COMPARISON OF CONTINEOUS AND SURGE FLOW ON ALTERNATE AND CONVENTIONAL FURROW IRRIGATION

BAYUSH KEBEDE MULUGETA

A Thesis Submitted to the Department of Water Resources Engineering,

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for The Degree of Masters in Water Resources Engineering (Irrigation Engineering)

Office of Graduate Studies

Adama Science and Technology University

Adama, Ethiopia

October, 2020

COMPARISON OF CONTINEOUS AND SURGE FLOW ON ALTERNATE AND CONVENTIONAL FURROW IRRIGATION

Bayush Kebede Mulugeta

Advisor - Dr. Boja Mekonnen (PhD)
Co - Advisor - Dr. Tilahun Hordofa (PhD)

A Thesis Submitted to the Department of Water Resources Engineering,
School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for The Degree of Masters In
Water Resources Engineering (Irrigation Engineering)

Office of Graduate Studies
Adama Science and Technology University

Adama, Ethiopia
October, 2020

APPROVAL SHEET

We, the undersigned, members of the Board of Examiners have read and evaluated the MSc Thesis entitled“**Comparison of Contineous and Surge Flow on Alternate and Conventional Furrow Irrigation**” prepared and presented by Miss. **Bayush Kebede Mulugeta**.

This is, therefore, to certify that the thesis has been accepted as partial fulfillment of the requirement of the Degree of Master’s in Water Resources Engineering (Specialization in Irrigation Engineering)

____________________	____________________	____________________
Advisor	Signature	Date
____________________	____________________	
Co-advisor	Signature	Date
____________________	____________________	____________________
External Examiner	Signature	Date
____________________	____________________	____________________
Internal Examiner	Signature	Date
____________________	____________________	____________________
Chair Person	Signature	Date

Final Approval and Acceptance

____________________	____________________	____________________
Head of Department	Signature	Date
____________________	____________________	____________________
School Dean	Signature	Date
____________________	____________________	____________________
Post Graduate Dean	Signature	Date
____________________	____________________	____________________
School Dean	Signature	Date
____________________	____________________	____________________
Postgraduate	Signature	Date

DECLARATION

I hereby declare that this MSc Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

Name: Bayush Kebede Mulugeta

Signature: ________________

This MSc Thesis has been submitted for examination with my approval as thesis Advisor.

Advisor: Boja Mekonnen (PhD)

Signature: _________________

Name: Tilahun Hordofa (PhD)

Signature: _________________________

Date of submission: _______________

ADVISOR’S APPROVAL SHEET

To: Water Resource Engineering Department

Subject: Thesis Submission

This is to certify that the thesis entitled “**Comparison of Contineous and Surge Flow on Alternate and Conventional Furrow Irrigation**” submitted in partial fulfillment of the requirements for the degree of Master‘s in **Water Resource Engineering (Specialization in Irrigation Engineering)**, the Graduate program of the department of **Water Resource Engineering,** and has been carried out by **Bayush Kebede Mulugeta**, Id. No: Pgr/18281/11, under our advice. Therefore, we recommend that the student has fulfilled the requirements and hence hereby she can submit the thesis to the department.

Name of major Advisor Signature Date

Name of co-advisor Signature Date

ACKNOWLEDGEMENT

I am grateful to the Almighty of God for his unfailing grace shared upon me throughout the period of my studies. I want to express my sincere gratitude to my advisors, Dr Boja Mekonnen and Dr Tilahun Hordofa for my thinking and keeping momentum going during topic selection (problem identification), intellectual stimulation, professional guidance, encouragement, and inspiring discussions during the project work and valuable criticism of the thesis.

I also appreciate Melkassa Agricultural Research Center for permitting to do the thesis experiment work by providing all possible support for the experiment work. It is my pleasure to acknowledge field labors for helping me to lay out the experiment into ground and their advice on the field work. And also I like to acknowledge all staff members in Melkassa Agricultural Research Center especially irrigation department.

I thank my friends and colleagues at the department for a nice time and good working environment. Finally, I would like to express my grateful acknowledgement especially to my father and mother, and also to my brothers and sisters, continuous help, and sacrifices they made to enable me to pursue my studies.

I am strongly indebted to thank Adama Science and Technology University for awarding me scholarship to study this Master of Science degree in Water Resources Engineering (Irrigation Engineering).

This research project is funded by Adama Science and Technology University under the grant number ASTU/SM-R/052/19, Adama Ethiopia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDEX TABLE

LIST OF APPENDEX FIGURES

ACRONYMS AND ABBREVATIONS

AFI	Alternate Furrow Irrigation
ANOVA	Analysis of Variance
CFI	Conventional Furrow Irrigation
CR	Cycle Ratio
CWR	Crop water requirement
CV	Coefficient of Variance
DAP	Di Ammonia Phosphate
DU	Distribution uniformity
EA	Application efficiency
EC	Electric conductivity
ED	Distribution efficiency
ETc	Crop Water Requirement
ETO	Reference Evapotranspiration
FC	Filed Capacity
HD	Hydro dynamic
IWR	Irrigation water requirement
K_c	Crop Coefficient
KW	Kinematic wave
LSD	List Significance Difference
MARC	Melkassa Agricultural Research Center
OM	Organic Matter
PH	Power of Hydrogen
PWP	Permanent Wilting Point
RCBD	Randomize Complete Block Design
SAS	Statistical Analysis Software

SIRMOD	Surface Irrigation Simulation Model
S_1	Surge Irrigation Cycle ratio 1/3
S_2	Surge Irrigation with Cycle ratio 1/2
USDA	United State Development Authority
VB	Volume balance
ZI	Zero Inertia

ABSTRACT

Furrow irrigation is the most widely practiced form of surface irrigation in the central valley of Ethiopia. The system is ineffective and inefficient form of irrigation requiring improvement of irrigation water management practices. Field study was undertaken at Melkassa Agricultural Research Center to compare continuous and surge flow on alternate and conventional furrow irrigation with a field grown with Haricot bean Awash II variety. The experiment consists of two irrigation systems, viz., alternate and conventional furrow irrigation and three irrigation flow methods viz., continuous, surge-1wih cycle ratio 1/3 and surge-2 with cycle ratio ½. Six treatment combinations replicated three times were arranged in a randomized complete block design. The results of advance and recession of water showed that water advance for ½ cycle ratio of surge on alternative furrow irrigation was very rapid and reached the lower end of the furrow in a shorter time followed by cycle ratio 1/3 and continuous flow which resulted in longer advance time. The interaction effect of the irrigation system and irrigation flow methods did not show a statistically significant difference ($p<0.05$) in the performance indicators, crop yield and water use efficiency. The furrow irrigation systems don't have significant effect on the yield of haricot bean. However, the irrigation flow methods were significantly affected the irrigation performance indicators viz., application efficiency, distribution uniformity and storage efficiency. Higher crop yield (2383.3 kg/ha), water use efficiency (0.76 - 0.99kg/m3), application efficiency (55.31–60.82 %), distribution uniformity (78.9 – 84.0 %), storage efficiency (71.2-75.3 %) and distribution efficiency (80.67-82.76 %) were obtained from both surge flow and alternate furrow irrigation. Surge irrigation was found in the study area as it saves water, reduces irrigation period, and increases the crop yield.

Keyword: Furrow irrigation, alternate furrow, conventional furrow, surge flow, Advance flow, recession flow

1 INTRODUCTION

1.1 Background

Irrigation is an age-old art, perhaps as old as human civilization. Nevertheless, the increasing need for crop production due to the growing population in the world is necessitating a rapid expansion of irrigated agriculture throughout the world (Awulachew *et al*., 2005). Ethiopia is the second-most populous country in Africa with a population of 110 million at current population growth rate of 3.2% and an estimated population of 145 million by 2050 (Awulachew *et al*., 2010). It has been loudly stated that if our country is to feed this ever-increasing population and lessen the risk of drought, continuous and extensive effort needs to be made towards developing intensive irrigated agriculture.

Surface irrigation is by far the dominant irrigation method applied throughout the world. However, water use efficiency with surface irrigation methods tends to be low (Narayana and Brook, 2014). It is an irrigation method where water drains by gravity, using the agricultural soil surface as part of the water distribution system (Lima *et al*., 2014). The low irrigation efficiency combined with the decreasing water availability for irrigation seems to be detrimental to agriculture. Poor on-farm irrigation water management practice is leading to erosion and sedimentation of reservoirs, poor water distribution and salinity development of irrigated lands. Most farmers practiced conventional furrow irrigation (CFI) in the country. Frequent irrigation under CFI may result in higher evaporation from the soil surface, especially during the early growing season with incomplete ground cover. The field application efficiency of the traditional irrigation system in the country is very low, only 30% to 50% (FAO, 1995, 1997). However, well-managed irrigation application systems have better water productivity compared to that of the already practiced irrigation practices in the country (Kifle *et al*., 2008).

Several management techniques have been developed to reduce water losses during the application of irrigation water at the field level. Those are intermittent application of water (surge flow) and alternate irrigation. In alternate furrows irrigation, two neighboring furrows alternately irrigated during the consecutive watering period. It offers an opportunity for reducing the size of irrigation and permits irrigating a field in a shorter time with a given water supply. The reduced size of irrigation may not reduce yields appreciably; rather increase irrigation water use efficiency (Ashinie *et al*., 2016; Yemane *et al*., 2018). Besides, AFI saves quite a good amount of water and is very useful and crucial in areas with scarce water resources (Jemal and Mukerem, 2017).

Continuous flow system in conventional and alternate furrow irrigation usually causes excessive deep percolation at the upper part of the furrows and insufficient irrigation at the lower part, and considerable runoff resulting in low application efficiency and distribution uniformity. To improve its performance, several methods have been developed among which the technique of surge flow system is important. The surge flow system is an intermittent application of water and it is accomplished by making on and off application between two irrigation sets. It is becoming a commonly used method for improving irrigation performance and is often the only way to complete the advanced phase by altering the infiltration characteristics of the soil. It is accomplished by clogging the siphon outlets or removing them from the furrows.

Haricot bean (*Phaseolus Vulgaris* L.) is an important food grain legume grown in the tropics and sub-tropics. The crop is a well-established component of Ethiopian agriculture and is among the five most important food legumes (faba bean, field pea, chickpea, lentils and haricot bean). It has been an export crop for about 50 years and has often grown as a cash crop by small-scale farmers. These days there is an increasing demand for the crop especially in the export markets (Kebere *et al.,* 2006). In the central rift valley, the crop is grown during the dry season (February –May) and wet season (June – September) as irrigated and rain-fed crops, respectively. These areas have a favorable environment and high potential for further expansion of the crop. However; the shortage of water is one of the major challenges of production (Habtu *et al.,* 1996).

In general, this study was conducted on comparison of continuous and surge flow on alternate and conventional furrow irrigation. In these irrigation systems, due to infiltration, there are variations in the flow depth at furrow section with time as well as in the flow rate with furrow length. Furthermore, the depth of flow along the furrow length varies gradually. In recent years, a number of surface irrigation simulation models for assessing surface irrigation system performance have been developed. Simulation in surface irrigation systems is the process of mathematically describing the hydraulic characteristics of water as it flows from one end of the field to the other. This is achieved by use of computer models based on mathematical equations known as Saint Venant equations, SIRMOD (Walker, 2005).

Hence, this study was conducted on the comparison of continuous and surge flow using alternate and conventional furrow irrigation.

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. Therefore, irrigation is the most vital source of crop production in Ethiopia under the dry season. Furrow irrigation is a widely used irrigation system in Ethiopia and is practiced by many farmers and state farms. However, The smallholding irrigation practice is characterized as less efficient, high water loss during application and low uniformity during distribution. The losses have been observed largely by improper irrigation management practices.

Saving unproductive losses creates an opportunity for the optimized use of a limited supply of irrigation water. Improved irrigation scheduling and water application methods are among the means of cutting losses and increasing efficiency. To allocate scarce water resources among users, identifying irrigation methods and proper choice of application strategy which maximizes crop water productivity using available water is an obligatory work.

This study was taken up to check the effect of surge flow on conventional and alternate furrow irrigation systems. Alternate furrow irrigation offers opportunities for reducing the size of irrigation and permits irrigating a field in a shorter period with a given water application. The reduced size of irrigation may not reduce yield appreciably and thus increase irrigation water use efficiency. Using a surge flow system on alternate furrow irrigation is important for improving irrigation efficiency. Surge flow irrigation system is the intermittent application of water used to improve distribution uniformity along a furrow. This technique is more commonly used to accelerate the advance phase while reducing the volume of applied water and increasing the uniformity of applied depths (Purkey and Wallender 1989). The intermittent application of irrigation water in furrows permits a more uniform distribution of infiltrated depth, a considerable reduction of the volumes of water required, the possibility of using lighter irrigation, less water loss from deep percolation and reduced leaching of fertilizers (Walker and Skogerboe, 1987).

1.3 Objectives of the Study

1.3.1 General objectives

The general objective of this study was to check the irrigation water application performance through the application of surge flow in conventional and alternate furrow irrigation.

1.3.2 Specific objectives

i. To compare advance and recession times under surge and continuous flow system

ii. To estimate performance under continuous and surge flow on alternate and conventional furrow irrigation using the SIRMOD model.

iii. To assess the performance indicators under continuous and surge flow on alternate and conventional furrow irrigation systems.

1.4 Research Question

i. Does the adaptation of surge flow have an impact on the advance and recession?

ii. Does estimation of performance of continuous and surge flow on furrow irrigation methods were done by the SIRMOD model?

iii. Is the performance improved by the use of surge flow furrow irrigation?

1.5 Significance of the Study

Investigating field evaluation methods in furrow irrigation is used to provide information about field water management techniques for users. The innovation of irrigation water management strategies is used to meet rising food demands for the growing population and to ensure water management techniques for sustainability water use and to optimize agricultural water productivity. Generally, the study has contributed to improving furrow irrigation performance and has given knowledge about water management technique

1.6 Scope of the Study

The proposed study was covered on the evaluation of the surge and continuous flow on alternate and conventional furrow irrigation. It is limited to investigating the effects of surge flow on the advance, recession, and performance on furrow irrigation in water stress areas on the analysis of both continuous and surge flow. The study was carried out only on one cycle time and two-cycle ratio and two furrow irrigation systems and also used only the SIRMOD model for estimation of the furrow irrigation methods performances.

2 LITERATURE REVIEW

2.1 Water Application Methods

The main objective of irrigation is to supply the essential moisture for plant growth and leach or dilute salts in the soil. The method and timing of irrigation have significant effects on crop production. Irrigation management is often designed to maximize efficiency and minimize labor and capital requirements (Walker, 1987). Farm irrigation systems must supply water at rates, in quantities, and at times needed to meet farm irrigation requirements and schedules. They divert water from a water source, convey it to the cropped area of the farm, and distribute it over the area being irrigated (James, 1988). Irrigation water may be applied to crops by flooding it on the field surface (surface irrigation), by applying it beneath the soil surface (subsurface irrigation), by spraying it under pressure (sprinkler), or by applying it in drops (drip) (Michael, 1978).

2.2 Furrow irrigation

Furrow irrigation water application system is the most popular form of surface irrigation, as it requires a smaller initial investment compared to other types of irrigation water application systems (Brouwer *et al.*, 1985). This type of irrigation method is the most widely used in our country in almost all-large and small irrigation schemes (FAO, 2001). It has been reported by FAO (2001) that 97.8% of irrigation in Ethiopia is done by surface irrigation methods, especially by the furrow system in farmers’ fields and the majority of the commercial farms. Apart from the conventional method, the use of furrow irrigation can be modified to alternate furrows so that it can maintain relatively dry soil conditions.

Ali (2011) pointed out that furrow irrigation is one of the oldest controlled irrigation methods. A furrow is a small, evenly spaced, shallow channel installed down or across the slope of the field to be irrigated parallel to row direction. In this method, water is applied to furrows using small discharges to favor water infiltration while advancing down the field. Furrow irrigation can thus be defined as a partial surface flooding method of irrigation (normally used with clean-tilled crops), where water is applied in furrows or rows of sufficient capacity to obtain the designed irrigation system.

2.2.1 Conventional furrow irrigation, CFI

Conventional furrow irrigation (CFI) or traditional irrigation means irrigating all furrows during consecutive watering. Frequent irrigation under CFI may result in higher evaporation from the soil surface, especially during the early growing season with incomplete ground cover (Sepaskhah and Kamgar-Haghighi, 1997). This irrigation system has sped up the processes of decomposition and removal of organic elements and mobile forms of nutrients in the root zone that eventually, brought to soil fertility losses (Karajeh *et al*., 2000).

2.2.2 Alternate furrow irrigation, AFI

Alternate furrow irrigation (AFI) meant one of the two neighboring furrows alternately irrigated during consecutive watering. It offers an opportunity for reducing the size of irrigation and permits irrigating a field in a shorter time with a given water supply. The reduced size of irrigation may not reduce yields appreciably and thus increase irrigation water use efficiency (Ashinie *et al*., 2016). Besides this, The AFI save quite a good amount of water and is very useful and crucial in areas of water scarcity (Jemal and Mukerem, 2017). Alternate furrow irrigation has been put forward and practiced in the field by furrow or drip irrigation (Kang and Zhang, 2004). It is a new irrigation method which requires that approximately half of the root system is exposed to drying soil while the remaining half is irrigated for full irrigation (Kang *et al*., 2001).

Zhang *et al*. (2000) alternate furrow irrigation method uses less irrigation water but can maintain the same grain yield production as that of conventional furrow irrigation with high irrigation amounts. This is believed to be because of continuous regulation by root drying signal on stomata inhibition and reduced leaf transpiration. When roots are in drying soil, even in a situation where only part of the root system is dry, substantial ABA is produced in the roots and transported through the xylem to the shoots where stomata opening are regulated. AFI takes advantage of this physiological response and exposes part of the root system alternatively to the drying soil. This method of the watering can lead to continuous stomata inhibition and reduced leaf transpiration. Photosynthesis and dry matter accumulation are less affected by such partial stomata closure because photosynthesis and stomata opening has a saturation relationship. Maximum stomata opening does not necessarily lead to maximum photosynthesis and transpiration and stomata opening, however, have a linear relationship (Zhang and Davies, 1991).

2.2.3 Design of furrow irrigation system

Efficient irrigation by the furrow method is obtained by selecting proper combinations of spacing, length and slope of the furrow and suitable size of the irrigation stream and duration of the water application (Michael, 1978). A furrow system may be designed only after gathering information about soils, crops, topography, size and shape of the area to be irrigated. Most furrows in row crops are either parabolic in cross-section or have flat bottoms or about 2:1 side slopes (Hart *et al.*, 1980). Furrow irrigation designs are often needed either for new irrigation schemes or existing projects where improvements are needed (Walker, 1987).

a. Furrow spacing

Furrow can be spaced to fit the crops grown and the type of machines used for planting and cultivation. Furrows should be spaced close enough to ensure that water spreads to the sides into the ridge and the root zone of the crop to replenish the soil moisture uniformly. The lateral movement of water in soils with uniform profiles depends primarily upon the texture of the soil. The spacing in clay soils more than the spacing in sandy soils (Michael, 1978). The spacing of furrows depends on the crop to be irrigated, the type of tillage machinery and the wetting pattern which can be obtained by lateral movement of water in the soil (Booher, 1974). Whereas James (1988) mentioned that standard furrow spacing is often used for some different crops that make use of the same farm equipment. Sandy soils that tend to have a vertical wetted pattern should have closer furrow spacing than clay or loam soils. Soils with non-uniform profiles will generally have the greater lateral movement of water than soils lying above less permeable layers or above abrupt changes in soil texture.

b. Furrow slope

The slope or grade of the furrow is important because it controls the speed at which water flows down the furrow. A minimum furrow grade of 0.05 percent is needed to ensure surface drainage (Michael, 1978).

Ali (2011) reported that furrows can be longer when the land slope is steeper; the maximum recommended furrow slope is 0.5% to avoid soil erosion. Furrows can also be level and are thus very similar to long narrow basins. However, a minimum grade of 0.05% is recommended so that effective drainage can occur following irrigation or excessive rainfall. When the land slope is steeper than 0.5% then furrows can be set at an angle to the main slope or even along the contour to keep furrow slopes. To obtain high irrigation uniformity, the largest stream of water is not the cause of erosion in each furrow at the beginning of irrigation. The reason behind using large stream size was that the entire furrows were wetted as quickly as possible to enable the soil to absorb water evenly through the entire furrow length.

c. Furrow stream size

The size of the furrow stream is one factor that can be varied after the furrow irrigation system was installed. The size of the furrow stream usually varies from 0.5 to 2.5 liters per second (Michael, 1978). Criddle *et al.* (1956) mentioned that the maximum stream need not always be used for good irrigation. A smaller stream will be satisfactory if it will reach the lower end of a field with a" one-fourth time" criterion. Ali (2011) indicated that normally stream sizes up to 0.5 l/s will provide adequate irrigation provided the furrows are not too long. The maximum stream size that will not cause erosion will depend on the furrow slope. In any case, it is advisable not to use stream sizes larger than 3.0 l/s. Furrow stream sizes must be carefully selected to obtain the desired blend of irrigation effectiveness and convenience of operation (James, 1988). Michael (1978**)** suggested the maximum non-erosive flow rate based on the furrow slope as:

$$Q_{max} = \frac{0.6}{S} \tag{2.1}$$

Where q = maximum non-erosive stream, lit/sec, S =slope of furrow expressed as percent**.**

d. Furrow length

The optimum length of a furrow is usually the longest furrow that can be safely and efficiently irrigated. Proper furrow length depends largely on the hydraulic conductivity of the soil. The length of furrow which can be efficiently irrigated may be as short as 45 m for irrigating soils which take up water rapidly, or as much as 300m or longer on soils with low infiltration rates (Michael, 1978). Solomon (1988) stated that optimal furrow length is primarily controlled by the intake rate of the soil and the stream size. The length of furrows varies from 30 meters or less for gardens to as much as 450 meters for field crops and furrow lengths of 90 meters to 200 meters are common (Israelsen and Hansen, 1962). Relatively short furrows are required on sands and other soils with rapid infiltration characteristics and low water-holding capacities. Furrow length can normally be increased as the average depths of an application become larger. (James, 1988) mentioned that furrows can be much longer for deep-rooted crops on clay soils than shallow-rooted crops grown in sandy soils, while Booher (1974) recommended that furrow length should be adjusted according to soil type and slope in fields with large soil and slope variations.

