EFFECT OF IRRIGATION WATER CUT-OFF POSITION ALONG FURROWS ON WATER SAVING AND PRODUCTIVITY

Benjamin Lembanyanja Banda

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Masters in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology

Arusha, Tanzania

August, 2024

ABSTRACT

Despite being widely practised technique by smallholder farmers, cut-off technique continues to register low productivity and has not been adequately investigated to improve the status quo. This study aimed to investigate the scenarios to improve water use efficiency and productivity for the cut-off irrigation technique. Three cut-off treatments where water supply was stopped with the advance phases reaching 75%, 80% and 90% of furrow length were investigated with eight irrigation events. The crop grown under these scenarios was maize. Soil analysis showed that in all the three subplots, the soils were sandy loam with an average of 69% sand and 31% silt. The initial soil moisture content was 14% and other corresponding moisture properties were 33.5 mm/hr infiltration rate, 9% permanent wilting point and 12% available moisture. Mean application efficiencies with significant differences ($P<0.05$) of 70%, 66.4% and 63% were achieved for the 75%, 80% and 90% length treatments respectively. Corresponding uniformities and water productivities of 90%, 89.9%, 89.2% and 1.54 kg/m^3, 1.38 kg/m^3,1.18 kg/m^3 respectively were obtained with no significant difference ($P>0.05$). The results demonstrated the 75% cut-off has the potential of saving water of up to 26% without compromising water productivity. It is recommended therefore that the 75% cut-off position of water supply be promoted among the smallholder farmers and that research studies should now be carried out for less than 75% cut-offs.

AUTHOR'S DECLARATION

I, Benjamin Lembanyanja Banda, do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this is my own original work and and that it has neither been submitted nor being concurrently submitted for degree award in any other University.

Benjamin Lembanyanja Banda

-- 14/08/2024

Name and signature of candidate **Date**

The above declaration is confirmed

Prof. Hans Komakech

-- 14/08/2024

Name and signature of Supervisor 1 **Date**

Prof. Kelvin Mtei

-- 19.08.2024

Name and signature of Supervisor 2 **Date**

CERTIFICATION

The undersigned certify that they have read and hereby recommend for examination of a dissertation entitled; ***Effect of Irrigation Water Cut-Off Position Along Furrows on Water Saving and Productivity***, to be accepted in partial fulfilment of the requirements for the Degree of Masters of Science in Hydrology and Water Resources Engineering of the Nelson Mandela African Institution of Science and Technology Arusha, Tanzania.

Supervisor 1

Prof. Hans Komakech

14/08/2024

Signature **Date**

Supervisor 2

Prof. Kelvin Mtei

19.08.2024

Signature **Date**

ACKNOWLEDGEMENTS

First and foremost, I thank the Lord Almighty for giving me healthy life and guiding me throughout the execution of this research work. It was His will and mercy that made this work possible.

Secondly, let me acknowledge the Government of Malawi for sponsoring my studies including this research and WISE-Futures of The Nelson Mandela African Institution of Science and Technology, Tanzania for material support.

Thirdly, I would like to express my appreciation to my supervisors Prof. Hans Komakech and Prof. Kelvin Mtei for their tireless efforts in reading and correcting my work right from proposal development to this end. Their time dedicated to my work has been the most valuable ingredient to this quality achieved in this work. As someone who never know and thought of a publication of research work, this achievement could not have happened without their guidance and encouragement. And many thanks to the rest of Materials, Energy, Water and Environment Science (MEWES) School staff for their valuable contributions and constructive questions during Graduate seminar presentations. These shaped up this research work. I am equally grateful to Ms Zuhura in the Dean's office for not getting tired with frequent communications with a student based in a foreign country; surely it would not have been possible without this effort.

I extend my acknowledgement to my colleagues who assisted me in different ways, proof reading and correcting my work, their efforts were not in vain; Rosemary Kavishe, Getrude Mushi and all Water, Environmental science and Engineering (WESE) cohort 7 students.

My appreciation to the Mwenyekiti and the farmers of Lekitatu Irrigation Scheme for their endless support, provision of land, water and security throughout the research period.

Lastly, let me appreciate the support from the students' welfare office, the international office, my fellow international students, students' union, librarians, laboratory technicians and the Nelson Mandela community at large.

DEDICATION

Firstly, I dedicate this work to my family who waited patiently as I was away on journey resulting into this work and to colleagues at my workplace for covering me up while I was on study leave.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND SYMBOLS

Aw	Consumed Water
Cd	Coefficient of Discharge
D_{av}	Average depth of water infiltrated over the whole field
D_{lp}	Average depth of water infiltrated in the lower one quarter of the field
DU	Water Distribution Uniformity
Ea	Water Application Efficiency
EC	Electrical Conductivity
ETc	Crop Evapotranspiration
ETo	Reference Evapotranspiration
GPS	Global Positioning System
GY	Grain Yield
hr	Hour
IE	Irrigation event
IOT	Infiltration Opportunity Time
Kc	Crop Coefficient
MEWES	Materials, Energy, Water and Environmental Science
OM	Organic Matter
pH	Measure of alkalinity or acidity
Q	Discharge measured in volume of water per unit time
TZS	Tanzania Shilling
USDA	United States Department of Agriculture
WESE	Water, Environmental Science and Engineering
WISE-Futures	Water Infrastructure and Sustainable Energy
WP	Water Productivity

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Worldwide, agriculture accounts for about 70 % of all freshwater withdrawals (Calzadilla *et al*., 2010). In dry areas such as Middle East and North Africa, irrigation do take up to 95% of all water withdrawn (Boutraa, 2010) and in East Africa, withdrawals for irrigation are up to 87% (Global Water Partnership, 2015). With undependable rain-fed agriculture, agricultural policies of most developing countries are aligned to improving and upscaling irrigated agriculture (Siebert *et al*., 2013) to improve peoples' livelihoods and food security.

In expanding irrigation, surface irrigation systems remain widely practised by both commercial and smallholder farmers. Water is supplied to the farmland through a network of distribution and feeder canals and water flows through them by gravity. It is a preferred method over other methods such as drip, sprinkler and centre pivots because of its simplicity in terms of operation and maintenance and less capital investment (Elsheikh *et al*., 2014) . Furrow irrigation is one kind of surface irrigation where water is supplied to the field from a feeder canal through narrow depression channels known as furrows dug at specified and usually equal intervals, with a nearly uniform slope (Assefa *et al*., 2017; Elsheikh *et al*., 2014). As water flows through these furrows, it infiltrates the soil and spreads laterally to saturate the root zone of the crops.

Surface irrigation in general and furrow irrigation system in particular has low water application efficiency and productivity. Depending on different climatic conditions, soils and crop characteristics, and water management practices application efficiency for conventional furrow irrigation usually ranges from 45% to 65% (Irmak *et al*., 2011). This in turn reduces the water productivity of furrow irrigation system greatly. With the continued dwindling of water resources, improvements in the existing water application methods and water management practices are therefore more critical than before (Sarwar *et al*., 2001).

A number of studies (Assefa *et al*., 2017; Manabaev *et al*., 2015; Öztekin, 2013; Yonts *et al*., 2003) all have investigated on effects of physical parameters such as slope, furrow length and flowrates on water application efficiency, distribution uniformity and productivity. Similarly there are several irrigation methods, which have been investigated and have proved to improve efficiency in furrow irrigation. These methods include surge flow, cut-off, cut-back and bunds

(Bishop *et al*., 1981; Elsheikh *et al*., 2014; Salahou *et al*., 2016; Trout, 1990; Walker & Skogerboe, 1987). Bishop *et al*. (1981) defined surge irrigation as 'the intermitted application of irrigation water creating series of on and off moves at constant or variable time spans', a method introduced by in 1979 by String ham and Kelly. Bunds are strips constructed along the furrow run to increase the time interval between water application and infiltration. Cut-back principle involves applying a large initial non eroding flow rate in which water which can reach the tail end of the furrow in a short period, then thereafter the inflow rate is reduced to nearly as the infiltration rate of soils forming the furrow (Trout, 1990; Walker & Skogerboe, 1987). With the cut-off irrigation method the practice is to stop the water supply at the head of the furrow when the advance wetting phase reaches about three quarters of the furrow length (Elsheikh *et al*., 2014; Issaka *et al*., 2015) and the recession flow will continue to wet the remaining part of the furrow.

With reported efficiencies of as low as 45 % (Irmak *et al*., 2011), investigations on ways of improving water use efficiency and productivity in furrow irrigation are more crucial than ever in these times of continued dwindling of water resources. This study, therefore, aimed at investigating scenarios in the cut-off irrigation technique to improve water application efficiency, distribution uniformity, and productivity.

1.2 Statement of the Problem

Despite the reported low water efficiency, furrow irrigation is still widely practiced by both commercial and smallholder farmers. Among the techniques tried and tested to improve application efficiency and distribution uniformity is the cut-off irrigation technique which is adopted by most smallholder farmers. The other techniques such as surge and bunds have been largely adopted because these methods are perserved costly to smallholder farmers as they require additional labour for controlling the on and off supply and for making bunds in furrows. In addition the techniques require presence of measuring equipment and able to deliver the varying amounts of water in temporal space as designed.

Studies (Elsheikh *et al*., 2014; Issaka *et al*., 2015; Mohammed *et al*., 2015), have reported lowest figures application and distribution efficiencies in cut-off irrigation technique among the tested techniques. In the cut-off technique, field experience has shown that most of the smallholder farmers apply water up to the end of the furrow or somewhere around 90 percent length of the furrow run before the water is cut off at the head of the furrrow. This practice results into water loss due to runoff and deep percolation. This not only reduces the crop water productivity but also deprives the other users the right to use the resource. Little has been documented on the cut-off method regarding the effect on water saving and productivity when water supply is cut-off with the advance phase reaching various positions along the furrows. This study therefore aimed at investigating the effect of cutoff position on water application efficiency, distribution uniformity and productivity through a field experiment.

1.3 Rationale of the Study

In irrigated agriculture, for so long, emphasis has been on land productivity, that is yield per unit area but it is high time more emphasis should be on water productivity with the ever dwindling of water resources.

There are many campaign messages on the need to adopt water efficient technologies such as drip, sprinkler and centre pivot irrigation systems but their adoption rate among smallholder farmers remains very low mainly owing to their high operational and maintenance requirements. As such surface furrow systems are still highly practiced by resource constrained smallholder farmers. Cutoff technique is in use but is not widely studied to improve water efficient and productivity.

The study findings would provide an opportunity for smallholder farmers on how to improve desirable water application efficiency, distribution uniformity and ultimately maximize production from their fields even without land levelling. The finding would also be a basis for further studies on the area.

1.4 Research Objectives

1.4.1 General Objective

To investigate the effect of varying water application cut off position along furrows on water application efficiency, distribution uniformity and productivity in a furrow irrigated maize field.

1.4.2 Specific Objectives

(i) To estimate the crop water and irrigation requirements for maize crop

(ii) To establish the variations in water application efficiency and distribution uniformity in varying water application cut off position along furrows.

(iii) To establish water productivity in the three irrigation treatments.

1.5 Research Questions

(i) What amounts of water does the maize crop require over its growing season?

(ii) What are the variations in water application efficiency and distribution uniformity in varying water application cut off position along furrows?

(iii) What is the impact on water productivity in the three irrigation treatments?

1.6 Significance of the Study

In irrigated agriculture, for so long, emphasis has been on land productivity, that is production per unit area cultivated, but it is high time more emphasis should be on water productivity with the ever dwindling of water resources (Oweis, 2014). The fast-growing population and improvement in living standards have raised the amount of water demand in industrial and domestic needs, leaving even less water to the agriculture industry. Despite other high water efficient irrigation systems such as drip and overhead sprinklers, smallholder farmers continue to prefer the surface furrow or basin system because of their low operation costs amid cultivation of low value crops.

The study findings will provide an opportunity for smallholder farmers how to improve desirable water application efficiency and distribution uniformity and ultimately maximize productivity from their fields in water-stress environments. The findings would also be a basis for further studies in this field of irrigation water management.

1.7 Delineation of the Study

This research study was carried to investigate effect of varying cut-off positions of irrigation water in furrow system on efficiency, distribution uniformity and productivity. A field experiment was mounted to collect data that was needed for this investigation. Three replications were used to get well balanced data set water applied, water consumed and crop yield.

CHAPTER TWO

LITERATURE REVIEW

For long-term functioning of an irrigation system, improvements in the existing methods of water application and water management practices appear more to be more crucial (Sarwar *et al*., 2001). Efforts have in recent years intensified in identifying and utilization of most efficient water application methods to increase water use efficiency and productivity. At farm level, water application efficiency and water distribution uniformity are the two irrigation performance indicators of water use efficiency and productivity.

Water application efficiency (Ea) is a measure of the portion of the total amount of water delivered to the field that is kept in the crop root zone to meet the crop water requirements (Irmak *et al*., 2011) and usually expressed as percentage. Ea pertains to an individual irrigation event. On the other hand, Water distribution uniformity (WDU) in irrigation is defined as the average infiltrated depth of water in the low quarter of the field divided by the average infiltrated depth over the whole field (Irmak *et al*., 2011; Walker, 1989). The key characteristic of irrigation is uniform distribution of applied water within the entire root zone, as uneven water distribution brings unwanted outcomes such as crop stress and salt accumulation. Both water application efficiency and distribution uniformity affect the crop yields subsequently affecting the overall water productivity. In crop production, water productivity (WP) defines the relationship between crop produced and the amount of water used expressed as a ratio of yield of the crop to the amount of water consumed by the crop in a growing season (Ali & Talukder, 2008). It is expressed as a ratio of crop produce to the amount of water consumed by the crop during its growing season (Molden *et al*., 2010). Water productivity is an important indicator assessing the efficient use of water. It is also a basis for virtual water trading at the global, regional or local level (Liu *et al*., 2007).

2.1 Crop Water Requirements and Irrigation Requirements

Crop water requirement refers to amount of water that should be supplied from the source while crop evapotranspiration is what is released by the crop for tissue growth. The crop water requirement module includes calculations, producing the irrigation water requirement of the crop daily and over the total growing season as variance between the crop evapotranspiration under standard conditions. From the crop coefficient (Kc) and reference evapotranspiration

(ETo), the CROPWAT through the crop module calculates crop evapotranspiration (ETc) through the relationship ETc =Kc x ETo

The Food and Agriculture Organisation (FAO) developed CROPWAT, a software that has been very important tool in coming up with comprehensive crop water requirements and irrigation schedule for a variety of crops. The software uses climate data (temperature, solar radiation, relative humidity, wind speed and sunshine hours) to estimate reference evapotranspiration (ETo), rainfall data, soil water data and crop data.

From the effective rainfall and crop water requirements, the CROPWAT estimates how much water should be supplied though irrigation as irrigation requirements. Should the effective rainfall be equal to or above crop water requirements (typical in wet season), the software indicates no requirement for irrigation.

Several crop water requirements and irrigation schedules have been developed for various crops and various places using different versions of CROPWAT (Adeniran *et al.*, 2010; Kore *et al*., 2017; Nithya *et al*., 2015; Saravanan & Saravanan, 2014).

2.2 Water Use Efficiency and Distribution Uniformity

In furrow irrigation, furrow characteristics (length and slope), irrigation technique (cut-back, bunds, surge and cut-off), soil conditions, crop type and weather conditions all affect water application efficiency and distribution uniformity and subsequently water productivity.

2.2.1 Varying Furrow Length

Several studies have conducted studies on the effect of furrow length have found varying but comparable results. Assefa *et al*. (2017) found the average DU of 88.15%, 86.28%, and 85.33%, for furrow lengths of 100 m, 150 m, and 200 m respectively indicating longest furrows had lowest DU and vice versa for the furrow length as a standalone varied parameter. Manabaev *et al*. (2015) reported that varying furrow length between 100 m and 200 m had resulted in distribution uniformities ranging 0.5 to 0.7 which on the contrary indicates that with longer furrows had higher DU with a loss of crop yields ranging from 2% to 15%. Similar findings were reported by Feyen and Zerihun (1999).

Another study conducted by Mekonen (2006) found out the average application efficiency of 40.46%, 33.6% and 28.9% for furrow lengths of 50 m, 35 m and 24 m, respectively. As for the irrigation distribution uniformity 99.2%, 86.9% and 93.35% were achieved for the 50 m, 35 m and 24 m furrow lengths, respectively. Similarly, Eshetu (2007) found higher application efficiencies for 40 m furrows followed by 25 m furrows and finally lowest efficiency was for the 10 m furrows.

The studies, which have found the lower application efficiencies and distribution uniformities for longer furrows, all have attributed to the fact that for the longer furrows water takes longer time to reach the lower end of the furrow and hence the water tends to infiltrate into deep zone in the upper section of the furrow or furrow head. On the other hand, the treatments which had combined parameters of furrow length and flow rates, higher efficiencies and uniformities ware found in longer furrow length supplied with higher flow rates because with higher flow rates water tend to move faster along furrows and thereby taking lesser time to reach the far lower end of the furrow(s). This means that the infiltration opportunity time is closer along the furrow(s) and thereby making it possible to achieve a higher distribution uniformity. In shorter furrows higher flow rates would result in increased runoff loses which would reduce the application efficiency and distribution uniformity. These studies however do not specify the length of furrow that gives optimum productivity even for respective crops they were conducted on. In addition, from experience, farmers make furrows to cover full plot size (maximizing land productivity) hence varying furrow length may not be an option that could be easily adopted. Also, if shorter furrow lengths are adopted for a bigger field, it means having more sub-fields with independent feeder canals for the same size of field to supply water as demonstrated in Fig. 1.

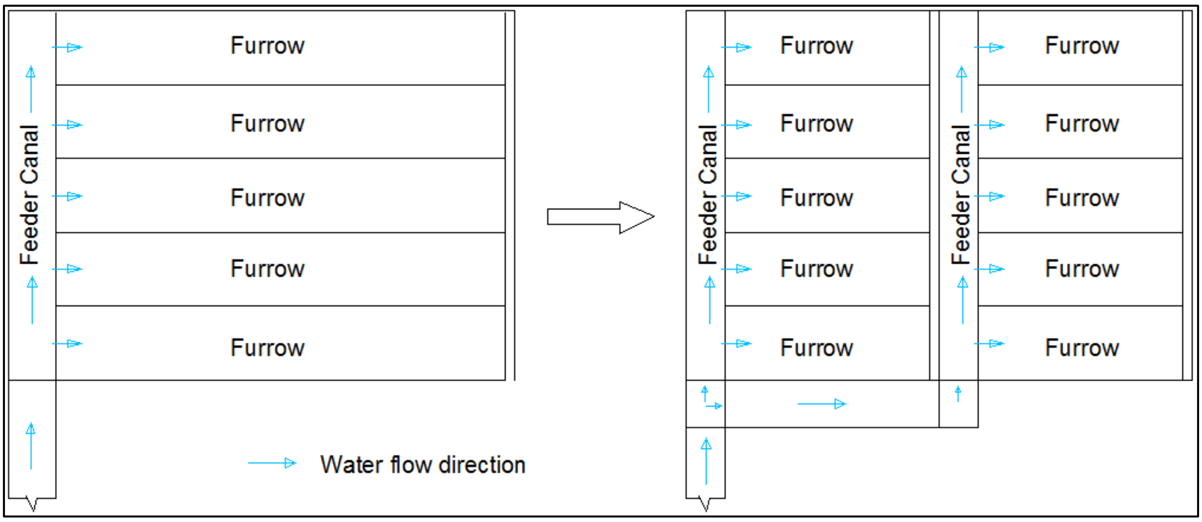


Figure 1: Typical modifications made to accommodate shorter furrows, which have better water distribution uniformity

This could not only mean more developmental costs as well as increased periodic operation and maintenance costs to sustain the system but also reducing the net area for production as more canal and drainage networks take away some area. Therefore, shortening the furrow lengths may not be an obvious option without considering the cons described herein.

2.2.2 Slope Modification (Land Levelling)

Assefa *et al*. (2017) investigated and concluded that water distribution uniformity showed an increasing trend as longitudinal slope of the furrow increased. The distribution uniformity ranged from 85.9% to 87.4% for corresponding range of longitudinal furrow slopes of 0.05% to 0.1%.

This was so because as the slope increases the advance phase become faster and the infiltration opportunity time (IOT) become more uniform. This increased uniformity of IOT leads to improvement of DU. Faster movement of applied water on greater slope values has on the other hand a possibility of causing non-uniform distribution of nutrients including fertilizers which could be washed away to the lower ends of the furrow(s). Land leveling plays a contributing factor in the performance of surface irrigation as it helps making land surface even, promoting uniform infiltration distribution, thus leading to more uniform crop growth (Li *et al*., 2001; Öztekin, 2013; Pereira *et al*., 2007; Savva & Frenken, 2002b). Land leveling provides for substantial decrease of the irrigation advance time and water required (Miao *et al*., 2017). The process of land leveling in most cases is beyond manual labour and therefore requires mechanical equipment. The cost of such mechanical land leveling is quiet substantial, requires skilled operators (Miao *et al*., 2017) and is therefore well beyond the capacity of smallholder farmers. Even donor funded irrigation development projects do not factor in land leveling for the high costs reason.

2.2.3 Varying Flow Rate

Assefa *et al*. (2017) found water distribution uniformity of 88.76%, 87.14% and 84.03% for 6 litres/second, 5 litres/second and 4 litres/second, a general increasing trend with increase in flow rate for the same reason that with the higher flow rates water tend to move faster along furrows and thereby taking lesser time to reach the far lower end of the furrow(s). This means that the infiltration opportunity time is closer along the furrow(s) and thereby making it possible to achieve a higher distribution uniformity. Similarly, Mekonen (2006) found out that the application efficiency values of, 36.9%, 32.8% and 32.9% for the flow rates of 0.5

litres/second, 0.4 litres/second and 0.3 litres/second respectively.

However, maintaining constant supply in furrow irrigation can be challenging considering that most water conveyance canals have no permanent water measuring structures or devices. In addition, the canals are usually in bad shape due to lack of maintenance and this could result in losses of water even after passing the measuring devices.

2.2.4 Surge, Bunds, Cut-backs and Cut-off Irrigation Techniques

Surge, Bunds, Cut-backs and cut-off are some of the techniques used in furrow irrigation with the objective of increase irrigation efficiency. Surge flow is applying water in a series of individual pulses with each surge defined by a cycle time (on time and off time). Bunds are strips made at some interval along the furrow designed to lengthen the contact time between applying the water and infiltration. Cut-back principle is based upon applying an initial large but non eroding flowrate which can reach the lower end of the furrow in a short time, then the inflow is reduced as close as possible to a stream size equal to the infiltration rate of the furrow. For a cut-off irrigation technique, the practice is to stop flow when the advance wetting phase reaches a certain percentage of the furrow length.

