \quad (3.7)$$

where, SMD is the depth of soil moisture depleted at time of moisture testing in mm; θ_{FC} is soil moisture contents at FC in g/g; θ_{SMC} is soil moisture content at time of moisture testing in g/g, ρ_b is the bulk density of the soil and ρ_w is the density of the water in g/cm³, and D_z is the maximum effective root zone depth at times of sampling (mm).

The depth of irrigation supplied at any time was obtained from a simplified water balance equation which is expressed as:

$$IRn = ETc - P_{ef} \quad (3.8)$$

Where, IRn is the net irrigation depth (mm); ETc is the crop water requirement (mm) and P_{ef} is the effective rainfall (mm) which is a part of rainfall that enters in to the soil and

makes available for crop production. The effective rainfall will be estimated using dependable rain method as given by (Allen *et al.*, 1998) as.

$$P_{ef} = 0.6 * P - 10 \quad \text{for } P(\text{monthly}) \leq 70 \text{ mm} \quad (3.9)$$

$$P_{ef} = 0.8 * P - 24 \quad \text{for } P(\text{monthly}) > 70 \text{ mm} \quad (3.10)$$

Where, P_e is the effective rainfall (mm) and P is the monthly rainfall (mm).

The gross irrigation requirement was computed by adopting a field application efficiency of 60% (FAO, 1989). According to Raine and Bakker (1996), border irrigation application efficiencies normally vary from 45-60%. In this experimental setup, water was applied with precise measurement; border were short and end-diked. As a result, there was no run-off and no deep percolation. Therefore, a higher value of application efficiency (60%) was adopted and used in the following equation:

$$IRg = \frac{IRn}{E_a} \quad (3.11)$$

Where, IRg is the gross irrigation depth (mm) and E_a is the field application efficiency (%).

The determined amount of irrigation water applied to the plots was measured using a 3 inch parshall flume installed at the upper stream near the experimental field. Accordingly, the time required to deliver the desired depth of water into each plot was calculated using the equation below.

$$T = \frac{(IRg * W * L)}{(60 * q)} \quad (3.12)$$

where, IRg is gross depth of water applied in mm; W and L is plot width and length of the experimental plot in m; T is application time in min and q is flow rate in l/s.

Irrigation interval was computed using the equation below.

$$I = \frac{RAW}{ET_c} \quad (3.13)$$

where, RAW is readily available water is mm; I is irrigation interval (days) and ET_c is Crop water requirement in mm/day.

3.7. Data collection

3.7.1. Water productivity

Water productivity (WP) in this study was determined by dividing yield to the net amount of irrigation water used by the crop as indicated by the following equation (Heydari, 2014)

$$WP = \frac{Y}{WA} \quad (3.14)$$

Where, WP is water productivity in Kg/m³, Y is yield per unit area in Kg/ha and WA is net water used to produce the grain yield of tef in m³/ha.

3.7.2. Yield response factor

The yield response factor was calculated according to the procedure mentioned by Doorenbos and Kassam (1979) as follows:

$$1 - \frac{Y_a}{Y_m} = K_y \left[1 - \frac{ET_a}{ET_m} \right] \quad (3.15)$$

where, K_y is yield response factor; Y_a is the actual yield obtained in t/ha; Y_m is maximum yield obtained in t/ha; ET_a is the actual crop evapotranspiration in mm and ET_m is the maximum crop evapotranspiration in mm.

Crop physiological data

Crop physiological data collected were plant height, number of tiller and lodging percentage.

3.7.3. Plant height

Plant height was measure in every ten days interval from the tagged sample plants of each experimental plot. The height of plant was measured the main stem from the soil surface up to its tip. This measurement taken when the tef pods were matured. All measurements make on representative plants recorded and the average height of a group of plants from each treatment use to compare effects.

3.7.4. Grain yield and yield component data

Grain yields were measured after maturity from samples of an area of 5.0 x 3 m² in each plot. The crop were harvested manually. The grain and total biomass fresh weight were weighted at maturity and then dry and weighted on a sensitive balance. Finally the yield per plot were convert to yield in quintals per hectare (q/ha).

3.8.Statistical Analysis

The collected data were subjected to statistical analysis of variance appropriate to split plot design using SAS software version 9.0 for windows. Whenever treatment effects were found significant, treatment means were compared using the least significant difference (LSD).

4. RESULTS AND DISCUSSION

The response of tef to different deficit irrigation application and row planting under border irrigation systems are presented and discussed in the following sub sections.

4.1. Soil Properties of Experimental Site

Some of the physical and chemical properties of the soil on experimental site such as texture, bulk density, field capacity, permanent wilting point, infiltration, pH, EC, organic matter content, organic Carbon and total Nitrogen were analyzed and summarized (Table 4.1 and 4.2).

4.1.1. Soil Physical properties

Physical soil properties analysis showed that the average composition of clay, silt and sand percentages were 26.5, 40 and 33.5, respectively. Thus, according to the USDA soil textural classification, the particle size distribution of experimental site revealed that the soil textural class is loam soil which is suitable for tef.

The bulk density result shows that slight increase with depth. It varied from 1.06 g/cm³ at the upper root zone (0-15 cm) to 1.26 g/cm³ at the lower root zone layer (45-60 cm). This could be because of slight decrease of organic matter with depth and compaction due to the weight of the overlying soil layer (Brady and Weil, 2002). The average weighted bulk density of the experimental site was 1.16 g/cm³.

Observed average soil moisture content on weight base at FC was shows variation within depths of 0-15, 15-30, 30-45 and 45-60 cm were 33.8, 36.5, 39.3 and 37.7%, respectively. The observed soil moisture content on weight base at PWP was also showed a variation within depths 0-15, 15-30, 30-45 and 45-60 cm were 20.8, 21.1, 23.5 and 22.9%, respectively. Average moisture content on weight base at FC (1/3 bar) and PWP (15 bar) of tef root depth were 36.8% and 22.1%, respectively. The total available water (TAW) that is the amount of water that a crop can extract from its root zone was directly related to variation in FC and PWP. The observed TAW was also showed a variation within depths of 0-15, 15-30, 30-45 and 45-60 cm were 20.7, 26.6, 28.2 and 28.0 mm, respectively. Volumetric TAW was 103.4 mm with the tef root depth of 0.6m and readily available water, with optimum depletion level of 25%, was calculated as 25.8 mm.