2.3. Surge Flow

The concept of surge flow irrigation was introduced in Bulgaria as a method for improving the uniformity of moisture distribution along the furrow (Varlev, 1971). Stringham and Keller (1979) presented surge flow as a new approach for automating surface irrigation systems in which problems with slow advance and excessive surface runoff occur. Surge irrigation was originally devised as a method to cutback inflow volumes during later stages of irrigation because of the difficulty of automatically reducing flow rates. Now the technique is more commonly used to accelerate the advance phase while reducing the volume of applied water (Walker and Skogerboe 1987) and increasing the uniformity of applied depths (Purkey and Wallender 1989). The ability of surge irrigation to alter soil surface characteristics offers the possibility of increasing the uniformity of application rates. Surge irrigation does not necessarily reduce the variability of infiltration rates.

The benefits of the technique are derived from the ability to reduce intake rates. The primary mechanisms responsible for this decline are a consolidation of the soil surface, filling of cracks with water and/or sediment load, surface sealing during the recession of each inflow cycle and accelerated disintegration of soil aggregates as the result of rapid wetting (Kemper *et al*. 1988). Decreased infiltration rates translate to faster water advance rates so that the advance phase can be completed more quickly with far less water. Hence, the surging technique reduces the absolute difference in opportunity times between the two ends of the field. The ratio of on to off times is the cycle ratio. Although the Cycle time varies during the irrigation, the cycle ratio must remain constant, i.e.the on time equals to the off-time (James, 1988).

Each surge is characterized by cycle time and cycle ratio. The cycle times range from one minute to as much as several hours. Cycle ratios typically range from 0.25 to 0.70. By regulation these two parameters, surge flow can improve irrigation efficiency and uniformity (Walker, 1987). More rapid advance improves the uniformity of the irrigation and allows higher application efficiency to be achieved. Surge irrigation required 20-25% less water than continuous irrigation. Many irrigators found it impossible to complete the advanced phase of irrigation following major cultivation because of the high intake rate. Today, surge flow management practice can be applied to many surface irrigated conditions. It can be either to “cut back” the inflow after an advance and minimize tail water and/or to accelerate the advance on problematic soils (Varlev *et al.*, 1995). When comparing surge and continuous irrigation surge irrigation reduced advance inflow times an average of 20%. Cut-back and surge flow simulation resulted in 5-7% savings in applied volume of water when compared to continuous flow simulation respectively (Izadi *et al.*, 1990). Stated that possible causes for the faster advance rate under surge irrigation include:-

1. Decreased furrow roughness and a more stable cross-section during the infiltration of water between pulses.
2. Redistribution of water during the time that water is turned off, which causes a decrease in the hydraulic gradient in the topsoil layer for the next surge.
3. Air entry and entrapment occurring between pulses.
4. Surface sealing and consolidation of the soil matrix near the soil surface, which decreases the hydraulic conductivity of the topsoil layer.

Kanber *et al*. (2001) compared surge and continuous furrow methods for cotton in the Harran plain. Surge flow reduced the water intake of a surface soil loosened by tillage by 13-23% as compared to continuous flow, thus manifesting an incomparable advantaged to the level furrow systems.

Evans and Leib (2003) illustrated that the advantages of surge flow surface irrigation fall into three broad categories are:

a) Surged water advances to the end of the field at least as rapidly as continuous flow irrigation with the same inflow rates but it had a smaller volume of water, thus greatly improving the uniformity of application during the advance phase.

b) Growers can reduce tail water and deep percolation losses and can improve Application efficiency under proper automated management.

c) Surge irrigation provides an inexpensive means of automating, managing, and accurately controlling the surface application of water to afield while reducing labor requirements.

Mahmood *et al*. (2003) and Ismail *et al*. (2004) studied surge irrigation in Egypt and they found that surge irrigation improves irrigation performance and irrigation water use efficiency, it is imperative to test its validity under different soil and crop conditions.

Horst *et al*. (2007) assessed the impacts of surge-flow irrigation on water saving and Productivity of cotton. The best irrigation water productivity (0.61kg/m3) was achieved with sure -flow on alternate furrows, which reduced irrigation water use by 44% (390mm) and led to high application efficiency, near 85%. Results demonstrated the possibility of applying deficit irrigation in this region.

Sial *et al*. (2006**)** studied the performance of surge irrigation under borders. Keeping in view different parameters like the volume of water, distribution uniformity, application efficiency, deep percolation losses, and yield of wheat. The surge mode of irrigation was convincingly better compared with conventional/continuous irrigation even under the border irrigation.

Valpour (2013) studied different types of inflow regimes include continuous flow, cutback, fixed surge, and variable surge and showed that surge irrigation method Was able to increase irrigation efficiency to the amount of 28.37% and reducing Inflow to the amount of 16.6m^3 water saving.

Horst *et al.* (2005) study on cotton furrow irrigation has shown that cutting the volumes applied by controlling the cut-off times and the adoption of alternate-furrow irrigation could lead to considerable water savings relative to traditional furrow irrigation. The same study also identified the need to better adjust the irrigation timings because the traditional irrigation results in small soil moisture deficits at the time of irrigation, thus leading to high percolation and runoff volumes. The need to assess the potential water saving when adopting surge flow was then identified

2.4 Soil Infiltration Characteristics

The movement of water from the surface into the soil is called infiltration. Infiltration characteristics of soil are one of the most important parameters in the design, of furrow irrigation (Holzapfel *et al*., 2012). It is the dominant factor in determining the efficiency and uniformity of furrow irrigation applications. The infiltration characteristic controls the rate of advance and recession, whereby high infiltration results in slow advance and rapid recession. Accurate estimation of infiltration parameters is time-consuming and cost-effective to design an efficient irrigation system since infiltration properties exhibit temporal and spatial variability; therefore, many measurements are needed to explain average field conditions (Hamed, 2010). Indeed, the infiltration rate is one of the most sensitive and difficult hydraulic parameters in surface irrigation systems that should be measured or estimated. There are several methods for measuring soil infiltration, depending on the type of irrigation, e.g., basin, border, or furrow irrigation. In furrow irrigation systems, soil surface exposed to water is relatively parabolic and water infiltrates into the soil under two-dimensional conditions. Each method that is used to measure infiltration rate has to simulate irrigation condition as well, e.g. blocked end furrow, inflow–outflow, double-ring infiltrometer, two-point (Elliott and Walker,1998), advance (Benami and Ofen, 1984), and multi-objective optimization methods (Walker, 2005). The accurate estimation of soil infiltration parameters is crucial to the accurate simulation of surface irrigation. Walker (2005) and Gillies *et al.* (2007) have shown that the methods with more intensive data lead to the best outcome, consequently, methods that employ runoff and/or recession data, as well as the full inflow hydrograph, are preferable.

2.4.1 Infiltration measurement

Infiltration data are collected with ring infiltrometer, the ponding method, the blocked furrow technique, the inflow - outflow method, and recirculating infiltrometer. Infiltration characteristics can also be determined from advance data using the two-point method (James, 1988 and Walker, 1989).

a. Ring infiltrometer

Cylinders are driven in the soil using a driving plate set on the top of the infiltrometer and a heavy hammer. The infiltration rate has estimated the rate at which water is added to the inside by cylinder, (Michael, 1978; James, 1988 and Walker, 1987). Double ring infiltrometer is the most commonly used method for determining the infiltration rate as described by Haise *et al,* (1956), and Michael (1978). A double-ring infiltrometer consists of two concentric rings usually about 25 cm deep and are formed of 2 mm rolled steel. The inner cylinder, from which the infiltration measurements are taken, is usually 30 cm in diameter. The outer one 60 cm in diameter provides a buffer pond of water that minimizes the lateral movement of water from the inner ring when the wetting front has penetrated below the bottom of the rings. The ring infiltrometer data may not agree with the actual amount of infiltration that occurs during irrigation, they are often adjusted utilizing measured inflow, runoff, advance and recession data (James, 1988). The results obtained with cylinders are indicative of the rate to be expected during irrigation and considerable departure usually occurs when furrows or sprinklers apply the irrigation water. Hence, the cylinders are generally used to obtain an index from which design values can be obtained based on local experience (Israelsen and Hansen, 1962).

b. The inflow- outflow method

Inflow-outflow methods for determining infiltration provide good measures of total infiltration (Walker, 1989). In the inflow-outflow method, the infiltration rate is determined by measuring the rates of flow into and out of a section of a furrow when the depth of flow in the furrow is changing slowly, the infiltration equals the difference between the inflow and outflow rates. Flumes or weir plates can be used for measuring inflow and outflow (Michaell, 1978 and James, 1988).

c. The blocked furrow method

Blocked furrow technique, the furrow cross-section must be measured. Thus the cumulative infiltration function is developed in the same way as for cylinder and pond measurements (Walker, 1987). The blocked furrow method involves installing cutoff plates at the up and downstream ends of test sections in three adjacent furrows. Infiltration is measured in the center furrow by measuring the volume of water required to maintain a constant water level. The furrows on each side of the test furrow provide a buffer that improves accuracy. The depth of infiltration is computed by dividing the measured infiltration volume by the product of furrow spacing times the length of the test section (James, 1988).

d. The pounding method

Ponds can be created using earth bunds or dykes around an area on the ground surface and operated in the same manner and by using the same procedures as for cylinders (Schwab et *al.*, 1981 and Walker, 1989). The disadvantage of this technique is that the edge effect can be significant (Walker, 1989).

e. Recirculating infiltrometer

A recirculating infiltrometer is an inflow-outflow device. It is used for evaluating infiltration primarily in furrows. The primary advantage of this device is that both the geometric and hydraulic conditions in the field furrow are simulated during the test (James, 1988 and Walker, 1987).

2.4.2. Infiltration models

a) Simple Kostiakov equation

Kostiakov Equation (1932): it expresses cumulative infiltration capacity as

$$Z = kt^{a} \tag{2.2}$$

Where, Z is Cumulative infiltration capacity

k and *a* are local parameters with k > 0 and 0 < a< 1.

To determine a and b parameters, taking natural logarithm to both side

$$lnZ = \ ln(Kt^{a}), \quad \text{and this can be written as}$$

$$lnZ = lnk + alnt \tag{2.3}$$

Different cumulative infiltration capacity at different time and lnt was arranged on excel and then graph was used to find *lna* as intercept and *b* as slope.

b) Modified Kostiakov - Lewis infiltration model

The modified Kostiakov infiltration equation is the rate of flow of water along the surface is affected by the magnitude of infiltration or entry of water into the soil profile. The higher the infiltration rate, the slower the advance of water down the bay or furrow and rapid recession. The infiltration characteristic of the soil is therefore a key variable that determines the performance of a surface irrigation application system (Raines and Smith, 2007). The most commonly used model to describe the soil infiltration characteristic for surface irrigation is the Kostiakov-Lewis equation

$$Z = kt^{a} + f_{o}t \tag{2.4}$$

where; Z is the cumulative infiltration (m^3/m), t is the time (min) from the commencement of infiltration, *k* ($m^3/min/m$) and *a* (non-dimensional) are fitted parameters and *fo* ($m^3/min/m$) approximates the steady or final infiltration rate.

2.5 Flow Phases of Furrow irrigation

When water is applied to the soil surface by any the three surface irrigation methods (furrow, border strip, or basin) it infiltrates in the soil to the required depth to bring the soil back to field capacity. Using the furrow irrigation method part of the soil is wetted and the water movement through the soil is both vertical and lateral (FAO, 1989).

2.5.1 Advance phase

The advance phase begins when water is applied onto the field at the upstream end and ends when it reaches the downstream end of the field. The stream size applied at the head of the furrow, border strip and basin should be greater than the soil infiltration rate. This means that part of the water advances over the soil surface to the end of the field and part of the water infiltrates into the soil. The advance rate in the furrow is a function of soil texture and furrow design. In soils that are fine in texture, water is absorbed slowly and higher advance rates are observed. Where soils are quite permeable, more water is infiltrated and advance rates are lower. Furrows that are narrow and deeper exhibit a lower amount of water infiltration and faster advance rate. This configuration is used to discourage excessive percolation at the upper end. On the contrary, shallow and wide furrows leave more wet areas for the water to infiltrate resulting in lower advance rate (Michael, 2008). The performance of furrow irrigation can be improved by measuring furrow irrigation advance rate, from which optimized values for irrigation parameters can be determined and implemented in subsequent irrigation.

When water is applied to the field, it advances across the surface until the water extends over the entire area (Walker, 1987). While Bassett *et al.* (1980) reported that the advance phase is that portion of the total irrigation time during which water advances in overland flow from the upstream end of the field towards the lower field boundary. The advance phase ends when water reaches the downstream end of the field. During the advance, a sharply defined waterfront with water on the inflow side of the front and dry field on the other side moves across the field (James, 1988). Walker (1987) mentioned that there are two important measurements necessary during the advance phase and these are:

a) The discharge hydrograph into the field or the test furrows.
b) The elapsed time from the introduction of the water until the advancing front reaches each of the stations along the direction of flow.

The rate of advance decreases with time as the wetted area behind the water front increases.

2.5.2 Storage or ponding phase

Walker (1987) stated that the interval between the end of the advance and when the inflow is cut off could be called the wetting or pounding phase (storage phase). It occurs only if the inflow to the field continues after the water has advanced to the downstream end of the field (Bassett *et al.,* 1980)

2.5.3 Depletion phase

After stopping the inflow at the head end, water may continue to pond on the soil surface for a while. Some water still infiltrates the soil, with the excess being collected as runoff. At a certain moment, water will start receding from the head end. The time between the stop of the inflow at the head end and the appearance of the first bare soil that was underwater is called the lag time or depletion phase. James (1988) stated that the depletion phase begins when the storage phase ends and ends when the depth of flow at the inflow end of the field becomes zero.

2.5.4 Recession phase

For surface irrigated fields the recession phase ends when surface water disappears at each measuring station. The interval during which water will infiltrate at a specific location is called the intake opportunity time. It begins when the water flow first reaches the point (advance) and ends when the water eventually drains from that point (recession). Because infiltration is assumed to be uniform over the field, the variation in intake opportunity time is also an indication of application uniformity (Walker, 1987). James (1988) stated that the recession phase begins when the depletion phase ends, A drying front moves from the inflow to the downstream end of the field. Recession continues until either the dry front reaches the end of the field or it encounters a receding front moving towards the inflow end of the field.

$$t = ax^b \tag{2.5}$$

Where t is a time of waterfront recession at distance X and “a” and “b” are constants.

2.6 Surface Irrigation Hydraulic Models

In surface irrigation, water flows along the surface as it infiltrates into the soil profile. Due to the variability of soil intake rates (Walker 1989), the flow is both spatially varied and unsteady (Walker and Skogerboe 1987). This condition is hydraulically similar to unsteady open channel flow and thus can be described by Saint Venant equations. These equations are based on the principle of conservation of mass or continuity.

2.6.1 Volume balance model

A computer model was developed to use runoff data for calculating the Kostiakov-Lewis infiltration equation parameters. This model uses a simple volume balance approach to estimate the parameters from commonly collected field data (Gillies and Smith 2005). Several field data sets have been used to verify the model. Infiltration parameters were calculated using both advance and runoff data. This procedure was the most beneficial when the infiltration parameters are expected to represent soil hydraulic characteristics for times greater than the completion of the advance phase. The volume balance equation (law of conservation of mass) can be used to describe the flow of water longitudinally down the furrow, including the infiltration of water into the soil.

$$Q_{ot} = V_{I+}V_s + V_r \tag{2.6}$$

The Kostiakov-Lewis infiltration equation yields the cumulative infiltrated volume as a function of time. The model attempts to minimize the difference between the calculated and measured advance distances during the advance phase and between the calculated and measured runoff volumes during the storage phase by incrementing the parameters of the Kostiakov-Lewis infiltration equation. The algorithms for each phase are:

$$SSE = \sum_{i=1}^{Na}\left[\frac{Q_0 t_i}{\delta_y A_o + \delta_{z1} k t i^a + \delta_{Z_2} f_o t i^a}\right]^2 \tag{2.7}$$

$$SSE = \sum_{i=1}^{Nr}\left[V_{Ri} - Q_0 t_i \;-\; \delta_y A_o L + \delta_{z1} k t i^a L + \delta_{Z_2} f_o t i^a L\right]^2 \tag{2.8}$$

Where SSE = standard square error; xi = measured advance distance; ti = time; VRi = runoff volumes; Na = the number of advance points; Nr = number of runoff volumes; σz2 and σz1 = subsurface shape factors; Ao = flow area; Q_o = inflow discharge; and σys = surface shape factor.

2.6.2 Hydrodynamic model

The hydrodynamic models are based on the solution of the full Saint-Venant equations, *i.e.* both the equations of conservation of mass and momentum. Due to their accuracy, they are often used for the calibration and evaluation of simpler models (Gillies, 2008). The hydrodynamic equations used in the mathematical models for describing the overland flow in surface irrigation are the equations of conservation mass and momentum, known as the Saint-Venant equations (Chow,1959 and Strelko, 1969) as stated in (Ahmed *et al.*,2005). These equations are:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}+\frac{\partial Z}{\partial \tau}=0 \tag{2.9}$$

$$\frac{1}{Ag}\frac{\partial Q}{\partial t}+\frac{2Q\partial Q}{A^2g\partial x}+\left(1-\frac{Q^2T\partial Z}{A^2g\partial \tau}\right)\frac{\partial y}{\partial x}-S_O+S_f \tag{2.10}$$

Where, Y is depth of flow (m) ; T is the time from the beginning of irrigation (s); τ is intake opportunity time (s); Q is discharged (m^3/s); X is the distance along the field length (m); Z is infiltration rate (m/s); g is the acceleration due to gravity (m/sec^2); So is the longitudinal slope of the field (m/m); Sf is the slope of energy grade line and also called friction slope (m/m); A is cross-sectional area (m^2) and T is top width of flow (m).

2.6.3 Zero inertia model

The zero inertia models are a simplified form of the full hydrodynamic model without the acceleration and inertia terms. Strelko and Katopodes (1977) therefore simplified the full hydrodynamic equations by neglecting the inertial terms in the Saint Venant equations. The inertia terms are neglected

$$\frac{\partial y}{\partial x}=s_0-s_f \tag{2.11}$$

Where, So is the longitudinal slope of the field (m/m); Sf is the slope of energy grade line and also called friction slope (m/m)

2.6.4 Kinematic wave model

The kinematic wave model assumes that flow depths are at normal depth everywhere along the field. It is as accurate as zero inertia or a hydrodynamic model under conditions at which the normal depth assumption is valid –steep slopes - and experiences fewer computational problems (Lima *et al.,* 2014). However, it assumes a unique relationship between discharge and depth. The kinematic wave model cannot model irrigation systems with a closed downstream boundary, which exhibits backwater effects. For most applications, users will not have to select the solution model. The kinematic wave model uses further simplifications and uniform flow assumptions. The simplest model, the depth gradient of the flow (δy/δx) and inertial terms of the momentum equation are often small in comparison with those of the bottom and friction slopes. Therefore, Eqn. (2.10) can be further simplified by assuming that the depth gradient and inertial terms are negligible and thus Equation (2.5) is obtained (Raines *et al*., 2007) as follows:

$$S_o = S_f \tag{2.12}$$

This assumption shows that the depth of flow at a point along the field is uniform. This approximation greatly simplifies the mathematical solution of the momentum equation.

2.7 Surface Irrigation Simulation Model, SIRMOD

In recent years some surface irrigation simulation models for assessing surface irrigation system performance have been developed. Simulation in surface irrigation systems is the process of mathematically describing the hydraulic characteristics of water as it flows from one end of the field to the other. This is achieved by the use of computer models based on mathematical equations known as Saint Venant equations, SIRMOD (Walker, 2005). SIRMOD was developed by the University of Utah (Raine and Walker, 2004). The software can be used to simulate surface irrigation processes such as furrow and border irrigation and to optimize the irrigation technical parameters such as the cross-section of furrows, ditches and borders, inflow rate and field slope (Clemmens *et al.*, 1999). Based on the zero-inertia, kinematic wave and hydrodynamic models, the software also has a function that can simulate, evaluate and design the irrigation technical parameters of furrows, borders and basins (Li *et al*., 2012). SIRMOD is composed of an infiltration model and a simulation model. The infiltration functions are based on the modified Kostiakov–Lewis equation and combined with the water balance equation (Clemmens *et al*., 1999).

