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A GIS-BASED APPROACH FOR IDENTIFYING SUITABLE SITES FOR RAINWATER HARVESTING TECHNOLOGIES IN KASUNGU DISTRICT, MALAWI

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In Collaboration with

A GIS-BASED APPROACH FOR IDENTIFYING SUITABLE SITES FOR RAINWATER HARVESTING TECHNOLOGIES IN KASUNGU DISTRICT, MALAWI

By

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A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Integrated Water Resources Management of the University of Zimbabwe

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DECLARATION

I, **FRED TIGO NYIRENDA**, hereby declare that this thesis is a product of my own investigation apart from where acknowledged being submitted to the University of Zimbabwe. This is my own work which has never been accepted for an award for the degree at any university.

Signed Date

DEDICATION

To my wife Florence and Son Tawonga thank you for believing in me, it could not have been achievable without your support and encouragement.

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God bless you

ABSTRACT

Kasungu district in Malawi has mainly been affected by erratic rainfall that are characterised by dry spells. Almost each year the district receives rainfall that is unevenly distributed spatially and temporal hence threatens crop production leading to food insecurity. Soil moisture retention is vital in crop production hence Rainwater harvesting (RWH) technologies have been recommended in literature to mitigate dry spells. In the recent past, the Malawi Government has advocated for the implementation of RWH technologies. Proper planning in identification of suitable sites for various RWH technologies can improve the effectiveness of the technologies. The objective of the study was to develop a GIS-based approach for identifying suitable sites for RWH technologies in Kasungu District of Malawi. Field surveys were conducted in the villages of Chipala Extension Planning Area (EPA), in order to identify and evaluate performance of existing RWH interventions, and establish factors for locating suitable areas for RWH. Soil moisture content was used to test for performance of RWH technologies. A GIS based Soil Conservation Service (SCS) Curve Number method was used to map runoff potential areas for RWH. The results from field study revealed that the most commonly implemented technologies were soil mulching (50%), contour tied ridges (39%), planting pits (7%) and infiltration pits (4%). Performance assessment of the RWH technologies reviewed that there was *a statistically significant difference (α=0.05) in the moisture measurements for the various RWH technologies (P< 0.05). A RWH potential map was developed that showed 87% of the land in the study area being suitable for RWH. The model was validated by comparing locations of existing RWH technologies to the suitability map that showed that 79 % of RWH technologies were located in the high suitable area and moderate areas, 17 % in areas of low suitability whilst only 4 % were located in areas of very low suitability. Hence the model can reliably be used to identify suitable areas for RWH technologies.*

Key Words: RWH; GIS; RS; Curve NC, contour tied ridging, mulching, infiltration and planting pits

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ABREVIATIONS AND ACRONYMS

EPA	Extension Planning Area
FAO	Food and Agricultural Organisation of the United Nations
GIS	Geographic Information System
GoM	Government of Malawi
IWRM	Integrated Water Resources Management
LRCD	Land Resources Conservation Department
MoAIWD	Ministry of Agriculture, Irrigation and Water Development
MCE	Multi-Criteria Evaluation
NGO	Non-Governmental Organization
RS	Remote Sensing
RWH	Rainwater Harvesting
SADC	Southern Africa Development Community
SCS-CN	Soil Conservation Services- Curve Numbers
SDGs	Sustainable Development Goals
SPSS	Statistical Package for Social Sciences

CHAPTER 1

1 Introduction

Agriculture is the major source of livelihoods for about 70 % of the population in the semi-arid areas of Africa (Community Adaptation and Sustainable Livelihoods-CASL, 2006). These livelihood activities face many constraints due to erratic rainfall patterns which could be as low as 500mm for the past decade. Other factors include torrential rainfall which could lead to high run-off; high rate of evapotranspiration which results in low crop yield and high weeds invasion, which favourably compete for water with crop plants; low organic matter levels and poor crop response to fertilizers (CASL, 2006).

Water is a key factor in agricultural development and its erratic supply proves to be a major problem in the sector. For instance, 85% of agricultural production in Malawi is rain fed in which soil water losses through surface runoff and evaporation is one of the major limiting factors (Ngongondo and Alemaw, 2011). There is large spatial and temporal rainfall variability frequently resulting in dry spells resulting in total crop failure. To deal with this uncertainty; there is need for increased water control for the enhancement of efficient water use and conservation wherever and whenever possible (Oxfam, 2011).

Rockström and Falkenmark, (2015) recommended investing in Rainwater Harvesting (RWH) technologies for agricultural production in contrast to the conventional practices of drawing water from rivers and underground. A number of researchers have also confirmed the potential of RWH to improve water productivity by mitigating temporal and spatial variability of rainfall (Makurira et al., 2009; Mwenge Kahinda et al., 2007; Rockström and Barron 2007; Rosegrant et al., 2002). RWH reduces the susceptibility of crops to the adverse effects of frequent dry spell events, and has the ability to reduce inter-seasonal crop yield variability associated with erratic climatic patterns (Rockström & Barron, 2007).

The Ministry of Agriculture, Irrigation and Water Development of Malawi through Land Resources Conservation Department (LRCD) has started to promote RWH on a broad scale since RWH offers an alternative for Malawi to meet its food security. However the implementation of RWH in Malawi has been faced with several challenges such as excessive loss of water due to high rates of evaporation and seepages (Mloza-Banda, 2006). This has been attributed mainly to poor location of RWH technologies (Nhira and Mapiki, 2006). Prinz et al. (1998) found that the most important factors for identifying suitable sites for RWH are rainfall, soil texture and depth, topography and vegetation cover. Therefore understanding and quantification of these factors is essential.

Most of the decisions on where to locate the RWH technologies are spatial hence different layers of selected factors will need to be combined to determine their suitability. This is best done using multi- criteria evaluation techniques which combines suitability levels (degree to which a certain value in a given factor influences the location of RWH technology) of each factor and their important weights. The use of geospatial technologies such as Remote Sensing (RS) and Geographic Information System (GIS) has been found to be effective tool for identifying suitable areas for RWH (Kahinda et al., 2008; Jasrotia et al., 2009; Jha et al., 2014). GIS is a computer programmed tool that store, process and retrieve spatial data from the real world (Burrough, 2000). GIS has been recommended for use in making decision during planning for RWH. In the recent past, the effectiveness of geospatial techniques in identifying potential sites for RWH has been reported by some researchers (Kahinda et al., 2008; Mbilinyi, Tumbo and Mahoo, 2007; Mwenge Kahinda, Taigbenu and Sejamoholo, 2009; Weersinghe, Schneider and Low, 2010). However to the best of my knowledge, in Malawi GIS has not been used in identification of suitable sites for RWH is not documented (Nthala et al, 2008).

1.1 Problem Statement

Although the Government of Malawi and non-governmental organizations have been promoting the implementation of RWH to improve the food security of rural people, the implementation has faced a lot of challenges resulting in low adoption. The RWH technologies that have been implemented have not been performing well in terms of harvesting and storing adequate water in the soil to meet the crop water requirement for various crops because the majority of the technologies are planned without much knowledge about the conditions of the sites which results in various challenges such as; water logging, high seepage, siltation and insufficient water collection by the structures. Nhira & Mapiki (2006) indicated that the main reason for failure and the low adoption of the RWH technologies is the poor selection of sites and matching of the practice with the technical and socio economic requirements. Thus there is a need for systematic methodology that enables the assessment of the suitable sites for RWH (Mbilinyi et al., 2007). This study investigated the use of a GIS-based approach for identifying suitable sites for implementation of rainwater harvesting technologies.

1.2 Objectives

1.2.1 Main Objectives

To develop a GIS-based approach for identifying suitable sites for rainwater harvesting technologies in Kasungu District of Malawi.

1.2.2 Specific Objectives

i. To identify and evaluate performance of existing rainwater harvesting (RWH) technologies in Kasungu District.
ii. To establish factors for locating suitable areas for RWH interventions in Kasungu District.
iii. To integrate factors for locating and mapping suitable areas for RWH interventions in a GIS based platform and apply the developed integrated GIS based platform to locate land suitable for RWH in Kasungu District.

1.3 Justification

To successfully implement RWH technologies there is need for integration of socio-economic and environmental factors for sustainability of the technologies. Therefore RWH technologies implemented in the study area need to be identified. It is also necessary to understand how they perform in order to assist implementing agencies to promote well performing RWH technologies. The implementation of RWH technology needs a spatial criterion that would indicate the fields' suitability for RWH. Therefore there is need to establish the factors that are considered for implementation of RWH in the area. GIS has been recommended for use in decision-making in RWH during the planning process.

1.4 Thesis Structure

This thesis has five chapters. Chapter 1 introduces the background of the study, main and specific objectives, and problem. Chapter 2 reviews literature on RWH technologies from related studies. Chapter 3 describes the study area in terms of its location, soil type, climate and the socio-economic activities that are conducted in Kasungu District. Methods used to collect and analyze data have also been described. Chapter 4 indicates results and discussion of the study. Finally chapter 5 of this report presents conclusions from the research and recommendations.

CHAPTER 2

2 Literature Review

This chapter reviews literature on RWH in general and use of Remote Sensing and Geographic Information Systems in identifying suitable sites for RWH in particular. In addition, it discusses literature on rainfall runoff modelling and RWH suitability assessments such as use of the Multi Criteria Decision Making Methods (MCDM) that combines and processes spatial data (Input) into resultant decision (Output) proposed by Malczewski, (2004).

2.1 Rainwater harvesting technologies

2.1.1 Definition of rainwater harvesting

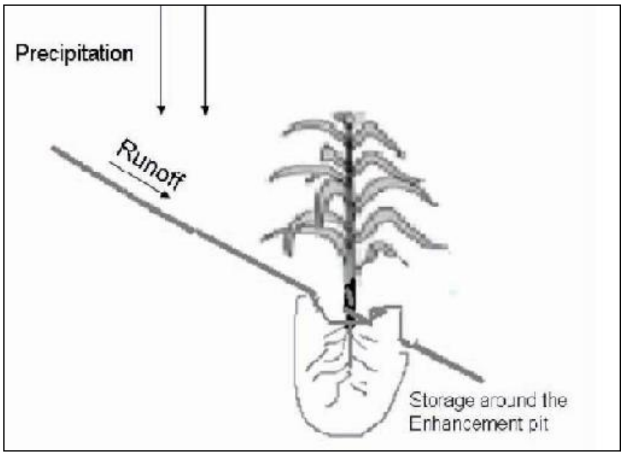
The term rainwater harvesting (RWH) is used in different ways and thus no universal definition has been adopted (Ngigi, 2003). According to Mzirai and Tumbo, (2010) RWH is the process of intercepting and concentrating rainwater in order to increase water infiltration into the soil for direct use by plants or in reservoirs for later application when needed to mitigate dry spells. Sekar and Randhir, (2007) defined RWH as a technique which can be used to minimize water loss and to supplement water supplies in watershed systems. Global Development Research Center (2002) reported that the first use of RWH techniques is believed to have originated in the Neo Babylonian Empire now called Iraq over 5000 years ago, in the Fertile Crescent, where agriculture once started some 8000 BC. The history of RWH practices in Ethiopia can be traced as early as 560 BC, during the Axumite Kingdom. Around 20th Century the focus for RWH was on domestic water supply until middle of the century when most scientists changed their focus for crop production (Seyoum, 2003). Today RWH is practiced in many parts of the world including Australia, Brazil, Netherlands, Ethiopia, Kenya and Zimbabwe (HABITAT, 2013).

In Malawi before independence in 1964, there was promotion of soil and water conservation technologies where water was stored in the crop root zone for use during dry days while ensuring that excess water is safely channelled away without causing erosion. Generally erosion control measures are considered to be soil conservation measures (Thomas, 1997). Since independence the aim of erosion control measures are no longer just erosion control but also water harvesting for moisture retention for plant growth because of increased incidences of rainfall variability (Wiyo et al., 2000). In order to mitigate the effects of droughts a number of RWH technologies have been introduced and are being implemented in many parts of Malawi and other Southern African countries.

2.1.2 Types of rainwater harvesting technologies

All RWH technologies have a catchment area for runoff generation and a storage area for collection and storage of runoff water. The amount of runoff generation is determined by the characteristics of the catchment area thus the less permeable the catchment the higher the runoff is generated and vice versa. The collected water can be directly channeled to the field for infiltration into the soil (in-situ) or stored in a reservoir or tank (ex-situ) to be utilized elsewhere at another time.

