ASSESSMENT OF THE POTENTIAL OF RAINWATER HARVESTING FOR IMPROVING RAIN-FED MAIZE PRODUCTION IN SWAZILAND

The Case of Lubombo Plateau

Sanele Sacolo

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By

Sanele Sacolo

A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of Master (Integrated Water Resources Management) of the University of Dar es Salaam

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a dissertation entitled: **Assessment of the Potential of Rainwater Harvesting for Improving Rain-fed Maize Production in Swaziland, The Case of Lubombo Plateau,** in Partial fulfilment of the requirements for the degree of Master (Integrated Water Resources Management) of the University of Dar es Salaam.

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Dr. S.H. Mkhandi

(Supervisor)

Date: ………………………………………..

DECLARATION

AND

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I**, Sanele Sacolo**, declare that this dissertation is my own original work and that it has not been presented and will not be presented to any other University for a similar or any other degree award.

Signature …………………………………….

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Now all glory to Jehovah God, who is able, through His mighty power at work within us, to accomplish infinitely more than we might ask or think.

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DEDICATION

This piece of work is dedicated to the two most amazing women in my life:

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To my mother, Nester Sibongile Matsebula thanks Mkholo lonsundvu for supporting me in all decisions I take, even when I had to fly to distant lands. I had always remembered the tears you shed when I had to say my goodbyes.

This is what I went away for, I'm bringing it home!

LIST OF ABBREVIATIONS

ACAT	African Cooperative Action Trust
AFDB	African Development Bank
AHP	Analytical Hierarchy Process
CA	Catchment Area
CB	Cropped Basin
CN	Curve Number
CSIR	Council for Scientific and Industrial Research
CWR	Crop Water Requirements
DEM	Digital Elevation Model
DOY	Day of Year
ETc	Crop Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
HSG	Hydrologic Soil Group
IFAD	International Fund for Agricultural Development
LRS	Length of Rainy Season
MCE	Multi Criteria Evaluation
RWH	Rainwater Harvesting
SNL	Swazi Nation Land
TDL	Title Deed Land
UNEP	United Nations Environmental Programme
WFP	World Food Programme

ABSTRACT

Swaziland has persistently experienced below average and dwindling maize production chiefly due to low rainfall as well as erratic patterns. Extended dry periods occurring during critical maize crop development stages, result in widespread crop losses and reduced yields in the Lubombo Plateau. The objective of the study was to assess the potential of rainwater harvesting for rain-fed maize production in Swaziland. In order to achieve this, rainy season characterization, determination of maize crop net irrigation requirements, and assessment of runoff potential and identification of suitable rainwater harvesting sites in the Lubombo Plateau was carried out. Rainy season characterization was carried out in INSTAT Plus Statistical software by analyzing for the onset, cessation and length of the rainy season as well the total seasonal rainfall and probability of dry spells. The maize net crop irrigation requirement was calculated using CROPWAT 8.0 while ArcCN-Runoff tool was used to estimate the potential runoff volume generated in the study area. Multi-layer merging of rainfall, slope, runoff, soil texture and land use layers was performed in GIS environment to locate potential rainwater harvesting sites. The study showed that the rainfall is highly variable and insufficient to meet maize crop water requirements. It also revealed that the probabilities of prolonged dry spells are relatively higher at the beginning and towards the end of the season. Maize irrigation requirement was found to be 28.400 Mm^3. About 35% of the area is high to highly suitable for water harvesting. A total runoff volume of 37.181 Mm^3 can be harvested per year for crop production. This study concluded that rainwater harvesting for rain-fed maize production is feasible in the Lubombo Plateau.

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CHAPTER ONE

INTRODUCTION

1.1 General Introduction

Rain-fed agriculture is responsible for a great percentage of the food consumed by the world. It is carried out in an area that is about four fifth of the total global farmland, and provides about 70% of the essential foodstuff in the world, producing the most food for underprivileged populations in less developed countries. More than 90% of the agricultural land in Sub-Saharan Africa is under rain-fed agriculture (Barron, 2009; Falkenmark *et al*., 2001).

In rain-fed agricultural systems, as the name suggests, rainfall is the most important input. In areas where rainfall is generally low and coupled by pronounced erratic patterns, low yields have always crippled farming communities (Sharma *et. al*., 2009; UNEP, 2009). However, as Barron (2009) noted, it is beyond doubt that agriculture contributes immensely in reducing poverty as well as promoting economic development of rain-fed communities. Therefore, it is crucial that rain-fed agricultural systems be improved. In less developed countries, well-organized rainwater harvesting schemes can be very helpful in crop production and provision of water for other purposes (Barron, 2009). Conclusions from Pretty and Hine (2001) revealed that there much higher yield increase prospective in rain-fed agricultural systems in less developed countries than there is in irrigated agricultural systems.

In Swaziland, as is the case with most rain-fed agricultural systems, the total seasonal rainfall and its distribution is erratic, making crops vulnerable to moisture deficit.

Sharma *et al.* (2009) found that rainwater harvesting for supplemental irrigation during prolonged dry spells has a great potential of stabilizing and increasing crop yields in rain-fed agriculture. In semi-arid rain-fed regions, the total seasonal rainfall mostly occur as few rainfall events of high intensity thus resulting in high losses through runoff and evapotranspiration. Therefore, it is beneficial to intercept and utilize it for crop production purposes.

FAO (2006) noted that the Kingdom of Swaziland has continued to experience below average and dwindling maize production as a consequence of low rainfall as well as erratic patterns, which are intensifying the effects of mounting unemployment and pronounced poverty. Since rain-fed agriculture depends on rainfall as its sole source of water, it is therefore imperative to maximize the efficiency of rainwater use (Babiker *et al.*, 2015). Although results from studies carried out in Swaziland, amongst others by Dlamini *et al.* (2012), have reported that farmers recommended rainwater harvesting as one of the solutions to avert the persistent low maize production in the country, there is limited literature on feasibility studies carried in this regard. Studies, such as by Singwane and Kunene (2010); Vilane *et al.* (2010); only focused on the feasibility of rooftop rainwater harvesting for domestic purposes.

1.2 Statement of the Problem

According to a report by (FAO, 2015), the Lubombo plateau has one of the highest rate of food insecurity in Swaziland. Extended dry periods that often occur during critical maize crop development stages, result in widespread crop losses and reduced yields. This region has an average maize yield below the national average of 1.4

tonnes/ha and at the same time exhibit high variability. However, World Vision Swaziland (2010) pointed out that in the Lubombo plateau there is good potential to increase maize production.

In view of the fact that researchers have noted that rainwater harvesting offers a promising solution in minimizing the adverse effects of dry spells in rain-fed regions of the world, Swaziland included, this study was undertaken.

1.3 Objectives

1.3.1 General Objective

The general objective of the study was to assess the potential of rainwater harvesting for improving rain-fed maize production in Swaziland.

1.3.2 Specific Objectives

The specific objectives of the study were:

1. To determine the agronomical characterization of rainfall in the Lubombo Plateau.
2. To determine net irrigation requirement for maize in the study area.
3. To assess runoff potential and identify suitable rainwater harvesting sites in the study area.

1.4 Research Questions

1. What are the agronomic characteristics of rainfall in the study area?

2. Is the seasonal rainfall sufficient to meet maize crop water requirement in the Lubombo Plateau?
3. Can the maize crop water requirements in the study area be met through harvested rainwater?

1.5 Significance of the Study

Since in Swaziland irrigation accounts for more than 95% of the total water abstraction, (Swaziland Government, 2009), this study provides an alternative source of water for agriculture. The study reveals the potential of rainwater harvesting for improving rain-fed maize production in Swaziland, specifically the Lubombo Plateau. The runoff potential informs decision-making in rainwater harvesting planning in the region. The results also give guidelines for the best possible time of maize cropping and the selection of appropriate maize varieties matching this agro-climate in order to reduce dry spell associated risks.

1.6 Scope of the Study

The scope of the study was limited to the feasibility of rainwater harvesting for agriculture in the Lubombo Plateau region of Swaziland, specifically runoff harvesting for maize, although the results can also be useful in planning rainwater harvesting in general. Spatial documentation on location of rainwater harvesting structures in the Lubombo Plateau is not available. Therefore, validation of the potential rainwater harvesting sites could not be performed.

CHAPTER TWO

LITERATURE REVIEW

2.1 Climate and Agro-ecological Zones in Swaziland

2.1.1 Climate

The climate is generally humid and subtropical with hot, wet summers (October to March) and cold, dry winters (April to September). The rainfall regimes in Swaziland are convectional with tropical storms during summer and frontal showers during winter. Approximately 75% to 83% of annual rainfall falls in the summer months and 25% falls in the winter months. Annual rainfall is unevenly distributed across the country and varies from approximately 1,500 mm in the extreme west to less than 500 mm in the south-east.

2.1.2 Agro-ecological Zones

There are four agro-ecological zones (AEZ) within Swaziland, namely: Highveld, Middleveld, Lowveld and Lubombo Plateau, which are clearly distinguished by elevation and relief. The climatic features of each zone are detailed below:

1. The Highveld AEZ has temperate climate characterised by wet summers and dry winters with an average annual rainfall of 1,500 mm. The temperatures vary between 33 ^{o}C in mid-summer to a minimum of 0 ^{o}C at night in mid-winter.
2. The Middleveld AEZ is subtropical and somewhat drier than the Highveld region, with an annual rainfall of approximately 850 mm.
3. The Lowveld has a subtropical climate and receives the lowest annual rainfall of the four regions (approximately 450 mm). The Lowveld AEZ is

characterised by semi-arid areas with erratic rainfall and is the most drought-prone agro-ecological zone in the country. This zone is also characterised by a large diurnal temperature range and maximum temperatures often reach above 40 ^{o}C.

4. The Lubombo Plateau has an annual rainfall of 700 mm and an average annual temperature of 19 ^{o}C.

2.2 Characteristics of Agriculture in Swaziland

2.2.1 Agricultural Systems

Swaziland's agriculture sector has dual land tenure systems consisting of the Swazi Nation Land (SNL) and Title Deed Land (TDL). The TDL is a vibrant commercial sector covering about 40% of the country. It is estimated that 97% of irrigated agriculture, known to employ advanced technologies for cash crop production, is found in this tenure system (World Vision Swaziland, 2010).

The Swazi Nation Land, covers 60 percent of the country's land area, and is regarded as a very important resource from which a majority of the Swazi population derive their income. This land is known to be a customarily and communally based, since chiefs apportion the land on behalf of the King to the people. Families are allowed to utilize the land but cannot exchange it for money (Swaziland Government, 2009).

Small scale rain-fed, partially commercial agriculture with shared grazing mainly of cattle and goats characterize the SNL. Main crops grown consist of maize, cotton, vegetables, and groundnuts. The principally smallholder Swazi Nation Land, a home for more than 75 percent of the country's population, is characterized by low yields, unsatisfactory commercialization, comparatively low returns and prevalent poverty (World Vision Swaziland, 2010).

The rainfall in Swaziland is sporadic, mostly occurring as short heavy down pours and there are frequently long-lasting episodes of drought. This has resulted in widespread death of cattle in the dry Lowveld region (Swaziland Government, 2002). A great percentage of rainwater is lost by run-off and evaporation and crops experience recurrent water shortage immediately rainfall stops. Studies by Rockstrom *et al.* (1998) have shown that about 15-30% of rainfall in savannah environments of sub-Saharan Africa is typically utilized for production crop growth. This percentage has been found to be even less on smallholder farms under unsustainable soil and water management practices employed (Rockstrom, 1999).

2.2.2 Maize Production

Although maize production is extremely responsive to drought, its production under rain-fed condition is the principal source of livelihood for farmers in the Swazi Nation Land. Thriving endeavours to increase yields and to lessen risk and production costs are therefore very essential (IFAD, 2001).

It has been observed that subsistence farmers in Swaziland are persistent in growing maize despite the fact that they always get low yield due to the limited and erratic rainfall patterns (ACAT, 2013). Since efforts to discourage maize production in areas of low rainfall are failing, means to improve the farming techniques are crucial if maize production is to increase.

2.2.2.1 Temperature Requirements

Verheye (2010) regards maize as a warm-weather crop, although modern cultivars are now developed to be adapted to cooler climates also. Maize requires a frost-free growing period. In the case of Swaziland, at tasselling temperatures between 21-30^{o}C are favourable while temperature of 18-21^{o}C are required (Swaziland Government, 2002).

2.2.2.2 Water Requirements

For utmost yield a medium maturity maize crop needs more than 500 mm of water with a slight variation caused by different climatic conditions (FAO, 2015). The rainfall should be well-distributed over the growing period, with periods of clear warm weather between the rain storms (Verheye, 2010). According to the Swaziland Government (2002), in Swaziland, rainfall in excess of 760 mm during the growing season is required for full maturity.

Even though maize seems moderately tolerant to water shortages during the initial and late stages, it requires a regular moisture supply and suffers from intermediate dry periods. Immense decline in grain yields is as a result of erratic rainfall distribution at tasselling and silking. The Lowveld areas of Swaziland are regarded unsuitable for maize cultivation save for when irrigation is employed (Swaziland Government, 2002).

2.2.2.3 Soil Requirements

Maize does well on a broad variety of soil types all over Swaziland which their pH is neutral to slightly acidic, but favours deep, well-drained soils (Swaziland Government, 2002).

2.3 Challenges of Crop Production in Swaziland

The Kingdom of Swaziland has experienced a considerable decline in agricultural production, principally the staple cereal, maize, particularly in the Lubombo Plateau (Mhazo *et al*., 2007). The threat to food security in the country is blamed on erratic rains, drought, high costs of inputs, lack of manpower due to chronic illnesses and deaths resulting from HIV and AIDS (FAO, 2005; WFP Swaziland, 2009), in some cases resulting to late planting which is associated with low yields and sometimes complete crop failure (Flory, 1991). Nevertheless, several reports have pointed out that there are a number of untapped opportunities for improving rain-fed crop production in Swaziland. According to Flory (1991), very simple, inexpensive alterations to agricultural practice could result in huge yield increase. Timeliness in agricultural operations is vital to success.

Most Swazi families residing in the rural areas (80 percent) are subsistence farmers who rely on rain-fed agriculture. Prolonged dry spells and poor rainfall have contributed to low yields over the past few years, particularly in the Lowveld and Lubombo Plateau. The occurrence of extreme climate variability such as may be characterized by a prolonged dry period or heavy rainfall spell coinciding with the critical stages of crop growth and development may lead to significantly reduced crop yields and extensive crop losses (Oseni and Masarirambi, 2011).

The existence of some cultural institutions also hinders the adjustment of the farming calendar in rural areas. Mlipha (2005) pointed out that farmers do not have complete freedom to decide when to commence cultivation but the traditional authority sanction the start and, likely, the end of the farming season. A study by Flory (1991) unveiled that a number of farmers confirmed that they are prevented from ploughing as early as they would like because the chief waits too long to call for the removal of the cattle from their fields.

Another challenge facing crop production in Swaziland, specifically in the Lubombo Plateau is scarcity of water owing to limited flowing streams on the plateau as well as topography, consequently restricting the development of irrigation schemes (Mlipha, 2005).