2.8 Crop Water Requirement and Irrigation Scheduling

Several factors can affect soil-crop-water regime such as weather, crop characteristics, management and environmental factor. The principal weather parameters affecting crop water requirement are radiation, air temperature, humidity and wind speed sunshine hour. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different evapotranspiration levels in different types of crops under identical environmental conditions (Allen *et al.,* 1998).

2.8.1 Estimation of crop water requirement

The term crop water requirement is defined as the amount of water required to compensate the evapotranspiration loss from the cropped field. For the determination of crop water requirement, the effect of climate on crop water requirement, which is the reference crop evapotranspiration (ETo) and the effect of crop characteristics (Kc) are important (Doorenbos and Pruitt, 1977). The growth and yield of any crop is 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). The accuracy of determination of crop water requirements will be largely dependent on the type of the climatic data available and the accuracy of the method chosen to estimate the evapotranspiration (Allen et al., 1998). Based on the comparative studies of the reference evapotranspiration methods and recommendations of a panel of experts and researchers organized in FAO, Rome, in 1990, the Penman Monteith equation has been adopted as the globally best performing method of estimating evapotranspiration.

The calculation can be done using CROPWAT model. Reference evapotranspiration (ET_o) is calculated based on the FAO Penman-Monteith method (Allen et al., 1998) as:

$$\mathrm{ETo} = \frac{0.408\Delta(\mathrm{Rn}-\mathrm{G})+\gamma\frac{900}{\mathrm{T}+273}(\mathrm{es}-\mathrm{ea})}{\Delta+\gamma(1+0.34\mathrm{u}_2} \qquad (2.13)$$

where, ET_o is reference evapotranspiration (mm/day), Rn is net radiation at the crop surface (MJ/m2/day), G is soil heat flux density ($MJ/m_2/day$), T is mean daily air temperature at 2 m height (°C), U_2 is wind speed at 2 m height (m/s), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), $e_s - e_a$ is saturation vapor pressure deficit (kPa), Δ is slope of vapor pressure curve (kPa/°C), γ is psychometric constant (kPa/ °C).

The equation uses standard climatological records of solar radiation (sunshine), air temperature, humidity and wind speed. To ensure the integrity of computations, the weather measurements should be made at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water. The updated values of crop coefficients are determined from Allen *et al.* (1998).

$$ETc = ETo * Kc \qquad (2.14)$$

Where, ETc is crop evapotranspiration (mm/day); Kc is crop coefficient; ET_o is reference evapotranspiration (mm/day) Reference evapotranspiration (ET_o) can be estimated using the Penman-Monteith equation. Various crop growth stages and their respective lengths are identified for the locations of interest, and then Kc for the various stages of the crop is determined. Kc values are then adjusted for frequency of wetting condition for rain or irrigation. Then crop coefficient curves are developed to determine Kc values for periods of any length. Crop ET is then calculated for well-watered conditions for each period of interest as the product of ET_o and Kc. Having ETc and all necessary meteorological data, crop water requirement can be computed with the aid of CROPWAT program (Allen et al., 1998).

2.8.2 Irrigation scheduling

Irrigation scheduling should be based on sound principles and techniques for sustaining greater control over the soil-crop-water regime and for optimizing water productivity in relation to all other essential agricultural inputs and operations. There are certain limits for soil water. Field capacity is when the soil pores are so full of water that the next drop will leach downward out of the rooting zone. The opposite extreme is wilting point, the level at which plant roots can no longer take in water. Thus the goal of a soil, water and plant continuum is to maintain the soil, water between these extremes, allowing nutrient movement, aeration and supplying water in excess of evaporation and transpiration (Yi Lou *et al.*, 2006).

2.9 Performance Evaluation of Furrow Irrigation

Furrow irrigation performance indicators are water application efficiency (Ea), Storage efficiency (Es) and distribution uniformity (DU). Ea is a management performance indicators and DU characterizes the irrigation system (ASABE.2003).

2. 9.1 Water application efficiency

Wigginton and Raine (2001) indicated that application efficiency is the percentage of water delivered to the field that is ready for crop use. As the application efficiency is a measure of how efficiently water has been applied to the root zone of the crop. Thus, application efficiency (Ea) is calculated as:

$$E_a = \frac{\text{water storde in the root zone } (\mathrm{D_{ad}}\ )}{\text{water applied to the field} (\mathrm{D_{ap}})} \qquad (2.15)$$

Where E_a is application efficiency %, Dad is the depth of water stored in the root zone (mm) and D_{ap} is the depth of water applied to the furrow (mm).

According to Jurriens et *al*. (2001), application efficiency is a common yardstick of relative irrigation losses and this definition is valid for all situations and all irrigation methods. Losses From the field occur as deep percolation and as field tail water or runoff and reduce the Application efficiency. To compute Ea, it is necessary to identify at least one of these losses as well as the amount of water stored in the root zone. This implies that the difference between the total amount of root zone storage capacity available at the time of irrigation and the actual water Stored due to irrigation be separated, i.e.the amount of under irrigation in the soil profile must be determined as well as the losses (FAO,1989).

Lesley (2002) explained and defined the situation of application efficiency with time and event-specific. The equation could be used for a single irrigation event or more as a term reflecting seasonal performance. The difference in how it is used can be quite dramatic. For example, the first irrigation event using furrow irrigation can have a very low application efficiency if the length of the run is so much longer, furrows are freshly corrugated stream size is wrong, or for several other reasons.

2.9.2 Storage efficiency

The concept of water storage efficiency shows how completely the water needed before irrigation has been stored in the root zone during irrigation. It is defined as follows:

$$\mathrm{Es} = \frac{\mathrm{Ws}}{\mathrm{Wn}} * 100 \tag{2.16}$$

Where Es % is water storage efficiency (%); Ws is water stored in the root zone during irrigation and Wn is water needed in the root zone before irrigation.

2.9.3 Distribution uniformity

An important component of the evaluation of in-field irrigation performance is the assessment of distribution uniformity. Distribution uniformity concerns the distribution of water over the actual field and can be defined as the infiltrated depth or volume in the least-irrigated 25 percent of the field divided by the infiltrated depth or volume over the whole field: Distribution uniformity (DU) is an expression that describes the evenness of water application to a crop over a specified area, usually a field, a block or an irrigation district. It applies to all irrigation methods as all irrigation systems incur some non-uniformity. Distribution uniformity (*DU*) was determined as defined by Jemes (1988) as follows::

$$\mathrm{DU} = \frac{D_{min}}{\mathrm{D_{ave}}} * 100 \tag{2.17}$$

Where, DU = Distribution uniformity (%), D_{min} = the minimum infiltrated depth (mm), and $\mathrm{D_{ave}}$ = the mean of depths infiltrated over the furrow length (mm)

3 MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location and Description

The field experiment was conducted at Melkassa Agricultural Research Center, MARC during the dry season of 2019/20. The center is geographically located (8°24′36” N - 8°26′24” N latitude and 39°19′12” E - 39°21′48” E longitude at an altitude of 1,550 m.a.s.l) in the Central Rift Valley of Ethiopia, Oromia Regional State. The center is about 107 km to the east of Addis Ababa, the capital city of Ethiopia and 17 km Southeast of Adama.

3.1.2 Long- term climatic data

The long-term climatic data (1977-2017) indicate that the average annual rainfall in the area is 810.26 mm with a mono-modal rainfall pattern. The daily mean maximum and minimum temperature of Melkassa was 28.7 and 13.8°C, respectively. The monthly mean maximum temperature is between 30.95°C and 27.57°C during May and December respectively (MoA, 2000)

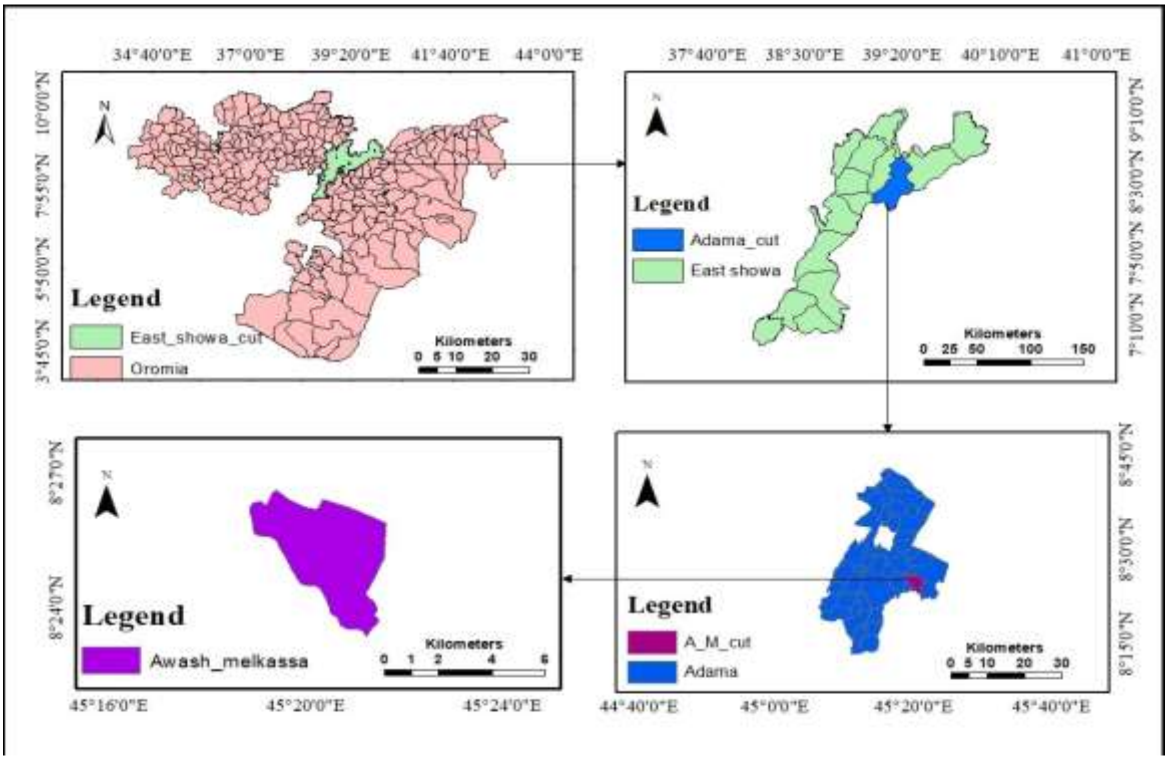


Figure 3.1. Location Map of Melkassa Agricultural Research Center

3.2 Soil Sampling and Analysis

Representative soil samples were taken to investigate some of the soil's physical and chemical properties in the study area. Composite soil samples were taken from 0 – 15, 15–30 and 30 – 60 cm depth of the soil at three equal distances within the experimental field.

3.2.1 Soil physical characteristics

The soil samples collected from the different depths were analyzed for texture, field capacity and permanent wilting points following standard procedure for soil laboratory.

Soil texture: Hydro-metric method was used to identify the particle size distribution of sand, silt and clay content from a soil sample collected. The textural classes of the soils were then determined using the USDA textural triangle (1975).

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

Bulk density (BD): For the determination of bulk density, undisturbed soil samples were collected from a depth of (0-15, 15-30 and 30-60) cm and oven-dried for 24 hours at a temperature of 105^0C. Then compute as:

$$\rho_b = \frac{w_d}{v_s} \tag{3.1}$$

Where, pb is the bulk density of the soil (g/cm^3), w_d is the weight of oven-dry soil in (gm) and Vs is the volume of the same soil sample/ core sampler (cm^3).

3.2.2. Soil chemical characteristics

The soil chemical characteristics such as PH, electric conductivity (EC), and organic matter (OM) were analyzed from the composite samples using standard procedures for laboratory analysis (Sahlemedhin and Taye, 2000).

3.2.3 Soil infiltration rate

The infiltration test was carried out within the experimental field using a double-ring infiltrometer to determine the basic infiltration rate of the soil as described by Michael (1978). The double ring infiltrometer was placed at three equal distances within the experimental field. The cylinders were carefully driven into the ground to a depth of about 10 cm with an ordinary hammer and using a short wooden plank to prevent damage to the edges of the metal cylinder. Care is taken to keep the installation depth of the cylinders the same in all trials. The drop-in water level in the inner ring was recorded from the measuring ruler attached to the inner ring. The levels of water in the inner and outer rings were maintained identical. Readings were taken from the inner ring at a predetermined time interval with an extended interval between readings. The reading continued for a minimum of three hours until the drop in water level for two consecutive reading of 30 minutes reading remained the same.

3.3 Experimental Treatments and Design

The experimental treatments include two irrigation application, viz., Alternate furrow irrigation (AFI) and conventional furrow irrigation (CFI) and three irrigation flow system, viz., continuous flow (C), Surge flow$_1$ (CR = 1/3) and Surge flow $_2$ (CR = 1/2) of 10 minutes cycle time. The experiment had six treatment combinations with three replications. The experiment was arranged in a Randomized Complete Block Design. The details of the experimental treatment setting and treatment combinations are present in Table 3.1.

Table 3.1 Experimental treatment combinations.

Irrigation application	Irrigation level	Treatment combination	Treatment numbers
Conventional (CF)	Continuous(C)	CFC	T_1
	Surge flow1 (s_1)	CFS_1	T_2
	Surge flow2 (s_2)	CFS_2	T_3
Alternative (AF)	Continuous flow(C)	AFC	T_4
	Surge flow1 (s_1)	AFS_1	T_5
	Surge flow2 (s_2)	AFS_2	T_6

From the known furrow length and width, stream size and depth of application, surge parameter can be mathematically computed as follows:

$$Tc = Ton + Toff \tag{3.2}$$

Where, Tc = cycle time, Ton = cycle on time, Toff= cycle off time

$$Sn = Tn/Ton \tag{3.3}$$

$$Tr = Ton/Tc \tag{3.4}$$

Where, Sn = numbers of surges, Tr = cycle ratio

$$\mathrm{Toff} = \frac{(1-\mathrm{Tr})}{\mathrm{Tr}} * \mathrm{Ton} \tag{3.5}$$

3.4 Preparation of the Experimental Site

The experimental field was divided into 18 plots and the plot size was 50 m length by 3m width dimension with 1.8 m between the plots, 3 m free space between the replications. Each plot has five furrows and four ridges for irrigation water application with 60cm furrow spacing and 50 m furrow length (Fig. 3.2.) The five consecutive furrows were used for each treatment application and data were collected from the center three furrows, whereas the outer furrows were used as buffers to reduce border effect.

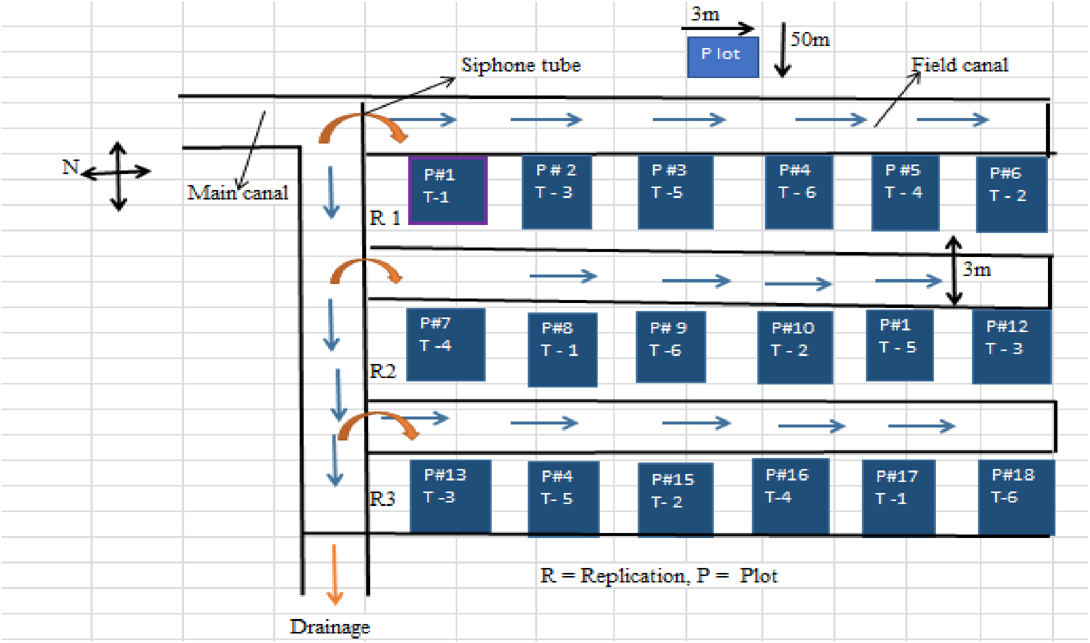


Figure 3.2. Experimental layout

3.5 Crop Establishment and Management Practice

The selected haricot bean variety was sown on a well-prepared field on March 13, 2020. A gentle furrow gradient was maintained to all plots. Each plot was pre-irrigated well before sowing. Seeds were sown at a spacing of 60cm between rows and 10cm between plants two days after pre-irrigation. Sowing was done at top of ridges to a depth of 5cm. The recommended rate of 100Kg/ha DAP and 100 Kg/ha Urea were uniformly applied as per the recommendation made for the center. Urea was applied in two splits, half at sowing and another half twenty days after sowing (at the end of establishment stage or beginning of vegetative stage). Light irrigation was given right after sowing. The rooting depth of the haricot bean during the establishment stage is 30 cm (Doorenbos *et al*., 1979). Thus the plots were initially given irrigation for 30 cm root depth at germination to attain uniform establishment and treatment was then started after establishment irrigation. Irrigation was applied at the constant head from the supply channel constructed at the upper side of each plot for all plots. All other cultural practices other than treatment variables were done to all plots per the recommendations made for the area.

3.6 Data Collection

The primary data was collected from field focusing on furrow irrigation practices and used as the basic input for SIRMOD software models were collected from the furrows field, viz., field topography, inflow rate, furrow geometries (furrow length, furrow depth, furrow width, furrow spacing, furrow bottom slope, furrow cross-sectional area and wetted perimeter), soil infiltration parameters, soil roughness, application depth and cutoff time. Also, the secondary data collected from the institution include climate data, crop type and pattern. The required data such as furrow characteristics, soil moisture contents and soil infiltration parameters were collected from February to June 2012. The climatic conditions and soil properties of the research center were the main input data for the experiment.

3.6.1 Meteorological data

Metrologic data including maximum and minimum temperature mean daily relative humidity, daily sunshine hours, wind speed, rainfall, and evaporation were obtained from the meteorological observatory of Melkassa agricultural research center that is situated near the experimental field. The collected data were used as input for the determination of reference evapotranspiration, ETo using FAO cropwat8.0 software (Allen et al., 1998).

3.6.2 Soil moisture content determination

The soil moisture was determined gravimetrically using soil auger. Soil samples are collected from successive stations along the furrows. The soil sample was taken at 0.15m increments from the soil surface to a depth of 0.6 m before and after irrigation. Soil samples were oven-dried at 105°C for 24 hours, and then weighted to determine moisture content as a percentage on dry mass basis following Eq. (3.2).

$$\theta_M = \frac{M_w - M_d}{M_d} * 100 \tag{3.6}$$

Where θ_M is moisture content on a mass basis (%), Mw is the mass of wet soil sample (gm) and M_d is the mass of the oven-dry soil sample (gm).

To convert the moisture content from mass basis to moisture content on a volume basis as percentage and depth basis (cm/m depth) the corresponding bulk density was multiplied by moisture content on a mass basis

$$\theta v = \frac{\rho_b}{\rho_w} * \theta m * 100 \tag{3.7}$$

Where θ_V is volumetric moisture content (%) and *p*d is soil bulk density (g/cm^3) θm is moisture content on a mass basis (%)

3.7 Determination of Crop Water Requirement and Irrigation water Management

3.7.1 Determination of crop water requirement

CROPWAT software was used for determining reference evapotranspiration (ETo) using FAO Penman-Month method. The daily climatic data, viz., maximum and minimum temperature, humidity and sunshine hours are used by the model to calculate ETo. Excel sheet was used to compute crop water requirements and estimation of irrigation requirements. Crop data, crop coefficient and soil data were utilized as input in the determination of crop water requirement and irrigation requirement. The calculation for crop water requirement was based following Eq. (3.4).

$$ET_C = kc * ET_O \tag{3.8}$$

Where, ETc is crop requirement (mm/day), Kc is the crop coefficient (Fraction) and ET_O is reference crop evapotranspiration (mm/day).

Table 3.2 Date of dry bean growth stage and crop coefficient (kc)

Growth stage	Initial	Dev't	Mid	Late
Dev't days	15	25	35	15
Root depth(m)	0.3	0.6	0.8	0.8
kc	0.37	0.4	1.15	0.35

Source: Allen et al., 1998

3.7.1 Irrigation water scheduling

The depth of water to be applied was based on allowable soil moisture depletion fraction (p) and irrigation water was applied at regular soil moisture observation when 40% of the total available water (TAW) depleted within the root depth during the growing season. Allen et al. (1998) indicated the p-value for dry bean to be 0.45 and pointed out that for hot dry weather conditions, where ETc is high, the depletion fraction is 10-25% less than the value indicated.

The irrigation schedule was fixed based on readily available soil water (RAW), the fraction of TAW that a crop can extract from the root zone without suffering water stress and ultimate provide maximum crop production. The RAW was obtained from the following expression.

$$RAW = p * TAW \tag{3.9}$$

Where, RAW is the readily available water (mm), p is depletion fraction (fraction) and TAW is the total available water in the root depth (mm/ depth of soil).

