



Optimizing Furrow Irrigation Decision Parameters Using WinSRFR Model: The  
Case of Batu Degaga Small Scale Irrigation Scheme

By

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## 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.

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## ADVISOR’S APPROVAL SHEET

To: Water Resources Engineering Department

Subject: Thesis submission

This is to certify that the thesis paper entitled “Optimizing Furrow Irrigation Decision Parameters Using WinSRFR Model: The Case of Batu Degaga Small Scale Irrigation Scheme” submitted in partial fulfillment of the requirements for the degree of Master’s in Water Resources Engineering (Irrigation Engineering) has been carried out by Chari Abelti Tufa (Id. No: PGR/ 18086//11) under our supervision. Therefore, we recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

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## LIST OF ABBREVIATIONS AND ACRNOMYS

DP	Deep percolation fraction
DU	Distribution Uniformity
DU <sub>min</sub>	Minimum Distribution Efficiency
EA	Application Efficiency
ER	Requirement Efficiency
MoA	Ministry of Agriculture
NRMSE	Normal Root Mean Square Error
PAE	Potential Application Efficiency
Ro	Run off fraction
RE	Relative Error
USDA	United State Department of Agriculture

## ABSTRACT

*Surface irrigation simulation models have the potential to improve the efficiency of irrigation systems and thus deliver significant water savings which can be achieved by optimizing the design and management decisions at the field level. The measurement, evaluation and optimization of furrow irrigation is restricted to a single furrow or small number of adjacent furrows due to the measurement process is too intensive to be applied at the full field scale. So, it is necessary to assume that the infiltration characteristics and inflow rates of the measured furrow(s) represent the remainder of the field. Therefore, the aim of this study was to optimize decision parameters of furrow irrigation using WinSRFR model so as to improve furrow irrigation efficiency of onion field at Batu Degaga small-scale irrigation scheme. Field experiment were conducted on six blocked-ended furrows with the length of 40 meter and slope of 0.2 % and two inflow treatments (1.0 and 1.5 l/s) for three irrigation events. All field measurements used for input parameters were collected from four middle furrows and the other two were taken as buffer furrows. The collected data's were processed by Microsoft EXCEL and data analysis was conducted using WinSRFR software. The statistical indicators of NRMSE,  $R^2$ , RE, d, and  $\lambda$  were used for the comparison between measured and simulated advance time, recession time and performance parameters. The results of these indicators were very good and showed that WinSRFR simulation was acceptable. So, WinSRFR software was employed to optimize the combination of irrigation parameters such as inflow rate, cut-off time and field geometry. Then, optimum combination of furrow irrigation decision parameters were determined to obtain the maximum performance. Results showed that using combination of 40m furrow length under 0.2% bed slope with 2 l/s inflow rate and 0.18 hour cutoff time can obtain maximum application efficiency of 95%. In addition, this study revealed that under different furrow inflow rates and furrow bed slopes (i.e. 0.1, 0.2, 0.3, 0.4 and 0.5%) using 40m furrow length has maximum hydraulic performance than other furrow lengths (i.e. 60, 80 and 100m). Finally, even though high performance was obtained under short furrow length, for effective management and use of irrigation water the longer furrow length (i.e. 100m) was suggested for the study area.*

**Keywords:** Furrow Irrigation, Decision Parameters, Irrigation Scheme, WinSRFR, optimization

# 1. INTRODUCTION

## 1.1. Background

Furrow irrigation is a widely used irrigation method; however, the systems are often inefficient because of poor irrigation performance (Smith, 2018). It is considered as low water application efficiency and distribution uniformity (Clemmens, 2009). Water application efficiency is influenced principally by the amount of water applied, the intake characteristics of the soil and the rate of advance of water in the furrows (Tesfaye, 2016). The inappropriate management, design, and implementation are the important reasons for poor performance of surface irrigation systems (Ebrahimiyan and Liaghat, 2011). According to Manisha (2016), the reduced level of performance in furrow irrigation system can be attributed to incorrect dimensioning, and also the poor design and evaluation managements are generally responsible for inefficient irrigation, leading to the waste of water, water logging, salinization and pollution of surface and ground water resources.

Furrow irrigation system finds an important place among the surface irrigation methods. Furrow designed on the basis of soil, crop, topography, size and shape of the irrigated area. It has several design variables that affect its hydraulic performance. These are the inflow rate, the length of the run in the direction of the flow, cutoff time and soil surface roughness and infiltration characteristics parameters. Optimal furrow length and cutoff time can be determined, as related to soil infiltration characteristics. The inflow rate, cut-off time and field characteristics are the most important parameters affecting performance of furrow irrigation (Bautista, 2009). Bai (2010) and Chen (2012) studies suggested that geometric parameters (i.e. field length, width and slope) affect the irrigation performance. Proper use of furrow design parameters is one of the practices in irrigated agriculture to maximize irrigation efficiencies and enhanced crop yield as well as the water use efficiency (Narayana and Brook, 2014). Field irrigation management practice has a significant impact on performance but has received only limited consideration to date. It is fact that with the optimum combination of decision and design parameters the maximum efficiency and uniformity can be achieved. Therefore, irrigation system designers must strive to find the best design and management activities in order to improve performance of irrigation system at field level. It is possible to design, evaluate and optimize furrow irrigation systems using different simulation models.

In order to reduce costs and decrease time in analysis of performance indicators, it is essential to use the mathematical models for simulation of surface irrigation (Mehdizadeh, 2015). Computer simulation models have the potential to improve the efficiency of irrigation systems and thus deliver significant water savings. This can be achieved by optimizing the design and management decisions at the field level (Koech, 2010). 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 based on mathematical equations known as Saint Venant equations (Bautista, 2009). Advanced simulation models of surface irrigation have been proved to be effective for the evaluation of system design and management, and to improve furrow irrigation performance. So, this study mainly focus on using surface irrigation simulation model known as WinSRFR to improve the irrigation performance of furrow irrigation system.

## **1.2. Statement of the Problem**

Surface application is the dominant irrigation method applied throughout the world. However, water use efficiencies with surface irrigation methods tend to be low (Narayana and Brook, 2014). Surface irrigation has been dominantly experienced in modern and traditional irrigation. Old-style surface irrigation accounts about 56% of the total countrywide irrigated zones (Awulachew, 2010). Even though the irrigation has contributed in improving the quality of life for rural populations, the sustainability of irrigated agriculture is under question. Efficient utilization of irrigation water has been major challenge in irrigation scheme. Declining water supplies, drought, increased competition from other users, undesirable consequences of irrigation such as: salinity problem, sodicity, water logging are encouraging many producers to improve the irrigation efficiency of their irrigation systems. In Batu Degaga irrigation scheme every liter of water has cost that is manifested through electric bill used to pump the irrigation water. The farmers use very short traditional furrows averagely eight meters and due to poor application efficiency there was also some indicators of salt accumulation in the furrows. However most irrigation performance studies were focused on long furrows. So, this study aims to determine and optimize decision variables that can improve the performance of furrow irrigation practice under short furrows.

### **1.3. Objectives of the Study**

#### **1.3.1. General objective**

The general objective of this study was to optimize decision parameters for furrow using WinSRFR model so as to improve on farm irrigation efficiency of small-scale irrigation.

#### **1.3.2 Specific objectives**

The specific objectives of the study were:

- ✓ To evaluate the performance of furrow irrigation under field operation conditions;
- ✓ To determine parameters that can increase furrow hydraulic performance of the area, and
- ✓ To optimize furrow irrigation decision variables in order to improve performance.

### **1.4. Research Questions**

1. What was the hydraulic performance of short furrow irrigation practices?
2. Which decision variable affect most the performance of furrow irrigation?
3. Which optimum combination of irrigation decision variables can improve irrigation efficiency of furrow irrigation system of the area?

### **1.5. Significance of the Study**

Irrigation management guidelines for in-field irrigation management are generally lacking due to the high cost and time involved in obtaining data for traditional evaluations. In such case simulation modeling can be used for identifying irrigation performance indices and guidelines for improving management practices of irrigation plots. So, this study has a great role in identifying optimum irrigation technical parameters that can improve efficiency and save a significant amount of irrigation water. This in turn will reduce ground water level rise and salt accumulation on the surface that can affect irrigated land productivity which is the current major problem in Batu Degaga irrigation scheme.

### **1.6. Scope of the Study**

The study focuses on evaluation and optimizing parameters that can improve hydraulic performance of furrow irrigation in Batu Degaga Small-Scale Irrigation Scheme. The observed data of study area were used for design, evaluation and analysis in WinSRFR software. Finally, WinSRFR was used for determination of optimum combination of furrow irrigation decision parameters that can improve irrigation efficiency of the study area.

## **2. LITERATURE REVIEW**

### **2.1. Irrigation in Ethiopia**

Ethiopian irrigation development was practiced during ancient times even if its exact date of emergence is unknown. Ancient use of irrigation water was through use of surface irrigation methods. Traditional small-scale irrigation schemes have existed for perhaps several hundred years. Modern irrigation was started at the Awash River basin with bilateral cooperation of Ethiopia and Dutch company. This was started during the 1950s for the productions of commercial crops such as sugar cane and cotton. The development of irrigation and agricultural water management holds significant potential to improve productivity and reduce vulnerability to climactic volatility in any country (Awulachew, 2010). The experience in modern small-scale irrigation (SSI) development and management started in the 1970s by the Ministry of Agriculture (MoA), in response to major droughts, which caused wide spread crop failures and consequent famine. However, the study estimates that total irrigable land potential in the country is 3.7 million ha assuming use of currently available technologies. Among the irrigation methods, surface irrigation, which is public in different part of the world has been dominantly experienced in modern and traditional irrigation (Gebremedhin and Asfaw, 2015).

### **2.2. Surface Irrigation**

Surface irrigation is an irrigation method where water drain by gravity, using the agricultural soil surface as part of the water distribution system. When surface irrigation systems are properly designed, operated and managed, higher irrigation efficiencies and uniformities can be achieved (Lima, 2014). Suitable design and logical management of the surface irrigation can lead to increased water use efficiency and cultivated area (Lalehzari and Boroomand Nasab, 2017). Surface irrigation is the oldest and common irrigation method due to the low cost and energy requirements compared to sprinkler and drip irrigation. Surface irrigation has evolved into an extensive array of configurations which can be broadly classified as: basin irrigation; border irrigation; furrow irrigation, and uncontrolled flooding. The selection of the method and approach depends on factors such as water availability, crop type, soil characteristics, land topography, and associated cost. Because of suitable aeration in the root zone, furrow irrigation is the best method in surface irrigation (Wu, 2017).

### **2.3. Furrow Irrigation**

Furrows are small channels which carry water down the land slope between the crop rows and designed on the basis of soil, crop, topography, size and shape of the irrigated area. Furrow irrigation is suitable to most soils except sandy soils that have very high infiltration water and provide poor lateral distribution water between furrows. Most recently, furrow irrigation has become important because of the high cost of energy in pressurized irrigation methods and the incorporation of automation in its operation (Holzapfel and Arumí, 2010). In furrow irrigation the most important points are to adequately select furrow irrigation variables (furrow length, time of cutoff, and discharge). The factors that can affect furrow hydraulic performance are inflow rate, the length of the run in the direction of the flow, cutoff time and soil surface roughness and infiltration characteristics parameters (Hsiao, 2007).

### **2.4. Furrow Irrigation Design Parameters**

Irrigation furrow design should consider constraints in available land area and local conditions when trying to achieve improved irrigation efficiencies. Furrow design parameters are often chosen with limited or no analysis of unique local conditions. The shape, length and spacing are determined by natural circumstances, i.e. slope, soil type and available stream size. However, other factors may influence the design of a furrow system, such as the irrigation depth, farming practice and the field length (Hsiao, 2007).

#### **2.4.1. Furrow geometry and slope**

Furrow geometry parameters are required for evaluating furrow irrigation. The parameters of furrow geometry that needed for evaluating the hydraulic performance irrigation are; cross sectional area, top flow width, flow depth, bottom, middle and top width. Narrow, deep V-shaped furrows are desirable to reduce the soil area through which water percolates. In clay soils, there is much more lateral movement of water and the infiltration rate is much less than for sandy soils. As a rule, for sandy soils the spacing should be between 30 and 60 cm, i.e. 30 cm for coarse sand and 60 cm for fine sand. Uniform flat or gentle slopes are preferred for furrow irrigation and these should not exceed 0.5%, usually a gentle furrow slope is provided up to 0.05% to assist drainage following irrigation or excessive rainfall with high (Narayana and Brook, 2014).

### **2.4.2. Stream size**

Normally stream sizes up to 0.5 l/sec will provide an adequate irrigation provided the furrows are not too long. The size of the furrow stream usually varies from 0.5 to 4 l/sec at 0.1% to 0.5% slopes. In furrow irrigation, the size of the furrow stream i.e. furrow discharge was the one factor which can be varied as per the irrigation requirement. To obtain high irrigation uniformity, the largest stream of water was not the cause for 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 so as to enable the soil to absorb water evenly through the entire furrow length. The theoretical maximum size of irrigation stream that was used at the start of the irrigation has to be limited by considerations of erosion in the furrows, overtopping of furrows and prevention of runoff at the downstream end of the furrows (FAO, 1989).

### **2.4.3. Set time and cutoff ratio**

The appropriate set time depends on slope, intake rate and length of run. Run off and the uniformity of water infiltrated along the furrow are related to cutoff ratio. The cutoff ratio is the ratio of the time required for the water to advance to the end of furrow to the total set time. Choosing the appropriate cutoff ratio depends on soil factors and irrigation system configuration. With proper cutoff ratio uniform water application, minimum deep percolation and runoff losses can be achieved (C.Dean, 2007).

### **2.4.4. Soil type and cultivation practice**

When the farming is mechanized, furrows should be made as long as possible to facilitate the work. Short furrows require a lot of attention as the flow must be changed frequently from one furrow to the next. However, short furrows can usually be irrigated more efficiently than long ones as it is much easier to keep the percolation losses low. In sandy soils water infiltrates rapidly. Furrows should be short (less than 110), so that water will reach the downstream end without excessive percolation losses. Furrows can be much longer on clayey than on sandy soils (FAO, 1989).

### **2.5. Advance and Recession of Water Front**

The advance of water front down the furrow is the rate at which the waterfront advances through the furrow. The advance water front rate is influenced by soil conditions (size, soil infiltration and surface roughness of the furrow), time to cutoff, slope and inflow rate.

The length of time the water is to flow in the furrows depends on the amount of water required to replenish the root zone and the infiltration rate of the soil and the rate of lateral spread of water in the soil (Manisha,2016). The recession time of waterfront over the field surface is the elapse time until water drained from the point following the cutoff of inflow or the time of water disappearance from surface. The advance and recession of the waterfront over the field surface, measured as the elapse time needed for the inflow to advance to a point on the field, or the elapse time until water has drained from the point following the cutoff of inflow, is required and should be among the most carefully made measurements in the field.

## **2.6. Soil Infiltration Characteristics and Manning roughness**

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. Accurate estimation of infiltration parameters is time consuming and cost effective in order 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, 2011). The infiltration parameters and the Manning roughness coefficient are critical variables in the design and evaluation of surface irrigation systems (Rodríguez and Martos, 2010).

The accurate estimation of soil infiltration parameters is crucial to the accurate simulation of surface irrigation. The most commonly used model to describe the soil infiltration characteristic for surface irrigation is the Kostiakov-Lewis equation (1939);

$$I = k\tau^a + f_o\tau \quad [2.1]$$

Where I is the cumulative infiltration ( $m^3/m$ ),  $\tau$  is the time (min) from the commencement of infiltration, k ( $m^3/min/m$ ) and a are fitted parameters and  $f_o$  ( $m^3/min/m$ ) approximates the steady or final infiltration rate. Many surface irrigation simulation models incorporate the above infiltration model.

## **2.7. Performance of Furrow Irrigation**

The performance of furrow irrigation system is the degree to which it achieves desired objectives and the evaluation of furrow irrigation at field level is an important aspect of both management and design of irrigation system.

The performance of furrow irrigation depends on the interaction of many factors such as the inflow rate, cutoff time, furrow length, the soil infiltration characteristic, soil roughness, field slope and the cross-sectional area of the flow. The better management is dependent upon appropriate methods and measures by which irrigation system performance can be evaluated relative to the management objectives (Lima, 2014).

### 2.7.1. Application efficiency

Zerihun (2001) defined water application efficiency ( $E_a$ ) as the ratio between the volume of water held in the root zone of the soil profile after the irrigation and the total volume of water applied during the irrigation process as stated in (Rogers, 2007).

$$E_a = \frac{\int_0^L Z dx - \int_0^{L_{ov}} Z dx + Z_r L_{ov}}{\int_0^{t_{co}} Q_0 dt} * 100 \quad [2.2]$$

Where,  $E_a$  = application efficiency;  $Z_r$  = the volume of water required by the crop in each irrigation ( $m^3 m^{-1}$ );  $L$  = the length of the furrow (m) ;  $Q_0$  = the inlet flow rate ( $L min^{-1}$ );  $t_{co}$  = the cutoff time of the irrigation (min);  $L_{ov}$  = the length of the furrow reach over which the infiltrated water amount equals or exceeds and  $Z$  = the amount of infiltrated water ( $m^3 m^{-1}$ ).

