EFFECTIVENESS OF SOIL MOISTURE CONSERVATION TECHNIQUES IN SORGHUM UNDER SPATE IRRIGATION IN EWASO NYIRO SOUTH DRAINAGE BASIN

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A Thesis Submitted to the Graduate School in Partial Fulfillment for the Requirement of Master of Science Degree in Agricultural Engineering of Egerton University

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DECLARATION AND RECOMMENDATION

Declaration

I hereby do declare that this thesis is my original work and to the best of my knowledge has not been submitted for the award of any degree in any University.

Signature…………………………………. Date…………………………………….

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Recommendation

This thesis is the candidate's original work and has been prepared with our guidance and assistance; it is submitted with our approval as the official university supervisors.

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DEDICATION

This thesis is dedicated to my parents, my siblings and to my son Navin for their love, perseverance and prayers during this period of study.

ACKNOWLEDGEMENT

Firstly, I thank the Almighty God for giving me strength, wisdom and perseverance that contributed greatly to my prosperity in my research.

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ABSTRACT

Crop production is influenced by on-site soil moisture availability and application of water conservation methods for dry areas. This research explored the interactive effects of spate irrigation as an application method and the soil moisture conservation techniques. The objective of this research was to analyze the effectiveness of soil moisture conservation techniques and its correlation to water productivity for sorghum production under spate irrigation. The soil water holding capacity was investigated based on four moisture conservation techniques; mulching, ridging, ridge-furrow mulch and control. Soil moisture was monitored for 125 days under which Seredo sorghum variety was planted. A field experiment was set up using a Randomized Complete Block design (RCB), with three blocks each covering an area measuring 10 m by 10 m with replications. The effect of the treatments on moisture retention was monitored using digital YL-69 moisture sensors installed at 20 cm and 40 cm depths respectively. In addition, the crop coefficient and crop water requirement (CWR) were assessed during the crop's growth period under the different treatments. Normalized Difference Vegetation Index (NDVI) was estimated from growth images obtained from sentinel 2 and then the NDVI used to establish the crop coefficient (Kc). The reference evapotranspiration was determined using the Hargreaves method and the values were then combined with the crop coefficients to obtain the crop water requirement. Results show that K_c values ranged from 0.44 in the initial crop development stage to 0.91 in the mid-season stage and varied with the type of moisture conservation technique. The K_c linearly increased with the increase in NDVI under the different moisture conservation techniques, with a regression coefficient ranging from 0.75 in the combined ridges and mulch to 0.86 in the mulch treatments. The maximum crop water requirement values under each moisture conservation technique were 41.8 mm, 95.1 mm, 177.6 mm and 82.6 mm in the initial development, mid-season and late stages respectively. In addition, the seasonal water requirement of sorghum variety ranged from 386 mm to 395.7 mm. The combined ridges and mulch had the highest water productivity of 2.08 kg/m^3 as compared to the ridges, mulch and finally the control which had values of 1.83 kg/m^3, 1.66 kg/m^3 and 1.45 kg/m^3 respectively. The findings from this study are important as they can be used by agriculturalists, farmers and relevant stakeholders in prioritized soil moisture conservation for increased sorghum crop production especially in ASAL areas.

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LIST OF ABBREVIATIONS/ ACRONYMS

Abbreviation	Description
ASAL	Arid and Semi-Arid Land
ET_c	Crop Evapotranspiration
ET_o	Reference Evapotranspiration
C	Control
CCI	Climate Change Initiative
ESA	European Space Agency
EWS	Early Warning Systems
FAO	Food and Agricultural Organization of the United Nations
FC	Field Capacity
GIS	Geographic Information System
GOK	Government of Kenya
IFAD	International Fund for Agricultural Development
K_c	Crop Coefficient
M	Mulch
NDVI	Normalized Difference Vegetation Index
NIR	Near infrared
PWP	Permanent Wilting Point
R	Ridges
RCBD	Randomized Complete Block design
RM	Ridges and Mulch
RMSE	Root Mean Squared Error
RS	Remote Sensing
UNDP	United Nations Development Programme
VI	Vegetation Indices
WDR	World Development Report
WP	Water Productivity

DEFINITION OF TERMS

Terminology	Description
Wadis	Arabic term that means a valley (dry riverbed that holds water only during heavy rains)
Water productivity	Ratio of crop yield per cubic meter of water consumed
Spate irrigation	Type of water management unique to the semi-arid environments where the flood water diverted from mountainous catchments is diverted from the riverbed to the farmlands
Sentinel 2	Earth observation mission developed to perform terrestrial observations
R software	Free software environment for statistical computing and graphics
Flat file	File having no internal hierarchy

CHAPTER ONE

INTRODUCTION

1.1 Background information

Water that infiltrates into an agricultural field can be conserved for increased crop production. Several field water application methods into the field exist. These include basin, furrow, border, sprinkler, drip and spate irrigation methods. In this research, spate irrigation was explored as a way of utilizing flood water for crop production in arid and semi-arid lands. It involves the diversion of flood water to agricultural fields through a dry riverbed (Kyagulanyi *et al*., 2016). Spate irrigation is usually practiced when the rate of evapotranspiration is greater than the precipitation rate to cater for crop water deficit. Spate irrigation is being practiced in some parts of Africa, Asia and America (Steenbergen *et al*., 2010). Kenya has a land mass of 582,000 km^2 out of which approximately 80% is Arid and Semi – Arid Land (ASAL) that receive a mean annual rainfall less than 750 mm. The ASAL supports about 20 % of population in Kenya. This clearly shows that Kenya is poorly endowed with a potential for practicing rain-fed agriculture. However, the recurrent flash floods can be used for spate irrigation which targets 50,000 ha as outlined in Kenya's Vision 2030 development blue print (GOK, 2007) and other sectorial plans. This will also help in achieving Sustainable Development Goals (SDG's) number 1 and 2 which focus on no poverty and zero hunger. With increased food production, there will be reduced food security issues and in turn improved livelihoods. Therefore, this study focused on the use of soil moisture conservation techniques in spate irrigation in Ol Donyo Nyoike area, Ewaso Nyiro South Drainage Basin. Ol Donyo Nyoike area is one of the areas in Kajiado County that face frequent flooding and has a large potential for spate irrigation. These conservation measures are meant to increase the amount of moisture content in the soil and in turn improve the agricultural productivity in the study area.

Agricultural productivity in semi-arid areas depends on water availability. Despite being endowed with recurrent flash floods, Ewaso Nyiro South Drainage Basin is an arid and semi-arid area with an average of 600 mm of rainfall per year (Gichuki *et al*., 1998). This amount of rainfall is highly variable in terms of spatial and temporal distribution. This in turn leads to very low amounts of rainfall in some areas and others who depend on the flood water only. This prompts the need for application of conservation measures to help in maintaining optimum soil moisture content at any given time. Globally, different techniques to conserve soil moisture content have been developed (Thomas *et al*., 1997; AHI, 2000). The conservation measures are mainly used to retain soil moisture and nutrients with the end goal of increasing crop yields. Utilization of rainfall, good irrigation practices and control of runoff depends on the water retention characteristics of the soil. Different methods and equipment have been developed to ensure reliable measurement of moisture content in the soils. These methods include: gravimetric method, neutron scattering method and more recently the use of real time soil moisture sensors (RTSMS). The Time Domain Reflectometry (TDR) and capacitance probe methods are mainly used because they can measure both temporal and spatial changes in soil moisture content (Jones, Wraith, & Or, 2002).

The main parameter evaluated in the assessment of spate irrigation efficiency is water productivity (WP). According to Mdemu *et al*. (2009), improving water productivity is one important strategy for addressing future water scarcity. Molden (1997), stated that water productivity (WP) takes different forms with different units. According to Heydari (2014), WP is an indicator of agricultural productivity in relation to the crop's consumptive use of water. Productivity enhancements are accompanied by optimum resource utilization and maximization of the marginal production. Improving water productivity in agriculture reduces competition for scarce water resources, and subsequently lead to enhanced food security. Since water is a scarce resource, water productivity, is a critical indicator on performance of the system with respect to production (Rao, 1993)

1.2 Statement of the problem

According to Rono (2013), degradation of natural resources in Ol Donyo Nyoike area has led to the occurrence of frequent flash floods. Despite the cyclic occurrence of flash floods in the sub-catchment, the amount of flood water available for spate irrigation in the area has not been determined. To ensure the success of agriculture in the arid areas, the amount of flood water in the area should be estimated for optimum water utilization. Different soil moisture conservation techniques can be applied on agricultural land to preserve moisture and in turn improve the irrigation efficiency and water productivity (Thomas *et al*., 1997; AHI, 2000). However, the effectiveness of moisture conservation techniques for improving the moisture retention and water productivity has not been widely investigated in Ol Donyo Nyoike. According to Heydari

(2014), insufficient amount of water within a region leads to insufficient hydrological information about the water requirement for various crops. Since little agriculture is practiced in Ol Donyo Nyoike due to limited water sources, there is insufficient information about crop water requirement (CWR) for various crops. The information on effectiveness of soil moisture conservation techniques and its correlation to water productivity for sorghum production under spate irrigation is scanty hence the need for investigation in this research.

1.3 Objectives

1.3.1 Broad objective

The broad objective of this study was to analyze the effectiveness of moisture conservation techniques in water productivity of spate-irrigated sorghum in Ewaso Nyiro South Drainage Basin.

1.3.2 Specific objectives

The specific objectives were to:

i. Evaluate the effectiveness of moisture conservation techniques (mulch, contour ridges, a ridge-furrow mulch and no conservation measure) on soil moisture retention for sorghum field under spate irrigation.
ii. Determine the Crop Water Requirement (CWR) for sorghum crop growth under different moisture conservation techniques using remotely sensed and NDVI data.
iii. Determine the water productivity (WP) of sorghum in assessment of the effectiveness of spate irrigation under different moisture conservation techniques.

1.4 Research questions

i. How effective are the soil moisture conservation techniques in retaining soil moisture for spate-irrigated sorghum field?
ii. How does the CWR of spate irrigated sorghum determined using remote sensing vary with different soil moisture conservation techniques?
iii. How does the WP of spate irrigated sorghum vary with different soil moisture conservation techniques?

1.5 Justification

Ewaso Nyiro south sub-catchment, specifically Ol Donyo Nyoike group ranch, experiences flash floods which affect the neighboring Kamukuru town and even cause damage to property. However, if well managed, these flash floods can be of beneficial use in spate irrigation for food production to address recurrent food insecurity. A study on the effect of different conservation techniques on the crop yield under spate irrigation is important in determining which methods are recommended and applicable for moisture retention. These findings are important as they can be used by agriculturalists, farmers and relevant stakeholders in prioritized soil moisture conservation for increased crop production.

Specific crop study for the region is important in the development of sustainable agriculture since most of the people from the region suffer cyclic drought and famine occasioned by erratic rains. Sorghum was chosen for the study because it is the most preferred crop in the area and can either be used as food crop and/or as fodder. Also, sorghum can tolerate temporal waterlogging which is a common experience in the sub-catchment. Therefore, the study of sorghum's evapotranspiration was important in that it helped in determining the crop water requirement in relation to the quantity of water available.

CHAPTER TWO
LITERATURE REVIEW

2.1 Spate irrigation

According to Tesfai and Sterk (2002), spate irrigation uses flash flood draining from the highlands. The flash flood is then diverted to the fields using temporary irrigation structures. Spate irrigation is majorly practiced in the arid lands and is characterized by the unpredictable nature of the floods to be harnessed and the high sediment loads that come with the floods (Steenbergen *et al*., 2010). Sedimentation is advantageous in that it improves the soil fertility of the area wherever it is deposited. However, sedimentation is disadvantageous since it causes the command area to rise and block the intakes and irrigation water conveyance channels. Spate irrigation is a type of flood-based farming systems and differs from the other irrigation methods in that it depends on short duration floods which last weeks or months. Spate irrigation is mostly practiced in large scale, especially by farmers who form groups, unlike other systems where farming is done by individual farmers (Steenbergen *et al*., 2010). It fits well in communal farming systems more so in areas where land is owned by the community.

Globally spate irrigation was invented and is practiced in Africa, South Asia, Central Asia and Latin America. Generally, it is a crop production activity, with low returns, generating highly variable incomes in different years. In spate irrigation, it is costly to maintain the intakes, canals and the entire field system because it is highly labour intensive (Steenbergen *et al*., 2010). Also, whenever other convenient and economical livelihood opportunities are available, these spate irrigation schemes are abandoned and the local management structures undermined (Steenbergen *et al*., 2010).

In Kenya, flood-based farming systems are mainly practiced at a private level. In the past however, flood recession was practiced along the Tana River where crops such as rice and bananas were grown. The practice was not successful due to lack of detailed studies on water harvesting and storage of flood water (Muthigani, 2011). In the North-Eastern part of Kenya, flood-based farming is practiced in Wajir and Mandera counties (Muthigani, 2011). According to Kitheka *et al*. (2005), flood recession is also practiced in the flood plains and the delta area of the Tana River. The floods in the area are mainly experienced during the months of April and June.

Moinde-Fockler *et al.* (2007), also concluded that on the lower Tana valley, riverbank and flood recession is practiced by the Pokomo people. Although spate irrigation has been practiced, water productivity and effectiveness combined with soil moisture conservation techniques has not been explored.

2.2 Basic design principle for spate irrigation

In spate irrigation, the floods originate from highlands and mountainous areas. These floods are diverted to irrigate adjacent land in the lowlands using diversion and other hydraulic structures. The water is usually diverted before the planting period (Tesfai and Stroosnijder, 2001). The water infiltrates into the soil hence providing residual moisture content for the crops to grow. After the flooding has subsided, the crops are then planted.

To use the floods for irrigation, a diversion structure is constructed in the river to divert much of the water to the agricultural land. The site of the diversion structure is usually selected at a lower point where the gradient of the flood torrent is not so steep that its momentum increases immensely (Karim and Muhammed, 2011). The height of this diversion structure is normally 3 to 4 m with a base of approximately 5 m for small riverbeds and 10 m for large riverbeds (Tesfai and Stroosnijder, 2000). At the end of the diversion structure a primary distribution canal is then built. This primary distribution canal distributes or channels the water to the secondary canals which direct it to the irrigable area. The primary canal size varies depending upon the area of the irrigated land. Earthen bunds are constructed within and outside the irrigation area. The bunds within the fields (interior bunds) are constructed to steer the direction of the flood water (Tesfai and Stroosnijder, 2000). They also help to slow down the flow. This leads to a reduction in transport capacity of the flow and consequently allow the sediments to be deposited. The outside (exterior) bunds are constructed around the edges of the individual spate fields. They could be as high as 1.5 m and are used to keep the flood water from flowing to adjacent farm blocks. The irrigated fields are designed in such a way that water flows into the individual fields under the influence of gravity (Tesfai and Stroosnijder, 2000).

In spate irrigation, there are at least four methods for distributing water at field level. According to Steenbergen *et al*., (2010), the water distribution methods are; field to field distribution or individual field distribution and extensive or intensive distribution. In field-to-field irrigation or individual field distribution, there are neither tertiary nor secondary canals. An earthen bund is used to divert the flow from the canal to the bunded fields. When the upstream field has been fully and well irrigated, a cut is made on the downstream field bund to allow water flow to the next field. This process is repeated until all the fields receive irrigation water. One of the challenges facing the field to field distribution method is the sharing of water at the watershed level. However, in different spate irrigation schemes, the water conflict issue has been reduced by setting up different irrigation schedules during a crop's growth period. This schedule ensures that the water is available to many of the members at the required time. Appropriate water sharing rules have also been put in place to ensure the downstream farmers acquire water and avoid conflicts (Steenbergen *et al*., 2010).

Extensive or intensive distribution method offers a higher control of water distribution. This is due to the presence of secondary or tertiary canals which help reduce scouring and allow farmers to irrigate downstream fields without damaging upstream fields. This method of water distribution is highly suitable for large scale farming (Steenbergen *et al*., 2010).