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:

$$TAW = (FC - PWP) * Sg * Drz \tag{3.10}$$

Where FC and PWP (% weight basis); Drz is the maximum effective root zone depth (mm) and Sg is the specific gravity.

The soil moisture depleted between irrigation at any time was computed using the equation

$$SMD = ((\theta_{FC} - \theta smc) * BD * D_{rz}) \tag{3.11}$$

Where, SMD is the depth of soil moisture depleted after last irrigation at the time of moisture testing (mm), θ_{FC} is soil moisture contents at FC (g/g); θ_{SMC} is soil moisture content at the time of moisture testing (g/g), BD is bulk density, and D_{rz} is the maximum effective root zone depth at times of sampling (mm).

The gross irrigation requirement, IRg was computed by adopting field application efficiency, Ea of 60% for surface irrigation and computed from the following expressions:

$$IRg = \frac{RAW}{Ea} \tag{3.12}$$

Where, IRg is the gross depth of irrigation (mm), RAW readily available water (mm) and Ea is the field application efficiency (%).

The depth of irrigation water to be applied in each furrow was measured using a 32 mm diameter pipe buried in the upstream of each furrow and adapted 8 cm head above the center of the pipe. The flow of water to each plot was controlled by the height of difference between the water level in the field ditch and free water level at the outlet of a 4.2 cm diameter siphon tube was estimated by using Eq. (3.10) (Michael, 1997)

$$\mathrm{Q} = 0.65 \times 10^{-3} \times a \times \sqrt{2gh} \tag{3.13}$$

Where, Q is discharged from siphon tube (l s^{-1}), a is the cross-sectional area of the tube (cm^2), g is the acceleration due to gravity (9.81 cm s^{-2}) and H is effective head causing flow (cm).

Accordingly, the time required to deliver the desired depth of water into each furrow was calculated using the following equation.

$$T = \frac{IRg * A}{60 * q} \tag{3.14}$$

Where, IRg is the gross depth of water applied (mm), A is the area of each furrow (m^2), T is application time (min) and q is the flow rate (l/s.)

Irrigation interval was computed using the following equation:

$$I = \frac{RAW}{ETc} \tag{3.15}$$

Where, RAW is mm, I is irrigation interval (days) and ETc is crop water requirement (mm/day).

3.8. Furrow cross-sectional area

Furrows were made by using a tractor-drawn ridge. The bed of furrows was leveled manually and the parabolic shape was determined. The parameters (wetted perimeter, top width, and bottom width and flow depth) were measured with tape meter and a more detailed look at the furrow shape measurements could be provided. A flat wooden placed horizontally across the furrow at every 5m distance along the furrow length and local wooden pieces installing vertically was used to measure the furrow geometry such as width, depth and cross-sectional area.

The average of all furrows was calculated to get the overall furrow shape parameters. The geometry of furrows is important when evaluating hydraulic flow characteristics and surface storage. The flow cross-sectional area and wetted perimeter of furrow are estimated as parabolic channel was measured.

3.9 Furrow-bed Slope

The bed or bottom slope of furrow was maintained as 0.2 % with the help of staff level and carefully checked by manual to level the bed slop of furrows. The slope of furrows that determined in the field was used for evaluating of furrow irrigation system. The slope of the furrows bed was measured by used the simple procedure of surveying instrument. A surveying instrument was used to adjust the level of the land at different locations throughout furrow lines and the weighted average method was used to calculate an average furrows slope, where each line was divided into 5m intervals and the slope was estimated for each individual furrow. Finally, a weight was assumed for each sector and the weighted average slope was selected of 0.2%. Tadolite, and level rod (staff level), stake and measuring tape were used to measure the bed slope of furrow. Wooden stakes were driven at the upstream end of the furrow at regular intervals of 5 m along the irrigation run and at the downstream end of the strip. The staff level was set up in furrow at convenient location from where several stations could be read. For accurate work the staff level was set up with some distance from the stations where the readings were taken. The first reading was taken on the stake established at the upstream end of the furrow assumed as the bench mark (B.M.). It was assumed the bench mark elevation as 100.00 m. The level reading on bench mark was added to elevation of the bench mark to obtain the height of the instrument. Leveling rod was then placed on the stakes downstream. The rod readings were subtracted to obtain the elevation of the station and the back site and foresight reading was taken at stations as continued as before until the downstream end of the furrow is reached. When the land slope is uniform, the percentage slope is determined as follows:

$$\text{Percentage slope} = \frac{\text{Difference in elevation betewen the first and last point}}{\text{Distance between the first and last point}} * 100 \qquad (3.16)$$

3.10 Surface Irrigation Process

To evaluate the irrigation efficiencies in surface irrigation, the experimental procedure was based on the following steps:

a. Out of five uniform furrow the two outer furrows are buffer and three test furrow with 0.6m spacing and 50 m long were chosen.
b. 10 stakes were set at 5 m spacing along the furrows.
c. A stream size of a mean value of 0.5 lit/sec was turned into each furrow using a buried pipe to the upstream of each furrow.
d. Using a stopwatch the time when the water reached each station in the tested furrow was recorded.
e. The time when the advancing front of water reached any station was recorded. Also, the times when the water was cut were recorded and the time when water was depleted was recorded.
f. Two-inch Parshall flume was installed at two points at mid of the furrow at 20 m distant between the two Parshall flume and measuring inflow and outflow for determination intake rate of the furrow for the determination of basic or steady sate infiltration rate (fo).

3.11 Determination of Infiltration Parameters

To characterize the infiltration process in irrigation measurements, a modified version of the Kostiakov infiltration equation, which is adopted in the surface irrigation simulation model SIRMOD (USU, 2001) was used. This mathematical model was used in this work to conduct numerical experiments to determine optimum irrigation management strategies. The best parameter values were obtained after several iterations with the simulation model SIRMOD aiming at minimizing the sum of the squares of the deviations between observed and simulated advance and recession times (Calejo et *al.*, 1998). The roughness parameter n is kept constant. In this method, two points on the advance curve (the mid and last points) are used to estimate the parameters of the modified Kostiakov equation which is in the following form:

$$Z = kt^{a} + f_{o}t \tag{3.17}$$

Where; Z is the cumulative infiltration (m^3/m), t intake opportunity time, *k* ($m^3/min/m$) and *a* (non-dimensional) are fitted parameters and *fo* ($m^3/min/m$) approximates the steady or final infiltration rate.

The initial values for the infiltration parameters f_o, α and k were determined using the "two-point" method (Walker and Skogerboe, 1987).

The steady infiltration rate, f_0, is determined by the inflow outflow method measured after the late irrigation.

$$f_{o} = \frac{Q_{in} - Q_{out}}{L} \tag{3.18}$$

Where; Q_{in} inflow discharge, Q_{out} is the runoff discharge from the end of the field was reached a steady value.

The furrow divided into two sections (at the mid and near endpoint) and Parshall flume was installed two section to measure the flow rate to determine the inflow and outflow volume of water for estimating infiltration of furrow for different water application system

The most important volume balance computation in surface irrigation occurs during the advance phase of the irrigation. To make this computation, one must assume a mathematical form for describing the field's cross-sectional flow area, the form of the infiltration function and the mathematical form of the advance trajectory. Walker and Skogerboe (1987), Walker (1989) and Clemmens et al. (1998) detail these analyses. The resulting volume balance equation.

$$Q_O t = \delta_y A_O x + \delta_z k t^a + \frac{f_O t x}{1+r} \tag{3.19}$$

Where Q_0 is the inflow discharge (m^3/min); A_0 is the cross-section area of inflow (m^2); σy is the surface profile shape factor (0.77). X is the distance from the inlet that the advancing front has traveled in t_x minutes in m; δz is the "subsurface shape factor" describing the average infiltrated depth and is described by:

$$\delta z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \tag{3.20}$$

The advance curve can be approximated by a power-law function and expressed as:

$$x = pt^r \tag{3.21}$$

$$r = \frac{\ln(2)}{\ln\left(t_l / t_{0.5l}\right)} \tag{3.22}$$

Where, t is the time taken for the wetting front to reach advance distance x, p and r the constants which can be determined from logarithmic transformation and two measured points of the advance curve.

The parameter of the modified Kostiakov equation infiltration parameters was calculated as follow

$$a = \frac{\ln\left(V_l / V_{0.5l}\right)}{\ln\left(t_l / t_{l/2}\right)} \tag{3.23}$$

$$K = \frac{V_l}{\delta_z t_l{}^a} \tag{3.24}$$

3.12 Advance and Recession Flow

Advance time was recorded at each station along the furrows. As the water reached the end of the furrows, storage time started and recorded until the required depth of water above the surface is equal in all stations along all the furrows. As the storage phase ended, the water supply was stopped and the recession time began. Recession time was recorded for all stations until the water in the furrow disappeared. Also, advance and recession times are measured for surge irrigation treatments, considering on-and-off times. The advance distances were also measured for all treatments.

3.12.1 The advance flow water tail

For determination of advance waterfront, stakes were fixed at 5 m distance along the furrow length up the end. The clock time was recorded when the irrigation water supply diverts into the furrows and when the advance waterfront reaches each stake or the station which is marked at 5 m distances from the furrows head in the advance phase as the inflow water entering the furrows and was reached each station. The water depth, surface water width, flow cross-section and wetted perimeter were determined. The relation of time of waterfront advance with the advance distance was found by a power form.

$$t = px^r \tag{3.25}$$

Where, X is distance was moved by the waterfront in the furrow (m); t is the time taken (min) by the waterfront to move the distance X; ‘P' and ‘r' are the constant

3.12.2 Recession flow water tail

After the irrigation is cut off, the tail water recedes downstream of the furrow. The rate of recession of the tail water or waterfront was determined by recording the times at which water just disappears from the upstream end and recedes downstream past the furrow or after the termination of the inflow, the time of water disappearance at each station recorded to determine the recession time. The model for predicting waterfront recession is expressed as:

$$t = aX^b \tag{3.26}$$

Where t is the time of waterfront recession at distance X and’’ a’’ and ‘’b’’ are the constants.

3.13 Estimation and Evaluation with SIRMOD Model

The furrow lengths of 50 m and slope of 0.2 % were selected to simulate SIRMOD models. Advance and recession times can be taken manually using markers with stake stations at known distances 5m. Calibration of the model for each event was achieved by inserting infiltration parameters measured from each treatment and existing design variables until the simulated advance and recession time matched as near as possible to the measured advance and recession time. Once models are successful, SIRMOD was used to simulate the performance (application efficiency, distribution uniformity, requirement efficiency and deep percolation efficiency) of furrow under both continuous and surge flow systems. The accuracy of the estimated irrigation performance was verified via simulation.

3.14 Performance Indicators

The technical performance of irrigation treatments was evaluated in terms of common performance measures like application efficiency (Ea), storage efficiency (Es) and Distribution uniformity.

3.14.1 Application efficiency, E_a

Application efficiency is a measure of how efficiently water is applied. It was computed by dividing the depth of water retained in the root zone of the soil by the actual depth applied. Water application efficiency (*Ea*) was calculated according to Walker (1989) as follows:

$$E_a = \frac{D_{ad}}{D_{ap}} * 100 \qquad (3.27)$$

Where, E_a is application efficiency (%), D_{ad} is the depth of water stored in the root zone (mm) measured by taking soil sample 24 hours after irrigation oven dried and measured moisture content in the sample and D_{ap} is the depth of water applied to the furrow (mm).

3.14.2 Storage efficiency, E_s

Storage efficiency indicates how well the irrigation satisfies the requirement to completely fill the target root zone soil moisture. The storage efficiency can be approximated by relating the average depth of water applied over the field to the target root zone deficit. The root zone deficit is calculated using soil type, crop root zone, and soil moisture content data. The storage efficiency is given as (Kifle *et al.*, 2008):

$$E_S = \frac{W_s}{W_n} \times 100 \qquad (3.28)$$

Where Es is water storage efficiency (%), Ws is water stored in the root zone during the irrigation (mm) and Wn is water need in the root zone during the irrigation (mm).

3.14.3 Distribution efficiency

The weighted average change in water content has been computed in three steps first, the water content before the irrigation and 24 hours after irrigation has been measured as a volume percent at three points and along a vertical line namely at 0.0—0.15, 0.15—0.30 and 0.30 -0.6 m incremental depths at 5, 25 and 45 m distance from the upper end of the furrow. The measured water content for these points was weighted by multiplying the water content for each point by its measuring depth. Second, the weighted average change in water content at any location was calculated by the summation of the change in water content in each point divided by the total measured depth. Third, the distribution efficiency was calculated by the mean at 5, 25 and 45 m from the upper end of the furrow using the following equation:

$$E_d = \left[1 - \left(\frac{y}{d}\right)\right] * 100 \tag{3.29}$$

Where: Ed is water distribution efficiency (%), d is the average depth of water stored along the run during the irrigation and y is an average numerical deviation from d.

$$d_{ave} = \frac{d1 + d2 + d3}{3} \tag{3.30}$$

$$y = \frac{|d1 - dave| + |d2 - dav| + |d3 - dave)|}{3} \tag{3.31}$$

The water stored in the soil was obtained gravimetrically. The gain in soil moisture (mm) in 0.6m depth was obtained at three locations along the run. The average depth of water stored along the run was calculated by summing up the depths in the three stations and then divided by three. The average numerical deviation of water depth from the mean at each station was determined.

3.14.4 Distribution uniformity

Distribution uniformity (DU) is usually defined as a ratio of the smallest accumulated depths in the distribution to the average depths of the whole distribution. The largest depths could also be used to express DU, but since the low values in irrigation are more critical, the smallest values are used (Burt *et al.*, 199. The average accumulated depth in the quarter of the field receiving the smallest depths is given by (Burt *et al.*, 1997): This term is used in the numerator of the DU calculation. A commonly used fraction in the lower quarter, which is the measure of how uniformly irrigation water infiltrated to the root depth along the furrow length. The soil sample was collected before and after irrigation, the weighted average change in water content has been computed. The water content before the irrigation and after 24 hours has been measured as a volume percent at twelve points and along a vertical line namely at 0.0—0.15, 0.15—0.30 and 0.30 — 0.6m incremental.

$$DU = \frac{Dmin}{Dave} \tag{3.32}$$

3.14.5 Water use efficiency

Water use efficiency computed by dividing yield by total applied irrigation water and is express as:

$$\text{WUE} = \text{Yield /Total water used} \tag{3.33}$$

Where, WUE is water use efficiency (Kg/m^3), Yield (kg/ha) Total water used in the season ($m^{3/}$ha).

3.15 Crop Data

Crop data required included the haricot beans dry biomass and yield was recorded in the field during the experimental period.

3.15.1 Aboveground dry biomass

An area of 1 m x 0.6m was selected to harvest the plants from the ground level. The harvested plants were sun dried for until a constant weight before measuring their weight, and then the aboveground biomass per hectare was estimated.

3.15.2 Crop yield

The data on final yield at the end of the season was also harvested together with the final biomass from the net area of 48 m by 1.2 m of haricot bean. The harvest index was then calculated by dividing the seed yield by the total biomass.

$$\text{HI} = \frac{\text{Y}}{\text{B}} \tag{3. 34}$$

Where, HI is harvest index is the yield per unit area in kg/ha and B is biomass in kg/ha

3.16 Statistical Analysis

The collected data during the field studies were subject to analysis of variance (ANOVA) appropriate for RCBD (Gomez and Gomez, 1984) using software packages (SAS). Whenever treatment effects were found significant, treatment means were compared using the least significant difference, LSD and least significant difference (LSD) was used for mean comparisons.

4 RESULTS AND DISCUSSION

4.1 Soil Analyses

The soil physical and chemical properties of the experimental field as obtained from laboratory and field tests were presented in Table 4.1 and 4.2 and Fig. 4.1.

4.1.1 Physical Properties of Soil

The laboratory results for the particle size distribution of the experimental field are presented in Table 4.1. The sand, clay and silt content of the experimental field were in general 33.7, 24.3 and 42.0%, respectively, and the texture is dominated by loam soil. The clay content increased with depth and ranged between 19.0 and 31.0 %.

Table 4.1 Textural class of soil under respective depth

Soil depth (cm)	Particle size distribution (%)			Textural class
	Sand	Clay	Silt	
0 – 15	32.0	19.0	49.0	Loam
15 – 30	36.0	23.0	41.0	Loam
30 – 60	33.0	31.0	36.0	Clay loam
Average	33.7	24.3	42.0	Loam

The soil moisture characteristics of the experimental field were shown in Table 4.2. The bulk density varies with depth and was found in a narrow range of 1.06 to 1.16 gm/cm^3 with an average bulk density of 1.12 gm/cm^3. The subsurface soil layer had slightly lower bulk density than the top surface and this might be due to high organic matter contents in the subsurface soil. In general, the average bulk density indicates suitability for root growth (Hunt and Gilkes, 1992). The topsoil layer (0-30cm) had lower FC (29.61%) while the subsoil 30-60cm has slightly higher FC (37.25%) due to higher clay content. He1nce the average FC of the soil in the profile was in the order of 34.05% on volume base. The PWP also shows a slight variation with depth and shows an average value of 18.47% at the surface (0-30 cm) and 21.25% at the subsurface (30-60cm) with the average value of 19.39%. The representative value of total available water (TAW), which is related to the difference between FC and PWP, was on average 163.3 mm/m of soil depth.

Table 4.2. Soil moisture characteristics and bulk density of experimental

Depth, (cm)	Soil moisture constants (%v)		BD (g/cm^3)	TAW (mm/m)
	PWP	FC		
0-15	18.40	29.61	1.13	126.70
15-30	18.53	35.28	1.16	194.30
30-60	21.25	37.25	1.06	169.60
Average	19.39	34.05	1.12	163.53

4.1.2 Soil chemical properties

As indicated in Table 4.2 the PH of the experimental site varied from 7.12 to 7.79 with an average. The average value of soil pH is 7.39 and according to Brady (2002), it is slightly alkaline and is within an acceptable range (6.0-7.5) for most crops. The electrical conductivity (EC) of soil varied between 0.16 and 0.28 ds/m which is classified as salt-free and had a negligible effect on most crop growth and yield (Murphy, 2007). 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.

Table 4.3 Selected soil chemical properties of the surface of the experimental field

Depth (cm)	PH	EC_s (dS/m)	%OC	%OM	p (ppm)	%N
0-15	7.12	0.28	1.08	1.86	6.55	0.10
15-30	7.79	0.17	1.08	1.86	6.56	0.09
30-60	7.25	0.16	1.36	2.34	6.61	0.09
Average	7.39	0.20	1.17	2.02	6.57	0.09

Based on the above classification the irrigation water quality of the study area was 0.46 ds/m classified as a medium salinity level. The soil has an electrical conductivity of 0.2 ds/m through 60 cm soil profile which is below the threshold value for yield reduction i.e. 1 ds/m (Smith *et al.*, 2011). The organic matter (OM) content for the surface soil (0-15 cm) was 1.86%, whereas in-depth (30-60cm) to 2.34%. The average organic matter content of the soil to 60 cm depth evaluated was about 2.01%.

4.1.3 Soil Infiltration Characteristics

The infiltration rate was determined soil characteristic at the maximum rate of water can enter the soil under specific field conditions. Before the experiment work was started, the test of soil was used double-ring infiltrometer at the furrow irrigation field and the infiltration rate was determined according to the result presented in figure 4.1. The basic infiltration rate was about 16 mm/hr. This rate of infiltration is in a range with a basic infiltration rate of 10 to 20 mm/hr for loam soils indicated by Brady (2002). In the beginning, water infiltrates rapidly. As more water replaces the air in the pores, the water infiltrates more slowly and eventually reaches a steady rate which the basic infiltration rate. The basic infiltration of the soil indicates that the soil is perfect for surface irrigation (London, 1991).

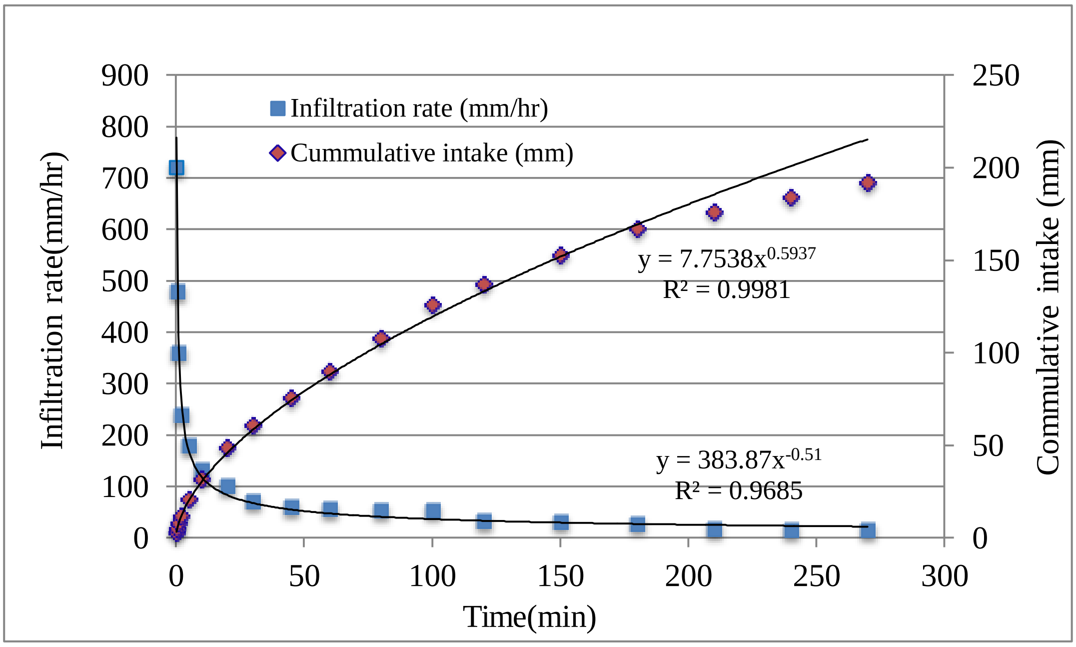


Figure 4.1 Infiltration rate and Cumulative infiltration depth curves

4.2 Crop Water Requirement

The depth of water required during the growing season and depth of water applied in each treatment plots is presented in Tables 4.4. Crop water requirement at the initial stage is low and increase during the development stage and mid-stage, and decreasing at the late growth stage.