According to Roger et al., (2007), it is possible to have high application efficiency and 50-90% can be used for general system type comparison. Lesley (2002) suggested that it could be in the range of 50-80%.

### 2.7.2. Water requirement/storage efficiency

The water requirement efficiency (storage efficiency) is defined as an indicator of how well the irrigation meets its objective of refilling the root zone (Hsiao, 2007). Water stored in the root zone is not 100% effective and water lost from the root zone by deep percolation. The requirement efficiency or water storage efficiency measures the effectiveness of the quantity of water stored in the root zone after the irrigation (Zerihun, 2001):

$$RE = \frac{\int_0^L Z dx - \int_0^{L_{ov}} Z_r L_{ov}}{Z_r L} * 100 \quad [2.3]$$

Where, RE= requirement efficiency;  $Z_r$ = the volume of water required by the crop in each irrigation ( $m^3m^{-1}$ ); L = the length of the furrow(m);  $L_{ov}$  = the length of the furrow reach over which the infiltrated water amount equals or exceeds and  $Z$  = the amount of infiltrated water ( $m^3m^{-1}$ ).

### 2.7.3. Distribution uniformity

Rogers (2007) explained that water lost to percolation below the root zone due to non-uniform application or over-application water runoff from the field all reduces irrigation efficiencies. One indicator used to represent the pattern of the infiltrated depths along the field length is the distribution uniformity (DU), which is defined as the minimum infiltrated depth divided by the average infiltrated depth. This is given in the form:

$$DU = \frac{\text{Minimum depth}}{\text{Average depth}} \quad \text{Or} \quad DU = \frac{Z_{\min}}{Z_{\text{av}}} * 100 \quad [2.4]$$

$$Z_{\text{av}} = \frac{\int_0^L Z dx}{L}$$

Where, DU= distribution efficiency;  $Z$  = the amount of infiltrated water ( $m^3m^{-1}$ ); L = the length of the furrow (m);  $Z_{\min}$ = minimum infiltrated amount;  $Z_{\text{av}}$  = average infiltrated amount over the length of run of the channel

### 2.7.4. Deep percolation fraction

Deep percolation defined as the net amount of water percolating below the plant root zone. Soil infiltration characteristics and the duration of ponding govern the amount of infiltration during surface irrigation and the amount of infiltration that results in deep percolation will depend on soil properties, root water extraction patterns and the water table depth (Bethune, 2008). It is the ratio of the volume of water percolated below the bottom boundary of the subject region to the total volume admitted into the subject region.

$$DP = \frac{\int_0^{L_{ov}} Z dx - Z_r L_{OV}}{\sum_{i=1}^I Q_{oi} \Delta t_i} * 100 \quad [2.5]$$

### 2.7.5. Runoff fraction

It is the ratio of volume of runoff to the volume of water diverted into the command area.

$$R_f = \frac{\int_{t_a(L)}^{t_r(L)} Q_L(t) dt}{\sum_{i=1}^I Q_{O_i} \Delta t_i} * 100 \quad [2.6]$$

Where,  $t_a(L)$  and  $t_r(L)$  = advance time and recession time corresponding to the downstream end of the channel (m), and  $Q_L(t)$  = time dependent of runoff rate function at the downstream end ( $m^3m^{-1}$ ).

## 2.8. Mathematical Models of Surface Irrigation

The mathematical models of surface irrigation are important for the evaluation and design purposes may be classified into four main categories. These models are the hydrodynamic, the zero inertia, the kinematic wave, and the volume balance (Valipour, 2012).

### 2.8.1. Hydrodynamic model

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. These equations are:

$$\frac{\sigma A}{\sigma t} + \frac{\sigma Q}{\sigma x} + \frac{\sigma Z}{\sigma \tau} = 0$$

$$\frac{1}{Ag} \frac{\sigma Q}{\sigma t} + \frac{2Q}{A^2g} \frac{\sigma Q}{\sigma x} + \left(1 - \frac{Q^2T}{A^3g}\right) = \frac{\sigma y}{\sigma x} - S_0 + S_f \quad [2.7]$$

Where,  $y$ = depth of flow (m) ;  $t$ =time from the beginning of irrigation (s) ;  $\tau$ =Intake opportunity time (s);  $Q$ =Discharge ( $m^3/s$ );  $x$ =Distance along the field length (m);  $Z$  =Infiltration rate (m/s)  $g$ =Acceleration due to gravity ( $m/s^2$ );  $S_0$ =longitudinal slope of the field (m/m);  $S_f$ =slope of energy grade line, also called friction slope (m/m);  $A$ =cross-sectional area ( $m^2$ );  $T$  = top width of flow (m).

### 2.8.2. Zero inertia model

The zero inertia models are a simplified form of the full hydrodynamic model without the acceleration and inertia terms. It was formed by neglecting the inertial terms in the full hydrodynamic equations of Saint-Venant equations. If the inertia terms are neglected, Eq. (2.7) is converted to Equation (2.8):

$$\frac{\sigma y}{\sigma x} = S_0 - S_f \quad [2.8]$$

Where,  $y$ = depth of flow (m);  $x$ =Distance along the field length (m);  $S_o$ =longitudinal slope of the field (m/m);  $S_f$ =slope of energy grade line, also called friction slope (m/m).

These models are less complex than the full hydrodynamic models. In theory, the zero-inertia model is accurate in comparison with a full hydrodynamic model under typical irrigation conditions. However, it experiences computational problems when the bottom slope is steep.

### 2.8.3. 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 and experiences fewer computational problems (Lima, 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 exhibit backwater effects. For most applications, users will not have to select for the solution model. The kinematic wave model uses further simplifications and uniform flow assumptions. Therefore, Eqn. (2.8) can be further simplified by assuming that the depth gradient and inertial terms are negligible and thus Equation (2.9) is obtained (Raines and Smith, 2007) as follows:

$$S_o = S_f \quad [2.9]$$

Where,  $S_o$ =longitudinal slope of the field (m/m) and  $S_f$ =slope of energy grade line, also called friction slope (m/m).

### 2.8.4. Volume balance model

The volume balance models only use the continuity equation as it is the dominant of the two equations and is the simplest approximation of the Saint Venant equations (McClymont 2007).

$$\frac{\sigma A}{\sigma t} + \frac{\sigma Q}{\sigma x} + \frac{\sigma Z}{\sigma \tau} = 0 \quad [2.10]$$

Where,  $t$ =time from the beginning of irrigation (s) ;  $\tau$ =Intake opportunity time (s);  $Q$ =Discharge ( $m^3/s$ );  $x$ =Distance along the field length (m);  $Z$ =Infiltration rate (m/s) and  $A$ =cross-sectional area ( $m^2$ ).

Valipour (2012) compared the HD, ZI, and KW models to optimize infiltration parameters in furrow irrigation systems. The author concluded that performance of the HD and ZI was similar and better than the KW model in all irrigation events.

## **2.9. Surface Irrigation Simulation model**

A number of models have been developed which aim to simulate surface irrigation systems. They have also been developed using user friendly computer programs with the ultimate aim of being used by irrigation practitioners as decision support systems (DSS). All the simulation models in surface irrigation including SIRMOD, SURDEV, FIDO, WinSRFR, SIPAR\_ID and SISCO. These models use numerical techniques to solve the hydrodynamic equations and generally use infiltration functions that are useful to simulate under uniform soils. It is possible to design and evaluate furrow irrigation systems using different simulation models. In past years, many researchers used some models to improve the performance of surface irrigation (Gillies, 2010; Koech, 2014; Morris, 2015). It is necessary to use simulation models such as SURDEV (Jurriens, 2001), SIRMOD (Walker, 2003), WinSRFR (Bautista, 2012), SIDES (Adamala, 2014), SURCOS (Burguete, 2014) and SISCO (Gillies and Smith, 2015) to reduce costs and design time (Mahdizadeh Khasraghi, 2015). Bautista (2009) used WinSRFR software to evaluate field events, characterize infiltration and optimize the combination of irrigation parameters.

### **WinSRFR**

WinSRFR is the latest of a series of surface irrigation hydraulic simulation models developed by the USDA Agricultural Research Service. It is an integration of the surface irrigation (basin, border and furrow) program SRFR, level furrow design program. Bautista (2014) provide an overview of the software and discuss its key technical elements. WinSRFR is structured around four main functionalities, referred to as Worlds tools in the software. Users can analyze field evaluation data, estimate field infiltration properties, and assess the performance of an observed irrigation event with tools of the Event Analysis World. A wide range of design and operational alternatives can be easily examined with the tools of the Physical Design and the Operations Analysis Worlds. WinSRFR employs simplified forms of the momentum equation (i.e., the zero-inertia or kinematic wave models). This modeling technique has been found by USDA-ALARC (2009) to be sufficiently accurate when used under the right conditions and is also computationally faster with accurate input data.

## **2.10. Optimization of Surface Irrigation**

Optimum management of water resources at the farm level is needed in view of increasing water demands, limited resources, and aquifer contamination. In irrigation system, significant improvement can be made with optimized irrigation and optimization of irrigation events individually. In irrigation system, significant improvement can be made with optimized irrigation and optimization of irrigation events individually (Smith, 2005). Total volume of water applied per irrigation can be saved substantially by implementation of a simple optimized irrigation system. Salient features of any improved method of irrigation is the controlled application of the required amount of water at desired time, which leads to minimization of range of variation of the moisture content in the root zone. Thus reducing stress on the plants (Ali, 2010). Optimum management of water resources at the farm level is needed in view of increasing water demands, limited resources, and aquifer contamination. When irrigation is required there are many available methods and management strategies (Holzapfel y Arumí, 2010). The potential for improving hydraulic performance parameters of furrow irrigation systems lies in the use of simulation models to predict furrow irrigation performance by evaluating and changing in design variables, which can lead to improvements in irrigation efficiency and uniformity (Montgomery and Wigginton, 2008).

Surface irrigation simulation models are useful tools both at the design and management stages of the surface systems. When used for irrigation design purposes, simulation models help to optimize surface irrigation variables such as field slope, length of the field and the design flow rate. These variables (particularly field slope and length) are difficult or expensive to vary once the system is operational. Time to inflow cut-off, inflow rate and the desired depth of application are management decisions that can be optimized using simulation models. This is often preceded by a field evaluation process to generate the data to be used by the simulation model. The optimized variables are used to modify future irrigations in order to achieve the desired level of performance (Koech, 2010).

### 3. MATERIALS AND METHODS

#### 3.1. Description of the Study Area

##### 3.1.1. Location and topography

Batu Degaga Irrigation Project is located in the Upper Valley of Awash River Basin near Sodore, around 7 km on the left side of the road from Melkassa town to Sodore in Eastern Shoa Administrative Region. Geographically the farm is located at a latitude of  $8^{\circ} 25'$  North and longitude of  $39^{\circ} 25'$  East. The elevation of the project area is around 1350 meters above sea level.

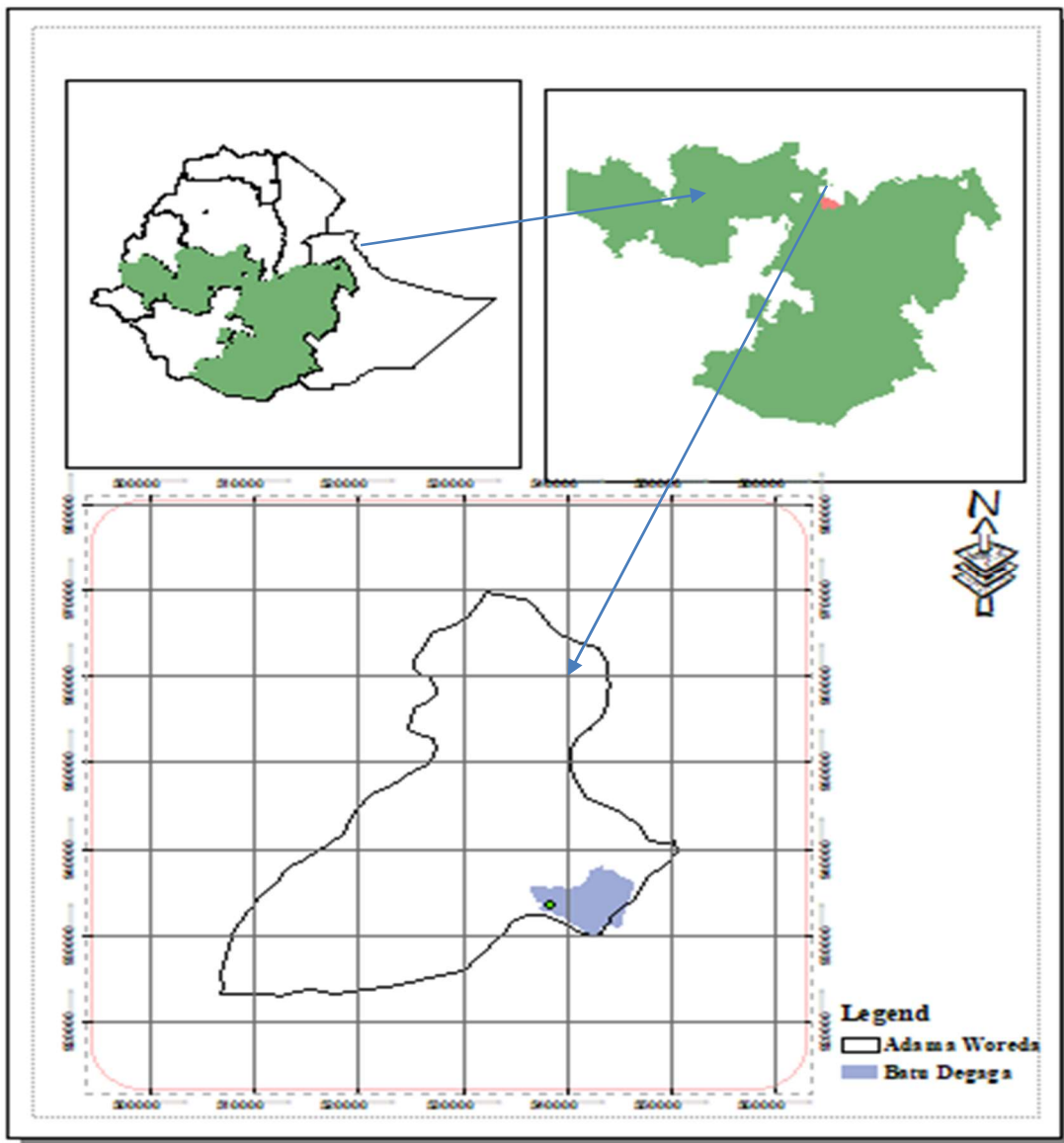


Figure 3.1 Location map of the study area

### 3.1.2. Climate and crop type

Based on the climatological data of Melkassa Research Center, the nearest weather station, the rainfall in the region can be estimated to vary between 700 mm to 860 mm mainly received from June to September followed by a distinct dry spell up to January. This is often preceded by secondary or small rainy season running from February to April. The average monthly minimum and maximum temperature in the project area is in the order of 11°C and 33°C, respectively. Generally the area is belonging to semi-arid drought prone region of the country (MoA, 2000). The land of irrigation project is characterized by plain land of very gentle slope, which is suitable for surface irrigation. Major crops grown in the scheme are Onion, Tomato, Maize and Pepper.

### 3.1.3. Water abstraction and distribution system

The irrigation project draws water from Awash River that has regulated discharge throughout the year at Koka dam. To abstract irrigation water from the river, the project has three electric pumps which are operating rotationally throughout the irrigation season. Pumping system comprises pump house, transformer, electric motors and main supply pipeline. The irrigation water pumped from the river is discharged to a small reservoir that is used to dissipate the energy. Then concrete made primary canal carries the water to secondary canals. The secondary canals runs longitudinally and with the help of several turnouts along the canal distributes the water to tertiary canals laterally. Individual farmers, according to their need, construct the tertiary canals to divert water into their fields. Farmers are diverting the water through their preferred direction as long as it is suitable to provide available head to irrigate their field.

## 3.2. Materials used for the Study

Table 3.1. Materials used for the field work

Material	Use
Core sampler, auger, ring and hammer	to take soil sample from field
Siphon	to apply irrigation water to furrow
Stake and stop watch	to mark and record advance and recession time
Wooden pieces, ruler	to determine furrow cross section
Tape meter, theodolite and staff levelling	to measure furrow length and bed slope

### 3.3. Data Sources and Data Collection Methods

The data were collected by measuring and determining all the input parameters required for the study. Field measurements such as furrow geometry, slope, and inflow discharge, furrow length, furrow spacing, advance time and recession times was done. And also soil physical characteristics like moisture, soil texture in different depths ranges was determined. The recorded data related to the study area such as necessary working materials, climate data mainly precipitation, temperature, and radiation were collected from the scheme manager, relevant zone/woreda office and Melkessa Agricultural Research Center.

#### 3.3.1. Field Experiment

Field experiment was carried out at Batu Degaga irrigation scheme starting from 1 March to 15 May 2020. In order to evaluate and optimize the performance of furrow irrigation at field level using WinSRFR experimental field was prepared. The experimental field had a size of 3.6m x 40m with six blocked ended furrows of 0.6m furrow spacing and 0.2% bed slope. There were two treatments 1 l/s and 1.5 l/s with three replications of irrigation events. The inflow to every furrow was applied using 4.2cm inner diameter siphon. Cutoff time was 25 and 20 minute for 1 l/s and 1.5l/s inflow rate respectively. All data were collected from four middle furrows and the other two furrows were taken as buffer furrows.