Generally, stored water could be used for agricultural and domestic purposes (Mzirai and Tumbo, 2010). According to UNEP (2014) in-situ RWH involves small movements of rainwater as surface runoff shown in figure 1a (Nthala et. al., 2008). In order to concentrate the water, there is no separation between the collection and the storage area. The water is collected and stored where it is going to be utilized. In situ water conservation includes small basins, pits and cultural field practices which harvest water within the fields. In this application there is no separation between the collection area and the storage area, water is collected and stored where it is going to be used (UNEP, 1997). Runoff-based systems are broad RWH technologies which harvest rain water from a catchment which is outside the fields (Senkondo et al., 2004). Ex situ RWH technologies capture rainfall that falls outside the farmland and require a reservoir that is used to store runoff for providing irrigation water when rainfall is insufficient to secure crop harvest as shown in Figure 1b.



a: In-situ rainwater harvesting (Biazin et al., 2012) b: Ex-situ rainwater harvesting

Figure 1: Types of rainwater harvesting

Generally classification of RWH is based on runoff generation process, type of storage and size of catchment (Ngigi, 2003). According to Critchley et al., (1991) RWH can also be classified into three systems based on runoff diversion into crop land and distinctive storage structures for supplemental usage; (i) micro-catchment systems (within fields), (ii) small catchments systems where runoff generated from small external catchments is diverted to crop land and (iii) macro-catchment systems where there is flood diversion from external catchments into crop lands as indicated in figure 2.

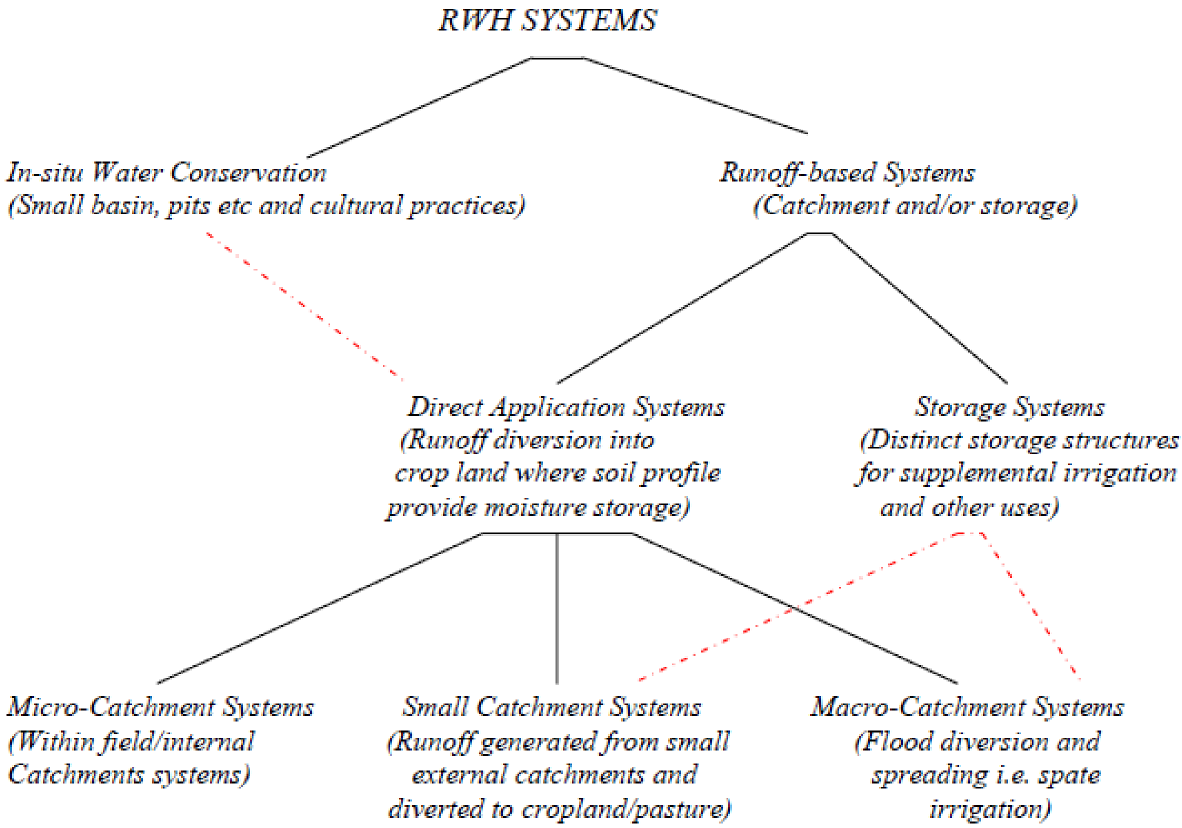


Figure 2: Classification of rainwater harvesting systems, Source (Ngigi, 2003)

2.2 Experiences of RWH in Sub Saharan Africa

Sub-Saharan Africa's rural economy is mostly based on agriculture as compared to other regions. However climate change and variability pose new agricultural challenges especially in Sub-Saharan African countries where the majority of the population depends on rain fed agriculture (Thompson and Ford, 2010). Rockstrom, (2000) reported that livelihoods security in Eastern and Southern Africa is strongly dependent on rainfall distribution and land management practices among smallholder farmers with over 95 % of the land used for food production based on rain fed agriculture. For instance in Kenya, 85 % of the population rely on rainfed while in Malawi the population is 90 % and Zimbabwe, is 70-80 % of the population. However rainfall remains a challenge in the Semi-arid regions as it is highly erratic and unreliable characterised with mid-season dry spells (Steiner and Rockström, 2003). Severe crop reduction is common due to dry spells that usually occur 1-2 out of 5 years and annual droughts once every 10 years resulting into total crop failure (Rockström, 2002).

Although the current crop production is low in most semi-arid regions it is still possible to increase crop yields if the problem of water shortage during dry spells can be contained. RWH is used in many semi-arid countries as a tool to upgrading rain fed farming by mitigating dry spells effects and their potential to enhance agriculture productivity and generate income under low rainfall conditions (Rockström, 2002). For instance, Amha, (2006) found out that adoption of RWH technologies in Ethiopia had a positive effect on value of crop production. Similarly other studies have also shown as positive impact of RWH technologies (Mhizha and Ndiritu, 2013; Motsi et. al, 2004; Mugabe, 2004; Tesfay, 2008).

Therefore RWH has been promoted in the region for example, in Kenya RWH has been used during colonial government time (Aroka, 2010). Mupangwa et al.,(2005) reported that in Southern Zimbabwe in situ RWH technologies have been promoted for some time. These are mainly graded contour ridges (slope less than 5 %), dead level contours and *Fanya Juus*. In a study carried out by Motsi et al., (2004) a participatory approach was used to introduce a range of RWH technologies to farmers in Mudzi, Gutu and Chivi districts of Zimbabwe. On the other hand, tied- ridging has been promoted in Malawi as an on-field RWH technology to ensure high crop fields during prolonged dry or drought years (Wiyo and Feyen, 1999).

2.3 Farmers experiences with rainwater harvesting

Although countries in the arid and semi arid regions have been promoting the use of RWH, adoption rate is still low (Ariane, 2004). Ahmed, et al, (2013) indicated that in situations where RWH technologies performance is poor it's mainly due to decision makers placing too much emphasis on technology itself while ignoring farmers' own knowledge. The decision makers fail to recognize the processes by which farmers learn and adopt new practices. To remedy the situation, indigenous and innovative technologies were promoted involving various types of RWH technologies (Mati et al, 2005). Thus poor performance of many

RWH technologies in Ethiopia was partly explained by the improper selection of the targeted area with less suitable factors such as soil and rainfall. This was attributed to lack of proper planning, implementation and management.

Mbilinyi et al., (2005) found out that farmers in Tanzania had significant knowledge of RWH technologies as well as the knowledge on identification of suitable sites for different RWH technologies. Thus it was concluded that farmers' selection of physical factors such as soil types and topography was based on experience and indigenous knowledge. According to Mbilinyi et al., (2005) indigenous knowledge, also referred to as traditional knowledge, is the knowledge that people in a given culture or society have developed over time based on experience. Indigenous knowledge has now been recognized and accepted as a vital knowledge source (Chimaraoke et al, 2003).

2.4 Suitability of sites for RWH

2.4.1 Factors affecting suitability of site for RWH

Extensive literature exists on the social and economic significance of RWH sites and how they benefit the communities that use them (Amha, 2006; Kessler, 2006; Ketsela, 2009; Mbilinyi et al., 2005). Bulcock and Jewitt (2013) indicated that research has also been done to assess the suitability of selected research catchments for the sitting of RWH technologies. Amha, (2006) in his study in Ethiopia reported that there are two major steps that need to be followed when selecting RWH technologies and sites where they can be implemented. These are (i) setting priorities the people's choice and (ii) technical knowhow and criteria.

Selection of a specific technique must consider the social and cultural aspects prevailing in the area of interest as they are vital and will determine the success or failure of the technique implemented. This is mostly essential in the arid and semi-arid regions and may help to explain and understand the failure of many projects that did not consider the people's priorities. In arid and semi-arid areas, the majority of the population experienced fundamental regimes over the centuries which set priorities for their survival.

In addition to the socio-economic considerations, Hatibu and Mahoo, (1999) indicated that RWH technologies can be sustainable if they also fulfills a number of basic technical criteria as shown in figure 3. The criteria consider factors such as soil type and slope for suitability of RWH. Thus soils with high water holding capacity are considered more suitable for RHW as compared to those with low water holding capacity. Slope of less than 5 % is considered more suitable for contour tied ridging while slope of more than 5 % is considered to be more suitable for *Fanya juu* and *Negarim*. On the other hand sometimes farmers have their own criteria when selecting sites such as; easy access to get runoff, location of the plot from residence and size of the plot. FAO (2003) reported that the suitability of the area for RWH depends on a number of factors such as, rainfall, soil, land use, topography and socio-economic factors. Thus other researchers have used these parameters in identifying RWH suitable sites. For instance, Prinz et al., (1998) in their study considered used rainfall and topography to identify potential RWH sites. Kahinda et al., (2008) in South Africa identified six key factors when identifying RWH sites: This are; hydrology (rainfall–runoff relationship and intermittent watercourses), topography, crop characteristics, soils types and socio-economic like work force, people's priority, population density, experience with RWH, land tenure, accessibility and water laws. Therefore it was recommended to integrate socio-economic factors when deciding the suitability of an area to RWH (Critchley, 1991). Similarly Amha, (2006) reported that consideration of social and cultural aspects is particularly important in the arid and semi arid regions of Africa and may help to explain the failure of the technology.

The chart in figure 3, illustrates the fundamental selection criteria for the different RWH technologies based on soil moisture regime. In this criteria moisture is assumed to be affected by soil type and slope of the area Therefore an area is considered suitable for RWH if it has soils with high water holding capacity such as clay loam while RWH is not suitable for areas that have shallow sandy soils because due to low water holding capacity. This agrees with the study by Mbilinyi et al., (2014) that recommended RWH technologies to be implemented on soils with high water holding capacity. On the other hand, area with slope of less than 5 % are considered suitable for RWH which also agrees with Critchley, (1991).