Although the services of the National Meteorological Services department produces weather forecast, a number of farmers seem not to benefit. Some of the concerns are that the forecast reports are too technical for the average farmer. The other challenge is the accessibility of this information, especially the agro-meteorological bulletin. The forecasts that are aired on the local radio and television stations are mainly daily forecasts. As a consequence, farmers in the rural areas still depend on their local knowledge (which its level of accuracy and reliability cannot be confirmed) to predict rainfall situation in their areas (Mlipha, 2005).

Lack of crop diversification is also another factor as farmers prefer maize to other crops such as sorghum, albeit their being drought-resistant (WFP Swaziland, 2009). Just like in other sub-Saharan African countries, farmers in Swaziland are fond of growing maize as the maize crop and have refused efforts to promote the growing of sorghum as substitute even though the drought-related threats linked with maize production are well known.

Hybrid seed, especially maize, is not favoured by the local farmers as it is believed to be lighter and less tasty than indigenous maize. The challenges stated above may be sufficient to call for farmers to implement other farming tactics to mitigate the impacts of erratic rainfall and persistent drought on maize yields.

Farming has turn out to be too uncertain under conventional farming practices and existing weather conditions. There is an apparent call for promotion of improved methods coupled with advocacy for a better policy environment including reasonable prices and market facilitation on the other (World Vision Swaziland, 2010).

2.4 Efforts to Improve Crop Production in Swaziland

Even though research and knowledge tells us that it is not easy to profitably grow maize under rain-fed conditions in some areas of Swaziland, the fact that maize is the staple food for the people is a reason enough to explain why it continues to be produced in such areas (ACAT, 2013).

Government as well as non-governmental organisations have been encouraging farmers to grow different crops so that in case maize crop fails the other crops will act as substitute food sources (ACAT, 2013; World Vision Swaziland, 2010). More appropriate methods of farming, such as conservation agriculture, introduction of drought tolerant crops such as sorghum is being promoted. A study by Oseni and Masarirambi (2011) suggested rainwater harvesting/soil conservation techniques, intercropping, and growing of short duration/early maturing maize varieties as possible interventions to improve rain-fed maize production in Swaziland.

The National Meteorological Services Department has made remarkable efforts in improving its weather and climate prediction capacity through acquisition of modern technology and equipment. Agro-meteorological updates are published as part of their early warning wing. However, the accessibility and usefulness of this data to the small scale subsistence farmers on SNL still need to be ascertained (Mlipha, 2005).

2.5 Policies Related to Rainwater Harvesting

According to the Swaziland Government (2002), RWH has not been formally introduced and encouraged amongst the farming communities in the country nor have there be policies in place to support it. It had mainly been advocated by the private sector and practiced by few subsistence farmers (Swaziland Government, 2009). The National Water Policy aims to promote and support improved rainwater harvesting and tillage techniques to enhance the productivity of rain-fed agriculture. It also aims to encourage the conservation of water through appropriate incentives and penalties. The promotion of rainwater harvesting and water conservation are planned to be achieved through a number of strategies ranging from creating an enabling environment, socio-economic and physical means like infrastructure development.

2.6 Dry Spell

2.6.1 Dry Spell Definition

Various definitions of a dry spell have been given. Generally, all these point out dry spell as a number of days without substantial precipitation. A dry spell is a series of dry days separated by wet days on both sides. According to Falkenmark *et al.* (2001), during crop growth, a dry spell is short episode of water deficiency, and in most cases it only last for a few weeks. A critical aspect in all these descriptions is the designation of a significant rainfall threshold in the definitions of a dry day.

2.6.2 Dry Spells and Crop Production

It has been realized that droughts and dry spells are chiefly to blame for low yields and widespread crop failure than utter water shortage in terms of total rainfall (Falkenmark, *et al*., 2001; Hatibu, *et al.*, 2000). These dry spells occur during critical development stages whereby the crop is susceptible to water deficiency, such as grain-filling in maize, thus adversely affecting crop yields.

Understanding of the probability of dry spell occurrence during a rainy season is crucial if the prospective of rain-fed farming is to be harnessed. This helps the farmer to make well informed crop selection decisions. With reliable knowledge of dry spell distribution during rainy season, scheduling of supplementary irrigation and projection of irrigation requirements can be easily done (Simba, *et al*., 2012).

2.6.3 Managing dry spells

Poor rainfall distribution often results in dry spells. Dry spells can be efficiently managed through the use of rainwater harvesting structures such as earth dams and farm ponds, among others. It is necessary for planners to be able to determine the amount of water required to alleviate dry spells (Hatibu, *et al.*, 2000).

2.7 Rainwater Harvesting

Rainwater harvesting (RWH) is the collective term referring to a broad set of practices of capturing rainfall and its successive storage within the soil or in man-made storage structures. The result is improved water availability for various purposes (Falkenmark *et al*., 2001; Oweis *et al.*, 2001; UNEP, 2009). One of such uses is supplementary irrigation in order to alleviate dry spells and droughts in plant production. RWH is therefore the collection of runoff for productive purposes.

2.7.1 Characteristics of Rainwater Harvesting

RWH plays an important role in minimizing impacts of unpredictable amounts of available water in a season brought about by dry spells and drought (AFDB, 2008). Mutually, yields and consistency of production can be appreciably improved through RWH. Thus, enhanced rainwater management contributes to food security. In relatively dry areas where overland flow has a sporadic nature, rainwater harvesting is common. A run-off generating area commonly termed catchment area (CA) and a run-off exploitation area generally termed cropped basin (CB) are features of a rainwater harvesting system in crop production systems.

The produced runoff may be accumulated within the soil mass, in ponds or underground storages for later application. Thus storage is essential in rainwater harvesting systems (Hatibu and Mahoo, 1999).

2.7.2 Forms of Rainwater Harvesting

According to Hatibu and Mahoo (1999), rainwater harvesting systems are classified into various forms, principally based on the distance between the catchment area and cropped basin. These categories are: in-situ rainwater harvesting, micro-catchment and macro-catchment rainwater harvesting.

2.7.2.1 In situ Rainwater Harvesting

In-situ rainwater harvesting system entails techniques used to enhance the water quantity accumulated in the soil profile by capturing and storing it as it reaches the soil surface. In-situ RWH is sometimes not categorized as rainwater harvesting, but referred to as water conservation (Hatibu and Mahoo, 1999). Runoff is not permitted and evaporation loss is reduced. This is attained by slowing down rainwater and extending the retention time thus improving infiltration. Favourably, this form is practised on soils with high water retention potential and where rainfall is not more than the crop water requirements (Hatibu and Mahoo, 1999).

The in-situ RWH is accomplished through deep tillage, contour farming and ridging, as well as agronomic measures such as mulching, timely weeding, and cover crops, among others. These methods basically help in increasing soil moisture holding capacity, enhancing infiltration, reducing surface runoff as well as lessening soil water evaporation.

2.7.2.2 Micro-catchment Rainwater Harvesting

Micro-catchment RWH is sometimes called in-field rainwater technique. These are the technologies that accumulate runoff in the vicinity of the growing crop and replenish the soil moisture (Mati, *et al.*, 2007). Although the CA and CB are in adjoining areas, there is a clear distinction between the two. Micro-catchment RWH is characterised by overland flow which is harvested from short catchment length. The run-off is captured into the soil profile and there is normally no provision for overflow. The ratio of CA: CB usually varies from 1:1 to 3:1(Hatibu and Mahoo, 1999). Plant growth is generally even.

Mati, *et al*. (2007) observed that micro-catchment technologies are generally employed for growing crops with moderate water requirement such as groundnuts and maize.

2.7.2.3 Macro-catchment Rainwater Harvesting

These technologies refer to the capturing of overland flow from huge sites which are a bit distant from the point of use (Mati, *et al.*, 2007). This, therefore, necessitates external water storage as well as structures of diversion and distribution networks.

The catchment area may vary from 0.1 hectares to thousands of hectares. Slope of the CA typically ranges between 5 and 50 percent while the accumulate runoff is utilized on CB area (Hatibu and Mahoo, 1999). External catchments systems are characterised by harvesting of runoff which is accumulated in the soil profile. The catchment is generally 30-200 metres in length and the CA: CB ratio is usually between 2:1 and 10:1. In these systems, spill over of surplus water is not catered for. It is common to find uneven plant growth unless the land is levelled. Macro-catchment technologies are able to manage huge overland flows drawn from various sources such as grazing lands (Mati, *et al*., 2007).

2.8 Application of RWH

AFDB (2008) found rainwater harvesting to be beneficial when applied in rain-fed agriculture producing low yield (less than a tonne per hectare). In areas where runoff is unacceptably high, RWH helps by diverting it for productive purpose, thus also controlling soil erosion. RWH is helpful in mitigating risks of dry spells caused by inadequate and poor seasonal rainfall distribution resulting in improved crop yields (AFDB, 2008). It is therefore beyond doubt that rainwater harvesting plays an appreciable role towards food security.

The choice of RWH techniques is influenced by rain fall and rain pattern, soil type, crop, landscape, slope and accessibility to affordable materials and labour requirements. In addition to rainfall characteristics, several other catchment specific factors influence the occurrence and volume of runoff. These factors include soil type which determines the infiltration rate of a soil. Vegetation is another factor having influence on runoff by intercepting raindrops as well as slowing down surface flows. Steep slopes in general produce more runoff compared to gentle slopes. The size of the catchment too affect runoff; runoff volume per unit area increase with decreasing catchment size.

2.9 Critical factors for RWH site selection

The detection of prospective areas appropriate for rainwater harvesting is crucial for rainwater harvesting undertaking to perform well. Limited scientific backing in site selection for rainwater harvesting structures has been found to be among responsible factors for the collapse of such structures.

Various studies in different areas have been undertaken using Geographical Information Systems and remote sensing to try and identify appropriate sites for rainwater harvesting by combining the various factors or aspects. The advantage of employing GIS and remote sensing is the time required for conventional geographic surveys.

Hameed (2013) identified suitable zones for rainwater harvesting to construct small and medium dam sites in Erbil governorate in Iraq using slope, land cover, soil texture, rainfall, and drainage network as criteria in GIS and Multi Criteria Evaluation decision support tool.

Nketiaa *et al.* (2013) used a GIS-based model as a decision support framework for locating best rainwater harvesting areas. Rainfall, soil texture, slopes and land use/cover were used as model development indicators.

Saravanan *et al.* (2015) in a study in a small rural community at Bhavani basin, Tamilnadu, India identified possible runoff producing locations, and consequently highly-ranked sites for runoff harvesting utilizing remote sensing and GIS. Potential runoff producing areas and consequently best runoff harvesting sites harvesting were selected considering catchment characteristics, land cover, slope, soil, and harvesting potential. Socio-economic criteria used by Saravanan *et al.* (2015) were distance from settlements and croplands.

Kahinda *et al.* (2008) presented a GIS-based model, which encompassed physical, ecological and socio-economic parameters such as proportion of households below poverty line, to determine the suitability of RWH in the Republic of South Africa. Rainfall, aridity zones, soil texture, soil depth and land cover encompassed physical factors.

De Winnar *et al.* (2007) considered physical parameters such as slope information, soil, rainfall, and land use as well as distance from homesteads and croplands in identifying potential runoff harvesting locations, and consequently main runoff harvesting sites at Potshini using Geographical Information Systems.

Tumbo *et al*. (2014) recognized crucial parameters for the identification of rainwater harvesting potential sites as land cover, rainfall, drainage patterns, soil texture, soil depth, and sloper. Rejani *et al.* (2015) used thematic maps of slope, soil, rainfall and land use for locating infield soil and water conservation measures for feasible management of dry lands.

2.10 RWH Experiences

A study was carried out by Hatibu *et al.* (2003) in Tanzania where farmers are fond of growing maize as the maize crop and have refused efforts to promote the growing of sorghum as substitute even though the drought-related threats linked with maize production are well known. Experiments carried out over a period of seven years found rainwater harvesting to have reduced drought risk when carried out under experts' supervision.

Another study was carried out by Motsi *et al.* (2004) at three areas in Zimbabwe which receive rainfall below 500 mm per year and only well distributed once in every five years. The study aimed at evaluating and proposing RWH practices that improves water retention making it available for crops. Tied ridges were found to have high moisture retention and consequently higher yields than under the normal tillage practices.

A similar study carried out by Mhazo *et al*. (2007) between 2006 and 2007 at Luyengo in Swaziland concluded that production of maize on tied ridges could increase maize yield by making water available to the plants over longer periods.

The tied-ridges demonstrated a prospective in improving maize growth through prolonged moisture retention between ridges in times of uncertain rainfall occurrences. The total seasonal rainfall in the study area during the season was 502 mm. Much of the rain was received at the beginning; between October and December 2006 when the crop was in the early stages of growth.

2.11 Methods for Estimation of Runoff

The estimation of runoff volume of a catchment is an important aspect in engineering planning, environmental impact assessment, flood forecasting and water balance calculations. There are basically two types of methods for the estimation of runoff namely the direct method and the indirect method. The direct method is based on the direct measurements while the other one is based on the equations.

Direct methods includes the use of current meters, staff gauge and crest stage gauge. In ungauged catchments, the indirect methods are used and some will be discussed in the following sections.

2.11.1 The US Soil Conservation Services (SCS) Method

The US Soil Conservation Service developed an empirical model, the SCS Curve Number method, for rainfall abstractions which is based on the capability for the soil to absorb a particular amount of moisture. It is extensively used to estimate direct runoff volume on large agricultural watershed. Based on the field observations, the potential storage, S, was linked to a curve number (CN) which is an attribute of the soil type, land use and initial level of saturation identified as the antecedent moisture condition. This method has found worldwide application throughout the entire spectrum of hydrology, and it is one of the most common means of determining runoff quantities in un-gauged catchment areas (Rallison and Miller, 1982).

The US Soil Conservation Service model presents a reliable foundation for the approximation of surface runoff volumes under different land use and soil types. The parameters of the model can be related in the equation that follows:

$$P = Ia + F + Q \qquad \text{...(2.1)}$$

Where:

P is rainfall, in mm;

Ia is Initial abstraction, in mm;

F is cumulative infiltration, in mm, other than Ia;

Q is direct runoff, in mm.

Initial abstraction (Ia) is function of the maximum potential abstraction (S). For the estimation of runoff, the following equation is used:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad \text{...(2.2)}$$

Where:

Q is Direct runoff depth, in mm;

P is Average daily precipitation, in mm;

S is Potential maximum soil water retention, in mm.

The value of Potential maximum soil water retention, S, in mm is defined as:

$$S = \frac{25400}{CN} - 254 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.3)$$

2.11.2 Rational Method

The Rational Method uses an empirical linear equation to determine peak runoff rate from a selected period of uniform rainfall intensity. Originally developed more than 100 years ago, it continues to be useful in estimating runoff from simple, relatively small drainage areas. The Rational Method is commonly used for the determination of flows from small watersheds, and it can be applied in most geographic areas. The method uses existing rainfall data and land use in estimating peak runoff from small drainage areas that are less than 15 km^2.

It is important to note that the Rational Method can be used only to compute peak runoff rates. Since it is not based on total storm duration, but rather a period of rain that produces the peak runoff rate, the method cannot compute runoff volumes unless the user assumes total storm duration. It is particularly useful if local stream flow data do not exist, and it can be used to make a rough estimate of flow from large watersheds if other options do not exist.

The Rational Formula is given by the following equation:

$$Q = 0.278CiA \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.4)$$

Where:

Q is the Quantity of Flow (Runoff), in Cubic Meters per Second (m3 /s).