Figure 3.2 Field Experiment

### 3.3.2. Soil physical characteristics

Soil Texture analysis and bulk density were determined for the experimental field. Soil lab analysis was conducted at Melkassa Agricultural Research Center. Bulk density was analyzed by collecting undisturbed soil samples depths. It was determined by taking undisturbed soil samples from effective root zone at 20 cm interval using a known volume of core sampler. The soil moisture sampling of 60 cm root zone was conducted at 0-20 cm, 20-40 cm and 40-60 cm depth intervals using core sampler. These samples were collected from three locations covering field head, middle and tail sections. Gravimetric method was used to calculate soil moisture and bulk density, which comprised oven drying of the soil samples for 24 hours at 105<sup>0</sup>C. The gravimetric soil moisture was converted to volumetric soil moisture by multiplying with bulk density and depth of soil layer.

$$SM (\%) = \frac{W_m - W_d}{W_d} \times 100 \quad [3.1]$$

$$\rho_b \left( \frac{g}{cm^3} \right) = \frac{M_s}{V_b} \quad [3.2]$$

Where, SM - soil moisture, W<sub>m</sub>- weight of moist soil (g), W<sub>d</sub>- weight oven dried soil(g), ρ<sub>b</sub>- Soil bulk density (g/cm<sup>3</sup>), M<sub>s</sub>- mass of soil after oven dry (g), V<sub>b</sub>- volume of bulk soil sample (cm<sup>3</sup>) and ρ<sub>b</sub>- bulk volume of soil (cm<sup>3</sup>).

### 3.3.3. Soil infiltration rate

Infiltration in a furrow was determined through inflow and outflow analysis by taking a representative segment of the furrow.

$$Y = \frac{1}{L * P} (V_{in} - V_{out} - V_s) \quad [3.3]$$

$$P = 0.265 \left[ \frac{Q*n}{s^{0.5}} \right]^{0.425} + 0.227 \quad [3.4]$$

$$V_s = \frac{L}{0.305} \left[ 2.947 \left( \frac{Q*n}{s^{0.5}} \right)^{0.735} - 0.0217 \right] \quad [3.5]$$

Where y-equivalent depth of infiltration(mm); L- length of the furrow segment (m); p- adjusted wetted parameter (m); V<sub>in</sub>- volume of inflow (l); V<sub>out</sub>- volume of water outflow (l); V<sub>s</sub>- volume of stored (l); s- furrow slope in (m/m); n- roughness coefficient and Q- discharge (l/s).

### 3.3.4. Furrow configuration

The geometry of furrows -is important when evaluating its hydraulic characteristics. For each selected four furrow selected evaluation, the cross-sectional geometry was measured. Furrow cross sections such as width, depth and cross-sectional area were determined using installing wooden pieces along each furrows. A flat wooden placed horizontally across furrow at every 5m distance along the furrows length and local wooden pieces installing vertically (see figure 3.3). The slope of the furrows bed was measured by using surveying instrument. The staff level was set up in furrow at convenient location from where several stations could be read. 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. The slope of furrows that determined in the field was used for evaluating of hydraulic furrow irrigation.

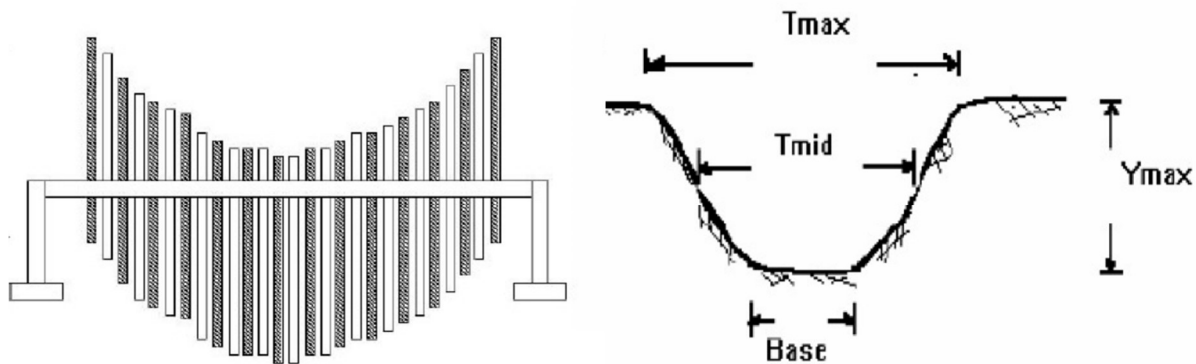


Fig 3.3. Determination of furrow geometry using local wooden pieces system

### 3.3.5. Advance and recession time

The advance rate of the water front down the furrow is the rate at which the water front advances through the furrow. The advance rate is influenced by both soil conditions (size, slope and roughness of the furrow) and inflow rate. For determining advance rate, stakes were fixed at every 5 m distance along the furrow length at eight stations up to 40 m. The time was recorded when the irrigation water supply was applied to each furrow and when the advancing front reaches each stations. After the irrigation is terminated, the tail water recedes downstream of the furrow. Recession times were recorded at time when water disappeared from the furrow bed at each stations. Then, the collected advance and recession time were used as an input for WinSRFR software to determine infiltration functions.

### 3.4. Data analysis

The collected data's was processed by Microsoft EXCEL. Then data analysis, execution, simulation and interpretation was conducted using WinSRFR software. All input parameters required for WinSRFR model operation were obtained from field. Then the simulated outputs were compared with observed data to identify the accuracy of model using four statistical indicators such as Normalized Root Mean Square Error (NRMSE), distribution to 45° line ( $\lambda$ ), Wilmot agreement (d), coefficient of determination ( $R^2$ ) and Relative Error (RE). Model was validated and different optimal combinations decision variables of irrigation (i.e. inflow rates, cut-off time, length of run, and slope) were identified and suggested by changing irrigation design variables

#### 3.4.1. WinSRFR software

WinSRFR is a new software for evaluating and simulating the surface irrigation. WinSRFR needs different data to analyze irrigation performance. Data required for software include inflow, geometric properties and depth of water application. WinSRFR software consists of Zero-Inertia and Kinematic Wave model. The WinSRFR model has been extensively used 16-20 for evaluation and optimization of surface irrigation performance throughout the world. The WinSRFR is coded into four colors worlds with the names Event Analysis World (Irrigation event analysis and parameter estimation functions), Physical Design World (Design functions for optimizing the physical layout of a field), Operations Analysis World (Operations functions for optimizing irrigations) and Simulation World (simulation functions for testing and sensitivity analysis) (Bautista, 2015) .

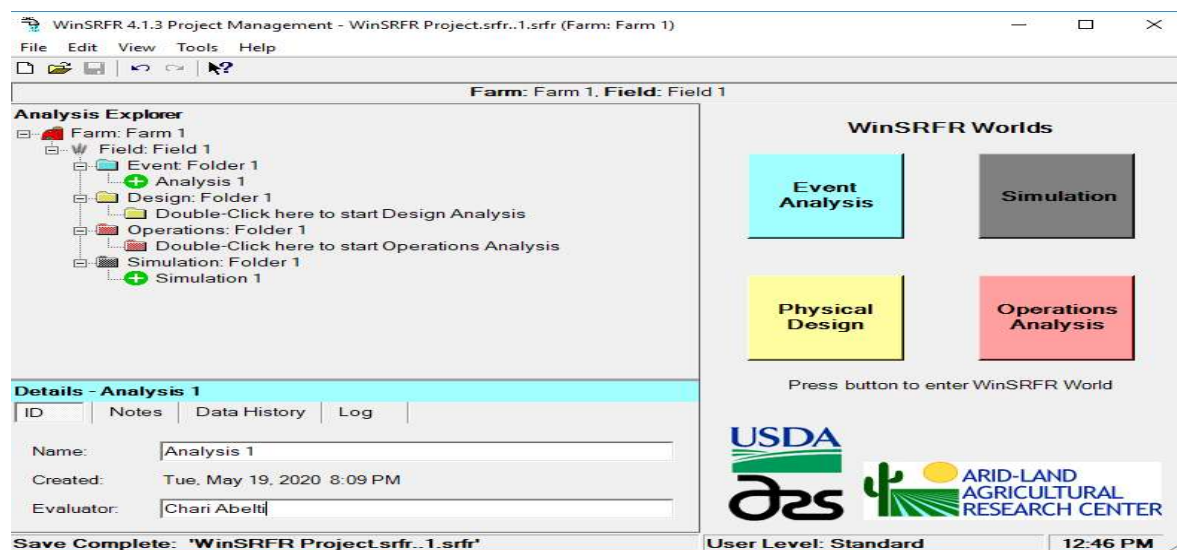


Figure 3.4. WinSRFR worlds screen

### 3.4.2. Calibration of infiltration parameters

Due to the sensitivity of furrow irrigation performance to infiltration parameters, it is necessary to calibrate them. In this paper, Kostiakov-Lewis coefficients were calibrated using Event Analysis World and Merriam and Keller (1978) method in the WinSRFR software.

$$Z=k t^a+bt+c \quad [3.6]$$

In which  $t$  = opportunity time  $k$  [L/Ta] – constant,  $a$  [.] - exponent,  $b$  [L/T] – steady infiltration rate and  $c$  [L]– instantaneous infiltration depth (through cracks and macro pores). In practice,  $b$  is a fitting parameter determined from infiltration measurements. The equation is commonly identified in the literature as the Kostiakov-Lewis equation. In many field situations, infiltration is dominated by water flow through cracks and macro pores. To account for this effect, the Kostiakov equation was further modified in the SRFR program by adding a constant  $c$ . The infiltration represented by  $c$  is assumed to take place instantaneously. This document and the software refers to this combined expression as the Modified Kostiakov formula. Thus, inputs that need to provided are  $k$ ,  $a$ ,  $b$ , and  $c$ . These inputs need to be provided in consistent units. In this study, infiltration coefficients were calibrated manually. To estimate  $k$ , different combinations of  $a$ ,  $b$  ( $f_0$ ) and  $c$  were tested over an approximate range until the measured and simulated advance-recession curve could found the best convergence.

### 3.4.3. Statistical analysis

The advance-recession curve was simulated by the WinSRFR software. In this study, four statistical criteria were used to analyze software's accuracy. These statistical criteria were: Normalized Root Mean Square Error (NRMSE), distribution to 45° line ( $\lambda$ ), Wilmot agreement ( $d$ ), coefficient of determination ( $R^2$ ) and Relative Error (RE) as follows [3.4] to [3.7]. In addition, the Relative Error (RE) criterion was used to compare the field and simulated performance parameters [3.8].

$$NRMSE = \left( \frac{1}{\bar{O}} \sqrt{\frac{\sum_1^N (O_i - P_i)^2}{N}} \right) * 100 \quad [3.7]$$

$$\lambda = \frac{P_i}{O_i} \quad [3.8]$$

$$d = 1 - \left[ \frac{\sum_1^N (O_i - P_i)^2}{\sum_1^N (|O_i - \bar{O}| + |P_i - \bar{O}|)^2} \right] \quad [3.9]$$

$$R^2 = \left[ \frac{1}{N} \frac{\sum (y_m - \bar{y}_m)(y_s - \bar{y}_s)}{(\sigma y_m - \sigma y_s)} \right] \quad [3.10]$$

$$R E = \frac{V_o - V_s}{V_s} * 100 \quad [3.11]$$

Where in equation [3.7, 3.8 and 3.9]  $O_i$  and  $P_i$  are the observed and predicted values of the advance and recession times, respectively; and  $(\bar{O})$  is the average measurement. In equation [3.10]  $y_m$  and  $y_s$  are the observed and predicted values of the advance and recession times, respectively;  $\bar{y}_m$  and  $\bar{y}_s$  are the average observed and predicted values of the advance and recession times, respectively;  $\sigma y_m$  and  $\sigma y_s$  are the standard deviation of observed and predicted values of the advance and recession times, respectively and  $N$  is the number of measurements. In equation [3.11]  $V_s$  and  $V_o$  are the simulated and observed performance indicator values respectively. If  $\lambda < 1$  it's means  $O_i$  is more than  $P_i$  and if  $\lambda > 1$  means  $P_i$  is more than  $O_i$ . Also the high accuracy in simulation in when  $d=1$ .

### 3.5. Irrigation performance analysis

Anwar (2016) reported that application efficiency and distribution uniformity are the common indicators for evaluation of surface irrigation; while, Gonzlez (2011) used distribution uniformity as performance indicator. Chen (2012) used application efficiency, average depth applied and distribution uniformity. Kifle (2017) used different indicators such as application efficiency, distribution uniformity, and deep-percolation and runoff volume, as indicators. In this study, three parameters were used to estimate performance of irrigation. For this purpose, soil moisture samples were taken using Auger core sampler before and after two days (48h) irrigation from three (upper, mid and end) points along the furrow and at three depths (0–20, 20–40 and 40–60cm). Finally, three performance parameters were determined in this study including Application Efficiency, Distribution Uniformity and Deep-percolation.

#### 3.5.1. Application Efficiency

Application efficiency (AE) is the ratio between the depth of water held in the root zone of the soil profile after the irrigation and the total depth of water applied during the irrigation.

$$AE = \frac{Z_i}{Z_d} \times 100 \quad [3.12]$$

Where  $Z_i$  and  $Z_d$  are the depth of water added to the root zone (mm) and depth of water applied to the furrow (mm) respectively.

### 3.5.2. Deep Percolation

It is the ratio of the depth of water percolated below the bottom boundary of the root zone to the total depth admitted into the subject region.

$$DP = \frac{Z_p}{\bar{Z}} \times 100 \quad [3.13]$$

Where depth  $Z_p$  and  $\bar{Z}$  are the depth of deep percolated water (mm) and the mean of depths infiltrated over the furrow length (mm) respectively.

### 3.5.3. Distribution Uniformity

Distribution uniformity (DU) was determined as the minimum infiltrated depth divided by the average infiltrated depth.

$$DU = \frac{Z_{LQ}}{\bar{Z}} \times 100 \quad [3.14]$$

Where  $Z_{LQ}$  and  $\bar{Z}$  are the mean water depth infiltrated in the lower quarter (mm) and the mean of depths infiltrated over the furrow length (mm) respectively.

## 3.6. Optimization of Furrow Irrigation Decision Parameters

Bautista (2009) revealed that the functionality of WinSRFR was defined based on the analytical process typically followed in assessing and improving the hydraulic performance of surface irrigation systems. Program functionalities of WinSRFR are Event Analysis, Operation Analysis, Physical Design, and Simulation, users can analyze the performance irrigation events and estimate field-average infiltration parameters based on field measured data, formulate design and operational alternatives, and conduct simulation studies. WinSRFR is mainly a practical tool, but will also serve as foundation for future development of hydraulic modeling and analysis techniques for surface irrigation. Bautista (2009) evaluated surface irrigation using WinSRFR and suggested that inflow rate and cut-off time can led to maximum performance of furrow irrigation system and they are the most effective parameters compared to other parameters. Salahou (2018) also reported that by increasing and decreasing inflow rate, the irrigation performance indicators increased and decreased, respectively.

Bai (2010) and Chen (2012) studies suggested that geometric parameters (i.e. field length, width and slope) affect the irrigation performance. According to Chen (2012) geometric parameters such as slope, length and cross section are effective parameters and suitable field geometry could increase irrigation application efficiency up to 26.7%. Xu (2019) also reported that application efficiency values reduce by increasing field length. Efficient furrow irrigation system can be ensured by selecting proper combination of decision parameters mainly furrow length (depending on the available field size), slope of furrows, and suitable stream size of the irrigation stream and duration of water application. In this Study, different combinations of inflow rate, cut-off time, furrow length and slope were employed to improve the performance. Therefore, inflow rate (i.e. 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 l/s), furrow slope (i.e. 0.1, 0.2, 0.3, 0.4 and 0.5%), furrow length (i.e. 40, 60, 80 and 100m) for different cutoff times were tested using model and optimal combination of parameters were determined in order to improve furrow irrigation performance.

## 4. RESULTS AND DISCUSSIONS

### 4.1 Soil Physical Properties

The soil data samples were taken from the field for determination of the soil physical properties (bulk density, the infiltration rate and moisture content). As per the results obtained which was presented in Table 4.1 the soil textural class was Sandy loam. According to the soil sample analysis was presented in Table 4.2, the average bulk density was observed as 1.11 g/cm<sup>3</sup>. The moisture contents were obtained in weight and volume base. According to the result obtained the maximum and minimum moisture content was observed as 20.47 and 24.52 % of volume base respectively in the top and bottom of soil layers. Infiltration rate of soil was measured and obtained as 12 mm/hr.