Table 4.1: Analysis of physical properties of soil of experimental site

Soil Physical Properties								
Soil depth (cm)	Particle size distribution			Textural class	Bulk density (g/cm ³)	FC mass base (%)	PWP mass base (%)	TAW volume base (mm)
	Clay (%)	Silt (%)	Sand (%)					
0-15	26.5	45.0	28.5	Loam	1.06	33.8	20.8	20.7
15-30	24.0	42.5	33.5	Loam	1.15	36.5	21.1	26.6
30-45	29.0	35.0	36.0	Clay loam	1.19	39.3	23.5	28.2
45-60	26.5	37.5	36.0	Loam	1.26	37.7	22.9	28.0
Average	26.5	40.0	33.5	Loam	1.16	36.8	22.1	25.8

4.1.2. Soil and Water Chemical properties

The result of soil chemical analysis showed that, the average pH value of the soil is nearly neutral (6.74-7.12). Hence, tef can grow outstanding in this soil condition and the finding is in line with Olani and Fikre (2010) which conclude that pH range of tef between 6.0 and 8.0. The soil has an average electrical conductivity of 0.26 dS/m through 60 cm soil profile which is below the threshold value for yield reduction, i.e. 1.2 dS/m (Smith *et al*, 2011).

The analysis of applied irrigation water showed that pH value of 7.51 and EC_w value of 0.46 dS/m were obtained (Table 4.2). According to FAO (1999), water salinity has four classes: C1, C2, C3 and C4 accounting for low, medium, high and very high salinity levels with the value of 0.1-0.25 dS/m, 0.25-0.75 dS/m, 0.75-2.25 dS/m and > 2.25 dS/m, respectively. Based on the above classification the irrigation water quality of the study area was classified as medium salinity level. The pH of irrigation water is not a problem by itself, but it is an indicator of other problems such as sodium and carbonates. According to Bryan *et al*. (2007), the irrigation water is classified in terms of pH <7 low, 7-8 slight to moderate and >8 severe. Based on this classification, the pH value of the irrigation water in the study area found that slight to moderate.

Table 4.2: Analysis of chemical properties of soil

Depth (cm)	pH	EC (dS/m)	Total (OM) (%)	OC (%)	TN (%)
0-15	6.74	0.215	4.29	2.49	0.2145
15-30	7.07	0.229	3.9	2.26	0.195
30-45	7.08	0.305	3.04	1.76	0.152
45-60	7.12	0.299	1.95	1.13	0.0975
Average	7.0	0.26	3.3	1.91	0.16

Table 4.3: Analysis of chemical properties of Irrigation water

Parameters	Value
pH	7.51
EC(dS/m)	0.364

4.2. Agronomic Performance of Tef

The response of tef to deficit irrigation and row spacing was significant and detected in yield and yield components like number of tiller per plant, plant height, and lodging. (Table 4.3). All the yield components increase with subsequent increase in irrigation amount and row spacing. This shows that irrigation had significant effect on growth parameters of tef and subsequently influenced the crop yield. Al-Moshileh (2007) reported that with increasing soil water supply recorded plant growth parameters; i.e. plant height, number of tiller were significantly increased in the evaluation period.

Table 4.4. Plant Growth Parameters as affected by Deficit irrigation and row spacing

Treatments	Plant height (cm)	Number tillers per plant (No)	Lodging (%)
100% ET _c	112.33 ^a	3.22 ^a	78.662 ^a
85% ET _c	108.92 ^b	3.18 ^a	75.83 ^b
70% ET _c	99.72 ^c	2.86 ^b	71.13 ^c
55% ET _c	89.97 ^d	2.58 ^c	67.4 ^d
CV (%)	2.797	2.82	2.79
S ₄ (25 cm)	113.08 ^a	3.54 ^a	65.75 ^b
S ₃ (20 cm)	109.58 ^b	3.25 ^{ab}	67.50 ^b
S ₂ (15 cm)	100.31 ^c	2.82 ^{bc}	73.347 ^{ab}
S ₁ (10 cm)	87.64 ^d	2.23 ^c	86.39 ^a
CV (%)	3.707	3.71	3.71

Note: Means followed by different letters in a column differ significantly and those followed by the same letter are not significantly different according to LSD at $P < 0.01$ level of significance.

4.2.1. Plant height

According to the analysis of variance in Appendix Table 3, irrigation application level had shown highly significant difference for tef height ($P < 0.01$). As depicted in Table 4.3 above, there was significant difference among all the deficit levels ($P < 0.01$).