C= Runoff Coefficient. This coefficient is selected to reflect the watershed characteristics, such where: as topography, soil type, vegetation, and land use.

i = Average Rainfall Intensity for the selected frequency and for a duration equal to the Time of Concentration, in millimetres per hour.

A = Area of the watershed, in Hectares.

Runoff Coefficient (C) values reflect the differing watershed characteristics that influence runoff. The designer must develop experience and use judgment to select the appropriate value of C within the range shown. The value of C may change over the design life of the structure due to changes in land use such as a forest converted to agricultural land or from a fire in the watershed. Flow quantity is directly proportional to the selection of this coefficient.

Area (A) is simply the area of the watershed that contributes runoff to the drainage crossing. Its boundaries go from drainage divide to drainage divide and down slope to the crossing. On a roadway surface, the "drainage area" is the cut slope and road surface area between cross-drains or leadoff ditches.

Rainfall intensity (i) is the third factor, and the one often most difficult to obtain. It is expressed as the average rainfall intensity in millimetres per hour (mm/hr) for a selected recurrence frequency and for duration equal to the Time of Concentration of the watershed. At the beginning of a storm, runoff from distant parts of the watershed has not reached the discharge point (such as a culvert). Once water has reached the discharge point from all parts of the watershed, a steady state flow will occur. The estimated time when water from all parts of the watershed reaches the discharge point is the Time of Concentration.

2.11.3 Modified Rational Method

The Modified Rational Method is a rather recent adaptation of the Rational Method that can be used to not only compute peak runoff rates, but also to estimate runoff volumes and hydrographs. This method uses the same input data and coefficients as the Rational Method along with the further assumption that, for the selected storm frequency, the duration of peak-producing rainfall is also the entire storm duration. Since, theoretically, there are an infinite number of rainfall intensities and associated durations with the same frequency or probability, the Modified Rational Method requires that several of these events be analyzed in the method to determine the most severe. Use of the Modified Rational Method should also be limited to drainage areas less than 15 km^2 with generally uniform surface cover and topography.

CHAPTER THREE

DATA AND METHODOLOGY

3.1 Description of the Study Area

Swaziland is a small landlocked country in Southern Africa, with a total land area of 17 364 km^2. It lies between latitude 26^o and 28^o South and 31^o and 32^o East. It is bordered by the Republic of South Africa and Mozambique.

The country is a predominantly rural society, with a majority of the population reliant on subsistence agriculture for their living. Estimates of the total net arable land vary from 182,000 to 236,000 hectares. Maize is the most important crop of the small–scale rain-fed agriculture, covering about 80,000 hectares, whereas sugarcane dominates the irrigated agriculture (FAO, 2015).

3.1.1 Lubombo Plateau

3.1.1.1 Location

The Lubombo Plateau covers an area of about 1,321.2 km^2, which represents only one tenth of the country. The altitude ranges between 450 to 700 metres above mean sea level. The region lies extreme east of the country, as shown in Figure 3.1, along border with Mozambique.

3.1.1.2 Climate

The region climate is sub-humid to semi-arid with hot and wet summers and cold and dry winters. The annual rainfall is between 550 – 850 mm while the average temperature is 19^oC.

3.1.1.3 Topography

Lubombo Plateau is undulating and deeply cut apart by the gorges of the major rivers that navigate the country from the West to the East. It is composed of flat rocky exposures, disrupted only by sharp slopes and these deep river gorges.

3.1.1.4 Soils

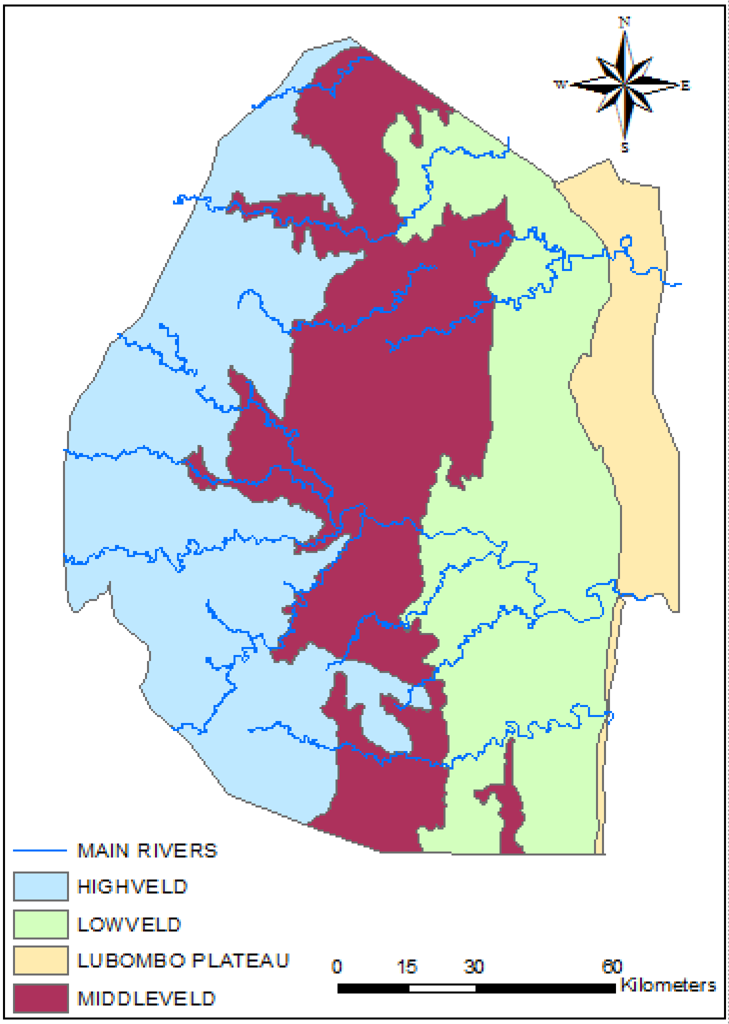
The plateau soils differ significantly, from shallow sands to deep loams, depending on the composition of the volcanic lavas that form the bedrock. The soils are deep red and medium to heavy texture. The Lubombo Plateau has about 12% arable soils of good to fair quality.

3.1.1.5 Water Resources

The Lubombo Plateau has insufficiency of water owing to limited flowing streams (Figure 3.1) on the plateau as well as topography, consequently restricting the development of irrigation schemes (Mlipha, 2005).

3.1.1.6 Maize Production

Maize is grown on a subsistence small scale. It occupies approximately 8,638 hectares. Maize production is almost exclusively rain-fed and yields are highly variable mostly as a result of the rainfall patterns. There is generally less crop diversification in this region.



Source: Swaziland Government (2002)

Figure 3. 1: Map of Swaziland showing agro-ecological zones and main rivers

3.2 Data

3.2.1 Rainfall Data

Observed daily rainfall data in the study area was available for Lomahasha and Tikhuba stations while for Siteki only monthly totals were available. This data was obtained from the Swaziland Meteorological Services. Table 3.1 shows the stations used in the study.

Table 3. 1: Rainfall data used in the study

Station Name	Longitude	Latitude	Altitude (m)	Period of record	No. of Years of record
Lomahasha	31.984	-25.984	550	1980-2015	36
Tikhuba	31.100	-26.633	500	1985-2015	31
Siteki	31.95	-26.45	647	1980-2013	34

3.2.2 Other Data

The following sets of data were used in the study:

1. A 30 m resolution Digital Elevation Model (ASTER GDEM), raster format, was downloaded from ASTER GDEM website (http://gdem.ersdac.jspacesytems.or.jp/).
2. Land use map of Swaziland was obtained from the Ministry of Agriculture and Cooperative in shapefile format.
3. The soil map of Swaziland was obtained from the Ministry of Agriculture and Cooperatives. The soil map describes colour, texture and depth of the soil. The data type of this map is a shapefile.

3.3 Methodology

The methodology of this research comprises the activities that were carried out to achieve each of the three objectives, and is presented below:

3.3.1 Agronomical Characterization of Rainfall in the Lubombo Plateau

The agronomical characterization of the rainfall consisted of determining the timing of the onset date and cessation of rains, length of rainy season, and total seasonal rainfall and probability of dry spells. This was carried out with the help of INSTAT (v 3.37) statistical software (Stern *et al.*, 2006). Daily rainfall data was arranged into hydrological years starting the year with July for ease of using INSTAT software. This is because the rainy season in Swaziland begins in one year and ends in the next, i.e. from October to March.

3.3.1.1 Onset of Rainy Season

The onset of rains defined as the first occasion after October 15 when the rainfall accrued over the previous 10 days is at least 25 mm and no dry spells of more than 9 days in the subsequent 20 days was used as a successful planting date, modified from Tadros *et al.* (2005). A rainfall threshold of 2 mm was used.

3.3.1.2 End of Rainy Season

The end of the rainy season was obtained by looking for the last day on which the cumulative 25 mm over 10 days occurred.

3.3.1.3 Length of Rainy Season

The length of rainy season was the total number of days from the date of onset of rainfall to the end date of the rainfall.

3.3.1.4 Total Seasonal Rainfall

This was computed by summing the amount of rainfall between the start and end of the season.

3.3.1.5 Probability of Dry Spell

The Markov first order chain in INSTAT PLUS statistical package was used to determine the probability of occurrence of maximum dry spell lengths exceeding 5, 7, 10 and 15 days. The threshold of 2 mm was employed in the definition of a dry day.

The daily rainfall data was analysed to give maximum dry spell lengths probabilities starting from the onset of rain for each site until the cessation of rainfall. This was done to get a general idea of the drought situation for the duration of the maize growing period.

3.3.2 Determination of Net Irrigation Requirements for Maize

3.3.2.1 Crop Water Requirements

The maize crop water requirement was computed from reference evapotranspiration calculated in CROPWAT 8.0 software using the revised FAO Penman-Monteith equation. The climate data used for this purpose were acquired from the FAO database in FAO CLIMWAT 2.0 for CROPWAT for the Lubombo Plateau, as monthly pre-calculated means. These were maximum temperature, minimum temperature, relative humidity, wind speed and sunshine hours.

Effective rainfall was calculated using the USDA which defines it as the effective rainfall received during the growing period of a crop and is accessible to meet consumptive water requirements. It excludes surface runoff and deep percolation losses. The USDA SCS method is widely used in estimating the effective rainfall in agriculture water management (Temba and Sang-Ok, 2011; Wang *et al.,* 2009).

The effective rainfall is calculated as follows:

$$P_{eff} = P * (125 - 0.2 * P) \; / \; 125. \qquad \text{...}(3.1)$$

For P < 250 mm

$$P_{eff} \; = \; 125 \; + \; 0.1 \; * \; P \qquad \text{...}(3.2)$$

For P > 250 mm

Where:

P_{eff} is the effective rainfall

P is the gross monthly rainfall.

The maize crop evapotranspiration was calculated using Equation 3.3. The crop coefficients used in the study are presented in Table 3.2. Irrigation water requirement was determined as the crop water requirement less effective rainfall as shown in Equation 3.4.

$$ET_{crop} \; = \; Kc \; \times \; ET_{o}. \qquad \text{...}(3.3)$$

$$I_{net} \; = \; ET_{crop} \; - \; P_{eff}. \qquad \text{..}(3.4)$$

Where:
Kc is the crop coefficient and;

I_{net} is the net irrigation water requirement.

Table 3. 2: Maize main crop coefficients used in the study

Source: (Allen *et al*., 1998)

Stages/Coefficients	**Initial**	**Development**	**Mid**	**Late**	**Total**
Kc values	0.3		1.2	0.5	
Stage length (days)	20	30	40	30	120
Rooting depth (m)	0.3			1.0	
Critical depletion (fraction)	0.5	0.5	0.5	0.8	
Yield response factor (fraction)	0.4	0.4	1.30	0.5	1.25

3.3.3 Assessment of Runoff Potential and Identification of Suitable Rainwater Harvesting Sites

The methodology for generating runoff potential and merging of different layers for identification of potential sites for RWH is summarized in the following flow chart.

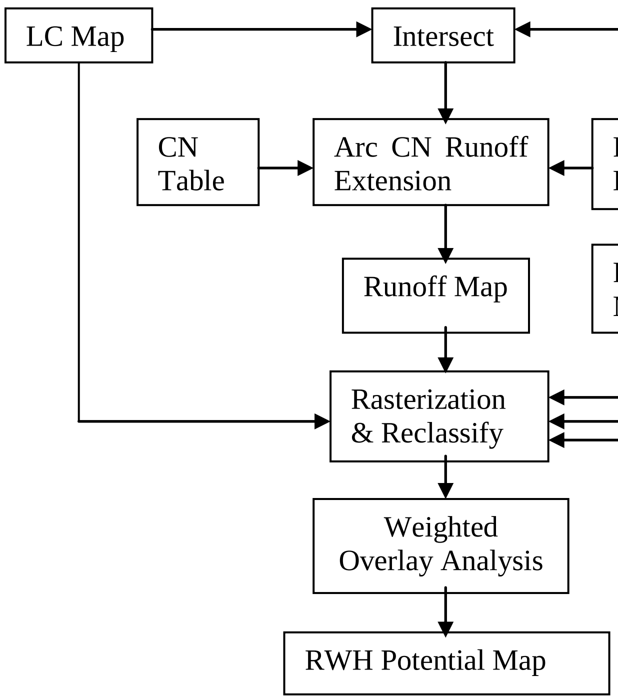


Figure 3. 2: Flow chart for identification of Potential RWH sites

3.3.3.1 DEM Hydro-processing

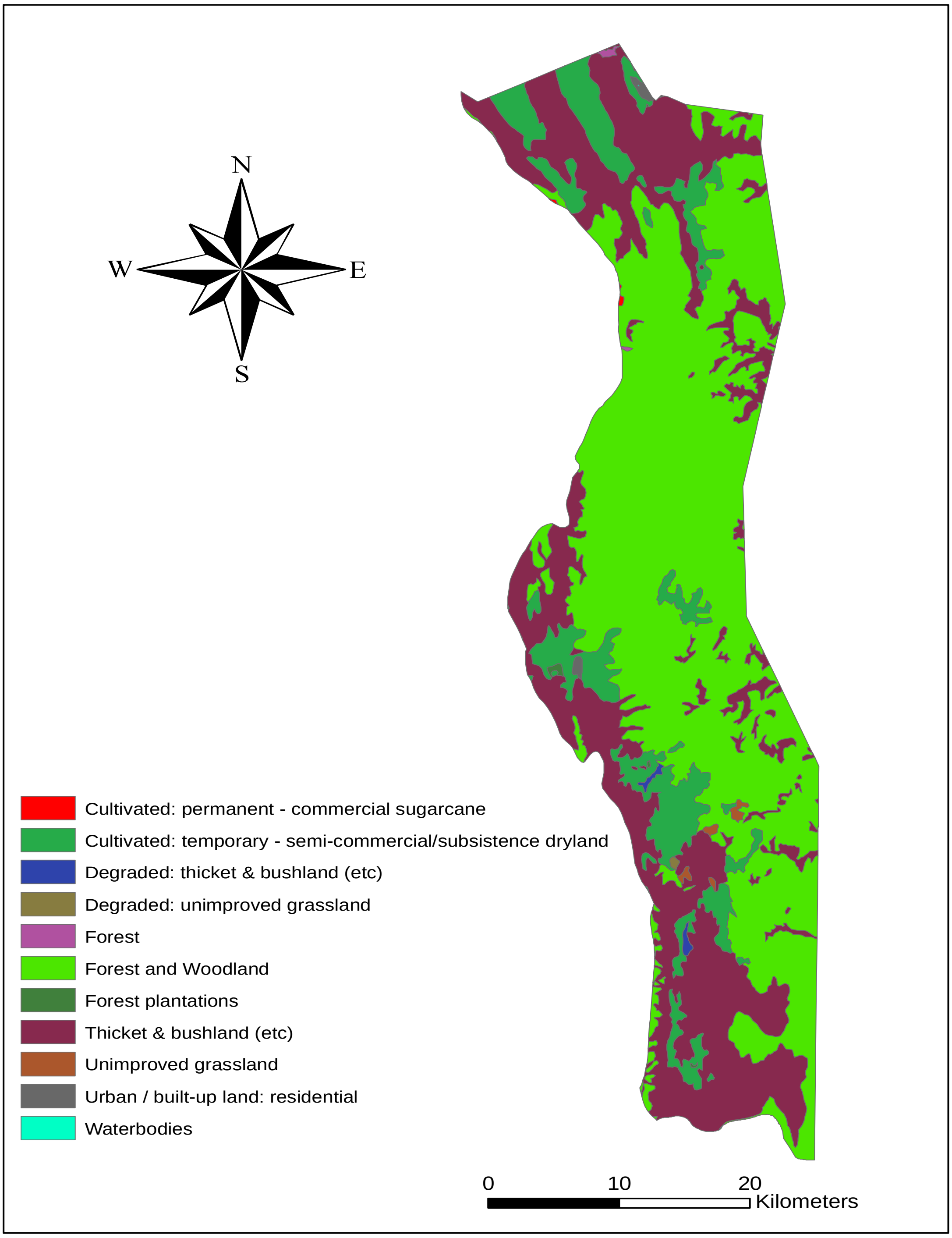
A 30 m resolution Digital Elevation Model (DEM) was the chief data used. The hydro-processing was performed using hydrological tools in Arc-GIS 10.2 software environment. The operations performed include fill sinks, flow direction, and flow accumulation.