2.3 Soil moisture

There are three different moisture content levels important for the growth and survival of plants. These levels are; the Field Capacity (FC), Permanent Wilting Point (PWP) and Wilting Point (WP). From these levels, Available Water (AW) can be established. The following sections 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.3.5 and 2.3.6 describe these terms.

2.3.1 Field Capacity (FC)

FC is the soil water content after the soil has been saturated and allowed to drain freely under the force of gravity for about 24 to 48 hours. It is also the moisture retained at 33 k Pa. Saturation of the soil occurs when all the pore spaces in a soil are filled with gravitational water hence resulting in low moisture tension. A study by Nachabe (1998), has raised concerns after the author predicted the soil water content at FC using the hydraulic conductivity curve alone. The author stated that during the drainage of an initially saturated soil, the influence of capillary forces as compared to the influence of gravity forces on the net movement of soil water is negligible. The study by the author found that the time taken to reach the FC after initial saturation in clay soils is larger than for sandy soils. These findings were further confirmed by Twarakavi *et al*., (2009); and Aschonitis *et al*., (2013) in a similar study.

2.3.2 Permanent Wilting Point (PWP)

PWP is the moisture content threshold below which plant tissues permanently die since they cannot extract any water from the soil hence cannot recover even after the application of water (Saxton & Rawls, 2006). It is the lowest in moisture content ranges at a suction pressure of 1500 kPa. At this point, the soil contains some amount of water but it's not available to the plants hence their tissue expires.

2.3.3 Wilting Point (WP)

WP is the moisture content of the soil (expressed as a percentage of the dry weight) when the leaves of the plant first undergo a permanent reduction in their moisture content as the result of a deficiency in the soil moisture supply. Like the FC, the WP is a dynamic value. The main factors that affect the rate of WP are the soil profile (soil texture, compaction and stratification), root distribution of a plant, transpiration rate of a plant and the environmental temperature (Saxton and Rawls, 2006).

2.3.4 Available Water (AW)

The plant available water is the range of soil water content between the FC and the PWP. It is the maximum amount of plant available water a soil can provide. However, a certain percentage of water can be removed from the soil and used by the plant.

2.3.5 Management Allowable Depletion (MAD)

This percentage is called the management allowable depletion (MAD). This factor varies but is usually at 50% (Nyvall, 2002). Already determined FC, PWP and available water values described using a procedure by Saxton and Rawls, (2006) are shown in Table 2.1.

Table 2. 1: FC, PWP, AW and MAD values for different soil textures

Soil texture	Field capacity (%)	Permanent wilting point (%)	Available water (%)	Management allowable depletion (%)
Sand	10	5	5	60
Loamy sand	12	5	7	50
Sandy loam	18	8	10	50
Sandy clay loam	27	17	10	-
Loam	28	14	14	50
Sandy clay	36	25	11	-
Silt loam	31	11	20	-
Silt	30	6	24	-
Clay loam	36	22	14	40
Silt clay loam	38	22	16	-
Silt clay	41	27	14	40
clay	42	30	12	30

2.3.6 Readily Available Water

This is the water in the soil that is easily extracted by the plant. The amount of RAW varies with soil type, crop, rooting depth and irrigation system. In this range of moisture content, the plants are neither water-stressed nor water logged.

2.4 Soil moisture conservation

The main aim of soil moisture conservation is to minimize the amount of water lost from the soil through evaporation and transpiration or combined, evapotranspiration. The availability of water and its retention are governed by its bulk density, hydraulic conductivity and the soil mechanical composition. For healthy crop growth, sufficient water is needed in the soil which is neither deficient nor in excess. Excessive flooding removes air from the soil hence leading to retarded growth. However, irrigation water application should raise the soil water to the FC level from maximum allowable depletion level.

Different soil moisture conservation measures have been developed and promoted to preserve moisture and provide additional nutrients to the soil thus increasing the irrigation efficiency

(Thomas *et al*., 1997; AHI, 2000). The most common moisture conservation measures include mulching, ridges, tied-ridges, plastic mulching, a combination of mulch and ridges or even the normal farmers' practice (acts as the control). Adoption of soil moisture conservation techniques such as tied ridges and mulching has shown improved soil moisture retention in a wide range of environment (Balenchew and Abera, 2010). The increase in irrigation efficiency in turn increases the crop yield. However, for proper planning, there is little information on the extent at which moisture conservation measures achieve the expected outcome. Soil moisture conservation practices are aimed at improving soil structure and soil porosity with an end goal of increasing the soil moisture content.

2.4.1 Contour ridges

Ridging is done by constructing small earth banks parallel to the contours of a slope. The water accumulates above the ridges and is thus allowed to infiltrate into the soil. It is mainly used on slopes with a gradient up to 7% (Anschutz *et al*., 2003). For the construction purposes, clay soils are highly preferred due to their relatively stable structure otherwise the ridges become undermined by runoff and get destroyed (Anschutz *et al*., 2003). The height of the ridges is usually 20-30 cm (Anschutz *et al*., 2003) and are as wide as furrows. The distance between the ridges varies from 1.5 m to 10 m and depends on the crop grown, the steepness of the slope and the climate (Anschutz *et al*., 2003). The main advantage of using the ridges is that they reduce both runoff and soil erosion as well as reduce nutrient loss. However, if improperly laid on the ground they can increase the risk of soil erosion and if the soils are heavy with low infiltration capacity then a lot of water might collect and in turn increase the chance of breaking. Crops are planted between the ridges and not on the ridges (Anschutz *et al*., 2003).

2.4.2 Mulching

Mulches are loose coverings or sheets of materials placed on the surface of cultivated soil. They are advantageous in that they help soils retain moisture, help in control of temperature fluctuations, suppress weeds, improve soil texture and protect plant roots from extreme temperatures. Mulches can either be biodegradable or non-biodegradable.

Biodegradable mulch breaks down to release nutrients into the soil and helps improve its structure. The layers need replacing once the material has worn out. The best materials are; leaf mould, garden compost, wood chippings, well-rotted manure among others. The non-biodegradable mulch does not boost the soil fertility or structure but helps suppress the weeds, retain the moisture as well as being decorative. The main challenge of applying mulch occurs if they are placed in direct contact with the stems of the trees since they cause the stems to soften making them vulnerable to diseases.

Mulching has been widely used for soil and water conservation purposes (Sarkar & Singh, 2007; Chakraborty *et al*., 2008). McDonald (2013), stated that mulch slows down evaporation and in turn reduces the irrigation water requirement. Adeoye (1984), recorded a high moisture content up to a depth of 60cm in grass-mulched soil together with good infiltration and reduced evaporation. Rice husks were more superior in maintaining optimum soil moisture for crop use than transparent and black polyethylene mulch (Chakraborty *et al.*, 2008). According to the study, the residual soil moisture was minimum indicating effective utilization of soil moisture by the crop.

Plastic mulch are highly preferred because they do not decompose. This is advantageous in that they provide a permanent solution hence no need of re-applying every year to save both time and money. On the other hand, using the plastic mulch is a problem in that due to its failure to decompose it causes environmental degradation. Hence, in this study the grass mulch which is readily and locally available was used in testing its effect on moisture retention on spate irrigated sorghum.

2.4.3 Ridge-furrow mulching technique

According to Li *et al*. (1999), mulches are used to reduce water loss through evaporation. Ridge –furrow mulching systems have been used in Kenya with good results in moisture storage. An experiment conducted in Kari-Katumani, currently Kenya Agriculture and Livestock Research Organization (KALRO), by Mo *et al*. (2016) on the effect of different mulching materials (transparent polyethylene, black polyethylene, grass-straw mulch and without mulch) showed that the mulch materials could retain moisture in the soil. Much of the moisture was retained by the transparent polyethylene.

Ren *et al.* (2016), conducted a study in Loess plateau that the ridge-furrow mulch generally improved the soil water storage with much of the increase at depths 0-100 cm and relatively small change from depths 100-200 cm. The highest levels of moisture retention were observed in the plastic mulch. However due to the plastic ban and its effect on the environment, the grass mulch is recommended rather than the plastic mulch.

2.5 Methods of determining soil moisture

Soil moisture content is used for a variety of biophysical processes such as seed germination, plant growth and plant nutrition. It can be measured using either the direct or indirect methods.

2.5.1 Direct methods

In the direct method, thermo-gravimetric method is used as the reference method since it is the only method under the classification. It is based on the weight measurement of a wet sample before and after oven drying at 105 ^{o}C for 24 hours (Evett *et al*., 2008). The difference in weight is expressed as a fraction of the soil's solid weight called gravimetric water content. Despite being used as a reference method, the method is laborious and time consuming (Evett *et al*., 2008).

2.5.2 Indirect methods

There are different methods that indirectly measure the amount of moisture content in the soil. The soil moisture content can be measured indirectly by methods that include:

i. Tensiometers

The tensiometric method uses the principle of capillary function of the soil (Vergouw, 2016). A tensiometer consists of a porous point or cup (usually ceramic) connected through a tube to a pressure-measuring device. The system is filled with water and the water in the point or cup comes into equilibrium with the moisture in the surrounding soil, water flows out of the point as the soil dries and creates greater tension, or back into the point as the soil becomes wetter and has less tension (Evett *et al*., 2008). A study by Alshikaili, (2007), stated that tensiometers exhibit hysteresis effect, that is, they tend to give a higher soil-moisture tension during soil drying than during soil wetting. Tensiometers are not suitable for measurements in dry soils because they only operate between saturation and about 70 Kpa (Alshikaili, 2007).

ii. Gypsum-porous blocks

The porous blocks operate on the principle that the electrical resistance of the blocks is proportional to its water content (Alshikaili, 2007). The method does not work well in coarse-textured, high shrink-swell and saline soils (Alshikaili, 2007). A study by the same author indicated that their sensitivity is poor in dry conditions but the method is quick, repeatable and relatively inexpensive.

iii. Neutron probes

High energy (fast) neutrons are emitted into the soil, slowed down by water from which the slow neutrons are detected. As hydrogen (H) is a very efficient thermalizer, the slow neutron count provides a measure of the H content and in turn that of the moisture content in the soil.

iv. Time-Domain Reflectometry (TDR)

TDR method involves the use of sensors that are buried into the soil whose moisture content is to be determined. In the past, soil sensors have been mainly used in smart agriculture. In the smart agriculture, the installed sensors detect the water level in the soil and send back the information to accordingly control the water supply. The method measures a variable that is affected by the amount of soil water and then it relates the changes of this variable to the changes in soil water content through calibration curves. The level of accuracy is higher for soil moisture measurements using sensors.

Previous studies for use of soil moisture sensors have been done though it has not been fully explored. TDR and capacitance probes have been used extensively to monitor and measure the soil moisture content in both scientific and land management applications. However, several studies have indicated that the capacitance probes are more sensitive to specific soil characteristics as compared to the TDR because of the difference in measurement frequency (Seyfried and Murdock, 2004). Gaskin and Miller (1996), designed a probe that used impedance to measure soil water. The probe was cheap, easily constructed and most importantly did not change the field conditions.

2.6 Crop Coefficient and Crop Water Requirement (CWR)

The main forcing variables in the estimation of CWR are the crop coefficients and the reference evapotranspiration. The crop coefficients are combined with the reference evapotranspiration to yield the CWR. Different methods have been developed and they are presented in sections (2.7) through to (2.8.5)

2.7 Crop coefficient

Crop coefficients (K_c) are properties of plants used in predicting the rate of evapotranspiration and vary according to growth stage and length of crop growth stage (Testa *et al*., 2011). According to Testa *et al*. (2011), crop coefficient represents an integration of the effects of crop height, albedo (reflectance) of the crop soil surface, canopy resistance and evaporation from soil. The crop coefficients primarily depend on the dynamics of canopies (cover fraction, leaf area index and greenness) (Testa *et al*., 2011). The most basic K_c is the ratio of evapotranspiration (ET) value observed for the crop studied to that observed for the well calibrated reference crop under same conditions. Studies by Testa *et al*. (2011), came up with some values for various crops under different environmental conditions. The crop coefficient values can be adapted or can be confirmed by practical measurements in the field.

2.7.1 FAO crop coefficients

According to Testa *et al*. (2011), there are two approaches that can be used in the determination of crop coefficient; single crop coefficient and the double crop coefficient. The single crop coefficient approach is used to express both plant transpiration and soil evaporation combined into a single crop coefficient. The dual crop coefficient uses two coefficients to separate the respective contribution of plant transpiration (k_{cb}) and soil evaporation (k_e) each by individual values (Allen *et al*., 1998). The tabulated crop coefficient values in FAO paper number 56 are not always applicable hence local calculations during the growing period is advised. The crop coefficient values calculated using the FAO approach can then be modified using Equation (2.1) as described;

$$K_{c\,stage(n)} = K_{c\,stage(n)(tab)} + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \tag{2.1}$$

Where:

$K_{c\ stage\ (n)}$ = Modified FAO K_c values (Dimensionless)

$K_{c\ stage\ (n)\ (tab)}$ = Standard values as described in the FAO approach in paper number 56 (Dimensionless)

u_2 = Value of daily wind speed at 2m height over grass during the growth stage (m/s)

RH_{min} = Value for daily minimum relative humidity during the growth stage (%)

h = Plant height (m)

Er-Raki *et al*. (2007), compared three methods used in crop coefficient estimation for wheat crop grown in Morocco. The authors compared the crop evapotranspiration to the actual evapotranspiration determined using the eddy covariance method and deduced that the Allen *et al*. (1998), was unable to estimate crop evapotranspiration accurately.

2.7.2 Estimation of crop coefficients using remote sensing data

Remote sensing is the acquisition of information without direct physical contact between the sensors and the objects being investigated (Charles, 1987). Remote sensing provides spatial coverage by measurement of reflected and emitted electromagnetic radiations, across a wide range of wavebands, from the earth's surface and the surrounding atmosphere (El-shirbeny *et al.*, 2014). Remote sensing techniques for estimating ET have been developed and are based on the use of satellite-based energy balance and thus producing estimates of actual ET (Bastiaanssen *et al*., 1998, Allen *et al*., 2007). The use of satellite imagery for agricultural purposes started in the early 70s (Bauer & Cipra, 1973). The first satellite to be launched was Landsat 1 (Mulla, 2013). Thereafter, other satellites were launched and they include Spot 1 which was launched in 1986 among others. Spot 1 had a spatial resolution of 20 m and its continued use and adoption for mapping purposes led to the design of new and highly improved satellite imaging systems. These satellite images include; modis, spot, Quick bird and sentinel 2 images. According to Gowda *et al*. (2008), the two main approaches for estimation of ET are the land surface energy balance and reflectance-based crop coefficient approaches.

The land surface energy balance approach is based on the law of conservation of energy. On land, the net radiation is converted to sensible heat (H), ground heat (G) and the latent heat fluxes (LE). Evapotranspiration (ET) consumes the latent heat. The mainly used approaches in this method are the Surface Energy Balance Algorithms for Land (SEBAL) and the Mapping

EvapoTranspiration at high Resolution with Internalized Calibration (METRIC). SEBAL uses the potential evaporation from a water body in the scene assuming that sensible heat and soil heat fluxes are zero (Vashisht, 2016). METRIC has been widely applied to estimate ET_a at field and regional scale over different crops such as wheat, corn, soybean and alfalfa, with errors ranging between 3 and 20% (Allen *et al*., 2007). A study by Bashir *et al*. (2008), derived a seasonal crop coefficient for sorghum using Landsat ETM+ images by dividing ETa computed using SEBAL by ETo estimated using the Allen *et al*. (1998) method. The authors concluded that surface energy balance models can be used to calibrate and validate existing crop coefficients for a region.