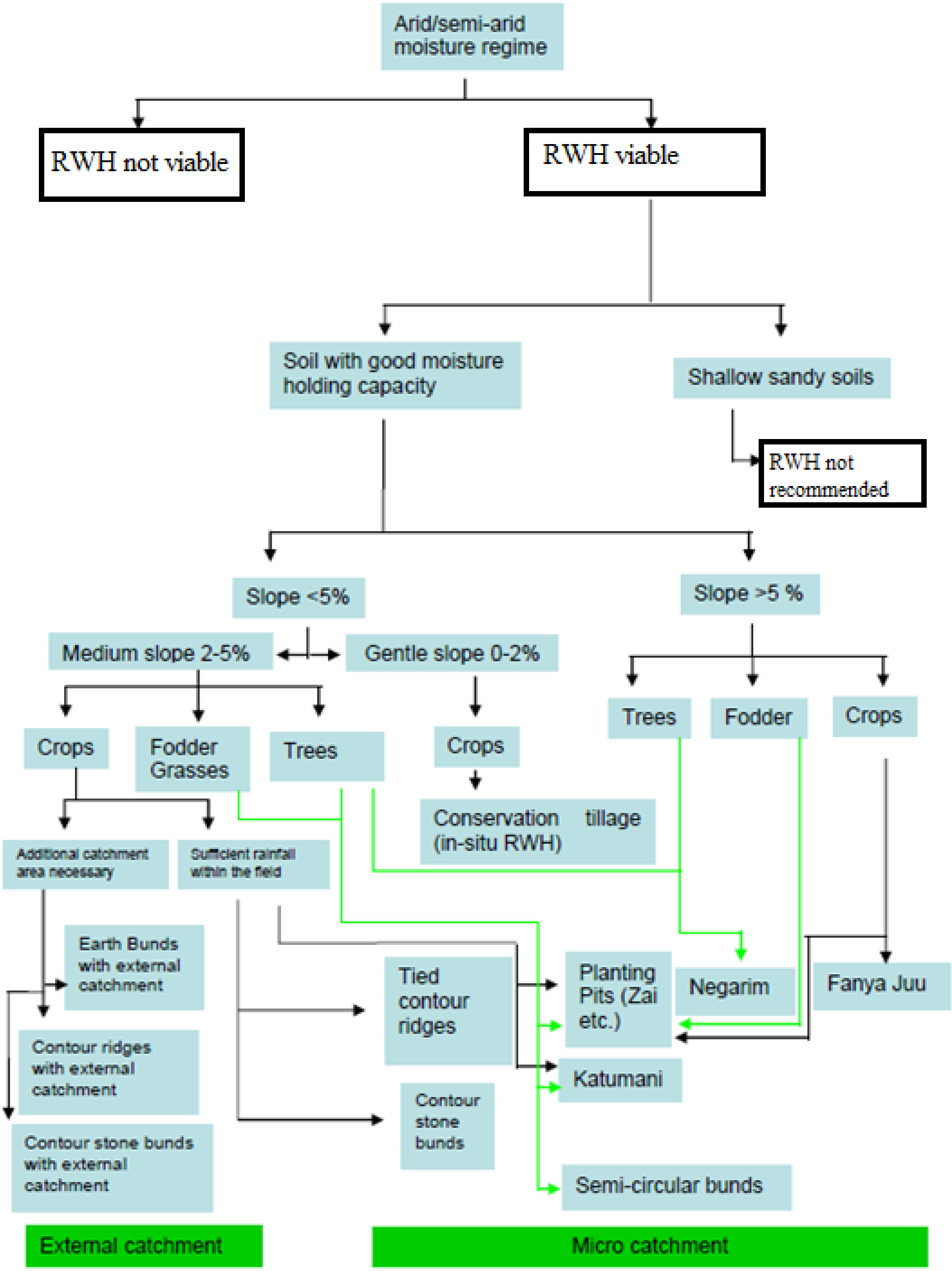


Figure 3: System selection or technical selection criteria (AfDB, 2008)

2.4.2 Techniques for site selection for RWH

Bulcock and Jewitt, (2013) noted that other researchers (Al-Adamat et al., 2012; Alazba and Shereif, 2014; Mbilinyi et al., 2007) have used one or more of the sets of criteria that was developed by Critchley et al., (1991) and Oweis et al.,(1998) or the Integrated Mission for

Sustainable Development (IMSD) that was devised to identify the physical suitable sites for RWH technologies in India (Jasrotia et al., 2009). The guidelines set by Oweis et al., (1998) are the most comprehensive since they consider land of complex terrain for RWH technology. They determine criteria for different types of RWH technologies and set ideal and suitable limits for factors such as rainfall, soil texture, soil depth, slope, land use (cover), socio-economic (population density) and ecological conditions.

According to FAO (2003) promotion of RWH technologies in areas receiving less than 100 mm/year or more than 1000 mm/year of rains is not recommended (Mati et al., 2006). There is no incentive to implement RWH technologies in areas with annual rains in excess of 1000 mm/year whilst there is hardly any productive water-based activity in areas with annual rainfall less than 100 mm/ year. Mwenge-Kahinda et al, (2008) used annual rainfall as one of the criteria for selecting potential areas for in-field RWH technologies.

The suitability of an area as a catchment area in RWH depends mostly on its soils characteristics. Soils with high infiltration rates, such as sandy soils, are not favourable for RWH technologies because large size of the soil particles determines how much rainwater can be stored in the soil profile. Tumbo et al., (2014) explained that soil texture determines the total water storage of the soil, which determines moisture availability in *in-situ* RWH for crops during dry spells. Similarly White, (1987) recommended that fine and medium textured soils are generally the more desirable for RWH because of their better retention of nutrients and water. However soils with high percentage of silt and clay particles have higher water-holding capacity (Ball, 2001). Therefore the main challenge in implementation of RWH technologies such as contour tied ridges and soil mulching is how to minimize water losses mainly due to evaporation and seepage respectively (Ngigia et al, 2005).

The soil depth must be deep enough to allow for excavation of RWH technologies as well as ensuring adequate rooting development and storage of the harvested water. Moges (2004) noted that the deeper the soil the higher is the water storage capacity and vice versa. Thus sites with deep soils are relatively suitable for location of RWH technologies than shallow ones as deep soils have higher capacity of storing the harvested runoff as well as providing a greater amount of total nutrients for plant growth (Ketsela, 2009). Thus the deeper the soil, the more suitable it is for in field RWH (FAO, 2003b). Ketsela (2009) and Mwenge Kahinda et al., (2009) also used soil depth as the factor for selecting in-field RWH suitable sites.

Alazba and Shereif, (2014) indicated that slope of the catchment affects how quickly water will runoff during a rain event. A steep area will shed runoff quickly while a less-steep, flatter area will cause the water to move more slowly, raising the potential for water to remain on the soil surface. Mati and Bock, (2006) recommended the use of slope of the land in site selection and implementation of all ground based RWH technologies. Critchley et al., (1991), recommended the use of In-situ RWH in areas where slopes are less than 5 % because of large quantities of earthwork required which is often costly and uneven distribution of run-off.

Mwenge-Kahinda et al., (2009) noted that there is a correlation between the runoff generated in a catchment and land use of the area for a particular rainfall event. Therefore the increase in the vegetation density in the area results in a consequent increase in interception, and infiltration rates hence runoff is reduced (Thompson, 1999). Therefore the design of RWH must take into account the runoff factor. In other studies (Ketsela, 2009; Mwenge-Kahinda et al., 2009; Critchley & Siegert, 1991; Ziadat et al., 2012) have recommended the use of socio-economic and ecological data in order to improve on the RWH suitability model.

Prinz and Singh, (2000), reported that the socio-economic conditions of a region being considered for any RWH during planning, designing and implementation. The community groups must be involved from early planning of RWH for sustainability of the technologies. The socio economic factors such as farming systems, population density, the financial capabilities of the average farmer and attitude of farmers to the new farming methods in the communities are also important issues. For instance in a study on RWH in Nigeria considered distance between the villages and suitable areas as a crucial factor (Tauer and Humborg, 1992), used the distance between the suitable areas and the villages as an important criterion.

2.5 Use of GIS and RS in selecting RWH sites

Computer technology has advanced greatly in recent decades, including Geographic Information Systems (GIS) packages supported by Remote Sensing (RS). These offer cost-effective and time-saving methods for identifying suitable sites for RWH (Ammar et al., 2016). RS can be used to obtain accurate information with high spatial and temporal resolution. For instance, land-cover information and curve numbers (CNs), which are needed for runoff estimation, can easily be extracted in GIS environments. GISs are very essential tools, particularly in areas where very little information is available, which is often the case in developing countries (Mahmoud and Alazba, 2014). GIS is a useful instrument for collecting, storing, analysing and retrieving spatial and non-spatial land data (Mati and Bock, 2006).

Several thematic layers can be generated by applying spatial analysis with GIS software. These layers can then be overlaid for identifying suitable sites for RWH. The use of RS and GIS in decision making and planning about the type of RWH technology to be implemented in a particular spatial watershed is extremely important to avoid investing on unproductive technologies. Kahinda et al., (2008) used GIS-based rainwater harvesting model (RSM) that gave satisfactory results by combining the physical, socio-economic and ecological layer in a MCE to generate RWH suitability maps in South Africa. Mahmoud and Alazba (2014) also used a GIS-based decision support system (DSS) that used RS data, field survey, and GIS to delineate potential RWH areas in arid regions. Ketsela (2009) in his study applied a GIS approach by integrating different factors such as, soil depth, soil texture, climate, land cover, slope and groundwater but did not include socioeconomic factors. Hence, socioeconomic factors (e.g. market access, infrastructure, population density) were recommended to be important for a complete assessment of the RWH land suitability.

Napoli et al., (2013) indicated the importance of carrying out the field surveys when identifying suitable sites that may have been missed by the GIS data. Again Mahmoud and Alazba (2014), in their study of RWH suitability model, which used the biophysical factors only, recommended that more work be carried out to improve the model and to include other ancillary data like environmental/ecological and socioeconomic factors to increase the models usefulness in coming up with suitability maps. The final suitability maps are very important as they give the farmers opportunity to state their needs (Ammar et al., 2016). Thus RS and GIS have been proven to be time saving, flexible and cost-effective tool for suitability of RWH technologies especially for large areas. The suitability maps are easy to understand and provide information to quickly identify areas that are more suitable than the other for implementation of RWH technologies.

Weighted overlay also known as Multi Criteria Evaluation (MCE) is the most commonly used GIS method of analysis that integrates data for several criteria. Malczewski (2004) in his study indicated that the use of Multi- Criteria decision making methods (MCDM) with GIS has considerably advanced the conventional map overly approaches to the land-use suitability analysis. Analytic hierarchy process (AHP) is one of the GIS- based MCDM that combines and processes spatial data (Input) into a resultant decision (Output). Key steps in AHP as indicated by Malczewski (2004) include; (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation and analysis, and (ii) the MCDM capabilities for merging geographical data and decision maker's preferences into uni-dimensional values of alternative decisions. Thus AHP is a very important decision making tool that can be used to assist in obtaining an appropriate decision over suitability assessment of RWH.

The process illustrated by Saaty, (2008) involves the identification of factors that are selected in a hierarchy manner starting from the overall goal to criteria, sub- criteria and alternatives. Saaty (2008) outlined four major steps in undertaking AHP organized in order to make a decision over alternatives. These are; (i) Definition of the problem to be considered, identify the goal which is the criteria that the other elements usually the alternatives will depend on which should be at the top of the decision making tree, (ii) develop a pair wise comparison matrix, (iii) Applying criteria to alternatives and rank alternatives, and (iv) Conduct sensitivity analysis by weighting. The weighing assigned to the thematic layer vary from one site to the other hence may not be replicated (Munyao, 2010).

Incorporating AHP in a GIS platform can be used to make decisions based on expert and indigenous knowledge and choose between alternatives. Indigenous knowledge has been used for years in developing RWH technologies which in turn have proved to be sustainable. The reason for this is that they are compatible with local lifestyles, local institutional patterns and local social systems (Mbilinyi et al., 2005). Researchers, planners, agricultural extension workers and development practitioners have realized that it is important to build on what local people know in order to develop sustainable RWH strategies (Mbilinyi et al., 2005).

2.6 Modeling rainwater harvesting

Rain water harvesting can best be visualised through hydrological models that are able to show directions of flow, runoff and run on area and identify locations for harvesting innovation. Quantification of harvested rainwater has been done using a Rainfall Runoff Modelling in order to determine the effects of different RWH technologies on soil moisture (Makurira et al., 2009). Researchers have used various models in modelling RWH with some focusing on specifically RWH while others used general hydrological models and others have even used a combination of RWH and hydrological models.

All runoff models are simplifications of the mathematical description of the actual process of runoff in nature (Jones, 2013). Some models are simplified than others but all have one thing in common thus the mathematical description that enables various factors that are being considered to make quantitative predictions (McCartney et al, 2004). Factors involved in runoff such as soil characteristics, differ extensively over small distances. It is difficult to account for each variation in space in a mathematical model (Jones et al., 2013). For this reason; average values taken for sets of variables are comparable.

Increasing the sophistication of a model by underlining more on the physical basis of the environmental processes does not essentially improve the performance of the model (Hughes et al, 1994). Making a particular model more physically based indicates that the input factors are also increased and are more complicated to attain (Stephenson and Paling, 1992). Several factors are obtained through measurements and are not often free of error. This error introduced into the model when the factors are processed contributes to the overall inaccuracy of the model (Todini, 1988). On the contrary the use of simpler empirical models also has its own challenges. Simple models usually tend to take a broader view of the environmental processes in a catchment resulting in a loss of both spatial and temporal information.