The study by Elsheikh *et al*. (2014) which investigated on furrow lengths of 250 m, 500 m and 750 m found the highest application efficiency of 74% in surge flow, and the lowest application efficiency of 59% in cut-off technique for the 250 m furrows. For the 500 m furrows, surge method recorded the highest application efficiency of 79% with cut-off method registering the lowermost application efficiency at 42%. In the 750 m furrows surge, cut back, cut-off techniques and bunds yielded 62%, 52%, 47% and 36% respectively. In terms of distribution uniformities for the four techniques, 250 m furrow registered almost an equal uniformity of 94%, 93% 92% and 89% for the surge, bunds, cut-back and cut-off technique respectively. For the 500 m furrows, cut back and surge techniques registered same uniformity of 93%, cut-off gave 80%, while bund technique recorded 91%. Lastly, for the 750 m furrow, surge gave the highest uniformity of 94% while cut-off registered the lowest uniformity of 76%.

In another study by Mohammed *et al*. (2015) the highest application efficiency of 82% was achieved with surge irrigation technique followed by bund at 64%, cut-back at 49% and cutoff at 32% respectively. Outcomes of distribution uniformity indicated the highest was for surge technique at 98% and then the cut-back (95%), bund (92%), and finally cutoff at 90% respectively.

From these studies it is evident that the cut-off method gives the lowest application efficiency, distribution efficiency and subsequently productivity. However, in other methods which reported improved application and distribution efficiencies in surge and bunds/microdam, the methods require additional labour for controlling the on and off supply and for making bunds in furrows which usually become erodible after each irrigation event. As such the methods are not extensively adopted by smallholder farmers practicising furrow irrigation. This aimed at investigating three scenarios for the cut-off irrigation technique to improve water application efficiency, distribution uniformity and overall water productivity.

2.3 Crop Water Productivity

Crop water productivity is the measure of crop yield realized per amount of water consumed by the crop in a growing season. Crop water productivity can also be defined and expressed in monetary terms as economic return from crop produced per volume of water, expressed in units of any currency equivalent, for example TZS/m3 (Igbadun *et al*., 2006).

Increasing water productivity in the agricultural sector, helps not only increase crop production, but it also ensures that water is made available to other uses in the awake of water shortage globally (Letseku & Grové, 2022).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The field experiment was carried out at Lekitatu Irrigation Scheme located in Meru district, Arusha Region, Tanzania (Fig. 2). The scheme lies between latitudes 3°23'03.8" and 3°25'50.9" S, longitudes 36°50'03" and 36°51'50.5" E, and at an average altitude of 1110 m above mean sea level. The climate is categorized as semi-arid, with mean annual evaporation of 6.03 mm/day, with average annual rainfall of 816 mm and a mean annual temperature of 22.4°C. The main source of water for the scheme is the Meru Mountains; the study area receives a lot of runoff generated in these highlands which, relatively receive higher amounts of rainfall.

Mains crops grown in Lekitatu Irrigation Scheme include paddy, maize, beans and vegetables. Maize crop was chosen for this study after discussion with plot owner and also taking into account that maize is usually grown in furrow system. The average yield for maize crop in Lekitatu is around 2 tonnes per hectare.

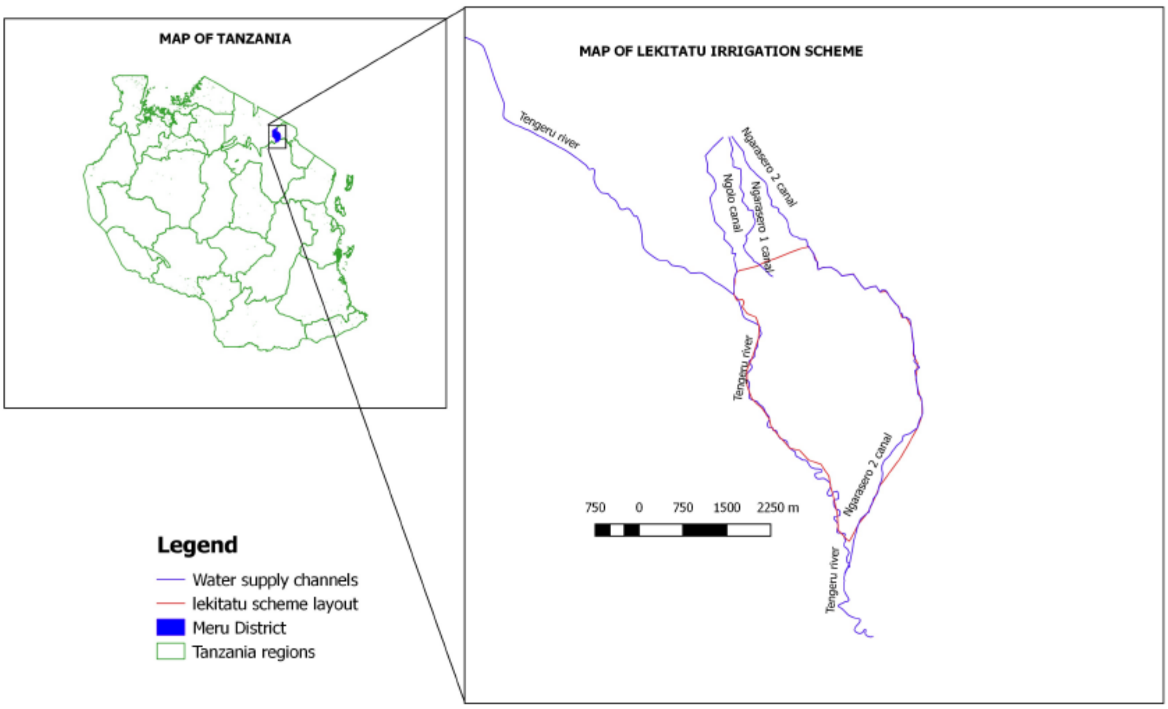


Figure 2: Country and region location of study area

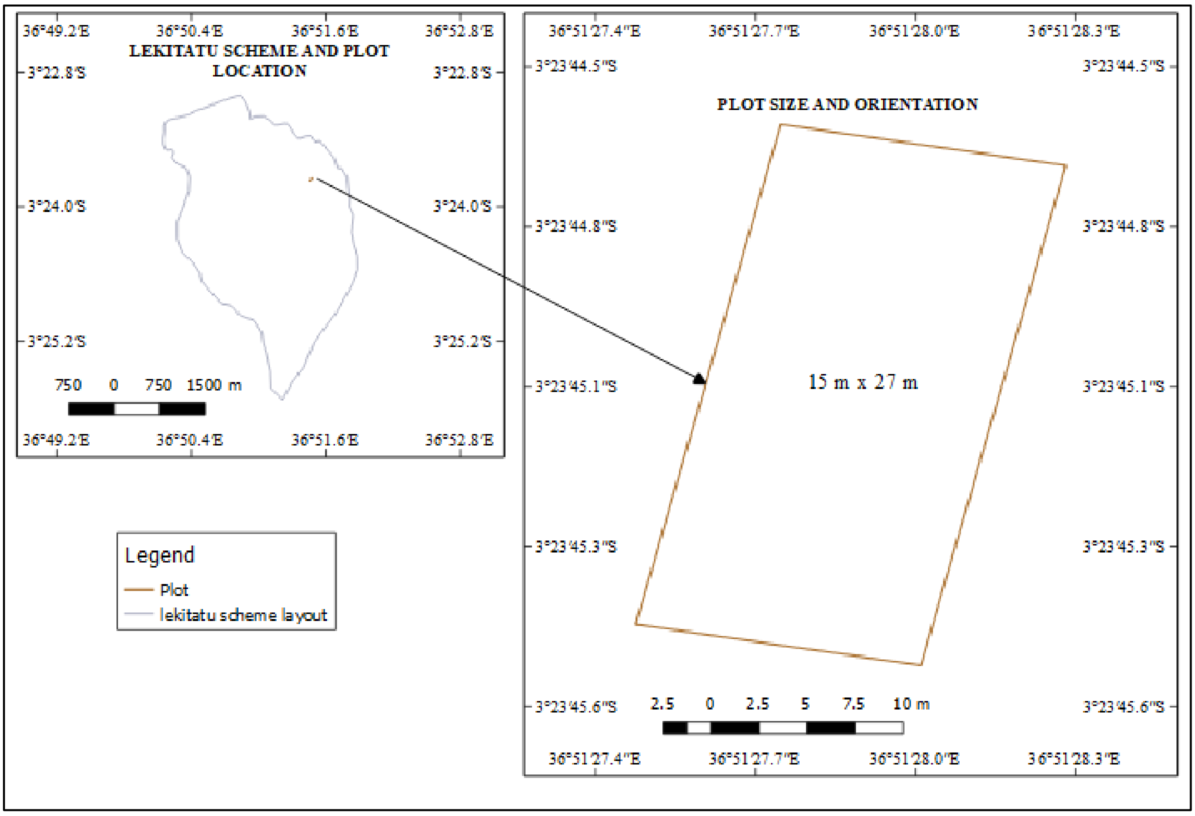


Figure 3: Size and location of experimental plot in Lekitatu Irrigation Scheme

3.2 Methods

3.2.1 Plot Selection and Layout

The experimental plot (Fig. 3) was set up in line with the orientation of major and minor slopes to achieve best water delivery. The parameter treated was the position of advance phase of the water applied along the run of furrow before stopping water supply at the furrow head. There were three replica sub-plots (Fig. 4) with similar characteristics such as soil type/properties, slope and climatic conditions. Within each sub-plot, there were three furrow sets consisting of five furrows each. In each furrow set, the inner three furrows were used for monitoring irrigation events and the two outer furrows acted as buffers. A V-notch weir was installed at the head of the feeder canal, just before the water reaches the experimental plot, to measure incoming flow rate. At the end of the last furrow in each furrow set, a hole was dug out for surface run-off collection.

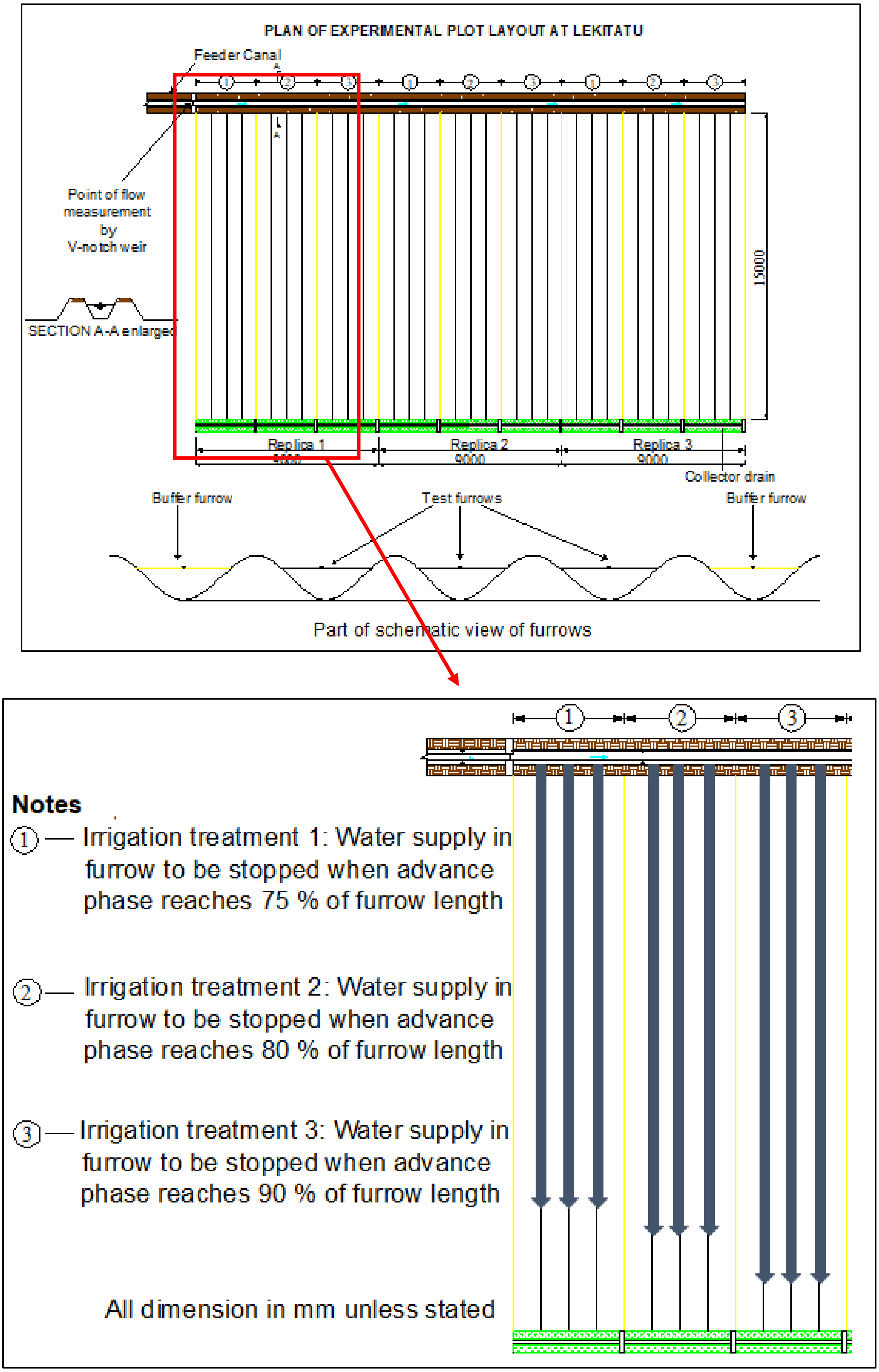

PLAN OF EXPERIMENTAL PLOT LAYOUT AT LEKITATU
Feeder Canal
Point of flow measurement by V-notch weir
SECTION A-A enlarged
15000
Replica 1
Replica 2
9000
Replica 3
9000
Collector drain
Buffer furrow
Test furrows
Buffer furrow
Part of schematic view of furrows
Notes
1 — Irrigation treatment 1: Water supply in furrow to be stopped when advance phase reaches 75 % of furrow length
2 — Irrigation treatment 2: Water supply in furrow to be stopped when advance phase reaches 80 % of furrow length
3 — Irrigation treatment 3: Water supply in furrow to be stopped when advance phase reaches 90 % of furrow length
All dimension in mm unless stated

Figure 4: Experimental plot layout

3.2.2 Collection of Topographic, Soil and Climate Data

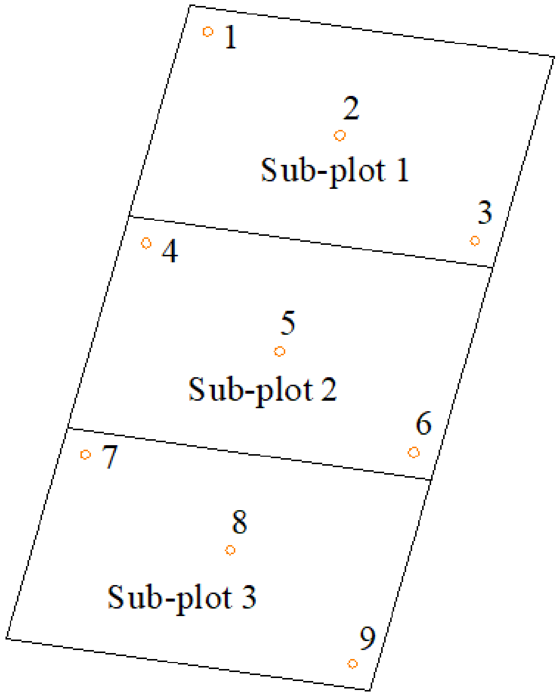
(i) Topographic Survey

The topography of the area was established by use of hand-held GPS for x and y coordinates while dumpy level was used to measure the elevations. A measuring tape obtained the horizontal distances. The purpose was to establish two slopes, one being the slope running from top to lower end of the plot along which the feeder canal was aligned and the other along which the furrows would run receiving water from the feeder canal.

(ii) Soil Sampling

Before land preparation, 9 stations were located for soil sampling, 3 in each sub-plot. Soil samples were taken using soil augers at each of the 9 established sampling stations, 3 in each of the sub-plot (Fig. 5). This number was more than enough for this 405 m^2 experimental plot as for irrigation projects at least 3 stations per hectare (ha) are adequate (Savva & Frenken, 2002a) Three samples were taken from each pit at the depths of 0-30, 30-60 and 60-100 cm (Fig. 6) thereby covering the entire effective root zone for maize crop (Savva & Frenken, 2002a). The samples were then transported in sealed plastic bags for laboratory analysis. Samples from corresponding depths for the pits in a sub-plot were mixed to form composite sample for the particular depth(s) and then re-sampling was done for sieve analysis.

Samples for measurement of bulk density were the undisturbed ones collected from the same pits where samples for other analysis such as particle size distribution, pH and EC were obtained.



Location of soil sampling points		
Soil sampling point	Coordinates (UTM)	
	Easting	Northing
1	262020.0164	9624406.1309
2	261957.9393	9624406.8415
3	262034.9436	9624397.5852
4	262021.5162	9624397.4851
5	261995.4718	9624398.029
6	262032.4434	9624388.9395
7	262019.0160	9624388.8394
8	261953.4582	9624389.8716
9	262029.9433	9624380.2937

Figure 5: Soil sampling positions in the experimental plot

Figure 6: One of the pits for soil sampling

(iii) **Laboratory Analysis of Soil Samples**

Soil texture was determined through sieve analysis using standard operating procedure based on ASTM 422-63, Standard Test Method for Particle Size Analysis of Soils. An average of 100 g of air-dried soil re-sampled from composite sample of each depth was passed through and separated through a series of sieves ranging from 2 mm to 15 µm openings, decreasing in opening sizes from the top to the bottom. Particle size distribution was determined by weighing the material retained on each of the sieves and dividing these weights by the total weight of the sample. The results of the analysis were interpreted using the United States Department of Agriculture (USDA) textural triangle.

Bulk density was estimated by the core method (Fig. 7) also known as the volumetric cylinder method (Al-Shammary *et al*., 2018; Ali, 2010; Yang *et al*., 2016; Zolfaghari *et al*., 2016) summarised in Fig. 7.

Through standard laboratory procedure, soil pH was measured by pH meter, after the meter had been calibrated with prepared standard buffer solutions of pH 4, 7 and 9.2. 20 g of air dried and sieved soil from each sample was put in a beaker and 40 ml. of distilled water was added. The soil/water mixture was stirred for 30 seconds and then waited for 3 minutes for a total of 5 stirring/waiting cycles. The mixture was then allowed to settle until a supernatant was formed above the settled soil. The pH meter electrodes were then dipped into the supernatant and the displayed value on the meter was monitored until it stabilized. The stabilized value was then recorded as the pH for the particular sample and soil. This procedure was repeated for all other samples. Following the same procedure as in soil pH determination, soil EC was measured by conductivity meter after it was calibrated pH 4 and pH 7 buffer solutions. Both the pH and EC affects water movement in the soil as the dissolved ions occupy pore water spaces (Visconti & de Paz, 2016)

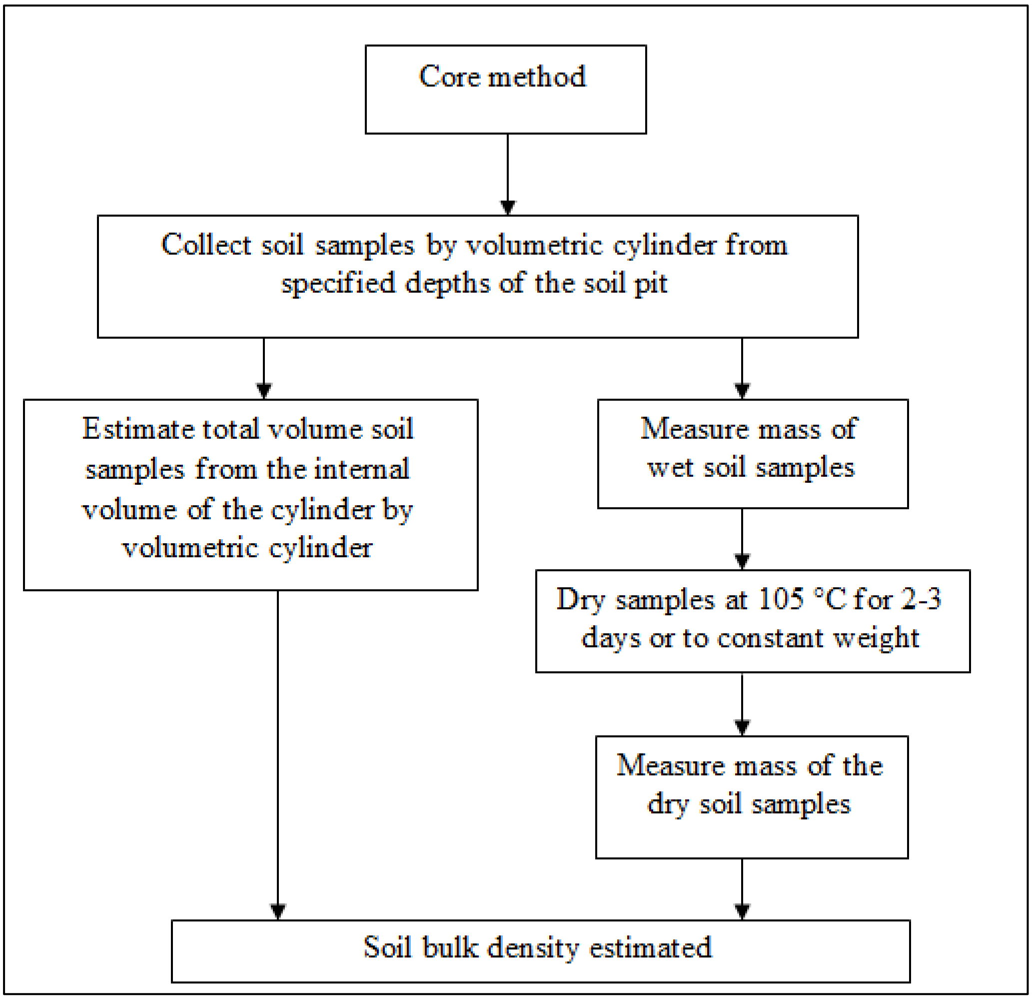
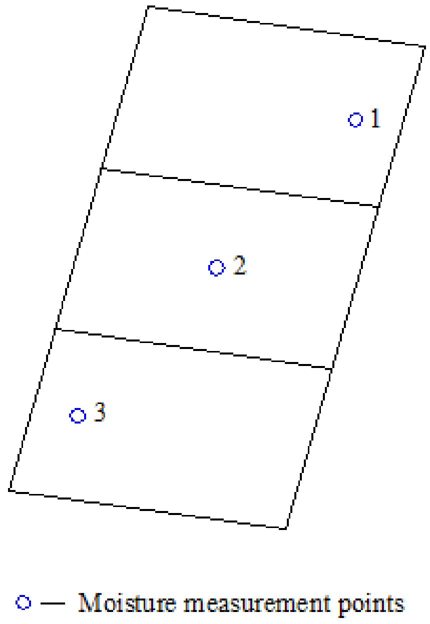


Figure 7: Flow Chart - Core method for bulk density measurement

(iv) **Measurement of Initial and Subsequent Soil Moisture Levels**

Initial soil moisture for the root zone was measured concurrently with the bulk density. Moisture content before and after each irrigation event was measured for the entire irrigation season. One sample from each of the depths 0-30, 30-60 and 60-90 cm was taken in each of the three sub-plots (Fig. 8). For continuity of data, observations were maintained at the same locations as much as possible for the whole season. The samples were weighed before being oven dried for 24 hours or to a constant weight at 105°C to a constant weight (Al-Shammary *et al*., 2018; Savva & Frenken, 2002a)



Location of soil moisture measurements		
Point	Coordinates (UTM)	
	Easting	Northing
1	262034.4307	9624401.1576
2	262026.9798	9624393.2123
3	262019.5290	9624385.2670

Figure 8: Moisture measurement locations

The soil moisture was then calculated using the following relationship (Savva & Frenken, 2002a):

$$M_c = \frac{W_w - W_d}{W_d} \times 100 \qquad \text{Equation 1}$$

Where M_c is the soil moisture content (%)

W_w is the weight of wet soil before oven drying (g)

W_d is the weight of dry soil after oven drying (g)

Figure 9: Oven drying of soil samples for moisture content and bulk density

(v) Climate and Weather Data

Historical climatic data (rainfall, temperature, relative humidity, solar radiation and wind speed) for Lekitatu spanning 32-year (1985-2017) (03°23'15.6"S latitude, 36°50'51.9"E longitude and 1162 m amsl altitude) was downloaded from Nasa power data base (https://cds.nccs.nasa.gov/data/). Current data (2019) was obtained from Lekitatu weather station installed in the area to serve the experiments taking place within the vicinity including this experiment.