In the reflectance-based approach, vegetation indices like the NDVI are used in which the red and the near infrared bands are used. Vegetation indices (VIs) were first developed in the 1970s to monitor terrestrial landscapes by satellite sensors. The VIs are mainly used to distinguish vegetation biophysical properties (Vashisht, 2016). Since then different studies have been conducted where vegetation indices have been used for remote sensing applications either individually or in combination with different spectral bands (Bannari *et al.*, 1995; Herrmann *et al.*, 2010). From the different studies it has been deduced that the vegetation indices are successful in assessing vegetation condition, foliage, cover, phenology, and processes related to the fraction of photosynthetically active radiation absorbed by a canopy as reported by Huete *et al*. (2008) and Glenn *et al*. (2008). The vegetation indices mainly used are the soil adjusted vegetation index (SAVI) and normalized difference vegetation index (NDVI).

Normalized difference vegetation index (NDVI) is an index which allows generation of an image showing the relative biomass. It is closely correlated to the green biomass and the leaf area. The chlorophyll absorption in the red band and the high reflectance of vegetation in the Near Infrared band (NIR) are used in the calculation of NDVI. For global vegetation monitoring the NDVI is preferred because it helps to compensate for changing illumination conditions, surface slope and aspect (Lillesand *et al*., 2004). Studies by Er-Raki *et al*., (2007), deduced that the reflectance-based crop coefficient approach to be 70-80% efficient as compared to the Allen *et al*. (1998) approach which was 44% efficient as indicated by Gowda *et al*., (2008). The use of these vegetation indices has been tested to predict K_c at field and regional scales (Rouse *et al*., 1974 and Huete, 1988). The crop coefficients generated from VIs determine ET_c better than a tabulated K_c because it represents the actual crop growth conditions and capture the spatial variability among different fields (Gontia & Tiwari, 2010; Kullberg *et al*., 2017). Carlson & Ripley, (1997) stated that NDVI is sensitive to fractional vegetation cover until full ground cover is reached. The same authors found that the regression relationship between NDVI and fractional cover is non-linear. This is because after the attainment of full ground cover, the NDVI becomes insensitive to increasing vegetation amount. The calculated NDVI is then used in calculation of the crop coefficient.

The crop coefficient can be determined using Equation 2.2 according to El-shirbeny *et al*.,(2014);

$$K_C = \frac{a}{b} \times NDVI - c \qquad (2.2)$$

Where:

K_C = Crop coefficient (Dimensionless)

a = Maximum K_c for crop (sorghum)

b = Difference between minimum and maximum NDVI value for sorghum

c = Minimum NDVI value for sorghum in that area

2.8 Crop water requirement

Crop water requirement (CWR) is the amount of water needed by crops to meet evapotranspiration requirements during their growth. In determination of the crop evapotranspiration, according to Allen et al., (1998), the crop coefficient is then multiplied with the reference evapotranspiration to acquire the crop evapotranspiration and this can be described using the following relation;

$$ET_C = K_C \times ET_O \qquad (2.3)$$

Where:

ET_c = Crop evapotranspiration (mm/day)

K_C = Crop coefficient (dimensionless)

ET_o = Reference evapotranspiration (mm/day)

Determination of the daily Reference Potential Evapotranspiration (ETo) is essential in the calculation of the crop water requirement (Shahidian *et al*., 2012). Crop evapotranspiration (ET_C) is significant for water resources planning and irrigation management. Crop water requirements should be estimated with high level of certainty to save water and to maximize water unit uses. Crop evapotranspiration represents crop water requirements in consideration with the water involved in plant tissue structure representing about 1% or less. Reference evapotranspiration (ET_O) is a key process in land surface studies. It mainly depends on water availability and incoming solar radiation and then reflects the interactions between surface water processes and climate (El-shirbeny *et al*., 2014). The reference evapotranspiration is determined from a hypothetical grass reference surface.

A crop usually requires certain amount of water at defined intervals throughout its period of growth. The objective of determining the crop water requirements is to make water available to cultivators with respect to location, time and quantity per the crop requirements (Doorenbos and Pruitt, 1977). The most common and practical approach for estimating crop water requirement was described by the FAO in the drainage paper 56 and involves the combination of a reference evapotranspiration (ET_o) and the crop coefficient (Allen *et al*., 1998).

2.9 Reference evapotranspiration

Different methods and models have been developed for the determination of reference crop evapotranspiration from which the crop water requirement can be calculated and they include pan evaporation method, Hargreaves formula, Penman Monteith formula and Blaney Criddle among others as discussed. Some of the mathematical relations are part of the inputs into the models.

2.9.1 Blaney-Criddle method

According to Doorenbos and Pruitt (1977), Blaney-Criddle method is suggested for areas with limited records of data and the only available climatic data is air temperature. Nonetheless, it has been shown to be one of the best temperature-based methods for humid location (Jensen *et. al*. 1990). The Blaney Criddle reference evapotranspiration can be calculated using Equation (2.4);

$$ET_O = p(0.46T_{mean} + 8.13 \qquad (2.4)$$

Where:

ET_o = Reference evapotranspiration (mm/day)

T_{mean} = Mean daily temperature (°C)

P = Mean daily percentage of annual daytime hours (%).

The only variable measured in this method is the mean temperature. Various studies indicate that the Blaney-Criddle equation show some bias under arid conditions. For semi-arid conditions of Iran, Dehghani Sanij *et al.* (2004) found that Blaney -Criddle overestimates ET_o during the growing season. Lopéz-Urrea *et al*. (2006), compared seven different methods for calculating ET_o in the semiarid regions of Spain and observed that the Blaney-Criddle method significantly over-estimated average daily ET_o.

2.9.2 Pan evaporation method

This is the simplest method to use when there is no rainfall. It involves filling an evaporation pan with water and then measuring the amount of the water lost. The main parameters considered in this method are the wind, temperature, radiation and humidity (Allen *et al*., 1998). However, this method has its limitations in that exposure to direct solar radiation causes heat energy storage in the pan. This leads to increased evaporation rates in the nights when there is no transpiration and high variation of temperature and humidity levels above the pan surface. (Allen *et al*., 1998). The reference evapotranspiration in this method is calculated as described in Equation 2.5.

$$ET_o = Kpan \times Epan \tag{2.5}$$

Where:

ET_o = Reference evapotranspiration (mm/day)

K_{pan} = Pan Coefficient from manufacturer (Dimensionless)

E_{pan} = Pan evaporation (mm/day)

This method was not feasible for this study.

2.9.3 Penman-Monteith method

This method is considered the best since it has minimum possible error in the calculation of reference crop evapotranspiration if the components required in the formula are available (Allen *et al*., 1998). This method requires climatological data which is mostly not available in developing countries. Also, the instruments required to measure weather parameters especially solar radiation and humidity are subject to stability errors (Droogers & Allen, 2002). According to Penman- Monteith, the following formula is used in the calculation of the reference evapotranspiration:

$$ET_o = \frac{0.408(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

(2.6)

Where:

ET_o = Reference evapotranspiration (mm/day)

R_n = Net radiation at the crop surface (MJ/m ^{2} /day)

G = Soil heat flux density (MJ/m ^{2} /day)

T = Mean daily air temperature at 2 m height (^{o}C)

u_2 = Wind speed at 2 m height (m/sec)

e_s = Saturation vapour pressure (k Pa)

e_a = Actual vapour pressure curve (k Pa /^{o}C)

γ = Psychrometric constant (k Pa /^{o}C).

Δ = Rate of change of saturation specific humidity with air temperature (Pa K^{-1})

The main limitation of using this method in irrigation is that it is data intensive, expensive and time consuming for one to acquire and process the necessary meteorological data (Doorenbos and Pruitt, 1977). Additionally, quantifying bulk surface resistance for complex canopies using this method is also a challenge (Allen *et al*., 1998).

2.9.4 CropWat model

CropWat is a decision support system developed by FAO for planning and management of irrigation systems. It is mainly used for standard calculation of reference evapotranspiration, crop water requirement and crop irrigation requirement. In determination of reference evapotranspiration, in-built Penman-Monteith equation is used. The main limitation of using this method is that the weather parameters required were not all available hence was not used. In addition, the process of acquiring and processing all the weather parameters is time consuming and expensive.

2.9.5 Hargreaves method

The Hargreaves formula is most applicable in areas where there is insufficient data availability. For areas with scarce data availability, it is recommended to use an equation with few parameters. This formula is highly recommended because it is simple and accurate (Jensen *et al*. 1997). The measured parameters used in this method are the maximum and minimum daily air temperature and the extraterrestrial radiation (Ra) which is an indication of the incoming global radiation (Doorenbos, 1992).

This method is quite easy to use. Due to the lack of availability of data in the study area, this method was used. According to Allen *et al*. (1998), T_{max} is high under clear skies since the atmosphere is transparent to incoming solar radiation and low during the night due to the outgoing long wave radiation. However, T_{max} is lower under cloudy conditions because some of the incoming solar radiation never reaches the earth and are relatively higher during the night. This high temperatures during the night are caused by the clouds which limit heat loss by outgoing long wave (Shahidian *et al*., 1998).

2.10 Factors influencing crop water requirements

The main influencing factors of CWR are climate (rainfall, temperature, sunlight and wind movement), soil type, crop type and the growth stage.

2.10.1 Climate

The amount of CWR required by a certain crop is directly proportional to the adverse climate within that region. For instance, the amount of water required by a crop in a sunny and hot climate is more as compared to the requirements of the same crop in a cloudy and cooler climate (Brouwer and Heibloem, 1986). Apart from sunshine and temperature, other climatic factors that influence crop water need are humidity and wind speed (Brouwer and Heibloem, 1986). The crop water needs are highest in hot, dry, windy and sunny areas and vice versa (Brouwer and Heibloem, 1986).

2.10.2 Crop type and growth stage

Different crops have different crop water needs since they have varying crop characteristics. The duration of the total growing season has the main effect on the crop type. The short duration crops, for example peas which has a growing season of 90- 100days, requires less water as compared to long duration crops such as melons. These long duration crops with a growing period of between 120- 160 days (Brouwer and Heibloem, 1986) require more water. Additionally, a fully-grown crop requires more water than a sprouting one (Brouwer and Heibloem, 1986).

2.10.3 Soil type

A soil's water holding capacity depends on its structure. In sandy soil, water infiltrates easily due to the many macro pores so the water required is more. However, in clayey soils the particles are less porous hence the water required is less due to reduced percolation.

2.11 Spate irrigation performance evaluation parameters

The efficiency and effectiveness of irrigation practices is mainly influenced by the climatic conditions, soil type and structure, plant type, plant growth stage as well as the irrigation techniques used among others. Right decisions on the crop type, irrigation scheduling, irrigation method, soil enhancement measures and the source of water can help in improving the efficiency of water irrigation practices (Diop, 2002).

2.11.1 Water productivity

Water productivity (WP) is the quantity or value of output in relation to the quantity of water beneficially consumed to produce this output (Molden, 1997). The value of product may be expressed in terms of biomass grain or even in terms of monetary value. The main principles of improving water productivity at the field level include; reducing all losses (such as seepage, deep percolation and drainage), increasing the effective use of rainfall and increasing the marketable yield of the crops for each unit of water transpired. Agricultural water productivity is an important parameter which if increased can help sustain and improve food production towards ensuring sustainable food security in the food insecure region. It varies from one place to another depending on factors such as: crop pattern, climate patterns, irrigation technology, field management and the type of input used (Cai & Rosegrant, 2003). Water productivity data across scales are useful in assessing whether water drained from upstream is reused effectively downstream.

2.12 Case studies of moisture conservation techniques under irrigation

Different studies on moisture conservation have been carried out. Recently, a study by Uwizeyimana *et al* (2018) was conducted in Cyili sub-catchment in Rwanda. The main objective of the study was to identify the best method of water conservation measures in order to generate the maximum grain yield in hotter and dryer regions where maize is grown. The treatments used were the rainfed (control), ridges, mulching and supplementary irrigation. From the experiment, it was concluded that the moisture conservation techniques (mulching, ridges and supplementary irrigation) could retain some soil moisture and in turn improve the grain yield in the area. However, the extent to which the moisture was retained was not evaluated. In this study, the exact amount of soil moisture retained by each conservation technique was evaluated.

Crutchfield (2016), conducted a field study to compare fields with similar soil types farmed with soil conserving practices in Central Ohio to determine if no-till and cover crops can influence soil moisture retention through the build-up of soil organic matter content. The soil moisture content was measured at depths 0-20 cm, 20-40 cm and 40- 60 cm. From the experiment, the author concluded that the use of cover crops did not influence the amount of soil moisture retained. Due to the heavy amounts of rainfall received during the study period, the author did not draw conclusions on the relationship between soil organic matter content and moisture retention. Hence, the extend of moisture retained per conservation technique was not evaluated.

A study was conducted by Salifu (2015), to assess the effect of soil and water conservation on cowpea and maize performance in the Northern and Upper East regions of Ghana. The author employed contour farming, half-moon, contour ridges and the control as the moisture conservation techniques. From the results, the author concluded that the best technique for cowpea and maize production in the area was contour farming.

CHAPTER THREE
MATERIALS AND METHODS

3.1 The study area

Ol Donyo Nyoike area located within Ewaso Nyiro South sub-basin is the focus of this study. This area is a communally owned piece of ranch land covering approximately 5,000 households and is used for livestock grazing by the Maasai people. The main river in the sub-basin is called River Ewaso Nyiro which flows from the Mau Escarpment to the south through the Rift Valley and to the east of Nguruman Escarpment. Ewaso Nyiro River has many tributaries which traverse different parts of the county. For example, Ol Donyo Nyoike ranch is fed by river Olkeju Ng'iro which is one of its tributaries (Gichuki *et al*., 1998). The sub-basin lies between latitudes 1° 41′ 58.26″ and 1° 41′ 57.39″ S and between longitudes 36° 23′ 22.35″ and 36° 23′ 21.82″ E and it covers an area of approximately 4.176 km^2. It is as illustrated in Figure 3.1.

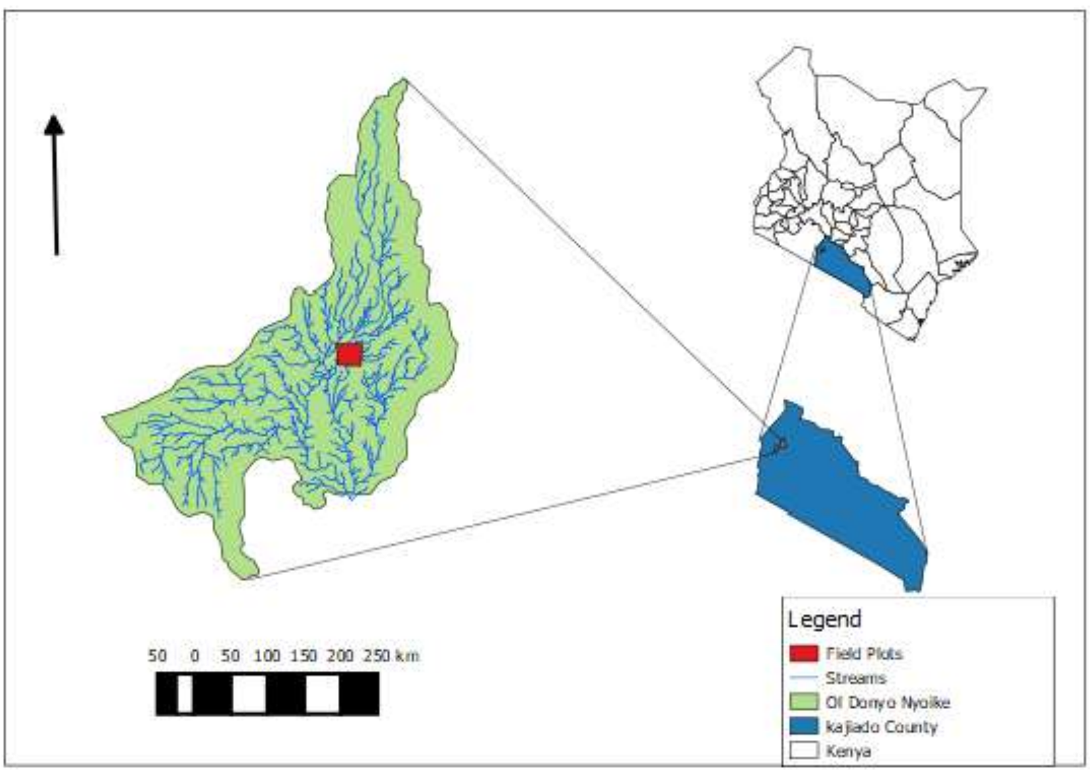


Figure 3. 1: Map of Kajiado County showing Ol Donyo Nyoike sub-catchment

The study area experiences bimodal distribution of rainfall with the long rains running from March to May and the short rains from October to December. The annual mean rainfall is 600 mm and varies with altitude. For instance, the amount of rainfall increases from 500 mm in the plains to 1250 mm in the highlands. The temperature also varies with altitude and range from 12^0C in the highlands to 34^0C in the plains (Gichuki *et al*., 1998). The study area receives heavy rains around Ngong hills at an average of 1250 mm while the lowlands such as Magadi area receive an average rainfall of less than 500 mm per annum (Berger, 1993).