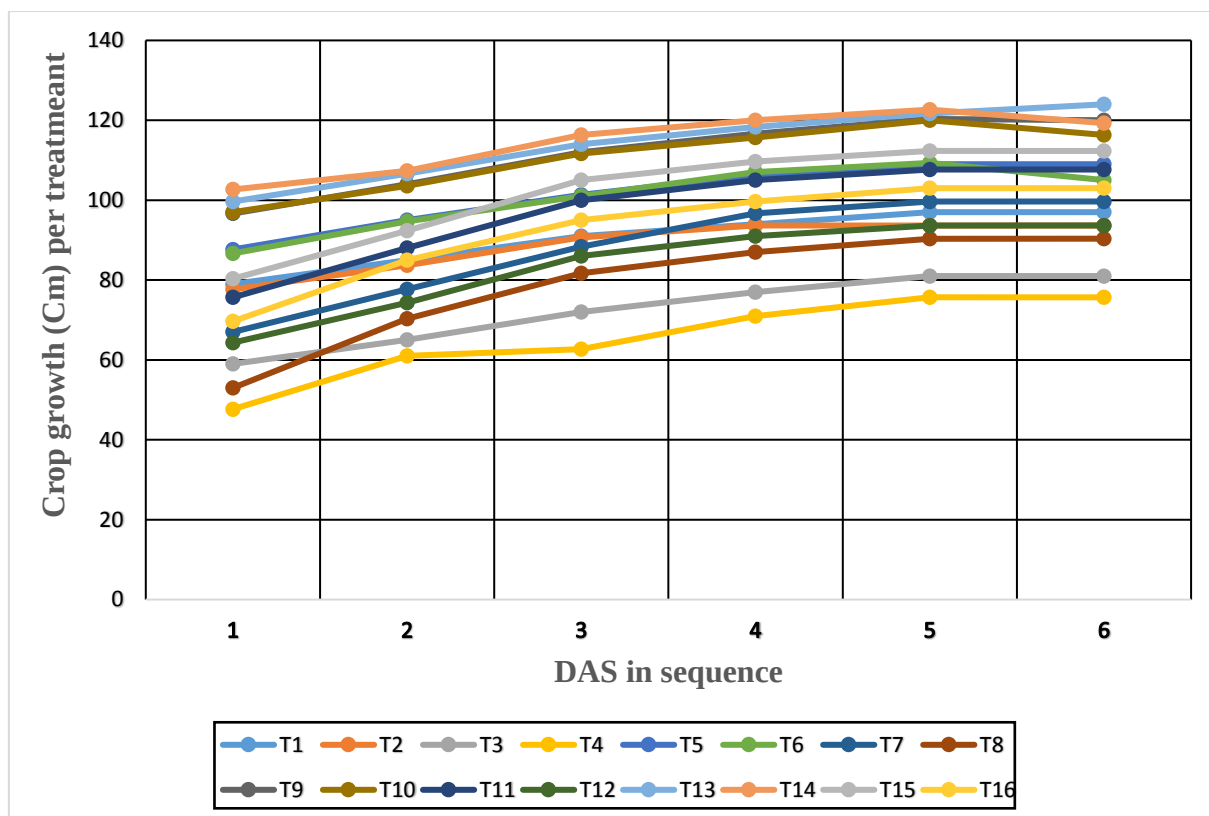


Figure 4.1: Growth height of Tef measured in days after sowing per irrigation level treatments

The tallest tef height (122.7 cm) was observed at 100% ET_c with 25 cm row spacing and the shortest plant height (75.69 cm) was observed at 55% ET_c with 10 cm row spacing. Generally, the mean table showed increasing trend in plant height with increasing water application level and row spacing indicating that direct relationship between vegetative growth and water use. However, there was no significant difference between 100% ET_c and 85% ET_c for plant height. The interaction effect of deficit levels and row spacing had significant impact on plant height.

A similar finding has been reported by (Kidist and Tena, 2017), who concluded that a 50% (ET_c) resulted in 54.6 cm height of tef whereas, a 60, 70, 80, 90 and 100% (ET_c) 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% (ET_c) resulted in 43.5 cm height of pepper whereas, a 75 and 100% (ET_c) resulted in 56.8 and 60.7 cm height, respectively. A Similar finding was reported by Shahzad et al. (2007). Over all, plants grown at 10 cm row spacing had significantly shortest plant height than those grown at the other row spacing's (Appendix table 3)

Table 4.4: Interaction effect of row spacing and irrigation depth on plant height.

Row Spacing (cm)	Plant height			
	100% ETc	85% ETc	70% ETc	55% ETc
10	99.5 ^{ghi}	96.11 ^{ij}	80.33 ^l	74.56 ^m
15	107.78 ^{def}	104.33 ^{fgh}	98.56 ^{hij}	89.44 ^k
20	119 ^{ab}	116.78 ^{bc}	107.89 ^{de}	93.56 ^{jk}
25	123 ^a	118.44 ^{ab}	112.11 ^{cd}	102.33 ^{fgh}
C V (%)	2.944			

There are 13 groups (a, b, c, etc.) in which the means are not significantly different from one another.

4.2.2. Number of effective tillers

Number of tillers was significantly ($P < 0.01$) affected by the main effects of irrigation depths and row spacing. The highest number of tillers per plant was recorded from full irrigation (100% ETc) and had no significant difference with 85% ETc application. The lowest number of tillers per plant was recorded from 55% ETc application and inferior to all other treatments.

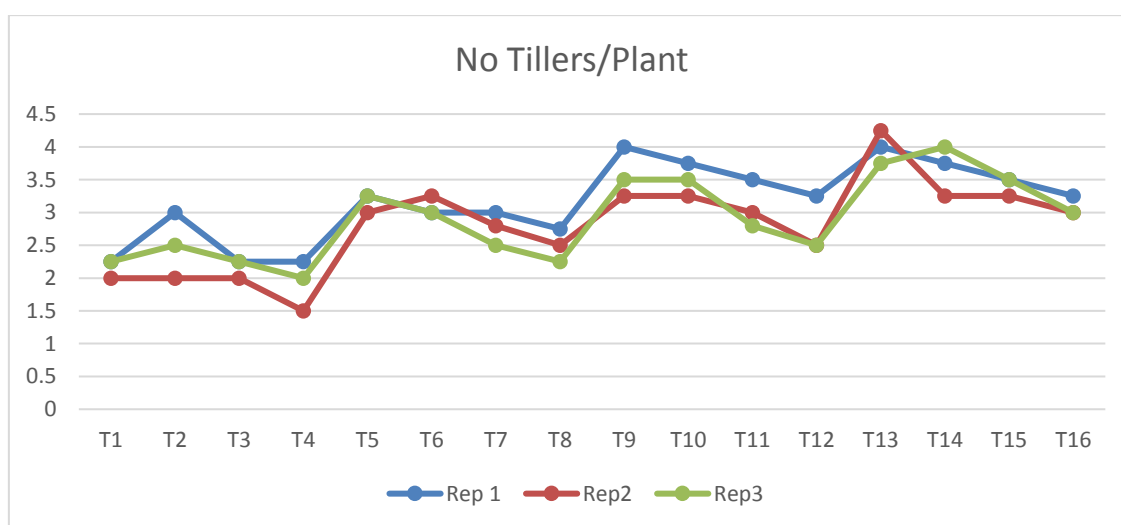


Figure 4.2: Number of effective tillers

Row spacing of 25 cm gave the highest number of tillers per plant and had no significant difference with 20 cm row spacing. The lowest number of tillers was recorded from 10 cm row spacing. (Appendix table 4). As the distance between plant stands decreases competition for space, light and soil nutrients increase, resulting in lower tiller production.