3.2.3 Estimation of maize crop water and irrigation water requirements

Crop water requirements, which refer to water required for crop cell development and transpiration, were calculated using the CROPWAT 8.0 software (which is based on soil water balance) by inputting data for the study area.

(i) Estimation of ETo from Climate Data

As ETo is the evaporating capacity of the atmosphere, it is affected by climatic factors and not necessarily by soil and crop characteristics (Kore et al., 2017). From inputted climate data (minimum and maximum temperature, relative humidity, wind speed and sunshine hours), CROPWAT calculated the ETo. The software uses the Penman-Monteith relationship embedded within the software which combines the mass transfer and energy balance methods.

(ii) Estimation of Effective Rainfall

Effective rainfall was calculated from the monthly rainfall data using the USDA Soil Conservation Method embedded within the CROPWAT software.

(iii) Crop Data Input

Data for crop, maize in this case, included crop planting dates, the crop coefficient (Kc), duration, rooting depth, allowable soil moisture depletion levels and yield response factors (Ky) at the various growth stages of the crop (initial, mid and late). Global values as outlined in FAO (1998a) and Doorenbos and Kassam (1986) were used as crop data with the length of growth stages adjusted to suit local conditions.

(iv) Soil Data Input

The soil water characteristics were obtained from the soil analysis and the parameters such as readily available moisture (which is the difference between the moisture at field capacity and wilting point), infiltration rate, maximum rooting depth and initial depletion levels.

(v) Estimation of Crop Water and Irrigation Requirements

After the input of all above data, the CROPWAT then calculated the crop water requirements for the maize crop. The programme assumes all months have 30 days subdivided into three decades of 10 days each, and the crop water requirements are calculated on a decade (10-day) basis. The crop water requirement module includes calculations, producing the crop water requirement of the crop daily and over the total growing season as variance between the crop evapotranspiration under standard conditions. From the crop coefficient (Kc) and reference evapotranspiration (ETo), the CROPWAT through the crop module calculates crop evapotranspiration (ETc) through the relationship ETc =Kc x ETo.

From the effective rainfall and crop water requirements, the CROPWAT estimates how much water should be supplied though irrigation. Should the effective rainfall be equal to or above crop water requirements (typical in wet season), the software indicates no requirement for irrigation.

3.2.4 Measurement of Water Application Efficiency and Distribution Uniformity

(i) Planting and Irrigation Management

Before planting the entire plot was supplied with initial water, which, solely was for wetting purposes as a common practice with the quantity of water supplied recorded. After 24 hours, maize seed was planted as per recommended practice. With the furrows or rows spaced at 75 cm apart, the seeds were planted at the recommended population and spacing of one seed per hole and 30 cm between holes along each row respectively.

All the sub-plots received water from the same water source and feeder canal. The quantity irrigation water conveyed to the experimental plots per unit time was measured using a 90^{o} V – notch weir (Fig. 10). The discharge through the weir is a function of water level, so water level above the crest of the weir was measured using staff gauge. The discharge through a v-notch weir is given using the following relationship (Henderson, 1996):

$$Q = \frac{8}{15} C_d H^{5/2} \sqrt{2g} \tan\frac{\theta}{2}$$ Equation 2

where Q is the quantity of irrigation water (m^3/s),

H is the height of water above the weir crest (m),

θ is the vertex angle of the weir crest (degrees),

C_d is the coefficient of discharge (unit less)

g is the acceleration due to gravity (m/s^2).

Just before the point of discharge measurement, a stabilizer/energy dissipating ditch was excavated to facilitate the control and measurement of the incoming discharge.

Figure 10: Set up on the field - replicated plots (left) and V- notch weir for flow observation and control (right)

The first two irrigation events, water was applied equally to all the three treatments for seedlings establishment. Thereafter, eight irrigation events were applied to the three treatments. In the first treatment (sub-plot 1 or replica 1), water supply at the head of the furrows was stopped when the advance phase reached 75% of the furrow length. For the second treatment, the supply was stopped with the advance water reaching 80% of the furrow length. Finally, in the third treatment water supply was stopped when the advance phase reached 90% of furrow length and this generally complies with the local practice in the study area. Time taken to complete irrigating each plot was recorded to help calculate total amount of water applied to each plot. Soil moisture depletion levels were monitored through local practice and gravimetric measurements to determine next irrigation event.

(ii) Measurement of Water Application Efficiency

The field water application efficiency was calculated from the following relationship (Issaka *et al*., 2015):

$$E_a = \frac{W_{rz}}{W_f} \times 100 \qquad \text{Equation 3}$$

Where:

E_a = water application efficiency as percentage.

W_{rz} = amount of irrigation water stored in the root zone after irrigation (mm)

W_f = total amount of irrigation water delivered to the farm (mm).

Amount of water stored in the root zone was determined through conducting water balance whereby components such as deep percolation, runoff were taken out of the equation to calculate the water remaining in the root zone, part of which, is responsible for the crop evapotranspiration as indicated in this relationship (Savva & Frenken, 2002b)

$$W_{rz} = I + R_{eff} - D_{per} - S_{run} \qquad \text{Equation 4}$$

Where I = the amount of irrigation water applied that remains in the effective root zone (mm)

R_{eff} = effective rainfall (mm)

W_{rz} = amount of irrigation water stored in the root zone during irrigation and/or rainfall event (mm)

D_{per} = water loss out of the effective root zone due to deep percolation (mm) and depend on the permeability of the soil

S_{run} = soil surface runoff dependent on infiltration rate of the soils and surface slope (mm)

The V-notch flow rate and the duration of the irrigation were used to calculate the total amount of water applied (Abd El-Halim & Abd El-Razek, 2014) using the following formula:

$$d = Qt \times \frac{1000}{A} \qquad \text{Equation 5}$$

where d is the amount of water (mm), Q is the discharge over the V-notch (m^3/min), t is the time (min) taken to fully irrigate plot of area A (m^2).

Surface runoff (S_{run}) was measured by dug out located at the end of each furrow set. The hole was lined inside with a polythene sheet to prevent water percolation. The collected water was converted into mm depth covering each furrow set by the following conversion:

$$S_{run} = V_{sr} \div A \qquad \text{Equation 6}$$

Where S_{run} = soil surface runoff (mm)

V_{sr} = volume of surface runoff collected in dug out (litres)

A = area of the furrow set (m^2)

Deep percolation (D_{per}) was measured using the soil moisture probe, subtracting the depth of water that went beyond the root zone depth at each growing stage of the crop. And the relatively high water holding capacity of the soils, deep percolation was almost negligible as all the waters remained within the root zone.

On each rainy day, rainfall amount was recorded by automatic weather instrument installed within the study area. Effective rainfall was then calculated following the USDA Soil Classification Method.

(iii) Measurement of Water Distribution Uniformity

In order to find actual depth of infiltrated water, within 24 hours after each irrigation event, water depth measurements were taken at 9 locations in each furrow set. The depths of infiltrated water were measured by use of the manually fabricated soil moisture probe based on New Mexican State University Guide H-637. PH 4-206 “A Practical Way of Measuring Soil Moisture” and the September 2014 Primefact 1351 second edition by the NSW Department of Primary Industries “Making a soil moisture probe” as shown in Fig. 11. Measuring the depth uses the principle that the probe penetrates easily through the wetted soil profile but finds resistance when it reaches dry soil. The number of graduations penetrated into the soil before meeting resistance was counted. The in-between readings were confirmed with a measuring tape. The Distribution Uniformity was then calculated by applying the lower one-quarter principle in equation 7 as described by Walker (1989) and Irmak *et al*. (2011).

$$DU = \frac{D_{lp}}{D_{av}} \times 100 \qquad \text{Equation 7}$$

where DU = distribution uniformity (%)

D_{lp} = average depth of water infiltrated in the lower one quarter of the field (mm)

D_{av} = average depth of water infiltrated over the field (mm)

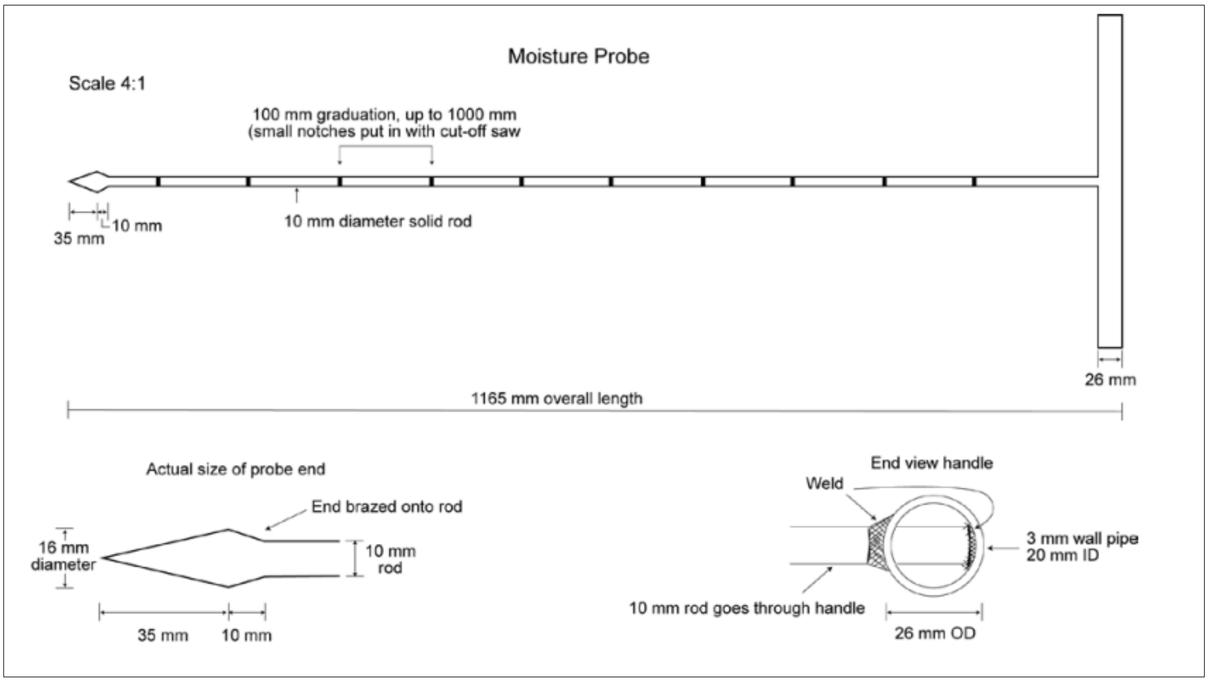


Figure 11: Manually fabricated soil moisture probe as per NSW Department of Primary Industries specifications

3.2.5 Measurement of Water Productivity

Water productivity (WP), was calculated according to Rodrigues and Pereira (2009) as follows:

$$WP = \frac{GY}{A_w} \quad \text{Equation 8}$$

where WP is the water productivity (to be measured in kg/m^3), GY is the grain yield (to be measured kg/ha) and A_w is the total amount of water consumed (m^3/ha).

The yield was estimated for both plots through measurement of the dried maize cobs. The grain from the cobs was weighed using an electronic scale. Then the results were extrapolated to represent production per hectare in each case. Total amount of water on the other hand was found by doing water balance for the root zone after each irrigation event during the entire growing season as follows (Allen *et al*., 1998):

$$\sum ETc = \sum ETo \times Kc \quad \text{Equation 9}$$

Where ETc = the amount of irrigation water applied that is taken up by the plant roots and transpired through the leaves (mm)

ETo = amount of that goes into the atmosphere due to crop transpiration and surface evaporation (mm)

Kc = crop factor

The total amount applied in m^3 was found by converting the amount in millimetres into metres and then multiplying the total area of the irrigated field in m^2.

3.2.6 Data Analysis

To check for standard error, significance among others, the results were put to statistical analysis, multiple comparisons by applying the Tukey Post hoc test on one-way ANOVA at 95% confidence level. SPSS software was used in the statistical analysis.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter presents findings on physical and climatic properties of the study area, water application efficiencies and distribution uniformities achieved as well as the water productivity for the research. Detailed experiment data is further provided in Appendix 2 and Appendix 3.

4.1 Physical Characteristics of the Study Plot

4.1.1 Topography

Topographic survey established slopes in each plot, one being the average slope of 3.3% running from top to lower end of the plot along the feeder canal and the other was 2.59 % along the furrow runs (Fig. 12)

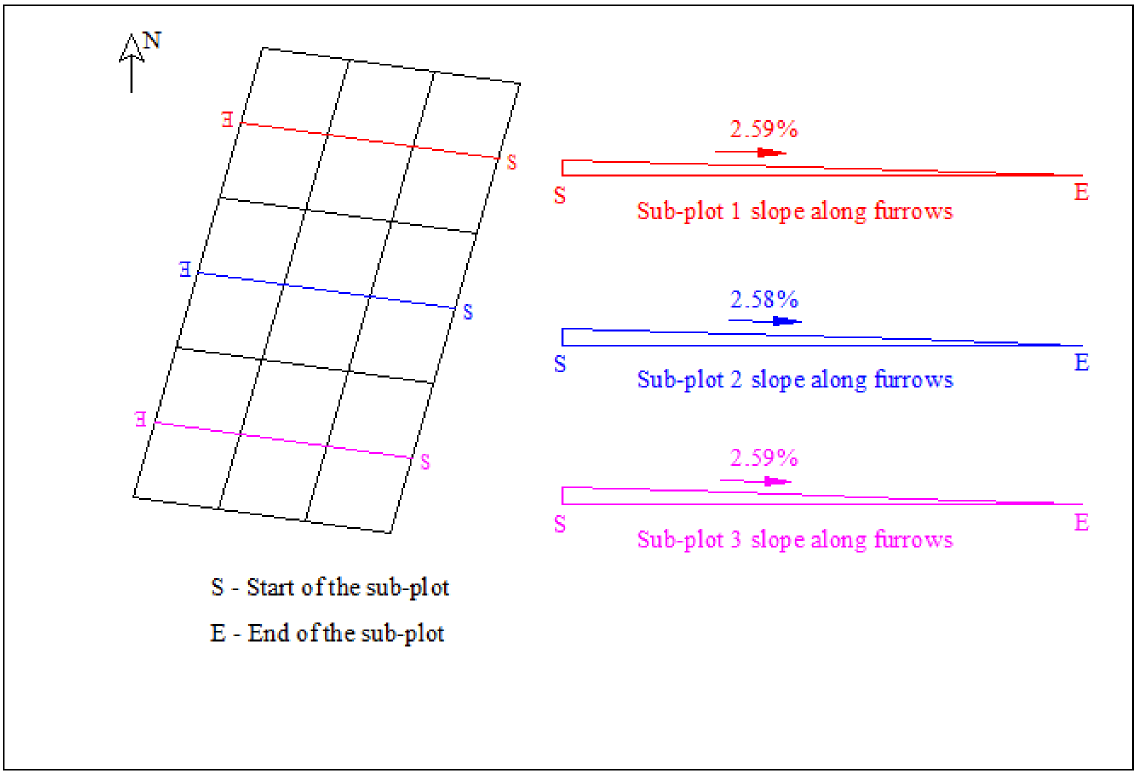


Figure 12: Topographic slopes for the experimental plot

4.1.2 Soil Properties

Table 1 summarizes results for the analysis of key physical properties of the soil in the experimental plot. From the results of particle size distribution and with reference to the

USDA soil textural triangle, all the three sub-plots had sandy loam soils up to the depth of 100 cm investigated. For sandy loam soil, moisture content at FC and PWP is 21% and 9 % respectively giving readily available moisture of 12%, and the infiltration rate is 33.5 mm/hr (Savva & Frenken, 2002b)

Table 1: Selected physical and chemical properties of soil in the study plot

Sub-plot No.	**Sampling depth, cm**	**Physical properties of plot soils**						
		Particle size distribution (%)		**Texture class**	**Bulk density** (g/cm^3)	**EC** (dS/m)	**pH**	**Initial Moisture Content** (%)
		Sand	**silt**					
1	0-30	69.0	30.7	Sandy loam	1.38	0.198	7.08	15.3
	30-60	68.6	31.1	Sandy loam	1.45	0.200	7.06	14.7
	60-100	68.6	31.2	Sandy loam	1.42	0.197	7.09	14.9
2	0-30	69.2	30.5	Sandy loam	1.39	0.198	7.07	15.0
	30-60	69.2	30.5	Sandy loam	1.45	0.199	7.02	14.5
	60-100	68.4	31.4	Sandy loam	1.41	0.197	7.06	14.6
3	0-30	69.9	29.9	Sandy loam	1.39	0.198	7.07	15.0
	30-60	70.0	29.8	Sandy loam	1.45	0.199	7.06	14.5
	60-100	68.4	31.4	Sandy loam	1.40	0.197	7.06	14.6

4.2 Soil Moisture Monitoring during the Experimental Period

The monitoring of soil moisture shows the water contents before and after each irrigation event were almost the same in all the three subplots oscillating between FC (21%) and PWP (9%) as indicated in Fig. 13.

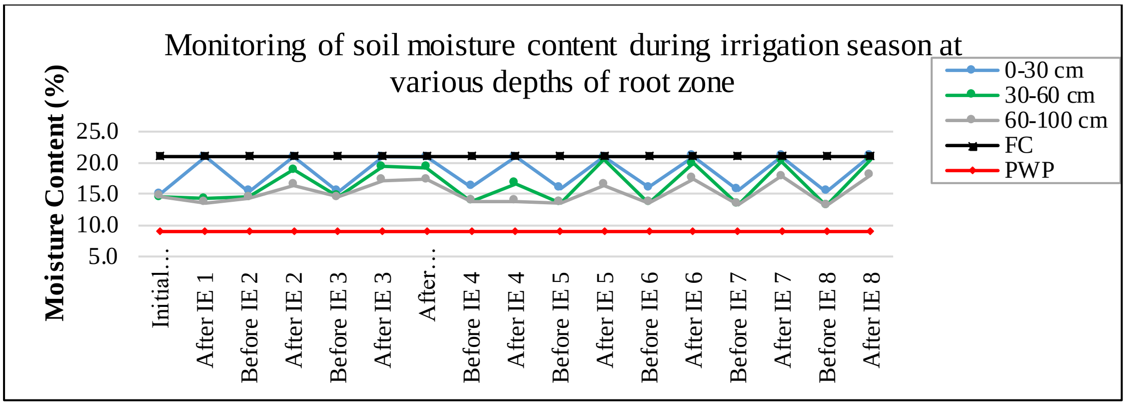


Figure 13: Monitored moisture content information from Table 4 presented in graphic form

4.3 Crop Water and Irrigation Requirements

As a safety net, the CROPWAT climate and rainfall data (Table 2) were used to calculate crop water and irrigation requirements (Fig. 14) as values for ETo were higher than those from the Enku method. Data measured on site by the installed weather station were incomplete (Table 3) and were just used to validate some of the parameters like temperature, and rainfall from the historical data. The validation showed considerable variations in solar radiation, wind, and relative humidity, while for temperature, the data from the two sources were almost the same.

The water and irrigation requirements were adjusted in the field depending on the prevailing rainfall events and initial soil moisture conditions. The calculated crop water and irrigation requirements for the maize crop on a decade (10-day) basis are shown in Table 4. Details of CROPWAT simulations are given in Appendix 1.