Table 4.4 Water requirement of haricot beans

Growth stage	Kc	D_{rz} (cm)	CWR (mm)	P eff (mm)	IRn (mm)
Initial	0.37	37	16.38	5.7	10.68
Initial	0.37	45	14.94	34	0.00
Develop	0.389	49.5	20.20	0.00	20.20
Develop	0.565	57.5	28.11	1.5	26.61
Develop	0.773	65.5	28.95	6.4	22.55
Develop	0.981	73.5	36.76	20.0	16.76
Mid	1.14	79.65	42.80	13.6	29.20
Mid	1.15	80	49.55	0.00	49.50
Mid	1.15	80	49.60	0.00	49.60
Late	1.05	80	47.42	0.00	47.42
Late	0.59	80	34.87	0.00	0.00
Total			369.6	81.2	288.4

A high water requirement was observed at mid-stage, Total Seasonal water requirement of Haricot been at MARC climatic condition was 369.6 mm while effective rainfall was 81.2 mm. It is reported that the water requirement of Haricot bean was between 300 and 500 mm depending on climate (Doorenbos and Kassam, 1979). The Irrigation water requirement (IWR) was estimated at 288.4 mm.

The total water applied depending on irrigation systems the highest 369.6 mm (CFI) to the lowest 225.4 mm (AFI) including effective rainfall and common irrigation. The maximum total depth of water was applied to the conventional furrow irrigation treatment.

Table 4.5 Amount of water applied during the season

Treatment	Treatment Combination	CWR (mm)	Peff (mm)	Net irrigation (mm)	Gross irrigation (mm)
T_1	CFI(C)	369.6	81.2	288.4	480.6
T_2	CFI(S_1)	369.6	81.2	288.4	480.6
T_3	CFI(S_2)	369.6	81.2	288.4	480.6
T_4	AFI(C)	225.4	81.2	144.2	240.3
T_5	AFI(S_1)	225.4	81.2	144.2	240.3
T_6	AFI(S_2)	225.4	81.2	144.2	240.3

Note, CFI= Conventional furrow irrigation, AFI = Alternative furrow irrigation= continuous flow, S1= Surge flow with CR 1/3 and S2 = surge flow with CR ½.

4.3 Furrow Cross- Section

The furrow cross-section was measured to each furrows irrigation system and measurement were made to determine the wetted cross-sectional area, wetted perimeter and top width for a depth of flow during each irrigation methods presented in Table 4.6 The depth, middle width, bottom width and top width of furrows were measured at different sections at 5 m intervals of distance along the flow run. These furrow cross-sections were measured with installed the local wooden pieces in-furrow at 5m interval along the furrow length. The depth of the furrows varied from 0.30 m to 0.23 m giving an average furrow depth of 0.26 m. Bottom width also varied from minimum and maximum as 0.12 m and 0.20 m respectively, and the average bottom width of the furrow was found to be 0.17 m.

Table 4.6 Unit width furrow cross-section of furrows.

Parameter	Measured value (m)
Top width	0.48
Middle width	0.30
Bottom width	0.17
Maximum depth	0.26

Similarly, the top width of the furrow had a variation ranging from a minimum of 0.41 m to a maximum of 0.55 m resulting in an average top width of 0.48 m, and the middle width varied from a minimum of 0.23 m to a maximum of 0.37 m and the average middle width of the furrows was found as 0.30 m.

4.4 Advance and Recession Time for Different Treatments

Advance and recession times behavior were different due to different irrigation treatments and also varied depending on furrow irrigation management techniques as shown in Table 4.7 1nd 4.8 The advance rate of the surge and continuous flows were shown in (Table 4.7) and the comparison of cumulative surges and continuous flows advance along the furrows with a constant discharge rate of 0.5l/s was considered. The highest average advance time values of 38.38 and 35.01 min were associated with (T4) and (T1) treatments as an average value for all irrigation events during the growing season, respectively. Meanwhile, the lowest advance time was recorded under surge flow with cycle ratio ½ with alternative furrow irrigation (T6) (31.17 min) followed by surge flow with cycle ratio ½ with conventional furrow irrigation (T3) (31.5 min), respectively.

Table 4.7 Advance Time (min) for Continuous and Surge Flow

Time (minutes)						
Distance from inlet (m)	Continuous flow		Surge flow CR1/3		Surge flow CR1/2	
	CFI(T_1)	AFI(T_4)	CFI(T_2)	AFI(T_5)	CFI(T_3)	AFI(T_6)
0	0.0	0.0	0.0	0.0	0.0	0.0
5	2.63	2.59	2.35	2.07	2.78	2.09
10	5.85	4.74	4.02	4.73	4.13	4.26
15	8.96	6.93	6.29	7.12	7.12	6.20
20	11.97	12.42	9.45	11.5	11.46	10.00
25	16.09	15.14	12.24	16.6	17.10	13.18
30	20.18	19.25	18.16	20.84	23.34	18.0
35	23.99	24.59	21.37	24.85	25.32	20.0
40	27.56	28.87	25.20	27.58	29.3	23.46
45	31.45	34.72	27.30	31.6	32.6	27.22
50	35.01	38.38	31.50	33.06	34.2	31.17

The results also indicated that less time is required to complete the advance phase under surge flow compared with continuous flow. This finding is per that report by Bishop et al., (1981), who found three to four times faster advance rate in surge flow compared to continuous flow in furrows. Similarly, the results were supported by the findings reported by (Stringham and Keller 1979, Allen.1980 and Mahamood *et al.*, (1995). While comparing Surge flow advance where faster advance time was recorded surge flow of cycle ratio of ½ than cycle ratio 1/3 because of CR ½ had less off time than CR 1/3. Advance time measurements with inflow rate 0.5 (l/s) for all irrigation events during the growing season showed that advance time is faster with surge-flow at the beginning of the growing season as compared with conventional irrigation, (CFI) when soil clods are yet formed. Therefore, the average water volume used to complete the advance time for all irrigation events during the growing season, with surge with cycle ratio ½ is about 18.79 % less than with continuous flow treatment (AFI) (T4). Later in the growing season, the advance times are practically the same because the furrows are then smoothed and no advantages in water use are observable for surge-flow.

Table 4.8 Recession Time (min) for Continuous and Surge Flow

Time (minutes)						
Distance from the inlet (m)	Continuous flow		Surge flow CR1/3		Surge flow CR1/2	
	CFI	AFI	CFI	AFI	CFI	AFI
0	64	64	62	61.63	63.8	62.45
5	75	75	68.43	70.5	71.34	70.73
10	88.35	88.34	71.45	74.6	79.5	78.65
12	96.32	100.00	82.23	79.54	86.3	82.35
20	106.06	107.3	89.64	82.6	90.6	89.6
25	110.27	115.4	94.62	87.9	98.53	93.40
30	118.32	123.00	100.21	92.75	104.6	100.5
35	123.02	127.6	104.6	98.54	111.34	108.6
40	128.15	134.6	112.4	100.34	117.62	115.6
45	132.1	140.3	118.8	105.64	121.8	121.9
50	138.1	143.6	125.6	109.8	124.92	127.83

Faster recession times were observed in alternative furrow irrigation technique, (AFI) with surge flow system due to lateral infiltration in the direction of non-irrigated furrows as compared to conventional irrigation, (CFI). Faster recession times (Table 4.8) showed that

(109.8 min) were observed with surge alternative furrow irrigation technique (T_5) was due to less amount of water volume applied as compared to conventional irrigation (CFI). In the case of surge flow treatment, faster recession time was recorded under a small cycle ratio (1/3) than cycle ratio ½ due to large off time was obtained on cycle ratio 1/3 of the surge flow system.

4.5. Determination of Advance and Recession Flow Waterfront

After the water was released into the furrows, the time advance waterfront was recorded at 5 m interval along lengths of the furrows. The stream was cut off when the waterfront reached to the end of the furrows. The relationships were developed for both of time advance and recession waterfront to distance. The power equations were fitted to develop relationships using EXCEL software. The power function was found as the best fit giving higher values of coefficient of determination (R^2) both for advance time versus distance, as well as recession time versus distance for each furrow as given in Table 4.9.

Table 4.9 Prediction time advance and recession of waterfront

Treatments	Advance waterfront	R^2	Recession Waterfront	R^2
T_1	$0.277x^{1.2284}$	0.999	$47.96x^{0.2626}$	0.9998
T_2	$0.925x^{1.1363}$	0.989	$41.502x^{0.2674}$	0.949
T_3	$0.7476x^{1.180}$	0.997	$45.948x^{0.249}$	0.9673
T_4	$0.1486x^{1.1409}$	0.995	$44.903x^{0.2958}$	0.9859
T_5	$0.577x^{1.1913}$	0.998	$48.908x^{0.1944}$	0.9402
T_6	$0.925x^{1.1363}$	0.997	$44.068x^{0.0.2254}$	0.9402

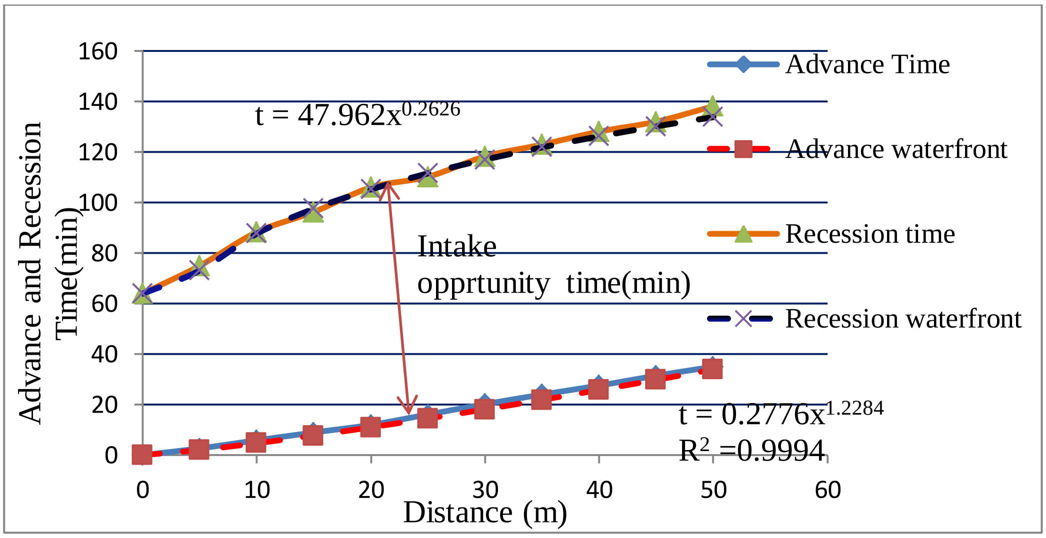


Figure 4.2 Advance and Recession curves for continuous flow

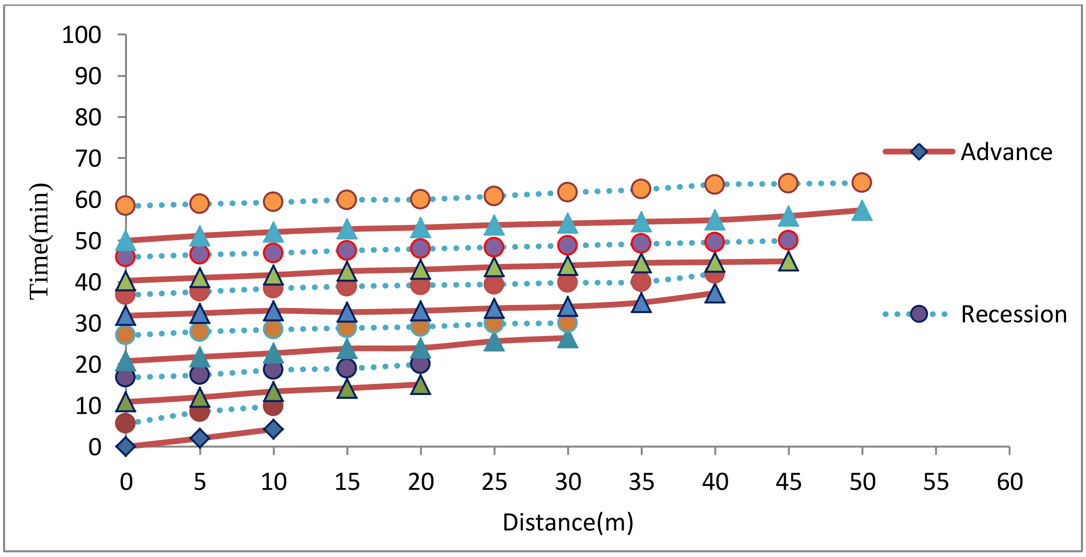


Figure 4.3 Waterfront advance and recession curve of the respective surge of treatment

4.6 Infiltration Parameter for Different Treatments

As shown in table 4.10 the furrow infiltration parameter was varied treatment with treatment in the case of the variation of the irrigation system as well as irrigation flow this due to the variation of advance and recession time of flow. Generally, less water is required to complete the advance phase by surge flow than with continuous flow. The effect of having reduced the infiltration rates over at least a portion of the field is that advance rates are increased. In this case, the basic intake rate was low on surge flow due to the high advance rate was recorded. There are some differences in the infiltration parameters under different furrow irrigation methods. It is because, in different treatments, the soil moisture and horizontal section of the surface soil are both different. Despite the short history of surge irrigation, several investigators have examined infiltration under surge flow conditions. Using furrow inflow-outflow measurements on a silt clay loam soil, Podmore and Duke (1982) found that steady-state infiltration rates under surge flow were one-half those measured under continuous flow. The steady-state infiltration rate is sometimes referred to as the basic, or final, infiltration rate. Coolidge *et al*. (1982) suggested that the surge effect in reducing infiltration occurs primarily during the first off-time**.** Due to the variation of basic infiltration rate and advance time the other infiltration parameters like k ,a and δ z was varied between treatments.

Table 4.10 Infiltration parameter

Infiltration parameters	Treatments					
	CFI C T_1	CFI S1 T_2	CFI S2 T_3	AFI C T_4	AFI S1 T_5	AFI S2 T_6
K	0.003602	0.003975	0.003969	0.003924	0.00396	0.003967
A	0.46263	0.474578	0.473857	0.468086	0.472733	0.47365
f o	0.000188	0.000012	0.000014	0.000026	0.000017	0.000015
Δz	0.80775	0.75428	0.75460	0.757189	0.755107	0.75469

4.7 Estimation and Evaluation Using SIRMOD Model

The evaluation includes the determination performance of the flow system as well as the irrigation method. SIRMOD simulation model inputs screens were shown in Appendix B (Figure.2-4). The illustrated inputs in Appendix Table A-3 were necessary to run the model for simulating the furrow irrigation method under study conditions. Therefore, field topography input in the appendix (Figure B-2), inflow controls input appendix (Figure B-3), and infiltration characteristics input appendix (Figure B-4), as well as the cutoff time, for furrow irrigation time was determined by the amount of irrigation water required to the field, replenish the root zone and the infiltration rate of the soil. This was done for irrigation events. After running the SIRMOD model, the values of application efficiency, distribution uniformity, requirement efficiency, Distribution efficiency and deep percolation loss percentages were obtained by feeding the inputs which were collected from field measurement in SIRMOD software. The model was calibrated with the control treatment (T_1), so the result obtained in the furrow irrigation length of 50 m and inflow rate of 0.5 l/sec with furrow blocked end boundary condition, the same amount of application efficiencies was observed in zero inertia models. The highest application efficiency (71.29%) was observed on $T_{5.}$

Table 4.11 Result of SIRMOD software using Zero Inertia model

Model	Treatment	RE (%)	AE (%)	DU (%)	DP (%)	ED (%)	Infiltration (m^3)	Error (%)
ZI	T1	99.67	65.7	97.81	19.54	76.92	1.5	0.03
	T2	99.42	67.23	91.74	30.85	68.55	1.45	0.16
	T3	99.65	71.27	90.62	20.84	77.35	1.3	0.86
	T4	99.31	61.31	97.92	18.95	76.39	1.4	0.06
	T5	99.38	71.29	91.04	23.52	75.19	1.4	1.00
	T6	89.53	63.28	76.81	27.74	66.38	1.3	0.48

4.8 Performance Measures for Different Treatments

4.8.1 Application efficiency (Ea)

The analysis of variance indicated that the application efficiency was not significantly affected ($p < 0.05$) by the main effect furrow irrigation system (Table 4.12). Mean application efficiencies of 56.99 and 59.65% were observed for the CFI and AFI, respectively. The result is supported by Zhang *et al.* (2000) and Kang *et al.* (2000) who reported that higher application efficiency was found for alternate furrow due to the lateral movement for the next furrow. The application efficiencies were 60.82, 58.49 and 55.63% for the Surge flow of CR1 (S1), CR2 (S2) and Continuous flow(C), respectively. The highest value of application efficiency was observed for the small cycle ratio (CR=1/3) of surge flow while the lowest application efficiency was observed for continuous flow irrigation (C). This could be due to the consolidating and sealing of the furrow during the large off time and the resulting reduction in the infiltration rate. Similarly, the analysis of variance showed that the interaction effect of irrigation and flow system were also significantly different ($p < 0.05$). The average application efficiency of continuous flow treatments ranged from 53.29 (AFI) to 57.65% (CFI), whereas the average application efficiencies of surge flow treatments were from 56.14 (T_6) to 61.55% (T_2).

Table 4.12 Application for the different treatment

Irrigation System	Flow system`			
	Application efficiency, Ea (%)			
	S1	S2	C	Mean
CFI	61.55^{a}	56.14^{b}	53.29^{bc}	56.99^{b}
AFI	60.09^{b}	60.87^{b}	57.98^{c}	59.65^{b}
Mean	60.82^{a}	58.49^{b}	55.63^{bc}	
	IS	FS	IS× FS	
LSD$_{(0.05)}$	0.65	3.373	2.273	
CV (%)	2.87	2.76	3.44	

This indicates that surge treatment combinations had better application efficiency than continuous treatments. The increased application efficiency for surge irrigation is due to the reduction of deep percolation losses. It can be observed that the average measured values of application efficiency (59.57% for surge and 52.14% for continuous). In the comparison of continuous and surge flow irrigation was 16.64 % high application efficiency was recorded on surge flow treatment.

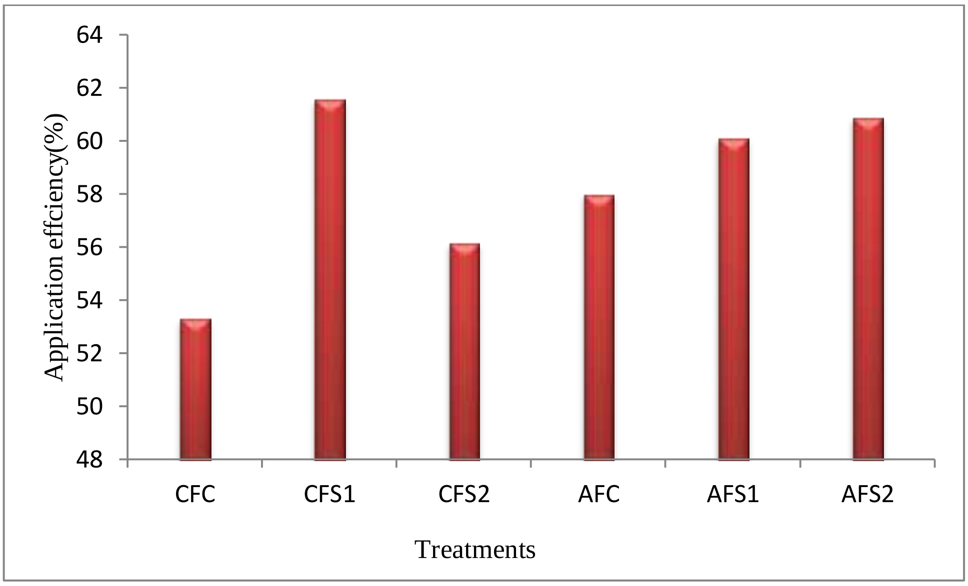


Figure 4.4 Histogram showing Application efficiency under different treatment

4.8.2 Distribution uniformity (DU)

Distribution uniformity was significantly affected by the irrigation application system. Irrigation flow has a significant effect on distribution uniformity as presented in Table 4.13. Analysis of variance indicated that the distribution uniformity is significantly affected ($p < 0.05$) by the main effect furrow irrigation system. Distribution uniformity of 81.9 and 81.0 % were observed for the AFI and CFI, respectively. The highest distribution uniformity was obtained for surge flow treatment S2 (84.23%) and the least for continuous C (77.33 %). This could be due to the soil macrospores are sealed with the soil silt particles for the surge flow treatments. Distribution uniformity was statistically different with the irrigation flow system. The mean distribution uniformity was 84.3, 82.83 and 77.33% for the Surge flow of CR2 (S2), CR1 (S1) and Continuous flow(C), respectively. This study is in line with Kifle *et al*. (2008), Kanber *et al*. (2001), Horst *et al*. (2007) and Yang *et al*. (2011) who concluded surge flow irrigation has better Distribution uniformity under onion, wheat and maize production. The average distribution uniformity of continuous flow treatments ranged from 78.67 (AFI) to 76% (CFI), whereas the average distribution uniformity of surge flow treatments was from 82.33 AFI (T_5) to 84.83 % AFI (T_6). In the comparison of continuous and surge flow irrigation was 7.94 % high distribution uniformity was recorded on surge flow treatment.