However there are several types of runoff models available for simulating runoff in the catchment. The main challenge is taking into account changes in land use/ cover to make the predictions of the model to be very useful. The models can facilitate to identification of areas that contribute to higher rates of runoff within the catchment. This information can be used to understand the changes in the catchment management practices in an effort to harvest more water in the catchment (Ncube, 2006).

2.6.1 Types of hydrological models

Models can be classified into deterministic and stochastic models basing on the mathematics of model. Deterministic models are considered by the same output when a single set of inputs is given, whilst stochastic models a single set of inputs can produce very different outputs due to random processes of the model. Further subdivision of rainfall-runoff models is done considering the spatial representation into lumped and distributed models (Zhanga et al, 2005).

Lumped modelling considers a catchment to be one unit and a single average value representing the whole catchment is used for the variables in the model. This result in single values being predicted (Beven, 2001). In this approach model variables are simulated by grid elements or cells, which can either be uniform or non-uniform (Zhanga et al, 2005). Values of factors that vary spatially are locally averaged within each grid element, instead of only one value over the entire catchment (Zhang et al, 2005).

According to Kenan,(2001), the main characteristics of lumped models include the following; (i) the system dynamics are represented in an integrated form. It relates to a catchment or sub-catchment as a whole by considering its overall behaviour (Todini, 1988), (ii) assumes catchment homogeneity, i.e. spatial variation of hydrological response characteristics such as climate, soils, slopes and land cover changes within a catchment are ignored (Schulze et al, 1992), and (iii)values are regarded as being representative of the whole catchment, which indicates the assumption of linearity of hydrological responses, thus violating one of the basic principles in hydrology of non-linearity (Schulze, 1998).

The characteristics of distributed models include the following (Angus, 1987); (i) the variable and heterogeneous character of the catchment is conserved by dividing the catchment into a number of relatively similar hydrological response units, (ii) the integrated response of all the individual units contributes to the total catchment response, (iii) each unit is assigned variables and factors describing the climate, topography, soils and vegetation characteristics unique to that unit, (iii) it has the potential for more accurate simulation of hydrological responses than a lumped model, because it avoids linear relationships.

According to Schulze, (1998) the main short falls of distributed models are: (i) they can be more complex than lumped models; however, more complex models do not necessarily perform better than simple models, (ii) division of a catchment into similar units is theoretically difficult because the dominant physical processes and their interactions for differently sized units vary and information cannot essentially be scaled up from a point to an area or from small homogeneous area to a larger homogeneous area, (iii) they require huge amounts of input data, which may not be readily available in the required spatial resolution, (iv) acquisition of the data is not only expensive but may require that the system that should be modelled be destroyed to get a complete spatial resolution and (v) in order to overcome the inadequate spatial resolution of some characteristics (e.g. soil and vegetation characteristics) the model parameters are assumed for larger areas than that covered by the data. This effectively means that for practical purposes distributed models are lumped although over smaller areas.

The models can further be grouped based on the phenomena of runoff within the catchment into; (i) Empirical models (black-box models) which do not help in physical understanding. They can be estimated only by using concurrent measurements of input and output, (ii) Theoretical models also known as white-box models which apparently are the consequences of the most important laws governing the phenomena and (iii) Conceptual models (grey-box models) are between empirical and theoretical models.

Black box models involve the simulation of empirical relations through the use of regression equations that have been developed over a long-term field observation. They use regression coefficients derived from observations and not from physical or theoretical background of natural process (Zhanga et al, 2005). A good example of black box is the U.S Soil Conservation Curve Number Method for estimating the amount of rainwater available to generate runoff (Soil Conservation Service, 1964).

Process models attempt to simulate the hydrological processes in a catchment by computing all processes using partial differential equations governing several physical processes and equations of continuity for surface and soil water flows. Deterministic and physically based models fall into this category (Zhanga et al., 2005). Process models require the use of many parameters hence is challenged by data limitations and difficulty in relating processes with theoretical equations (for instant Darcy's law and the Richards' equations), may not justify their use in runoff estimation. Even the most physically based models cannot reflect the true complexity and heterogeneity of the processes occurring in the field (Hornberger et al, 1985).

Process based models are usually very costly. Beven (2001) also argued that; (i) it is very difficult to estimate effective model parameter values for those equations at the element scale using current measurement techniques; it would not be possible to measure all the parameter values required without destroying the focus of interest. As such, a model may be soundly based on 'real' hydrology, but its data requirements so rigorous that they cannot be met with a reasonable degree of accuracy (Hughes, 1995) and (ii) while they are over parameterised for the purposes of estimating discharges, they have not been properly tested in terms of simulating the internal state variable that is their principal advantage over catchment scale models.

Conceptual models average inputs/outputs over an area and integrate several hydrological processes and their variability such that their "effective" factors rather than physically meaningful are used. The advantages of the conceptual models include the following (Schulze, 1998); (i) they can be developed without much real understanding of the modelled phenomena and they use relatively simple input, they lump spatial/temporal heterogeneity and short-circuit (or simplify) complex causal chains (Klemes, 1982), (ii) they are catchment oriented, as against single component oriented (Augstburger et al., 2001), (iii) they have limited data input demand, (iv) they use collected data with high cost effectiveness; are easy to use and are computationally fast. They are therefore highly applicable models that are often very useful engineering tools which give reasonable answers to practical problems and (v) they can interface easily with GIS and databases.

The disadvantages of the conceptual models stem mainly from their non physically based development in that processes are represented in a simplified/artificial way (Schulze, 1998), which include; (i) the physical interpretation and derivation of input parameters is seldom possible or vague (Bergstrom, 1991), (ii) Cause assumptions are sometimes false and the models may be too general in applicability or, alternatively, too site specific, (iii) limited empirical association of crudely expressed characteristics is likely to produce output of varying quality and of limited value in prediction. This implies that there is no justification in applying the models beyond the bounds for which the input parameters were derived, and extrapolation involves the risk of simulating large errors. Furthermore, attempts to improve the models, without additional restructuring, may lead to over-fitting of parameters (Klemes, 1982).

2.6.2 Hydrological models previously used for modelling RWH

2.6.2.1 ACRU

Agricultural Catchment Research Unit (ACRU) and Soil and Water Assessment Tool (SWAT). The ACRU agro-hydrological modelling system is structured on daily multi-layer soil water budgeting. Rainfall and/or irrigation not abstracted as interception by the vegetation canopy or stored on the surface is partitioned into stream flow and effective rainfall that enters the topsoil horizon (Schulze et al, 1992). Saturated drainage from the topsoil to subsoil horizon takes place when soil water in the topsoil exceeds field capacity. Again, when soil water in the subsoil horizon exceed field capacity, drainage to the intermediate and groundwater stores occur, from which base flow is generated. Unsaturated soil water redistribution between the two horizons occurs according to their relative soil water contents. ACRU has been developed as a multilevel model with several options available in many of its routines depending on the level of sophistication of available input data or the type of output required. An important opportunity in areas of complex land cover and soils is that ACRU can operate either at a point or as a lumped or as a semi-distributed cell type model as shown in figure 4 as illustrated by Tarboton and Schulze (1991).

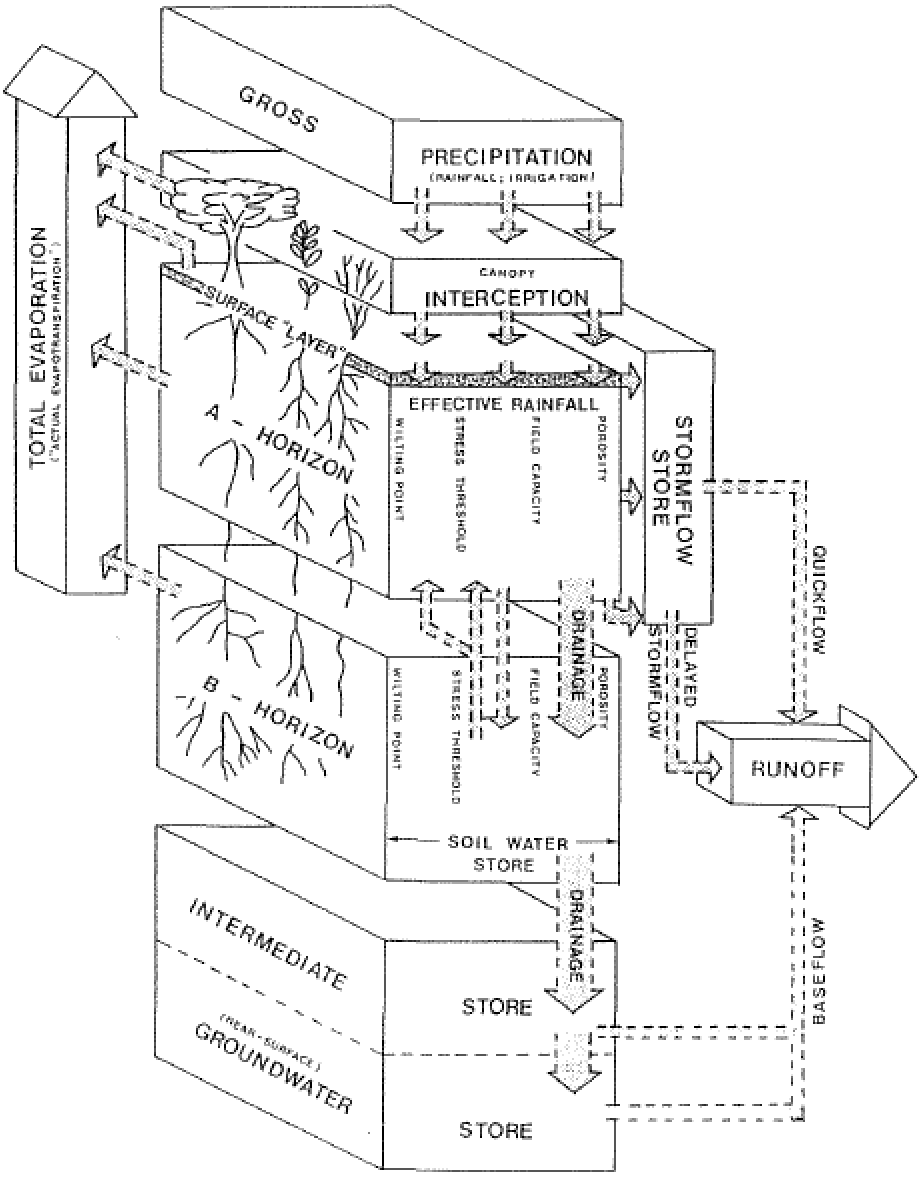


Figure 4: Representation of the water budget in the ACRU model

Input into the model includes information on catchment location, daily rainfall, evaporation, details on soils, vegetation/land cover, irrigation (including scheduling) and reservoir dimensions. Whilst outputs from the model include simulation of the hydrological soil water budget, runoff, reservoir status, sediment yield, crop yield and irrigation demand and supply (Tarboton and Schulze, 1991).

Ndidzano, (2012) indicated that ACRU has been mostly used in humid and temperate parts of South Africa for assessing the impacts of modifying land use on runoff generation. He further noted that ACRU has been less widely implemented in most parts of Africa and there appears to be very little documentation of the model. Therefore ACRU could not be adopted for this study.

2.6.2.2 SWAT

The Soil and Water Assessment Tool (SWAT) is a physically based, and continuous time hydrologic model, which is used on a large-scale agricultural watersheds for selecting suitable RWH areas (Arnold and Allen, 1992). The model has the ability to simulate surface and sub-surface flows, sediment transport and crop growth and yield (Neitsch et al, 2005). Additionally, it is capable of performing simulations in situations where data is scarce, as is the case of most developing countries. Several studies have shown that SWAT can be successfully used to model surface runoff and sediment yield in RWH (Gosain et al, 2006; Mishra et al, 2007; Tripathi et al, 2005).

Ndidzano, (2012), in his study used SWAT model to simulate runoff generated from the rainfall event based on the land surface characteristics and land management practices in a GIS platform. The study investigated the effect of RWH on runoff; therefore RWH was integrated into SWAT model at the point of rainfall incidence on the ground. The model was able to simulate the resultant runoff from the implemented RWH technologies. The model used various parameters such as Digital elevation models, soils, land use, meteorological and observed stream flow.