Table 2: Long-term climatic data and calculated ETo and effective rainfall for Lekitatu

Month	Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (/s)	Sunshine (hrs)	Radiation (MJ/m²/day)	Rain (mm)	ETo[a] (mm/day)
January	15.2	30.9	56.0	2.1	12.1	28.0	51.5	6.1
February	15.4	31.9	52.0	2.0	12.1	28.6	45.7	6.4
March	16.0	31.8	56.0	1.9	12.0	28.4	113.5	6.2
April	16.0	29.7	66.0	2.0	12.0	27.2	263.5	5.6
May	14.1	28.2	68.0	2.4	11.5	24.7	115.1	5.0
June	12.3	28.0	61.0	2.6	11.5	23.7	16.9	5.0
July	11.7	28.2	54.0	2.9	11.5	24.1	7.2	5.4
August	12.6	29.6	50.0	3.0	12.0	26.3	6.3	6.2
September	13.9	31.6	45.0	3.0	12.0	27.8	10.5	6.9
October	15.1	32.4	46.0	2.8	12.1	28.4	25.5	7.1
November	16.2	31.2	56.0	2.4	12.1	28.0	82.3	6.3
December	15.8	30.6	59.0	2.3	12.2	27.8	78.1	6.1

Table 3: Weather data measured by the installed automatic weather station

Measurement Date	Min Temp (°C)	Max Temp (°C)	Relative Humidity (%)	Wind (m/s)	Solar radiation (W/m^2)	Rainfall (mm)
May	16.2	30.1	90.5	0.4	129.0	280.8
Jun	12.7	28.0	83.5	0.4	122.0	2.3
Jul	9.8	29.1	77.1	0.5	159.3	0.9
Aug	13.1	29.7	76.6	0.5	177.7	21.0
Sep	13.0	30.4	70.3	0.6	230.6	0.0
Oct	17.6	31.1	84.0	0.6	205.6	313.3
Nov	17.9	32.2	81.0	0.6	230.7	79.9
Dec	14.6	31.7	85.0	0.6	204.6	118.7

Table 4: Estimated crop water and irrigation requirements for maize in the study plot

Month	Stage	Kc (coeff)	ETc (mm/day)	ETc (mm/dec)	Eff rain (mm/dec)	Irr. Req. (mm/dec)
Aug 1-10	Init	0.7	4.1	33.1	1.6	31.1
Aug 11-20	Init	0.7	4.3	43.0	1.9	41.2
Aug 21-30	Dev	0.8	5.0	54.7	2.4	52.3
Sep 1-10	Dev	1.0	6.5	64.7	2.7	62.0
Sep 11-20	Dev	1.2	8.0	80.0	3.0	77.1
Sep 21-30	Mid	1.3	8.8	87.7	4.7	83.0
Oct 1-10	Mid	1.3	8.8	88.2	5.5	82.7
Oct 11-20	Mid	1.3	8.9	88.7	6.6	82.1
Oct 21-30	Mid	1.3	8.6	94.3	12.3	82.0
Nov 1-10	Mid	1.3	8.3	82.8	20.2	62.6
Nov 11-20	Late	0.9	5.8	57.9	26.2	31.7

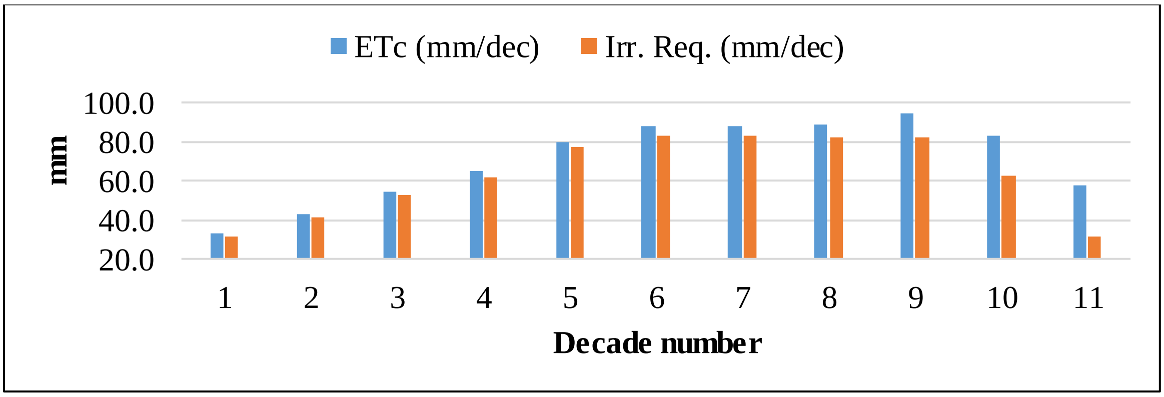


Figure 14: Calculated crop water and irrigation requirements

4.4 Water Application Efficiency and Distribution Uniformity

4.4.1 Water Applied

Tables 5 summarizes the amount of water applied and the amount that remained in the root zone for crop uptake. The average flow rate, which was constant for each day, was 1.4 litres/second. The amounts of water within the treatments were generally the same while across the treatments with the 0.9 cut-off receiving more water than the rest.

Table 5: Water applied to the field and remained in the root zone for crop evapotranspiration

Irrigation treatment	Total water applied (mm)				Actual water in root zone (mm)			
	Rep 1	Rep 2	Rep 3	Mean	Rep 1	Rep 2	Rep 3	Mean
75% cut off	235	253	235	**241**	168	172	168	169
80% cut off	265	284	264	**271**	174	182	173	176
90% cut off	318	341	316	**325**	196	206	194	199

Rep 1,2,3 = Replica 1,2,3

4.4.2 Application Efficiency (Ea)

Table 6 and Fig. 15 show the application efficiency for each treatment in each replica. The 75% cut off gave the highest Ea while the 90% cut off yielded the lowest. Fig. 4 gives the mean Ea value for each treatment; 75% cut-off gave the average highest Ea of 70% while the 90% achieved 63% Ea.

In table 7, Multiple Comparisons of the means indicate which group is different from each other. The Tukey post hoc test conducted on one-way ANOVA revealed a statistically significant difference in application efficiency between the 75% cut-off and the 80% cut-off treatments ($p = 0.003$), between the 75% cut-off and the 90% cut-off ($p < 0.001$) as well as between the 80% cut-off and the 90% cut-off ($p = 0.046$).

Table 6: Results for application efficiencies (Ea) and Distribution Uniformities

Replica no.	Application efficiency, Ea (%)			Distribution efficiency, DU (%)		
	Irrigation treatment			Irrigation treatment		
	75 % Cut-off	80 % Cut-off	90% Cut-off	75 % Cut-off	80 % Cut-off	90 % Cut-off
Rep 1	70.8	66.8	63.6	90.3	89.9	89.3
Rep 2	67.9	65.4	62.0	90.6	89.5	88.7
Rep 3	71.2	67.1	63.4	89.1	90.0	89.5
Mean	70.0	66.4	63.0	90.0	89.8	89.2

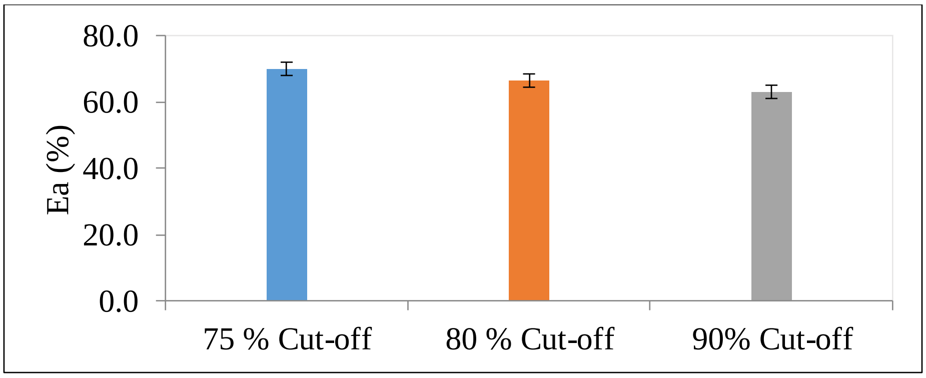


Figure 15: Mean water application efficiency for each treatment

Table 7: Statistical analysis of the variation in application efficiency among the treatments

Dependent Variable: Application Efficiency (%)						
Tukey HSD						
(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
75% Cut-off	80% Cut-off	5.4309*	1.4117	.003	1.873	8.989
	90% Cut-off	9.0396*	1.4117	<.001	5.481	12.598
80% Cut-off	75% Cut-off	-5.4309*	1.4117	.003	-8.989	-1.873
	90% Cut-off	3.6087*	1.4117	.046	.050	7.167
90% Cut-off	75% Cut-off	-9.0396*	1.4117	<.001	-12.598	-5.481
	80% Cut-off	-3.6087*	1.4117	.046	-7.167	-.050

*. The mean difference is significant at the 0.05 level.

As seen from the results, the 0.75 of furrow length treatments achieved highest average application efficiency of 70.0%. As all the three treatments had similar soil (sandy loam) and slope characteristics, this difference could be attributed to the fact that since water was stopped at 0.75 of furrow length, the remaining 0.25 of furrow length was adequate enough to accommodate all the recession water that was coming from the furrow head. Thus, there was less water that was lost as runoff or as deep percolation compared to the other two treatments. On the other hand, the 0.90 of furrow length treatments achieved lowest average application efficiency of 63% for the fact that some the remaining 10% dry portion of the furrow length was not adequate enough to contain all the recession water and therefore more water reached the drain as runoff compared to the other two treatments. These results fall within range of findings obtained by in other studies in which the application efficiency ranged from 64% to 71% for the cut-off method (Elsheikh *et al*., 2014; Issaka *et al*., 2015; Mohammed *et al*., 2015), and were conducted on same soil type. These results are therefore a representative of similar studies carried out on similar characteristics of soil and topography.

4.4.3 Distribution Uniformity (DU)

Table 6 and Fig. 16 show that DU had slightly different trend from Ea. Replica 3 had a different trend where the 80% cut-off gave a better DU than the other two treatments in the replica, possibly due to slight variations of in-furrow slope. However, on average as depicted in Fig. 5, highest DU of 90% in the 75% cut off and the lowest DU of 89.2% in the 90% cut off.

Multiple Comparisons in Table 8 revealed a statistically non-significant difference in distribution uniformity between the 75% cut-off and the 80% cut-off treatments ($p = 0.430$), between the 75% cut-off and the 90% cut-off ($p = 0.539$) as well as between the 80 % cut-off and the 90% cut-off ($p = 0.981$).

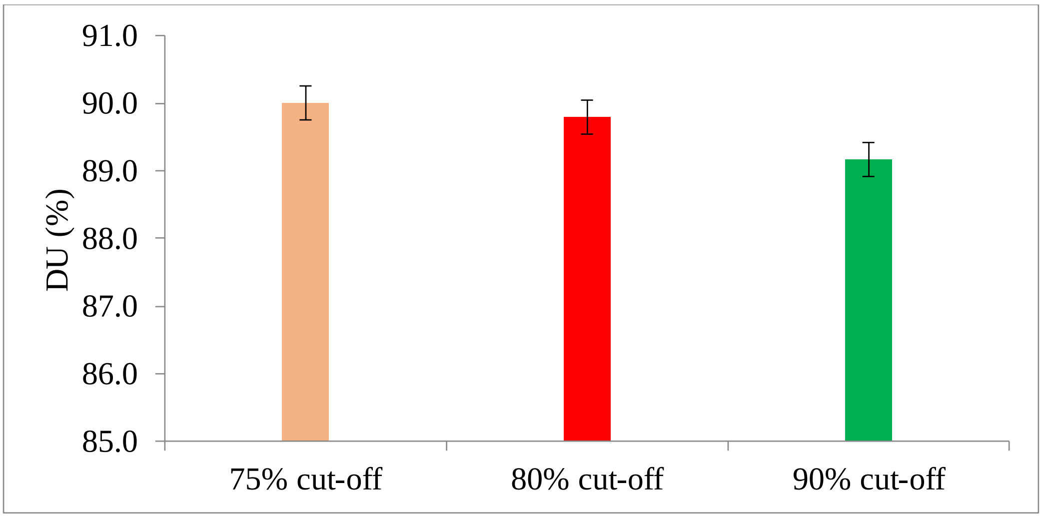


Figure 16: Average water distribution uniformity

Table 8: Statistical analysis of the variation in distribution uniformity among the treatments

Multiple Comparisons						
Dependent Variable: Distribution uniformity (%)						
Tukey HSD						
(I) Treatment	**(J) Treatment**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
75% Cut-off	80% Cut-off	.6719	.5316	.430	-.668	2.012
	90% Cut-off	.5722	.5316	.539	-.768	1.912
80% Cut-off	75% Cut-off	-.6719	.5316	.430	-2.012	.668
	90% Cut-off	-.0997	.5316	.981	-1.440	1.240
90% Cut-off	75% Cut-off	-.5722	.5316	.539	-1.912	.768
	80% Cut-off	.0997	.5316	.981	-1.240	1.440

For the distribution uniformity, all the treatments involved cutting the water supply before the advance phase reached the tail end of the furrow. This therefore improved the distribution uniformity as time for ponding phase, which usually result deep percolation at the upper section of the furrow, was reduced. The 0.75 of furrow run treatment had slightly higher uniformity than the other treatments and this is attributed to the fact that the remaining 20% furrow run was adequately watered by the ponding and recession phases coupled with suitable volume of water required to complete an advance which gives the potential to increase the distribution uniformity. These results too, agree with the findings obtained by similar studies in which distribution uniformity ranged from 85% to 91% for the cut-off method (Elsheikh *et al*., 2014;

Issaka *et al*., 2015; Mohammed *et al*., 2015).

As regarding the three sub-plots, there were very small differences for both application efficiency and distribution uniformity. This was attributed to the fact that the three replicas had almost identical physical properties that were analyzed, ranging from soil type and other properties, field slope, and were all irrigated with the same common feeder canal (mean same water quality) and same flow rate. The bigger furrow slope of the field (2.6%) made provided less time (opportunity time) for the ponding phase thereby reducing deep percolation. This agrees with findings of Assefa *et al*. (2017) on the effect of slope on distribution uniformity. Additionally, except for first irrigation event where applied depth exceeded the initial rooting depth, the subsequent applications were within the crop rooting zone making the deep percolation negligible. This was made possible through the adjustments in the flow rate between irrigation events but also due to the generally high water holding capacity of the sandy loam type of soil.

4.5 Yield and Water productivity

Table 9 and Fig. 17 indicate that higher yield for the 90% cut-off than the rest of the treatments. However, in terms of water productivity, the 75% cut-off produced the highest water productivity. The results had statistically significant difference ($p < 0.05$) for all the combinations as revealed by the Tukey post hoc test (Table 10).

Table 9: Yield and water productivity results from the three treatments

Replica no.	Yield (kg/ha)			Water productivity (kg/m3)		
	Irrigation treatment			Irrigation treatment		
	75 % Cut-off	80 % Cut-off	90% Cut-off	75 % Cut-off	80 % Cut-off	90 % Cut-off
Rep 1	8341	8415	8593	1.58	1.41	1.20
Rep 2	8356	8430	8622	1.47	1.32	1.12
Rep 3	8356	8445	8652	1.58	1.42	1.22
Mean	8351	8430	8622	1.54	1.38	1.18

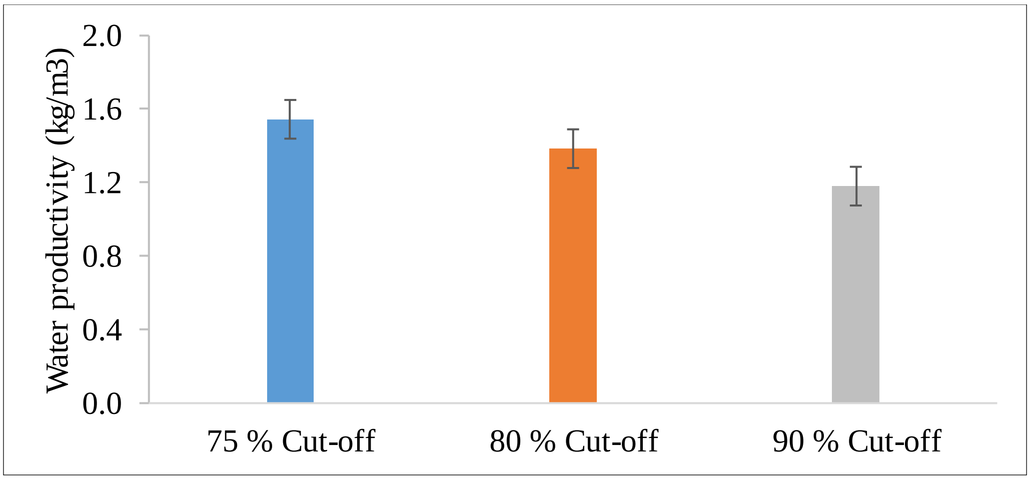


Figure 17: Water productivity for each treatment in each of the three sub-plots

Table 10: Statistical analysis of the variation in water productivity among the treatments

Multiple Comparisons						
Dependent Variable: Water productivity (%)						
Tukey HSD						
(I) Treatment	**(J) Treatment**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
75% Cut-off	80% Cut-off	.1598*	.0470	.034	.015	.304
	90% Cut-off	.3636*	.0470	.001	.219	.508
80% Cut-off	75% Cut-off	-.1598*	.0470	.034	-.304	-.015
	90% Cut-off	.2039*	.0470	.012	.060	.348
90% Cut-off	75% Cut-off	-.3636*	.0470	.001	-.508	-.219
	80% Cut-off	-.2039*	.0470	.012	-.348	-.060

*. The mean difference is significant at the 0.05 level.

For water productivity, though the difference is non-significant among the treatments with the highest water productivity of 1.58 kg/m^3 attained in the 75% cut off treatment, followed by the 80% cut-off and then the 90% cut-off being the lowest. These results are in tandem with the trend in water application efficiency and distribution uniformity values obtained in this experiment. The WP values in general, are within range of values found by other studies such as Abd El-Halim and Abd El-Razek (2014) who reported highest value of 1.09 kg/m^3 and Moayeri *et al*. (2011) who reported average WP of 1.45 kg/m^3. In experiments with controlled environments (usually at research stations where the recommended agronomic practices such as plant population, water application, pest control and fertilizer application are strictly followed and done at the right time) higher water productivity values are realized. In a controlled experiment of investigating water productivity of maize grown, Trout and DeJonge (2017) found water productivity of 2.0 kg/m^3 with 630 mm of crop evapotranspiration.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

The study has shown that varying the cutting off of irrigation supply in furrow system in relation to the position of the advance water has a bearing on both water application efficiency and distribution uniformity. From the investigated three treatments, it was evident that cutting off supply when advance phase reaches 0.75 of furrow length has the potential to save water of up to 26 % without compromising on water application efficiency, water distribution uniformity and water productivity. This saved water could be allocated to other uses or be used to cultivate extra area thereby increasing production. Further the study showed at least 13.6% of time spent on irrigation could be saved by following the 0.75 cut off technique which could be utilized in other productive activities. As the study was conducted in sloping conditions above the recommended slope range of 0.05% to 0.5% furrow irrigation (Brouwer *et al*., 1988; James, 1988) and with an average inflow rate of 1.4 litres/second, the results of application efficiency, distribution uniformity and water productivity are not much different conducted on more gentle slopes.

With the limited available land for irrigation (due to population pressure), the cut off technique would be very useful to apply in areas with slopes greater than 2% and for inflow rates higher than 1 litres/second to ensure uniform distribution and higher productivity while at the same time avoiding high run off losses and soil erosion.

As monitoring the physical position of cut off is easier than varying the flow rate with time, it is recommended that the cut-off position be promoted among the smallholder farmer schemes where water regulating structures are scarce.

REFERENCES

Abd El-Halim, A. E.-H. A., & Abd El-Razek, U. A. E.-H. (2014). Effect of different irrigation intervals on water saving, water productivity and grain yield of maize (Zea mays L.) under the double ridge-furrow planting technique. *Archives of Agronomy and Soil Science*, *60*(5), 587-596.

Adeniran, K. A., Amodu, M. F., Amodu, M. O., & Adeniji, F. A. (2010). Water requirements of some selected crops in Kampe dam irrigation project. *Australian Journal of Agricultural Engineering*, *1*(4), 119–125.

Al-Shammary, A. A. G., Kouzani, A. Z., Kaynak, A., Khoo, S. Y., Norton, M., & Gates, W. (2018). Soil bulk density estimation methods: a review. *Pedosphere*, *28*(4), 581-596.

Ali, H. (2010). *Fundamentals of Irrigation and On-farm Water Management* (Vol. 1). Springer Science & Business Media.

Ali, M., & Talukder, M. (2008). Increasing water productivity in crop production - A synthesis. *Agricultural Water Management*, *95*(11), 1201-1213.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, *300*(9), D05109.

Assefa, S., Kedir, Y., & Alamirew, T. (2017). Effects of Slopes, Furrow Lengths and Inflow Rates on Irrigation Performances and Yield of Sugarcane Plantation at Metehara, Ethiopia. *Irrigation & Drainage Systems Engineering*, *06*(01), 6–11. https://doi.org/10.4172/2168-9768.1000179.

Bishop, A. A., Poole, G. J., Allen, N. L., & Walker, W. R. (1981). Furrow advance rates under surge flow systems. *Journal of the Irrigation and Drainage Division*, *107*(3), 257-264.

Boutraa, T. (2010). Improvement of water use efficiency in irrigated agriculture: A review. *Journal of Agronomy*, *9*(1), 1-8.

Brouwer, C., Prins, K., Kay, M., & Heibloem, M. (1988). Irrigation water management: irrigation methods. *Training Manual*, *9*(5), 5-7.

Calzadilla, A., Rehdanz, K., & Tol, R. S. (2010). The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. *Journal of Hydrology*, *384*(3-4), 292-305.

Doorenbos, J., & Kassam, A. (1986). Yield Response to Water; FAO Irrigation and Drainage, Paper No. 33; Food and Agriculture Organization of the United Nations. *Water Resources and Development Service: Rome, Italy*, 7-13.

Elsheikh, M. A. E., Mohamed, A. E. E., & Salih, S. A. (2014). *Effect of Some Techniques on Long Furrow Irrigation Efficiency* Paper presented at the International Conference on Biological, Civil and Environmental Engineering (BCEE-2014), Dubai, UAE.

Eshetu, S. (2007). *Evaluation of the Effect of Flow Rate and Furrow Length on Irrigation Efficiencies and Water Use* [Thesis, Haramaya University].

Feyen, J., & Zerihun, D. (1999). Assessment of the performance of border and furrow irrigation systems and the relationship between performance indicators and system variables. *Agricultural Water Management*, *40*(2-3), 353-362.

Global Water Partnership. (2015). *Integrated Water Resources management in East Africa*.

Henderson, F. M. (1996). *Open channel flow*. MacMillan Publishing Co.

Igbadun, H. E., Mahoo, H. F., Tarimo, A. K. P. R., & Salim, B. A. (2006). Crop water productivity of an irrigated maize crop in Mkoji sub-catchment of the Great Ruaha River Basin, Tanzania. *Agricultural Water Management*, *85*(1–2), 141–150. https://doi.org/10.1016/J.AGWAT.2006.04.003

Irmak, S., Odhiambo, L. O., Kranz, W. L., & Eisenhauer, D. E. (2011). Irrigation efficiency and uniformity, and crop water use efficiency.

Issaka, R., Ibrahim, H., & Issah, M. (2015). Performance evaluation of furrow lengths and field application techniques. *International Journal of Scientific & Technology Research*, *4*(10), 278-281.

James, L. G. (1988). *Principles of farm irrigation systems design*. John Wiley and Sons Limited.

Kore, J. R., Nimbalkar, P. T., & Hirave, P. (2017). Crop water requirements and irrigation scheduling of some selected crops using CROPWAT 8.0: A case study of Khadakwasla dam irrigation project. *International Journal of Civil Engineering and Technology, 8*(5), 342–349.

Letseku, V., & Grové, B. (2022). Crop Water Productivity, Applied Water Productivity and Economic Decision Making. *Water (Switzerland)*, *14*(10). https://doi.org/10.3390/w14101598

Li, Y., Xu, D., & Li, F. (2001). Modeling on influence of land leveling precision on basin irrigation performance. *Nongye Gongcheng Xuebao(Transactions of the Chinese Society of Agricultural Engineering)*, *17*(4), 43-48.

Liu, J., Williams, J. R., Zehnder, A. J., & Yang, H. (2007). GEPIC–modelling wheat yield and crop water productivity with high resolution on a global scale. *Agricultural Systems, 94*(2), 478-493.