3.1.1 Experimental set- up and data acquisition

Before setting up the sensors, the study area was characterized on spatial domain into initial soil moisture content, water holding capacity of the soils, bulk density, soil texture, porosity, soil particle size distribution, field capacity and permanent wilting point of the soil as well as the infiltration rate of water and basic infiltration rate.

The soil water content was determined using the gravimetric method. This method involved weighing the moist samples and oven drying them at 105 ^{0} C for 48 hours. The mass of water lost was then calculated as a percentage of the mass of the dried soil. This relation is described in Equation 3.1.

$$\theta_g = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100\% \qquad (3.1)$$

Where:

θ_g = Gravimetric soil water content (%)

M_{wet} = Mass of wet soil sample (g)

M_{dry} = Mass of dry soil sample (g)

The soil samples from the three plots were collected at three different depths along the soil profile from 20-30, 40-50 and 50-60 cm given that the rooting depth of sorghum is 1.0 m as per a procedure outlined by Allen *et al*. (1998).

In determining the bulk density (ρ_b), also known as apparent specific gravity, the soil samples were taken from undisturbed soils and then heated in the oven at 105^{o}c for 48 hours. The oven dried sample was then weighed. The volume of the core ring was then determined after which the bulk density was determined as the ratio of the mass of the oven dried sample to the volume of the soil sample. The particle density, also known as specific gravity, was then estimated by computing the ratio of the mass of the soil particles to the volume of the soil solids. The porosity (n) was estimated based on measured dry bulk density and particle density as described in Equation 3.2.

$$n = \left[1 - \frac{\rho_b}{\rho_n}\right] \times 100 \tag{3.2}$$

Where:

n = Porosity (Dimensionless)

ρ_b = Dry bulk density (kg/m^3)

ρ_n = Particle density (kg/m^3)

The Laser Diffraction Particle size analyzer (LA-950V2 HORIBA) was used to analyze the particle size distribution of the soil particle sizes in the area. This analysis was done at World Agroforestry Centre (ICRAF) soil laboratories. The analysis was conducted in the wet mode where sodium hexametaphosphate (calgon solution) was used as the dispersing agent. Six samples were collected from the field with two samples from the three blocks. Each sample was thoroughly mixed for analysis. Two grams of each soil sample was inserted into the machine. Each sample had four iterative readings which were recorded by a computer directly linked to the machine. The readings recorded were in the form of a (. ngb) file format. To make it readable, the (. ngb) file was converted to a flat file and then to the percent soil proportions using an application developed with the R software. To determine the soil texture of the various soil samples, the soil textural triangle (Figure 3.2) was used. The percentages of each primary soil separate were used to determine the soil class.

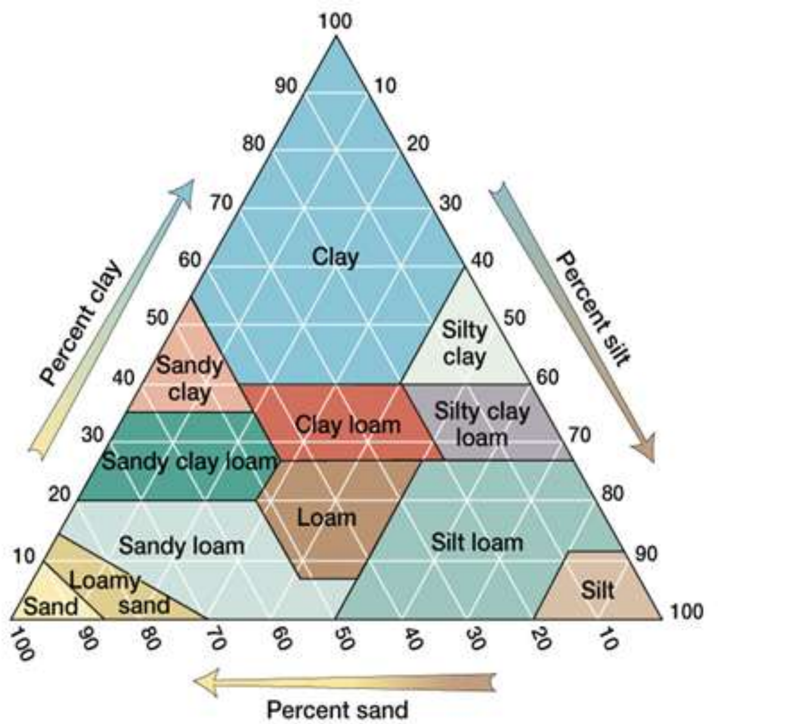
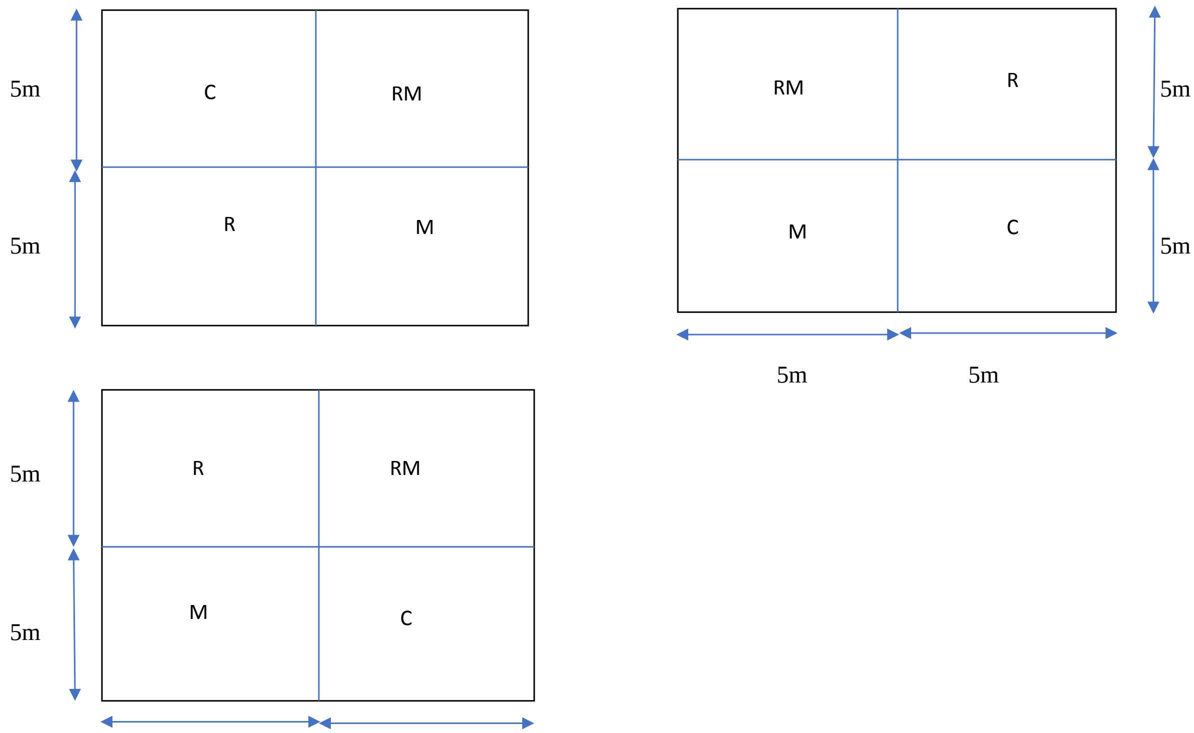


Figure 3. 2: Soil textural triangle

The soil textural triangle is illustrated in a way that the percentages of sand, silt and clay are plotted on an equilateral triangle. In the classification, the particles are assumed to be smaller than 2.0 mm and if detected otherwise then a correction is done to sum the three constituents, sand, silt and clay to 100%. The Field Capacity (FC), Permanent Wilting Point (PWP) and the Available Water (AW) of the soil in the study site were determined. In this research, FC was considered as the moisture content in soil after 2 to 3 days of free or gravity drainage following a period of thorough wetting of rainfall or irrigation (Aschonitis *et al*., 2013). To determine the FC, small portions in the three blocks were saturated with water. The water was allowed to drain freely under the influence of gravity for 4 days. Thereafter, two soil samples were taken from each block. The samples were weighed and then placed in the oven at 105 °C for 72 hours. After three days, the mass of the dried soil samples was determined by use of digital balance machine.

3.2 Effectiveness of moisture conservation techniques

After all the soil analysis tests were done, the experiment was then laid down in Randomized Complete Block Design (RCBD) in plots of 5 m by 5 m each as described in Figure 3.3.



Where:

C = Control

RM = Combined ridges and mulch

R = Ridges

M = Mulch

Figure 3. 3: Experimental layout in the field

Digital moisture sensors (YL-69) were placed in the soil at depths of 20 cm and 40 cm to measure the amount of moisture content in the soil at the respective depths. The YL-69 soil moisture sensors were used in this study due to their low cost, good operation ability and their high level of accuracy. To get useful soil moisture data, all the sensors placed in the field were calibrated against the available soil type. All the soil clogs were broken to ensure consistent water movement. The analogue output, which measures 1024 units, was used in the measurement of the soil moisture content in this study. The moisture content of a sensor not dipped in the soil was 0, which denoted the dry condition. With the saturated soils, the moisture condition was 1024. The values obtained were used as the threshold values or the baseline from which the other sensors were based upon. If the values were not the same as the values of the threshold then the potentiometer (the knob on the sideways) was used to adjust the values. To get the percentage soil moisture content, the values 0 to 1024 were mapped to 0 to 100%. The sensors were randomly placed in the field plots to ensure that the variability was catered for. Holes for the placement of the sensors were dug using a regular closed soil auger. The experimental block was then set out into blocks with respect to the conservation measures. This experiment was done in three replications. Different flood events were experienced during the growth period as discussed in the results section and they were the source of water for the growth of the sorghum crop. The plots were planted with sorghum on 7th September 2017. Significant flood events meant a flood event that exceeded the saturation point. The saturation water content of the soil was calculated as presented in Equation 3.3.

$$\theta_{sat} = 100(1 - \frac{\rho_b}{\rho_p}) \quad (3.3)$$

Where:

θ_{sat} = Volumetric soil-water content at saturation (%)

ρ_b = Bulk density of soil (g/cm^3)

ρ_p = Particle density of soil (g/cm^3)

The YL-69 moisture sensor is set up by two pieces; the electronic board and the probe. The probe has two pads that detect the water content. The sensor has a built-in potentiometer for sensitivity adjustment of the digital output (DO), a power LED and a digital output LED. The sensor works in a way that, the voltage that the sensor outputs changes according to the water content in the soil. A customized soil water content threshold is set allowing for dryer or wetter soil condition. When the soil is wet, the output voltage decreases and when dry the voltage increases. The output can either be a digital signal or an analogue signal. If digital, the output can be high or low depending on the water content. The moisture sensor specifications are described in the Appendix A.1.

3.3 Estimation of Crop Water Requirements

In estimation of the CWR of sorghum under spate irrigation at the different growth stages, the crop coefficient and the reference evapotranspiration was determined in each block as described in sub-sections 3.3.1 and 3.3.2.

3.3.1 Estimation of Kc using remote sensing and NDVI

During the growing period, Sentinel 2 images were downloaded from the ESA Copernicus Open Access Hub. The obtained sentinel images which were in .XML format were loaded into Sentinel Application Platform (SNAP). The procedure followed was: File > Open product > Then from the folder where the images are saved open MTD_MSIL1C. To process the image for NDVI, the ‘Optical’ option in the tool bar was clicked. This was followed by the ‘Thematic land processing’ tool and then ‘Vegetation Radiometric Indices’ and finally ‘NDVI Processor’. A dropdown menu appeared from which the bands 4 and 8 were chosen for the calculation. Bands 4 and 8 represent the red (R) and near infrared (NIR) band measurements respectively. NIR was considered to represent the reflectivity of plant materials in the near-infrared while the RED represented the chlorophyll pigment absorption in the red band (Lillesand *et al*., 2004). NDVI was calculated using the relation in Equation 3.4 as described by Lillesand *et al.* (2004):

$$NDVI = \left(\frac{NIR - RED}{NIR + RED} \right) \tag{3.4}$$

Where:

$NDVI$ = Normalized Difference Vegetation Index (Dimensionless)

NIR = Near Infra-Red band

RED = Red band

The obtained NDVI image was then opened in ArcMap where the it was clipped to the area of interest. The area clipped was an area of 100 m by 100 m. Sentinel 2 images were used in this study to monitor the crop through its growth period as is required in the study. In addition, the satellite images are free, full and open access.

The NDVI was calculated at different growth stages (initial, development, mid-season and late stages) since the chlorophyll content, crop age and planting density are different in each stage (initial, crop development, mid and end stages). The days in each growth period were used as tabulated by FAO (Allen *et al*., 1998). Theoretically, NDVI values range from -1.0 to +1.0 with the vegetated areas having a value greater than 0.2 and the non-vegetated less than 0.2 (El-Shirbeny *et al*., 2014). In practice the NDVI values range from -0.1 and +0.7. clouds, water, snow and ice give negative values while bare soil and other background materials produce NDVI values between -0.1 and +0.1. K_c values for sorghum were determined using a formula as described in Equation 2.5. The attained values were compared to the FAO computed values as described in Equation 2.4 and a relation was drawn from both values. The stage-dependent Kc was multiplied with the daily ETo to determine the daily crop water requirement under each treatment.

3.3.2 Estimation of CWR for sorghum

The reference evapotranspiration was computed using the Hargreaves formula as shown in the relation (Hargreaves *et al*., 1985).

$$ET_o = 0.0023 \times Ra \times (T_{ave} + 17.78) \times \sqrt{\Delta T} \quad (3.5)$$

Where:

R_a = Extraterrestrial radiation (mm/day)

ΔT = Temperature range (^{0}C)

The temperature range and its average were calculated using the following relations;

$$\Delta T = T_{\max} - T_{\min} \quad (3.6)$$

$$T_{ave} = \frac{T_{\max} + T_{\min}}{2} \quad (3.7)$$

Where:

T_{ave} = Average temperature (^{o}C)

T_{min} = Minimum temperature (^{o}C)

T_{max} = Maximum temperature (^{o}C)

This method was chosen because it is computationally simple and can be used over a variety of climates with a minimal amount of climate data required. The determined crop coefficient was then combined with the reference evapotranspiration at different growth stages to come up with the amount of water required. This relation is described in Equation 3.8.

$$ET_C = K_C \times ET_O \tag{3.8}$$

Where:

ET_c = Crop evapotranspiration (mm/day)

K_c = Crop coefficient

ET_o = Reference evapotranspiration (mm/day)

Analysis of variance (ANOVA) was used for the examination of the values obtained. The amount of CWR determined was compared to the recorded FAO standard values. The daily crop water requirement was summed up in relation to the number of days to get the total amount per crop development stage. The seasonal water requirement was obtained by summing the water requirement per development stage to get the total per moisture conservation technique as presented in Appendix A.5.