Table 4.13 Distribution uniformity for the different treatment

Irrigation System	Flow system			
	Distribution uniformity, DU (%)			
	S1	S2	C	Mean
CFI	83.33^{ab}	83.67^{ab}	76^{bc}	81^{b}
AFI	82.33^{abc}	84.8^{a}	78.67^{c}	81.9^{a}
Mean	82.83^{ab}	84.23^{a}	77.33^{b}	
	IS	FS	IS×FS	
LSD$_{(0.05)}$	0.7	1.2	1.3	
CV (%)	2.1	3.0	1.9	

LSD–least significant different, CV–coefficient of variance

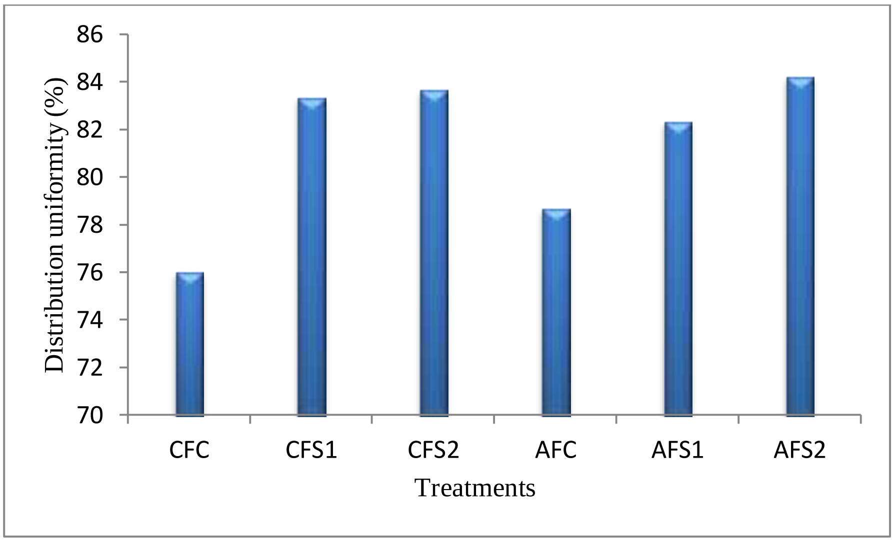


Figure 4.5 Histogram showing Distribution uniformity under different treatment

4.8.3 Distribution efficiency (Ed %)

The high distribution efficiency obtained may be due to the acceleration of the advance of the surge flow. The analysis of variance in Table (4.14) indicated that the distribution efficiency was not significantly affected ($p < 0.05$) by the main effect furrow irrigation system. Distribution efficiency of 80.57 and 79.99% were observed for the AFI and CFI, respectively. Distribution efficiency was statistically different from the irrigation flow system. The mean distribution efficiency was 82.76' 79.67 and 78.42 % for the Surge flow of CR1 (S_1), CR2 (S_2) and Continuous flow(C), respectively. The highest distribution efficiency was obtained for surge flow treatment S1 (82.76%) and the least for continuous C (78.42 %). Similar results were obtained by Elsheikh (2002) and Mostafazadeh (1990) who reported that higher advance rates reduced the differences in intake opportunity time between the head of the furrow and the lower end; this gives more uniform water distribution along the furrow. It was observed that the distribution efficiency obtained under both cycle ratios tested were almost the same and relatively high. The average distribution efficiency of continuous flow treatments ranged from 78.31 (CFI) to 78.53 % (AFI), whereas the average distribution efficiency of surge flow treatments was from 79.20 S2 (T_3) to 83.05 % (T_5).

Table 4.14 Distribution efficiency of each treatment

Irrigation System	Flow system Distribution efficiency, Ed (%)			
	S1	S2	C	Mean
CFI	82.47^{ab}	79.207^{ab}	78.31^{b}	79.99^{ab}
AFI	83.05 ^{a}	80.137^{ab}	78.53^{b}	80.57^{ab}
Mean	82.76^{ab}	79.67^{ab}	78.42^{b}	
	IS	FS	IS×FS	
LSD$_{(0.05)}$	2.9	5.43	5.98	
CV (%)	1.82	2.01	4.05	

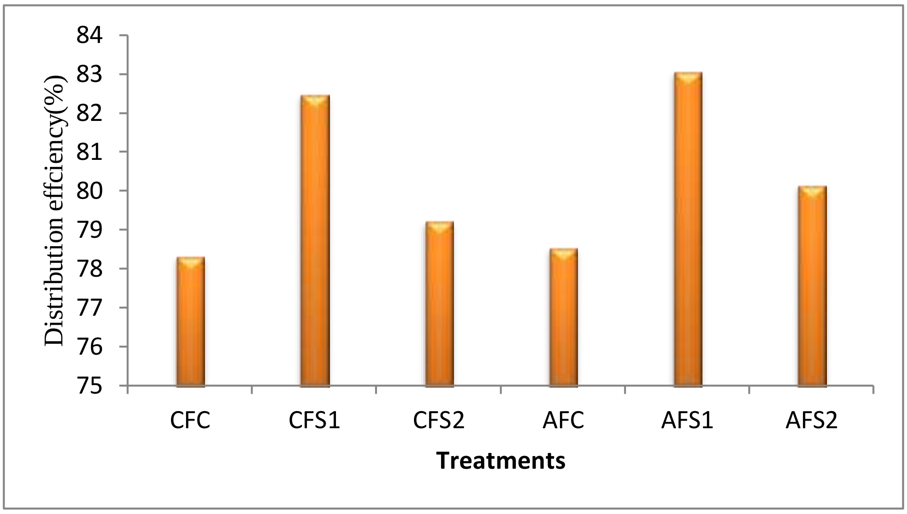


Figure 4.6 Histogram showing Distribution efficiency under different treatment

4.8.4 Storage efficiency (Es %)

Results of storage efficiency obtained under each flow system were shown in Table 4.15the highest storage efficiency of 79.7% was obtained under cycle ratio ½ with conventional furrow irrigation while the lowest storage efficiency of 68.5% was recorded by cycle ratio 1/3 with alternative furrow irrigation. The analysis of variance in Table (4.15) indicated that the storage efficiency was not significantly affected ($p < 0.05$) by the main effect furrow irrigation system. Storage efficiency of 71.2 and 74.53 % were observed for the AFI and CFI, respectively.

Table 4.15 Storage efficiency under different treatment

Irrigation System	`Flow system Storage efficiency, Es (%)			
	S1	S2	C	Mean
CFI	74.6^{ab}	79.7^{a}	69.3^{b}	74.53^{ab}
AFI	68.5^{b}	$70.9^{\ b}$	74.23^{ab}	71.2^{b}
Mean	71.55^{b}	75.3^{ab}	71.76^{b}	
	IS	FS	IS× FS	
$LSD_{(0.05)}$	3.1	2.65	6.8	
CV (%)	2.74	4.96	5.6	

Note, IS and FS are the Irrigation system and flow system, respectively.

Storage efficiency was not statistically different from the irrigation flow system. The mean storage efficiency was 75.3, 71.76 and 71.55% for the Surge flow of CR2 (S2), Continuous flow(C) and CR1 (S1), respectively. These results might be since in cycle ratio ½ the duration of the rest period was long enough for the water to infiltrate into the soil before the next cycle begins and this had resulted in higher storage efficiency compared to the other cycle ratios. Similar results were obtained by James (1988), Mostafazadeh and Mousavi (1989). In addition to that surge irrigation technique resulted in a longer contact time which increased the water infiltrated into the soil. This finding is supported by the work of Lal and Pandya (1977) and Abdeen (1999) who reported that in surge irrigation technique the intermittent water flow resulted in a long opportunity time as a result of the fast advance front Storage efficiency.

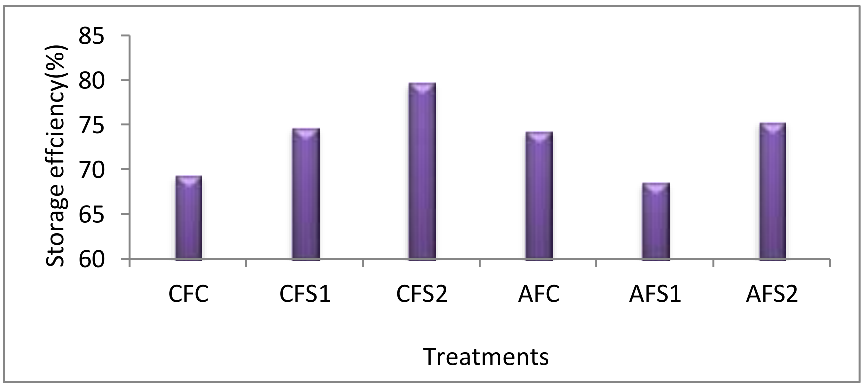


Figure 4.7 Histogram showing Storage efficiency under different treatment

4.9 Crop yield and Water Use Efficiency

Crop yield from each treatment is shown in table 4.16 the result indicated that the haricot bean yield was not significant affected by the irrigation application system, the interaction effect of irrigation system and irrigation flow.

Table 4.16 crop water uses efficiency and haricot bean yield of treatments

Treatment	ET_c (m^3/ha)	CWUE (kg/m^3)	Yield (kg/ha)
T_1	3696	0.58^b	2299.4^{bc}
T_2	3696	0.59^b	2355.3^{ab}
T_3	3696	0.86^{ab}	2466.0^a
T_4	2254	0.97^a	2189.5^c
T_5	2254	0.99^a	2241.2^{bc}
T_6	2254	1.02^a	2301.6^{bc}
LSD (0.05)		0.0536	142.21
CV (%)		3.69	3.39

This implies the treatment combination of continuous flow and alternate furrow has significant difference in yield with the other treatment combination. However, irrigation flow showed a significant effect on the yield of haricot bean.

The highest and lowest yield was obtained from conventional furrow irrigation with surge flow of cycle ratio ½ with conventional furrow irrigation (T_3) and alternative furrow irrigation with the continuous flow(T_4) was 2466.0 kg/ha and 2189.5 0kg/ha, respectively (Table 4.17). However, consecutive surge flow treatments (S1and S2) have not shown a statistically significant difference. Several research outputs conducted elsewhere in the world for example in supporting this study which all showed that the higher yield was obtained from surge flow treatments and least from the continuous flow (Horst *et al.*, 2007; Kifle *et al.*, 2008; Mahmood *et al.*, 2003).

Table 4.17 water use efficiency and haricot bean yield for AFI and CFI

Treatment	CWUE (kg/m3)	Yield (kg/ha)
CFI	0.59^{b}	2356.1^{a}
AFI	0.96^{a}	2244.1^{a}
LSD (0.05)	0.0383	143.09
CV (%)	1.38	1.77

No statistically significant yield reduction was observed for alternate furrow treatment combinations compared to the conventional furrow treatment combinations which are also in agreement with many previous studies (Zang *et al*., 2000; Kang *et al*., 2000; Yang *et al*., 2011). Their research outputs revealed that there were no significant differences in yield between alternate furrow and conventional furrow event.

Table 4.18 irrigation water uses efficiency and haricot bean yield for flow system

Treatment	CWUE (kg/m^3)	Yield (kg/ha)
C	0.72^{a}	2244.45^{bc}
S1	0.749^{a}	2298.25^{b}
S2	0.769^{a}	2383.8^{a}
LSD (0.05)	0.0551	82.4
CV%	3.28	3.29

As can be seen in Tables 4.17 and 4.18, irrigation flow and irrigation systems exhibit a significant effect on irrigation water use efficiency. Irrigation flow had a significant effect on irrigation water use efficiency. The highest irrigation water use efficiency was observed in surge flow S2 (0.769 kg/m^3) and the least from continuous C (0.72 kg/m^3) for the irrigation flow. (Kifle *et al*. (2008) and Horst *et al*. (2007) evidenced that the surge and continuous flows have shown the highest and least water use efficiency for onion and maize crops, respectively. Likewise, irrigation system showed a statistically significant effect on irrigation water use efficiency. In this study, better irrigation water use efficiency was obtained from alternate furrow (0.96 kg/m3) compared to the conventional furrow (0.59 kg/m3). In this case, the amount of yield obtained from the two treatments had no significant difference whilst the water applied to the alternate furrow was almost half of the conventional furrow. The study findings are in agreement with many studies conducted in other regions (Zang *et al*., 2000; Kang *et al*., 2000; Yang *et al*., 2011). These investigations showed that alternate furrow exhibited better irrigation water use efficiency compared to conventional furrow under different crops. As there are no statistically significant differences in water use efficiency for the interaction effects, farmers, users, water managers and decision-makers can prefer the best treatment combinations that consume less water and easy technique for application.

4.10 Dry Biomass

Table 4.19 dry biomass for treatments

Treatment	Dry Biomass (kg/ha)
T_1	6334.4^{c}
T_2	6809.5^{ab}
T_3	6830.5^{a}
T_4	5928.6^{d}
T_5	6010.0^{d}
T_6	6491.0^{bc}
LSD (0.05)	319.62
CV (%)	2.74

The analysis of variance showed that the irrigation system and the interaction effect of the Irrigation system and flow system had a significant effect on biomass production. The highest dry biomass was collected from (T_3) and the lowest dry biomass was also collected from treatment $T_{4.}$ The dry biomass and the crop yield have a direct relationship within the respective treatment

4.11 Yield Reduction and Harvesting Index

The harvest index (HI) which refers to the percentage dry matter allocated to grain yield is varied from 37.2% to 34.6% (Table 4.21). The highest and lowest harvest index was obtained from AFI (S1) and CFI (S1). The result showed that the alternate furrow irrigation method resulted in a higher harvest index than the conventional furrow irrigation method.

The highest yield reduction depended on the amount of water applied, as indicated by and Doorenbos *et al.* (1979). The result of yield reduction in Table 4.21, showed that the highest reduction yield obtained from AFI(C) treatment and the lowest was obtained from treatment T_6 (AFI S2).

Table 4.20 Yield reduction and harvesting index

Treatment	Grain yield(Kg/ha)	Biomass (kg/ha)	Harvest index (%)	Yield Reduction (%)
T-1	2299.4	6334.4	36.3	0
T-2	2355.5	6809.5	34.6	-2.4
T-3	2466.0	6830.5	36.1	-7.24
T-4	2189.5	5928.6	36.9	4.78
T-5	2241.2	6010.6	37.2	2.53
T-6	2301.6	6491.0	35.4	-9.57

Note, T_1, T_2 and T_3 are Conventional furrow irrigation with Continuous, surge-1 and surge- 2 flow, respectively. T_4, T_5 and T_6 are treatments with Alternative furrow irrigation with Continuous, surge-1 and surge- 2 flows, respectively.

5 CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

❑ This study was carried out to investigate the effect of surge and continuous flow on furrow irrigation under very short furrow length on advance and recession time, Surge flow advanced was found faster than the respective continuous flow. From the respective surge flow treatments, surge flow treatment with cycle ratio ½ performed better in reaching the tail end of the furrow with an advance time of 10% less compared with the respective continuous flow.

❑ The result of this study showed that irrigation system (AF and CF) as a factor has no significant effect on the yield of haricot bean. However, the irrigation flow methods (C, S1 and S2) significantly affected the irrigation performance indicators (application efficiency, distribution uniformity and storage efficiency) and likewise, irrigation water use efficiency and yield of haricot bean were significantly different.

❑ The highest yield was obtained from the surge flow with conventional furrow irrigation and the least yield was harvested from the continuous flow with alternative furrow irrigation. The highest irrigation water use efficiencies were obtained for the surge flow with an alternative furrow irrigation system which indicated a 20.8% increase in water productivity of surge flow irrigation over the continuous flow. Higher crop yield (2383.3 kg/ha), water use efficiency (0.76 - 0.99kg/m3), application efficiency (55.31–60.82 %) , distribution uniformity (78.9 – 84.0 %), storage efficiency (71.2-75.3 %) and distribution efficiency (80.67-82.76 %) were obtained from both surge flow and alternate furrow irrigation as compared to continuous flow and conventional furrow irrigation (every furrow water application) which was recorded less 2244.45 kg/ha, 0.59–0.72 kg/m3, 52.14–56.99%, 77.33–81.66%, 71.76-74.53% and 78.42-79.99% ,respectively.

- Generally, it can be concluded that surge flow irrigation was found to perform better than continuous flow irrigation in terms of water-saving. It can be applied by farmers in areas where irrigation water is limiting crop production.

5.2 Recommendations

From the results and conclusions of this study the following recommendations can be made:-

- Surge flow with cycle ratio ½ in alternate furrow irrigation for rapid advance should be considered.
- Surge flow with alternative furrow irrigation had to improve performance of furrow irrigation (Application efficiency, Distribution uniformity and storage efficiency).
- Generally the combination surge flow and alternative furrow irrigation had improve furrow irrigation performance with minimum yield reduction and better water use efficiency compare to conventional furrow irrigation and continuous flow. It is recommended that the combined use of surge flow and alternate furrow could be used to improve environmental flows and or to expand irrigation downstream under water scarcity condition.

REFERENCES

Ahmed, E., Luis, A., Garcia, A. S., El-Zaher, and Mohammed, K. (2005). Furrow Irrigation system design for clay soil in the Arid Region. *Journal of Agricultural Engineering*, 21(3): 411-420.

Ali, M.H. (2011). Practices of Irrigation and On-farm Water Management -Volume2.

Heidelberg, Germany: Springer, pp. 546.ISBN 978-1-4419-7636-9. *American Society of Agricultural Engineering* ISSN 0.883-8452, Vol.21 (3):411-420

Allen D.J., Ampofo, J.K.O., and Wortman, C.S. (1996). Pests, diseases, and nutritional disorders of the common bean in Africa: *A field guide. CIAT, Cali, Colombia*, 98p.

Allen, R.G.; L.S. Pereira; D. Raes and M. Smith (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage, Paper 56, 300 pp. UN-FAO, Rome, Italy.

ASABE, (2003). Evaluation of irrigation furrows. EP 419.1. In: ASABE Standards (Ed. M.I. Joseph). ASABE, 919-924

Ashinie, B., Wolfram, S., Setegn, G., Miguel, A., and Joachim, M. (2016) Alternate furrow irrigation of four fresh-market tomato cultivars under the semi-arid condition of Ethiopia – Part I: Effect on fruit yield and quality. *Journal of Agriculture and Rural Development Trop and Subtropics*, 117: 255–268.

Awulachew, S.B., Merrey, D.J., Kamara, A.B., Van Koopen, B., De Vries, F. P. & Boelle, E. (2005). Experiences and Opportunities for Promoting Small-Scale/Micro Irrigation and Rainwater Harvesting for Food Security in Ethiopia. *IWMI. Working Paper* 98.

Awulachew, S.B., Teklu, E., and Regassa, E., Namara. (2010). Irrigation potential in Ethiopia, constraints, and opportunities for enhancing the system: *international water management institute IWMI.*

Bakker DM, Plunkett G, Sherrard J.(2006). Application efficiencies and furrow infiltration functions of irrigations in sugar cane in the Ord River irrigation area of North-Western Australia and the scope for improvement. *Agricultural Water Management*, 83(2): 162–172.

Basset, D, L; Fangmeier, D.D; and Sterlkov, T. (1980). Hydraulics of surface irrigation. In design and Operation of Farm Irrigation Systems. (Ed.M.E.Jensen). Pp 447- 498. *American Society of Agricultural Engineering, Michigan.*

Bennett D (1931) Approximating Wetted Perimeter in Power-Law Cross Section. *Journal of Irrigation and Drainage Engineering,* 126: 98-109.

Berehe FT, Melesse AM, Fanta A, Alamirew T. (2013). Characterization of the effect of tillage on furrow irrigation hydraulics for the Dire Dawa area, Ethiopia. Catena, 110: 161–175.

Bishop, A.A., Walker. W.A., Allen N.L., Poole G.J., (1981). Furrow advance rates under surge flow systems. J. *Irrig. Drain*., ASCE, 107, 257-264

Booher, L.J. (1974). Surface irrigation. FAO Agricultural Development Paper No. (95). FAO Land and Water Development Series No. (3). Rome.