Number of effective tillers was significantly increased in response to increasing the row spacing from 10 to 25 cm for all depth of irrigation. This indicates that narrow row spacing

had a negative effect on the production of high number of effective tillers. However, there were no significance mean difference in effective tiller number between 100% ETc and 85% ETc at 20 and 25 cm row spacing. Similar result was reported by Mondal et al. (2013) and Tuhin et al. (2014) in rice. In addition Pandey et al. (2013) and Abreham et al. (2014) who reported that there was significant difference at ($P < 0.05$) of row spacing for the number of effective tillers per plant in wheat and tef crop.

4.2.3. Lodging

Lodging percentage was significantly ($P < 0.01$) affected by both the main effect of depth of irrigation and row spacing. The interaction effect of the two factors also significantly ($P < 0.05$) affected lodging percentage. The highest lodging percentage was observed when 10 cm row spacing with (100% ETc and 85% ETc) is 86.39%. The lowest lodging percentage was recorded for plants sown at row spacing of 20 and 25 cm with 55% ETc and 75% ETc (Appendix table 6). Lodging percentage decreased consistently in response to increasing the row spacing from 10 to 25 cm for all depth of irrigation under study. This indicates that narrow row spacing had a pronounced effect on the production of high number of plant population which may cause stiff inter-row competition that might have weak stock which led to lodging of tef and the genetic difference of the varieties (Amare and Adane, 2015). The present result is in agreement with Alemat *et al.* (2016).

4.2.4. Grain Yield

The analysis of variance revealed that grain yield was significantly ($P < 0.01$) affected by the main effect row spacing and irrigation depth. As can be seen in (Appendix table 8), in (T₁₃), 404.93 mm of irrigation water was applied for the growing season and produced mean maximum tef grain yield of (3076.5 kg/ha) and the lowest mean grain yield (2060.67 Kg/ha) was obtained in (T₄), 222.71 mm of applied irrigation water.

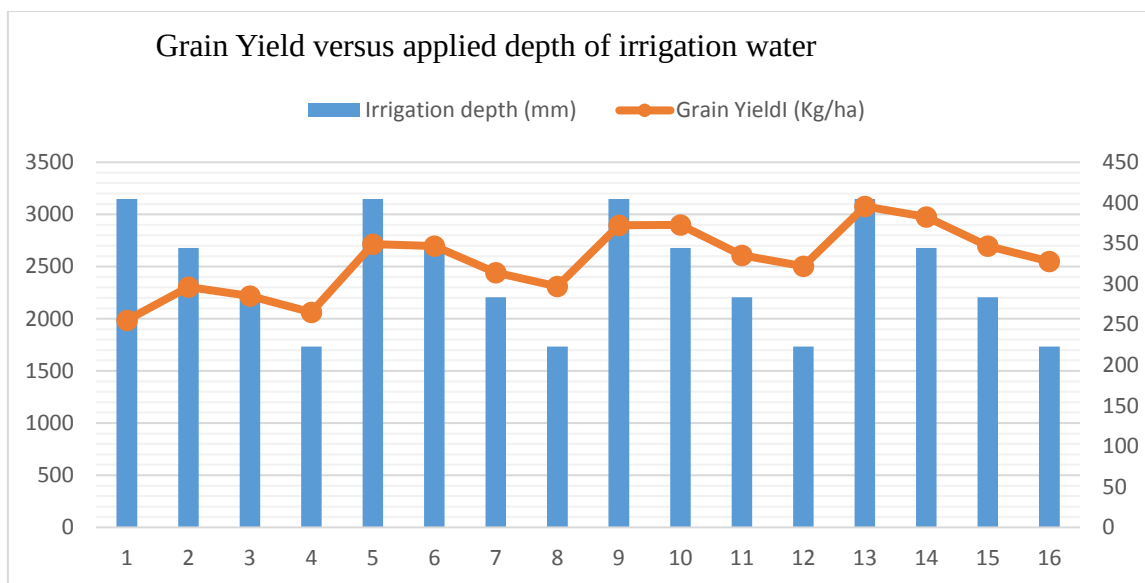


Figure 4.3: Mean grain yield of tef per hectare per applied depth of irrigation water

Grain yield of tef was significantly influenced by different irrigation levels, but, statistically there was no significant difference between T₉, T₁₀, T₁₃ and T₁₄ in grain yield (Appendix table 8). 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 tef, maximum yield of 3120 and 2910 Kg/ha respectively found from the treatment which received 281 mm of water. The reduction in grain yield in T₁ and T₂ with narrow row spacing 10 cm and 15 cm respectively could be due to crop lodging (Appendix picture 6), Lodging could decrease the potential grain yield that could have been gained from the improved vegetative growth. The decrease in grain yield of tef 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).

The yield components increase with subsequent increase in irrigation amount. This shows that irrigation had significant effect on growth parameters of tef and subsequently influenced the crop yield. Al-Moshileh (2007) reported that with increasing soil water supply recorded plant growth parameters; i.e. plant height and number of tillers were significantly increased in the evaluation period.