3.3.3.2 Land Cover Classification

Land cover is a vital factor in determining the potential runoff generated in an area. It plays a considerable role in the interception of rainfall, and thus runoff generation. Land use is one of the parameters used in the Soil Conservation Service Method to estimate the potential runoff of an area.

The Lubombo Plateau is dominated by forest and woodland as well as thicket and bush land as seen on the land use map (Figure 3.3). The land cover map of the Lubombo Plateau was reclassified into five different land use classes to conform to the conditions set by the SCS Curve Number Method for estimating runoff.

All cultivated lands were classified as agricultural land, water bodies were retained as water bodies, residential land as settlement, grasslands, thickets and bush lands were classified as rangeland, forests, forest plantations and woodlands were classified as forest land to yield to five classes as shown on Figure 3.4.



Source: CSIR (2002)

Figure 3. 3: Lubombo Plateau land use map

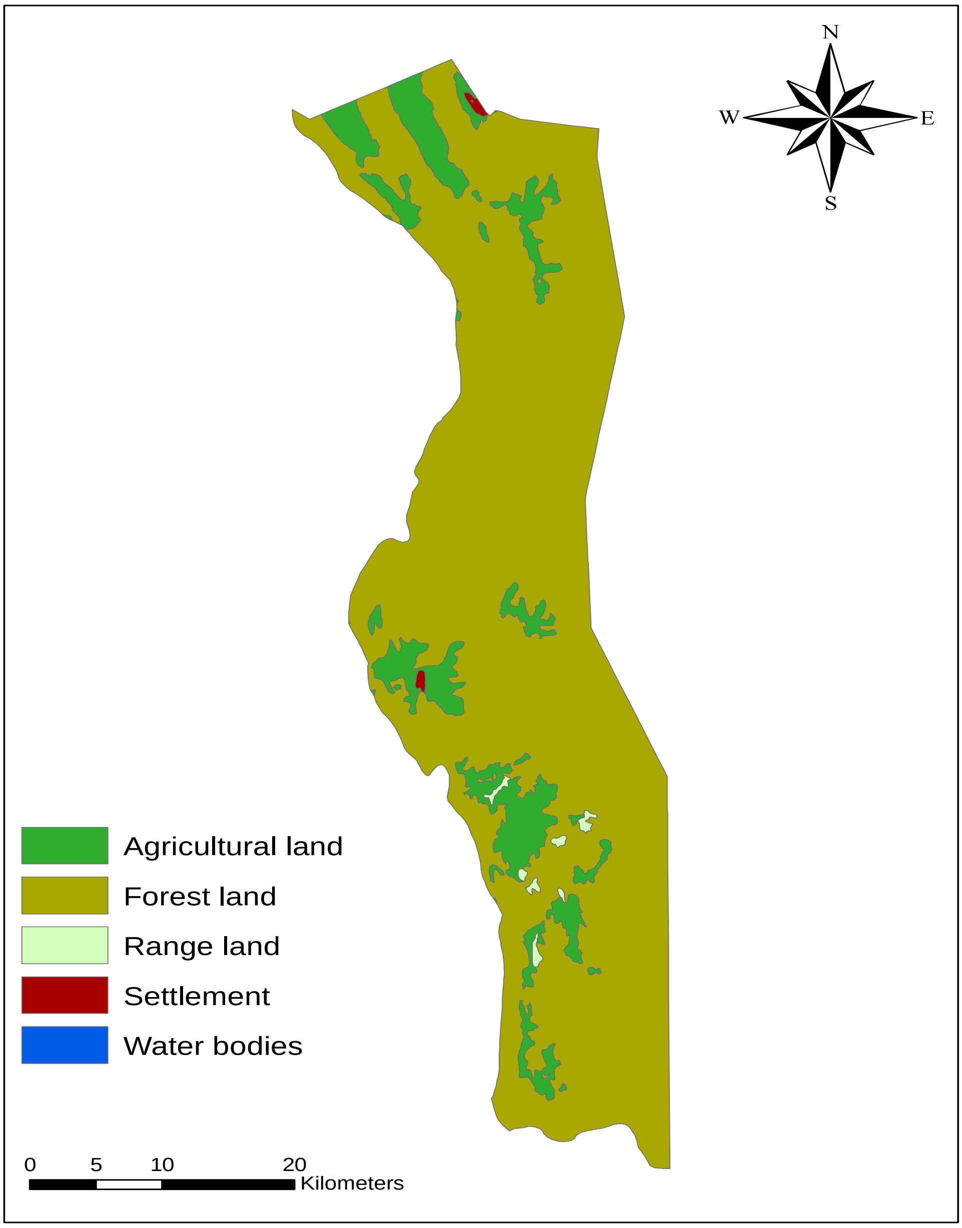
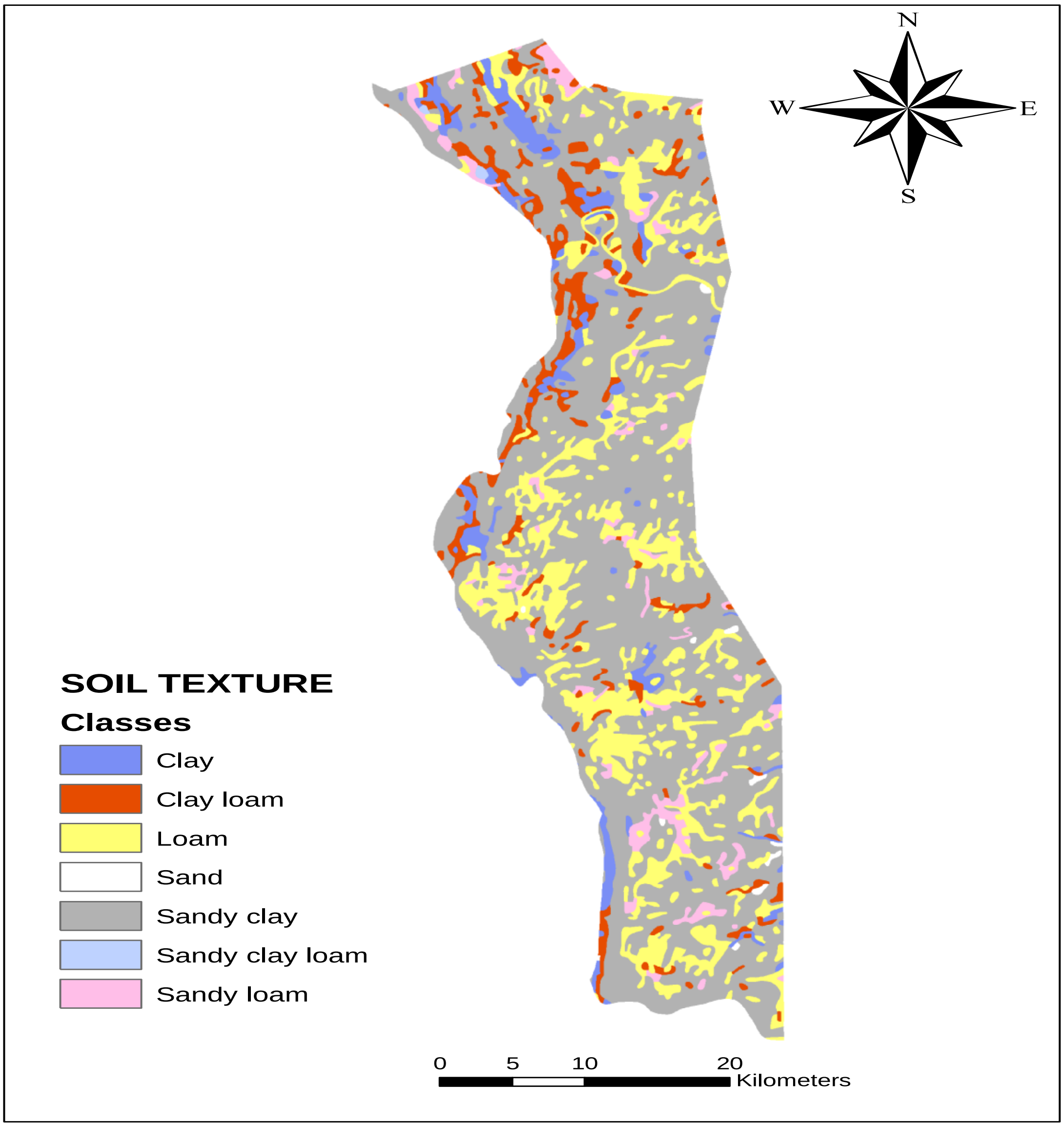


Figure 3. 4: Reclassified Lubombo Plateau land cover map

3.3.3.3 Soil Map

The Lubombo Plateau was found to have seven textural soil classes namely; clay, loam, sand, sandy loam, sand clay, clay loam and sandy clay loam soils. Figure 3.5 shows the spatial distribution of these soils. The texture of soils affects water infiltration, and consequently runoff generation.



Source: Murdoch (1970)

Figure 3. 5: Soil map of the Lubombo Plateau

3.3.3.4 Slope

The slope was developed from the DEM, and classified into five slope percentage classes in line with the FAO slope classification. The following table (Table 3.3) shows the classification of slope.

Table 3. 3: Slope classification for the Lubombo Plateau

Slope definition	Slope (%)	Area (km^2)	Fraction of total area (%)
Flat	< 2	365	26
Undulating	2-8	496	35
Rolling	8-15	70	5
Hilly	15-30	305	21
Mountainous	>30	195	14

3.3.3.5 Analysis of Rainfall Data

The daily and monthly rainfall totals at each station were used to compute annual total rainfall. ArcGIS 10.2 software was used to map the spatial locations of these stations as shown in Figure 3.6. To approximate rainfall for areas without rainfall station, interpolation was employed. For evaluation of potential rainwater harvesting sites, the design rainfall was taken to be one with 80% probability of exceedance (Kahinda *et al*., 2008).

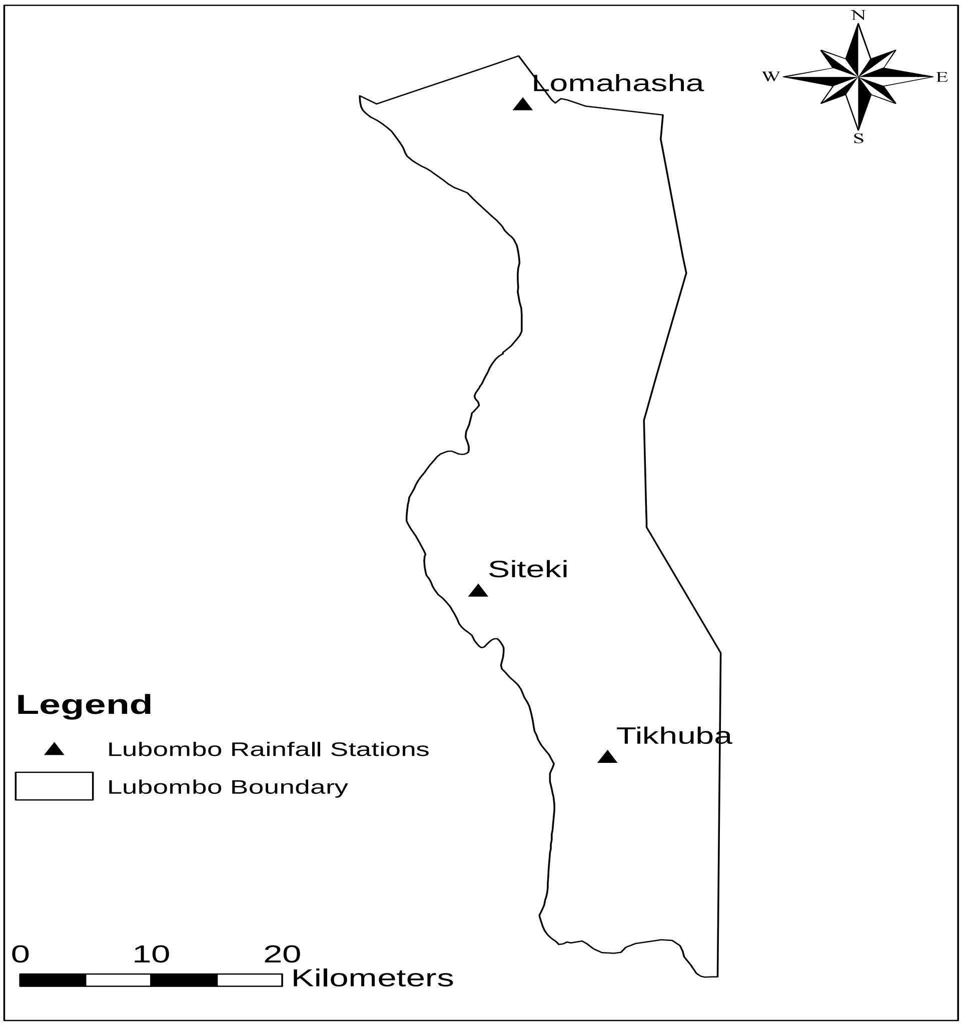


Figure 3. 6: Location of Rainfall stations in the Lubombo Plateau

3.3.3.6 Runoff Data Processing

ArcCN-Runoff tool, an extension of ArcGIS software, was used for the purpose of runoff modelling in the study area. According to Zhan and Huang (2004), this tool is designed to keep irregular boundaries unchanged, unlike raster mode.