Lebel, (2011) indicated that there are two methods for estimating runoff volume which are available in SWAT. The first one is the Soil Conservation Service (SCS) curve number (CN) methods and the second is the Green-Ampt infiltration method. The latter is only used for sub-daily time increments to determine the amount of infiltration from a rain storm, but mostly the CN method is preferred in situations where extensive data is scarce. The SCS CN is essentially a coefficient that reduces the total precipitation to runoff potential, after “losses” – Evaporation, Absorption, Transpiration, and Surface Storage (Schiariti, 2012). Therefore the higher the curve number value the higher the runoff potential will be. Senay and Verdin

(2004) indicated that in order to undertake a hydrological model using remote sensing data in GIS platform the SCS curve runoff model is mostly appropriate because of its reliance on land cover parameters which can be extracted from remote sensing. The soil conservation service (SCS) model depends on the runoff Curve Number (CN) which is estimated through the effect of soil and land cover on the rainfall runoff processes. The range of the CN is between 1 (100 % rainfall infiltration) and 100, lower values of the CN indicates lower runoff, while higher values of CN refer to higher values of runoff.

2.6.3 Model selection for RWH

According to Schulze, (1998) the appropriate models for runoff harvesting must have the following characteristics; (i) simple and relevant for use, (ii) widely accepted for use, (iii) model results that can be comparable to observed results and (iv) easily calibrated to the specific parameters of the area.

The SCS CN method which is under the SWAT model used for estimating runoff was selected to simulate runoff in the catchment area. Nachabe (2006) indicated that SCS CN is a simple, widely used and efficient method for determining the approximate amount of runoff from a rainfall even in a particular area. Gupta et al (1997) reported that SCS method is the most widely used approach in arid and semi arid regions for estimating surface runoff from small catchments after a rainfall event. Although the method is designed for a single storm event, it can be scaled to find average annual runoff values which make the scale to be more appropriate with the scale of RWH. Again the statistical requirements for this method are very low thus; rainfall amount and curve number (Gupta et al., 1997).

The hydrologic soil group, land use, treatment and hydrologic condition determine the curve number of the area. With this approach, the suitable areas for RWH technologies were located in areas with the highest capacity for runoff generation and nearby to the existing drainage lines (Ammar et al, 2016). Several researchers have also applied the SCS with the CN methods in identifying RWH suitable areas, by focussing on how much runoff could be generated from a runoff area (Benimana et al, 2014; De Winnaar et al, 2007; Gupta et al., 1997; Jedhe, 2014; Jha et al., 2014; Kadam et al, 2012; Munyao, 2010; Nagarajan et al, 2015). The SCS-CN method can be incorporated in a hydrological model and integrated with advanced tools such as RS and GIS to improve the accuracy and precision of runoff prediction, allowing faster and less costly identification of potential RWH locations (Ammar et al., 2016).

CHAPTER 3

3 Materials and Methods

3.1 Introduction

This chapter has two main sections; the first section gives a description of the study area including its physical location and hydrological characteristics, agricultural practices and water resources utilization and management. The second part gives details of the methods used in the study.

3.1.1 Description of the study area

Malawi is divided into twenty eight districts within three regions including Kasungu District which is located in the Central region. It is bordered by Zambia in the West and Mchinji, Dowa and Lilongwe district in the South, Mzimba in the North, Nkhotakota and Ntchisi district in the East. It is the only district in Malawi sharing more district boundaries with other areas. The district head quarters is approximately 127 km from Lilongwe, the Capital City of Malawi (NSO Atlas, 2002). Kasungu district has a total area of 7,878 square kilometres making up 8.4 % of the total land area of Malawi, which is 94,276 square kilometres (Kasungu SEP, 2013) (figure 5).

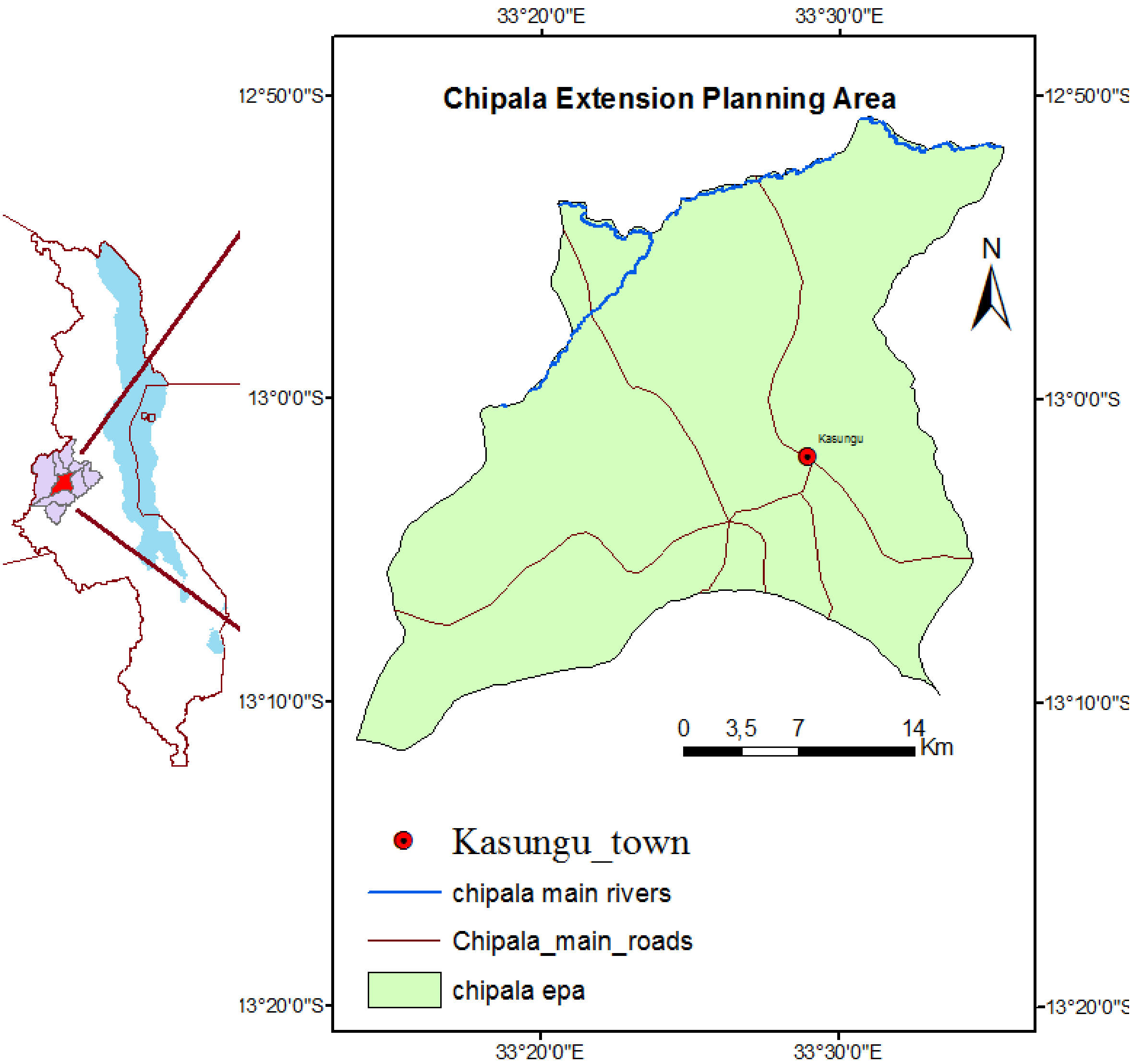


Figure 5: Location of Chipala EPA

3.1.2 Climatic characteristics

Kasungu experiences a cool to warm tropical climate. The minimum and maximum temperature in the district ranges from 12 ºC to 30 ºC with rainfall averaging 1000 mm per year. This amount of rainfall is enough to support the production of most crops grown in the area such as maize, tobacco and soy beans but the main problem is its variations in the onset and distribution pattern which results in crop failure. The district was targeted for this research because of its uneven rainfall distribution patterns which needs the implementation of RWH technologies so as to overcome effects of prolonged dry spells and ensure food security. During 2001/2002 season Kasungu district was the worst affected by dry spells in Malawi (Kasungu SEP, 2013).

The main problem is variations in the onset and distribution pattern for example 2004-2005 and 2005-2006 rainfall seasons have experienced erratic rains affecting most areas with dry spells. During this period only the south west and areas bordering Kasungu National Park had received rainfall first which had been steady to the end of the season. The starting season for rainfall is around 05th December and around 30th March. Rainfall is high during the month of January and February in the district (Kasungu SEP, 2009).

3.1.3 Soil characteristics

The district is dominated by ferralic and chronic cumbisols that are well drained, course to medium texture, reddish in colour. Sandy clay loam and pure sandy soils are very dominant in Kasungu North and North West areas while reddish soils are dominant in Kasungu East areas. The soil ph ranges from 5.5 - 6.5 (Kasungu SEP, 2009).

3.1.4 Socio economic activities

Kasungu is under the Kasungu Agricultural Development Division (ADD) which is one of the eight ADDs in the country and is further divided into eight Extension Planning Areas (EPAs) namely; Chulu, Kaluluma, Chipala, Chamama, Lisasadzi, Mkanakhoti, Mtunthama and Santhe (Kasungu SEP, 2013). Kasungu SEP, (2013) indicates that Kasungu district is mainly dominated by agriculture as the major economic activity and source of livelihood. Agriculture is the major sector in the District, which provides work for most of the people in Kasungu. Over 80 % of the people work in agriculture. Kasungu District has a total of 236,690 farm families, with an average land holding size of about 1.2 ha. The major crops grown are Maize, Tobacco, Groundnuts, Cassava and Sweet Potato. In the season 2014/15 maize covered almost 41.1 % of the total farmland and burley tobacco covered 10.2 %. Other crops grown included beans, millet, paprika, sunflower, sorghum and rice. For this research Chipala EPA was targeted because farmers have already started implementing RWH technologies in the area

3.2 Study Approach

The conceptual framework derived for the study was drawn from previous research and observations of rainfall-runoff processes summarised by Rockstrom, (2000) as shown in figure 6. In Sub-Saharan Africa region rainfed agriculture is characterised by huge amount of non-productive water flows in the water balance as part of direct evaporation from the soils, water bodies and intercepted water by the canopies. A productive part of water flow is transpiration with water escaping to the atmosphere. The partitioning of rainfall into various water flow components in rainfed agriculture shows that soil evaporation accounts for 30 -50 % of rainfall, surface runoff is often reported to account for 10 - 25 % of rainfall whilst 10 - 30 % of rainfall is drained as infiltration. This leaves productive water flow as transpiration accounting for 15 - 30 % of rainfall. The main portion of rainfall between 70-85 % is lost from the land surface through evaporation, interception, deep percolation and surface runoff. This shows that there is a high risk of soil water shortage in crop production, despite high annual rainfall figures. In order to increase the water available for productive use there is need for measures that will reduce the amount of water loses in terms of runoff and evaporation. RWH is one such technology that is widely used in order to reduce surface runoff, reduce evaporation and increase infiltration.

The study started by identifying the types of RWH technologies that are implemented in the district. This included seeking to understand reasons for adoption of particular technologies through focus group discussions and questionnaire surveys (Section 3.3.1- 3.3.4). The study also sort to verify effectiveness of the most common technologies through field soil moisture observations on fields with the RWH technologies (Section 3.3.5). Lastly the study modelled land suitable for RWH by considering runoff that leaves the fields with RWH technology. The more runoff that leaves a field the less the water that is retained in the field and hence the less effective the RWH technology becomes for that field. Consideration was made of other factors that make the retained water useful for improving crop yield (Section 3.5-3.6).