4.3. Effect of Different Irrigation Depths on Water Use Performance of Tef

4.3.1. Crop Water Productivity

As can be seen from (Appendix table 10), the highest water productivity (1.14 kg/m^3) of yield was obtained under 55% ET_c irrigation water application level (222.71 mm) and with 25 cm row spacing whereas the lowest water productivity (0.49 Kg/m^3) of tef yield was obtained in 100% ET_c level under irrigation depth of 404.93 mm with 10 cm row spacing. Crop water productivity was significantly influenced by different irrigation levels (Appendix table 10).

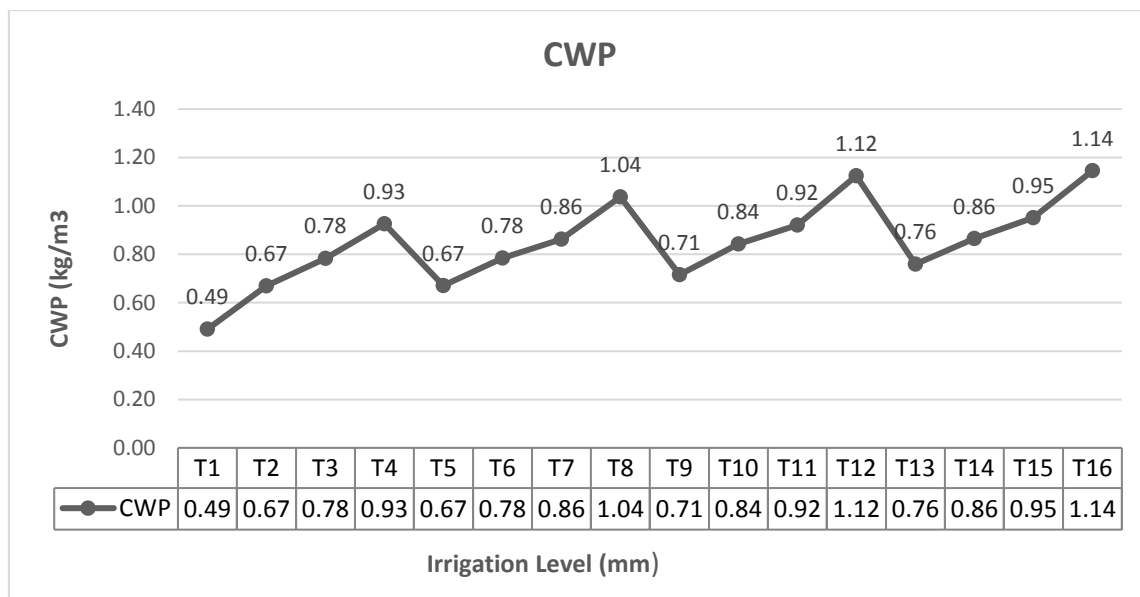


Figure 4.4: Crop water productivity (CWP) per irrigation levels treatments

And also, Figure 4.4 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 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/m³ for wheat, rice, cotton, and maize respectively. Similarly, Yihun, (2015) reported that higher water productivity of 1.16 and 1.08 kg/m³ 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 tef 2-3 times a year in water prone areas of Ethiopia. Crop water productivity also a function of the row spacing which implies that, Crop water productivity increase with increasing row spacing and decreasing with decreasing row spacing.

4.3.2. Yield response factor

The magnitude of ky value indicates the sensitivity of the irrigation protocol for water stress and subsequent yield decrease. Results of the analysis of yield and water, as indicated in Table 14 below, shows that the highest ky was 1.67 attained at 85% ETc under 10 cm and the lowest was 0.2 observed at 85% ETc under 25 cm row spacing. The ky for the most economical advantage treatment combination (i.e., 70% ETc under 10 cm) was 0.93. This shows that the treatment combination can resist the yield decrease associated with water deficit.

Treatments	Yield (t/ha)	ET _a (mm)	$\frac{ET_a}{ET_m}$	$\frac{Y_a}{Y_m}$	$1 - \frac{ET_a}{ET_m}$	$1 - \frac{Y_a}{Y_m}$	K _y
T ₁	1.99	404.93	1.00	0.65	0.00	0.35	-
T ₂	2.30	344.19	0.85	0.75	0.15	0.25	1.67
T ₃	2.22	283.45	0.70	0.72	0.30	0.28	0.93
T ₄	2.06	222.71	0.55	0.67	0.45	0.33	0.73
T ₅	2.72	404.93	1.00	0.88	0.00	0.12	-
T ₆	2.70	344.19	0.85	0.88	0.15	0.12	0.8
T ₇	2.44	283.45	0.70	0.79	0.30	0.21	0.70
T ₈	2.31	222.71	0.55	0.75	0.45	0.25	0.56
T ₉	2.90	404.93	1.00	0.94	0.00	0.06	-
T ₁₀	2.90	344.19	0.85	0.94	0.15	0.06	0.4
T ₁₁	2.61	283.45	0.70	0.85	0.30	0.15	0.5
T ₁₂	2.50	222.71	0.55	0.81	0.45	0.19	0.42
T ₁₃	3.08	404.93	1.00	1.00	0.00	0.00	-
T ₁₄	2.98	344.19	0.85	0.97	0.15	0.03	0.2
T ₁₅	2.70	283.45	0.70	0.88	0.30	0.12	0.4
T ₁₆	2.9	222.71	0.55	0.83	0.45	0.17	0.38

Table 4.5. The yield response factor values for irrigation treatments

The ky values greater than unity indicates the relative yield decrease is higher than the water deficit as stated by Smith and Kivumb (2002). According to Kirda *et al.* (1999), the ky value for field crops goes from 0.2 to 1.15 which agrees with the reported result.

5. CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

In many developing countries like Ethiopia incidence of recurrent drought has been the major cause of food insecurity problems with its root in non-uniform and insufficient rain fall on which they depend for agriculture. This situation is greatly aggravated by the high population growth rate and low food production level. It is imperative to bring large area of land in arid and semi-arid regions under irrigation. However, the scope for further irrigation development to meet food requirements in the coming years is severely constrained by decreasing water resources and growing competition for clean water. Novel irrigation technologies need to be generated and tested under local environments and particular agricultural production systems so that water productivity and sustainable water use for agriculture under both rain-fed and irrigated agriculture can be improved.