Manabaev, N. T., Aubakirova, F. H., Kenzhibaeva, G. S., Zhumabaeva, R. O., & Assylbekov, B. Z. (2015). Improved Technology of Furrow Irrigation on Mountain Slope Fields. *International Journal of Biology*, *7*(9), 182.

Mekonen, M. (2006). *Performance evaluation of Bato Degaga surface irrigation system* Alemaya University].

Miao, Q., Shi, H., & Li, R. (2017). Modernizing Surface Irrigation and Land Levelling in Hetao with Application of the Decision Support Systems SADREG. *Irrigation & Drainage Systems Engineering*, *6*(195). https://doi.org/doi: 10.4172/2168-9768.1000195

Moayeri, M., Pazira, E., Siadat, H., Abbasi, F., & Kaveh, F. (2011). Influence of planting and irrigation management methods on maize water productivity improvement in a semi arid region. *World Applied Sciences Journal*, *13*(5), 1218-1228.

Mohammed, A., Abdeen, N., & Hamid, A. R. (2015). Effect of irrigation technique on the efficiency of furrow irrigation. International Conference on Chemical, Environmental and Biological Sciences (CEBS-2015) March, Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management*, *97*(4), 528-535.

Nithya, B. ., Shreedhar, R., & Shivapur, A. V. (2015). Water Requirements of Selected Crops in Kunigal Command Area. *I-Manager's Journal on Civil Engineering*, *5*(2), 24–30. https://doi.org/10.26634/jce.5.2.3351

Öztekin, T. (2013). Short-term effects of land leveling on irrigation-related some soil properties in a clay loam soil. *The Scientific World Journal*, *2013*.

Pereira, L. S., Gonçalves, J., Dong, B., Mao, Z., & Fang, S. (2007). Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the upper Yellow River Basin, China. *Agricultural Water Management*, *93*(3), 109-122.

Salahou, M. K., Jiao, X.-y., & Liu, K. (2016). Irrigation Management Using Different Irrigation Scheduling Techniques in Blocked-end Furrows. 2016 5th International Conference on Energy and Environmental Protection.

Saravanan, K., & Saravanan, R. (2014). Determination of Water Requirements of Main crops in the Tank Irrigation Command area using CROPWAT 8.0. *International Journal of Interdisciplinary and Multidisciplinary Studies 1*(5), 266–272. http://www.ijims.com

Sarwar, A., Bastiaanssen, W. G., & Feddes, R. (2001). Irrigation water distribution and long-term effects on crop and environment. *Agricultural Water Management*, *50*(2), 125-140.

Savva, A. P., & Frenken, K. (2002a). *Module 2: Natural Resources Assessment* (Vol. 1). FAO Sub-Regional Office for East and Southern Africa Harare.

Savva, A. P., & Frenken, K. (2002b). *Module 4: Crop Water Requirements and Irrigation Scheduling* (Vol. 1). Sub-Regional Office for East and Southern Africa, Harare

Siebert, S., Henrich, V., Frenken, K., & Burke, J. (2013). Update of the digital global map of irrigation areas to version 5. *Rheinische Friedrich-Wilhelms-Universität, Bonn, Germany and Food and Agriculture Organization of the United Nations, Rome, Italy*.

Trout, T. (1990). *Surface seal influence on surge flow furrow infiltration* (Vol. 33).

Trout, T. J., & DeJonge, K. C. (2017). Water productivity of maize in the US high plains. *Irrigation Science*, *35*(3), 251-266.

Visconti, F., & de Paz, J. M. (2016). Electrical Conductivity Measurements in Agriculture: The Assessment of Soil Salinity. *New Trends and Developments in Metrology*, 99.

Walker, W. R. (1989). *Guidelines for designing and evaluating surface irrigation systems*.

Walker, W. R., & Skogerboe, G. V. (1987). *Surface irrigation. Theory and practice*. Prentice-Hall.

Yang, Q., Luo, W., Jiang, Z., Li, W., & Yuan, D. (2016). Improve the prediction of soil bulk density by cokriging with predicted soil water content as auxiliary variable. *Journal of Soils and Sediments*, *16*(1), 77-84.

Yonts, C. D., Eisenhauer, D. E., & Varner, D. L. (2007). Managing Furrow Irrigation Systems. *Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln*, *1338*.

Zolfaghari, Z., Mosaddeghi, M., & Ayoubi, S. (2016). Relationships of soil shrinkage parameters and indices with intrinsic soil properties and environmental variables in calcareous soils. *Geoderma*, *277*, 23-34.

APENDICES

Appendix 1: Outputs from CROPWAT simulations

Monthly ETo Penman-Monteith - C:\Users\user\Documents\Research\CROPWAT\Lekitatu ETo...

Country: Tanzania | Station: Lekitatu

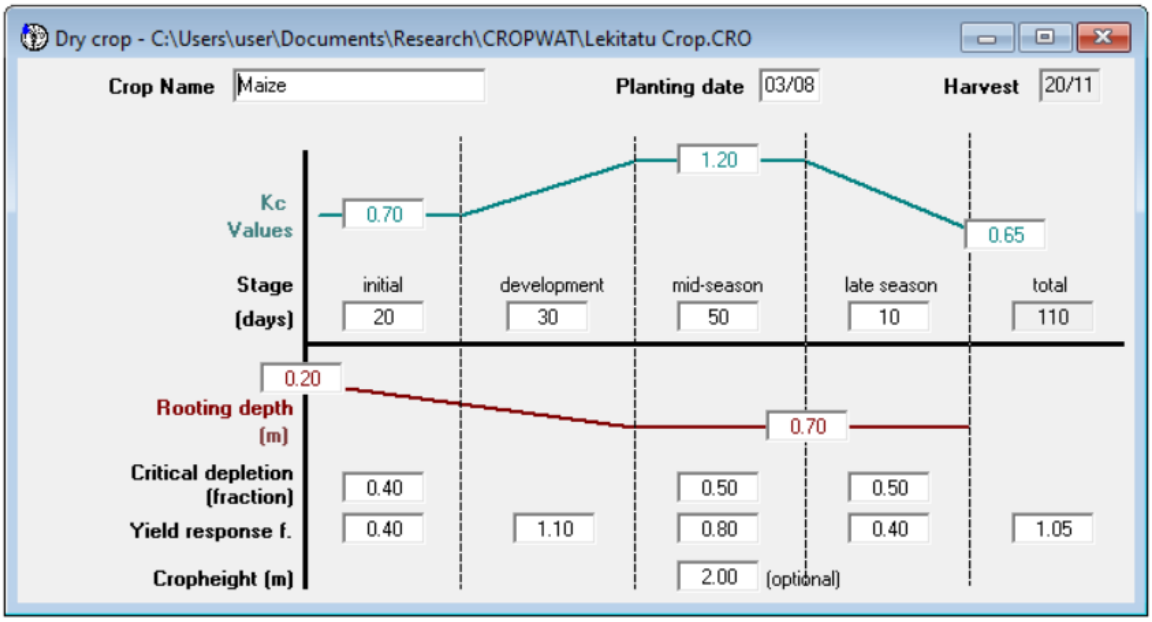
Altitude: 1162 m. | Latitude: 3.34 °S | Longitude: 36.85 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	m/s	hours	MJ/m²/day	mm/day
January	15.2	30.9	56	2.1	12.1	28.0	6.10
February	15.4	31.9	52	2.0	12.1	28.6	6.37
March	16.0	31.8	56	1.9	12.0	28.4	6.23
April	16.0	29.7	66	2.0	12.0	27.2	5.60
May	14.1	28.2	68	2.4	11.5	24.7	5.02
June	12.3	28.0	61	2.6	11.5	23.7	5.02
July	11.7	28.2	54	2.9	11.5	24.1	5.43
August	12.6	29.6	50	3.0	12.0	26.3	6.15
September	13.9	31.6	45	3.0	12.0	27.8	6.93
October	15.1	32.4	46	2.8	12.1	28.4	7.05
November	16.2	31.2	56	2.4	12.1	28.0	6.34
December	15.8	30.6	59	2.3	12.2	27.8	6.08
Average	**14.5**	**30.3**	**56**	**2.5**	**11.9**	**26.9**	**6.03**

Monthly rain - C:\Users\user\Documents\Research\CROPWAT\Lekitatu Rain.CRM

Station: Lekitatu | Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	51.5	47.3
February	45.7	42.4
March	113.5	92.9
April	263.5	151.3
May	115.1	93.9
June	16.9	16.4
July	7.2	7.1
August	6.3	6.2
September	10.5	10.3
October	25.5	24.5
November	82.3	71.5
December	78.1	68.3
Total	**816.1**	**632.1**



Soil name Sandy Loam

General soil data

Total available soil moisture (FC - WP)	120.0	**mm/meter**
Maximum rain infiltration rate	33	**mm/day**
Maximum rooting depth	90	**centimeters**
Initial soil moisture depletion (as % TAM)	50	**%**
Initial available soil moisture	60.0	**mm/meter**

Crop Water Requirements

ETo station Lekitatu **Crop** Maize

Rain station Lekitatu **Planting date** 03/08

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Aug	1	Init	0.70	4.14	33.1	1.6	31.1
Aug	2	Init	0.70	4.31	43.1	1.9	41.2
Aug	3	Deve	0.78	4.97	54.7	2.4	52.3
Sep	1	Deve	0.97	6.47	64.7	2.7	62.0
Sep	2	Deve	1.16	8.00	80.0	3.0	77.1
Sep	3	Mid	1.26	8.77	87.7	4.7	83.0
Oct	1	Mid	1.26	8.82	88.2	5.5	82.7
Oct	2	Mid	1.26	8.87	88.7	6.6	82.1
Oct	3	Mid	1.26	8.58	94.3	12.3	82.0
Nov	1	Mid	1.26	8.28	82.8	20.2	62.6
Nov	2	Late	0.94	5.96	59.6	26.2	33.5
					776.9	**87.1**	**689.4**

Appendix 2: Field experiment data

Field measurements of water depths after each Irrigation

Date of Irrigation: **5th August, 2019**

Time of Irrigation: **180 Minutes**

Days after planting: **2**

H (m) 0.05

Q (l/s) 0.77

Sub plot infiltrated water depths (mm) on 1st irrigation event — Flowrate(l/s) 0.77 — Area of f. set (m^2) 22.5

Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm) Distance along the furrow (m)			Water depth (mm) Average	Dug out collection		Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water aplied to each furrow set (mm)	Application efficiency (%)
			0.0	**7.5**	**15**		litres	mm				
1	75% of furrow length	1	29.0	27.0	23.0	26.0	5	0.2	6.0	18	36.8	70.72
		2	28.0	26.0	23.0							
		3	29.0	26.0	23.0							
	80% of furrow length	1	29.0	28.0	25.0	26.7	7	0.3	6.7	19	38.8	68.71
		2	29.0	26.0	24.0							
		3	29.0	26.0	24.0							
	90% of furrow length	1	32.0	28.0	26.0	28.8	10	0.4	8.8	21	42.9	67.09
		2	32.0	28.0	26.0							
		3	32.0	28.0	27.0							
2	75% of furrow length	1	30.0	28.0	26.0	27.6	4.8	0.2	7.6	20	40.9	67.45
		2	30.0	28.0	25.0							
		3	30.0	26.0	25.0							
	80% of furrow length	1	30.0	28.0	26.0	28.1	6.7	0.3	8.1	21	42.9	65.54
		2	30.0	30.0	25.0							
		3	31.0	28.0	25.0							
	90% of furrow length	1	33.0	30.0	27.0	30.6	9.8	0.4	10.6	23	47.0	65.04
		2	34.0	30.0	28.0							
		3	34.0	31.0	28.0							
3	75% of furrow length	1	29.0	27.0	24.0	26.2	5	0.2	6.2	18	36.8	71.32
		2	28.0	26.0	23.0							
		3	29.0	26.0	24.0							
	80% of furrow length	1	29.0	27.0	25.0	26.7	7	0.3	6.7	19	38.8	68.71
		2	29.0	27.0	24.0							
		3	30.0	26.0	23.0							
	90% of furrow length	1	33.0	28.0	26.0	29.2	10	0.4	9.2	21	42.9	68.13
		2	33.0	29.0	26.0							
		3	32.0	29.0	27.0							

Field measurements of water depths after each Irrigation

Date of Irrigation: **13th August, 2019**

Time of Irrigation: **105 Minutes**

Days after planting: **10**

H (m) 0.06

Q (l/s) 1.21

Sub plot infiltrated water depths (mm) on 4th irrigation event Flowrate(l/s) 1.2 Area of f. set (m^2) 22.5

Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm)				Dug out collection		Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set (mm)	Application efficiency (%)
			Distance along the furrow (m)			Average						
			0.0	**7.5**	**15**		litres	mm				
1	75% of furrow length	1	26.0	25.0	21.0	24.0	5.5	0.2	0.0	10.5	33.8	70.94
		2	26.0	24.0	21.0							
		3	27.0	24.0	22.0							
	80% of furrow length	1	27.0	26.0	23.0	24.8	7	0.3	0.0	11	35.4	69.91
		2	28.0	24.0	22.0							
		3	27.0	24.0	22.0							
	90% of furrow length	1	30.0	27.0	24.0	27.1	10	0.4	0.0	13	41.9	64.73
		2	30.0	27.0	24.0							
		3	30.0	27.0	25.0							
2	75% of furrow length	1	27.0	25.0	23.0	24.8	5	0.2	0.0	11	35.4	69.91
		2	27.0	25.0	22.0							
		3	28.0	24.0	22.0							
	80% of furrow length	1	30.0	26.0	24.0	26.9	6.8	0.3	0.0	12	38.7	69.55
		2	30.0	28.0	24.0							
		3	30.0	26.0	24.0							
	90% of furrow length	1	31.0	28.0	25.0	28.1	9.7	0.4	0.0	14	45.1	62.32
		2	30.0	28.0	26.0							
		3	30.0	29.0	26.0							
3	75% of furrow length	1	26.0	25.0	21.0	24.0	5	0.2	0.0	10.5	33.8	70.94
		2	26.0	24.0	21.0							
		3	27.0	24.0	22.0							
	80% of furrow length	1	29.0	25.0	23.0	25.0	7	0.3	0.0	11	35.4	70.54
		2	28.0	24.0	22.0							
		3	28.0	24.0	22.0							
	90% of furrow length	1	31.0	26.0	24.0	26.9	10	0.4	0.0	13	41.9	64.20
		2	31.0	26.0	24.0							
		3	30.0	26.0	24.0							

Field measurements of water depths after each Irrigation

Date of Irrigation: **20th August, 2019**

Time of Irrigation: **102.5 minutes**

Days after planting: **17**

H (m) 0.06

Q (l/s) 1.2

Sub plot infiltrated water depths (mm) on 4th irrigation event — Flowrate(l/s) 1.2 — Area of f. set (m^2) 22.5

Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm)				Dug out collection		Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set	Application efficiency (%)
			Distance along the furrow (m)			Average						
			0.0	**7.5**	**15**		litres	mm				
1	75% of furrow length	1	25.0	23.0	21.0	22.9	5	0.2	0.0	10	32.2	71.04
		2	24.0	23.0	21.0							
		3	26.0	22.0	21.0							
	80% of furrow length	1	26.0	22.0	20.0	22.6	6.5	0.3	0.0	11	35.4	63.64
		2	26.0	22.0	20.0							
		3	26.0	22.0	19.0							
	90% of furrow length	1	29.0	25.0	23.0	25.6	9.5	0.4	0.0	13	41.9	61.01
		2	29.0	24.0	23.0							
		3	29.0	26.0	22.0							
2	75% of furrow length	1	26.0	22.0	20.0	23.3	4.5	0.2	0.0	10.5	33.8	68.97
		2	27.0	24.0	21.0							
		3	27.0	23.0	20.0							
	80% of furrow length	1	27.0	22.0	19.0	22.6	6.3	0.3	0.0	11	35.4	63.64
		2	26.0	21.0	20.0							
		3	27.0	22.0	19.0							
	90% of furrow length	1	29.0	25.0	22.0	25.4	9.2	0.4	0.0	13	41.9	60.75
		2	29.0	24.0	23.0							
		3	29.0	25.0	23.0							
3	75% of furrow length	1	26.0	23.0	21.0	23.2	4.5	0.2	0.0	10	32.2	72.07
		2	26.0	23.0	21.0							
		3	26.0	22.0	21.0							
	80% of furrow length	1	26.0	21.0	20.0	22.4	6.5	0.3	0.0	11	35.4	63.33
		2	26.0	22.0	20.0							
		3	26.0	21.0	20.0							
	90% of furrow length	1	29.0	25.0	23.0	25.7	9.5	0.4	0.0	13	41.9	61.28
		2	29.0	24.0	23.0							
		3	30.0	26.0	22.0							

Field measurements of water depths after each Irrigation									H (m)	0
Date of rainfall: **24th August, 2019**									Q (l/s)	0.0
Time of Irrigation: **N/A**										
Days after planting: **21**										
Sub plot infiltrated water depths (mm) on 4th irrigation event					Flowrate(l/s)	0.0	Area of f. set (m^2)	45		
Sub plot No.	Water supply cut off point	Furrow No.	Rainfall (mm)	Effe. Rainfall (mm)		Dug out collection (litres)	Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set (mm)	Application efficiency (%)
1	75% of furrow length	1	11.4			0.0	0.0	0	0.0	
		2	11.4							
		3	11.4							
	80% of furrow length	1	11.4			0.0	0.0	0	0.0	
		2	11.4							
		3	11.4							
	90% of furrow length	1	11.4			0.0	0.0	0	0.0	
		2	11.4							
		3	11.4							
2	75% of furrow length	1	11.4			0.0	0.0	0	0.0	
		3	11.4							
		5	11.4							
	80% of furrow length	1	11.4			0.0	0.0	0	0.0	
		3	11.4							
		5	11.4							
	90% of furrow length	1	11.4			0.0	0.0	0	0.0	
		3	11.4							
		5	11.4							
3	75% of furrow length	1	11.4			0.0	0.0	0	0.0	
		3	11.4							
		5	11.4							
	80% of furrow length	1	11.4			0.0	0.0	0	0.0	
		3	11.4							
		5	11.4							
	90% of furrow length	1	11.4			0.0	0.0	0	0.0	
		3	11.4							
		5	11.4							

Field measurements of water depths after each Irrigation												H (m)	0.065
Date of Irrigation: **29th August, 2019**												Q (l/s)	1.5
Time of Irrigation: **75 minutes**													
Days after planting: 26													
Sub plot infiltrated water depths (mm) on 4th irrigation event				Flowrate(l/s)		1.5	Area of f. set (m^2)	22.5					
Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm)				Dug out collection		Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set (mm)	Application efficiency (%)	
			Distance along the furrow (m)			Average							
			0.0	**7.5**	**15**		litres	mm					
1	75% of furrow length	1	22.0	20.0	18.0	20.0	6	0.3	0.0	7	27.6	72.59	
		2	22.0	20.0	18.0								
		3	22.0	20.0	18.0								
	80% of furrow length	1	23.0	20.0	19.0	20.6	7.5	0.3	0.0	8	31.5	65.28	
		2	23.0	20.0	19.0								
		3	23.0	20.0	18.0								
	90% of furrow length	1	26.0	22.0	20.0	22.9	10.5	0.5	0.0	9.5	37.4	61.22	
		2	26.0	23.0	20.0								
		3	26.0	23.0	20.0								
2	75% of furrow length	1	23.0	19.0	18.0	20.3	5.5	0.2	0.0	7.5	29.5	68.88	
		2	24.0	20.0	18.0								
		3	23.0	20.0	18.0								
	80% of furrow length	1	24.0	21.0	19.0	21.3	7.3	0.3	0.0	8.5	33.5	63.77	
		2	24.0	21.0	19.0								
		3	24.0	22.0	18.0								
	90% of furrow length	1	28.0	23.0	20.0	24.0	10.2	0.5	0.0	10	39.4	60.98	
		2	28.0	24.0	20.0								
		3	28.0	24.0	21.0								
3	75% of furrow length	1	22.0	20.0	18.0	19.9	5.5	0.2	0.0	7	27.6	72.19	
		2	22.0	20.0	18.0								
		3	22.0	20.0	17.0								
	80% of furrow length	1	23.0	20.0	19.0	20.6	7.5	0.3	0.0	8	31.5	65.28	
		2	23.0	20.0	19.0								
		3	23.0	20.0	18.0								
	90% of furrow length	1	27.0	22.0	20.0	23.1	10.5	0.5	0.0	9.5	37.4	61.81	
		2	27.0	23.0	20.0								
		3	26.0	23.0	20.0								

Field measurements of water depths after each Irrigation

Date of Irrigation: **4th September, 2019**

Time of Irrigation: **62 minutes**

Days after planting: **32**

H (m) 0.07

Q (l/s) 1.8

Sub plot infiltrated water depths (mm) on 4th irrigation event   Flowrate(l/s) 1.8   Area of f. set (m^2) 22.5

Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm) Distance along the furrow (m) 0.0	7.5	15	Average	Dug out collection litres	mm	Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set (mm)	Application efficiency (%)
1	75% of furrow length	1	21.0	19.0	17.0	19.0	6.5	0.3	0.0	5.5	26.1	72.93
		2	21.0	19.0	17.0							
		3	21.0	19.0	17.0							
	80% of furrow length	1	22.0	20.0	18.0	20.0	7.5	0.3	0.0	6.5	30.8	64.96
		2	22.0	20.0	18.0							
		3	22.0	20.0	18.0							
	90% of furrow length	1	25.0	23.0	20.0	22.9	10	0.4	0.0	8	37.9	60.40
		2	25.0	23.0	21.0							
		3	25.0	23.0	21.0							
2	75% of furrow length	1	22.0	20.0	18.0	19.6	5.5	0.2	0.0	6	28.4	68.81
		2	22.0	19.0	18.0							
		3	22.0	19.0	16.0							
	80% of furrow length	1	23.0	21.0	18.0	20.9	7.3	0.3	0.0	7	33.2	63.00
		2	23.0	22.0	18.0							
		3	23.0	22.0	18.0							
	90% of furrow length	1	27.0	25.0	22.0	24.9	10.2	0.5	0.0	9	42.6	58.38
		2	27.0	25.0	23.0							
		3	27.0	25.0	23.0							
3	75% of furrow length	1	21.0	19.0	16.0	18.8	6	0.3	0.0	5.5	26.1	72.08
		2	21.0	19.0	17.0							
		3	21.0	19.0	16.0							
	80% of furrow length	1	23.0	21.0	18.0	20.2	7.5	0.3	0.0	6.5	30.8	65.68
		2	22.0	20.0	18.0							
		3	22.0	20.0	18.0							
	90% of furrow length	1	26.0	23.0	20.0	23.4	10.5	0.5	0.0	8	37.9	61.87
		2	26.0	24.0	21.0							
		3	26.0	24.0	21.0							