Table 4.1 Main physical properties of soil

Depth(cm)	pH	EC	Organic content	BD ( $g/cm^3$ )	Sand (%)	Clay (%)	Silt (%)	Textural Class
0-20	8.2	176	13.23	1.19	56	7	37	Sandy loam
20-40	8.39	187	13	1.05	54	9	37	Sandy loam
40-60	8.56	100	13.07	1.09	53	8	39	Sandy loam
Average	8.38	154	13.1	1.11	54.3	8	37.	Sandy loam

Note, BD- bulk density; pH- percent of hydrogen; EC- electrical conductivity

Table 4.2 Soil moisture before irrigation

Depth (cm)	Wet soil + can wt. (gm)	Dry soil + can wt. (gm)	Can wt. (gm)	BD( $g/cm^3$ )	Soil moisture (% wt.)	Soil moisture (% Vol)
0-20	230.5	200.6	33.6	1.19	17.20	20.47
20-40	235	202.7	34	1.05	19.86	20.85
40-60	216.8	182.9	32.2	1.09	22.49	24.52
Average				1.11	19.85	21.95

## 4.2. Furrow Geometry and Slope

The depth, middle width, bottom width and top width of furrows were measured at different sections at the 5m intervals of distance along the furrow length as presented in appendix (Table 13). This furrow cross sections were measured with installed the local wooden pieces in furrow at furrow length. As summarized in Table 4.3 the average furrow depth, top width, middle width and bottom width were found 187mm, 485mm, 304mm, and 122mm respectively. The measurements of bed slope of furrow were done for furrows with the help of leveling staff and the results was presented in appendix (Table 12). The average bed slope of the furrows was found to be 0.2%.

Table 4.3. The average furrow cross section

Parameter	Measured value (mm)
Top width	485
Middle width	304
Bottom width	122
Maximum depth	187

## 4.3. Advance and Recession Time

Advance and Recession times were recorded by fixing stakes at every 5 m distance along the furrow length at eight stations up to 40 m. The flow rate decreases as the water advances towards the irrigated portion due to infiltration. Result of field experiment indicated that the measured data of time advance and recession of waterfront was not the same for three of irrigation events under both 1 l/s and 1.5 l/s inflow rates. The reason for that can be soil infiltration characteristics, roughness and other factors. The detail measurements were presented in appendix (Table 4.14 and Table 4.15). The average advance and recession times of three irrigation events for selected furrow inflow rates were shown in Figure 4.1 and 4.2 below.

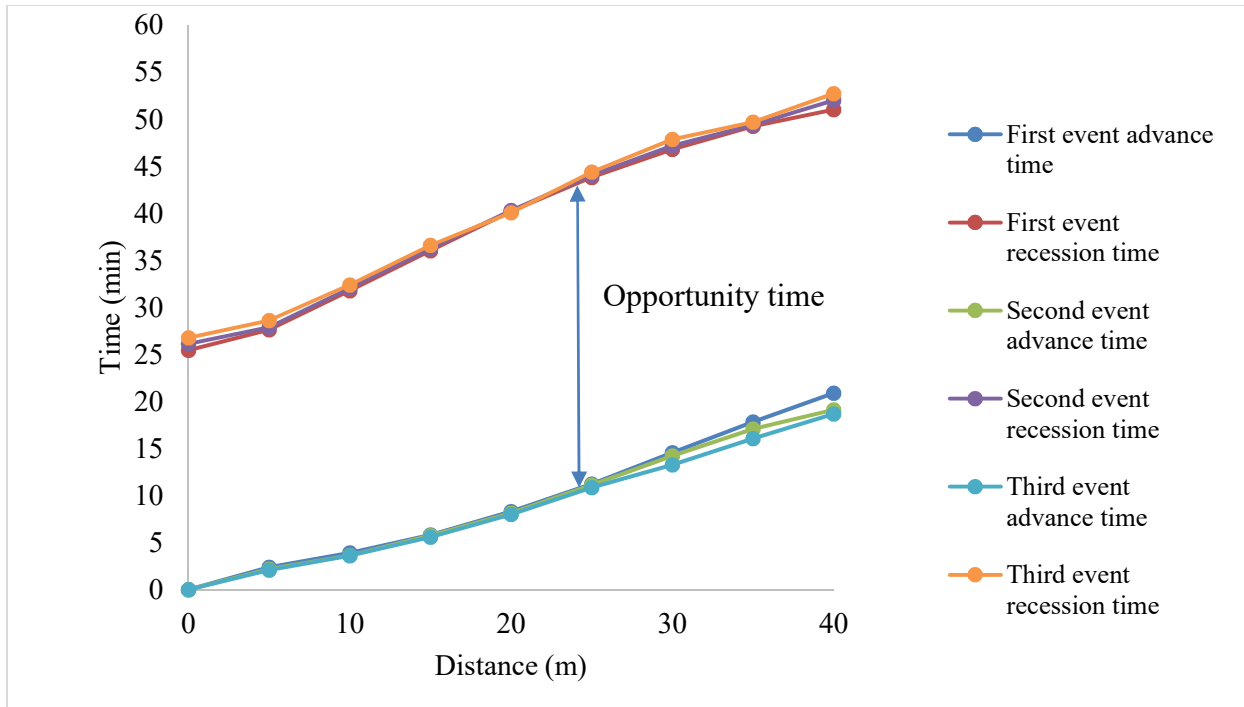


Figure 4.1. Average advance and recession time of four furrows (under 1 l/s) for three irrigation events

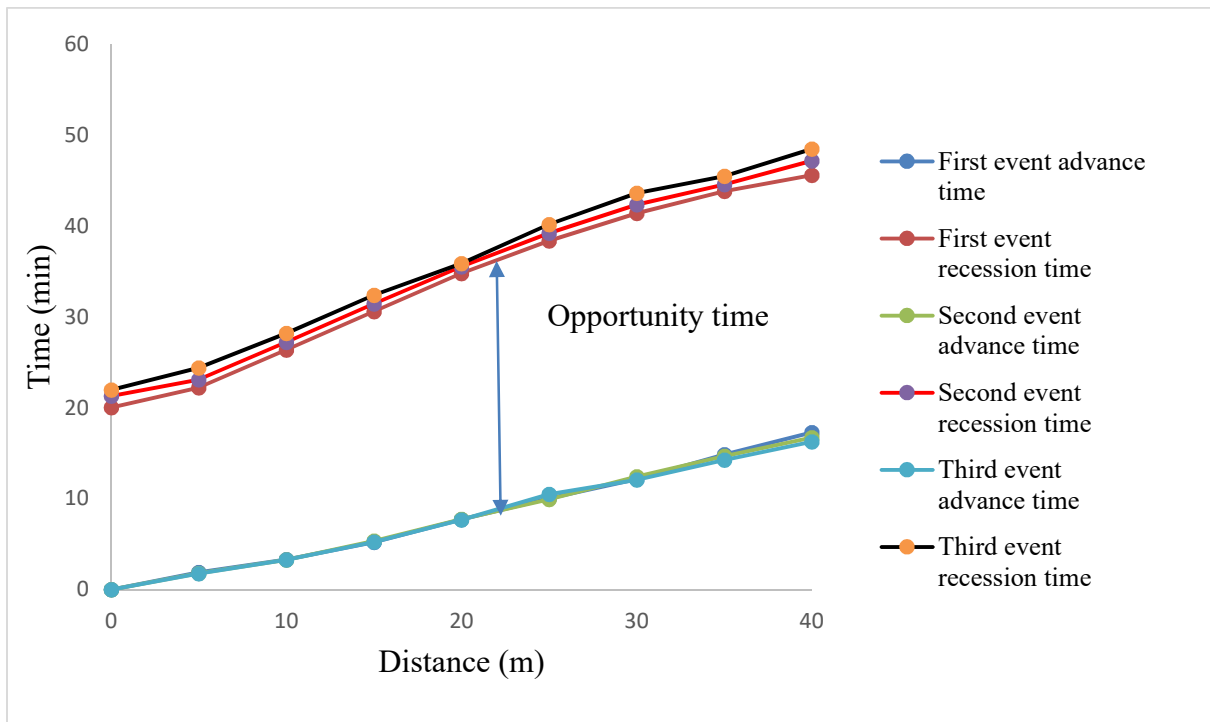


Figure 4.2. Average advance and recession time of four furrows (under 1.5 l/s) for three irrigation events.

#### 4.4. Simulation of Furrow Irrigation System

##### 4.4.1. Calibration of infiltration parameters

The surface irrigation systems were evaluated using the WinSRFR 4.1.3. In this study, the Event Analysis World was used to estimate and calibrate the infiltration parameters. Furthermore, the operation analysis and Physical Design World were used to evaluate the irrigation and geometric parameters and zero-inertia model was used to simulate and evaluate furrow irrigation performance.

Table 4.4 shows that inputs used for WinSRFR to calibrate modified Kostiakov formula infiltration functions and simulate advance time, recession time and performance of furrow irrigation. Field irrigation data were entered into the model using the Event Analysis World. The soil infiltration functions i.e. a, b, c and k parameters of Modified Kostiakov equation were determined using the calibrated model for each irrigation event and presented in Table 4.5.

Table 4.4. Inputs of WinSRFR Software

Field Topography/Geometry		
Field Geometry	Inputs	
Furrow length, m:	40	
Furrow spacing, m:	0.6	
Irrigation method	Furrow irrigation	
Downstream boundary condition	Blocked End	
Slope	0.2%	
Manning (n )	0.04	
Type of simulation model	Zero-inertia	
Run parameters	Inputs	
Required depth	40mm	
Furrow inflow rate (l/s)	1 l/s	1.5 l/s
Time of cutoff (min)	25min	20min

Table 4.5. Calibrated coefficients of modified Kostiakov-Lewis equation for three irrigation events

Inflow rate (l/s)	I.no	a	c	b(fo)	K
1	1	0.34	4	12	65.361
	2	0.32	4	12	64.819
	3	0.36	4	12	63.84
Average		0.34	4	12	64.673
1.5	1	0.25	4	12	78.009
	2	0.24	4	12	79.764
	3	0.24	4	12	77.9
Average		0.243	4	12	78.557

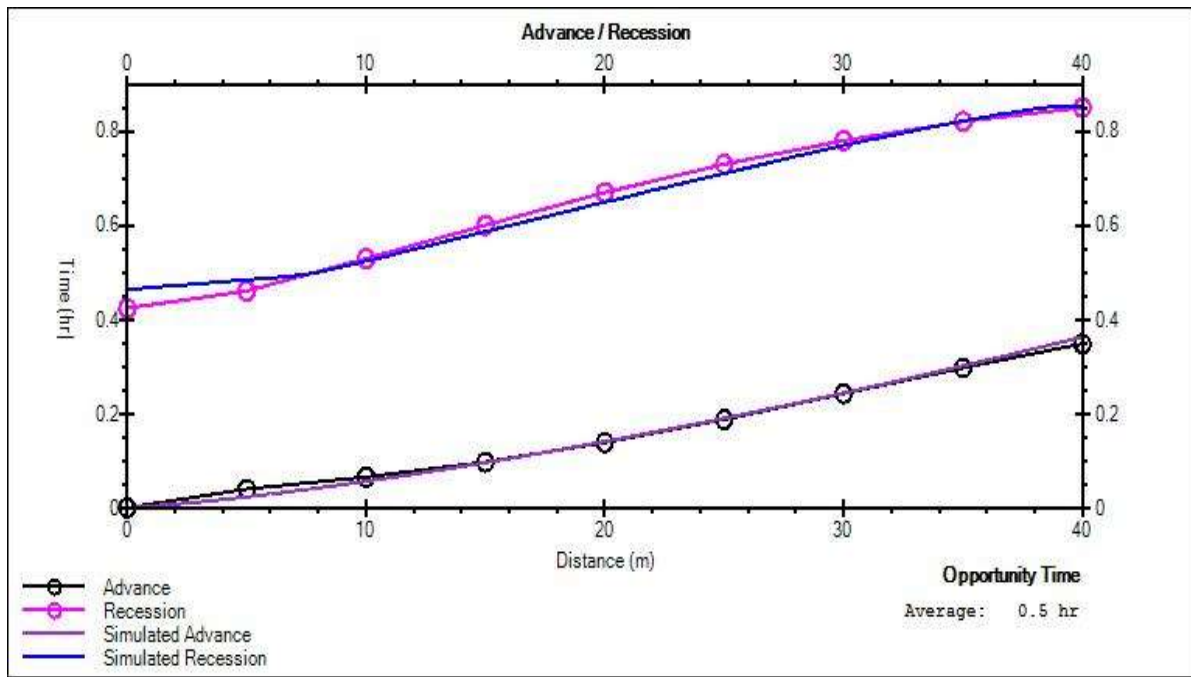


Figure 4.3. Measured and simulated advance and recession time trajectory curve (under 1 l/s) for first irrigation event.

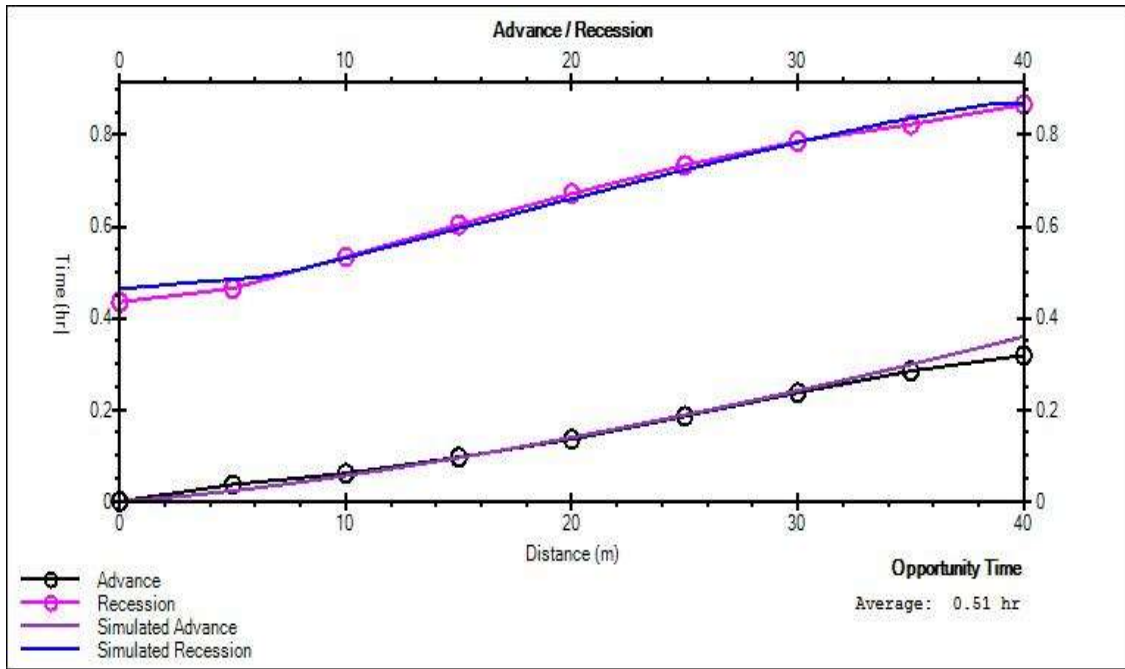


Figure 4.4. Measured and simulated advance and recession time trajectory curve (under 1 l/s) for second irrigation event.

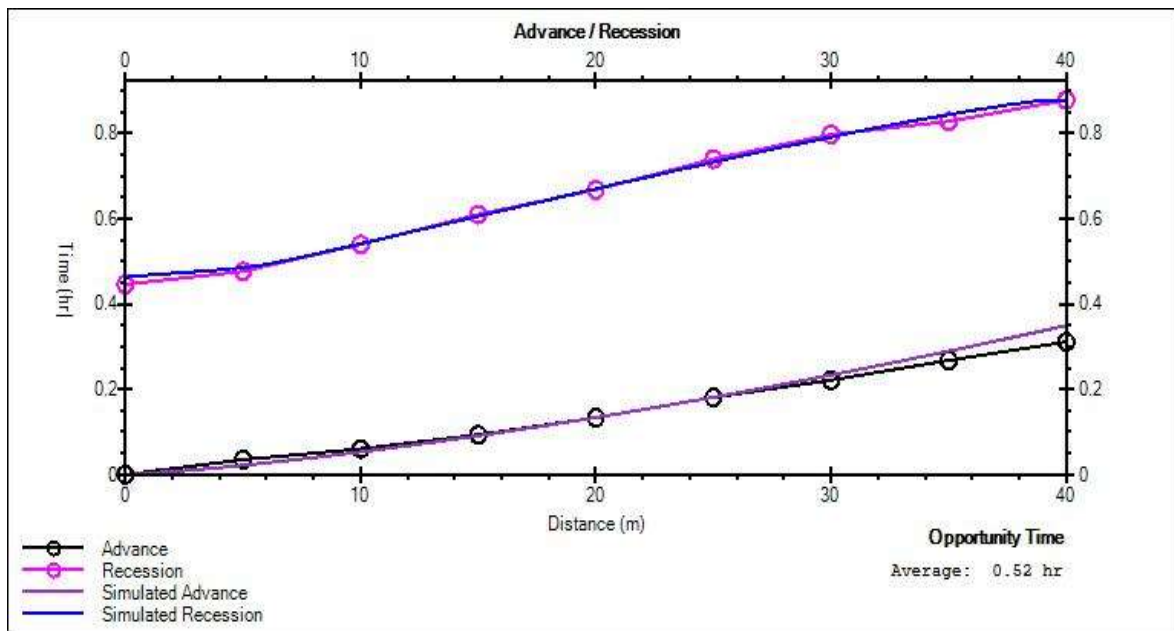


Figure 4.5. Measured and simulated advance and recession time trajectory curve (under 1 l/s) for third irrigation event.