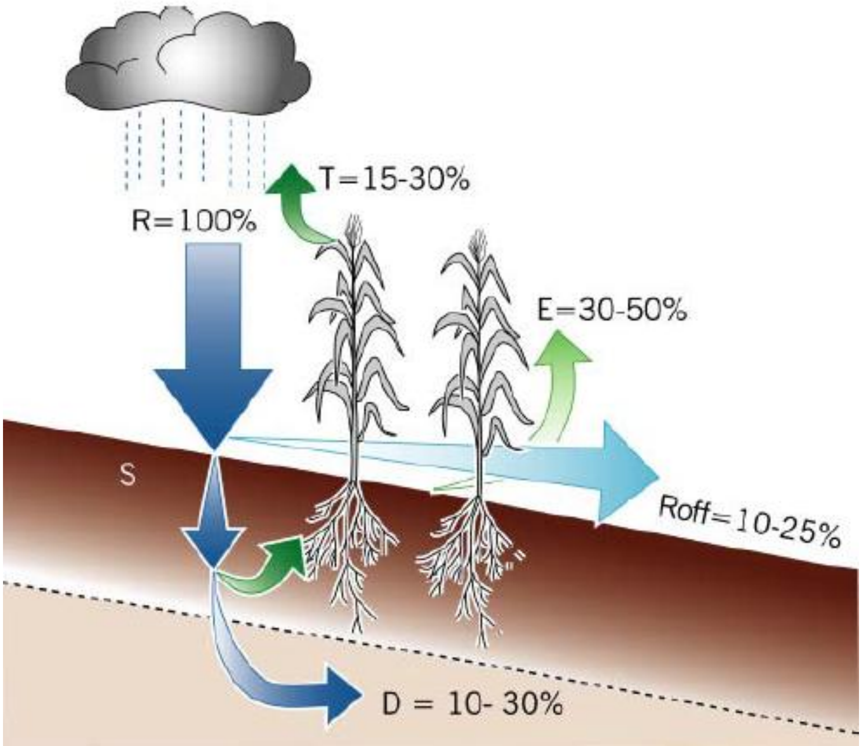


Figure 6: On-farm water balance for rainfed agriculture (Rockstrom, 2000)

3.3 Data collection

This section presents methods that were used to collect data for the study. Data was collected through desk top sources, key informant interviews, focus group discussions, field questionnaires and soil moisture observations. The collected data was used in the identification and performance evaluation of existing RWH in the area, performance assessment of widely adopted RWH technologies and establishment of factors for locating suitable land for RWH technologies.

3.3.1 Desktop sources

Desktop sources provided secondary data from relevant sources such as reports, socio-economic survey documents of the area, maps, and reports from government departments. Most of the maps (study area boundary map, soil classes, land use, and slope) used in this study were sourced as shape files from the Land Resources Conservation Department (LRCD) of the Ministry of Agriculture, Irrigation and Water Development of Malawi.

Climatic data including rainfall data for the past ten years from 2005 to 2015 was sourced from the meteorological gauging stations in the district as shown in figure 7. Rainfall remote sensing satellite data called Climate Hazards group Infrared Precipitation with Station (CHIRPS) which is a new land-only climatic database of precipitation, made available since early 2014 was downloaded online for the period of 34 years from 1981-2015. It contains three different kinds of information: world climatology, satellite estimates and in field observations (Michaelides, 2015). Socio economic data was sourced from the Malawi National Statistic Office while environmental data was sourced from the District Environmental Office and Forestry Office.

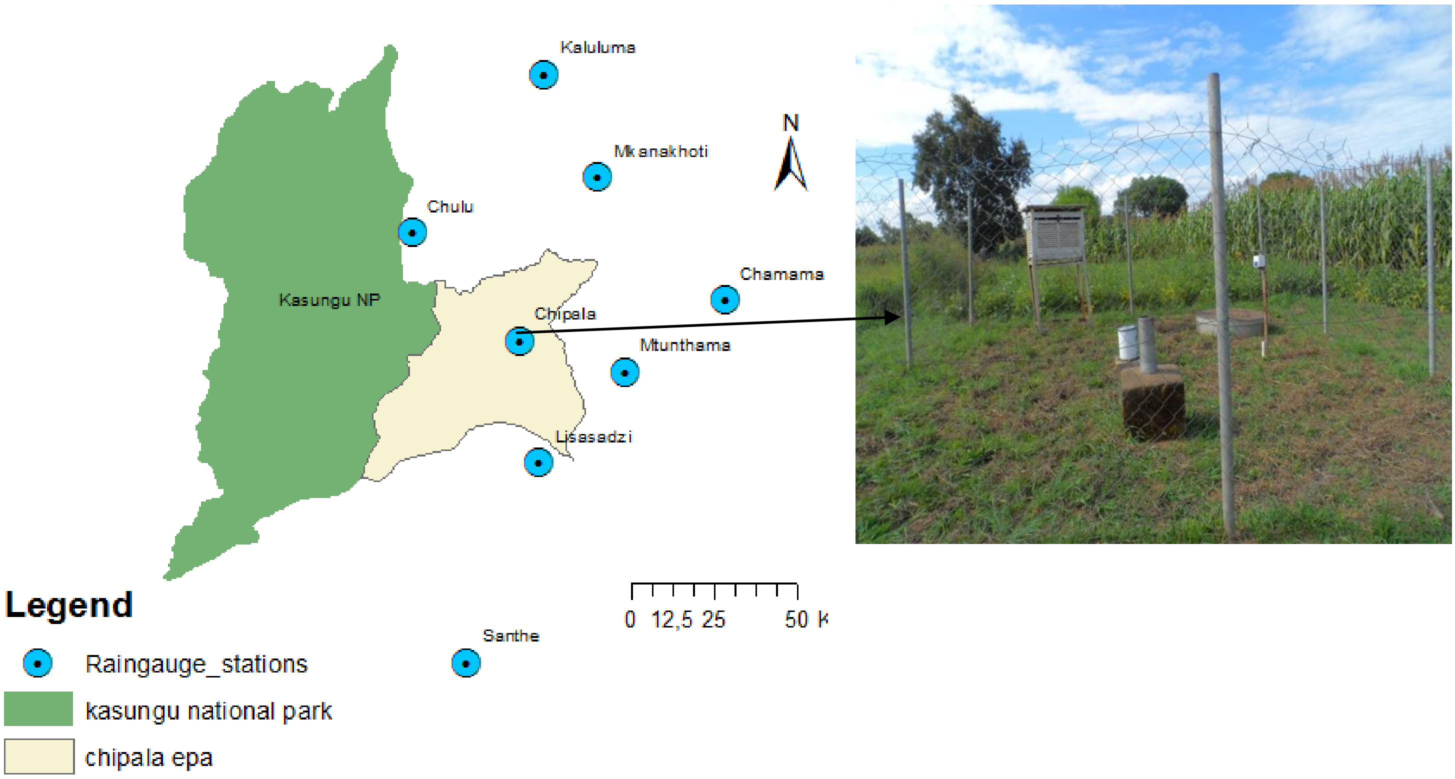


Figure 7: Location of rain gauging stations in Kasungu district

3.3.2 Key informant interviews

A stakeholder meeting was conducted to sensitise the stakeholders about the study as well as to get their views and opinions on RWH technologies implemented in the study area. Open ended questionnaires for key informants were used which focussed on extension officers (crop production and agricultural extension departments), and CARE Project officers which is a Non Governmental Organizations (NGO) working in the area. Key informant checklist has been attached in the appendix 7.2.

3.3.3 Focus group discussions

Krueger and Casey (2009), indicated that Focus Group Discussions (FGDs) are group interviews and are important method of investigating complex human behavior. Therefore FGDs were used in this study to collect data. Topics discussed considered the type of RWH technologies implemented in the area, factors considered for locating RWH technologies, farmers' evaluation of RWH technologies performance and challenges encountered in implementation of RWH technologies. One FGD was held for each of the four randomly selected villages. The FGDs composed of village heads, Village Natural Resources Management Committees' Chairpersons and RWH farmers. FGD checklist has been attached in appendix 7.3.

3.3.4 Administering field questionnaires

RWH farmers are relatively few in the area hence it was difficult to identify households of the rainwater harvester from that of the non-harvester, prompting the use of the snowball identification method as indicated in figure 8. Snowball identification is the method of sampling where identification of respondents is done by respondents who then refer researchers to other respondents (Atkinson and Flint, 2001). This method of sampling is cheap, convenient and time saving. Farmer identification targeted those farmers who were currently implementing any type of RWH technology in their fields. First eight farmers were identified with assistance from the extension worker who works in the area. Fellow farmers were able to know those that implemented RWH technologies because they frequently met during field days that were organized by government agricultural extension agents.

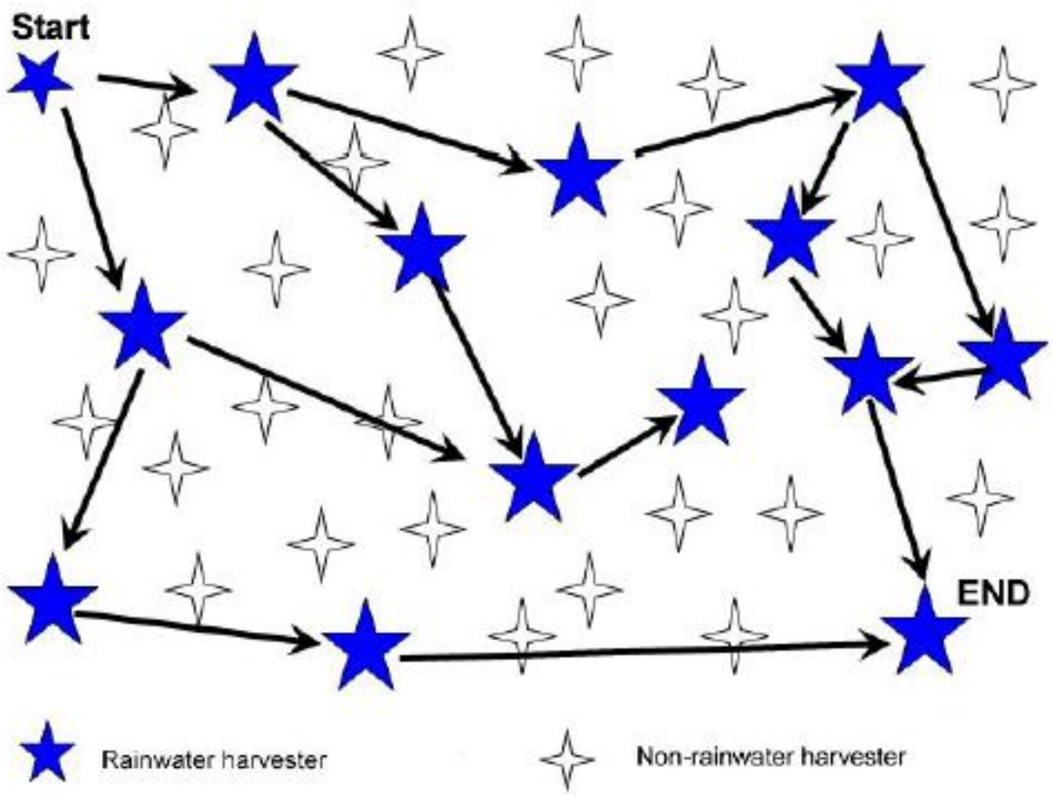


Figure 8: Snowball sampling illustration, Source (Blaxter et al, 2010) .

Pre-testing of the questionnaires was done to five respondents (about 10% of total targeted study respondents). Pre-testing of questionnaires helped to identify challenges that would arise when administering the questionnaire in the field. It also helped to assess the duration of time to be spent per respondent, clarity of questions and facilitated training of assistant enumerators in various elements of the research process.

A household questionnaire was used to collect both qualitative and quantitative data to reduce biasness and enhance validity of results (Yauch and Steudel, 2003), as attached in appendix 7.1. Household questionnaire comprising independent variables, such as household demographic, socio-economic and psycho-social (e.g. perceptions), was used to elicit data from 54 respondents, respondent details attached in appendix 7.4. Only household heads were interviewed per household. This helped in understanding clearly the different field characteristic and accessing information on RWH practices that a particular household implements. Coordinates for fields of all respondents were taken using the GPS.

3.3.5 Soil moisture observation on selected RWH technologies

Fields for moisture observation were selected from three zones, A,B and C of the study area since each zone has relatively uniform slope, soil type and land cover, and all the selected fields were under maize crop. From each zone three fields were selected for observation thus (i) field under contour tied ridging; (ii) field under mulching and (iii) field with no RWH technology acting as control field. This resulted into a total of nine target fields for all the zones, as shown in figure 9.