Field measurements of water depths after each Irrigation											H (m)	0.07
Date of Irrigation: **13th September, 2019**											Q (l/s)	1.8
Time of Irrigation: **62 minutes**												
Days after planting: **41**												
Sub plot infiltrated water depths (mm) on 4th irrigation event				Flowrate(l/s)		1.8	Area of f. set (m^2)		22.5			
Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm)				Dug out collection		Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set (mm)	Application efficiency (%)
			Distance along the furrow (m)			Average						
			0.0	**7.5**	**15**		litres	mm				
1	75% of furrow length	1	20.0	18.0	16.0	18.0	6.5	0.3	0.0	5.5	26.1	69.09
		2	20.0	18.0	16.0							
		3	20.0	18.0	16.0							
	80% of furrow length	1	23.0	19.0	15.0	19.2	7.5	0.3	0.0	6.5	30.8	62.43
		2	23.0	20.0	16.0							
		3	23.0	19.0	15.0							
	90% of furrow length	1	26.0	22.0	17.0	22.0	10	0.4	0.0	8	37.9	58.06
		2	27.0	23.0	17.0							
		3	26.0	22.0	18.0							
2	75% of furrow length	1	20.0	18.0	16.0	18.2	5.5	0.2	0.0	6	28.4	64.12
		2	20.0	19.0	16.0							
		3	20.0	19.0	16.0							
	80% of furrow length	1	24.0	21.0	17.0	20.3	7.3	0.3	0.0	7	33.2	61.32
		2	24.0	20.0	16.0							
		3	24.0	20.0	17.0							
	90% of furrow length	1	28.0	25.0	19.0	24.0	10.2	0.5	0.0	9	42.6	56.30
		2	28.0	26.0	18.0							
		3	28.0	25.0	19.0							
3	75% of furrow length	1	20.0	18.0	15.0	17.4	6	0.3	0.0	5.5	26.1	66.96
		2	19.0	17.0	15.0							
		3	20.0	18.0	15.0							
	80% of furrow length	1	23.0	19.0	15.0	19.2	7.5	0.3	0.0	6.5	30.8	62.43
		2	23.0	20.0	16.0							
		3	23.0	19.0	15.0							
	90% of furrow length	1	27.0	22.0	18.0	22.3	10.5	0.5	0.0	8	37.9	58.94
		2	27.0	23.0	17.0							
		3	27.0	22.0	18.0							

Field measurements of water depths after each Irrigation												H (m)	0.065
Date of Irrigation: **21st September, 2019**												Q (l/s)	1.5
Time of Irrigation: **67.5 minutes**													
Days after planting: **49**													
Sub plot infiltrated water depths (mm) on 4th irrigation event				Flowrate(l/s)		1.5	Area of f. set (m^2)			22.5			
Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm)				Dug out collection		Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set (mm)	Application efficiency (%)	
			Distance along the furrow (m)			Average							
			0.0	**7.5**	**15**		litres	mm					
1	75% of furrow length	1	18.0	16.0	15.0	16.2	6	0.3	0.0	6	23.6	68.70	
		2	18.0	16.0	15.0								
		3	18.0	15.0	15.0								
	80% of furrow length	1	19.0	16.0	15.0	16.7	7.5	0.3	0.0	7.5	29.5	56.46	
		2	19.0	17.0	14.0								
		3	19.0	17.0	14.0								
	90% of furrow length	1	24.0	20.0	18.0	20.2	10.5	0.5	0.0	9	35.4	57.09	
		2	24.0	19.0	17.0								
		3	24.0	19.0	17.0								
2	75% of furrow length	1	19.0	17.0	15.0	16.9	5.5	0.2	0.0	6.5	25.6	66.02	
		2	19.0	17.0	14.0								
		3	19.0	18.0	14.0								
	80% of furrow length	1	22.0	18.0	17.0	19.1	7.3	0.3	0.0	8	31.5	60.70	
		2	23.0	17.0	17.0								
		3	23.0	18.0	17.0								
	90% of furrow length	1	25.0	21.0	17.0	21.1	10.2	0.5	0.0	9.5	37.4	56.46	
		2	25.0	21.0	17.0								
		3	25.0	21.0	18.0								
3	75% of furrow length	1	18.0	16.0	14.0	16.1	5.5	0.2	0.0	6	23.6	68.23	
		2	19.0	16.0	14.0								
		3	18.0	16.0	14.0								
	80% of furrow length	1	19.0	16.0	15.0	16.9	7.5	0.3	0.0	7	27.6	61.30	
		2	18.0	18.0	14.0								
		3	20.0	18.0	14.0								
	90% of furrow length	1	23.0	19.0	17.0	19.1	10.5	0.5	0.0	8.5	33.5	57.13	
		2	22.0	18.0	16.0								
		3	23.0	18.0	16.0								

Date of Irrigation: **1st October, 2019**
Time of Irrigation: **67.5 minutes**
Days after planting: **59**
Sub plot infiltrated water depths (mm) on 4th irrigation event

Q (l/s) 1.8

Flowrate(l/s) 1.8 Area of f. set (m^2) 22.5

Sub plot No.	Water supply cut off point	Furrow No.	Water depth (mm) Distance along the furrow (m) 0.0	7.5	15	Average	Dug out collection litres	mm	Deep percolation (mm)	Average time to irrigate each furrow set (mins)	Total water apllied to each furrow set (mm)	Application efficiency (%)
1	75% of furrow length	1	22.0	21.0	18.0	20.4	6.5	0.3	0.0	6	28.4	71.93
		2	22.0	21.0	19.0							
		3	22.0	21.0	18.0							
	80% of furrow length	1	23.0	21.0	19.0	21.1	7.5	0.3	0.0	7	33.2	63.67
		2	23.0	21.0	19.0							
		3	23.0	21.0	20.0							
	90% of furrow length	1	29.0	24.0	23.0	25.2	10	0.4	0.0	9	42.6	59.16
		2	29.0	24.0	23.0							
		3	29.0	24.0	22.0							
2	75% of furrow length	1	23.0	22.0	19.0	21.2	5.5	0.2	0.0	6.5	30.8	68.93
		2	23.0	21.0	19.0							
		3	24.0	21.0	19.0							
	80% of furrow length	1	24.0	22.0	20.0	22.2	7.3	0.3	0.0	7.5	35.5	62.55
		2	24.0	23.0	21.0							
		3	24.0	22.0	20.0							
	90% of furrow length	1	31.0	25.0	22.0	25.9	10.2	0.5	0.0	9.5	45.0	57.53
		2	31.0	25.0	21.0							
		3	31.0	26.0	21.0							
3	75% of furrow length	1	23.0	21.0	18.0	20.4	6	0.3	0.0	6	28.4	71.93
		2	22.0	21.0	18.0							
		3	22.0	21.0	18.0							
	80% of furrow length	1	23.0	22.0	20.0	21.2	7.5	0.3	0.0	7	33.2	64.00
		2	23.0	21.0	19.0							
		3	23.0	21.0	19.0							
	90% of furrow length	1	29.0	25.0	23.0	25.6	10.5	0.5	0.0	9	42.6	59.94
		2	30.0	25.0	22.0							
		3	30.0	24.0	22.0							

Appendix 3: Summary of field experiment data

Date of Irrigation/ Rainfall	Treatment	Average inflow rate (l/s)	Total time to irrigate each furrow set (min)			Total water applied (mm)			Actual water depth in root zone (mm)			Deep Percolation (mm)			Surface Evaporation E_o (mm)			Surface runoff (mm)			Application Efficiency, Ea (%)	Water Distribution Uniformity, WDU (%)
			Current	Previous	Cumm.	Current	Previous	Cumm.	Current	Previous	Cumm.	Current	Previous	Cumm.	Current	Previous	Cumm.	Current	Previous	Cumm.		
5-Aug-19	75% cut off	0.8	18.7	0.0	18.7	38.1	0.0	38.1	26.6	0.0	26.6	6.6	0.0	6.6	6.2	0.0	6.2	0.2	0.0	0.2	69.83	91.4
	80% cut off	0.8	19.7	0.0	19.7	40.2	0.0	40.2	27.1	0.0	27.1	7.1	0.0	7.1	6.2	0.0	6.2	0.3	0.0	0.3	67.66	92.4
	90% cut off	0.8	21.7	0.0	21.7	44.3	0.0	44.3	29.5	0.0	29.5	9.5	0.0	9.5	6.2	0.0	6.2	0.4	0.0	0.4	66.06	91.9
13-Aug-19	75% cut off	1.2	10.7	18.7	29.3	34.4	38.1	72.5	24.3	26.6	50.9	0.0	6.6	6.6	6.2	6.2	12.3	0.2	0.2	0.4	70.19	90.5
	80% cut off	1.2	11.3	19.7	31.0	36.5	40.2	76.7	25.6	27.1	52.7	0.0	7.1	7.1	6.2	6.2	12.3	0.3	0.3	0.6	68.77	91.9
	90% cut off	1.2	13.3	21.7	35.0	43.0	44.3	87.2	27.4	29.5	56.9	0.0	9.5	9.5	6.2	6.2	12.3	0.4	0.4	0.9	64.92	91.4
20-Aug-19	75% cut off	1.2	10.2	29.3	39.5	32.8	72.5	105.3	23.1	50.9	74.0	0.0	6.6	6.6	6.2	12.3	18.5	0.2	0.4	0.7	70.04	91.2
	80% cut off	1.2	11.0	31.0	42.0	35.4	76.7	112.1	22.5	52.7	75.2	0.0	7.1	7.1	6.2	12.3	18.5	0.3	0.6	0.9	67.10	91.3
	90% cut off	1.2	13.0	35.0	48.0	41.9	87.2	129.1	25.6	56.9	82.4	0.0	9.5	9.5	6.2	12.3	18.5	0.4	0.9	1.3	63.65	91.2
25-Aug-19	75% cut off	11.4 mm		39.5	39.5		105.3	105.3		74.0	74.0		6.6	6.6	6.2	18.5	24.6		0.7	0.7	70.04	91.2
	80% cut off	11.4 mm		42.0	42.0		112.1	112.1		75.2	75.2		7.1	7.1	6.2	18.5	24.6		0.9	0.9	67.10	91.3
	90% cut off	11.4 mm		48.0	48.0		129.1	129.1		82.4	82.4		9.5	9.5	6.2	18.5	24.6		1.3	1.3	63.65	91.2
29-Aug-19	75% cut off	1.5	7.2	39.5	46.7	28.2	105.3	133.5	20.1	74.0	94.1	0.0	6.6	6.6	6.2	24.6	30.8	0.3	0.7	0.9	70.19	91.2
	80% cut off	1.5	8.2	42.0	50.2	32.1	112.1	144.3	20.8	75.2	96.0	0.0	7.1	7.1	6.2	24.6	30.8	0.3	0.9	1.2	66.59	89.9
	90% cut off	1.5	9.7	48.0	57.7	38.0	129.1	167.1	23.3	82.4	105.8	0.0	9.5	9.5	6.2	24.6	30.8	0.5	1.3	1.8	63.12	90.4
4-Sep-19	75% cut off	1.8	5.7	46.7	52.3	26.8	133.5	160.3	19.1	94.1	113.2	0.0	6.6	6.6	6.9	30.8	37.7	0.3	0.9	1.2	70.02	91.2
	80% cut off	1.8	6.7	50.2	56.8	31.6	144.3	175.8	20.4	96.0	116.4	0.0	7.1	7.1	6.9	30.8	37.7	0.3	1.2	1.6	66.22	89.8
	90% cut off	1.8	7.8	57.7	65.5	37.1	167.1	204.3	23.7	105.8	129.5	0.0	9.5	9.5	6.9	30.8	37.7	0.5	1.8	2.2	62.56	90.4
13-Sep-19	75% cut off	1.8	5.7	52.3	58.0	26.8	160.3	187.1	17.9	113.2	131.1	0.0	6.6	6.6	6.9	37.7	44.6	0.3	1.2	1.4	69.92	90.5
	80% cut off	1.8	6.7	56.8	63.5	31.6	175.8	207.4	19.6	116.4	136.0	0.0	7.1	7.1	6.9	37.7	44.6	0.3	1.6	1.9	65.59	88.8
	90% cut off	1.8	7.8	65.5	73.3	37.1	204.3	241.4	22.8	129.5	152.3	0.0	9.5	9.5	6.9	37.7	44.6	0.5	2.2	2.7	61.79	88.7
21-Sep-19	75% cut off	1.5	6.2	58.0	64.2	24.3	187.1	211.4	9.1	131.1	140.1	0.0	6.6	6.6	6.9	44.6	51.5	0.3	1.4	1.7	67.20	90.3
	80% cut off	1.5	7.5	63.5	71.0	29.5	207.4	236.9	10.5	136.0	146.5	0.0	7.1	7.1	6.9	44.6	51.5	0.3	1.9	2.2	64.82	88.6
	90% cut off	1.5	9.0	73.3	82.3	35.4	241.4	276.8	13.6	152.3	165.9	0.0	9.5	9.5	6.9	44.6	51.5	0.2	2.7	2.8	61.18	88.5
1-Oct-19	75% cut off	1.8	6.2	64.2	70.3	29.2	211.4	240.6	20.7	140.1	160.9	0.0	6.6	6.6	7.1	51.5	58.6	0.3	1.7	2.0	67.66	90.3
	80% cut off	1.8	7.2	71.0	78.2	33.9	236.9	270.9	21.5	146.5	168.0	0.0	7.1	7.1	7.1	51.5	58.6	0.3	2.2	2.6	64.65	89.1
	90% cut off	1.8	9.2	82.3	91.5	43.4	276.8	320.2	25.6	165.9	191.5	0.0	9.5	9.5	7.1	51.5	58.6	0.5	2.8	3.3	60.87	88.3

RESEARCH OUTPUTS

(i) Published paper in ASCE's Journal of Irrigation and Drainage Engineering

Investigating Cutoff Technique for Improved Water Saving and Productivity in Furrow Irrigation System

Benjamin L. Banda, S.M.ASCE[1]; Hans C. Komakech[2]; and Kelvin Mtei[3]

Abstract: The cutoff technique has not been adequately investigated despite being the most practiced among smallholder farmers. This study aimed at scenarios of improving water application efficiency, distribution uniformity, and productivity for the technique. Three cutoff treatments where water supply was stopped with the advance phases reaching 75%, 80%, and 90% of furrow length were investigated with eight irrigation events. Mean application efficiencies with significant difference ($P < 0.05$) of 70%, 66.4%, and 63% were achieved for the 75%, 80%, and 90% length cutoff treatments respectively. Corresponding uniformities and water productivities of 90, 89.9%, 89.2% and 1.54, 1.38, 1.18 kg/m^3, respectively, were obtained with no significant difference ($p > 0.05$). The results demonstrated the 75% cutoff has the potential of saving water of up to 26% without compromising water productivity. It is recommended therefore that the 75% cutoff position of water supply be promoted among the smallholder farmers and that research studies should now intensify for less than 75% cutoff. **DOI: 10.1061/(ASCE)IR.1943-4774.0001633.** *© 2021 American Society of Civil Engineers.*

Author keywords: Water productivity; Cutoff method; Root zone; Irrigation treatment; Subplot; Furrow head; Lekitatu.

Introduction

Worldwide, agriculture consumes about 70% of all freshwater withdrawals (Calzadilla et al. 2010). With undependable rain-fed agriculture, the agricultural policies of most developing countries are aligned to improving and upscaling irrigated agriculture (Siebert et al. 2013) to improve people's livelihoods and food security.

In expanding irrigation areas, surface irrigation systems remain widely practiced by both commercial and smallholder farmers (Keshavarz et al. 2020). Water is supplied by gravity to the farmland through a network of distribution and feeder canals and sometimes pipes. It is a preferred method over other methods such as drip, sprinkler, and center pivots because of its simplicity in terms of operation and maintenance and less capital investment (Keshavarz et al. 2020). Furrow irrigation is one kind of surface irrigation in which water is supplied to the field from a feeder canal through narrow depression channels known as furrows dug at specified and usually equal intervals with a nearly uniform slope (Assefa et al. 2017; Elsheikh et al. 2014). As water flows through these furrows, it infiltrates into the soil and spreads laterally to saturate the root zone where it is available for uptake by crop roots (Keshavarz et al. 2020).

Water application efficiency measures the portion of the total amount of water delivered to the field that is kept in the root zone to satisfy the crop water requirements (Irmak et al. 2011) and is usually expressed as a percentage. Water application efficiency pertains to an individual irrigation event. On the other hand, water distribution uniformity in irrigation is defined as the average infiltrated depth of water in the low quarter of the field divided by the average infiltrated depth over the whole field (Irmak et al. 2011; Walker 1989). Water productivity (WP) in crop production is defined as the relationship between crop produced and the amount of water transpired by the crop (Ali and Talukder 2008) and is an important measure of efficient use of water. It is expressed as a ratio of crop produced to the amount of beneficial water consumed by the crop during its growing season (Molden et al. 2010). Both water application efficiency and distribution uniformity affect crop yields and subsequently affect the overall WP. High application and distribution efficiencies of applied water within the entire root zone increase WP and vice versa.

In furrow irrigation, furrow characteristics (length and slope), irrigation technique, soil conditions, crop type, and weather conditions all affect water application efficiency and distribution uniformity.

Surface irrigation in general and furrow irrigation system in particular has low water application efficiency and productivity. Depending on different climatic conditions, soils and crop characteristics, and or water management practices, application efficiency for conventional furrow irrigation usually range from 45% to 65% (Irmak et al. 2011). This in turn greatly reduces the WP of the furrow irrigation system. With the continued dwindling of water resources, improvements in the existing methods of water application and water management practices therefore appear more to be more critical than before (Assefa et al. 2017; Sarwar et al. 2001).

Studies have investigated the effects of physical parameters such as slope, furrow length, and flow rates on water application efficiency, distribution uniformity, and productivity. Assefa et al. (2017) in their investigation, found application efficiencies ranging from 51.5% to 65% from different interactions of furrow lengths,

[1]Master's Candidate, Dept. of Water, Environmental Science and Engineering, Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha 23311, Tanzania (corresponding author). ORCID: https://orcid.org/0000-0003-1801-8279. Email: bandab@nm-aist.ac.tz

[2]Senior Lecturer, Dept. of Water, Environmental Science and Engineering, Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha 23311, Tanzania; Centre Director, WISE–Futures: Centre for Water Infrastructure and Sustainable Energy Futures, Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha 23311, Tanzania. Email: hans.komakech@nm-aist.ac.tz

[3]Senior Lecturer, Dept. of Water, Environmental Science and Engineering, Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha 23311, Tanzania; Dean, School of Business Studies and Humanities, Nelson Mandela African Institution of Science and Technology, P.O. Box 447, Arusha 23311, Tanzania. Email: kelvin.mtei@nm-aist.ac.tz

Note. This manuscript was submitted on November 17, 2020; approved on August 18, 2021; published online on October 4, 2021. Discussion period open until March 4, 2022; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, © ASCE, ISSN 0733-9437.

inflow rates, and furrow slopes. Higher application efficiency values were found for shorter furrow lengths and larger inflow rates. Similarly, Yigezu et al. (2016) found a mean application efficiency of 44 and a distribution uniformity of 54% by varying furrow length and flow rates.

Similarly, several irrigation methods have been investigated and have been shown to improve efficiency in furrow irrigation. These methods include surge flow, cutoff, cutback, and bunds or microdams. Issaka et al. (2015) in their study found average application efficiencies of 85% and 63% in the surge method and cutoff method, respectively, and distribution efficiencies of 94% and 81% in surge and cutoff methods, respectively. In a similar study done by Elsheikh et al. (2014), application efficiencies of 72% and 49% were achieved in surge and cutoff methods, respectively, while distribution efficiencies of 94% and 82% were achieved in surge and cutoff methods, respectively. Keshavarz et al. (2020) found that bunds or microdams constructed in furrows at 10 m spacing improved the application efficiency from 49% to 55% with a distribution efficiency of 99% and reduction of runoff losses of up to 45%. It is clear that the cutoff technique has been mainly investigated in comparison with other techniques (surge, bunds, cutback). Though these techniques have reported higher application and distribution efficiencies, they require additional labor for controlling the on and off supply and for making bunds in furrows that usually become erodible after each irrigation event. Further, the studies have been limited to investigating the improvement in application and distribution efficiencies (Elsheikh et al. 2014; Issaka et al. 2015; Mohammed et al. 2015), while the ultimate motivation for smallholder farmers to adopt a technique is productivity improvement. This paper therefore reports the findings of a study aimed at investigating three scenarios for the cutoff irrigation technique to improve water application efficiency and distribution uniformity and productivity.

Materials and Methods

Study Area Description

The field experiment was carried out at Lekitatu Irrigation Scheme located in Meru district, Arusha Region, Tanzania. The scheme area is about 826 ha. The climate is semiarid, where the mean annual evapotranspiration is 6.03 mm/day, average annual rainfall is 816 mm, and mean annual temperature is 22.4°C. The main sources of water for the scheme are rivers originating from the slopes of Mount Meru.

Experimental Setup

The field experiment was carried out at Lekitatu Irrigation Scheme located in Meru district, Arusha Region, Tanzania. The scheme area is about 826 ha. The climate is semiarid, where the mean annual evapotranspiration is 6.03 mm/day, average annual rainfall is 816 mm, and mean annual temperature is 22.4°C. The main sources of water for the scheme are rivers originating from the slopes of Mount Meru.

The experimental plot as presented in Fig. 1, which is a major modification of Assefa et al. (2017) study plot, was set up in line with the orientation of major and minor slopes to achieve the best water delivery. The parameter treated was the position of the advance phase of the water applied along the run of the furrow before stopping the water supply at the furrow head. The 90% position of the furrow length was chosen as close to the reality of common practice by smallholder farmers where water is applied to the full length of furrow The 75% position was adopted from a previous study (Issaka et al. 2015) though the study itself used the full furrow length. The 80% was chosen to strike a balance. There were three replicated subplots [Fig. 2(a)] with similar characteristics such as soil type/properties, slope, and climatic conditions. Within each subplot, there were three furrow sets consisting of five furrows each. In each furrow set, the inner three furrows were used for monitoring irrigation events and the two outer furrows acted as buffers. A V-notch weir Fig. 2(b)] was installed at the head of the feeder canal, just before the water reaches the experimental plot, to measure incoming flowrate. At the end of the last furrow in each furrow set, a hole was dug out for surface runoff collection.

Collection of Topographic, Soil, and Climate Data

The topography of the area was established by the use of handheld GPS for x and y coordinates while the dumpy level was used to measure the elevations. A measuring tape was used to obtain the horizontal distances.

Soil samples were taken using soil augers at each of the nine established sampling stations, three in each of the subplot. Three samples were taken from each pit at the depths of 0–30, 30–60, and 60–100 cm, thus covering the entire effective root zone for maize (Savva and Frenken 2002a). The samples were then transported in sealed plastic bags for laboratory analysis. Samples from corresponding depths for the pits in a subplot were mixed to form a composite sample for the particular depth(s) and then resampling was done for sieve analysis.