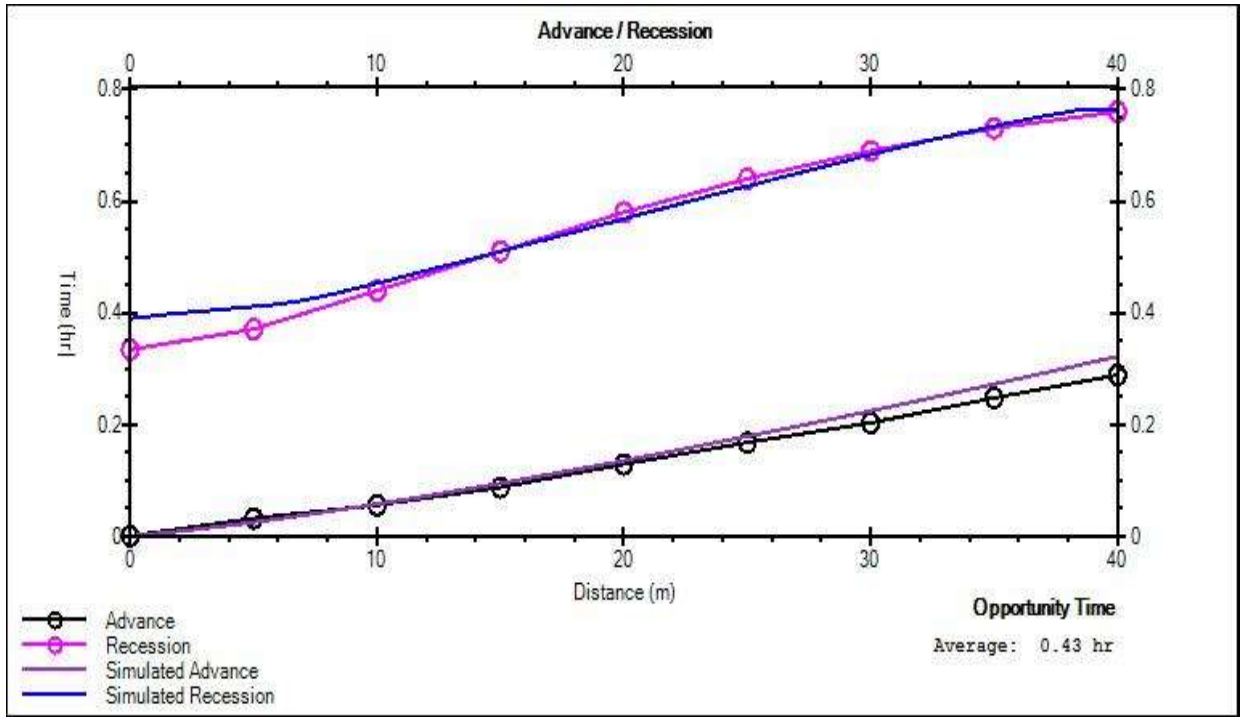


Figure 4.6. Measured and simulated advance and recession time trajectory curve (under 1.5 l/s) for first irrigation event.

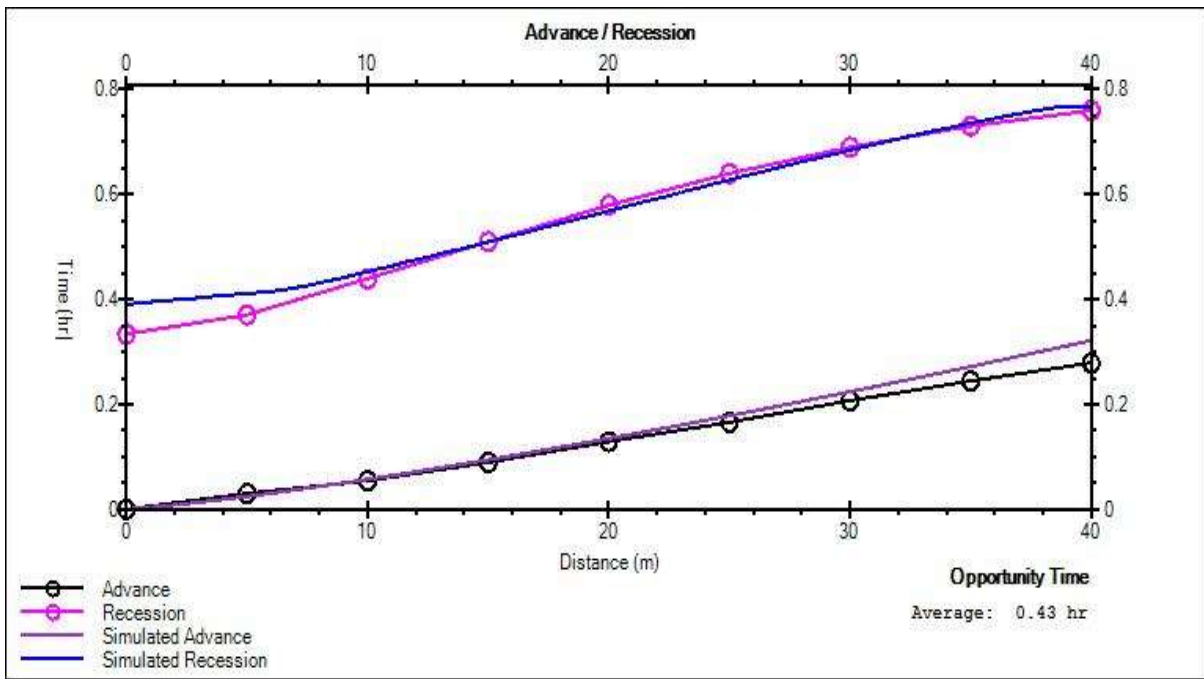


Figure 4.7. Measured and simulated advance and recession time trajectory curve (under 1.5 l/s) for second irrigation event.

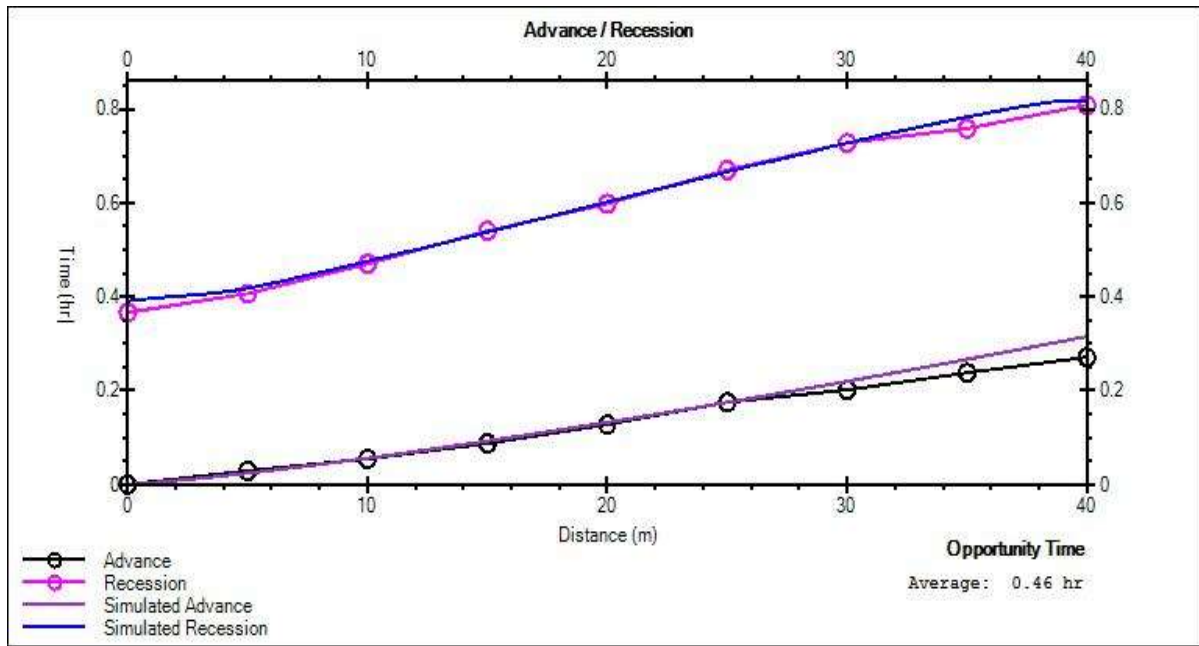


Figure 4.8. Measured and simulated advance and recession time trajectory curve (under 1.5 l/s) for third irrigation event.

#### 4.4.2 Statistical analysis

After execution the accuracy of the WinSRFR software in simulating advance and recession times was evaluated by comparing it with the measured data. The results of average advance and recession trajectory based on four statistical criteria Normalized Root Mean Square Error (NRMSE), distribution to 45° line ( $\lambda$ ), Wilmot agreement (d) and coefficient of determination ( $R^2$ ) for three irrigation events. As shown in Table 4.6 and Fig. 4.4 under furrow inflow rate of 1 l/s the relationship between the measured and simulated advance time expressed with, NRMSE, d,  $\lambda$  and  $R^2$  were 5.22%, 0.947, 0.999 and 0.998 for first irrigation event; 5.54 %, 0.964, 0.999 and 0.999 for second irrigation event and 11.76%, 0.976, 0.994 and 0.996 for third irrigation event respectively which indicate the high accuracy of simulating the advance time. For the measured and simulated recession time NRMSE, d,  $\lambda$  and  $R^2$  were 2.88 %, 1, 0.996 and 0.987 for first; 2.27 %, 1.01, 0.997 and 0.991 for second and 1.71, 0.997, 0.998 and 0.996 for third irrigation. The average statistical comparison between simulated and measured expressed with NRMSE, d,  $\lambda$  and  $R^2$  were 7.50%, 0.962, 0.997 and 0.997 for advance time; 2.29%, 0.999, 0.997 and 0.992 for recession time which indicates the accuracy of simulation is very good.

For furrow inflow rate of 1.5 l/s the relationship between the measured and simulated advance time expressed with NRMSE,  $\lambda$ , d and  $R^2$  were 12.27, 1.04, 0.993 and 0.998 for first irrigation event; 14.1, 1.04, 0.991 and 0.993 for second irrigation event and 14.3, 1.04, 0.991 and 0.994 for third irrigation event respectively. And also for the measured and simulated recession time NRMSE,  $\lambda$ , d and  $R^2$  were 4.34%, 1.03, 0.997 and 0.988 for first; 3.74%, 0.999, 0.994 and 0.991 for second and 2.21, 0.969, 0.998 and 0.995 for third irrigation. The average statistical comparison between simulated and measured expressed with NRMSE,  $\lambda$ , d and  $R^2$  were 13.56%, 0.994, 0.992 and 1.04 for advance time; 3.43%, 0.999, 0.996 and 0.994 for recession time which indicates the accuracy of simulation was very good. But the accuracy of simulation was high under 1 l/s than 1.5 l/s. Overall measured and simulated recession time were in the same trend with the comparison of measured and simulated advance time under the experimental conditions with very good predictions and acceptable outputs.

Table 4.6. Comparison of the measured and simulated advance and recession times using statistical indicators.

I.no	Inflow rate (l/s)	Advance time				Recession time			
		NRMSE (%)	$\lambda$	D	$R^2$	NRMSE (%)	$\lambda$	D	$R^2$
1	1	5.215	0.947	0.999	0.998	2.88	1.00	0.996	0.987
2		5.536	0.964	0.999	0.999	2.27	1.01	0.997	0.991
3		11.76	0.976	0.994	0.996	1.71	0.997	0.998	0.996
Average		7.504	0.962	0.997	0.998	2.29	0.999	0.997	0.992
1	1.5	12.27	1.04	0.993	0.998	4.34	1.03	0.997	0.988
2		14.1	1.04	0.991	0.993	3.74	0.999	0.994	0.991
3		14.3	1.04	0.991	0.994	2.21	0.969	0.998	0.995
Average		13.56	1.04	0.992	0.994	3.43	0.999	0.996	0.994

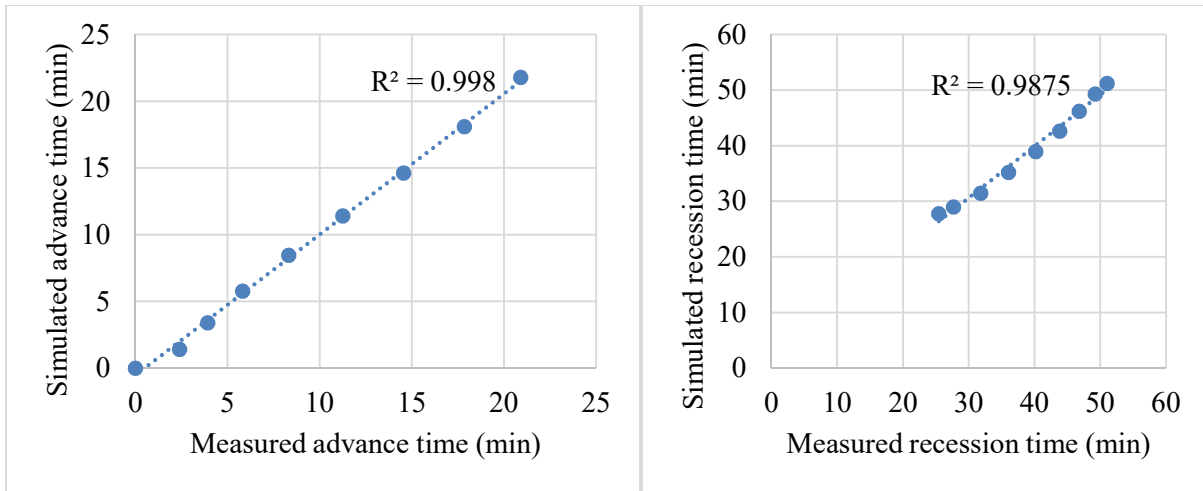


Figure 4.9. Comparison of measured and simulated advance and recession time for first irrigation event (under 1 l/s)

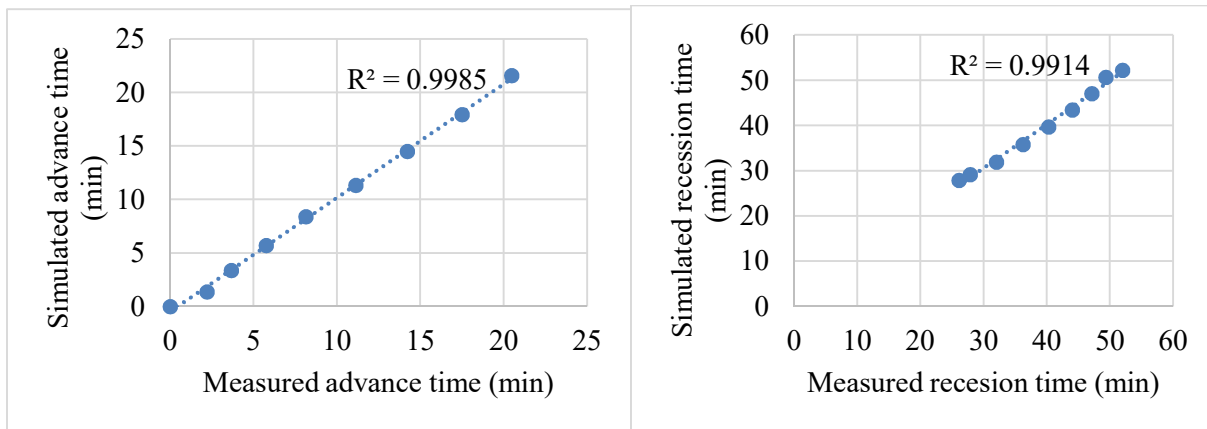


Figure 4.10. Comparison of measured and simulated advance and recession time for second irrigation event (under 1 l/s)

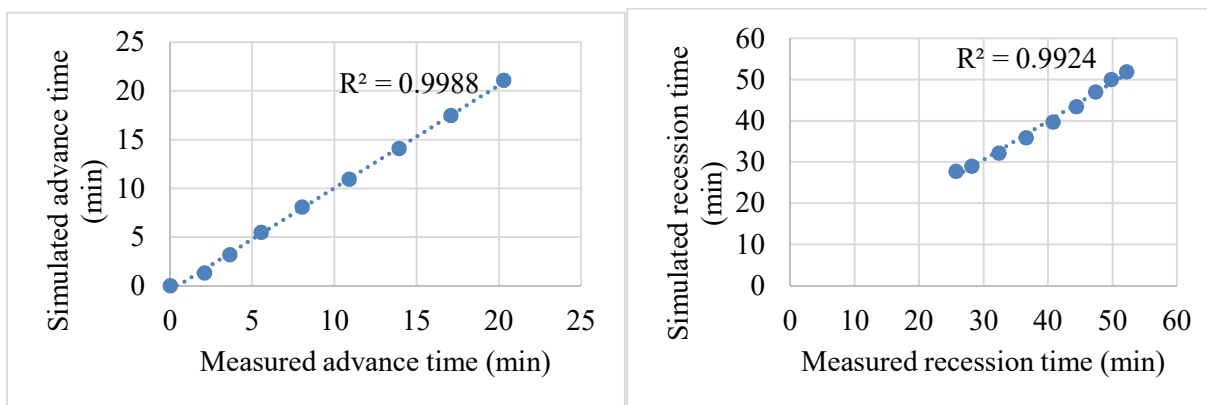


Figure 4.11. Comparison of measured and simulated advance and recession time for third irrigation event (under 1 l/s)