Required for the ArcCN-Runoff tool is land use and soil data as inputs. The land use data in Section 3.3.3.2 was added to ArcMap as a shapefile. The soil map in Section 3.3.3.3 was reclassified into Hydrologic Soil Groups as per the requirements of the tool. There are four Hydrologic Soil Groups according to the USDA land use and land cover classification system (A, B, C and D).

The classification of soil to hydrologic soil group is informed by the infiltration rates and the soil texture make-up (United States Department of Agriculture, 2007) as shown in the table below.

Table 3. 4: Hydrologic Soil Group Classification

Soil group	Runoff Description	Soil texture
A	Low runoff potential because of high infiltration rates.	Sand, loamy sand, and sandy loam
B	Moderately infiltration rates leading to a moderately runoff potential	Silty loam and loam
C	High / moderate runoff potential because of slow infiltration rates	Sandy clay loam
D	High runoff potential with very low infiltration rates	Clay loam, silty clay loam, sandy clay, silty clay and clay

This table was used to classify the soils in the study area into hydrologic soil groups resulting to Figure 3.7. Soil group D is the dominant group found, suggesting a high potential for runoff generation since these soils have very low infiltration rates. Land cover and hydrologic soil group shapefiles were intersected to produce one land-soil database in readiness for runoff modelling. The intersection process kept all details of the spatial variation of soil and land cover and hence could be regarded as considered truthful as compared to other methods of runoff calculation in the likes of raster grid or other widely used methods for curve number determination (Zhan and Huang, 2004).

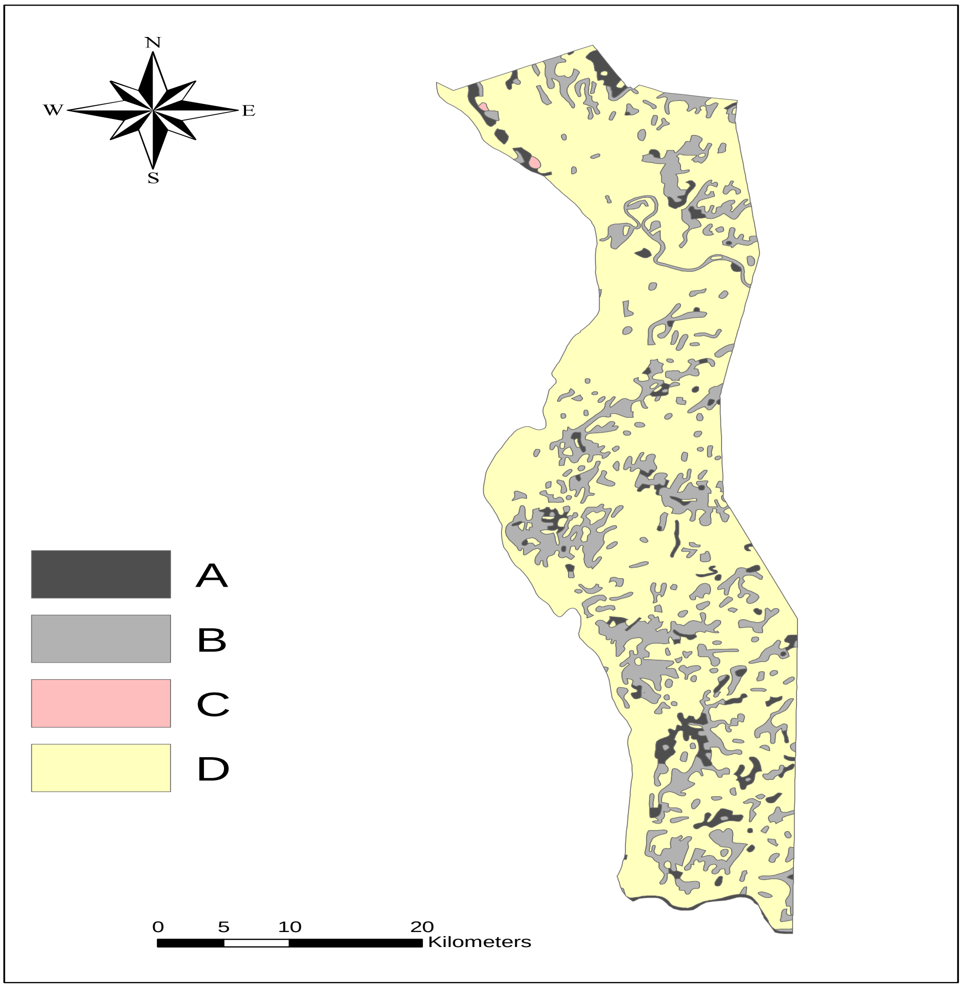


Figure 3. 7: Hydrologic Soil Groups in the study area

3.3.3.7 Modelling using ArcCN-Runoff

The ArcCN-Runoff tool was downloaded from Esri support website (http://www.arcsript.esri.com) and was loaded into ArcMap as an extension. An index table came with the tool. The index table is a general database that contains all the land use/cover types and their corresponding curve numbers in the different hydrological soil groups (A, B, C and D).

Inputs to the ArcCN-Runoff tool were; the land-soil data, index database and the average annual rainfall calculated in Section 3.3.3.5. The land-soil data contained the land use and the hydrologic soil groups in the study area. The land use in the land-soil database was matched with that of the index table which had curve numbers of different land uses.

3.3.3.8 Curve Numbers Determination

The ArcCN Runoff tool automatically computed the CN values for the diverse land cover types found in the study area. It also generated a map showing spatial variation of the curve numbers. Lower CN indicates lower runoff while higher CN refer to higher values of runoff.

3.3.3.9 Runoff Calculation

Runoff and runoff volume were calculated using ArcCN-Runoff tool, the latter was based on the area occupied by each land use type. The tool performs calculations based on the SCS Curve Number method, summarized in Equations 3.5 and 3.6. This method depends on the runoff Curve Number (CN) which is approximated through the impact of soil and land cover on rainfall runoff processes.

Runoff estimation used the following equation:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{..(3.5)}$$

Where:

Q is Direct runoff depth, in mm;

P is Average daily precipitation, in mm;

S is Potential maximum soil water retention, in mm.

The value of Potential maximum soil water retention, S, in mm is defined as:

$$S = \frac{25400}{CN} - 254 \qquad \text{(3.6)}$$

3.3.3.10 Evaluation of Potential Rainwater Harvesting Sites

Multi-criteria evaluation was used to perform layer merging of the factors (criteria) determining the rainwater potential in a site. The importance of these factors varies. Therefore, Analytical Hierarchy Process (AHP) was implemented to calculate the weights of each criterion through pair-wise comparison.

After successfully merging all the factors, rainwater harvesting suitability for sites within 150 metres from croplands was assessed. De Winnar *et al.* (2007) observed that generally there is a decrease in surface runoff harvesting feasibility with increasing distance from croplands. The potential runoff volume that can be harvested from these sites for maize production was also calculated.

3.3.3.10.1 Selection of Criteria

The choice of criteria used in the study was informed by reviewed literature, expert knowledge as well as available data for the Lubombo Plateau. In this study rainfall, slope, runoff potential, soil texture and land use were used. All these factors were reclassified into a suitability scale of 1 to 5; 1 being very low suitability and 5 being very high suitability while 3 being moderate suitability for ex-field rainwater harvesting.

Rainfall, amongst other factors, is important in evaluation of potential rainwater harvesting sites. Kahinda *et al*. (2008) observed that in very low rainfall receiving areas rainwater harvesting is discouraged, and the same applies for areas receiving very high rainfall since in both the resultant benefit is low. Table 3.5 presents rainwater harvesting suitability ratings for different annual rainfall ranges which were used in the study.

Table 3. 5: Rainfall suitability ranking for rainwater harvesting

Source: Kahinda *et al.* (2008)

Rainfall (mm)	Suitability
0-100	1
100-200	2
200-400	3
400-600	4
600-800	5
800-1000	3
>1000	1

Runoff potential as calculated in Section 3.3.3.8 provides the foundation for mapping runoff potential in the study area. The curve numbers were reclassified to provide suitability ranks for rainwater harvesting in the Lubombo Plateau (Table 3.6).

Table 3. 6: Runoff potential suitability ranking

Source: De Winnar *et al.* (2007)

Runoff Potential	Suitability
91-95	5
85-90	4
79-84	3
71-78	2
64-70	1

Soil texture affects runoff potential because of the differences in the rates in which water infiltrates through various soil particles. Higher infiltration rates means less water is available for runoff, and the opposite is true for soils with low infiltration rates like clay soils. The soil textural classes were reclassified from Section 3.3.3.3 to produce the suitability classes in Table 3.7.

Table 3. 7: Soil texture suitability ranking

Source: Kahinda *et al.* (2008)

Soil texture	Suitability
Clays	2
Sandy clays	5
Sandy clay loam	4
Sandy loams	3
Loamy sands to sands	1

The other important criterion used in the study was slope. The slope of land affects the speed at which rainwater flows on the land. In steeper slopes, the water has less time to infiltrate into the soil, thus it results to higher runoff, and the inverse is true for gentle slopes. Since slope affects runoff volume, it is an important parameter in determining the suitability of an area for RWH. The classified slope in Table 3.3 was ranked to produce the following table (Table 3.8).

Table 3. 8: Slope suitability ranking

Source: Dile *et al.* (2016)

Slope (%)	Suitability
2-8	5
8-15	4
< 2	3
15-30	2
> 30	1

The land use which affects the vegetation has an influence on the rate of infiltration and therefore on the resulting runoff in an area. Because the study aimed at assessing the feasibility of rainwater harvesting for maize production, agricultural areas were considered highly suitable amongst other land uses as shown in the table that follows.

Table 3. 9: Land use suitability ranking

Source: Dile *et al.* (2016)

Land cover type	**Suitability**
Agricultural land	5
Rangeland	3
Forest land	2
Water bodies	1
Settlement area	1

3.3.3.10.2 Calculation of Weights

The pair-wise comparison method was used for the calculation of the relative weights of evaluation criteria. The weights informs of the relative contribution of each factor towards achieving the overall goal of locating suitable locations for RWH in the Lubombo Plateau. A pair-wise matrix was constructed where each criterion in an upper level was used to compare the criteria in the level immediately below relative to its importance, on the scale presented in the next table.

Table 3. 10: Fundamental scale of absolute numbers for pair-wise comparison

Source: Saaty (2008)

Intensity of importance	Definition	Explanation
1	Equal Importance	Element ***x*** and ***y*** contribute equally to the objective
3	Moderate importance of one over another	Slightly prefers element ***x*** over ***y***
5	Essential importance	Strongly prefers element ***x*** over ***y***
7	Demonstrated importance	Element ***x*** is preferred very strongly over ***y***
9	Absolute importance	The evidence preferring element over ***x*** over ***y*** is of the highest possible order of importance
2, 4, 6, 8	Middle values between the two adjacent judgments	When compromise is needed. For example, 4 can be used for the middle value between 3 and 5

Note: Element *x* and *y* are any two of the criteria.

This was done to compare every possible pairing. Since the matrix is symmetrical, only the values of the lower triangle (shaded part in Table 3.11) actually needed to be calculated. The outstanding cells are only the reciprocals of the filled triangle (Drobne and Lisec, 2009).

Table 3. 11: Pair-wise comparison matrix

	Slope	Rainfall	Soil texture	Runoff potential	Land use
Slope	1	2	3	4	4
Rainfall	0.5	1	2	3	4
Soil texture	0.5	0.5	1	2	3
Runoff potential	0.33	0.33	0.5	1	2
Land use	0.25	0.25	0.33	0.5	1
Sum	**2.58**	**4.08**	**6.83**	**10.5**	**14**

The values in each column were summed as shown in Table 3.6. Dividing each element in the matrix by its column summation resulted in a normalized pair-wise comparison matrix (Table 3.12). The mean of each row in this matrix corresponds to the relative weights of the relevant criteria.

Table 3. 12: Normalized pair-wise comparison matrix for weight calculation

	Slope	Rainfall	Soil texture	Runoff potential	Land use	Weight
Slope	0.389	0.490	0.439	0.381	0.286	0.40
Rainfall	0.194	0.245	0.293	0.286	0.286	0.26
Soil texture	0.194	0.123	0.146	0.190	0.214	0.17
Runoff potential	0.128	0.081	0.073	0.095	0.143	0.10
Land use	0.097	0.061	0.048	0.048	0.071	0.07

3.3.3.10.3 Determining consistency of pair-wise comparison

A consistency ratio (CR) was estimated to find out the degree of consistency that had been utilized in coming up with the matrix ratings. If consistency ratio is less than 0.10, then some pair-wise values need to be reviewed and the procedure is done gain until the necessary value of less than 0.10 is realised.

The consistency ratio (CR) is defined as:

$$CR = \frac{CI}{RI} \qquad \text{...(3.3)}$$

Where:

CI is the consistency index which provides a measure of departure from consistency and;

RI is the random index.

The random index is the consistency index of the randomly generated pair-wise comparison matrix, and depends on the number of criteria being compared (Drobne and Lisec, 2009). This was established by means of the specific table prepared, Table 3.13, by Saaty in 1977 found in Saaty (2013), matching the order of the matrix. In this study, 5 criteria were used, and thus the value of the RI is 1.1.

Table 3. 13: Random index matching the number of criteria

Order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The consistency index is calculated as:

$$CI = \frac{\lambda - n}{n - 1} \qquad \text{...(3.4)}$$

Where:

λ is the average value of the consistency vector and;
n is the number of criteria.

The average value of the consistency vector was calculated through the following steps clearly explained by Hameed (2013):

1. The weight of the first criterion (slope = 0.40) in Table 3.12 was multiplied by the total of the first column of the initial pair-wise comparison matrix which is equal to 2.58 in the Table 3.11. The procedure was repeated for all the other criteria.
2. Finally, the summation of these values gave the consistency vector (λ=5 .28), which was used to compute the consistency index using equation (3.4).

The CR of this study was found to be 0.06 and is satisfactory since it is less than 0.10

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Agronomical characterization of rainfall in the Lubombo Plateau

The rainfall characterization was carried for the two rainfall stations in the study area, Lomahasha and Tikhuba, in terms of onset, end date, length of rainy season (LRS), total seasonal rainfall and dry spell length. The probability of dry spells was analyzed for lengths exceeding 5, 7, 10 and 15 days within the rainy season (October- March).

4.1.1 Onset, end, length of the rainy season and total seasonal rainfall

The results presented in the Table 4.1 revealed that, on an average, the rainy season starts on November 13 (Day of the year (DOY) 136) for Lomahasha, and on November 11 (DOY) 134) for Tikhuba station with CV of 17.3% and 24.3%, respectively. Normally, the rainy season ends on March 21 (DOY 265) and March 19 (DOY 263) for Lomahasha and Tikhuba with CV 4.3% and 3%, respectively.

The length of the rainy season at Lomahasha ranges from 65 to 186 days with a mean of 128 days, CV and SD of 22.5% and 29 days, respectively. At Tikhuba station, LRS shows variation from 49 to 175 days, with mean 129 days, CV 25.4 % and SD of 33 days. The total seasonal rainfall at Lomahasha area ranges from 173 to 1313 mm with a mean of 477 mm, CV and SD of 49.6% and 237 mm, respectively. At Tikhuba station the total seasonal rainfall shows variation from 69-1115 mm, with mean 483 mm, CV of 47.6 % and SD of 230 mm.