Brady N.C. and R.R. Weil, (2002). The nature and properties of soils. 13th (Ed). *Person Education Ltd., USA.*

Brouwer, C.,Prins, K., Kay, M., and Heibloem, M. (1985).Irrigation Water Management: Irrigation Methods. *FAO Training manual no 5. FAO. Rome, Italy.*

Burt C.M.; A.J. Clemmens; T.S. Strelkof; K.H. Solomon; R.D. Bliesner; L.A. Hardy; T.A. Howell and D.E. Eisnerhauer,(1997). Irrigation performance measures: Efficiency and uniformity. J. *Irrig. Drain. Eng*, 123 (6) 423-442.

Calejo, M.J., Sousa, P.L., Pereira, L.S.,(1998). Evaluation of the performance of surface irrigation systems: optimization of infiltration and roughness parameters. In: Pereira, L.S., Gowing, J.W. (Eds.), *Water and the Environment: Innovation Issues in Irrigation and Drainage (*1st Inter-Regional Conference on Environment– Water, Lisbon). E&FN Spon, London, pp. 140–148.

Criddle, W. D.; Davis, S.; Pair, C. H. and Shockley, D. G. (1956). Methods of evaluating irrigation systems. Soil Conservation Service, Agriculture Handbook No.82. *U.S. Department ofAgriculture*, Washington D. C.

Clemmens AJ, El-Haddad Z, & Strelkoff TS. (1999). Assessing the potential for modern surface irrigation in Egypt. *Transactions of the American Society of Agricultural Engineers*42(4): 995–1008.

Doorenbos J. and Kassam A.H (1979). Yield response to water. FAO Irrigation and Drainage Paper 33. Rome, Italy.

Evans, R.G., and B. Leib (2003). Surge Flow Surface Irrigation, Washington State University, *The U.S. Department of Agriculture,* Subject code: 340. EM4826, cru.cahe.wsu.edu/cepublications/em4826/em4826.pdf.

FAO.(2001).AQUASTAT-FAO's Information systems on water and agriculture.Http://www.wcainfonet.org/cds_static/en/quastat_fao_information_system water Ethiopian 569 -1436 (online 3/24/05).

FAO.(2011). The state of the world's land and water resources for food and agriculture: Managing systems at risk. FAO and London: Earth scan, Rome, Italy.

FAO, (1995). Water Development for Food Security, *FAO Water Resource Bulletin* No.112. FAO, Rome.

FAO, (1997). Guidelines for Predicting Crop Water Requirement: *Irrigation and Drainage Paper* No 24. FAO, Rome.

Gillis MH, Smith RJ, Raine SR. (2011). Evaluating whole field irrigation performance using statistical inference of inter-furrow infiltration variation. *Biosystems Engineering*, 110: 134–143.

Habtu A I. Sache and J.C. Zadoks, 1996. A survey of cropping practices and foliar diseases of common bean in Ethiopia. Crop Protection Bulletin 15, 179-186.

Hailu. D,. And Desalegn, C. (2014)Evaluation of surge and cutback flow furrow irrigation system for pepper(Capsicum Annuum) production. *Journal of Irrigation and drainage*,463-473

Hamed, E. and Abdolmajid, L. (2011). Field Evaluation of Various Mathematical Models for Furrow and Border Irrigation Systems, University of Tehran, Karaj, Iran.

Hart, W.E.; Collins, H. G.; Woodward, G. and Humpherys, A.S. (1980). Design and operation of gravity or surface irrigation. In the design and operation of farm systems. (Ed.M.E.Jensen). Pp 501—580. American Society of Agricultural Engineers, Michigan.

Holzapfel, E. Jara, J. Paredes, M and Billib, L. (2004). Infiltration parameters for furrow irrigation, department of water resources, university of Concepcion, Chillan Chile, Journal of Agricultural water management research.Vol.68 (1).

Horst, M. G., Shamutalov, S. S., Gonçalves, J. M., and Pereira, L. S. (2002**)**. Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. *Jornal of Agricultural water management*, 87 (2):115-127

Horst M.G., Shamutalov S.S., Pereira L.S., and Gonçalves J.M., (2005). Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea Basin. *Agric.Water Manag*, 77: 210-231.

Horst, M. G.; S. S. Shamutalov; J. M.., Goncalves and L. S. Pereira (2007). Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. *Agriculture Water Management,* 87: 115-127.

Hsiao, T., Steduto, P., and E. Fereres. (2007). A Systematic and quantitative approach to improve water use efficiency in agriculture. *Irrig. Sci*, 25:209-231.

Hunt, N., and Gilkes, R. (1992). Farm Monitoring Handbook. University of Western Australia, *Land Management Society and National Dryland Salinity Program, Nedlands, Australia.*

Ismail, S. M.; H. Depewege; B. Schultz (2004). Surge flow irrigation under short-field conditions in Egypt. Irrigation and Drainage Journal, Vol. 53, pp. 461–475.

Israelsen, O.W., and Hansen, V.E. (1962). Irrigation Principles and Practices. *John Wiley and sons*. New York.

Izadi, B.; Hearman, D.F. and Klute, A. (1990). The role of redistribution and hysteresis in the surge irrigation phenomena. Trans. A.S.A.E. 33(3): 799—806.

Jemal N.H. and Mukerem, T. (2017). Comparative Performance Evaluation of Alternate and Convectional Furrow Irrigation under Different Water Application Level on Cabbage Water Use Efficiency and Economic Analysis. American *Journal of Environmental and Resource Economics*,2(3):123-131

James, L.G.,(1988). Principles of Farm Irrigation System Design. John Wiley and Sons, Inc., New York, pp. 342–344.

Jurriens, M. and Lenselink, K. J. 2001. Straightforward furrow irrigation can be70% efficient. Journal of Irrigation and Drainage. 50:195 -204.

Kanber, R., Köksal, H., Önder, S., Kapur, S., Sahan, S., (2001). Comparison of the surge and continuous furrow methods for cotton in the Harran plain. *Agric. Water Management*, 47 (2), 119–135.

Kang, S., Ziang, Z., Pan, Y., Shi, P., and Zhang, J., (2000). Alternate furrow irrigation formalizes production in an arid area. *Agric. Water Manag*. 45 (3), 267–274.

Kang SZ, Pan YH, Shi PZ, Zhang JH. (2001). Controlled root-divided alternate irrigation—theory and experiments. *Journal of Hydraulic Engineering*,11: 80–86 (in Chinese with English abstract).

Kang SZ, and Zhang JH. (2004). Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. *Journal of Experimental Botany,*55(407): 2437–2446.

Karajeh, F., Mukhamedjanov, V. and Vyshepolskiy, F. (2000). On-farm water and drainage management strategy in Kazakhstan’s Arys-Turkestan area. Taraz, Kazakstan. Agricultural water management. 49: 35- 50.

Kebere, B., Ketema, B., and Sripichitt, P. (2006). Genetic Gain in Grain Yield Potential and Associated Agronomic Traits in Haricot Bean. *Kasetsart J.(Nat. Sci.),* 40: 835 - 847, Bangkok, Thailand.

Kemper W.D., Trout T.J., Hampherys A.S., and Bullock M.S., (1988). Mechanisms by which surge irrigation reduces furrow infiltration rates in silt loam soil. Trans. ASABE, 31(3):821-829.

Kiflea, M., Gebremicael, A. G., & Teferi, G., (2017). Effect of surge flow and alternate irrigation on the irrigation efficiency and water productivity of onion in the semi-arid areas of northern Ethiopia.*Agricultural Water Management, 187: 69–76.*

Kifle, M.; K. Tilahum and E. Yazem (2008). Evaluation of surge flow furrow irrigation for onion production in a semiarid region of Ethiopia. Irrigation Science, Vol.26, pp. 325 – 333

Khatri, KL., Smith, RJ. (2006). Real-time prediction of soil infiltration characteristics for the management of furrow irrigation. *Irrigation Science,* 25(1): 33–43.

Lima, V., Pordeus, R. Pereira, J., and Azevedo, M. (2014). Optimization of Furrow Irrigation systems with the continuous flow using the software applied to surface irrigation simulations-SASI. Afr. J. Agric. Res, 9(42): 3115-3125.

Li, P., Hu, XT., Cai, HJ., and Li, ZJ. (2012). Analysis of border irrigation efficiency based on SIRMOD and optimal irrigation technology elements. *Yellow River* 34(4): 77–83 (in Chinese with English abstract).

Lesley W. (2002) Irrigation Efficiency. Irrigation Efficiency Enhancement Report No 4452/16a, March 2002 Prepared for Land WISE Hawke's Bay. Lincoln Environment. USA.

Mahmood, S.; M.A. Kahan; M.L Atif and J.K. Sial (2003). Application of Surge Irrigation on Borders for Water Saving and Wheat Production: First-Year Study Result. Ital.J.Agron,7(1):49–55.

Malano H.M (1982) Comparison of the infiltration process under continuous and surge flow. *M.S Thesis Agricultural and irrigation engineering department. Utha state university*, Logan, pp.107

Manisha, L . (2016) Performance evaluation of furrow irrigation system for BRINJAL with different mulches (MS Thesis).

Michael, A.M. (2008). Irrigation Theory and Practice. 2nd edition. *Jupiter Offset Printers, Dehli*-32.568p.

Micheal, A.M. (1978). Irrigation**:** Theory and practice.Vikas. Publishing House PVT. LTD.

Murphy, Denis J. (2007). People, Plants, and Genes: The Story of Crops and Humanity. Oxford: Oxford University Press.

Narayana, K, and Brook, A. (2014). Hydraulic Performance of Furrow Irrigation system to Optimize Design Parameters Suitable to Onion Field In Hawassa, Ethiopia. *Journal of Science & Development*, 23-39.

Podmore, T. H., and H. R. Duke. (1982). Field evaluation of surge irrigation. ASAE Paper No. 82-2102, ASAE, St. Joseph, MI 49085-9659. 15. Poole,

Purkey, D.R., and W.W. Wallender (1988). Surge flow infiltration variability. Transactions of the ASAE, 32(3): 894-900.

Raines, R., Smith, R., and Bakker, D. (2005). Increased Furrow Irrigation Efficiency through Better Design and Management of Cane Fields. *Journal of Agricultural Management*, 71:117-130.

Raines. R and Smith, R.. J. (2007). Simulation modeling for surface irrigation evaluation: Training in using SIRMOD and IPARM. National Centre for Engineering in Agriculture.

Raine, SR, and Walker, WR. (2004). A design and management tool to improve surface irrigation efficiency. *Transactions of the American Society of Agricultural Engineers*, 10(3): 19–23.

Rao, M. D., Raghuwanshi, N. S., and Singh, R. (2006). Development of a physically-based infiltration model for seal formed irrigated soils. *Agric. Water Manage,* 84(1–2):164–174.

Rogers, D. H, and Sothers, M. W. (1995).Surge Irrigation. Irrigation Water Management Series. Cooperative extension service: *Manhattan, Kansas State University: USA*

Sahlemedhin, S., and Taye, B. (2000). Procedures For Soil And Plant Analysis. *Ethiopian Institute of Agricultural Center*. Technical paper No: 74

Schwab, G.O.; Frevert, R.K.; T.W. and Barnes, K.K. (1981). Soil and Water Conservation Engineering. John Wiley and sons. New York.

Solomon, K.H. (1988). Irrigation Notes. Center for Irrigation Technology. *California State University*, Fresno. California.

Sial, J. K.; M. A. Khan and N. Ahmad (2006). Performance of surge irrigation under borders. *Pakistan Journal of Agricultural Science*s, 43(3- 4): 186-192.

Sirjani, F., and Wallender, W.W., (1989). Stochastic Infiltration from Advance Furrows.*Trans. of the ASAE,3*2(2): 649-654.

Sepaskhah, A.R. and Kamgar-Haghighi, A.A. (1997). Water use and yield of sugar beet grown under every-other furrow irrigation with different irrigation intervals. Agriculture Water Management.34:71-79.

Stringham, GE, Keller, J (1979) surge flow automatic irrigation In: Proceedings of the ASCE irrigation and drainage division especially conference, Albuquerque; NM:13-14.

Testezlaf, R., Elliot, R.L, and Garton, J.E.(1987).Furrow infiltration under surge flow irrigation. Transaction of the ASAE, 39(1):193-197.

Papova, Z.; Gospodinov, I. and Tsiourtis, N.X. (1971). furrow irrigation by surges as water-saving technology. Water resources management under drought or water shortage conditions. *Proceedings of the EWRA95 Symposium, Nicosia, Cyprus,* 14—18.

Valipour, M. (2013**).** Increasing irrigation efficiency by management strategies: cutback and surge irrigation. ARPN Journal of Agricultural and Biological Science, Vol. 8, No. 1

Varlev, I.; Papova, Z.; Gospodinov, I. and Tsiourtis, N.X. (1971). furrow irrigation by surges as water-saving technology. *Water resources management under drought or water shortage conditions.* Proceedings of the EWRA95Symposium, Nicosia, Cyprus, 14—18,

Walker, W.R. (1987). Guidance for design and evaluation of surface irrigation system. FAO, Irrigation and Drainage, Rome, Italy, 45:

Walker, W.R. (2003). SIRMOD III - Surface Irrigation Simulation, Evaluation, and Design. Guide and Technical Documentation. *Department of Biological and Irrigation Engineering,* Utah State University, Logan, Utah.

Walker, W.R., and Skogerboe, G.V. (1987). Surface Irrigation: ’Theory and Practice’. Prentice-Hall: *Englewood Cliffs, New Jersey, USA*

Walker, WR. (2005). SIRMOD II - Surface Irrigation Simulation, Evaluation, and Design. User's Guide and Technical Documentation. *Utah State University*

Yang, C., Huang, G., Chai, Q., Luo, Z.,(2011). Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of Northwest China. Field Crops Res, 124 (3), 426–432.

Yemane, M., Abraham, W., and Solomon, H., (2018). The response of onion (Allium cepa l.) to deficit irrigation under different furrow irrigation water management techniques in Raya Valley, Northern Ethiopia. *Africa journal of Plant Science,* 12(5):105-113

Yi Luo. , Z. Lei, L. Zheng, Sh. Yang, Z. Ouyang and Q. Zhao, 2006.A stochastic model of soil water regime in the crop root zone. Journal of Hydrology (2007) 335, 89-9.

Zhang, H., Pala, M., Oweis, T., Harris, H.,(2000). Water use and water use efficiency of chickpea and lentil in a *Mediterranean environment. Aust. J. Agric, Re*s. 51, 295–305.

Zerihun, D., Wang, Z., Rimal. S., and Feyen. J., (1997). Analysis of surface irrigation performance terms and indices. *Agricultural Water Management,* 34: 25-46

Zhang, J., and Davies, J.W. 1991. Anti-transparent activity in the xylem sap of maize plants. J*ournal Experimental Botany*. 42:317-321..\

APPENDIXES

Appendix A Relations of soil type, bulk density, soil moisture contents, and soil infiltration and climatic data

Appendix Table - 1: Bulk density of the experimental soil

depth (cm)	the volume of core sampler (cm3)	weight of sampler (gm)	weight of dry sample +core (gm)	weight of dry soil sample (gm)	bulk density (gm/cm3)
0-15	98	33	143.5	110.7	1.13
15-30	98	33.1	146.2	112.8	1.15
30-60	98	33.4	148.1	104.7	1.06
Average					1.116
0-15	98	33	142.3	109.3	1.11
15-30	98	33.4	147.8	111.4	1.16
30-60	98	33	138.5	105.5	1.07
Average					1.113
0-15	98	33. 1	142. 8	109.7	1.119
15-30	98	33.4	147.5	114.1	1.164
30-60	98	33	136.6	103.6	1.057
Average					1.113
Grand mean					1.114

Appendix Table -2 Discharge and Head relation in the siphon

Head	Q(L/s)	Head	Q(L/s)
4	0.80	28	2.12
6	0.98	30	2.20
8	1.14	32	2.27
10	1.27	34	2.34
12	1.39	36	2.41
14	1.50	38	2.48
16	1.61	40	2.54
18	1.70	42	2.60
20	1.80	44	2.66
22	1.88	46	2.72
24	1.97	48	2.78
26	2.05	50	2.84

Appendix Table -3: Soil infiltration data of the experimental area

elapsed time (minuet)	Cumulative Time (minuet)	reading (cm)	Difference (mm)	Cumulative intake (mm)	Infiltration rate (mm/hr)
0	0	12.5	0	0	0
0.25	0.25	12.2	3	3	720
0.25	0.5	12	2	5	480
0.5	1	11.7	3	8	360
1	2	11.3	4	12	240
3	5	10.4	9	21	180
5	10	9.3	11	32	132
10	20	7.6	17	49	102
10	30	6.4	12	61	72
15	45	4.8/12.7*	15	76	60
15	60	11.3	14	90	56
20	80	9.3	18	108	54
20	100	7.5	18	126	54
20	120	6.4/13.2*	11	137	33
30	150	11.6	16	153	32
30	180	10.3	13	166	26
30	210	9.3	10	176	18
30	240	8.5	8	184	16
30	270	7.7	8	192	16

Appendix Table -4 Input data for furrow irrigation design process

1.Field Topography/Geometry	
Furrow Geometry	Input depending on furrow length
Field length, m	50
A field width, m	3
Furrow spacing, m	0.6
Flow cross-section	
Top width(m)	0.4
Middle width(m)	0.25
Bottom width(m)	0.16
Maximum depth(m)	0.18
Field system	Furrow irrigation
Downstream boundary	Blocked
Slopes	0.2%
First distance for the first slope:	25
Second distance for the second slope:	25
Simulation shutoff control:	Simulation time or No. of surges/ by a target application
Inflow regime control	Continuous inflow and fixed- cycle surge flow
Type of simulation model:	Hydrodynamic, kinematic-wave and zero-inertia
Number of surges	For CR ½, 12 and CR 1/3, 18

Appendix Table -5 Daily climate and ETo of haricot bean crop during the experiment at Melkassa condition for February (Source: MARC)

Day	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun hours	Rad MJ/m/day	ETo mm/day
13	14.5	21.5	86	277	1.3	10.7	2.31
14	14.5	24.5	73	259	6.4	18.3	3.92
15	12	29.5	56	251	9.9	23.6	5.65
16	16.5	31.5	46	173	10.5	24.5	5.82
17	14.5	33.5	46	164	10.4	24.4	5.91
18	16.5	33.5	49	233	9.5	23.1	6.31
19	15.5	32.5	50	199	9.5	23.2	5.88
20	14.5	32.5	47	242	9.7	23.5	6.33
21	16	32	54	259	10	24	6.24
22	17	31.5	50	285	9.8	23.7	6.48
23	16.5	31.5	52	277	10.1	24.2	6.4
24	17	32.5	47	216	9.6	23.5	6.19
25	12	33.5	46	138	10.4	24.8	5.71
26	18	31	49	294	9.6	23.6	6.54
27	17.5	30.5	53	302	9.9	24.1	6.4
28	16.5	31.5	51	190	9.8	24	5.84

Appendix Table – 6 Daily ETO of haricot bean crop during the experiment at Melkassa condition for March (Source: MARC).

Day	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun Hours	Rad MJ/m?/day	ETo mm/day
1	15	33.5	42	199	9.6	23.7	6.3
2	12.5	32.5	42	190	9.8	24.1	6.11
3	14	33.8	40	121	9.2	23.2	5.48
4	16.5	34	42	130	8.8	22.6	5.55
5	16	34	43	138	8.9	22.8	5.65
6	14.5	33.5	41	164	8.2	21.8	5.75
7	17	34	38	216	10.1	24.7	6.81
8	16	33.5	37	216	10	24.6	6.74
9	18.5	33	44	173	9.2	23.4	6.02
10	17.5	32.5	50	233	8.7	22.7	6.19
11	18.6	30.5	52	233	3.4	14.5	4.9
12	17.5	33	47	164	10	24.7	6.04
13	14	34.5	44	121	9.0	23.2	5.54
14	17.5	33	47	216	9.1	23.4	6.31
15	17.5	33.5	48	199	6.8	19.8	5.74
16	19.5	32.5	57	156	5.6	18	4.84
17	16.5	32	60	61	5.5	17.9	3.97
18	16	32	57	207	8.4	22.4	5.69
19	16	32.5	55	302	9.4	24	6.61
20	18.5	32.6	55	173	7.6	21.2	5.46
21	16	24.1	55	121	6.3	19.2	4.11
22	17	24	54	173	5.6	18.1	4.32
23	15.6	20.8	72	86	2.8	13.7	2.82
24	15.5	23	64	86	10.8	26.2	4.65
25	16	23	68	121	10	25	4.56
26	16.5	22.5	62	207	10.8	26.3	5.05

27	13.5	22	48	181	11	26.6	5.16
28	12.5	22.3	51	121	11.3	27.1	4.85
29	14.5	23.8	49	121	11.4	27.2	5.09
30	13.5	23	49	156	11.6	27.5	5.21
31	19	26	48	164	11.5	27.4	5.78

Appendix Table -7 Daily ETo of haricot bean crop during the experiment at Melkassa condition for April (Source: MARC).