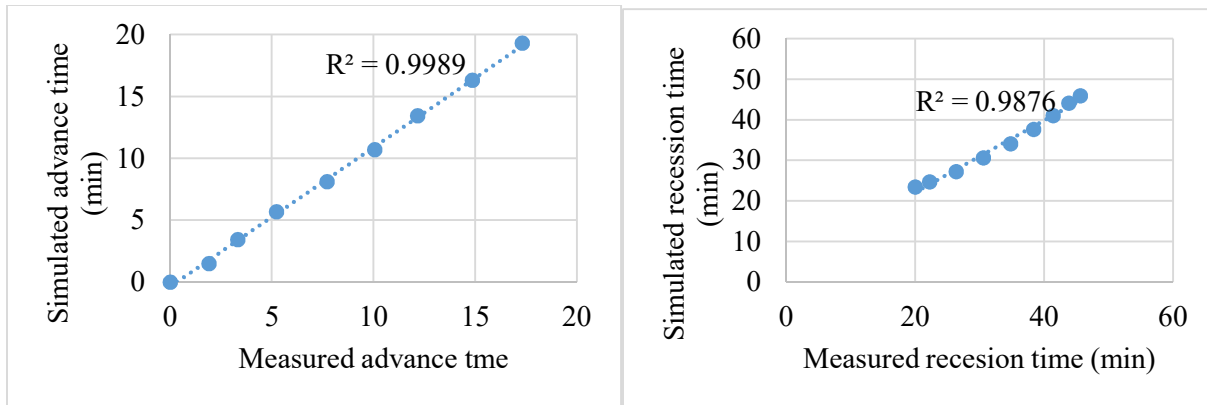


Figure 4.12. Comparison of measured and simulated advance and recession time for first irrigation event (under 1.5 l/s)

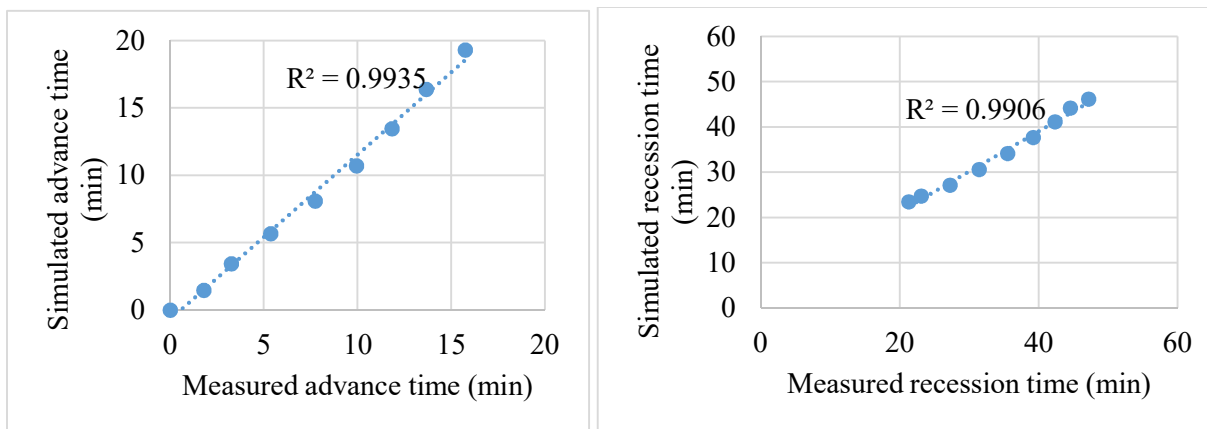


Figure 4.13. Comparison of measured and simulated advance and recession time for second irrigation event (under 1.5 l/s)

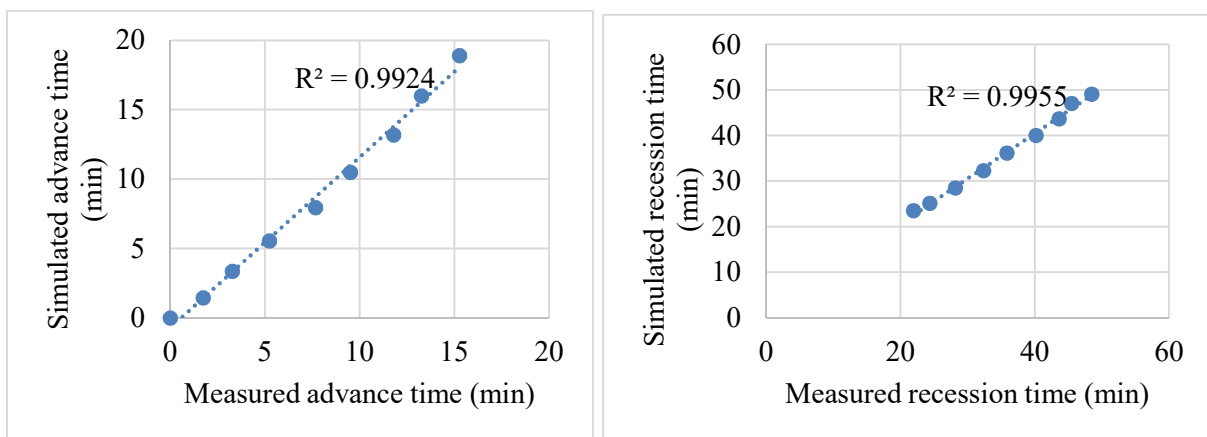


Figure 4.14. Comparison of measured and simulated advance and recession time for third irrigation events (under 1.5 l/s)

#### 4.5. Irrigation Performance Analysis

The irrigation indicators such as application efficiency, deep percolation and distribution uniformity were determined on the field and also simulated using WinSRFR model. Then the measured and simulated values were compared using two statistical indicators: Relative Error and Coefficient of Determination. Table 4.7 summarizes the average results of for three irrigation events and comparison between experimental data and simulated results based on the statistical indicators RE and  $R^2$ . The results shows that the average Relative Error (RE) between simulated and measured AE, DP and DU were 6.68%, 13.89% and 12.06% and the values of  $R^2$  were 0.915, 0.975 and 0.993 for three irrigation events respectively. The average RE and  $R^2$  between observed and simulated were 10.87% and 0.961 for 1 l/s; 4.33 and 0.966 for 1.5 l/s respectively which indicates the simulation ability of WinSRFR on irrigation performance parameters also good and acceptable. The application efficiency of the furrow irrigation was poor which is averagely 60.6% for 1 l/s and 56.74% for 1.5 l/s under field operation. This is because of many reasons and the most important reason may be that the inflow volume and cut-off time was greater than required values. So, it is important to determine and optimize decision parameters that can improve performance of furrow irrigation.

Table 4.7. Relative error between average measured and simulated of performance parameters

Performance indicator	Furrow inflow rate ( $Q_0=1$ l/s)				Furrow inflow rate ( $Q_0=1.5$ l/s)				
	Measured (%)	Simulated (%)	RE (%)	$R^2$	Measured (%)	Simulated (%)	RE (%)	$R^2$	
Application Efficiency	60.6	65	6.6	0.91	56.74	54	5.07	0.98	
Deep Percolation	38.8	35	13.8	0.97	42.34	46	3.61	0.91	
Distribution Efficiency	85.3	97	12.0	0.99	89	93	4.3	0.99	
Average			10.8	0.96				4.33	0.96

#### 4.6. Optimization of Decision Parameters

In this study, the calibrated infiltration functions were used for optimizing and developing different design alternatives using the design and operational analysis worlds of WinSRFR model. The physical design and operational analysis worlds of the WinSRFR software were used to identify optimal combination of furrow length, slope, and furrow inflow rate and cutoff time. In the optimization stage, the model was set to develop performance contours as a function of length and inflow rate. The performance contours were used for identifying impact of optimizing field length, slope, inflow rate and cutoff time irrigation performance. In this section, different combinations of inflow rate, cut-off time, furrow length and slope were employed to improve the performance. Additionally ten furrows per set of 6m width (i.e.0.6m furrow spacing) and 50 mm minimum required depth were considered as input for physical design and operational analysis. By varying different inflow rates under different furrow bed slopes (i.e. 0.1 %, 0.2 %, 0.3 %, 0.4 % and 0.5%) and different furrow lengths (i.e.40m, 60m, 80m and 100m) for different cutoff times, combination of parameters which can improve furrow irrigation performance were employed and identified. Table 4.8 shows that the maximum attainable (potential) values of application efficiency and distribution efficiency and minimum value of deep percolation.

According to this study increasing inflow rate from 0.5 to 5 l/s by decreasing cutoff time increase application efficiency and minimize deep percolation. Furrow irrigation performance was increased under all furrow length using high furrow inflow rate as furrow slope decreases. As presented in Table 4.8 as furrow length and bed slope increases from 0.2 % to 0.5 % the performance of furrow decreases. In this study under combination of 2 l/s inflow rate, 40m length and 0.2% slope the highest attainable performance was obtained which is 95%. Ghani (2016) study also revealed that using WinSRFR irrigation performance can be improved by optimizing the existing field sizes for the available inflow rate and cut-off time, evidenced by maximum achievable potential application efficiency of 97% for furrow bed. The maximum performance can also obtained under 0.2% bed slope of 60 m furrow length with 2.5l/s inflow rate and 0.22 hour; under 0.2% bed slope of 80 m furrow length with 4l/s inflow rate and 0.30 hour and under 0.2% bed slope of 100 m furrow length with 5l/s inflow rate and 0.19 hour (see Table 4.8). Generally for all selected bed slopes and inflow rates maximum values of application efficiency and distribution efficiency and minimum value of deep percolation were obtained under 40m furrow length than other lengths.

Table 4.8. Results of maximum irrigation performance under different parameters combination

Slope (%)	Furrow length (m)	Furrow inflow rate (Qo) (l/s)	Potential Application Efficiency (PAE) (%)	Deep Percolation (DP) (%)	Distribution Uniformity (DUmin)	Cutoff time (t <sub>co</sub> ) (hr)
0.1	40	2.5	89	10	0.901	0.15
	60	3	86	13	0.867	0.22
	80	4	85	14	0.857	0.20
	100	5	81	18	0.814	0.22
0.2	40	2	95	4	0.955	0.18
	60	2.5	93	6	0.936	0.22
	80	4	91	8	0.916	0.18
	100	5	90	10	0.904	0.19
0.3	40	1.5	93	6	0.939	0.24
	60	2	90	10	0.9	0.28
	80	3	89	11	0.889	0.25
	100	4	88	12	0.879	0.30
0.4	40	1.5	91	9	0.914	0.24
	60	2	89	11	0.887	0.28
	80	2.5	87	13	0.867	0.31
	100	3.5	86	14	0.860	0.28
0.5	40	1.5	89	11	0.895	0.25
	60	2	87	13	0.871	0.29
	80	2.5	85	15	0.857	0.31
	100	3	84	16	0.844	0.33

The figure 4.15 below illustrates that the maximum attainable application efficiency 95% can be achieved for furrow length of 40 m under 0.2% furrow bed slope with inflow rate of 2 l/s and 0.18 hour cut off time.

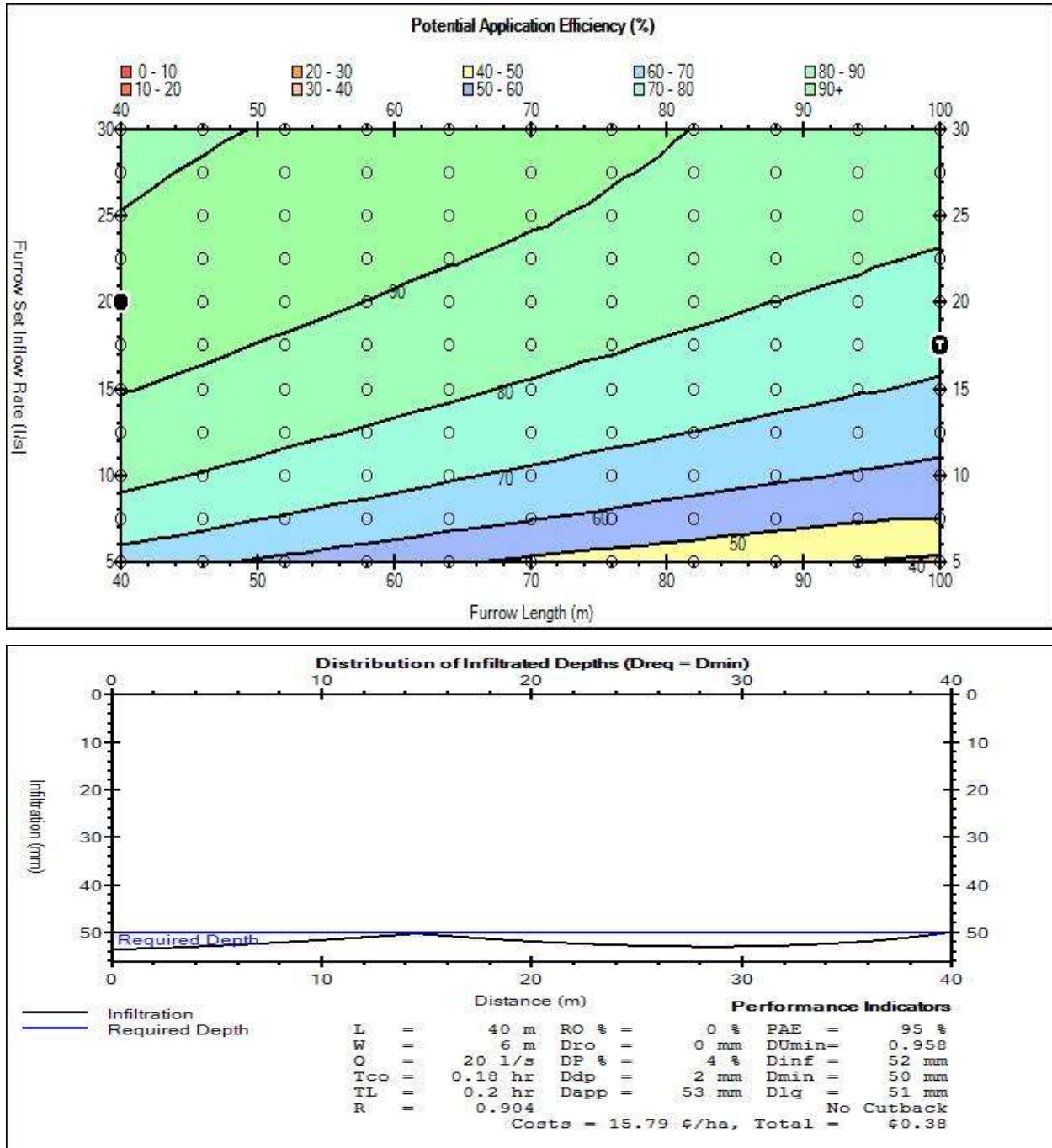


Figure 4.15 Simulated performance contours of maximum irrigation performance for 40 m furrow length

As performance contour indicated in figure 4.16 below shows for 60m furrow length under 0.2% bed slope with 2.5 l/s inflow rate and 0.22 hour cutoff time, the maximum attainable application efficiency was 93%.