3.4 Determination of Water Productivity (WP)

The water productivity for the different plots was assessed by analyzing the yield from each plot in relation to the crop water requirement of sorghum crop. This helped in understanding which conservation practice is effective in providing high-water productivity and the source of variability. According to Molden (1997), the WP was obtained using the relation presented in Equation 3.9.

$$WP = \frac{Y}{ET_S} \tag{3.9}$$

Where:

WP = Water productivity (kg/m^3)

Y = Seasonal crop fresh yield (kg/ha)

ETs = Seasonal crop evapotranspiration (ET) (m^3/ ha).

The water productivity from the different plots under different conservation measures were statistically analysed using ANOVA and compared to assess their effectiveness in crop productivity.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Effectiveness of moisture conservation techniques on moisture retention

In analyzing the moisture retention under the different moisture conservation techniques, several catchment characteristics were analyzed. These catchment characteristics were the initial moisture content, the bulk density, particle density, the porosity of the soil, basic infiltration rate the soil texture and the particle size distribution.

4.1.1 Bulk density, particle density and porosity of soil

From the laboratory analysis, the bulk density, particle density and porosity of the soil at three different depths was determined and the values are summarized in Table 4.1.

Table 4. 1: Soil hydraulic properties

Depth (cm)	Bulk density (g/cm^3)	Particle density (g/cm^3)	Solid space (%)	Porosity (%)
20-30	1.23	2.58	47.67	52.33
40-50	1.28	2.60	49.23	50.77
50-60	1.53	2.63	58.17	41.83

The values of bulk density (BD) ranged from 1.23 g/cm^3 to 1.53g/cm^3. Studies by Chaudhari *et al*. (2013), stated that the normal ranges of BD for clay soil ranges from 1.0 g/cm^3 to 1.6 g/cm^3 with potential plant growth restriction occurring on a soil with a BD value greater than 1.4 g/cm^3. For this study, the BD was observed to increase with depth from 1.23 to 1.53 g/cm3 at a depth of 50-60 cm. A study by Chaudhari *et al*. (2013), confirmed that the BD increases with profile depth. An increase in BD with depth is attributed to compaction, less organic matter and less root penetration (Kamalakar & Khan 2012). The lowest BD of 1.23 g/cm^3 was observed on the top 0-20 cm depth soil layer and this could be attributed to the high levels of organic matter content on this layer since the land was virgin.

The particle density increased with an increase in depth. The lowest value was recorded as 2.58 g/cm^3 at the depth of 0-20 cm and the highest was 2.63 g/cm^3 at the depth of 50-60 cm. There was no trend observed in the particle density values in this study just like a study done by

Kamalakar & Khan (2012). However, the particle density values increased with depth. The increase of particle density with depth could be attributed to the concurrent decrease in organic matter content. The values obtained were slightly lower than the normal range of 2.65 g/cm^3 (Brady and Weil, 2002).

The porosity decreased with increase in depth. The highest value was 52.33% at the top depth of 0-20 cm and the lowest was 41.83% at the bottom depth of 50-60 cm. The porosity values were in the range of 34% to 57% as given by Morris and Johnson (1967). On further analysis of the relationship between bulk density and porosity, the BD was found to be inversely proportional to the porosity of the soil samples. From the analysis, a negative correlation value of 0.99 was obtained as illustrated in Figure 4.1.

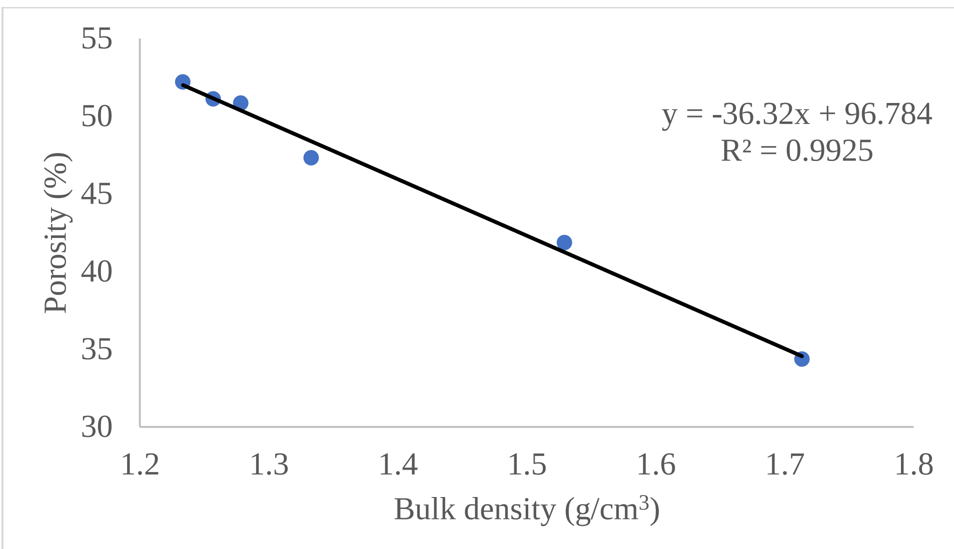


Figure 4. 1: Relationship between porosity and bulk density

Studies by Chaudhari *et al*. (2013), showed similar results as in this study indicating a negative correlation of 0.6332 of the clay content between the bulk density and the porosity. Studies conducted by Kakaire *et al*. (2015) had similar results with a negative correlation coefficient of 0.9149. The negative correlation coefficient indicated that a decrease in the soil bulk density depicted an increase in the porosity.

4.1.2 Soil particle size distribution

Soil sample analysis was conducted to determine each proportion of soil. The results of the particle size distribution using the laser diffraction machine are presented in Table 4.2.

Table 4. 2: Particle size distribution, soil water statistics and soil texture

Block	Clay (%)	Silt (%)	Sand (%)	Soil texture	FC (%)	PWP (%)	Available water (mm)
A	52.14	37.10	10.76	Clay	37.73	16.11	47.66
	69.52	30.00	11.77	Clay	41.05	20.25	46.49
B	69.52	25.53	4.95	Clay	42.85	20.78	49.31
	60.52	32.09	7.39	Clay	40.35	18.54	48.73
C	81.52	15.30	3.18	Clay	45.79	23.68	49.41
	52.17	36.54	11.29	Clay	37.59	16.37	47.42

From an analysis of the six samples, two samples from each block, clay had the highest percentage of the soil proportions followed by silt and then sand texture. Also, variability in particle size distribution through the three blocks was evident. The different soil types had varying proportions with clay content varying from 52.14 % to 81.52%, silt between 15.3% to 37.1% and sand from 3.18% to 11.77%. Amongst all the three, clay had the highest variability. Using the soil textural triangle presented in Figure 3.2, the average soil texture of the three field blocks was found to be clay.

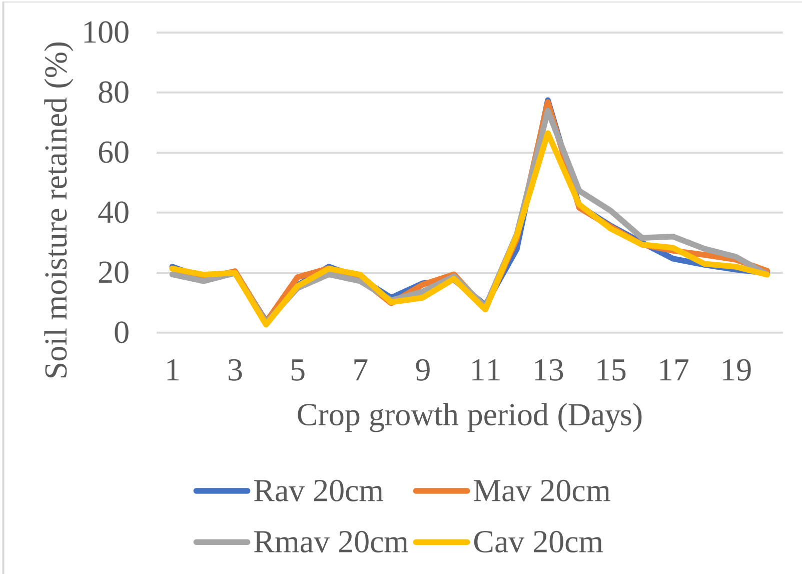
4.1.3 Field capacity and permanent wilting point

As described in Table 4.2, the field capacity (FC) values ranged from 37.59% in Block C to 45.79% in the same block. In block A, the FC values were 37.73% and 41.05% while in Block B the values were 42.85% and 40.35%. According to studies by Saxton and Rawls (2006), the amount of FC for a clay textured soil is 42%. Hence from this study, the FC values were slightly different with the biggest variation of 5% recorded in Blocks A and C. The permanent wilting point values (PWP) in this study ranged from 16.11% to 23.68%. These values were below the 30% determined by Saxton and Rawls (2006).

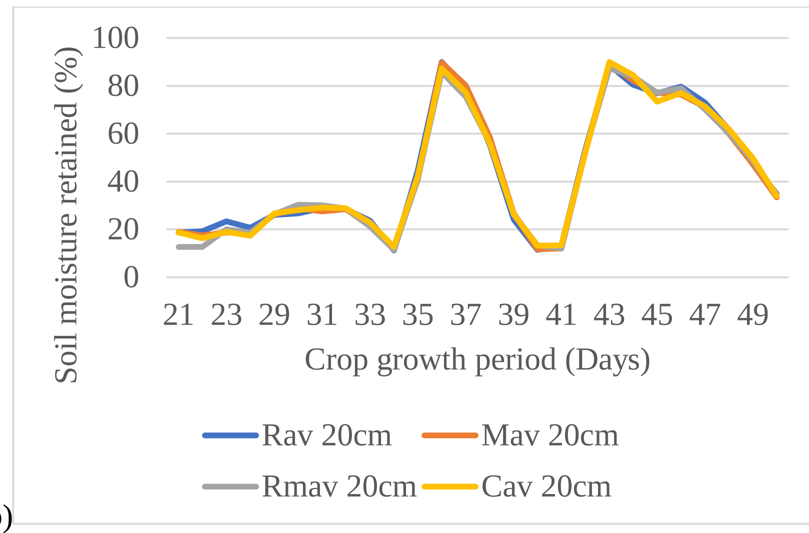
4.1.4 Moisture retention at different depths

Different flood events of different magnitudes occurred during the sorghum growth period. From Equation 3.3, the volumetric soil water content at saturation was determined to be 53.6% above which a flood event was observed. The much significant events occurred during the 18th of September and, 11th and 18th of October 2017. From analysis of the data, a similar trend of flood recession was observed under the different moisture conservation measures. However, amount of moisture retained per conservation measure varied. The moisture retained increased with an increase in flood magnitude and the moisture content reduced with time when another flood did not occur. The moisture content was recorded every 15 minutes for the entire growth period but for analysis purposes, the average daily moisture content readings were used.

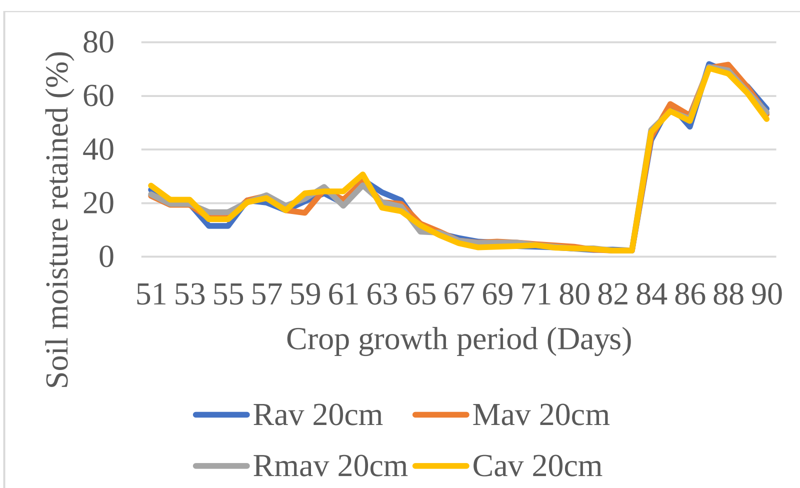
The moisture retained was monitored by moisture sensors placed at depths 20 cm and 40 cm. The soil type was assumed to all clay in the field plots. Four significant flood events were observed during the entire growth period. The observed sorghum crop growth period was a total of 125 days, with the planting done on the 7th September 2017 and harvesting on 10th January 2018. It took the crop 20, 30, 45 and 30 days for the initial, crop development stage, mid-season stage and late-season stage respectively. The moisture retained under the different moisture conservation techniques from 7th September 2017 (represented by day 1) to 10th January 2018 (represented by day 125) is as illustrated in Figure 4.2 (a-d). The growth period is divided into four representing the four crop growth stages. Days 1-20, 21- 50, 51-90 and 91- 125 represent the initial stage, development stage, mid-season and late stages respectively.


100
80
60
40
20
0
Soil moisture retained (%)
1 3 5 7 9 11 13 15 17 19
Crop growth period (Days)
Rav 20cm
Mav 20cm
Rmav 20cm
Cav 20cm

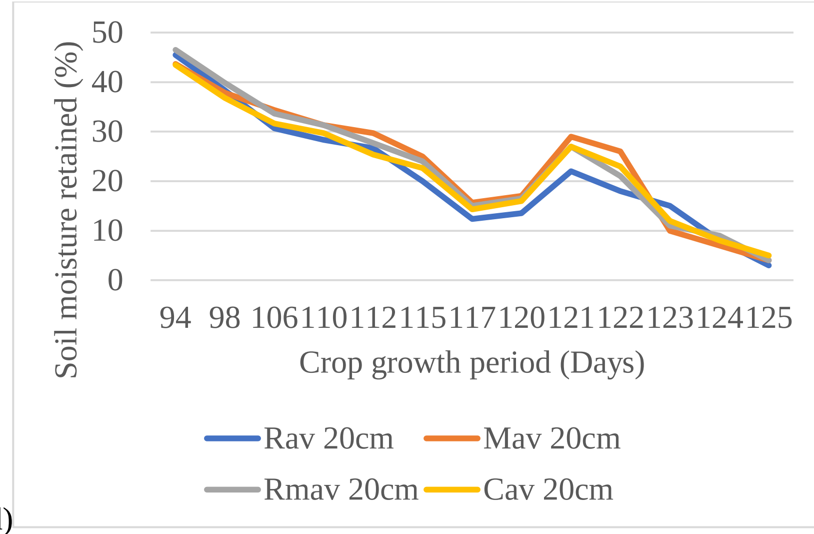
(a)


100
80
60
40
20
0
Soil moisture retained (%)
21 23 29 31 33 35 37 39 41 43 45 47 49
Crop growth period (Days)
Rav 20cm
Mav 20cm
Rmav 20cm
Cav 20cm

(b)


80
60
40
20
0
Soil moisture retained (%)
51 53 55 57 59 61 63 65 67 69 71 80 82 84 86 88 90
Crop growth period (Days)
Rav 20cm
Mav 20cm
Rmav 20cm
Cav 20cm

(c)

(d)


Rav = Ridges average Mav = Mulch average RMav= Combined ridges and mulch Cav = Control average

Figure 4. 2 (a-d): Moisture retained at 20-cm depth

In the beginning of the crop growth period, a flood event occurred on the 12th day of the crop growth period. The moisture conservation measures followed the same trend where the moisture content increased with the increase in the flood magnitude and reduced with time. Different levels of moisture content were absorbed by the different treatments ranging from 66.5% to 77.5% by the end of the day. The ridges and mulch recorded the highest amount of moisture content at 77.5% and 76.8% respectively. The control treatment recorded the least moisture content at 66.5%. With time the moisture retained was highest under the combined ridges and mulch followed by the mulch, ridges and finally the control. On the 28th day the combined ridges and mulch, the control, the ridges and the mulch had values of 18.7%, 17.3%, 20.7% and 18.7% respectively. On the 34th and 41st days, two significant events were observed both of which were recorded at 3 p.m. From both events, the conservation measures followed the same trend where the moisture levels increased with the occurrence of the floods and reduced with time. At the end of the month, day 56, the mulch and ridges retained much of the moisture content at 21%% while the combined ridges and mulch and the control had values of 20.3%.