Table 4. 1: Onset, end, length of rainy season (LRS) and seasonal rainfall

Station		Lomahasha	Tikhuba
Onset (DOY)	Minimum	107	107
	25th percentile	117	107.75
	50th percentile	133	124
	75th percentile	155	146
	Maximum	194	220
	Mean	136	134
	SD	24	33
	CV (%)	17.3	24.3
End (DOY)	Minimum	259	259
	25th percentile	259	259
	50th percentile	259.5	259
	75th percentile	263.3	260.75
	Maximum	303	286
	Mean	265	263
	SD	11	8
	CV (%)	4.3	3.0
LRS (DOY)	Minimum	65	49
	25th percentile	103.8	113.75
	50th percentile	129.5	138
	75th percentile	152	152
	Maximum	186	175
	Mean	128	129
	SD	29	33
	CV (%)	22.5	25.4
Rainfall (mm)	Minimum	173	69
	25th percentile	336.8	323.9
	50th percentile	406.3	477.45
	75th percentile	545.1	614.31
	Maximum	1331	1115
	Mean	477	483
	SD	237	230
	CV (%)	49.6	47.6

The quantity of rain during the rainy season is important for the maize crop to give the highest yield. According to FAO (2015), for highest yield a medium maturity maize crop needs a minimum of 500 mm and more as influence by the areas' climatic conditions.

The mean starting date of the rainy season in the study area has high standard deviation of 24 and 33 days for Lomahasha and Tikhuba respectively, hence the onset date of the season is unstable. The high standard deviation signifies that the onset date of the season is unpredictable and subsequently presenting a threat on decision-making relating to timing of crop planting and associated operations (Gebremichael *et al*., 2014). The same is seen with the length of the rainy season and the total seasonal rainfall in both the stations found in the study area, making the area susceptible to drought.

Comparable conclusions were drawn from a study carried by Mamba *et al*. (2015) in the Middleveld, a region of Swaziland with almost the same climate as the study area. It was found that there is high variability in the onset and total rainfall received making it difficult to foretell the amount of rainfall to be available for crop production in a given season. This rainfall pattern is what was termed as erratic by FAO (2006) and branded as one of the causes of low maize yields in Swaziland, the Lubombo Plateau included.

4.1.2 Dry spell length analysis

The analysis of the probability of occurrence of maximum dry spell allows the farmer to make well informed decisions on which crops to grow as well as the suitable varieties. Farmers can make decisions on when to plant, among other associated activities, and prepare in advance for supplementary irrigation. Generally, when the probability of long-lasting dry spells is minimal, planting can be safely carried out since the soil moisture content would be conducive.

Daily rainfall was fitted to the Markov first order chain to determine the probability of dry spell length exceeding 5, 7, 10 and 15 days within the rainy season (October-March) using Instat Statistical software Version 3.37 (Stern *et al*., 2006).

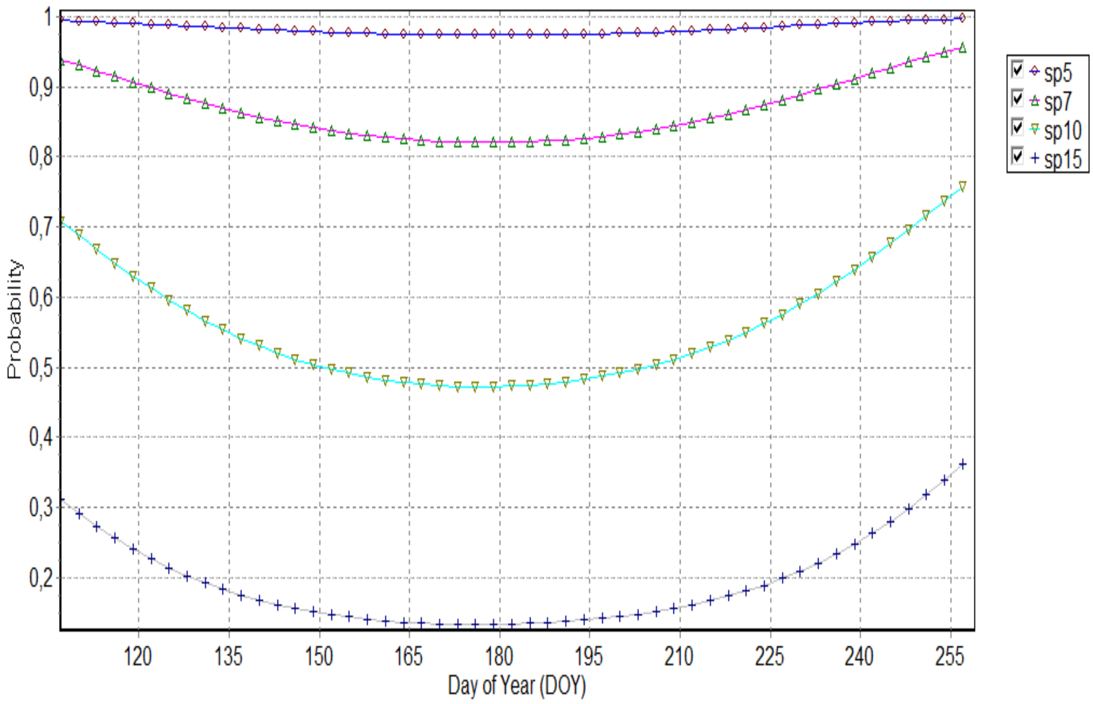


Figure 4. 1: Probability of dry spells at Lomahasha.

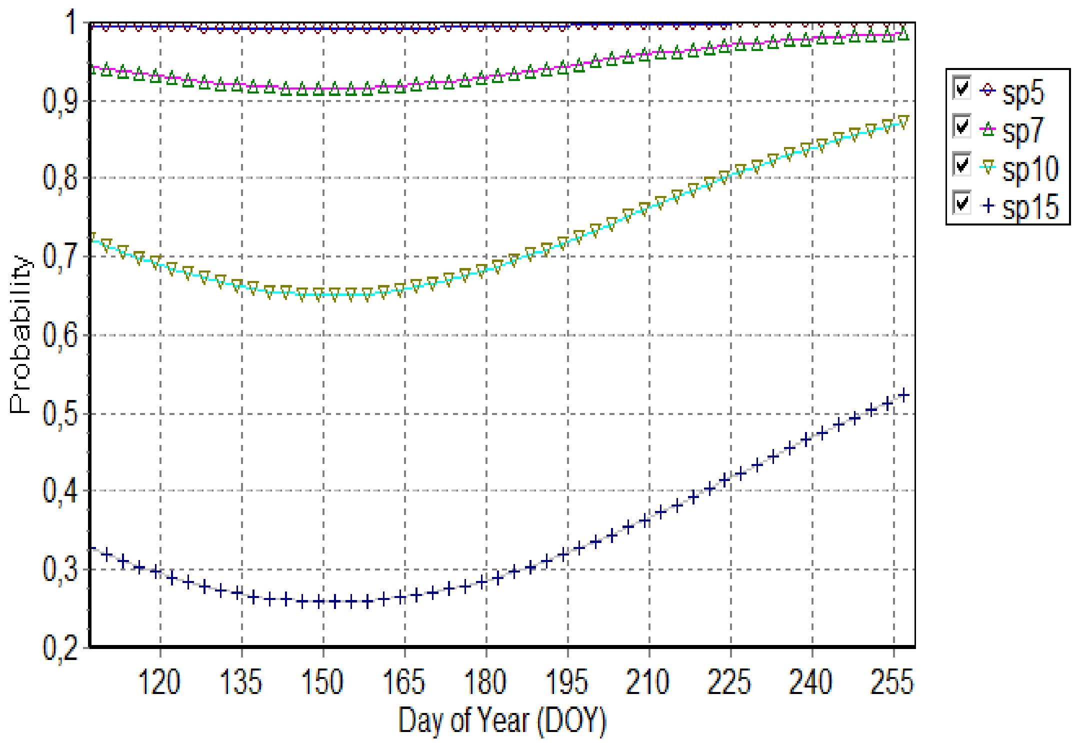


Figure 4. 2: Probability of dry spells at Tikhuba.

From Figures 4.1 and 4.2 it can be seen that the probability of a dry spell exceeding 5 days is always close to 100% throughout the rainy season in the study area. The same can be observed with the probability of a 7-day dry spell which above is 80% throughout the season.

For Lomahasha, looking at the 10 and 15 days dry spells; they are relatively higher (70% and 30% respectively) at the beginning and towards the end of the season, reaching their minimum (46% and 11% respectively) in December. The same pattern is observed at Tikhuba, although the probabilities of the 10 and 15 day dry spells rapidly shoots up from the beginning of January reaching up to about 90% and 52%, respectively, at the end of the season. This corresponds with the amount of rainfall received during these months.

The declining probabilities of the 10 and 15 days dry spells are crucial and the rainfall is beneficial for crop growth and development. Favourably, planting should thus be carried out when prolonged dry spells (10-15 days and above) have lessened, for example in December where the 15-day dry spell probability is close to 10% would provide good moisture for germination and emergence. However, planting in the last two weeks of November would ensure that there is enough moisture for initial crop vegetative development during the next couple of weeks where the probabilities of the prolonged dry spells are low.

The increase in the probability of dry spells from January coincides with flowering and grain-filling stages of maize and is regarded as the most critical. This is in agreement with other reports attributing poor maize yields to the January dry spells that occur at critical stages of maize in the Kingdom of Swaziland (FAO, 2015; Mamba *et al*., 2015).

In line with the observation of Simba *et al.* (2012), understanding the occurrence pattern of dry spells during the rainy season is vital for planning the scheduling of supplementary irrigation. The irrigation can be applied to target the dry spells that coincides with the critical growth stages of maize in the Lubombo Plateau. From this phase, it would be necessary to determine the amount of water required to alleviate these dry spells as pointed out by Hatibu *et al.* (2000).

4.2 Determination of net irrigation requirement for maize

The following table, Table 4.2 summarizes the results of the calculation of maize crop irrigation water requirements using CROPWAT 8.0 software.

Table 4. 2: Crop water requirement for maize in the Lubombo Plateau

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Eff. Rain mm/dec	Irr. Req. mm/dec
Nov	2	Init	0.30	1.33	10.7	23.1	0.0
Nov	3	Init	0.30	1.37	13.7	29.1	0.0
Dec	1	Dev	0.41	1.91	19.1	28.9	0.0
Dec	2	Dev	0.70	3.38	33.8	29.6	4.3
Dec	3	Dev	1.02	4.95	54.4	30.3	24.1
Jan	1	Mid	1.20	5.89	58.9	31.8	27.1
Jan	2	Mid	1.20	5.96	59.6	32.9	26.6
Jan	3	Mid	1.20	5.81	63.9	31.0	32.9
Feb	1	Mid	1.20	5.66	56.6	28.7	27.9
Feb	2	Late	1.07	4.92	49.2	27.1	22.1
Feb	3	Late	0.86	3.80	30.4	25.7	4.7
Mar	1	Late	0.65	2.75	27.5	25.0	2.5
Marc	2	Late	0.51	2.07	4.1	4.8	4.1
Total					**481.8**	**348.0**	**176.2**

For the study area, a 120-days maturing maize variety was chosen in line with FAO (2015) proposition. The calculations were performed for a maize crop planted on November, 13, and harvested on March, 12. For the first few decades there is no need for supplementary irrigation since rainfall is able to meet the maize crop water requirements. During this period, the probability of prolonged dry spells is low, but as the probability increases the need for supplementary irrigation is realised.

The total maize crop water requirement was found to be 481.8 mm, while 176.2 mm would be required as supplementary irrigation. Most of the supplementary irrigation is required between January and February which corresponds to the critical stages of the maize crop as well as high probabilities of prolonged dry spells. Assuming that all the 16,100 hectares (currently maize is grown on only 8,638 hectares) of cropland are utilized for maize production, a total irrigation volume of 28.4 Mm^3 would be required for supplementary irrigation of the crop.

4.3 Assessment of Runoff Potential and Identification of Suitable Rainwater Harvesting Sites

4.3.1 Curve Number

One of the outputs of the ArcCN-Runoff tool was the Curve Numbers of different land use- soil group complex (Figure 4.3). The lowest CN was 0 while the highest was 93. A large part of the study area has curve numbers between 72 and 82, signifying a relatively high runoff potential. This may be attributed mainly to the fact that most of the area is covered by hydrologic soils of group D which have low infiltration rates.

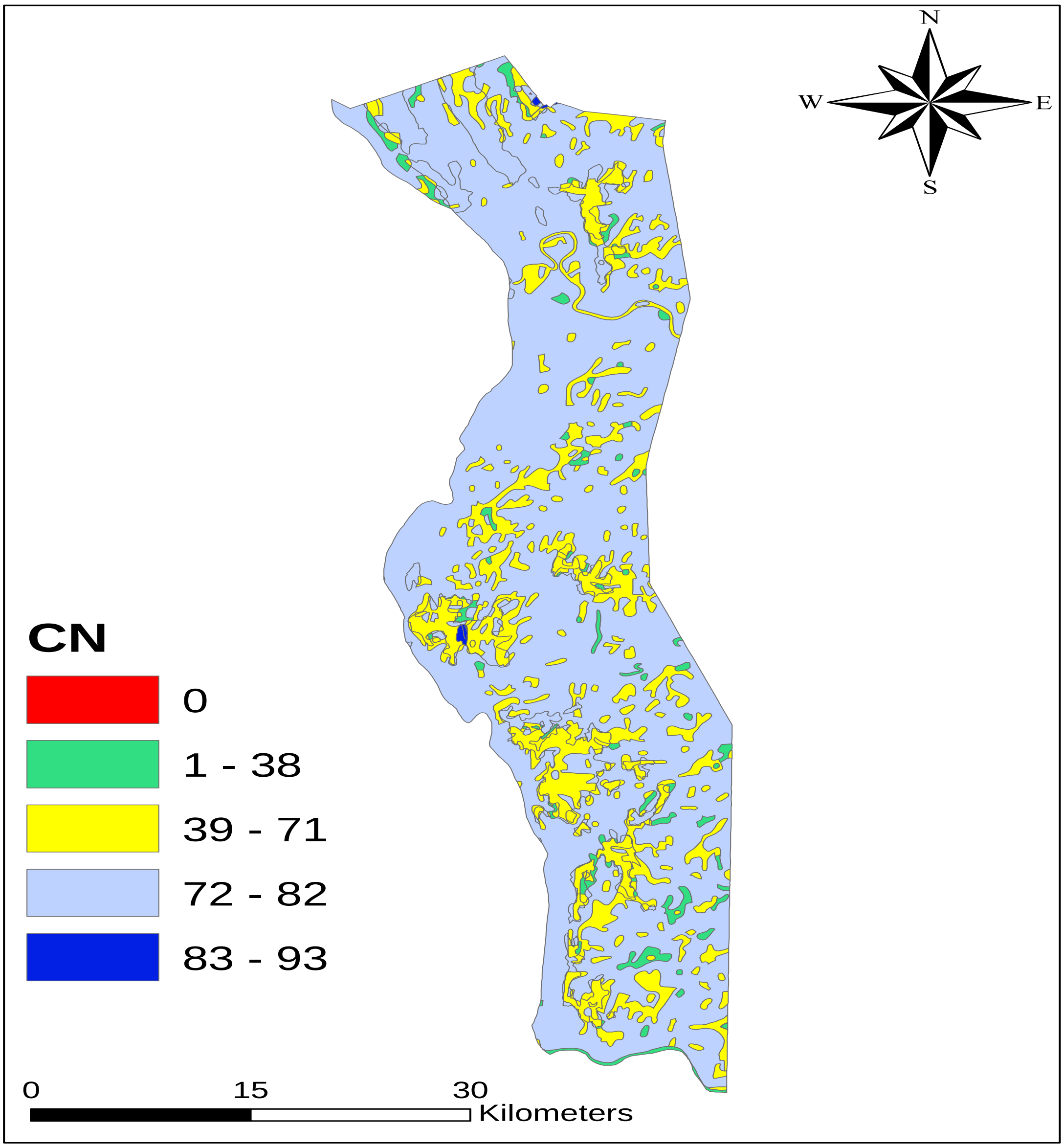


Figure 4. 3: Curve number map for the study area

4.3.2 Surface Runoff

From the Curve Numbers, ArcCN-Runoff tool produced potential runoff depth (Figure 4.4). These were based on the annual average rainfall of the study area which was found to be 614 mm at 80% probability of exceedance. The value of runoff ranged from 0 (found in water bodies) to 592 mm/m^2 in settlement areas.