Soil texture was determined through sieve analysis using a standard operating procedure based on ASTM D422-63(2007)e2 (ASTM 2007), Standard Test Method for Particle Size Analysis of Soils. The results of the analysis were interpreted using the USDA textural triangle. Bulk density was estimated by the core method also known as the volumetric cylinder method (Al-Shammary et al. 2018; Ali 2010; Yang et al. 2016; Zolfaghari et al. 2016) Using the standard laboratory procedure, soil pH was measured by a pH meter after the meter had been calibrated with standard buffer solutions of pH 4, 7, and 9.2. This procedure was repeated for all other samples. Following the same procedure as in soil pH determination, soil EC was measured by a conductivity meter after it was calibrated with pH 4 and pH 7 buffer solutions. Both the pH and EC affects water movement in the soil as the dissolved ions occupy pore water spaces (Visconti and de Paz 2016)

Measurement of Initial and Subsequent Soil Moisture Levels

Initial soil moisture for the root zone was measured concurrently with the bulk density. Moisture content before and after each irrigation event was measured for the entire irrigation season. One sample from each of the depths 0–30, 30–60, and 60–90 cm was taken in each of the three subplots. For continuity of data, observations were maintained at the same locations through the placing of physical pegs and matching of Universal Transverse Mercator (UTM) coordinates taken by handheld GPS (Garmin GPSMAP 64 s series with as low as 1 m accuracy) that was available for the entire period of the experiment. The samples were weighed before being oven dried for 24 h or to a constant weight at 105°C (Al-Shammary et al. 2018; Savva and Frenken 2002b), and the dried samples were then weighed again. The soil moisture was then calculated using the following relationship:

$$M_c = \frac{W_w - W_d}{W_d} \times 100 \quad (1)$$

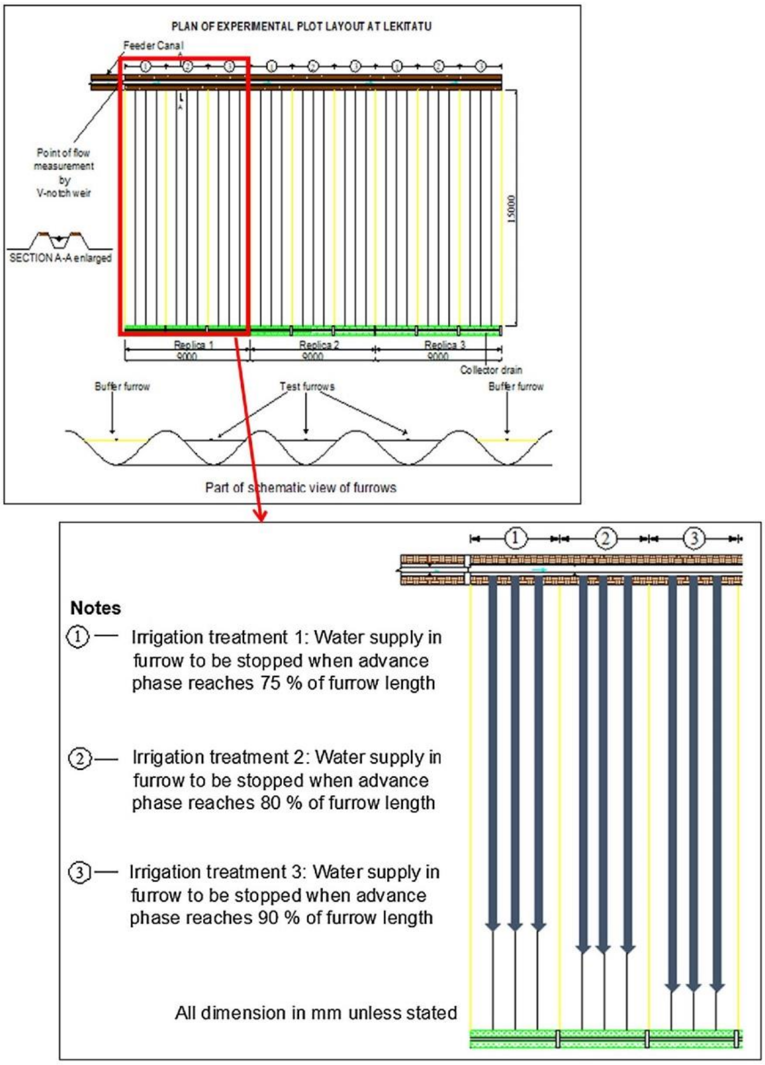


Fig. 1. Experimental plot layout. (Data from Assefa et al. 2017.)

where M_c = soil moisture content (%); W_w = weight of wet soil before oven drying (g); and W_d = weight of dry soil after oven drying (g).

Historical climatic data (rainfall, temperature, relative humidity, solar radiation, and wind speed) for Lekitatu spanning 32-year (1985–2017) (03°23'15.6"S latitude, 36°50'51.9"E longitude and 1,162 m above mean sea level altitude) was accessed from NASA POWER [Prediction of Worldwide Energy Resource (LaRC)], while the part of 2019 season data were measured by the installed automatic weather station at Lekitatu scheme. The directly measured data on site were specifically to validate the long-term historical data other than rainfall obtained from Nasa power. The validation showed considerable variations in solar radiation, wind, and relative humidity (Tables 3 and 4), while for temperature, the data from the two sources were almost the same.

Measurement of Water Application Efficiency and Distribution Uniformity and Productivity

1. *Calculation of reference evapotranspiration (ETo)*

   Climate data were used to estimate reference evapotranspiration. In an attempt to compare the resulting ETo, two methods were used to estimate reference evapotranspiration, the CROPWAT version 8.0 software of the FAO and the simple temperature method developed by Enku and Melesse (2014). For the CROPWAT software version 8.0, data for minimum and maximum temperature, wind speed, solar radiation, relative humidity, and sunshine hours were inputted into the software to estimate the ETo. In the simple temperature method, the long-term daily maximum temperature was used together with developed constants.
2. *Estimation of crop water requirements and irrigation water requirements*

(a) (b)

Fig. 2. Set up of the experimental plot: (a) replicated sub-plots; and (b) V-notch weir for flow observation and control.

Crop water requirements, which refer to water required for crop cell development and transpiration, were calculated using the CROPWAT software version 8.0, which is based on soil water balance by inputting data for the study area. The data included reference ETo, rainfall data, soil water data, and crop data.

Data input for crop included crop planting dates, crop coefficient (Kc) based on the crop type (maize in this case) and stages of growth, duration of growth stages, crop rooting depth at the various growth stages, allowable soil moisture depletion levels, and yield response factors (Ky). Global values as outlined in Allen et al. (1998) were used as crop data with the length of growth stages adjusted to suit local conditions. The values covered the initial, mid, and late growing stages of the crop.

Effective rainfall was calculated from the rainfall data using the most commonly used USDA soil conservation method embedded within the CROPWAT software.

The soil water characteristics were obtained from the soil analysis and the parameters such as readily available moisture, which is the difference between the moisture at field capacity and wilting point, infiltration rate, maximum rooting depth, and initial depletion levels.

After the input of all the presented data, the CROPWAT then calculated the crop water and irrigation requirements for the maize crop. The program assumes all months have 30 days subdivided into three decades of 10 days each, and the crop water requirements are calculated on a decade (10-day) basis.

3. *Planting and irrigation management*

Before planting, the entire plot was supplied with initial water to attain field capacity moisture content and the quantity of water supplied was recorded. After 24 h, in each of the subplots, maize seed was planted with two seeds per hole at 30 cm spacing between holes along each row and the rows spaced at 75 cm.

All the subplots received water from the same water source and feeder canal. The quantity of irrigation water conveyed to the experimental plots per unit time was measured using a 90° V notch weir. The discharge through the weir is a function of water level, and water level above the crest of the weir was measured using a staff gauge. The discharge through a V-notch weir is determined using the following general relationship (Henderson 1996):

$$Q = \frac{8}{15} C_d H^{5/2} \sqrt{2g} \tan\frac{\theta}{2} \quad (2)$$

where Q = quantity of irrigation water (m^3/s); H = height of water above the weir crest (m); θ = vertex angle of the weir crest (degrees); C_d = coefficient of discharge (unit less); and g = acceleration due to gravity (m/s^2). Just before the point of discharge measurement, a stabilizer/energy dissipating ditch was constructed to facilitate the control and measurement of the incoming discharge.

Eight irrigation events were applied to the three irrigation treatments. In the first treatment (replica 1), water supply at the head of the furrows was stopped when the advance phase reached 75% of the furrow length. For the second treatment, the supply was stopped with the advance water reaching 80% of the furrow length. Finally, in the third treatment, the water supply was stopped when the advance phase reached 90% of furrow length, and this generally complies with the local practice in the study area. Time taken to complete irrigating each plot was recorded to help calculate the total amount of water applied to each plot.

4. *Measurement of water application efficiency*

The field water application efficiency was calculated from the following relationship (Issaka et al. 2015):

$$E_a = \frac{W_{rz}}{W_f} \times 100 \quad (3)$$

where E_a = water application efficiency as a percentage; W_{rz} = amount of irrigation water stored in the root zone during irrigation (mm); and W_f = total amount of irrigation water delivered to the farm (mm).

The amount of water stored in the root zone was determined through conducting water balance whereby components such as deep percolation and runoff were taken out of the equation to calculate the water remaining in the root zone, part of which is responsible for the crop evapotranspiration as indicated in this relationship

$$W_{rz} = I + R_{eff} - D_{per} - S_{run} \quad (4)$$

where I = the amount of irrigation water applied that remains in the effective root zone (mm); R_{eff} = effective rainfall (mm);

J. Irrig. Drain Eng., 2021, 147(12): 04021059

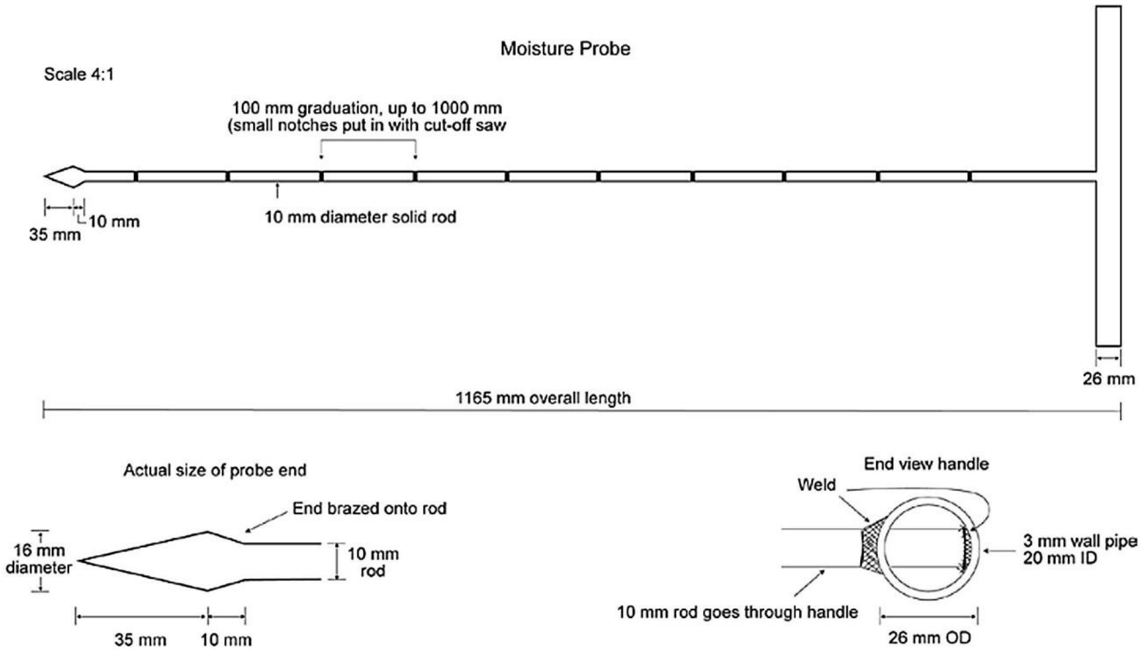


Fig. 3. Manually fabricated soil moisture probe as per NSW Department of Primary Industries specifications.

W_{rz} = amount of irrigation water stored in the root zone during irrigation and/or rainfall event (mm); D_{per} = water loss out of the effective root zone due to deep percolation (mm) and depend on the permeability of the soil; and S_{run} = soil surface runoff dependent on infiltration rate of the soils and surface slope (mm)

The V-notch flowrate and the duration of the irrigation were used to calculate the total depth of water applied (Abd El-Halim and Abd El-Razek 2014) using the following formula:

$$d = Qt \times \frac{1000}{A} \tag{5}$$

where d = amount of water (mm); Q = discharge over the V-notch (m^3/min); and t = time (min) taken to fully irrigate plot of area A (m^2).

Surface runoff (S_{run}) was measured by dug-out holes located at the end of each furrow set. The hole was lined inside with a polyethylene sheet to prevent water percolation. The collected water was converted into mm depth covering each furrow set by the following conversion:

$$S_{run} = V_{sr}/A \tag{6}$$

where S_{run} = soil surface runoff (mm); V_{sr} = volume of surface runoff collected in the dug-out hole (liters); and A = area of the furrow set (m^2).

Deep percolation (D_{per}) was measured using the soil moisture probe, subtracting the depth of water that went beyond the root zone depth at each growing stage of the crop. In addition, for the relatively high water holding capacity of the soils, deep percolation was almost negligible as all the waters remained within the root zone.

On each rainy day, rainfall amount was recorded by an automatic weather instrument installed within the study area. Effective rainfall was then calculated using the USDA S.C. method

5. *Measurement of water distribution uniformity*

In order to find the actual depth of infiltrated water, within 24 h after each irrigation event, water depth measurements were taken at nine locations in each furrow set. The depths of infiltrated water were measured by use of the manually fabricated soil moisture probe based on New Mexican State University Guide H-637. PH 4-206 "A Practical Way of Measuring Soil Moisture" and the September 2014 Primefact 1351 second edition by the NSW Department of Primary Industries "Making a soil moisture probe," as shown in Fig. 3. Measuring the depth uses the principle that the probe penetrates easily through the wetted soil profile but finds resistance when it reaches dry soil. The number of graduations that penetrated the soil before meeting resistance was counted. The in-between readings were confirmed with a measuring tape. The distribution uniformity was then calculated by applying the lower one-quarter principle in Eq. (7) as described by Walker (1989) and Irmak et al. (2011)

$$DU = \frac{D_{lp}}{D_{av}} \times 100 \tag{7}$$

where DU = distribution uniformity (%); D_{lp} = average depth of water infiltrated in the lower one-quarter of the field (mm); and D_{av} = average depth of water infiltrated over the field (mm)

6. *Measurement of WP*

WP was calculated according to Rodrigues and Pereira (2009) as follows:

$$WP = \frac{GY}{A_w} \quad (8)$$

where $WP =$ WP (to be measured in kg/m^3); GY = grain yield (to be measured kg/ha); and A_w = total amount of water consumed (m^3/ha).

The yield was estimated for both plots through measurement of the dried maize cobs. The grain from the cobs was then weighed using an electronic scale. Then, the results were extrapolated to represent production per hectare in each case. The total amount of water on the other hand was found by doing water balance for the root zone after each irrigation event during the entire growing season as follows (Allen et al. 1998):

$$\sum ETc = \sum ETo \times Kc \quad (9)$$

where ETc = the amount of irrigation water applied that is taken up by the plant roots and transpired through the leaves (mm); ETo = amount of that goes into the atmosphere due to crop transpiration and surface evaporation (mm); and Kc = crop factor

The total amount applied in m^3 was found by converting the amount in millimeters into meters and then multiplying by the total area of the irrigated field.

Data Analysis

To check for standard error, significance among others, the results were put to statistical analysis, multiple comparisons by applying the Tukey post hoc test on one-way ANOVA at 95% confidence level. SPSS software was used in the statistical analysis.

Results

Physical Characteristics of the Subplots

The topographic survey established slopes in each subplot, one being the average slope of 3.3% running from the top to the lower end of the plot along the feeder canal and the other was 2.59% along the furrow runs.

Table 1 summarizes results for the analysis of key physical properties of the soil in the experimental plot. From the results of particle size distribution and with reference to the USDA soil textural triangle, the soils were classified as sandy loam. For sandy loam soil, moisture content at field capacity (FC) and permanent wilting point (PWP) is 21% and 9%, respectively, giving readily available moisture of 12%, and the infiltration rate is 33.5 mm/hr (Savva and Frenken 2002b)

Crop Water and Irrigation Requirements

As a safety net, the CROPWAT climate and rainfall data (Table 2) were used to calculate crop water and irrigation requirements as values for ETo were higher than those from the Enku method. The water and irrigation requirements were adjusted in the field depending on the prevailing rainfall events (Table 3) and initial soil moisture conditions. Table 4 shows CROPWAT's calculated crop water and irrigation requirements for the maize crop on a decade (10-day) basis.

Water Applied

Table 5 summarizes the amount of water applied and the amount that remained in the root zone for crop uptake. The average flowrate, which was constant each day, was 1.4 L/s. The amounts of

Table 1. Selected physical characteristics of the subplots

		Physical properties of plot soils						
		Particle size distribution (%)						
Subplot no.	Furrow slope (%)	Sand	Silt	Texture class	Bulk density (g/cm^3)	EC (dS/m)	pH	Initial moisture content (%)
1	2.59	68.7	31	Sandy loam	1.42	0.198	7.06	14.8
2	2.58	68.9	31	Sandy loam	1.42	0.198	7.07	14.8
3	2.59	69.4	31	Sandy loam	1.41	0.198	7.06	14.8

Table 2. Long-term climatic data and calculated ETo and effective rainfall for Lekitatu

Month	Minimum temperature (°C)	Maximum temperature (°C)	Humidity (%)	Wind (/s)	Sunshine (h)	Radiation (MJ/m^2/day)	Rain (mm)	ETo[a] (mm/day)	ETo[b] (mm/day)
January	15.2	30.9	56.0	2.1	12.1	28.0	51.5	6.1	5.3
February	15.4	31.9	52.0	2.0	12.1	28.6	45.7	6.4	5.5
March	16.0	31.8	56.0	1.9	12.0	28.4	113.5	6.2	5.5
April	16.0	29.7	66.0	2.0	12.0	27.2	263.5	5.6	5.1
May	14.1	28.2	68.0	2.4	11.5	24.7	115.1	5.0	4.8
June	12.3	28.0	61.0	2.6	11.5	23.7	16.9	5.0	4.6
July	11.7	28.2	54.0	2.9	11.5	24.1	7.2	5.4	4.6
August	12.6	29.6	50.0	3.0	12.0	26.3	6.3	6.2	4.7
September	13.9	31.6	45.0	3.0	12.0	27.8	10.5	6.9	5.1
October	15.1	32.4	46.0	2.8	12.1	28.4	25.5	7.1	5.3
November	16.2	31.2	56.0	2.4	12.1	28.0	82.3	6.3	5.2
December	15.8	30.6	59.0	2.3	12.2	27.8	78.1	6.1	5.2

[a]ETo values calculated using the CROPWAT version 8.0 software.
[b]ETo values calculated using the Enku method.

Table 3. Weather data measured by the installed automatic weather station

Measurement date	Minimum temperature (°C)	Maximum temperature (°C)	Relative humidity (%)	Wind (m/s)	Solar adiation (W/m^2)	Rainfall (mm)
May	16.2	30.1	90.5	0.4	129	280.8
June	12.7	28	83.5	0.4	122	2.3
July	9.8	29.1	77.1	0.5	159.3	0.9
August	13.1	29.7	76.6	0.5	177.7	21
September	13	30.4	70.3	0.6	230.6	0
October	17.6	31.1	84	0.6	205.6	313.3
November	17.9	32.2	81	0.6	230.7	79.9
December	14.6	31.7	85	0.6	204.6	118.7

Table 4. Estimated crop water and irrigation requirements for maize in the study plot

Month	Stage	Kc (coefficient)	ETc (mm/day)	ETc (mm/dec)	Eff rain (mm/dec)	Irr. Req. (mm/dec)
August 1–10	Init	0.7	4.1	33.1	1.6	31.1
August 11–20	Init	0.7	4.3	43.0	1.9	41.2
August 21–30	Deve	0.8	5.0	54.7	2.4	52.3
September 1–10	Deve	1.0	6.5	64.7	2.7	62.0
September 11–20	Deve	1.2	8.0	80.0	3.0	77.1
September 21–30	Mid	1.3	8.8	87.7	4.7	83.0
October 1–10	Mid	1.3	8.8	88.2	5.5	82.7
October 11–20	Mid	1.3	8.9	88.7	6.6	82.1
October 21–30	Mid	1.3	8.6	94.3	12.3	82.0
November 1–10	Mid	1.3	8.3	82.8	20.2	62.6
November 11–20	Late	0.9	5.8	57.9	26.2	31.7
				775.2	87.1	687.6

Note: Eff rain = Effective rainfall; dec = decade.

Table 5. Water applied to the field and remained in the root zone for crop evapotranspiration

Irrigation treatment	Total water applied (mm)				Actual water in root zone (mm)			
	Rep 1	Rep 2	Rep 3	Mean	Rep 1	Rep 2	Rep 3	Mean
75% cutoff	235	253	235	241	168	172	168	169
80% cutoff	265	284	264	271	174	182	173	176
90% cutoff	318	341	316	325	196	206	194	199

Note: Rep 1,2,3 = Replica 1,2,3.

Table 6. Results for application efficiencies (Ea) and Distribution Uniformities

	Application efficiency, Ea (%)			Distribution efficiency, DU (%)		
	Irrigation treatment			Irrigation treatment		
Replica no.	75% cutoff	80% cutoff	90% cutoff	75% cutoff	80% cutoff	90% cutoff
Rep 1	70.8	66.8	63.6	90.3	89.9	89.3
Rep 2	67.9	65.4	62.0	90.6	89.5	88.7
Rep 3	71.2	67.1	63.4	89.1	90.0	89.5
Mean	70.0	66.4	63.0	90.0	89.8	89.2

water within the treatments were generally the same while across the treatments with the 0.9 cutoff receiving more water than the rest.

Application Efficiency

Table 6 shows the application efficiency for each treatment in each replica. The 75% cutoff gave the highest application efficiency (Ea) while the 90% cutoff yielded the lowest. Fig. 4 gives the mean Ea value for each treatment; 75% cutoff gave the average highest Ea of 70%, while the 90% achieved 63% Ea.

In Table 7, multiple comparisons of the means indicate which group is different from each other. The Tukey post hoc test conducted on a one-way ANOVA revealed a statistically significant difference in application efficiency between the 75% cutoff and the 80% cutoff treatments ($p = 0.003$), between the 75% cutoff and the 90% cutoff ($p < 0.001$) as well as between the 80% cutoff and the 90% cutoff ($p = 0.046$).