In the month of November, days 57 to 86, small flood events were observed. In late November, day 83, a flood event was observed that raised the moisture content of the different moisture conservation techniques to levels between 43.5% to 46.5%. At the end of the month, day 85, the moisture levels had raised to levels between 54.3% to 57%. The moisture content reduced with time and in a day, another flood event was observed. This flood was observed on day 86 of the growth period. The moisture content increased to levels between 70.3% and 71.8%. The amount of moisture content in the soil increased with the inflow of the flood water. The different conservation techniques followed the same trend in which the moisture content reduced with time. At the end of the month of December, day 117, the moisture content recorded at the ridges, mulch, combined ridges and mulch and the control was 12.3%, 15.7%, 15% and 14.3% respectively. The last flood event occurred on day 120 at 9.00 am which translated to an increase in the soil moisture levels to a moisture content of between 22% to 29%. The moisture content reduced with time and at harvesting, day 125, the moisture content recorded was 5% at the control and 3% for the ridges and 4% on the combined ridges and mulch and finally the mulch. The low values of moisture retained in the ridges and the combined ridges and mulch could be attributed to the washed away ridges since the surface area under direct evaporation was increased.

To statistically assess the effect of different moisture conservation techniques on moisture retention, an analysis of variance (ANOVA) was done. An analysis of variance (ANOVA) was conducted to determine the effect of different conservation techniques in soil moisture retention. This analysis was conducted at 95% confidence interval and results are presented in Table 4.3.

Table 4. 3: ANOVA test at 20 cm depth

Moisture conservation technique	Count	Sum	Average	Variance
RM	3	99.94	33.31	4.10
M	3	100.11	33.37	0.54
C	3	98.99	32.99	6.98
R	3	99.61	33.20	3.63
Block 1	4	130.95	32.74	0.18

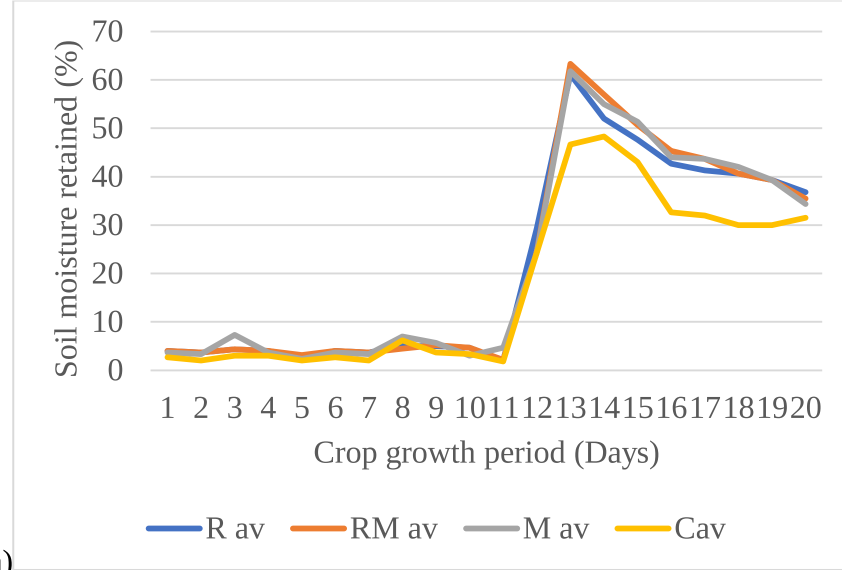
Block 2	4	126.77	31.69	0.66
Block 3	4	140.94	35.23	0.57

C = Control M = Mulch RM = Combined ridges and mulch R = Ridges

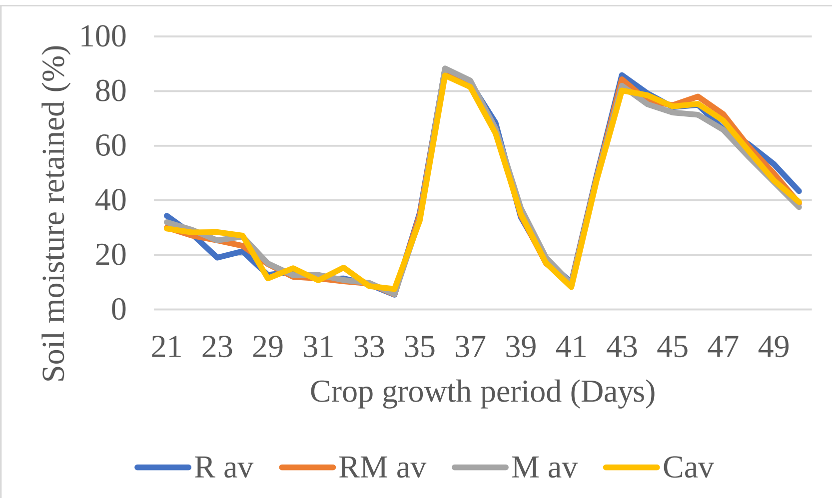
Source of variation	df	SS	MS	F	Fcritical	P-value
Treatments	3	0.24	0.08	0.12	4.76	0.94
Blocks	2	26.50	13.25	19.94	5.14	0.002
Error	6	3.99	0.66			
Total	11	30.72				

From the results summarized in Table 4.3, it was evident that there was no significant difference at the 20-cm depth in terms of moisture retention from the different treatments. A study conducted by Gicheru (1990), concluded that there were no significant differences between the treatments in soil moisture within the soil profile. However, there was a statistical difference in terms of the percentage amount of water retained per block. The highest amount of 35.23% was retained in block 3 followed by block 1 with a mean of 32.74 and finally block 2 with a mean of 31.69. Despite the lack of significant statistical difference among the treatments, different means were observed with the highest recorded under the mulch conservation at 33.37%. This was followed by the combined ridges and mulch which had a value of 33.31%, then the ridges with a value of 33.20% and finally the control which had a value of 32.99%. From the means, it was clear that the control is not effective in moisture retention since all other conservation techniques had higher means than the control. The observed p-value was 0.94. This value was high in comparison to the level of significance of 0.05 hence the lack of significant difference in how the treatments retained moisture content. A study conducted by Salifu (2015), to assess the effect of soil and water conservation measures on cowpea cultivation in Ghana confirmed the same that ridges conserved soil moisture better than the normal farmer’s practice.

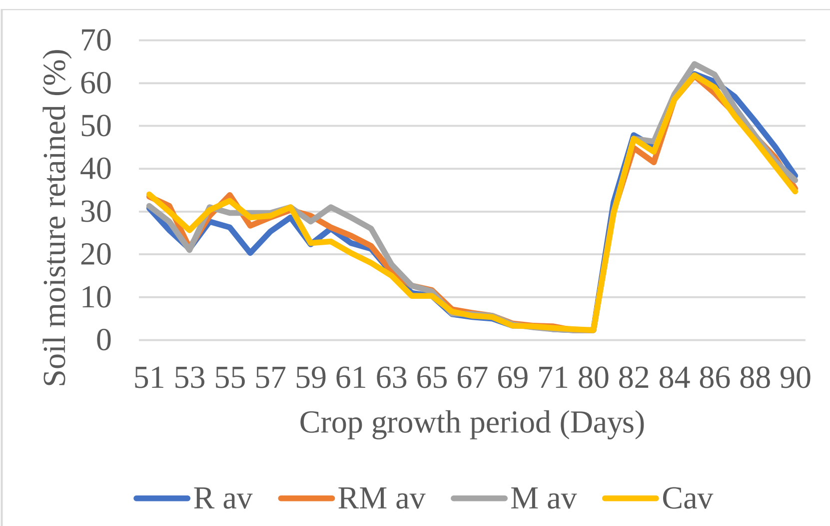
At the 40-cm depth, soils were not saturated. The moisture conservation curves are illustrated in Figure 4.3 (a-d).


70
60
50
40
30
20
10
0
Soil moisture retained (%)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Crop growth period (Days)
R av
RM av
M av
Cav

(a)

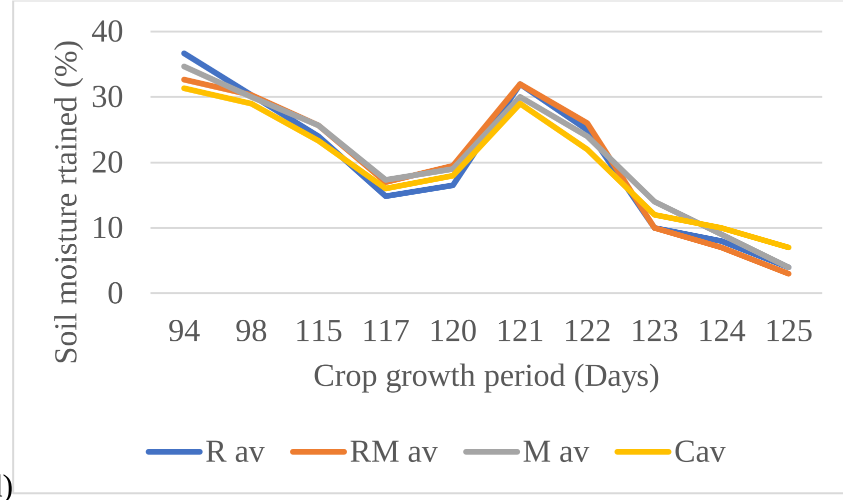

100
80
60
40
20
0
Soil moisture retained (%)
21 23 29 31 33 35 37 39 41 43 45 47 49
Crop growth period (Days)
R av
RM av
M av
Cav

(b)


70
60
50
40
30
20
10
0
Soil moisture retained (%)
51 53 55 57 59 61 63 65 67 69 71 80 82 84 86 88 90
Crop growth period (Days)
R av
RM av
M av
Cav

(c)

(d)



Rav = Ridges average RMav = Combined ridges and mulch average Mav = Mulch average Cav = Control average

Figure 4. 3 (a-d): Moisture retained at 40-cm depth

The moisture content was at a level between 0 and 10% before the significant flood event that occurred on day 12. After the occurrence of the flood, the moisture conservation techniques absorbed a significant amount of moisture content ranging from 25.3% to 28%. Three hours later, the moisture content under all treatments had increased to values between 46.7% and 63.3%. Under the four moisture conservation techniques, the amount of moisture in the soil increased with the amount of flood and reduced with time. By day 25, the control recorded the highest value of 28.3% followed by the mulch and the combine ridges and mulch with a value of 25.3 % and finally the ridges with 19%.

Between days 26 to 56, clear curves of how the moisture was retained were observed after the flood event of day 36. The moisture content in all treatments increased to levels between 85% and 90%. After six days, the moisture content in all treatments had reduced to levels below 10% after which another flood event was observed on day 43. The moisture content increased to levels between 80% and 85%. The moisture content took a while to reduce to the extremes and at the end of the month the levels were between 21% and 25%. At the end November, days 57 to 86, another

flood event was observed on day 84. The moisture content increased to levels of between 40% and 50% in day 85. The moisture content kept on increasing up to levels between 60% and 70%

in day 88. The moisture levels then reduced tremendously until a slight flood event on the 121st day which again increased the levels from values between 10% and 15% to values between 28% and 30%. During harvesting, 125th day, the moisture content was at 4%, 3%, 4% and 5% under ridges, combined ridges and mulch, mulch and control respectively. The moisture retention curves of the sensors at this depth are illustrated in Figure 4.5. In determination of the most suitable technique, the statistical analysis was conducted. Using ANOVA, the results are presented in Table 4.4.

Table 4. 4: ANOVA test at 40 cm depth

Moisture conservation technique	Count	Sum	Average	Variance
RM	3	94.83	31.61	12.54
C	3	91.16	30.39	14.39
M	3	95.05	31.68	10.52
R	3	94.77	31.59	15.44
Block 1	4	115.24	28.81	0.92
Block 2	4	118.70	29.68	0.20
Block 3	4	141.87	35.47	0.38

C = Control M = Mulch RM = Combined ridges and mulch R = Ridges

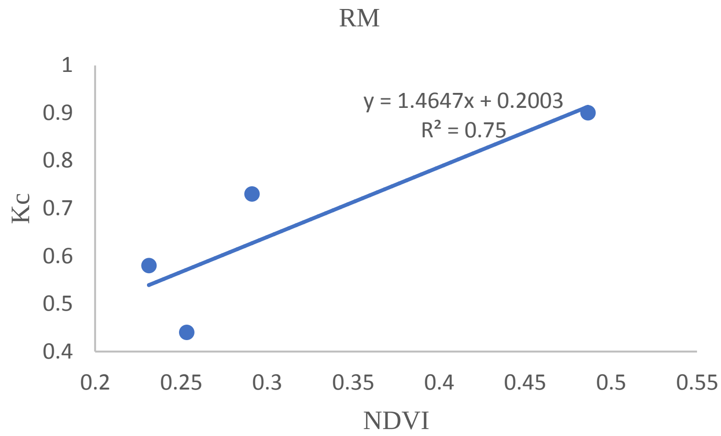
Source of variation	df	SS	MS	F	Fcritical	P value
Treatments	3	3.48	1.16	6.99	4.76	0.02
Blocks	2	104.78	52.39	315.44	5.14	8.36E-07
Error	6	0.99	0.17			
Total	11	109.27				

From the analysis, it was deduced that at least one of the moisture conservation techniques was different from the others in terms of moisture retention. From the analysis, the treatments had a p-value of 0.02 which was less than the alpha level of 0.05 meaning there was a significant difference on at least one of the treatments. To determine the best treatment in retaining moisture content in that area an analysis of their means was done. The mulch treatment had the highest value of 31.68%. This was closely followed by the combined ridges and mulch which had a mean of 31.61% and then ridges which had a mean of 31.59% and finally the control which had a mean of 30.39%. The results therefore indicate that the maximum moisture retention at 40-cm depth was under mulch compared to other techniques. Teame *et al.* (2017), gave similar results by conducting a study in Ethiopia to assess the effect of organic mulching on soil moisture yield and yield contributing factors of sesame. The authors indicated that at depth 21 cm to 40 cm, Sudan grass conserved the highest soil moisture content of 17.3% as compared to other materials. This coincides with the results of this study in that the experimental plots under mulch retained the highest amount of moisture content though with different moisture content values. A study conducted by Gicheru (1990) in Laikipia, Kenya under similar clay conditions to assess the effect of tillage and residue mulching on soil moisture conservation concluded that residue mulching was effective in conserving moisture than both the conventional tillage and tied ridging.

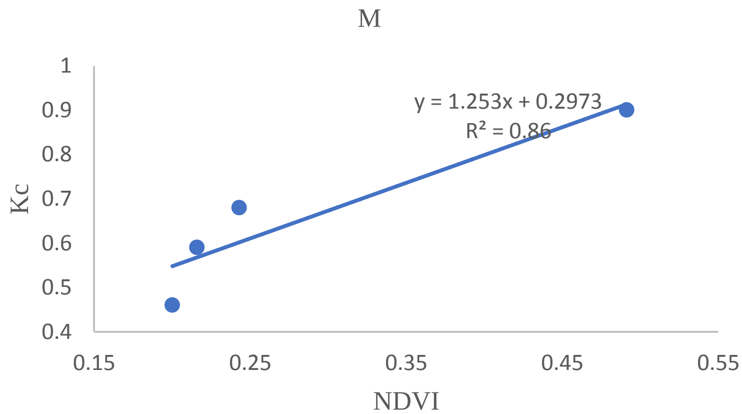
The findings indicate a significant difference in the moisture retention per block. The p-value recorded is 8.36E-07 which is way lower than 0.05 which is the significant level. The results show that, blocks 3, 2 and 1 retained moisture with a mean of 35.47%, 29.68% and 28.81% respectively.