With the intention of testing the effect of deficit irrigation application under different row spacing using tef as a test crop a study was conducted in Oromiya Regional State at Melkassa Agricultural Research Center. Three irrigation deficit levels 55% ET_c, 70% ET_c, 85% ET_c and a control 100% ET_c set as subplot factors and four row spacing (10 cm, 15 cm, 20 cm and 25 cm) set as main plot factors were arranged in split plot design. The effect of irrigation treatments were tested using yield and yield components like plant height, effective tillering, and lodging.

The experimental soil had loam texture with bulk density of 1.12 gcm⁻³ and basic infiltration rate of 16.6 mmhr⁻¹. The characteristic TAW of the soil was 170.4 mm/m. Irrigation treatments had significant yield effect and yield components considered in the study. The yield components observed at 85% ET_c and 100% ET_c irrigation application levels had no significant difference. Similarly, 20 cm and 25 cm row spacing were not significantly different for the aforementioned parameters ($P < 0.01$).

In the same way like yield components, the total yield was significantly affected both by irrigation level and row spacing. Plant height was not significantly different for 85% ET_c and 100% ET_c irrigation levels ($P < 0.01$).

The highest water productivity (1.14 kg/m³) of yield was obtained under 55% ET_c irrigation water application level (222.71 mm) and with 10 cm row spacing whereas the lowest water productivity (0.49 Kg/m³) of tef yield was obtained in 100% ET_c level under irrigation depth of 404.93 mm with 10 cm row spacing.

Generally, among all irrigation treatments 85% ETc deficit level applied with 25 cm row spacing was efficient in conserving significant irrigation water at the same time attaining higher yield and yield quality. It was also economically feasible because of its higher return rates. Therefore, it could be concluded that increased water saving and water productivity through irrigation at 85% ETc deficit level with 25 cm would ensure the scope of further irrigation development, so as to alleviate food insecurity issues that emanate from water shortage.

5.2. Recommendation

Based on the finding of the study the following important recommendations are drawn;

✚ In situation where irrigation water but irrigable land is limiting tef farming in the study area are advised to use 85% ETc the crop requirement applied with 25 cm row spacing in to border so as to obtain more benefit.

✚ The soil moisture monitoring (gravimetical) method should be substituted with other modern soil moisture monitoring instruments like tensiometers, neutron probe and TDR to effectively account the in-situ and real time soil moisture.

✚ In water scarce areas, tef producing farmers are recommended to avail irrigation water from rain water harvesting as well as from dug well or bore well and adopt boarder irrigated tef production in dry periods as well as supplemental irrigation when rainfall is not sufficient in the normal tef growing seasons,

✚ For water scarce areas and water shortage situations, the strategy is to increase water productivity, therefore, it is recommended to irrigate tef at 55% ETc level (222.71 mm), since it has found the highest crop water productivity under this water level,

✚ Based on the findings of this study, it is recommended to produce tef from less water by using border irrigation system. 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 tef, sowing methods, irrigation interval and different climatic conditions under border irrigation system.

6. REFERENCE

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7. Appendix A. Table

Appendix table 1. Long-term monthly climatic data of the study area

Month	T _{min} , °C	T _{max} , °C	Humidity, %	Wind, m/s	Sunshine, hr	ETo, mm/day	Rainfall, mm
January	11.7	27.9	51.0	8.6	9.0	7.3	16.0
February	13.4	29.1	48.7	9.1	9.2	8.2	24.1
March	15.1	30.5	49.2	8.6	8.5	8.4	52.3
April	15.5	30.5	50.8	7.8	8.2	8.1	53.9
May	15.5	31.0	51.2	7.5	8.8	8.1	61.0
June	16.4	30.2	53.1	9.0	8.4	8.1	69.0
July	15.7	26.8	66.4	9.1	7.0	5.9	204.2
August	15.4	26.3	69.2	7.0	7.1	5.3	183.1
September	14.5	27.6	65.8	4.9	7.3	5.4	99.8
October	11.7	28.8	50.0	6.6	8.7	7.2	39.3
November	10.8	28.3	46.7	8.3	9.6	7.8	12.6
December	10.4	27.6	48.8	8.9	9.5	7.5	9.6

Appendix table 2: Split plot Design (SSP) Crop growth height (cm)

Treatment	Irrigation level (mm)	Block - 1	Block - 2	Block - 3	Treatment total	Treatment mean
T ₁	404.93	96	97	95	288	96
T ₂	344.19	99	98	96	293	97.7
T ₃	283.45	81	79	83	243	81
T ₄	222.71	76	72	79	227	75.7
T ₅	404.93	109	105	113	327	109
T ₆	344.19	111	106	112	329	110
T ₇	283.45	101	95	103	299	99.7
T ₈	222.71	91	87	93	271	90
T ₉	404.93	120	117	124	361	120
T ₁₀	344.19	121	118	123	362	121.7
T ₁₁	283.45	107	109	107	323	107.6
T ₁₂	222.71	96	91	94	281	93.7
T ₁₃	404.93	122	121	122	365	122.7
T ₁₄	344.19	123	122	123	368	121.7
T ₁₅	283.45	112	112	115	339	113
T ₁₆	222.71	102	102	105	309	103
REP Total		437.4	438.3	438.3	311.56	1664.5
Block Grand mean						102.74

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

Appendix table 3: Analysis of variance for Tef growth height

Source of variation	DF	SS	MS	F value	P value
REP	2	60.17	30.08		
Mplot	3	5003.26	1667.82	578.34	< 0.001
Subplot	3	3514.8	1171.36	235.63	< 0.001
Mplot*Subplot	9	185.10	20.57	4.14	0.0026
Error	24	119.31	4.97		
Total	47				
C.V			2.17		