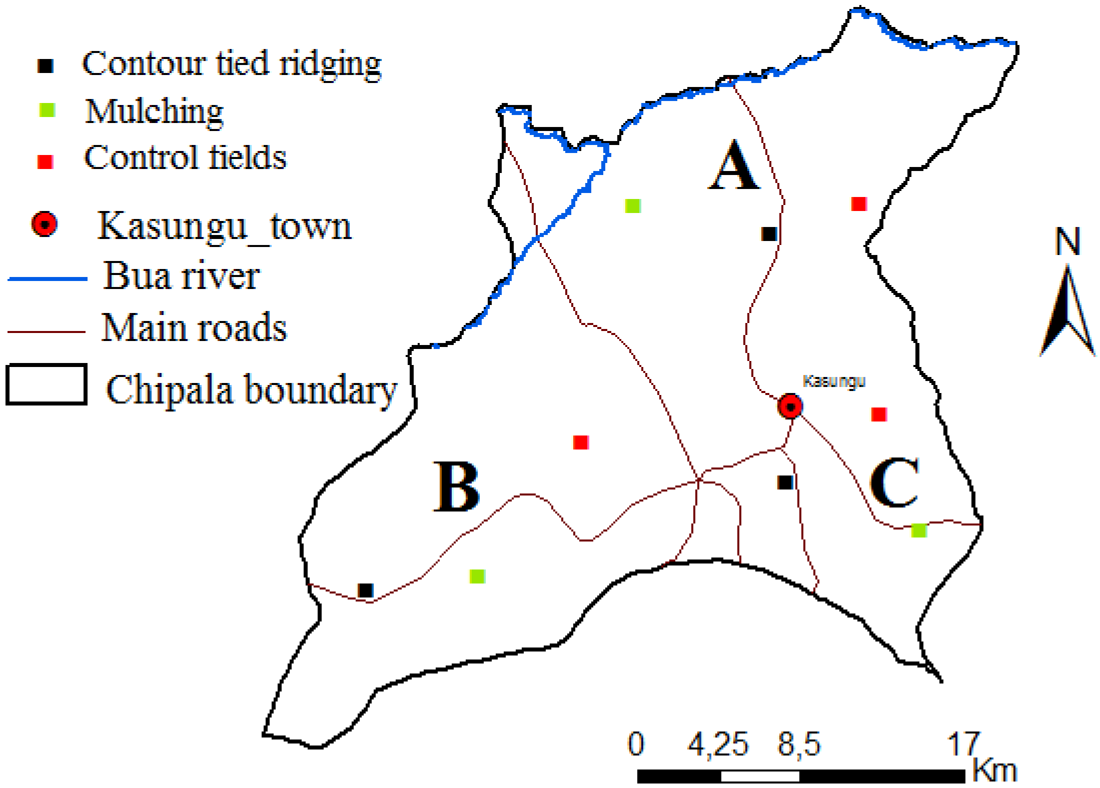


Figure 9: Map of Chipala EPA showing soil sampling fields

Following schematic illustrations in figure 10, soil samples were taken randomly at three different points in each field at the depth of 15cm during four different periods (before rains had started, soon after rains had started and crops were planted, at mid-season and after harvest) in the season, which corresponded to four stages as recommended by Doorenbos and Pruitt, (1977). Soil samples were taken three days after the fields received rainfall exceeding 60mm/day (Mhizha and Ndiritu, 2013) except for the period when the rains had not started.

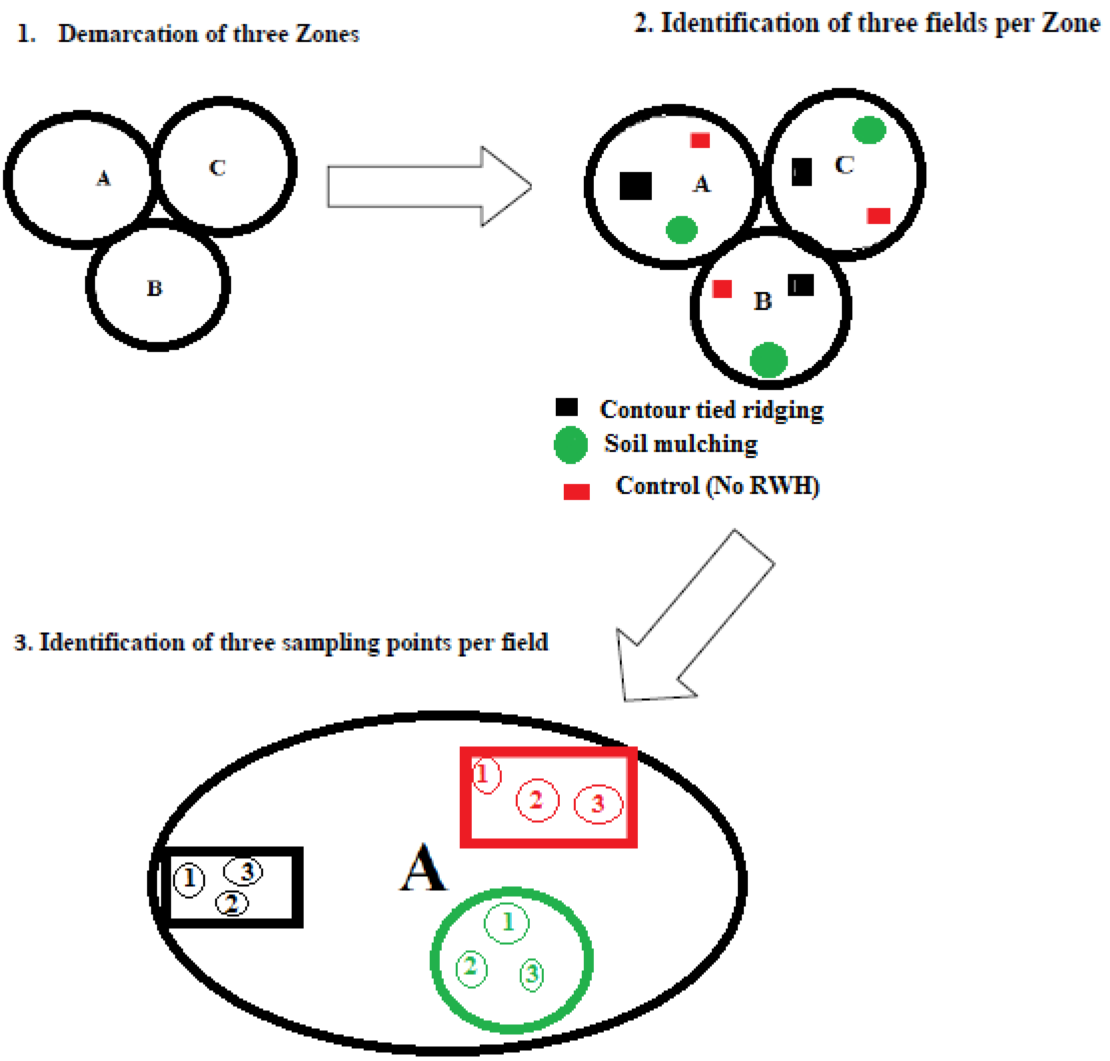


Figure 10: Schematic illustration of soil sampling

Soil moisture was measured based on the method described by Black, (1965). The samples were weighed fresh, oven-dried at 105 ^{o}C for 24 hours and reweighed, and then gravimetric moisture content was calculated by expressing the percentage moisture on dry mass basis. Soil moisture data was entered in tables for comparing moisture content in the RWH technologies and control field (no RWH technology). Materials and tools that were used included the following; Drying oven, a sensitive balance of precision of ±0.001 g, aluminium weigh tins and auger for collecting soil samples, as shown in figure 11.

a: Drying oven b: Sensitive balance (Scale)

Figure 11: Some of the equipment used in soil moisture measurement

The following steps were carried out during moisture measuring;

i. Weigh the aluminium tin (metal cap), and record the weight (tare) in grams.
ii. Place a soil sample of about 10 g in the tin and record this weight as (wet soil + tare).
iii. Place the sample in the oven 105 ^{o}C, and dry for 24 hours.
iv. Weigh the sample, and record this weight as weight of (dry soil + tare).
v. Return the sample to the oven and dry for 30 minutes, and determine the weight of (dry soil +tare).
vi. Repeat step (v) until there is no difference between any two consecutive measurements of the weight of (dry soil+tare).

The moisture content in dry weight basis (θd) in grams was calculated using the formula in equation 3.1 adopted from Black, (1965), and expressed as percentage moisture on dry mass basis.

$$\theta d = \{(Wt\ of\ wet\ soil + tare) - (wt\ of\ dry\ soil + tare)\} / \{(wt\ of\ dry\ soil + tare) - (tare)\}$$

Equation 3.1

Soil moisture data was entered into tables indicating the amount of moisture content for the commonly implemented RWH technologies as elaborated in section 4.2.

3.4 Data Analysis

The Statistical Package for Social Sciences (SPSS) was used to analyse data such as the descriptive and qualitative data. SPSS is the data statistical analysis tool which has the ability to process data. SPSS is used essentially because it stores questionnaire data in a spreadsheet-like table and generates routine descriptive statistical data for querying responses. Most quantitative data is commonly analyzed by SPSS which generates graphical presentations of questionnaire data and explains relationships among responses to various questions. Qualitative data from FGDs and key informant interviews were collated into themes for simplicity and meaningful interpretation of the data. Descriptive analysis such as means, and frequencies in the form of histographs, pie charts and tables were used to summarise the data obtained.

Moisture data was analysed by comparing soil moisture content among the sampled fields which was done by carrying out a one-way Analysis of Variance (ANOVA) of SPSS on mean soil moisture in the fields being compared at 95 % confidence level. The comparisons were first carried out within treatments and then among the treatments.

3.5 Identification of areas suitable for RWH

The determination of potential sites for RWH needs basic understanding of the rainfall characteristics and a detailed assessment of soil properties, topography and land use of a particular area (Rao and Bhaumik, 2003). Therefore the process of locating suitable areas for RWH is a multi-objective and multi-criteria process that is dependent on physical, socio-economic and environmental factors of a specific location. De Winnaar et al., (2007) reported that appropriate RWH technologies which are developed for a particular region cannot merely be replicated in another location.

In order to identify suitable areas for RWH an area measured by pixel size of 30 m by 30 m was analysed for RWH suitability. A field study was conducted that reviewed that RWH in the area is based only on surface runoff collection in the cultivated fields where water is stored in the soil for crop production. To carry out this multi-objective and multi-criteria analysis, the following steps were taken; (i) Selection of factors, (ii) assessment of suitability levels for the factors, (iii) assignment of weights to the factors (iv) collection of spatial data for the factors such as coordinates which supplemented information for generation of map layers, (v) developing a GIS-based model that combines all maps layers through MCE process (weighted overlay) and (vi) Generation of suitability map. A detailed methodology is shown in figure 12 adopted from (Kadam et al., 2012).