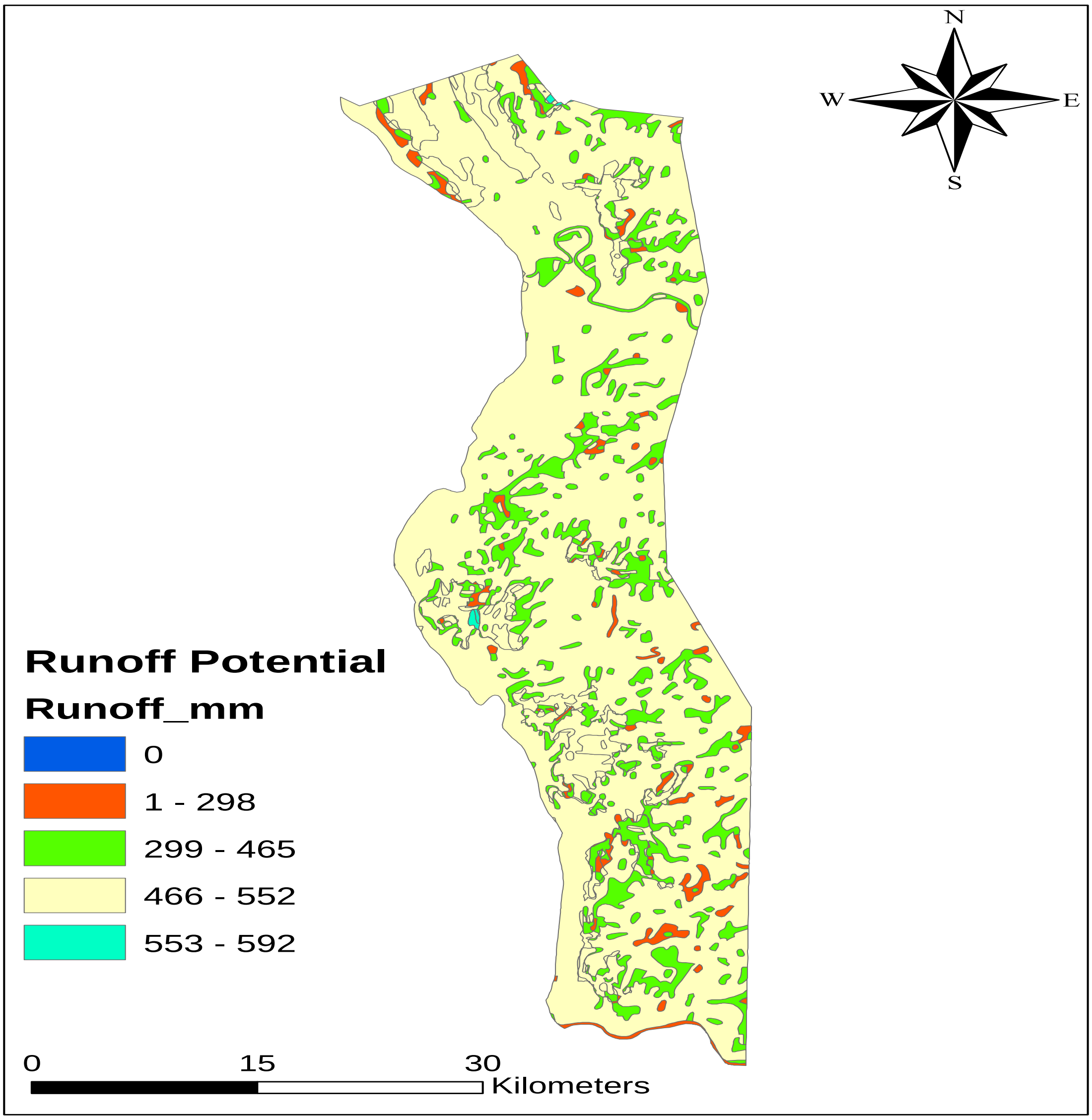


Figure 4. 4: Runoff depth potential map for the study area

4.3.3 Potential Rainwater Harvesting Sites

The multi-layer merging of rainfall, slope, runoff, soil texture and land use layers produced a map showing potential rainwater harvesting sites as shown in Figure 4.5.

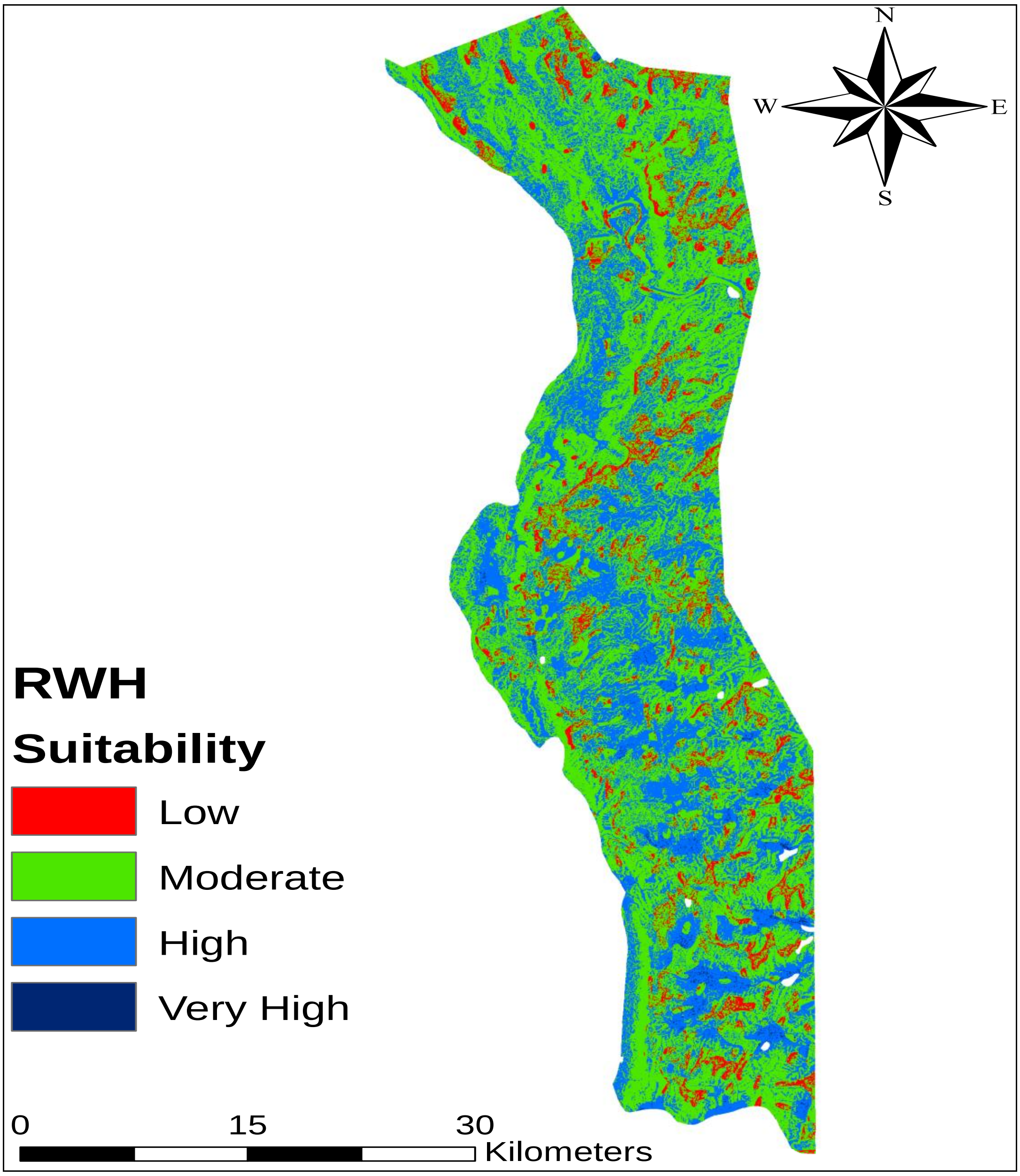


Figure 4. 5: Rainwater harvesting potential map of the study area

The proportion of area covered by different rainwater harvesting suitability levels in the whole study area is summarized in Table 4.3 as well as the respective percentage of the total area they occupy.

Table 4. 3: Rainwater harvesting suitability levels in the study area

Suitability	**Area (km^2)**	**Area (%)**
Very High	4.6	0.3
High	484.3	34.8
Moderate	797.5	57.2
Low	106.7	7.7
Very low	0.0	0.0

The suitability of rainwater harvesting in the study area was evaluated on a scale of 1 to 5 (from very low to very high). Only 0.3% of the total area was found to have very high suitability, 34.8% with high suitability, and 57.2% representing moderate suitability while only 7.7% indicate low suitability. No sites were found to have the very low rainwater harvesting suitability level. The Lubombo Plateau is dominated by fine textured soils and highly conducive rainfall amount (see Table 3.5) which favours ex-field rainwater harvesting by availing high surface runoff.

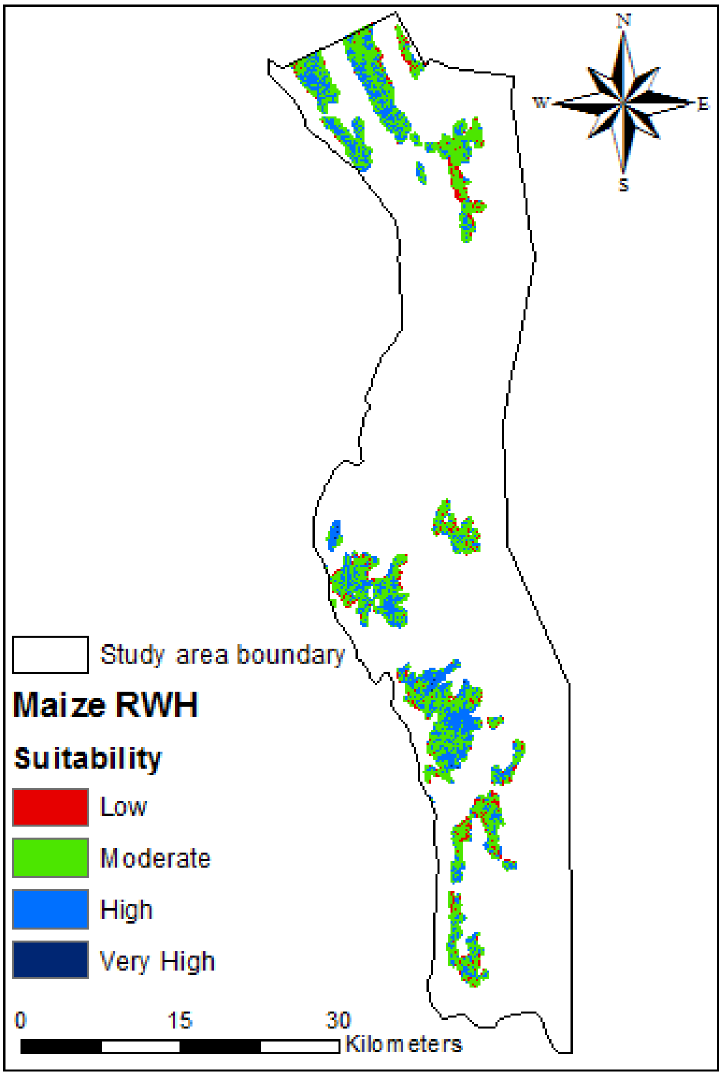


Figure 4. 6: Rainwater harvesting suitability for maize production

The suitability of rainwater harvesting for areas designated as cropland was of utmost importance in this study. It is within these areas, croplands, that rainwater can be harvested for maize production in the Lubombo Plateau. However, other areas can also be utilized for rainwater harvesting for other purposes or for crop production in future, should it be decided so. Table 4.4 shows the runoff volume that can be harvested from the croplands shown in Figure 4.6 (which includes areas that are within 150 metres) for maize production. Research has shown that in general, harvesting rainwater near the point of use is more feasible.

Table 4. 4: Runoff volume for crop production in the Lubombo Plateau

Suitability Level	Runoff Volume (m^3)
Very High	28 011
High	11 361 758
Moderate	25 791 414

The previous table (Table 4.4) shows the potential runoff volumes that can be harvested annually for crop production. A total runoff volume of 37.181 Mm^3 can be harvested per year. This is above the 28.400 Mm^3 calculated in section 4.2 as the net irrigation volume for maize production in the study area.

From the comparison of the maize irrigation requirements and potential runoff volumes, it can be seen that the maize crop water requirements in the Lubombo Plateau can be met through harvested rainwater. Similarly, an experiment carried out by Mzezewa and van Rensburg (2011) demonstrated that by adopting rainwater technique smallholder farmers could harness an additional water to meet a reasonable portion of maize water requirements.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study showed that on an average, the rainy season in the Lubombo Plateau starts mid November while the end of the rainy season is mid March. The length of rainy season at Lomahasha ranges from 65 to 186 days while at Tikhuba it ranges from 49 to 175 days. The mean length of the rainy season is about 128 days. The total seasonal rainfall at Lomahasha ranges from 173 to 1313 mm and 69 to 1115 mm at Tikhuba. The mean seasonal rainfall in the study area is about 480 mm. The onset of rains, length of rainy season and total seasonal rainfall have high standard deviation implying that the rainfall pattern is unpredictable and consequently decisions pertaining crop planting and associated operations are jeopardized.

The study also revealed that the probability of a dry spell exceeding 5 and 7 day is generally high, above 80%, throughout the rainy season. The probabilities of the 10 and 15 days dry spells; they are relatively higher at the beginning and towards the end of the season, reaching their minimum in December. This corresponds with the amount of rainfall received during these months.

For best crop establishment, planting should be done from mid-November when the probability of prolonged dry spell is low and rainfall is generally high. The increase in the probability of dry spells from January coincides with flowering and grain-filling stages of maize and thus responsible for poor yields. Supplementary irrigation should be planned to target this period.