4.2 Crop water requirement (CWR) for sorghum

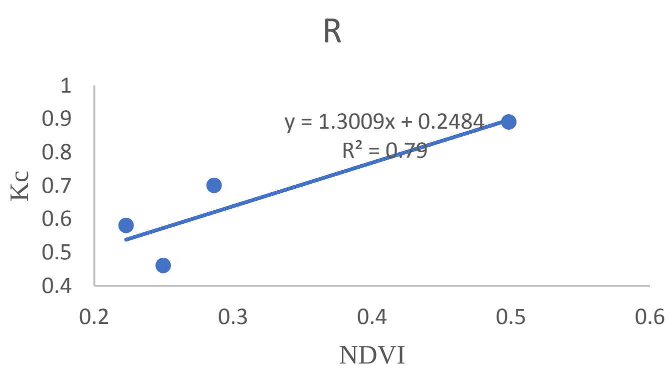
The crop coefficient was first established for CWR determination. In estimation of the crop coefficient, values at the different crop growth stages were determined and the average value for each growth stage was calculated. The K_c values were calculated using Equation 2.2. The maximum value of K_c for sorghum used in this equation was 1.15 (Allen *et al*., 1998). The NDVI values were obtained from 15 Sentinel 2 images obtained during the growth period. The maximum and minimum value of NDVI value for vegetation varied with every image and the growth period. The developed relationship between K_c and NDVI from the data is as illustrated in Figure 4.4 (a-d).



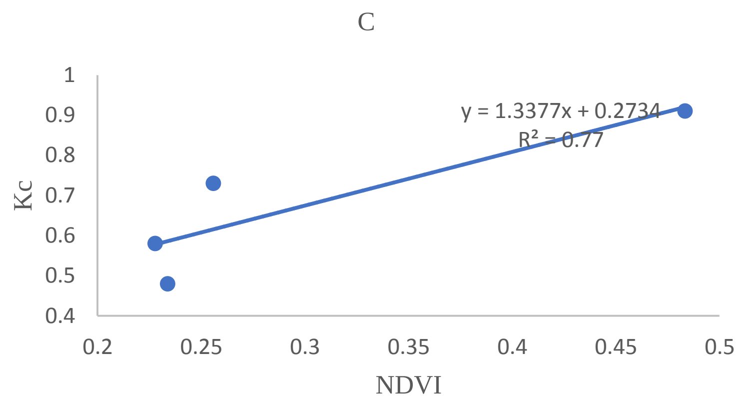
(a)



(b)



(c



(d)

C = Control M = Mulch RM = Combined ridges and mulch R = Ridges

Figure 4. 4 (a-d): Variation of Kc with NDVI

From the analysis, it was observed that the K_c linearly increases with the increase in NDVI under the different moisture conservation measures as presented in Figure 4.4. The regression coefficient from the relationship between the NDVI and Kc was found to be 0.75, 0.86, 0.79 and 0.77 for the combined ridges and mulch, mulch, ridges and control respectively. The different NDVI and K_c values calculated at the four main crop growth stages under the different moisture conservation techniques are summarized and presented in Tables 4.5 and 4.6.

Table 4. 5: NDVI values under moisture conservation techniques

	NDVI			
Crop growth stage	**C**	**M**	**RM**	**R**
Initial	0.25	0.20	0.25	0.23
Development stage	0.29	0.24	0.29	0.26
Mid-season	0.50	0.49	0.49	0.48
Late season	0.22	0.22	0.23	0.23

C = Control M = Mulch RM = Combined ridges and mulch R = Ridges

Table 4. 6: Kc values under different moisture conservation techniques

	Kc			
Crop growth stage (Days)	**C**	**M**	**RM**	**R**
Initial (0-20)	0.48	0.46	0.44	0.46
Development (20-50)	0.73	0.68	0.73	0.7
Mid-season (50-95)	0.91	0.90	0.90	0.89
Late-season (95-125)	0.58	0.59	0.58	0.58

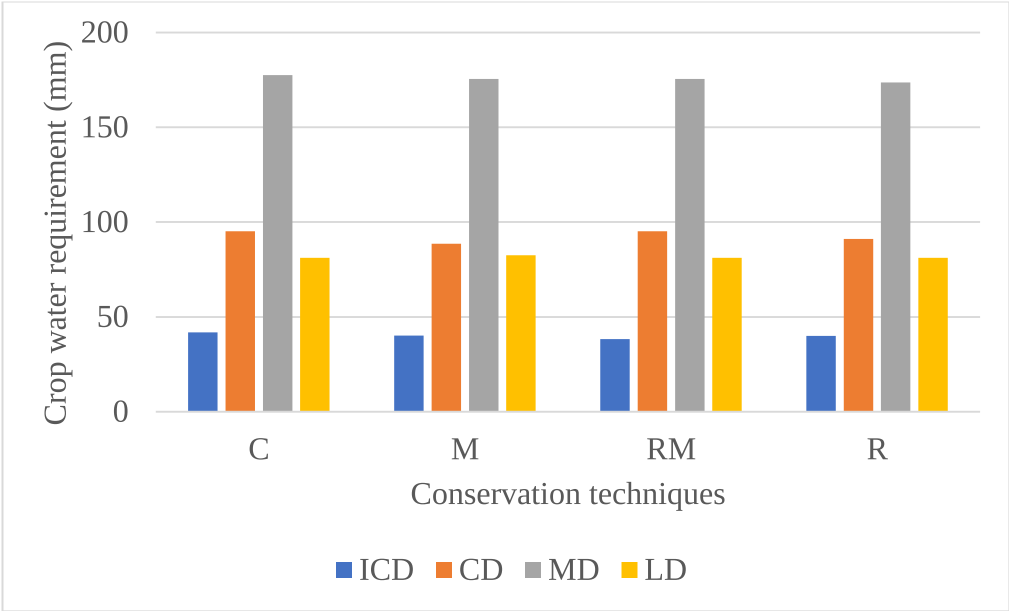
C = Control M = Mulch RM = Combined ridges and mulch R = Ridges

From the results, K_c values exhibit wide variation across the four crop development stages under the different moisture conservation measures. The K_c values ranged from 0.44 in the initial stage to 0.91 under the mid- season stage. However, under all the treatments the K_c values increased with the growth stages due to the increased ground cover from the crop. These values were slightly different and it was observed from the graphs that the combined ridges and mulch had slightly higher values of K_c than other conservation measures.

The increase in ground cover led to an increase in the rate of evapotranspiration. The high values of K_c value under the mid-season stage reflected a high rate of evapotranspiration. The values of K_c began to fall at the end of the mid-season stage to the late-season stage. The reduction of K_c was due to the reduction in leaf development and their maturity hence the reduction of evapotranspiration (ET). A similar trend was reported by Shenkut in a study conducted in 2013 at Melkassa in Ethiopia though the values were higher than in this study (Shenkut *et al*., 2013). The author indicated that the highest amount of K_c was recorded during the mid-season stage with a value of 1.18. Studies by Piccinni *et al.* (2009) conducted in South Texas confirmed the same trend where a difference was observed in the late stage. In the study, the crop coefficients at the initial, crop development and final stages were 0.40, 0.80 and 0.75 respectively.

The predicted K_c values by FAO were computed after the input of the crop height and the relative humidity of the study area as described in Equation 2.1. The height of the sorghum was similar under the mid-season and late development stages at 150 cm. In comparison to the FAO indicative values, all the treatments had a correlation coefficient of 0.9. The K_c values in the initial stage were high due to the high levels of evaporation in that area caused by the high temperatures and lack of vegetation cover since it was during a dry season. The arid and semi-arid zones have long hours of bright sunshine which leads to high radiation incidence leading to higher ET rate (Indinoba *et al*., 2008). The results of this study compared well with a study conducted by Sheng-Feng *et al* (2006) who studied the crop coefficient of sorghum grown in the year 1996 to 1998 and realized that the coefficients were 0.44, 0.71, 0.87 and 0.62 in the four stages, respectively. The calculated crop coefficient values fell within the acceptable limits and compared well with findings by Allen *et al*. (1998). Under the mid-season stage, low K_c values were recorded in comparison with values by Allen *et al*. (1998) as illustrated in the Appendix A.3. The growth period of sorghum in A.3 is 130 days.

In estimation of the crop water requirement, the Hargreaves model was used as described in Equation 3.5 through to Equation 3.8. The results of the analysis are presented in Appendix A.4. From the analysis, it was found that the water requirement of the same crop was slightly different under the different moisture conservation measures. The water requirement per growth stage ranged from 38.3 mm in the initial stage to 177.6 mm in the mid-season stage. In addition, the seasonal water requirement of sorghum in this study ranged from 386.9 mm to 395.7 mm as presented in Figure 4.5 and Appendix A.5.



ICD = Initial crop development, CD = Crop development, MS = Mid- development LD = Late development

Figure 4. 5: CWR of sorghum under different moisture conservation techniques

This range of total ET_c of the sorghum in this study was outside the range of previous studies by Piccinni *et al.* (2009) who found out that the ET_c of sorghum ranged from 491 to 533 mm and a study in Ethiopia that stated that the ET_c of sorghum was 500.7 mm (Shenkut *et al.*, 2013). Another study found out that the ET_c to be between 450 mm and 650 mm (Steduto *et al.*, 2012). According to the aforementioned studies, the ET_c from this study is lower than their documented values. Another study done in 2006 indicated that the range for the seasonal ET_c of sorghum was between 210 to 293 mm (Sheng-Feng *et al.*, 2006). These values are way below the ET_c of the sorghum in this study. Another study was carried out at Melkassa at three different planting dates; early, optimal and late planting dates (Shenkut *et al*., 2013). The findings were that the seasonal water requirement varied with the dates with the highest ET_c of 418.05 mm recorded under the early dates followed by the optimal dates of 401.25 and finally 267.13 mm under the late planting dates. The observed differences in the seasonal ET_c values is attributed to the difference in soil, climatic and crop varieties. The lower values of ET_c in this study could also have been associated with higher daily temperatures during the crop growth season which could have led to faster growing degree days accumulation leading to a shorter crop season.

4.3 Water productivity (WP) for sorghum

In assessing the water productivity under each treatment, the WP under each soil moisture conservation technique mount of sorghum harvested was evaluated and a summary of the results is presented in Table 4.7.

Table 4. 7: WP values under different moisture conservation techniques

Treatment	WP			
	1	2	3	Average
C	1.00	2.45	0.88	1.45
M	1.80	2.21	0.98	1.66
RM	1.28	4.10	0.87	2.08
R	0.93	2.98	1.58	1.83

C = Control M = Mulch RM = Combined ridges and mulch R = Ridges

From Table 4.7, WP varied with the moisture conservation techniques and with the blocks. The highest and lowest WP values of 4.10 kg/m^3 and 0.87 kg/m^3 were recorded under the combined ridges and mulch. The main contributing factor of the variabilities in the WP values among the different treatments was the difference in the amount of yield which was attributed to shading effect of the trees. The average WP values under the four treatments were 1.45, 1.66, 1.83 and 2.08 kg/m^3 for control, mulch, ridges and combined ridges and mulch respectively. To understand the most productive moisture conservation technique, ANOVA was conducted as presented in Table 4.8

Table 4. 8: ANOVA analysis of WP

Moisture conservation technique	Count	Sum	Average	Variance
C	3	4.34	1.45	0.75
M	3	4.99	1.66	0.39
RM	3	6.25	2.08	3.09

R	3	5.49	1.83	1.09
Block 1	4	5.02	1.25	0.16
Block 2	4	11.74	2.93	0.71
Block 3	4	4.32	1.08	0.11

C = Control M = Mulch RM = Combined ridges and mulch R = Ridges

Source of variation	**df**	**SS**	**MS**	**F**	**Fcritical**	**P value**
Treatments	3	0.66	0.22	0.58	4.76	0.65
Blocks	2	8.40	4.20	11.07	5.14	0.01
Error	6	2.28	0.38			
Total	11	11.33				

From the ANOVA analysis, there is no significant difference in WP between the different moisture conservation techniques. However, different means are observed with the highest WP value of 2.08 kg/m^3 recorded under the combined ridges and mulch. The findings of this study are consistent with results by Hadebe (2015) who gave values that ranged from 0.6 to 2.7 kg/m^3 as the normal for sorghum production. Cook *et al*. (2006), stated that water productivity for sorghum could either be bad or good based on their values of 0.5 kg/m^3 and 1.5 kg/m^3 respectively. The results show that combined ridges and mulch were most productive (2.1 kg/m^3), followed by the ridges, the mulch and finally the control (1.3 kg/m^3). The control represents the current scenario where sorghum is grown under no water conservation measures. From these results, in this study area, production can be optimized by use of combined ridges and mulch since the productivity increases by 55.8% when combined ridges and mulch conservation measures are used.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The broad objective of this research was to assess the effectiveness of moisture conservation techniques in sorghum productivity in Ol Donyo Nyoike area, Ewaso Nyiro South Drainage Basin. Under the general objective were the specific objectives which gave rise to the following specific conclusions:

i. The amount of moisture retained per conservation measure varied. At the 20-cm depth, there was no statistical difference in terms of the moisture retained from the different moisture conservation techniques. However, at the 40-cm depth the mulch retained much of the moisture content with a mean of 31.68. This was closely followed by the combined ridges and mulch which had a mean of 31.61 and then ridges which had a mean of 31.59 and finally the control which had a mean of 30.39.

ii. The entire growth period for the sorghum crop in this research period took 125 days. The crop water requirement for sorghum was 395.7 mm, 386.9 mm, 390.1 mm and 386.0 mm under control, mulch, combined ridges and mulch and ridges respectively.

iii. The water productivity recorded under the different moisture conservation techniques was 1.45 kg/m^3, 1.66 kg/m^3, 2.08 kg/m^3 and 1.83 kg/m^3 under control, mulch, combined ridges and mulch and ridges respectively. The WP was not significantly different between the treatments. However, the combined ridges and mulch had the highest mean and improved production by 55.8% in comparison to control.

5.2 Recommendations

For further research in the same field the following recommendations were suggested:

i. The moisture retained was only analysed at two depths. However, the analysis can be done at depths reaching the rooting depth of sorghum at different growth periods.

ii. From the study, it was evident that the crop coefficients and the crop water requirement varies with the local conditions of where the research is done. This therefore emphasizes on the need for local calibration for each sorghum variety. Since this study was carried out for one season in a single site, further research over varied sites and several seasons would be highly recommended for provision of reliable results.

iii. On productivity of sorghum, the combined ridges and mulch are recommended. This is because they increase the productivity of sorghum by 55.8% as compared to the control.