Distribution Uniformity

Table 6 shows that distribution uniformity (DU) had a slightly different trend from Ea. Replica 3 had a different trend where the 80% cutoff gave a better DU than the other two treatments in the replica possibly due to slight variations of the in-furrow slope. However, on average, as depicted in Fig. 5, the highest DU of 90% was in the 75% cutoff and the lowest DU of 89.2% was in the 90% cutoff.

Multiple comparisons in Table 8 revealed a statistically nonsignificant difference in DU between the 75% cutoff and the 80% cutoff treatments ($p = 0.430$), between the 75% cutoff and the 90% cutoff ($p = 0.539$), as well as between the 80% cutoff and the 90% cutoff ($p = 0.981$).

Yield and WP

Table 9 indicates a higher yield for the 90% cutoff than the rest of the treatments. However, in terms of WP, the 75% cutoff produced the highest WP, as shown in Fig. 6 The results had a statistically significant difference ($p < 0.05$) for all the combinations, as revealed by the Tukey post hoc test (Table 10).

Discussion

As seen from the results, the treatments with a furrow length of 0.75 achieved the highest average application efficiency of 70.0%. As all the three treatments had similar soil (sandy loam) and slope characteristics, this difference could be attributed to the fact that since the water was stopped at 0.75 of furrow length, the remaining 0.25 of furrow length was adequate enough to accommodate all the recession water that was coming from the furrow head. Thus, there was less water that was lost as runoff or as deep percolation compared to the other two treatments. On the other hand, the treatments with a furrow length of 0.90 achieved the lowest average application efficiency of 63% for the fact that some of the remaining 10% dry portion of the furrow length was not adequate enough to contain all the recession water and therefore more water reached the drain as runoff compared to the other two treatments. These results fall within the range of findings obtained in other studies in which the application efficiency ranged from 64% to 71% for the cutoff method (Elsheikh et al. 2014; Issaka et al. 2015; Mohammed et al. 2015) and was conducted on the same soil type. These results are therefore representative of similar studies carried out on similar characteristics of soil and topography.

For the DU, all the treatments involved cutting the water supply before the advance phase reached the tail end of the furrow. This generally improved the DU as the time for the ponding phase which usually results into deep percolation at the upper section of the furrow, was reduced. The treatment with water cut-off position at 0.75 of furrow length had a slightly higher uniformity than the other treatments, and this is attributed to the fact that the remaining 20% furrow run was adequately watered by the ponding and recession phases coupled with a suitable volume of water required to complete an advance that gives the potential to increase the DU. These results also agree with the findings obtained by similar studies in which DU ranged from 85% to 91% for the cutoff method (Elsheikh et al. 2014; Issaka et al. 2015; Mohammed et al. 2015).

Regarding the three replicas, there were very small differences for both application efficiency and DU. This was attributed to the fact that the three replicas had almost identical physical properties that were analyzed, ranging from soil type and other properties, field slope, and were all irrigated with the same common feeder canal (meaning same water quality) and same flow rate. The bigger furrow slope of the field (2.6%) provided less time (opportunity

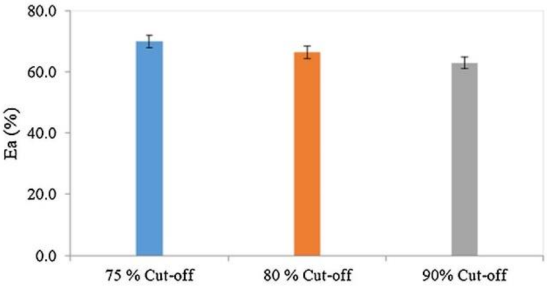


Fig. 4. Mean water application efficiency for each treatment.

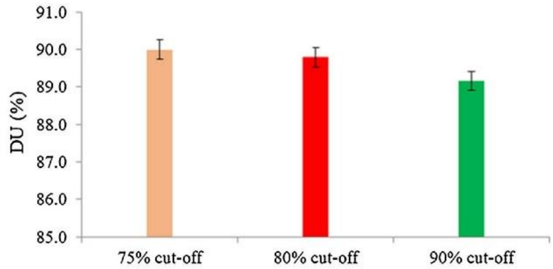


Fig. 5. Average water DU.

Table 7. Statistical analysis of the variation in application efficiency among the treatments

Multiple comparisons						
Dependent variable: Application efficiency (%)						
Tukey HSD						
					95% Confidence interval	
(I) Treatment	(J) Treatment	Mean difference (I-J)	Standard error	Sig.	Lower bound	Upper bound
75% cutoff	80% cutoff	5.4309[a]	1.4117	0.003	1.873	8.989
	90% cutoff	9.0396[a]	1.4117	<0.001	5.481	12.598
80% cutoff	75% cutoff	−5.4309[a]	1.4117	0.003	−8.989	−1.873
	90% cutoff	3.6087[a]	1.4117	0.046	0.050	7.167
90% cutoff	75% cutoff	−9.0396[a]	1.4117	<0.001	−12.598	−5.481
	80% cutoff	−3.6087[a]	1.4117	0.046	−7.167	−0.050

Note: Sig. = significance.
[a]The mean difference is significant at the 0.05 level.

Table 8. Statistical analysis of the variation in DU among the treatments

Multiple comparisons

Dependent variable: Distribution uniformity (%)

Tukey HSD

(I) Treatment	(J) Treatment	Mean difference (I-J)	Standard error	Sig.	95% Confidence interval Lower bound	Upper bound
75% cutoff	80% cutoff	0.6719	0.5316	0.430	−0.668	2.012
	90% cutoff	0.5722	0.5316	0.539	−0.768	1.912
80% cutoff	75% cutoff	−0.6719	0.5316	0.430	−2.012	0.668
	90% cutoff	−0.0997	0.5316	0.981	−1.440	1.240
90% cutoff	75% cutoff	−0.5722	0.5316	0.539	−1.912	0.768
	80% cutoff	0.0997	0.5316	0.981	−1.240	1.440

Note: Sig. = significance.

Table 9. Yield and WP results from the three treatments

Replica no.	Yield (kg/ha) Irrigation treatment 75% cutoff	80% cutoff	90% cutoff	Water productivity (kg/m^3) Irrigation treatment 75% cutoff	80% cutoff	90% cutoff
Rep 1	8,341	8,415	8,593	1.58	1.41	1.20
Rep 2	8,356	8,430	8,622	1.47	1.32	1.12
Rep 3	8,356	8,445	8,652	1.58	1.42	1.22
Mean	8,351	8,430	8,622	1.54	1.38	1.18

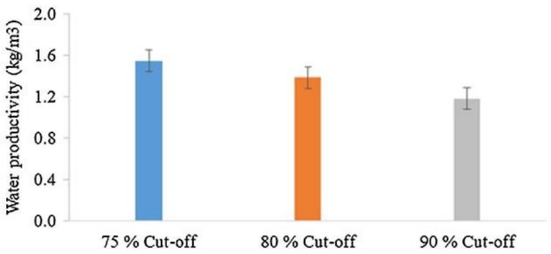


Fig. 6. WP for each treatment in each of the three subplots.

time) for the ponding phase, thereby reducing deep percolation. This agrees with the findings of Assefa et al. (2017) on the effect of slope on DU. Additionally, except for the first irrigation event where applied depth exceeded the initial rooting depth, the subsequent applications were within the crop rooting zone, making the deep percolation negligible. This was made possible through the adjustments in the flow rate between irrigation events but also due to the generally high water holding capacity of the sandy loam type of soil.

For WP, though the difference is nonsignificant among the treatments, the highest WP of 1.58 kg/m^3 was attained in the 75% cutoff treatment, followed by the 80% cutoff, and then the 90% cutoff being the lowest. These results are in tandem with the trend in water application efficiency and DU values obtained in this experiment.

Table 10. Statistical analysis of the variation in WP among the treatments

Multiple comparisons

Dependent variable: Water productivity (%)

Tukey HSD

(I) Treatment	(J) Treatment	Mean difference (I-J)	Standard error	Sig.	95% confidence interval Lower bound	Upper bound
75% cutoff	80% cutoff	0.1598[a]	0.0470	0.034	0.015	0.304
	90% cutoff	0.3636[a]	0.0470	0.001	0.219	0.508
80% cutoff	75% cutoff	−0.1598[a]	0.0470	0.034	−0.304	−0.015
	90% cutoff	0.2039[a]	0.0470	0.012	0.060	0.348
90% cutoff	75% cutoff	−0.3636[a]	0.0470	0.001	−0.508	−0.219
	80% cutoff	−0.2039[a]	0.0470	0.012	−0.348	−0.060

Note: Sig. = significance.
[a]The mean difference is significant at the 0.05 level.

The WP values in general are within a range of values found by other studies such as Abd El-Halim and Abd El-Razek (2014) who reported the highest value of 1.09 kg/m^3 and Moayeri et al. (2011) who reported an average WP of 1.45 kg/m^3. In experiments with controlled environments (usually at research stations where the recommended agronomic practices such as plant population, water application, pest control, and fertilizer application are strictly followed and done at the right time) higher WP values are realized. In a controlled experiment investigating the WP of maize grown, Trout and DeJonge (2017) found a WP of 2.0 kg/m^3 with 630 mm of crop evapotranspiration.

Conclusions

The study has shown that varying the cutting off of irrigation supply in a furrow system in relation to the position of the advance water has a bearing on both water application efficiency and DU. From the investigated three treatments, it was evident that cutting off supply when the advance phase reaches 0.75 of furrow length has the potential to save water of up to 26% without compromising water application efficiency, water DU, or WP. This saved water could be allocated to other uses or be used to cultivate extra area thereby increasing production. Further, the study showed at least 13.6% of time spent on irrigation could be saved by following the 0.75 cutoff technique that could be utilized in other productive activities. As the study was conducted in sloping conditions above the recommended slope range of 0.05%–0.5% furrow irrigation (Brouwer et al. 1988; James 1988) and with an average inflow rate of 1.4 L/s, the results of application efficiency, DU, and WP are not much different from those conducted on more gentle slopes. With the limited available land for irrigation (due to population pressure), the cutoff technique would be very useful to apply in areas with slopes greater than 2% and for inflow rates higher than 1 L/s to ensure uniform distribution and higher productivity while at the same time avoiding high runoff losses and soil erosion.

As monitoring the physical position of cutoff is easier than varying the flow rate with time, it is recommended that the cutoff position be promoted among the smallholder farmer schemes where water regulating structures are scarce.

Data Availability Statement

Some or all of the data that support the findings of this study are available from the corresponding author on request.

- Data on field experiment measurements,
- Climate data used to calculate potential evapotranspiration and irrigation water requirements,
- CROPWAT software and its outputs,
- SPSS software outputs,
- Soil analysis, and
- Installed weather station data measurements from April 2019 to December 2019.

Acknowledgments

This study was supported by the Government of Malawi and WISE-Futures of the Nelson Mandela African Institution of Science and Technology, Tanzania.

Notation

The following symbols are used in this paper:

A = area (m^2 as specified);
C_d = coefficient of discharge (unit less);
D_{av} = average depth of water infiltrated over the field (mm);
D_{lp} = average depth of water infiltrated in the lower one-quarter of the field (mm);
D_{per} = deep percolation (mm);
D_U = distribution uniformity (%);
d = amount of water (mm);
E_a = water application efficiency as percentage;
g = acceleration due to gravity (m/s^2);
H = height of water above the weir crest (m);
I = amount of irrigation water applied that remains in the effective root zone (mm);
Q = quantity of irrigation water (m^3/s or as indicated);
M_c = soil moisture content (%);
R_{eff} = effective rainfall (mm);
S_{run} = soil surface runoff (mm);
t = time (min);
V_{sr} = volume of surface runoff (L);
W_d = weight of dry soil after oven drying (g);
W_f = total amount of irrigation water delivered to the farm (mm);
W_{rz} = amount of irrigation water stored in the root zone during irrigation (mm);
W_{rz} = amount of irrigation water stored in the root zone during irrigation and/or rainfall event (mm);
W_W = weight of wet soil before oven drying (g); and
θ = vertex angle of the weir crest (degrees).

References

Abd El-Halim, A. E.-H. A., and U. A. E.-H. Abd El-Razek. 2014. "Effect of different irrigation intervals on water saving, water productivity and grain yield of maize (Zea mays L.) under the double ridge-furrow planting technique." *Arch. Agron. Soil Sci.* 60 (5): 587–596. https://doi.org/10.1080/03650340.2013.825900.

Ali, H. 2010. Vol. 1 of *Fundamentals of irrigation and on-farm water management*. New York: Springer.

Ali, M., and M. Talukder. 2008. "Increasing water productivity in crop production—A synthesis." *Agric. Water Manage.* 95 (11): 1201–1213. https://doi.org/10.1016/j.agwat.2008.06.008.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. "Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56." *FAO, Rome* 300 (9): D05109.

Al-Shammary, A. A. G., A. Z. Kouzani, A. Kaynak, S. Y. Khoo, M. Norton, and W. Gates. 2018. "Soil bulk density estimation methods: A review." *Pedosphere* 28 (4): 581–596. https://doi.org/10.1016/S1002-0160(18)60034-7.

Assefa, S., Y. Kedir, and T. Alamirew. 2017. "Effects of slopes, furrow lengths and Inflow rates on irrigation performances and yield of sugarcane plantation at Metehara, Ethiopia." *Irrig. Drain. Syst. Eng.* 6 (179): 2. https://doi.org/10.4172/2168-9768.1000179.

ASTM. 2007. *Standard test method for particle-size analysis of soils (withdrawn 2016).* ASTM D422-63(2007)e2. West Conshohocken, PA: ASTM.

Brouwer, C., K. Prins, M. Kay, and M. Heibloem. 1988. "Irrigation water management: Irrigation methods." *Training Manual* 9 (5): 5–7.

Calzadilla, A., K. Rehdanz, and R. S. Tol. 2010. "The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis." *J. Hydrol.* 384 (3–4): 292–305. https://doi.org/10.1016/j.jhydrol.2009.12.012.

Elsheikh, M. A. E., A. E. E. Mohamed, and S. A. Salih. 2014. "Effect of some techniques on long furrow irrigation efficiency." *Proc., Int. Conf. on Biological, Civil and Environmental Engineering (BCEE-2014)*. Phuket, Thailand: International Institute of Chemical, Biological and Environmental Engineering. https://doi.org/10.15242/IICBE.C0314187.

Enku, T., and A. M. Melesse. 2014. "A simple temperature method for the estimation of evapotranspiration." *Hydrol. Processes* 28 (6): 2945–2960. https://doi.org/10.1002/hyp.9844.

Henderson, F. M. 1996. *Open channel flow*. New York: MacMillan Publishing.

Irmak, S., L. O. Odhiambo, W. L. Kranz, and D. E. Eisenhauer. 2011. *Irrigation efficiency and uniformity, and crop water use efficiency*. Biological Systems Engineering: Papers and Publications. 451. Lincoln, NE: Univ. of Nebraska–Lincoln.

Issaka, R., H. Ibrahim, and M. Issah. 2015. "Performance evaluation of furrow lengths and field application techniques." *Int. J. Sci. Technol. Res.* 4 (10): 278–281.

James, L. G. 1988. *Principles of farm irrigation systems design*. New York: Wiley.

Keshavarz, M. S., H. Ebrahimian, F. Abbasi, and E. Playán. 2020. "Effect of micro-dams on water flow characteristics in furrow irrigation." *Irrig. Sci.* 38 (3): 307–319. https://doi.org/10.1007/s00271-020-00674-3.

Moayeri, M., E. Pazira, H. Siadat, F. Abbasi, and F. Kaveh. 2011. "Influence of planting and irrigation management methods on maize water productivity improvement in a semiarid region." *World Appl. Sci. J.* 13 (5): 1218–1228.

Mohammed, A., N. Abdeen, and A. R. Hamid. 2015. "Effect of irrigation technique on the efficiency of furrow irrigation." In *Proc., Int. Conf. on Chemical, Environmental and Biological Sciences (CEBS-2015)*, 18–19. Phuket, Thailand: International Institute of Chemical, Biological and Environmental Engineering. . https://doi.org/10.15242/IICBE.C0315068.

Molden, D., T. Oweis, P. Steduto, P. Bindraban, M. A. Hanjra, and J. Kijne. 2010. "Improving agricultural water productivity: Between optimism and caution." *Agric. Water Manage.* 97 (4): 528–535. https://doi.org/10.1016/j.agwat.2009.03.023.

Rodrigues, G. C.; and L. S. Pereira. 2009. "Assessing economic impacts of deficit irrigation as related to water productivity and water costs." *Biosyst. Eng.* 103 (4): 536–551.

Sarwar, A., W. G. Bastiaanssen, and R. Feddes. 2001. "Irrigation water distribution and long-term effects on crop and environment." *Agric. Water Manage.* 50 (2): 125–140. https://doi.org/10.1016/S0378-3774(01)00094-4.

Savva, A., and K. Frenken. 2002a. *FAO (irrigation manual): Module 4 crop water requirements and irrigation scheduling*. Harare, Zimbabwe: Sub-Regional Office for East and Southern Africa.

Savva, A. P., and K. Frenken. 2002b. *Natural resources assessment*. Lusaka, Zambia: Sub-Regional Office for East and Southern Africa.

Siebert, S., V. Henrich, K. Frenken, and J. Burke. 2013. *Update of the digital global map of irrigation areas to version 5*. Bonn, Germany: Rheinische Friedrich-Wilhelms-Universität.

Trout, T. J., and K. C. DeJonge. 2017. "Water productivity of maize in the US high plains." *Irrig. Sci.* 35 (3): 251–266. https://doi.org/10.1007/s00271-017-0540-1.

Visconti, F., and J. M. de Paz. 2016. "Electrical conductivity measurements in agriculture: The assessment of soil salinity." In Vol. 1 of *New trends and developments in metrology*, 99–126. London: IntechOpen.

Walker, W. R. 1989. *Guidelines for designing and evaluating surface irrigation systems*. Rome: Food and Agriculture Organization.

Yang, Q., W. Luo, Z. Jiang, W. Li, and D. Yuan. 2016. "Improve the prediction of soil bulk density by cokriging with predicted soil water content as auxiliary variable." *J. Soils Sediments* 16 (1): 77–84. https://doi.org/10.1007/s11368-015-1193-4.

Yigezu, T. T., K. Narayanan, and T. Hordof. 2016. "Effect of furrow length and flow rate on irrigation performances and yield of maize." *Int. J. Eng. Res.* 5 (4): 602–607. https://doi.org/10.17577/IJERTV5IS040846.

Zolfaghari, Z., M. R. Mosaddeghi, and S. Ayoubi. 2016. "Relationships of soil shrinkage parameters and indices with intrinsic soil properties and environmental variables in calcareous soils." *Geoderma* 277 (Sep): 23–34. https://doi.org/10.1016/j.geoderma.2016.04.022.

(ii) Poster presentation

EFFECT OF IRRIGATION WATER CUT-OFF POSITION ALONG FURROWS ON WATER SAVING AND PRODUCTIVITY

Benjamin L. Banda, Hans C. Komakech, Kelvin Mtei

The Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, Tanzania

INTRODUCTION

- With the continued dwindling of water resources, improvements in the existing methods of water application and water management practices are therefore more critical than before (Sarwar et al., 2001).
- This study aimed at investigating the scenarios to improve water use efficiency and productivity for the cut-off irrigation technique.

OBJECTIVES

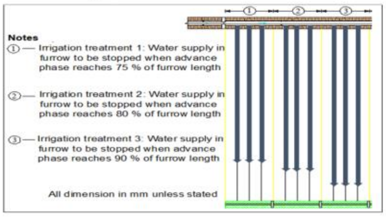
General Objective: To investigate the effect of varying water application cut off position along furrows on water application efficiency, distribution uniformity and productivity in furrow irrigated field.

Specific objectives

1. To estimate the crop water and irrigation requirements for maize crop
2. To establish the variations in water application efficiency and distribution uniformity in varying water application cut off position along furrows.
3. To establish water productivity in the three irrigation treatments.

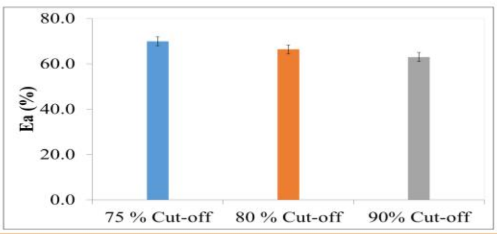
MATERIALS AND METHODS

- An experiment conducted at Lekitatu Irrigation Scheme in Meru District
- Field plot with 3 replications (sub-plots) with similar characteristics (soil, slope)
- 75 %, 80 % and 90 % cut-off positions investigated
- Measurements of water application (Ea) and distribution (DU) efficiencies, and productivity

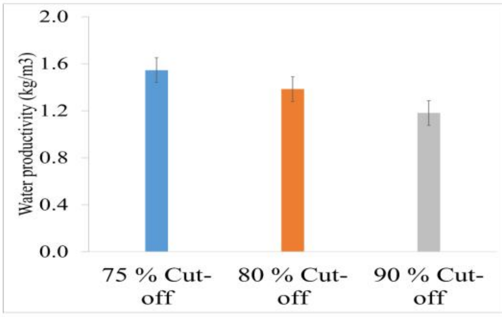


RESULTS AND DISCUSSION

Figure 2: Crop stand in the field plot after 8 irrigations



There was a significant difference in application efficiency between the 75 % cut-off and the 80 % cut-off treatments ($p = 0.003$), between the 75 % cut-off and the 90 % cut-off ($p < 0.001$) as well as between the 80 % cut-off and the 90 % cut-off ($p = 0.046$).



In terms of water productivity, the 75% cut-off produced the highest water productivity. The results had statistically significant difference ($p < 0.05$) for all the combinations

CONCLUSIONS

- From the investigated three treatments, it was evident that cutting off supply when advance phase reaches 0.75 of furrow length has the potential to save water of up to 26 % without compromising on water productivity.
- Further the study showed at least 13.6 % of time spent on irrigation could be saved by following the 0.75 cut off technique which could be utilized in other productive activities.
- With the limited available land for irrigation (due to population pressure), the cut off technique would be very useful to apply in areas with slopes greater than 2 % and for inflow rates higher than 1 l/s to ensure uniform distribution and higher productivity.
- As monitoring the physical position of cut off is easier than varying the flow rate with time, it is recommended that the cut-off position be promoted among the smallholder farmer schemes.

SELECTED REFERENCES

- Abd El-Halim, A. E.-H. A., & Abd El-Razek, U. A. E.-H. (2014). Effect of different irrigation intervals on water saving, water productivity and grain yield of maize (Zea mays L.) under the double ridge-furrow planting technique. *Archives of Agronomy and Soil Science*, *60*(5), 587-596.
- Ali, H. (2010). *Fundamentals of irrigation and on-farm water management* (Vol. 1). Springer Science & Business Media.
- Ali, M., & Talukder, M. (2008). Increasing water productivity in crop production—A synthesis. *Agricultural water management*, *95*(11), 1201-1213.