The study found that for 120 days-maturity maize variety planted on November 13 and harvested on March 12, the crop water requirement was found to be 481.8 mm of which 176.2 mm would be required as supplementary irrigation. Assuming that all the 16,100 hectares is planted with maize, a total irrigation volume of 28.4 Mm^3 would be required. Most of the supplementary irrigation is required between January and February which corresponds to the increased probability of dry spells.

The potential RWH sites map shows that the areas with high and very high suitability areas cover 488.9 square kilometres (about 35% of the total study area). The area of low suitability zones is only 106.7 square kilometres (about 8% of the total area), while the moderate suitability area was 797.5 square kilometres (about 57% of the total area).There were no sites found with very low suitability.

A total runoff volume of 37.181 Mm^3 can be harvested per year for crop production from areas within 150 metres from croplands. This is above the 28.400 Mm^3 calculated as the net irrigation volume for maize production in the study area. This study therefore concludes that rainwater harvesting for rain-fed maize production is feasible in the Lubombo Plateau.

5.2 Recommendations

The study has confirmed the occurrence of dry spells during the rainy season in the Lubombo Plateau, as well as insufficient rainfall to fulfil maize crop water requirement. It is relieving, however, that the study has found that the Lubombo

Plateau has the potential for runoff generation which could help meet maize crop water requirements in the area. It is therefore recommended that:

1) The government should consider improving the meteorological stations network in the country as well as data management to make modelling results more applicable to all portions of a study area.
2) Government, researchers and relevant stakeholders should map the location of existing rainwater harvesting structures in the country.
3) The government should consider encouraging and assisting in the construction of rainwater harvesting dams in the dry regions of the country to provide supplementary irrigation during dry spells, especially during the flowering and grain-filling stages of maize.
4) Field surveys and socio-economic factors should be incorporated into this study before it can be implemented on the ground.

REFERENCES

AFDB (African Development Bank) (2008). Rainwater Harvesting Handbook: Assessment of Best Practises and Experience in Water Harvesting. African Development Bank.

African Cooperative Action Trust (ACAT) (2013). Annual Report for the year ended February, June 2013, Mbabane, Kingdom of Swaziland.

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

Babiker, K.E., Mohamed, A.A.W., Ali-Babiker, I.A. and Mohamed, H.O. (2015). Managing Rainfall Variability in Arid Rainfed Agriculture Using Adaptive Varieties and In-situ Water Harvesting, Sudan Academy of Sciences Journal-Special Issue (Climate Change), Volume 11, 74-82.

Barron, J. (Ed) (2009). Rainwater harvesting: a lifeline for human well-being, United Nations Environment Programme/SEI, Nairobi, Kenya.

CSIR (2002). The SADC National Land-cover Database 2000. Council for Scientific and Industrial Research. Digital Format.

De Winnaar, G., Jewitt, G.P.W. and Horan, M. (2007). A GIS-based approach for identifying potential runoff harvesting sites in the Thukela River basin, South Africa. Physics and Chemistry of the Earth, Volume 32, 1058–1067.

Dile, Y.T., Rockström, J. and Karlberg, L. (2016). Suitability of Water Harvesting in the Upper Blue Nile Basin, Ethiopia: A First Step towards a Mesoscale Hydrological Modeling Framework. Advances in Meteorology, Volume 2016, Article ID 5935430, 12 pp. doi:10.1155/2016/5935430.

Dlamini, S.I., Masuku, M.B. and Rugambisa J.I. (2012). Technical efficiency of maize production in Swaziland: A stochastic frontier approach. African Journal of Agricultural Research Vol. 7(42), pp. 5628-5636. Available online at http://www.academicjournals.org/AJAR DOI: 10.5897/AJAR12.1204.

Drobne, S. and Lisec, A. (2009). Multi-attribute Decision Analysis in GIS: Weighted Linear Combination and Ordered Weighted Averaging, University of Ljubljana, Faculty of Civil and Geodetic Engineering, Slovenia 2009.

Falkenmark, M., Fox, P., Persson, G. and Rockstrom, J. (2001).Water harvesting for upgrading of rain fed agriculture problem analysis and research needs. Foundation for Strategic Environmental Research. Stockholm International Water Institute Sveavägen. Stockholm, Sweden. SIWI. Rep. 11.8.

FAO (Food and Agriculture Organization) (2005). FAO/WFP crop and food supply assessment mission to Swaziland. Special report. Food and Agriculture Organization, Rome, Italy.

FAO (Food and Agriculture Organization) (2006). Crop and food supply assessment mission to Swaziland. Food and Agriculture Organization, Rome, Italy.

FAO (Food and Agriculture Organization) (2015). Special Report: FAO/WFP Crop and Food Assessment Mission to Swaziland. Food and Agriculture Organization, Rome, Italy.

Flory, B. (1991). Land Tenure and other Constraints to Commercial Agriculture on Swazi Nation Land: A Survey of Swaziland's Advanced Farmers. The Land Tenure Center University of Wisconsin Madison and The Research and Planning Division , Ministry of Agriculture and Cooperatives.

Gebremichael, A., Quraishi, S. and Mamo, G. (2014). Analysis of Seasonal Rainfall Variability for Agricultural Water Resource Management in Southern Region, Ethiopia. Journal of Natural Sciences Research www.iiste.org.ISSN 2224-3186 (Paper) ISSN 2225-0921 (Online) Vol.4, No.11.

Hameed, H.M. (2013). Water harvesting in Erbil Governorate, Kurdistan region, Iraq Detection of suitable sites using Geographical Information System and Remote Sensing. Thesis for the award of Master’s degree at Lund University, Lund, Sweden, pp. 15–34.

Hatibu, N. and Mahoo, H. (1999). Rainwater harvesting technologies for agricultural production: a case for Dodoma, Tanzania. In: *Conservation tillage with animal traction- A resource book of the Animal Traction Network for Eastern and Southern Africa (ATNESA) (*Edited by Hatibu N, Mahoo H, Kaumbutho PG, and Simalenga, T.E.) , Harare. Zimbabwe, pp. 161–171.

Hatibu, N., Kajiru, G. J. and Senkondo, E. M. (2000). Technical integration of RWH in to development plans: think globally, plan locally. In: *Rainwater harvesting for natural resources management, a planning guide for Tanzania, Regional Land Management* (Edited by Hatibu, N.,and Mahoo ,H.). ((RELMA / Sida) Technical Handbook no. 22:39-57, ICRAF House, Nairobi, Kenya.

Hatibu, N., Young, M.D.B., Gowing, J.W., Mahoo, H.F. and Mzirai, O.B. (2003). Developing Improved Dryland Cropping Systems For Maize In Semi-Arid Tanzania. Part 1: Experimental Evidence for the Benefits of Rainwater Harvesting. Experimental Agriculture, Volume 39, Pp. 279–292. Cambridge University Press.

IFAD (International Fund for Agricultural Development) (2001). Smallholder Agricultural Development Project, Kingdom of Swaziland, Interim Evaluation Report, October 2001, Report No. 1206-SZ.

Mamba, S.F., Salam, A. and Peter, G. (2015). Farmers Perception of Climate Change a Case Study in Swaziland. Journal of Food Security, Volume 3, No. 2: 47-67. Doi:10.12391/jfs-3-2-3.

Mati, B., De Bock, T., Malesu, M., Khaka, E., Oduor, A. Nyabenge, M. and Oduor, V. (2007). Mapping the Potentials for Rainwater Harvesting Technologies in Africa. A GIS overview of development domains for the continent and nine selected countries. Technical manual No. 6, World Agroforestry Centre (ICRAF) and UNEP, Nairobi, Kenya.

Mhazo, N., Masarirambi, M.T. and Dlamini, M.L. (2007). Evaluation of soil and water conservation techniques on performance of maize at Luyengo, Swaziland. Paper presented at the *8th WaterNet/WARFSA/GWP-SA Annual Symposium*, 31 October -2 November, Lusaka, Zambia.

Mlipha, M. (2005). Rainfall Prediction, Management and Utilization for Crop Production in Conservation Agriculture Plots at Shewula. Paper presented at the *6th WaterNet/WARS/GWP-SA Symposium*. 1-3 November, Ezulwini, Kingdom of Swaziland.

Motsi, K.E., Chuma, E. and Mukamuri, B.B. (2004). Rainwater harvesting for sustainable agriculture in communal lands of Zimbabwe. Physics and Chemistry of the Earth 29 (2004) 1069–1073.

Murdoch, G. (1970). Soil and Land Classification in Swaziland. Ministry of Agriculture, Mbabane, Swaziland.

Mwenge Kahinda, J., Lillie, E., Taigbenu, A., Taute, M. and Boroto, R. (2008). Developing suitability maps for rainwater harvesting in South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 33(8): pp. 788-799.

Mzezewa, J. and van Rensburg, L.D. (2011). Effects of tillage on runoff from a bare clayey soil on a semi-arid ecotope in the Limpopo Province of South Africa. *Water SA*, *37*(2), 165-172. Retrieved August 12, 2016, from http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1816-79502011000200005&lng=en&tlng=en.

Nketiaa, A.K., Forkuob, E.K., Asamoaha, E. and Senayaa , J.K. (2013). Using GIS-based model as a decision support framework for identifying suitable rainwater harvesting sites. International Journal of Advanced Technology and Engineering Research (IJATER). Volume 3, Issue 4, ISSN No. 2250-3536.

Osen, T.O. and Masarirambi, M.T. (2011). Effect of Climate Change on Maize (Zea mays) Production and Food Security in Swaziland. American-Eurasian Journal of Agriculture and Environmental Science, 11 (3): 385-391.

Oweis, T., Prinz, D. and Hachum, A. (2001). Water Harvesting: Indigenous Knowledge for the Future of the Drier Environments. ICARDA, Aleppo,Syria. 40 pp.

Pretty, J.N. and Hine, R. (2001). Reducing Food Poverty with Sustainable Agriculture: A Summary of New Evidence. Final Report of the "SAFE-World" (The Potential of Sustainable Agriculture to Feed the World) Research Project. Centre for Environment and Society, University of Essex, Colchester.

Rallison, R. E. and Miller, N. (1982). Past, present and future SCS runoff procedure, Rainfall-runoff relationships. International Symposium on rainfall – runoff, Mississippi State University, Mississippi: pp. 353 – 364.

Rejani, R., Rao, K.V., Osman, M., Chary, G.R., Pushpanjali, S., Reddy, K. and Srinivusa, R.C.H. (2015). Location specific insitu soil and water conservation interventions for sustainable management of drylands. Journal of Agrometeorology, 17(1): pp. 55-60.

Rockström, J. (1999). On Farm green water estimates as a tool for increased food production in water scarce regions. Physics and Chemistry of the Earth (B), 24 (4): pp. 375 – 383.

Rockström, J., Jonsson, P.E. and Barron, J. (1998). Seasonal rainfall partitioning under runon and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modelling. Journal of Hydrology, 210 : pp. 68 – 92.

Saaty, T.L. (2008). Decision making with analytical hierarchy process. International Journal of Services Sciences, Vol.1, pp 83-98.

Saaty, T.L. (2013). Analytic Network Process. Encyclopaedia of Operations Research and Management Science, pp. 64-72.

Saravanan, K., Mohan, K., Kasiviswanathan, K.S. and Saravanan, S. (2015). A GIS-Based Approach for Identifying Potential Runoff Harvesting Sites in the Bhavani Watershed, Tamilnadu, India. Australian Journal of Basic and Applied Sciences, 9(27): 479-486.

Sharma, B., Madziva, F., Rwehumbiza, F.B., Tumbo, S., Bouitfirass, M., Boufaroua, M., El Mourid, M. and Adouba ould Salem, A. (2009). Chapter 4: Rainwater harvesting in the management of agro-eco systems. In: *Rainwater harvesting: a lifeline for human well-being* (Edited by Baron, J.). United Nations Environment Programme/SEI, Nairobi, Kenya.

Simba, F.M. Seyitini, L. Murwendo, T. Mapurisa, B. Chayangira, J. Matete, C. Chirima, J. Mashonjowa, E. and Mufandaedza, J. (2012). Analysis of trends in dry spells during rainy seasons for Masvingo airport and Zaka stations in Masvingo province, Zimbabwe. Journal of Environment Research and Development 7(1), pp. 218-228.

Singwane, S.S. and Kunene, S.G. (2010). Viability of rainwater harvesting in supplying domestic water in rural areas of Swaziland: A case of Mpaka community. Journal of Sustainable Development in Africa (Volume 12, No.2). ISSN: 1520-5509 Clarion University of Pennsylvania, Clarion, Pennsylvania.

Stern, R., Rijks, D., Dale, I. and Knock, J. (2006). INSTAT climatic guide. Statistical Services Centre, The University of Reading, Reading, UK.

Swaziland Government (2002). Swaziland First National Communication to the UNFCCC. Ministry of Public Works and Transport, Department of Meteorology, Mbabane, Kingdom of Swaziland.

Swaziland Government (2009). National Water Authority. National Water Policy Final Draft. Ministry of Natural Resources and Energy, Mbabane, Kingdom of Swaziland.

Tadross, M.A., Hewitson, B.C. and Usman, M.T. (2005). The Inter-annual Variability of the Onset of the Maize Growing Season Over South Africa And Zimbabwe Journal of Climate. 18(16): 3356–3372.

Temba, N. and Sang-Ok, C. (2011). Assessing the Effects of Climate Change on Irrigation Water Requirement for Corn in Zimbabwe. Journal of the Korean Society of Agricultural Engineers, Volume 53, No. 1, pp. 47-55, DOI: 10.5389/KSAE.2011.53.1.047.

Tumbo, S.D., Mbilinyi, B.P., Mahoo, H.F. and Mkilawinyi, F.O. (2014). Identification of suitable indices for identification of potential sites for rainwater harvesting. Tanzania Journal of Agricultural Sciences, Volume 21 No. 2, 35-46.

UNEP (2009). United Nations Environmental Programme, Rain water Harvesting: A life line for human well-being, Stockholm Environmental Institute, SEI.

United States Department of Agriculture (2007). Hydrologic soil groups, Chapter 7. National Engineering Handbook (Part 630 hydrology). National Resources Conservation Service, Engineering Division. Washington, DC.

Verheye, W. (2010). Growth and Production of Maize: Traditional Low-Input Cultivation . In: *Land Use, Land Cover and Soil Sciences. Encyclopedia of Life Support Systems (EOLSS) (*Edited by Verheye, W.). UNESCO-EOLSS Publishers, Oxford, UK. http://www.eolss.net.

Vilane, B.R.T., Mkhwanazi, M.M. and Shongwe, M.I. (2010). The Potential of Rooftop Rainwater Harvesting in Swaziland. Department of Land Use and Mechanization, Faculty of Agriculture, University of Swaziland, Luyengo, Kingdom of Swaziland.

Wang, Y.M., Traore, S. and Kerh, T. (2009). Applying Evapotranspiration Reference Model and rainfall contribution index for agricultural water management plan in Burkina Faso. African Journal of Agricultural Research Vol. 4 (12), pp. 1493-1504.

WFP Swaziland (2009). Annual Report, United Nations World Food Programme. Mbabane, Kingdom of Swaziland.

World Vision Swaziland (2010). Agricultural Task Force Report: Agricultural Development Recommendations, January, Mbabane, Kingdom of Swaziland.

Zhan, X. and Huang, M.L. (2004). ArcCN-Runoff: An ArcGIS Tool for Generating Curve Number and Runoff Maps. Environmental Modelling and Software, Vol. 19, No. 10, pp. 875-879.