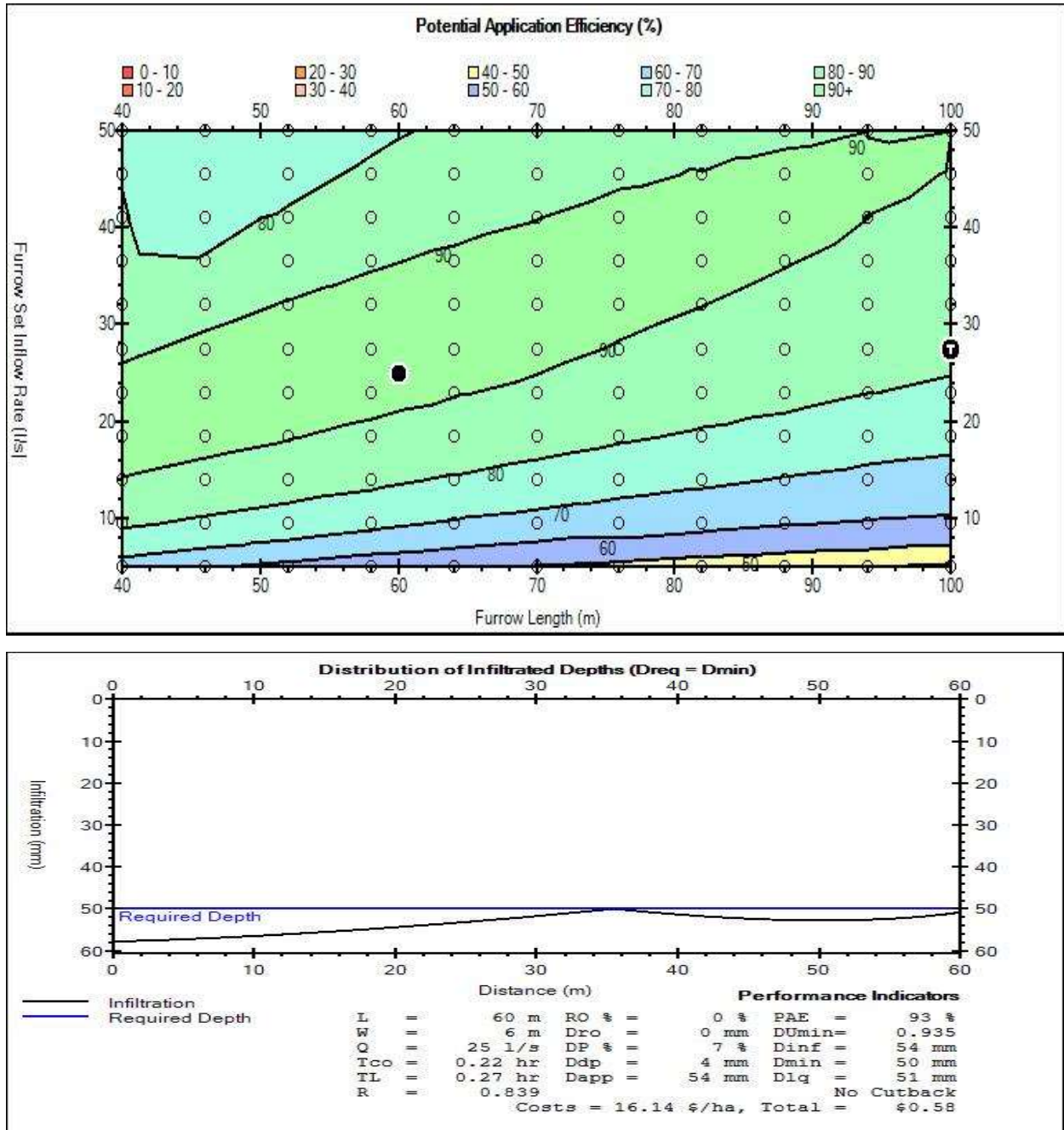


Figure 4.16 Simulated performance contours of maximum irrigation performance for 60 m furrow length

The performance contour shown in figure 4.17 below shows that maximum performance under 80m furrow length can be obtained when furrow inflow rate is in between 3l/s to 4l/s. The maximum attainable application efficiency of 91% was achieved under combination of 80m furrow length and 0.2% bed slope with 4 l/s inflow rate and 0.18 hour cutoff time.

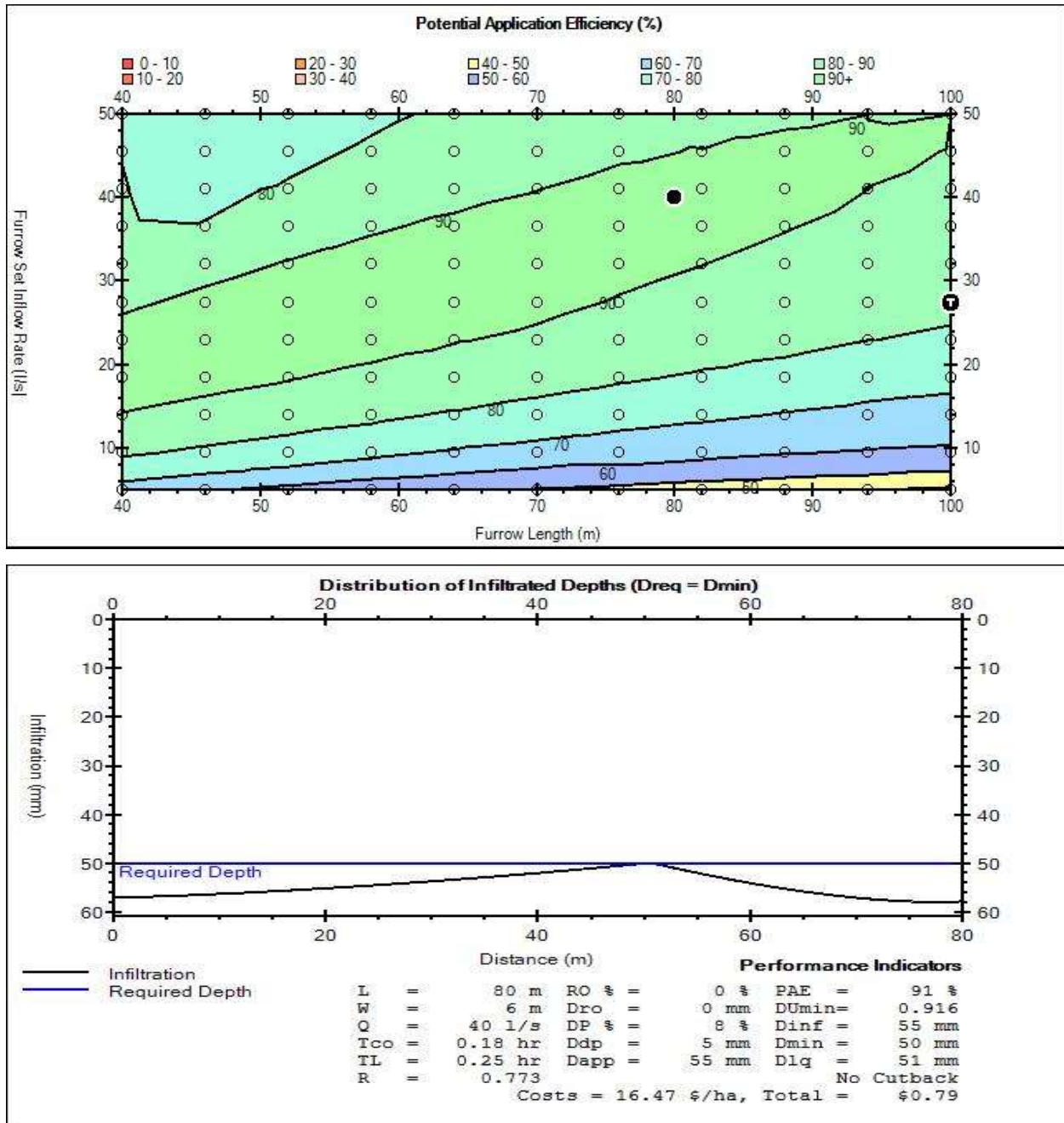


Figure 4.17 Simulated performance contours of maximum irrigation performance for 80 m furrow length

The figure 4.18 below indicates that maximum performance can be obtained under 100m furrow length by increasing inflow rate. For 100m furrow length, choosing inflow rate greater than 2.5 l/s with appropriate cutoff time, more than 80% application efficiency can be achieved. Maximum attainable application efficiency was 90%. Under 0.2% bed slope with 5 l/s inflow rate and 0.19 hour cutoff time. But, non-erosive inflow rate should be considered.

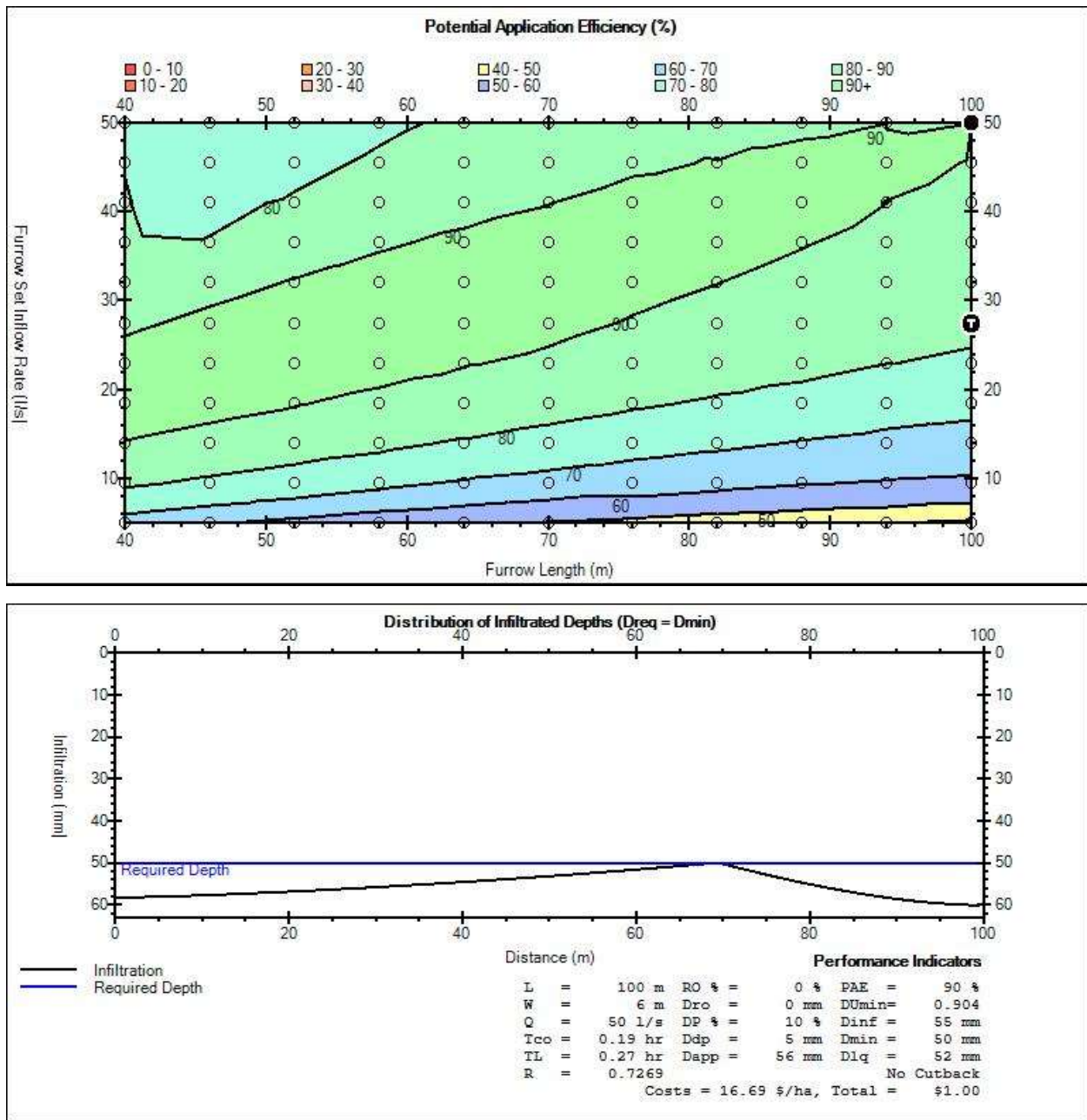


Figure 4.18 Simulated performance contours of maximum irrigation performance for 100 m furrow length

The optimal application efficiency has been observed, when the cutoff time to be the minimum and inflow rate to be increased for the given furrow slope and length. To achieve maximum performance the furrow length to be optimal with reduced the recession time and reduced the total irrigation time at maximized or improved hydraulic performance parameters of furrow irrigation. Hence, different combination of parameters for four different furrow lengths (i.e. 40, 60, 80 and 100m) were tested and simulated using WinSRFR to obtain maximum furrow irrigation performance. Finally, the maximum irrigation performance was obtained under 40m furrow length than other furrow lengths.

## 5. CONCLUSION AND RECOMMENDATION

### 5.1. Conclusion

This study was conducted to evaluate and optimize furrow decision parameters in order improve furrow irrigation performance using WinSRFR software. Field experiment was done on furrow length of 40 m under slope of 0.2% using 1 and 1.5 l/sec furrow inflow rate. The aim of field experiment was to validate the simulation models with adequate study on design, evaluation and optimization of hydraulic performance parameters of furrow irrigation system. The measured data of experimental site was inserted in the WinSRFR software which provided predictions for. The modified Kostiakov–Lewis equation was employed to estimate the infiltration characteristics and calibrated using Merriam-Claire volume balance method. The statistical indicators of NRMSE,  $R^2$ , RE,  $d$ , and  $\lambda$  were used for the comparison between measured and simulated advance time, recession time and performance. The results of these indicators were very good and showed that WinSRFR simulation was acceptable. According to result obtained, the application efficiencies of furrow irrigation were 60.6% and 56.74% under 1 l/s and 1.5 l/s furrow inflow rates respectively which was poor.

Then, WinSRFR software was used to determine optimum furrow decision parameters under furrow length less than 100m depending on maximum field length of the study area. In this study four furrow lengths (i.e. 40m, 60m, 80m and 100m); five bed slopes (i.e. 0.1%, 0.2%, 0.3%, 0.4% and 0.5%) and inflow rates (i.e. 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 l/s) under different cutoff times were employed to determine optimum combination of parameters which can lead to high performance. According to this study, changing inflow rate and cut-off time led to maximum efficiency than other parameters (i.e. furrow length and slope).

Finally, the result showed that 40m furrow length under 0.2% bed slope with 2 l/s inflow rate and 0.18 hour cutoff time had the best performance. In addition, results also showed that by combinations of the 2.5 l/s inflow rate for 60m furrow length and 0.2% bed slope; 4 l/s inflow rate for 80m furrow length and 0.2% bed slope; 5 l/s inflow rate for 100m furrow length and 0.2% bed slope high furrow irrigation performance can be achieved. Generally, based on this study, even though short furrow length has maximum performance for selected furrow bed slopes and inflow rates, using longer furrow length (i.e. 100m) is good for effective management and use of irrigation water as it is also suggested by most researchers from different point of view.

## **5.2. Recommendation**

At Batu irrigation Project huge amount of money have been invested to construct structures. Farmers at the project were using very short traditional furrows not greater six to eight meter. Even if these short furrows has advantages on irrigation management and water distribution efficiency, irrigation water was considerably wasted by their application system and this can lead to salt accumulation in the furrows. The furrow irrigation has been practiced traditionally which leads to less efficiency and uniformity.

The hydraulic performance of furrow irrigation can be significantly improved by using combination of furrow irrigation parameters suggested in the results. In this study, optimized hydraulic performance parameters have been seen and suggested under sandy loam soil condition as analyzed with WinSRFR software model. Hence, the suggested optimal combination of parameters should be used to improve hydraulic performance of furrow irrigation of the study area. This in turn can make more appropriate for management and save irrigation water.

Finally, still most studies were focused on long furrows. So, further study about the short furrow hydraulics is important and optimal design of furrow irrigation system should be practiced. Thus, to improve the performance of furrow irrigation the optimal furrow length, inflow rates and cutoff time at suitable furrow slopes should be identified and suggested for other soil conditions.

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## APPENDIX

Table 4.9. Bulk density measurement

S.N	Soil depth (cm)	can+dry soil wt (gm)	can wt (gm)	Dry soil wt (gm)	Bulk density pb (gm/cm <sup>3</sup> )
1	0-20	151.6	34.1	117.5	1.19
2	20-40	137.1	33.3	103.8	1.05
3	40-60	141.2	33.2	108	1.09
Average					1.11

Table 4.10. Average soil moisture content before and after irrigation

Furrow inflow rate (Q <sub>o</sub> )	Soil depth (cm)	Moisture content (%)			
		B		A	
		Wt. basis	Vol. basis	Wt. basis	Vol. basis
1 l/s	0-20	18.82	20.56	19.15	22.79
	20-40	20.16	21.86	21.80	22.90
	40-60	22.78	23.84	23.05	25.12
Average		20.58	22.08	21.33	23.60
1.5 l/s	0-20	19.18	22.82	19.69	23.44
	20-40	20.67	21.7	24.31	25.53
	40-60	21.74	23.69	23.51	25.63
Average		20.53	22.74	22.50	24.87

\*B-before irrigation \*A-after irrigation

Table 4.11. Measured irrigation performance parameters

I.no	Inf. Depth (Zi) (mm)	App. depth (Zd) (mm)	Perc. depth (Zp) (mm)	Av.inf. depth (Z) (mm)	Low quarter inf.depth (Z <sub>Lq</sub> ) (mm)	Application Efficiency (AE) %	Deep percolation (DP) %	Distribution Efficiency (DU) %
1	31.21	50	18.79	50	42.63	62.42	37.58	85.25
2	29.75	50	20.25	48.78	42.59	59.51	41.5	87.32
3	27.14	50	22.86	50	41.75	54.28	45.72	83.5
Av.	30.33	50	19.67	49.35	42.12	60.66	38.86	85.36
1	45.17	75	29.83	74.62	64.69	60.22	39.98	86.7
2	42.44	75	32.56	72.05	65.56	56.59	45.19	91
3	40.05	75	34.95	76.21	68.05	53.4	45.86	89.3
Av.	42.55	75	32.44	76.63	68.20	56.74	42.34	89

Table 4.12. Furrow slope determination

F.N	Station	Distance	BS	HI	FS	Elevation
	1(BM)	0	1.45	1351.45	–	1350
	2	10			1.455	1349.995
	3	15			1.462	1349.951
F-1	4	20			1.467	1349.946
	5	25			1.47	1349.943
	6	30			1.479	1349.934
	7	35			1.486	1349.927
	8	40			1.493	1349.92
<b>Slope</b>						<b>0.20</b>
	1(BM)	0	1.447	1351.447	–	1350
	2	10			1.515	1349.932
	3	15			1.518	1349.927
	4	20			1.52	1349.925
F-2	5	25			1.522	1349.923
	6	30			1.524	1349.921
	7	35			1.527	1349.918
	8	40			1.53	1349.915
<b>Slope</b>						<b>0.2125</b>
	1(BM)	0	1.451	1351.451	–	1350
	2	10			1.456	1349.995
	3	15			1.46	1349.99
	4	20			1.463	1349.987
F-3	5	25			1.472	1349.978
	6	30			1.481	1349.969