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APPENDICES

A.1: Specifications of YL-69 moisture sensor

Vcc power supply	3.3 v or 5 v
Signal output voltage	0 – 4.2 v
Digital outputs	0 or 1
Analog	Resistance Ω
Panel dimension	3.0 cm by 1.6 cm
Probe	6.0 cm by 3.0 cm
GND	Connected to ground

A.2 NDVI and Kc values at different dates of the growth period

Date	Treatment	Block 1	Block 2	Block 3	NDVI average	High: Low	Kc
26/9/17	R	0.17	0.19	0.19	0.18		0.48
	M	0.18	0.16	0.15	0.17		0.46
	RM	0.17	0.18	0.11	0.15	0.62	0.44
	R	0.17	0.16	0.17	0.17	-0.23	0.46
1/10/2017	R	0.24	0.18	0.28	0.23	0.71	0.81
	M	0.16	0.19	0.25	0.20	-0.60	0.78
	RM	0.24	0.16	0.27	0.22		0.80
	C	0.24	0.19	0.24	0.22		0.79
	R	0.26	0.17	0.45	0.29	0.77	0.85
	M	0.22	0.17	0.25	0.21	-0.60	0.80
6/10/2017	RM	0.32	0.22	0.39	0.31		0.86

	C	0.32	0.17	0.27	0.25		0.81
11/10/2017	R	0.17	0.24	0.29	0.23	0.70	0.68
	M	0.19	0.22	0.25	0.22	-0.45	0.67
	RM	0.22	0.26	0.29	0.26		0.71
	C	0.19	0.26	0.24	0.23		0.70
16/10/2017	R	0.34	0.26	0.45	0.35	0.73	0.60
	M	0.32	0.28	0.29	0.29	-0.14	0.53
	RM	0.30	0.32	0.42	0.35		0.60
	C	0.30	0.28	0.23	0.27		0.50
21/10/2017	R	0.24	0.18	0.33	0.25	0.39	0.69
	M	0.22	0.17	0.26	0.22	-0.20	0.62
	RM	0.24	0.22	0.28	0.25		0.68
	C	0.24	0.17	0.22	0.21		0.60
	R	0.36	0.29	0.43	0.36	0.62	0.75
	M	0.32	0.32	0.29	0.31	-0.31	0.69
	RM	0.39	0.32	0.38	0.36		0.76
26/10/2017	C	0.39	0.32	0.35	0.35		0.75
31/10/2017	R	0.46	0.43	0.49	0.46	0.80	0.82
	M	0.44	0.45	0.44	0.45	-0.36	0.81
	RM	0.46	0.44	0.46	0.45		0.81
	C	0.46	0.45	0.42	0.44		0.80
5/11/2017	R	0.63	0.69	0.66	0.66	0.65	1.10
	M	0.65	0.63	0.68	0.65	-0.29	1.09
	RM	0.63	0.65	0.62	0.63		1.06

	C	0.63	0.63	0.67	0.65		1.08
20/11/2017	R	0.60	0.56	0.51	0.55	0.69	0.91
	M	0.52	0.55	0.60	0.55	-0.04	0.91
	RM	0.51	0.52	0.60	0.54		0.89
	C	0.51	0.55	0.54	0.53		0.87
30/11/2017	R	0.46	0.43	0.46	0.45	0.62	0.82
	M	0.43	0.45	0.44	0.44	-0.16	0.812
	RM	0.47	0.43	0.46	0.45		0.83
	C	0.44	0.45	0.44	0.44		0.81
15/12/2017	R	0.37	0.36	0.38	0.37	0.74	0.62
	M	0.37	0.42	0.37	0.39	-0.13	0.64
	RM	0.31	0.37	0.33	0.34		0.57
	C	0.31	0.32	0.40	0.34		0.58
20/12/2017	R	0.32	0.39	0.33	0.35	0.81	0.72
	M	0.32	0.35	0.40	0.36	-0.39	0.73
	RM	0.37	0.33	0.39	0.36		0.74
	C	0.37	0.35	0.33	0.35		0.73
30/12/2017	R	0.21	0.21	0.27	0.23	0.56	0.48
	M	0.21	0.25	0.24	0.23	-0.05	0.49
	RM	0.25	0.21	0.27	0.24		0.51
	C	0.24	0.25	0.24	0.24		0.50
9/1/2018	R	0.01	0.02	0.01	0.01	0.64	0.51
	M	0.03	0.02	0.02	0.02	-0.50	0.52
	RM	0.02	0.03	0.01	0.02		0.52
	C	0.02	0.01	0.01	0.01		0.51

Where: C = Control, R = Ridges, RM = Combined ridges and mulch, M = Mulch

A.3 FAO determined K_c values for sorghum

Crop growth stage	Initial	Development	Mid-season	Late-season
K_c Value	0.4	0.7-0.75	1.14	0.56

A.4: ETc of sorghum under different moisture conservation techniques

Dates	day of the year	Ra(Mj/m^2/day)	Ra (mm/day)	ETo (mm/day)	RM (ETc)	C (ETc)	M (ETc)	R (ETc)
7/9/2017	250	36.73	14.99	5.72	2.52	2.75	2.63	2.63
8/9/2017	251	36.78	15.01	5.88	2.59	2.82	2.70	2.70
9/9/2017	252	36.84	15.03	5.50	2.42	2.64	2.53	2.53
10/9/2017	253	36.89	15.05	5.40	2.38	2.59	2.48	2.48
11/9/2017	254	36.94	15.07	5.52	2.43	2.65	2.54	2.54
12/9/2017	255	36.99	15.09	5.86	2.58	2.81	2.69	2.70
13/09/2017	256	37.03	15.11	5.30	2.33	2.55	2.44	2.44
14/09/2017	257	37.08	15.13	4.00	1.76	1.92	1.84	1.84
15/09/2017	258	37.12	15.14	4.27	1.88	2.05	1.96	1.96
16/09/2017	259	37.16	15.16	2.31	1.02	1.11	1.06	1.06
17/09/2017	260	37.20	15.18	3.40	1.50	1.63	1.56	1.56
18/09/201	261	37.24	15.19	1.37	0.60	0.66	0.63	0.63

7								
19/09/2017	262	37.27	15.21	5.46	2.40	2.62	2.51	2.51
20/09/2017	263	37.31	15.22	4.04	1.78	1.94	1.86	1.86
21/09/2017	264	37.34	15.24	3.64	1.60	1.75	1.68	1.68
22/09/2017	265	37.37	15.25	2.39	1.05	1.15	1.10	1.10
23/09/2017	266	37.40	15.26	3.55	1.56	1.70	1.63	1.63
24/09/2017	267	37.43	15.27	5.93	2.61	2.85	2.73	2.73
25/09/2017	268	37.46	15.28	2.23	0.98	1.07	1.03	1.03
26/09/2017	269	37.48	15.29	5.37	2.36	2.58	2.47	2.47
27/09/2017	270	37.50	15.30	3.43	2.50	2.50	2.33	2.40
28/09/2017	271	37.52	15.31	6.03	4.40	4.40	4.10	4.22
29/09/2017	272	37.54	15.32	4.99	3.64	3.64	3.39	3.49
30/09/2017	273	37.56	15.32	2.34	1.71	1.71	1.59	1.64

1/10/2017	274	37.57	15.33	4.99	3.65	3.65	3.40	3.50
2/10/2017	275	37.58	15.33	4.33	3.16	3.16	2.94	3.03
3/10/2017	276	37.59	15.33	2.34	1.71	1.71	1.59	1.64
4/10/2017	277	37.60	15.34	3.37	2.46	2.46	2.29	2.36
5/10/2017	278	37.61	15.35	5.96	4.35	4.35	4.05	4.17
6/10/2017	279	37.62	15.35	5.39	3.93	3.93	3.66	3.77
7/10/2017	280	37.62	15.35	5.39	3.93	3.93	3.66	3.77
8/10/2017	281	37.62	15.35	4.95	3.61	3.61	3.37	3.47
9/10/2017	282	37.63	15.35	5.64	4.12	4.12	3.84	3.95
10/10/2017	283	37.62	15.35	4.99	3.64	3.64	3.39	3.49
11/10/2017	284	37.62	15.35	4.99	3.64	3.64	3.39	3.49
12/10/2017	285	37.62	15.35	2.67	1.95	1.95	1.81	1.87
13/10/2018	286	37.61	15.34	3.67	2.68	2.68	2.49	2.57
14/10/2018	287	37.61	15.34	3.67	2.68	2.68	2.49	2.57
15/10/2018	288	37.60	15.34	4.60	3.36	3.36	3.13	3.22
16/10/2017	289	37.59	15.34	4.60	3.35	3.35	3.12	3.22
17/10/201	290	37.58	15.33	4.55	3.32	3.32	3.09	3.18

7								
18/10/2017	291	37.56	15.33	4.94	3.61	3.61	3.36	3.46
19/10/2017	292	37.55	15.32	3.96	2.89	2.89	2.70	2.78
20/10/2017	293	37.53	15.31	4.15	3.03	3.03	2.82	2.91
21/10/2017	294	37.52	15.31	2.66	1.94	1.94	1.80	1.86
22/10/2017	295	37.50	15.30	5.11	3.73	3.73	3.48	3.58
23/10/2017	296	37.48	15.29	3.66	2.67	2.67	2.49	2.56
24/10/2017	297	37.46	15.28	4.58	3.34	3.34	3.11	3.21
25/10/2017	298	37.44	15.28	5.07	3.7	3.70	3.45	3.55
26/10/2017	299	37.42	15.27	3.34	2.43	2.43	2.27	2.33
27/10/2017	300	37.40	15.26	4.24	3.81	3.86	3.82	3.77
28/10/2017	301	37.37	15.25	4.34	3.91	3.95	3.91	3.87
29/10/2017	302	37.349	15.24	5.60	5.04	5.10	5.04	4.99

30/10/2017	303	37.32	15.23	5.34	4.81	4.86	4.81	4.76
31/10/2017	304	37.30	15.22	4.70	4.23	4.28	4.23	4.18
1/11/2017	305	37.27	15.21	4.02	3.61	3.66	3.61	3.57
2/11/2017	306	37.24	15.20	4.21	3.78	3.83	3.78	3.74
3/11/2017	307	37.22	15.18	4.61	4.15	4.20	4.15	4.11
4/11/2017	308	37.19	15.17	4.22	3.80	3.84	3.80	3.75
5/11/2017	309	37.16	15.16	4.00	3.60	3.64	3.60	3.56
6/11/2017	310	37.13	15.15	4.60	4.14	4.19	4.14	4.10
7/11/2017	311	37.10	15.14	4.016	3.61	3.65	3.61	3.57
8/11/2017	312	37.07	15.13	4.76	4.29	4.33	4.29	4.24
9/11/2017	313	37.04	15.11	4.92	4.43	4.48	4.43	4.38
10/11/2017	314	37.01	15.10	3.38	3.05	3.08	3.05	3.01
11/11/2017	315	36.98	15.09	3.71	3.34	3.37	3.34	3.30
12/11/2017	316	36.95	15.08	5.02	4.52	4.57	4.52	4.47
13/11/2018	317	36.92	15.06	2.30	2.07	2.09	2.07	2.04
14/11/2018	318	36.89	15.05	3.37	3.04	3.07	3.04	3.00
15/11/201	319	36.86	15.04	1.36	1.22	1.24	1.22	1.21

8								
16/11/2018	320	36.83	15.03	5.39	4.85	4.91	4.85	4.80
17/11/2018	321	36.80	15.02	4.56	4.11	4.15	4.11	4.06
18/11/2018	322	36.78	15.00	4.99	4.50	4.55	4.50	4.45
19/11/2018	323	36.75	14.99	4.26	3.84	3.88	3.84	3.79
20/11/2018	324	36.72	14.98	4.88	4.39	4.44	4.39	4.34
21/11/2018	325	36.69	14.97	2.88	2.59	2.62	2.59	2.56
22/11/2018	326	36.66	14.96	4.65	4.19	4.24	4.19	4.14
23/11/2018	327	36.64	14.95	4.48	4.03	4.08	4.03	3.99
24/11/2018	328	36.61	14.94	4.48	4.03	4.07	4.03	3.98
25/11/2019	329	36.59	14.93	4.43	3.98	4.03	3.98	3.94
26/11/2019	330	36.56	14.92	3.67	3.30	3.34	3.30	3.26
27/11/2019	331	36.54	14.91	4.69	4.22	4.27	4.22	4.18

28/11/2019	332	36.52	14.90	3.26	2.93	2.96	2.93	2.90
29/11/2019	333	36.49	14.89	4.14	3.72	3.77	3.72	3.68
30/11/2017	334	36.47	14.88	4.24	3.81	3.86	3.81	3.77
1/12/2017	335	36.45	14.87	5.20	4.68	4.74	4.68	4.63
2/12/2017	336	36.43	14.86	4.45	4.01	4.05	4.01	3.96
3/12/2017	337	36.41	14.85	4.34	3.90	3.95	3.90	3.86
4/12/2017	338	36.40	14.85	5.21	4.69	4.74	4.69	4.64
5/12/2017	339	36.38	14.84	5.53	4.98	5.03	4.98	4.92
6/12/2017	340	36.37	14.84	5.21	4.69	4.74	4.69	4.63
7/12/2017	341	36.35	14.83	5.32	4.79	4.84	4.79	4.74
8/12/2017	342	36.34	14.83	4.67	4.20	4.25	4.20	4.15
9/12/2017	343	36.33	14.82	5.32	4.79	4.84	4.79	4.73
10/12/2017	344	36.32	14.82	2.14	1.93	1.95	1.93	1.91
11/12/2017	345	36.31	14.81	5.18	3.01	3.01	3.06	3.01
12/12/2017	346	36.30	14.81	4.44	2.57	2.57	2.62	2.57
13/12/2017	347	36.29	14.81	4.32	2.51	2.50	2.55	2.51
14/12/201	348	36.29	14.80	4.44	2.57	2.57	2.62	2.57

7								
15/12/2017	349	36.28	14.80	4.07	2.36	2.36	2.40	2.36
16/12/2017	350	36.28	14.80	4.17	2.42	2.42	2.46	2.42
17/12/2017	351	36.28	14.80	4.55	2.64	2.64	2.68	2.64
18/12/2017	352	36.28	14.80	4.94	2.87	2.87	2.92	2.87
19/12/2017	353	36.28	14.80	2.76	1.60	1.60	1.63	1.60
20/12/2017	354	36.28	14.80	5.31	3.08	3.08	3.13	3.08
21/12/2017	355	36.28	14.80	4.81	2.79	2.79	2.84	2.79
22/12/2017	356	36.29	14.81	5.15	2.98	2.98	3.04	2.98
23/12/2017	357	36.30	14.81	4.44	2.57	2.57	2.62	2.57
24/12/2017	358	36.30	14.81	4.46	2.59	2.59	2.63	2.59
25/12/2017	359	36.312	14.82	4.67	2.71	2.71	2.75	2.71
26/12/2017	360	36.32	14.82	4.03	2.34	2.34	2.38	2.34

27/12/2017	361	36.33	14.82	4.83	2.80	2.80	2.85	2.80
28/12/2017	362	36.35	14.84	4.61	2.68	2.68	2.72	2.68
29/12/2017	363	36.36	14.84	5.43	3.15	3.15	3.20	3.15
30/12/2017	364	36.38	14.84	5.33	3.09	3.09	3.14	3.09
31/12/2017	365	36.39	14.85	5.43	3.15	3.15	3.21	3.15
1/1/2018	1	36.41	14.86	5.77	3.34	3.34	3.40	3.34
2/1/2018	2	36.43	14.86	5.22	3.03	3.03	3.08	3.03
3/1/2018	3	36.45	14.87	3.93	2.28	2.28	2.32	2.28
4/1/2018	4	36.47	14.88	4.83	2.80	2.80	2.85	2.80
5/1/2018	5	36.49	14.89	2.78	1.61	1.61	1.64	1.61
6/1/2018	6	36.52	14.90	4.69	2.72	2.72	2.77	2.72
7/1/2018	7	36.54	14.91	4.75	2.75	2.75	2.80	2.75
8/1/2018	8	36.56	14.92	5.11	2.96	2.96	3.01	2.96
9/1/2018	9	36.59	14.93	5.49	3.18	3.18	3.24	3.18

Where: C = Control, R = Ridges, RM = Combined ridges and mulch, M = Mulch

A.5: Crop water requirement for each conservation technique (mm)

Crop growth stage	C	M	RM	R
Initial	41.8	40.1	38.3	40.0
Development	95.1	88.6	95.1	91.2
Mid-season	177.6	175.6	175.6	173.7
Late stage	81.2	82.6	81.1	81.1
Total	395.7	386.9	390.1	386.0

Where: C = Control, R = Ridges, RM = Combined ridges and mulch, M = Mulch