Appendix table 4: Split plot Design (SSP) Number of effective tillers

Treatme nt	Irrigation Level (mm)	REP- 1	REP- 2	REP- 3	Treatment total	Treatment mean
T ₁	404.93	2.25	2	2.25	6.5	2.17
T ₂	344.19	3	2	2.5	7.5	2.50
T ₃	283.45	2.25	2	2.25	6.5	2.17
T ₄	222.71	2.25	1.5	2	5.75	1.92
T ₅	404.93	3.25	3	3.25	9.5	3.17
T ₆	344.19	3	3.25	3	9.25	3.08
T ₇	283.45	3	2.8	2.5	8.3	2.77
T ₈	222.71	2.75	2.5	2.25	7.5	2.50
T ₉	404.93	4	3.25	3.5	10.75	3.58
T ₁₀	344.19	3.75	3.25	3.5	10.5	3.50
T ₁₁	283.45	3.5	3	2.8	9.3	3.10
T ₁₂	222.71	3.25	2.5	2.5	8.25	2.75
T ₁₃	404.93	4	4.25	3.75	12	4.00
T ₁₄	344.19	3.75	3.25	4	11	3.67
T ₁₅	283.45	3.5	3.25	3.5	10.25	3.42
T ₁₆	222.71	3.25	3	3	9.25	3.08
REP Total		50.75	44.8	46.55	142.1	47.37
					REP Grand mean	2.96

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

Appendix table 5: Analysis of variance for Number of effective tillers

Source	DF	SS	MS	F	P
Rep	2	1.2929	0.64643		
Mplot	3	11.7551	3.91837	32.27	0.0004
Error Rep*Mplot	6	0.7285	0.12142		
Subplot	3	2.7253	0.90843	15.16	0.0001
Mplot*Subplot	9	0.3225	0.03583	0.60	0.7852
Error	24	1.3187	0.05994		
Total	45				
			C.V	8.27	

Appendix table 6: Split plot Design (SSP) of lodging

Treatme nt	Irrigation Level (mm)	REP- 1	REP- 2	REP- 3	Treatment total	Treatment mean
T ₁	404.93	94	89	91	274	91.33
T ₂	344.19	91	89	89	269	89.67
T ₃	283.45	85	85	84	254	84.67
T ₄	222.71	81	83	80	244	81.33
T ₅	404.93	86	84	76	246	82.00
T ₆	344.19	83	81	68	232	77.33
T ₇	283.45	73	77	57	207	69.00
T ₈	222.71	71	70	52	193	64.33
T ₉	404.93	73	68	75	216	72.00
T ₁₀	344.19	71	65	71	207	69.00
T ₁₁	283.45	67	64	68	199	66.33
T ₁₂	222.71	63	63	62	188	62.67
T ₁₃	404.93	70	67	73	210	70.00
T ₁₄	344.19	68	63	71	202	67.33
T ₁₅	283.45	65	60	68	193	64.33
T ₁₆	222.71	61	59	64	184	61.33
REP Total		1202	1167	1149	3518	1172.67
					REP Grand mean	73.29

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

Appendix table 7: Analysis of variance for lodging

Source	DF	SS	MS	F	P
Rep	2	79.57	39.76		
Mplot	3	3266.62	1088.87	10.22	< 0.0090
Error Rep*Mplot	6	639.26	106.54		
Subplot	3	860.17	286.72	59.55	< 0.0001
Mplot*Subplot	9	117.74	13.08	2.72	0.0244
Error	24	115.56	4.82		
Total	47				
		C.V	3.00		

Appendix table 8: Split plot Design (SSP) Tef grain yield (Kg/ha)

Treatment	Irrigation level (mm)	REP -1	REP -2	REP -3	Treatment total	Treatment mean
T ₁	404.93	1909.8	2061.4	1987.9	5959.1	1986.37
T ₂	344.19	2294.1	2258.4	2361.2	6913.74	2304
T ₃	283.45	2210.2	2147.7	2301.1	6659	2219.67
T ₄	222.71	1978.7	2108.7	2094.6	6182	2060.67
T ₅	404.93	2684.2	2789.5	2671.8	8145.5	2715.17
T ₆	344.19	2678.1	2749.6	2665.3	8093	2697.67
T ₇	283.45	2507.5	2499.4	2321.4	7328.3	2442.77
T ₈	222.71	2471.5	2348.4	2108.3	6928.2	2309.4
T ₉	404.93	2869.8	2957.8	2857.9	8685.5	2895.17
T ₁₀	344.19	2865.5	2960.6	2875.6	8701.7	2900.57
T ₁₁	283.45	2609.9	2610	2607.2	7827.1	2609.03
T ₁₂	222.71	2490	2430	2590.8	7510.8	2503.6
T ₁₃	404.93	2987.2	3094.2	3148.1	9229.5	3076.5
T ₁₄	344.19	3041.8	3008.8	2877.5	8928.1	2975.03
T ₁₅	283.45	2621.1	2747.6	2720.8	8089.5	2696.5
T ₁₆	222.71	2450.4	2578.3	2621.1	7649.8	2549.9
REP Total		40669.8	41350.4	40810.6	122919.6	42588.58
REP Grand mean						2558.94

Appendix table 9: Analysis of variance for grain yield

Source	DF	SS	MS	F	P
Rep	2	11274	5637		
Mplot	3	2969713	989904	66.05	0.0001
Error Rep*Mplot	6	89928	14988		
Subplot	3	1141647	380549	18.90	< 0.001
Mplot*Subplot	9	258922	28769	1.43	0.2312
Error	24	483355	20140		
Total	47				
		C.V	5.52		

Appendix table 10: Split plot Crop water productivity (Kg/m³)