Day	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m^2/day	mm/day
1	17.6	32.5	46	233	9.9	24.9	6.64
2	16.5	33	48	294	10.7	26.1	7.22
3	19	32.5	46	337	10.8	26.3	7.61
4	16.5	33	48	251	10.8	26.3	6.93
5	18.5	33	43	242	10.9	26.4	7.09
6	14	32.5	41	216	10.7	26.1	6.72
7	17	33	37	2160	10.9	26.4	6.99
8	13.5	34	39	181	10.9	26.4	6.64
9	13.5	34.2	41	121	11.1	26.7	6.04
10	14.5	34	43	138	10.6	25.9	6.1
11	15.5	34	43	181	10.9	26.4	6.6
12	18.6	31	47	268	8.1	22	6.37
13	16.5	28	70	216	4.5	16.4	4.13
14	15.5	33	55	181	10.1	25.1	6.06
15	16.6	27	69	138	6.6	19.7	4.23
16	16.5	28.5	65	138	5.4	17.8	4.17
17	18.5	30.6	55	199	5.5	18	5.03
18	16	31	60	147	7.8	21.5	5.04
19	16.5	29.5	63	138	7.7	21.3	4.78
20	17.6	31.5	59	138	6.8	19.9	4.85

21	15.5	26	71	181	3.2	14.4	3.53
22	15	30.5	57	190	8.3	22.2	5.4
23	18.5	29	59	207	3.2	14.4	4.33
24	17	23.5	78	104	0.1	9.6	2.35
25	13	31	56	138	11.4	26.9	5.71
26	16	32	54	112	9	23.2	5.21
27	16	32.2	55	147	7	20.1	5.05
28	16.6	28	66	104	3.8	15.2	3.58
29	17.2	33	56	156	9.9	24.5	5.8
30	16.5	29	67	130	6.4	19.2	4.31

Appendix Table -8 Daily ETo of haricot bean crop during the experiment at Melkassa condition for May (Source: MARC).

Day	Min Temp °C	Max Temp °C	Humidity %	Wind Km/day	Sun Hours	Rad MJ/m^2/day	ETo mm/day
1	17.5	31	62	190	8.03	22	5.32
2	16.5	28	69	181	5.6	17.9	4.22
3	17.5	29.5	66	95	8.4	22.2	4.65
4	18	29.2	64	86	5.3	17.4	3.92
5	15.5	30	62	104	10.9	25.9	5.25
6	14.5	30.5	60	138	10.6	25.4	5.42
7	16.2	28.4	69	112	7.3	20.4	4.31
8	15.5	28.5	66	156	8.4	22	4.76
9	15	20	62	156	9.9	24.3	4.39
10	14.5	20.5	61	156	11	25.9	4.61
11	15.5	32.6	52	156	11.2	26.2	6
12	12.5	32.2	47	156	10.8	25.6	5.9
13	11.5	33	48	156	10.8	25.5	5.95
14	13	34	43	173	10.6	25.2	6.29
15	15.5	34	52	199	10.7	25.3	6.37
16	17	34	50	190	10.9	25.6	6.41

17	17.5	31	55	147	7.5	20.5	5
18	14.5	32	54	190	8.8	22.4	5.63
19	19	32.5	54	138	7.7	20.7	5.14
20	17.5	32.4	56	199	7.0	19.7	5.35
21	16	31.5	57	216	10.3	24.6	5.95
22	17	31.0	65	138	6.4	18.7	4.48
23	17.5	31.5	60	173	9.4	23.2	5.46
24	19	32.5	54	190	10.1	24.2	5.99
25	18	33.5	53	147	10.9	25.4	5.93
26	16	32.5	54	164	10.5	24.7	5.81
27	17.8	33.5	51	181	10.7	25.0	6.19
28	18	30.0	58	190	7.4	20.1	5.06
29	17.5	31.0	59	181	5.5	17.3	4.68
30	18.5	33.0	54	225	8.5	21.7	5.94
31	18	33.0	53	251	8.8	24.1	54.8

Appendix Table - 9 Bed sloped of furrow

level Station	Distance from Upstream end of furrow	Back sight (B.S)	Height of instrument	Fore sight (F.S)	Furrow Reduced elevation (RL.m)
1(BM)	0	1.452	101.452	1.444	100.008
2	5			1.485	99.967
3	10			1.485	99.967
4	15			1.515	99.937
5	20			1.562	99.89
6	25			1.548	99.904
7	30			1.575	99.877
8	35			1.613	99.839
9	40			1.610	99.842
10	45			1.630	99.822
11	50			1.608	99. 844

Appendix Table -10 Randomized Complete Block AOV Table for grain yield (ton/ha)

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep.	2	0.00174	0.00087		
Trt.	5	0.13751	0.02750	4.50	<0.01
Error	10	0.06111	0.00611		
Total	17	0.20036			

Grand mean	2.3088
Coefficients of variation	3.39
Observations per Mean	3
Standard Error of a Mean	0.0451
Std Error (Diff of 2 Means)	0.0638

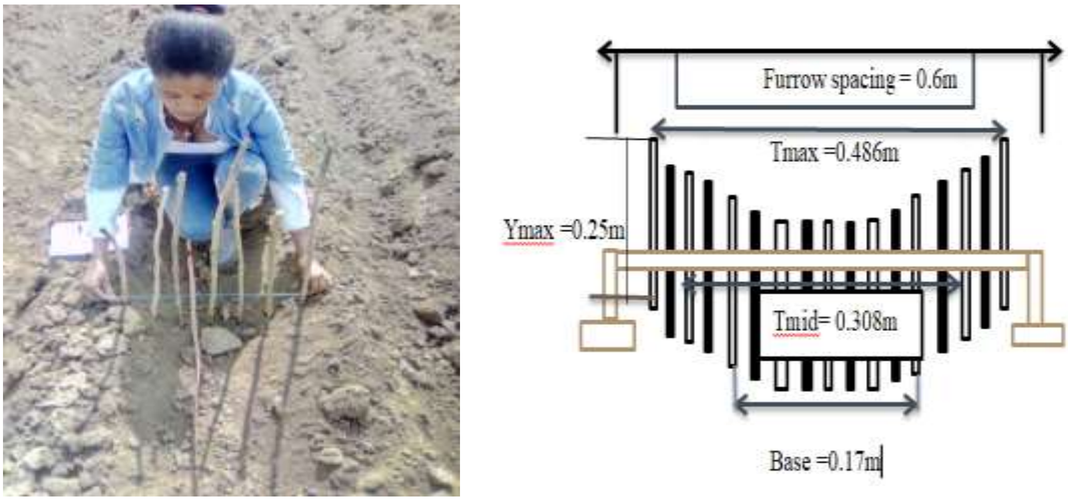
"<0.05" indicates a highly Significant difference at the probability level of 5% (p<0.05).

Appendix Table -11 Randomized Complete Block AOV Table for final biomass (ton/ha)

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep.	2	0.2865	0.14327		
Trt.	5	0.7043	0.44695	3.49	<0.01
Error	10	0.2175	0.107250		
Total	17	0.20083			

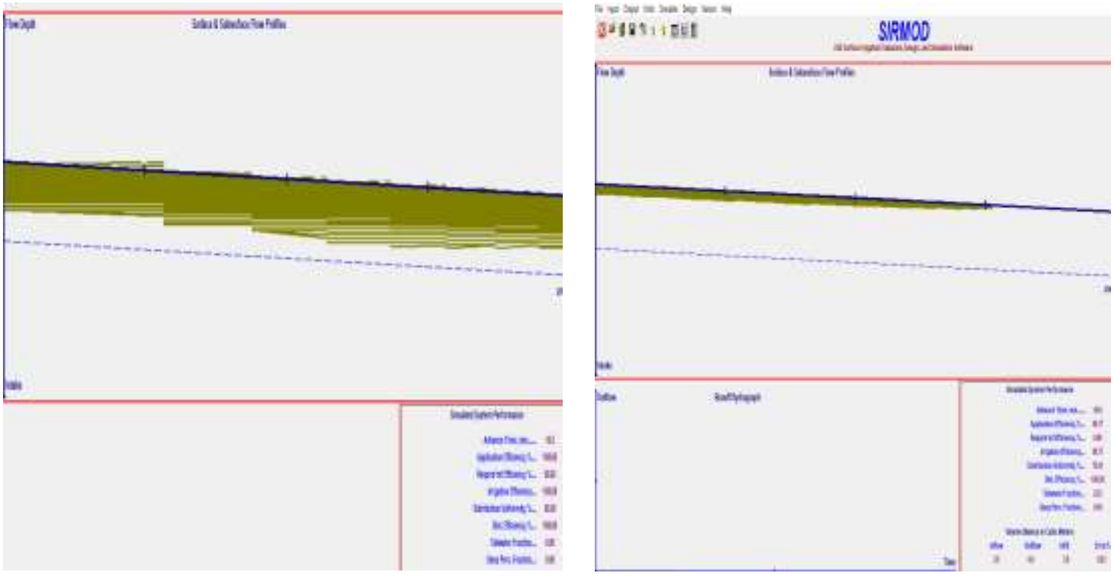
Grand mean	2.4159
Coefficients of variation	3.10
Observations per Mean	3
Standard Error of a Mean	0.1891
Std Error (Diff of 2 Means)	0.2674

Appendix Figure – 1 Data collection for Furrow elevation and soil sample

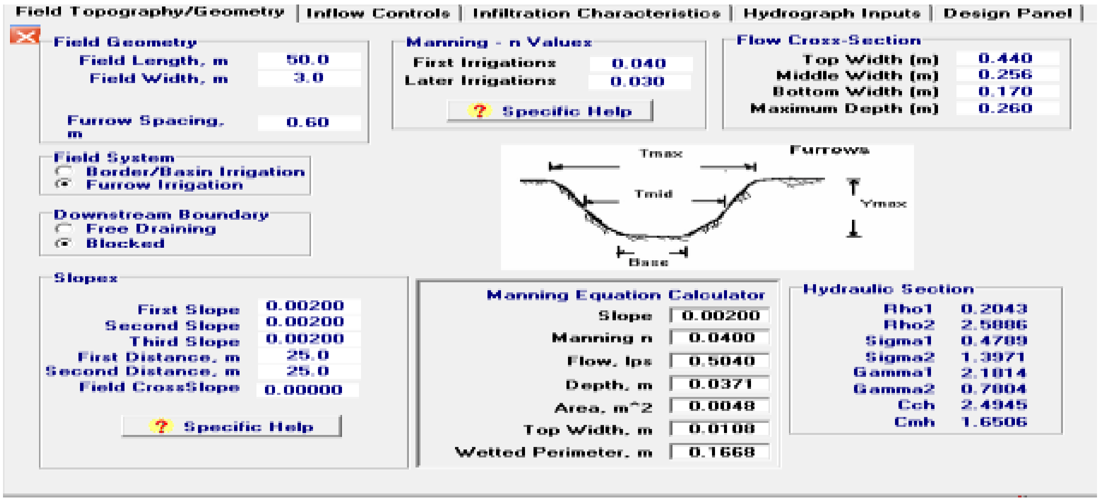


Appendix Figure -2 parabolic shape of furrow geometry

Appendix Figure -3 Infiltration rate measurements



Appendix Figure – 4 SIRMOD input screens for both continuous and surge flow system



Field Geometry

Field Length, m	50.0
Field Width, m	3.0
Furrow Spacing, m	0.60

Manning - n Values

First Irrigations	0.040
Later Irrigations	0.030

Flow Cross-Section

Top Width (m)	0.440
Middle Width (m)	0.256
Bottom Width (m)	0.170
Maximum Depth (m)	0.260

Field System

○ Border/Basin Irrigation
● Furrow Irrigation

Downstream Boundary

○ Free Draining
● Blocked

Slopes

First Slope	0.00200
Second Slope	0.00200
Third Slope	0.00200
First Distance, m	25.0
Second Distance, m	25.0
Field CrossSlope	0.00000

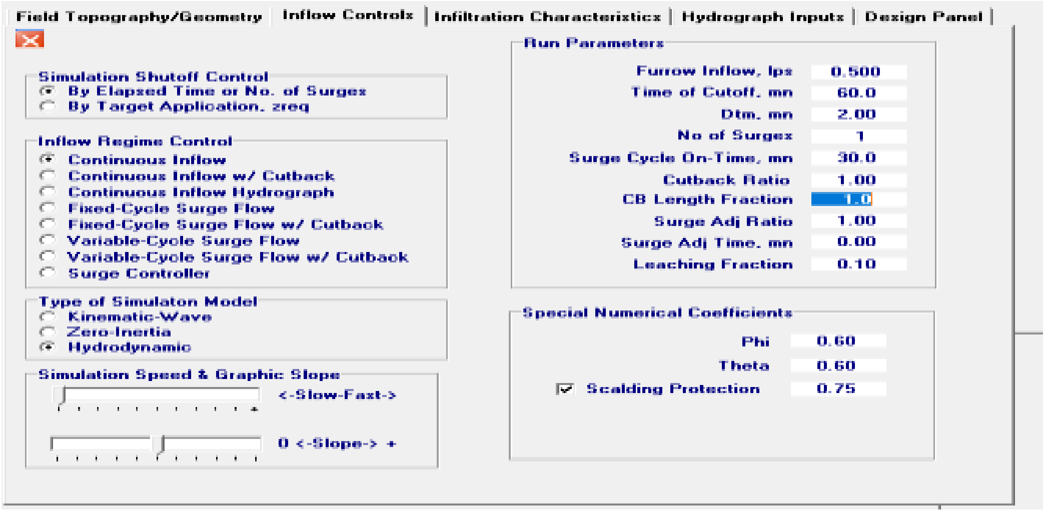
Manning Equation Calculator

Slope	0.00200
Manning n	0.0400
Flow, lps	0.5040
Depth, m	0.0371
Area, m^2	0.0048
Top Width, m	0.0108
Wetted Perimeter, m	0.1668

Hydraulic Section

Rho1	0.2043
Rho2	2.5886
Sigma1	0.4789
Sigma2	1.3971
Gamma1	2.1814
Gamma2	0.7804
Cch	2.4945
Cmh	1.6506

Appendix Figure - 5 Field topography input



Simulation Shutoff Control

● By Elapsed Time or No. of Surges
○ By Target Application, zreq

Inflow Regime Control

● Continuous Inflow
○ Continuous Inflow w/ Cutback
○ Continuous Inflow Hydrograph
○ Fixed-Cycle Surge Flow
○ Fixed-Cycle Surge Flow w/ Cutback
○ Variable-Cycle Surge Flow
○ Variable-Cycle Surge Flow w/ Cutback
○ Surge Controller

Type of Simulaton Model

○ Kinematic-Wave
○ Zero-Inertia
● Hydrodynamic

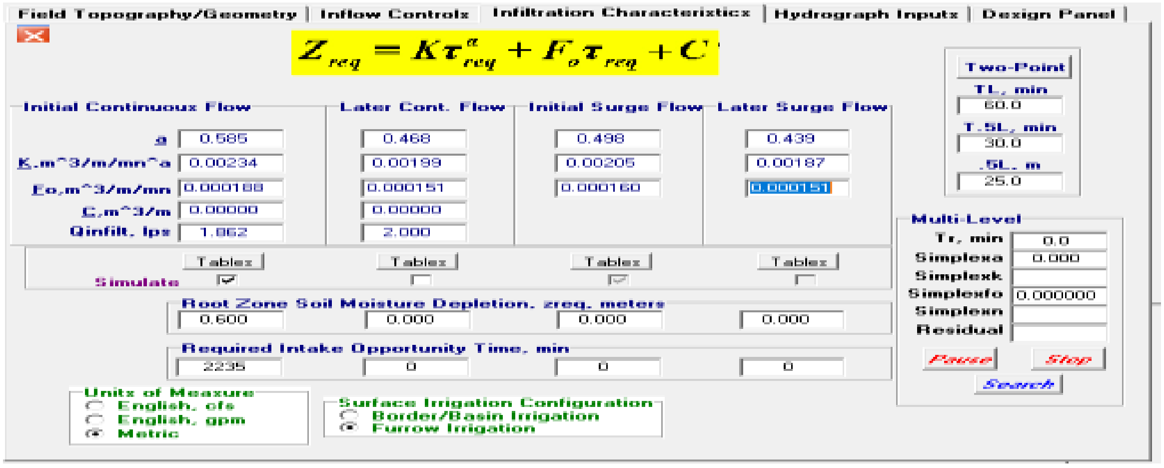
Run Parameters

Furrow Inflow, lps	0.500
Time of Cutoff, mn	60.0
Dtm, mn	2.00
No of Surges	1
Surge Cycle On-Time, mn	30.0
Cutback Ratio	1.00
CB Length Fraction	1.0
Surge Adj Ratio	1.00
Surge Adj Time, mn	0.00
Leaching Fraction	0.10

Special Numerical Coefficients

Phi	0.60
Theta	0.60
☑ Scalding Protection	0.75

Appendix Figure - 6 Inflow controls input (for hydrodynamic and zero inertia simulation)



$$Z_{req} = K\tau_{req}^{a} + F_o\tau_{req} + C$$

	Initial Continuous Flow	Later Cont. Flow	Initial Surge Flow	Later Surge Flow
a	0.585	0.468	0.498	0.439
K,m^3/m/mn^a	0.00234	0.00199	0.00205	0.00187
Fo,m^3/m/mn	0.000188	0.000151	0.000160	0.000151
C,m^3/m	0.00000	0.00000		
Qinfilt, lps	1.862	2.000		
Simulate	☑	☐	☑	☐
Root Zone Soil Moisture Depletion, zreq, meters	0.600	0.000	0.000	0.000
Required Intake Opportunity Time, min	2235	0	0	0

Two-Point

TL, min	60.0
T.5L, min	30.0
.5L, m	25.0

Multi-Level

Tr, min	0.0
Simplexa	0.000
Simplexk	
Simplexfo	0.000000
Simplexn	
Residual	

Units of Measure

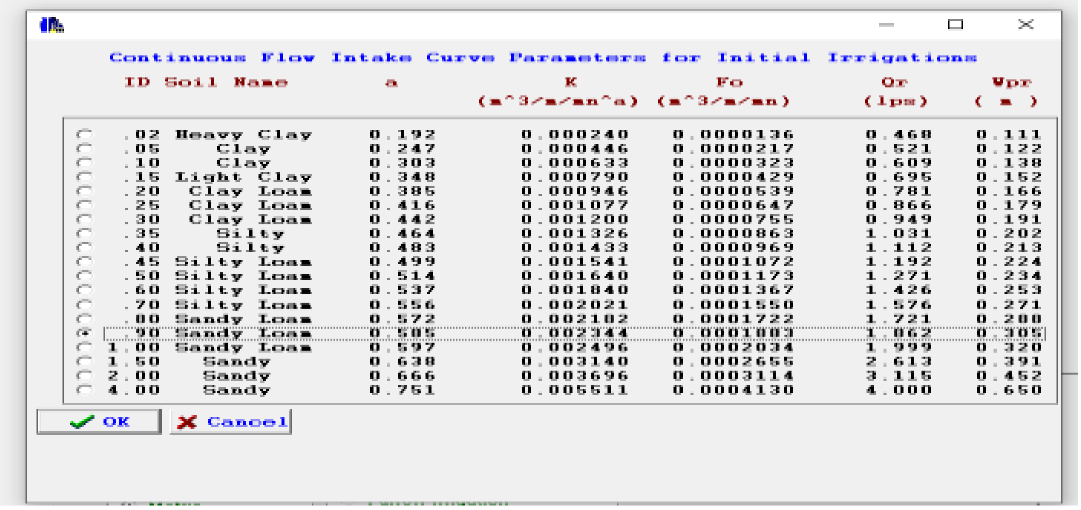
○ English, cfs
○ English, gpm
● Metric

Surface Irrigation Configuration

○ Border/Basin Irrigation
● Furrow Irrigation

Appendix Figure -7 Infiltration characteristics input

Appendix Table -1 infiltration coefficients for different function of flow



Continuous Flow Intake Curve Parameters for Initial Irrigations

	ID	Soil Name	a	K (m^3/m/mn^a)	Fo (m^3/m/mn)	Qr (lps)	Vpr (m)
○	.02	Heavy Clay	0.192	0.000240	0.0000136	0.468	0.111
○	.05	Clay	0.247	0.000446	0.0000217	0.521	0.122
○	.10	Clay	0.303	0.000633	0.0000323	0.609	0.138
○	.15	Light Clay	0.348	0.000790	0.0000429	0.695	0.152
○	.20	Clay Loam	0.385	0.000946	0.0000539	0.781	0.166
○	.25	Clay Loam	0.416	0.001077	0.0000647	0.866	0.179
○	.30	Clay Loam	0.442	0.001200	0.0000755	0.949	0.191
○	.35	Silty	0.464	0.001326	0.0000863	1.031	0.202
○	.40	Silty	0.483	0.001433	0.0000969	1.112	0.213
○	.45	Silty Loam	0.499	0.001541	0.0001072	1.192	0.224
○	.50	Silty Loam	0.514	0.001640	0.0001173	1.271	0.234
○	.60	Silty Loam	0.537	0.001840	0.0001367	1.426	0.253
○	.70	Silty Loam	0.556	0.002021	0.0001550	1.576	0.271
○	.80	Sandy Loam	0.572	0.002182	0.0001722	1.721	0.288
●	.90	Sandy Loam	0.585	0.002344	0.0001883	1.862	0.305
○	1.00	Sandy Loam	0.597	0.002496	0.0002034	1.999	0.320
○	1.50	Sandy	0.638	0.003140	0.0002655	2.613	0.391
○	2.00	Sandy	0.666	0.003696	0.0003114	3.115	0.452
○	4.00	Sandy	0.751	0.005511	0.0004130	4.000	0.650

Appendix Figure -8 measuring water head above the center of the pipe and applying

Appendix Figure.9 Measuring dries biomass from1m length of the furrow