F.N	Station	Distance	BS	HI	FS	Elevation
	7	35			1.494	1349.956
	8	40			1.527	1349.923
	<b>Slope</b>					<b>0.1925</b>
	1(BM)	0	1.445	1351.445	–	1350
	2	10			1.465	1349.98
	3	15			1.472	1349.973
	4	20			1.477	1349.968
F-4	5	25			1.484	1349.961
	6	30			1.49	1349.955
	7	35			1.497	1349.948
	8	40			1.519	1349.926
	<b>Slope</b>					<b>0.185</b>
	1(BM)	0	1.453	1351.453	–	1350
	2	10			1.458	1349.995
	3	15			1.462	1349.925
	4	20			1.457	1349.93
F-5	5	25			1.463	1349.924
	6	30			1.467	1349.92
	7	35			1.47	1349.917
	8	40			1.471	1349.916
	<b>Slope</b>					<b>0.21</b>
	1(BM)	0	1.449	1351.449	–	1350
	2	10			1.461	1349.988
	3	15			1.472	1349.957

F.N	Station	Distance	BS	HI	FS	Elevation
	4	20			1.478	1349.951
F-6	5	25			1.483	1349.946
	6	30			1.489	1349.94
	7	35			1.494	1349.935
	8	40			1.51	1349.919
<b>Slope</b>						<b>0.202</b>
<b>Total</b>						<b>0.2%</b>

Table 4.13. Furrow geometry data

F.N	Distance (m)	Depth (cm)	Top Width (cm)	Middle Width (cm)	Bottom Width (cm)
F-1	0	18.7	49.5	30.5	12.2
	5	18.5	49	29.3	12
	10	19	48	30.8	12.7
	15	18.6	47.8	29.6	11
	20	20	50	32	12.6
	25	19.4	49.4	30.2	12.2
	30	20	49.6	29.8	13
	35	19.7	49	30.6	11.8
	40	18	45	31	13.3
<b>Average</b>		<b>19.1</b>	<b>48.59</b>	<b>30.42</b>	<b>12.31</b>
F-2	0	19	48	31.5	12
	5	19.4	48.5	29.6	12.2
	10	20	49	30	11.9
	15	19.6	48.7	30.7	12
	20	19.5	49.3	30.5	13
	20	19	49	29.4	11.7
	30	18	47.3	30.4	12.6
	35	18.5	48.6	30	12.2
	40	18	48	31.4	12.4
<b>Average</b>		<b>19</b>	<b>48.49</b>	<b>30.39</b>	<b>12.22</b>
F-3	0	19	47.5	30.8	11.5

F.N	Distance (m)	Depth (cm)	Top Width (cm)	Middle Width (cm)	Bottom Width (cm)
	5	18.5	48.6	29.5	10.8
	10	19.8	49	30	11.8
	15	19	48.5	29.8	13
	20	17.5	49	31.5	12.7
	25	18.7	48.4	29.7	12.8
	30	17.8	47.5	29.2	11.5
	35	18.5	48.7	30.9	11.9
	40	18	49	32	13.4
<b>Average</b>		<b>18.533</b>	<b>48.47</b>	<b>30.38</b>	<b>12.16</b>
F-4	0	17.5	48.5	29.9	10.7
	5	18	47.8	32	11.7
	10	18	48	29.4	12.6
	15	18.7	49	30.5	13.4
	20	19.7	48.2	29.8	12.6
	25	18.5	48.7	30.4	13
	30	18	47.5	31	11.5
	35	18.6	48.8	30.3	10.8
	40	19.5	49	29.9	12.9
<b>Average</b>		<b>18.5</b>	<b>48.39</b>	<b>30.36</b>	<b>12.13</b>
F-5	0	18	48	29.5	10
	5	18.5	47.8	30.8	12.4
	10	18.7	48.5	29.8	13.2

F.N	Distance (m)	Depth (cm)	Top Width (cm)	Middle Width (cm)	Bottom Width (cm)
		18.4	49	30.7	12
	20	18.6	48.4	29.5	13.1
		18	48.3	31.3	12.3
	30	19	49.6	30.8	12.8
		18.5	49	31.6	12
	40	20	48.2	30	12
<b>Average</b>		<b>18.633</b>	<b>48.53</b>	<b>30.44</b>	<b>12.2</b>
F-6	0	18	48.5	31.3	11.7
	5	18.2	49.2	29	12.3
	10	18	47.6	30.7	13.4
	15	18.5	48.8	29.4	12
	20	19	49	29.3	12.6
	25	18.8	48.8	30.9	12.8
	30	18.5	48	31	13
	35	18.7	48.5	30.7	10.5
	40	18.5	49	30.5	11.6
<b>Average</b>		18.467	48.6	30.31	12.21
<b>Total</b>		<b>18.71</b>	<b>48.51</b>	<b>30.38</b>	<b>12.21</b>

Table 4.14. Measured average advance and recession time (under  $Q_0 = 1 \text{ l/s}$ )

Distance (m)	First event		Second event		Third event	
	Adv.time (hr)	Rec.time (hr)	Adv.time (hr)	Rec.time (hr)	Adv.time (hr)	Rec.time (hr)
0	0	0.424	0	0.435	0	0.446
5	0.04	0.461	0.037	0.465	0.035	0.477
10	0.065	0.53	0.061	0.534	0.06	0.54
15	0.097	0.6	0.096	0.604	0.093	0.61
20	0.139	0.67	0.136	0.672	0.134	0.668
25	0.188	0.73	0.186	0.734	0.181	0.74
30	0.243	0.78	0.237	0.786	0.221	0.797
35	0.297	0.821	0.285	0.823	0.268	0.828
40	0.365	0.85	0.349	0.867	0.345	0.878

Table 4.15. Measured average advance and recession time (under  $Q_0 = 1.5 \text{ l/s}$ )

Distance (m)	First event		Second event		Third event	
	Adv. time (hr)	Rec.time (hr)	Adv.time (hr)	Rec.time (hr)	Adv. time (hr)	Rec. time (hr)
0	0	0.334	0	0.355	0	0.366
5	0.032	0.371	0.030	0.385	0.029	0.406
10	0.055	0.439	0.054	0.454	0.055	0.469
15	0.087	0.510	0.089	0.524	0.087	0.540
20	0.129	0.579	0.129	0.592	0.128	0.598
25	0.168	0.64	0.166	0.654	0.175	0.669
30	0.203	0.69	0.207	0.706	0.201	0.727
35	0.247	0.730	0.245	0.743	0.238	0.758
40	0.288	0.760	0.279	0.787	0.271	0.808

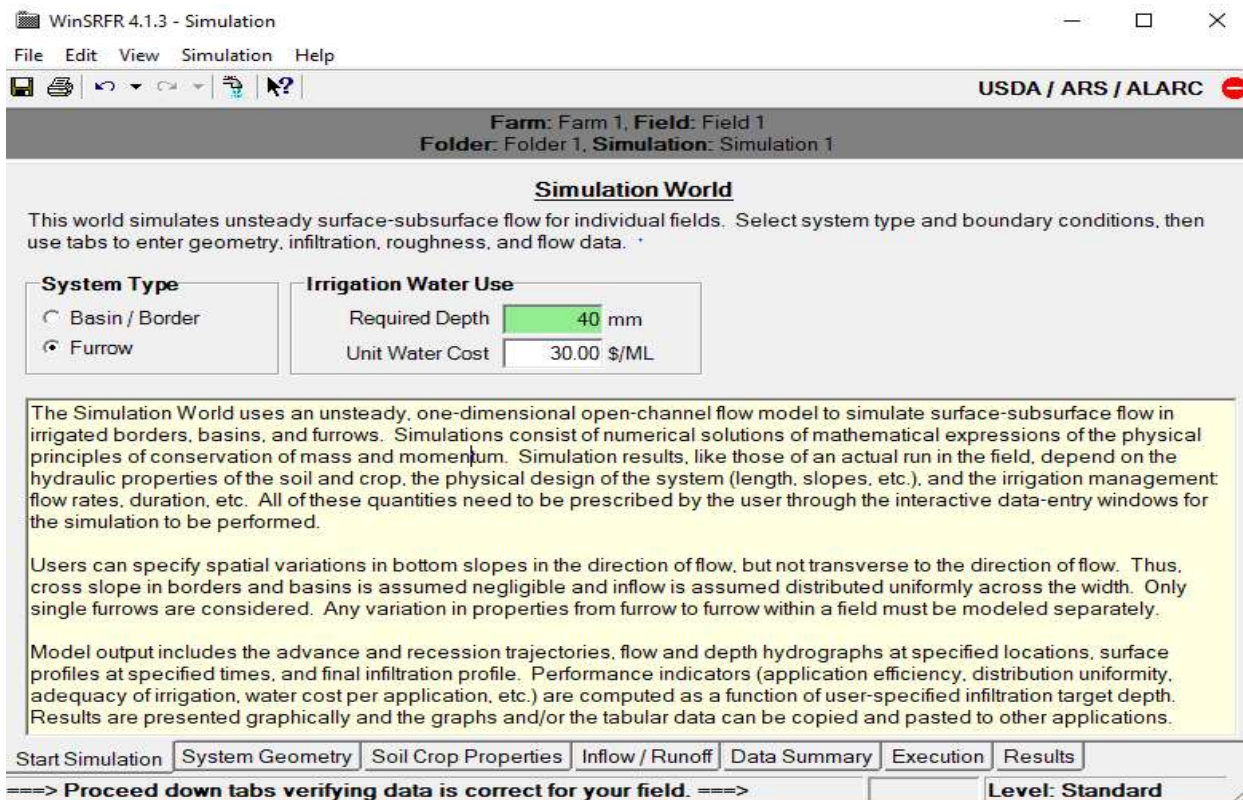
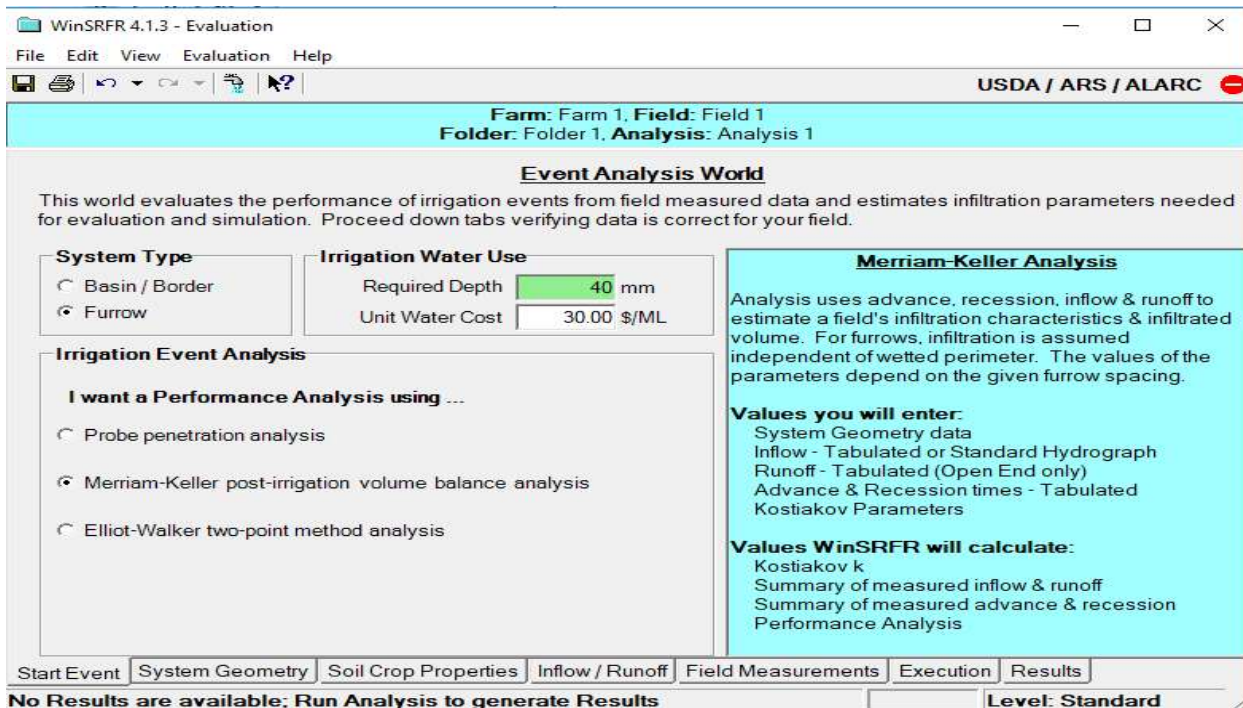


Figure 4.19. Event Analysis world

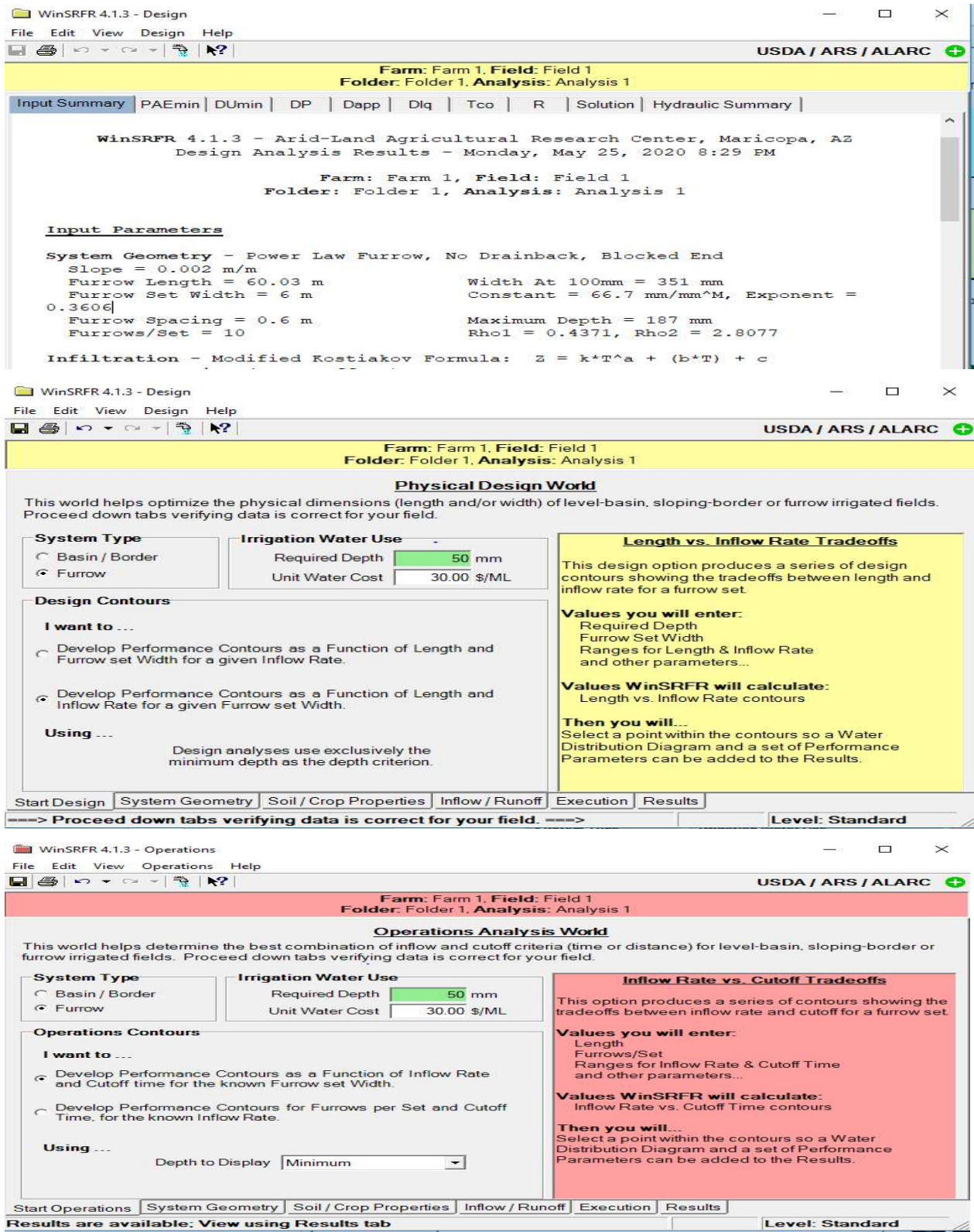


Figure 4.20. Physical Design and Operational Analysis world

Table 4.16. Discharge through siphon under varying heads

Head (cm)	Discharge (l/s) Internal siphon diameter (4.2cm)
4	0.8
6	0.98
8	1.13
10	1.26
12	1.29
14	1.30
16	1.60
18	1.70
20	1.79
22	1.88
24	1.96
26	2.04
28	2.12
30	2.19
32	2.26
34	2.33
36	2.40
38	2.47
40	2.53
42	2.39
44	2.65
46	2.71
48	2.77
50	2.83

Source: FAO, 1981