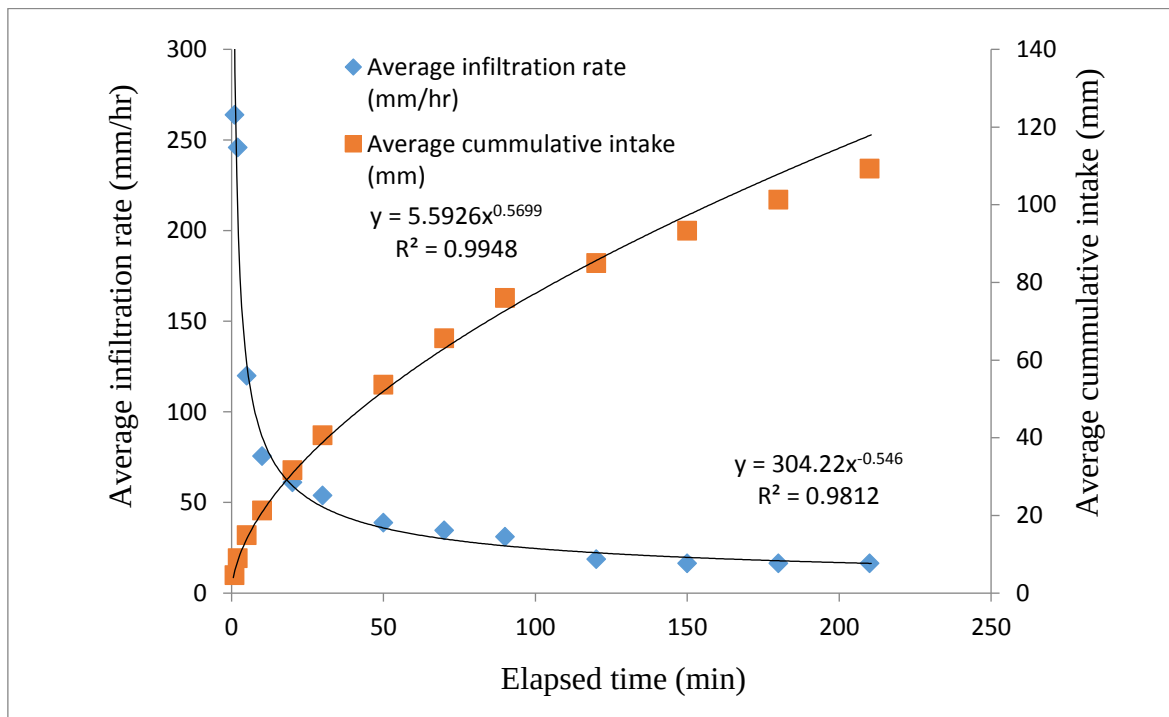
Treatment	Irrigation Level (mm)	REP-1	REP-2	REP-3	Treatment total	Treatment mean
T1	404.93	0.47	0.51	0.49	1.47	0.49
T2	344.19	0.67	0.66	0.66	1.98	0.66
T3	283.45	0.78	0.76	0.81	2.35	0.78
T4	222.71	0.89	0.95	0.94	2.78	0.93
T5	404.93	0.66	0.69	0.66	2.01	0.67
T6	344.19	0.78	0.80	0.77	2.35	0.78
T7	283.45	0.88	0.88	0.82	2.59	0.86
T8	222.71	1.11	1.05	0.95	3.11	1.04
T9	404.93	0.71	0.73	0.71	2.14	0.71
T10	344.19	0.83	0.86	0.84	2.53	0.84
T11	283.45	0.92	0.92	0.92	2.76	0.92
T12	222.71	1.12	1.09	1.16	3.37	1.12
T13	404.93	0.74	0.76	0.78	2.28	0.76
T14	344.19	0.88	0.87	0.84	2.59	0.86
T15	283.45	0.92	0.97	0.96	2.85	0.95
T16	222.71	1.10	1.16	1.18	3.43	1.14
REP Total		13.47	13.66	13.47	40.60	13.53
					REP Grand mean	0.85

Appendix Table 11. Infiltration test data using double ring infiltrometer

Ring # 1					Ring # 2			Ring # 3			Average intake d/nc (mm)	Average infiltration rate (mm/h r)	Average cum. Intake (mm)
Cumulative time (min)	Time difference (min)	Stick reading (mm)	Intake difference (mm)	Cumulative intake (mm)	Stick reading (mm)	Intake difference (cm)	Cumulative intake (mm)	Stick reading (mm)	Intake difference (mm)	Cumulative intake (mm)			
0	-	85	-	-	100	-	-	75	-	-	-	-	-
1	1	70	5	5	95	5	5	71	4	4	4.4	264. 0	4.7
2	1	66	4	9	91	4	9	66	5	9	4.1	246. 0	9.1
5	3	59	7	16	86	5	14	60	6	15	6.0	120. 0	14. 9
10	5	53	6	22	80	6	20	53/8 3*	7	22	6.3	75.6	21. 5
20	10	42/93 *	11	33	69	11	31	76	9	31	10.2	61.2	31. 6
30	10	83	10	43	61	8	39	67	9	40	9.0	54.0	40. 7
50	20	70	13	56	47/ 86*	14	53	55	12	52	13.0	39.0	53. 7
70	20	57	13	69	74	12	65	44/9 4*	11	63	11.6	34.8	65. 6
90	20	46/10 1*	11	80	64	10	75	84	10	73	10.4	31.2	76. 1
120	30	92	9	89	55/ 80*	9	84	75	9	82	9.4	18.8	85. 0
150	30	83	9	98	72	8	92	67	8	90	8.3	16.6	93. 5
180	30	75	8	106	63	9	101	59	8	97	8.0	16.6	101 .3
210	30	67	8	114	55	8	109	50	9	105	7.7	16.6	109 .3

* The measuring stick marks before and after water addition.

7. Appendix B. Figures



Appendix Figure 1. Infiltration characteristics of the experimental soil



Appendix Figure 2: Growth and development stage of Tef



Appendix Figure 3: Lodged tef due to high water application and narrow spacing



Appendix Figure 4: Tef at seed filling stage