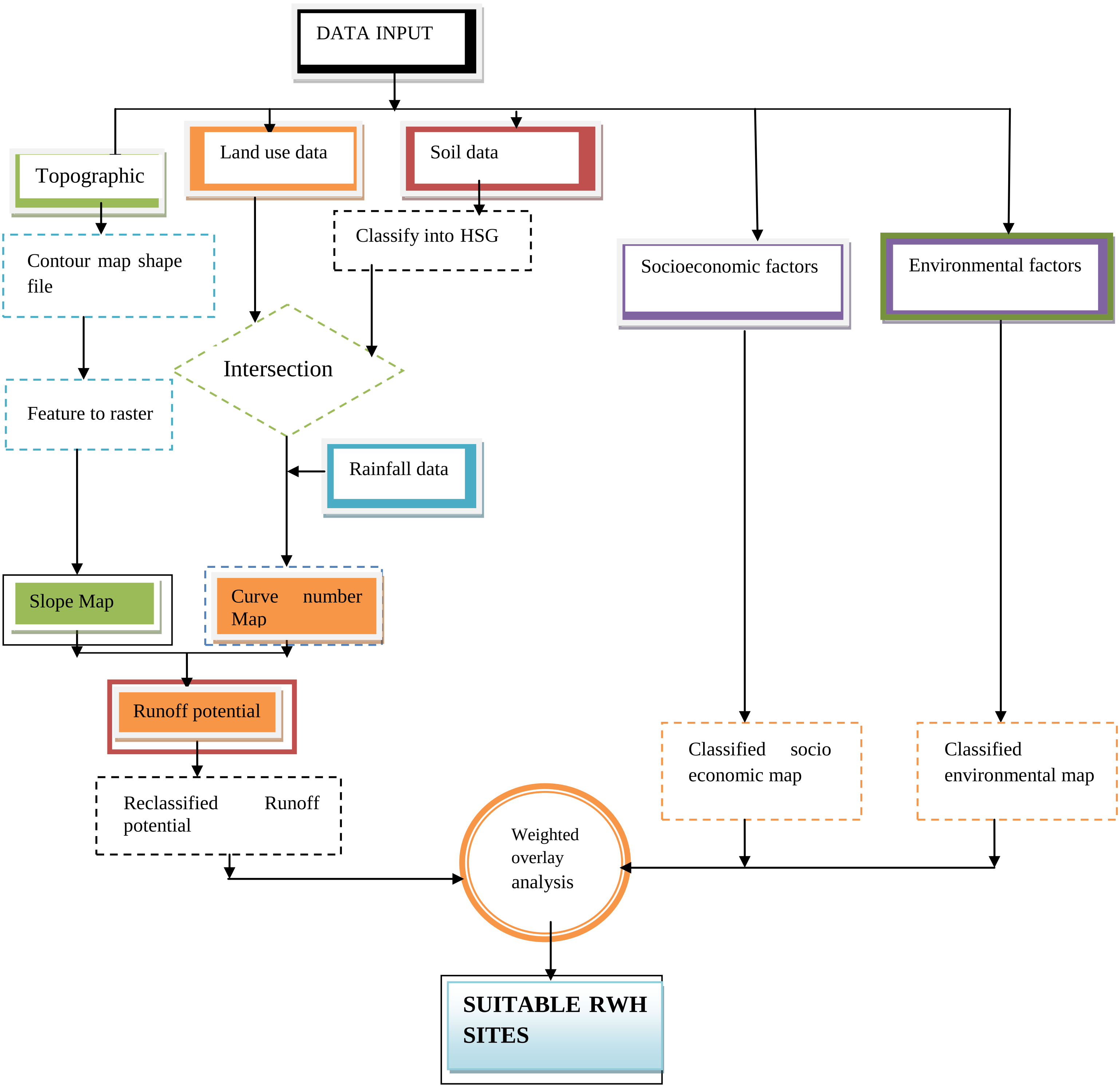


Figure 12: Methodology flow chat

3.5.1 Selection of factors (Criteria)

The selection of factors for identifying suitable sites involved the decision-making process ordered into three major phases adopted from Rao and Durga (2003), namely Intelligent, Design and Choice phases.

Intelligent phase involved analysing the study area environment for conditions which call for attention to reduce crop failure due to moisture stress. This involved asking questions such as which of the factors should be observed, selected, classified and recorded as data items which are pertinent to subsequent spatial decision problems. Key informants involvement in decision making for selecting factors at this point was very important. Once spatial decisions were identified, the data was manipulated and analysed to obtain information about the decision problem in hand. From the other studies in literature (Mbilinyi et al., 2014; Critchley and Siegert, 1991; Oweis et al., 1998; Mwenge Kahinda et al., 2009), different possible constraints were identified for selecting suitable sites for RWH.

Design phase involved analysing decision situation by structuring and formalizing the available data and information about the selected factor. Since the factors are measured on a different scale there was need for values contained in the factor map to be converted into comparable units in MCE. Therefore, the factor maps were re-classed into five comparable units i.e. suitability classes namely; 5 (very high suitability), 4 (high suitability), 3 (medium suitability), 2 (low suitability), and 1 (very low suitability). This ranking system was selected because it has been used in many studies (Ketsela, 2009; Malczewski, 2004; Mbilinyi et al., 2007; Mwenge Kahinda et al., 2008; Munyao, 2010; Oweis et al., 1998; Singh et al, 2008) and it has been found to be a vigorous and a reliable method (Mahmoud and Alazba, 2014).

Choice phase involved evaluating each factor and analysing them in relation to others in terms of specific decision rules of the Analytical Hierarchy Process (AHP) which is explained in detail in section 3.5.5. The rule is used to rank the alternatives under consideration. The ranking was done upon decision maker’s preference since GIS does not present a mechanism for representing factor of choice and priority in the perspective of evaluating contradictory factors and objectives (Carver, 1991). Several thematic maps (factor maps) were selected and organized for integration in GIS database ; (i) physical factors which included rainfall, land use, soil type and slope , (ii) social economic factors such as household income level, and (iii) environmental factors including impacts of implementing RWH.

3.5.2 Selection of factors (Physical factors)

The knowledge of rainfall characteristics (intensity and distribution) for the study area was considered important in identifying suitable areas for RWH. The availability of rainfall data series in space and time and rainfall distribution was used for understanding the rainfall-runoff process and also for determination of available soil moisture. A threshold rainfall events (e.g. of 5 mm/event) is used in many rainfall runoff models as a starting value for runoff to occur (Prinz and Singh, 2000). FAO, (2003b) recommends the use of RWH technologies in areas receiving more than 100 mm to 1000 mm/ year of rains. There is barely any productive water-based activity in areas that receive less than 100 mm/year of rain while there is no incentive to implement RWH technologies in areas with annual rains in excess of 1000 mm/year. Annual rainfall for the study area ranges from 941.84mm to 733.91mm as shown in figure 13.

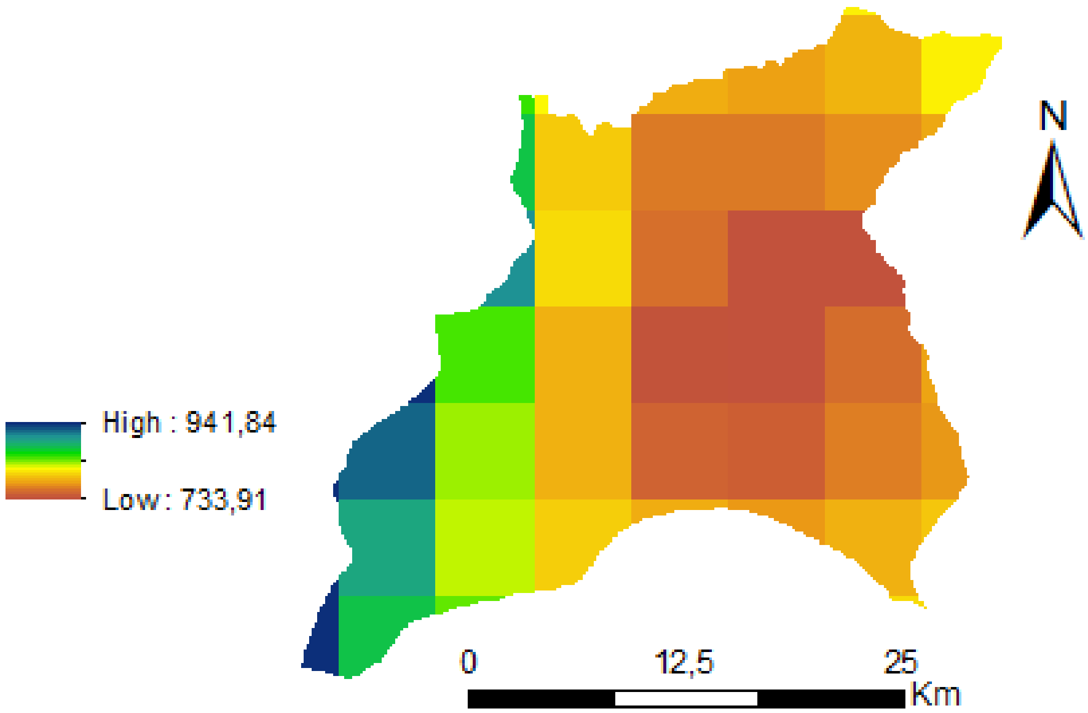


Figure 13: Average annual rainfall

Kasungu district is covered by several land uses such as built up areas, forestry, seasonal wetlands, range land and shrubs and cultivated land. Different land uses results in different amount of runoff generated during rainfall (Jedhe, 2014). For instance vegetation is a vital factor that affects the surface runoff. The study by Tauer and Humborg, (1992) proved that any increase in the vegetation cover of the area results in a subsequent increase in interception, retention and infiltration rates which result in decreased volume of runoff. Built up areas tend to generate more runoff due to paved and other impervious areas (Jha et al., 2014). Thus to identify suitable sites for RWH land cover shown in figure 14, was considered as a factor for this study.

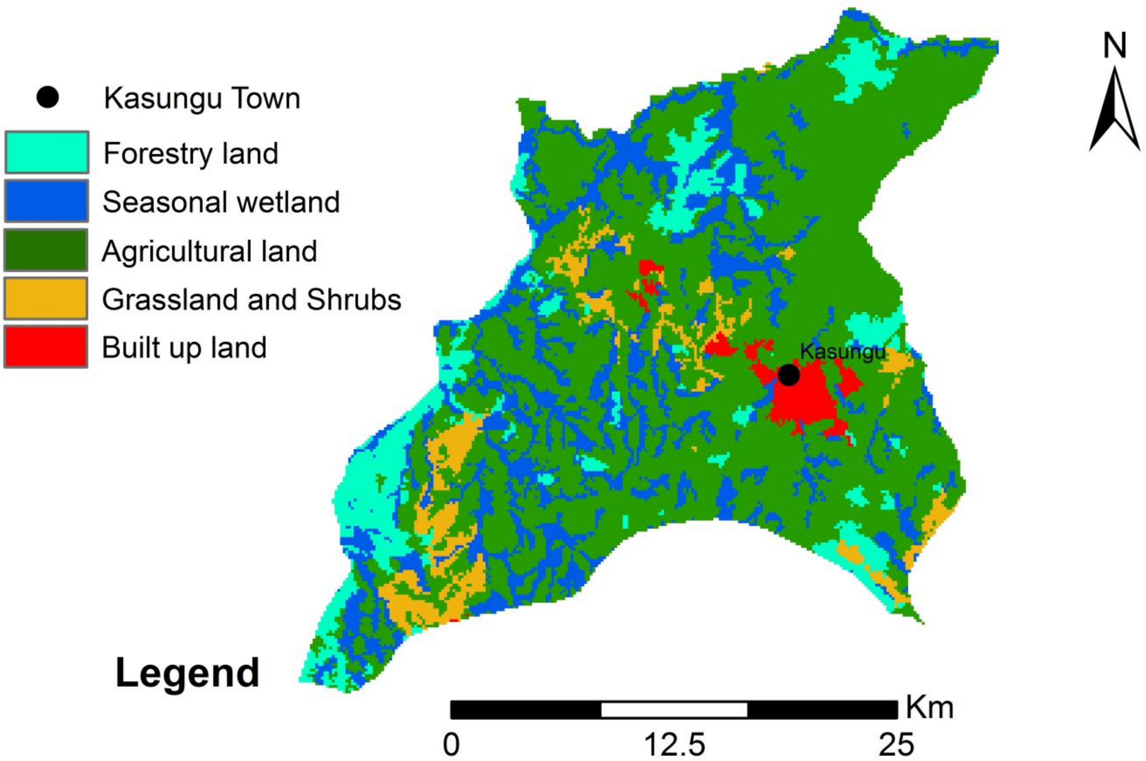


Figure 14: Different land uses in the study area

The suitability of an area in RWH depend strongly on its soils characteristics such as (1) surface structure; which affects the amount of the runoff generated (2) the infiltration rate; eventually determine water movement into the soil and (3) the soil texture and depth; which affects the amount of water stored in the soil (Prinz and Singh, 2000). In the study area soils range from sandy clay loam and pure sandy soils with soil depth ranging from less than 0.2 m to more than 0.75 m (Kasungu SEP, 2009). Soils with high water holding capacity are generally suitable for RWH. Sandy soils are not suitable therefore loamy soils are most suitable for RWH unlike clay soils which are less suitable because of their low infiltration capacity and risk of water logging (Mbilinyi et al., 2014). Soil depth is also important for identifying suitable areas for RWH (especially for crop production) as it ensures enough rooting development and storage of water. Critchley and Siegert, (1991) consider soil depth as one factor and suggest deeper soil depth as suitable for various RWH methods. (Kahinda et al., 2009) also used soil depth as one factor for selecting suitable land for RWH. The soil types in the study area were grouped into four hydrological soil groups. The soil groups were as follows; Group A: sand, loamy sand and sandy loam types of soils, Group B: silt, silt loam and loam soils, Group C: sandy clay loam soils and Group D: clay loam, silty clay loam, sandy clay, silty clay and clay soils as shown in figure 15.

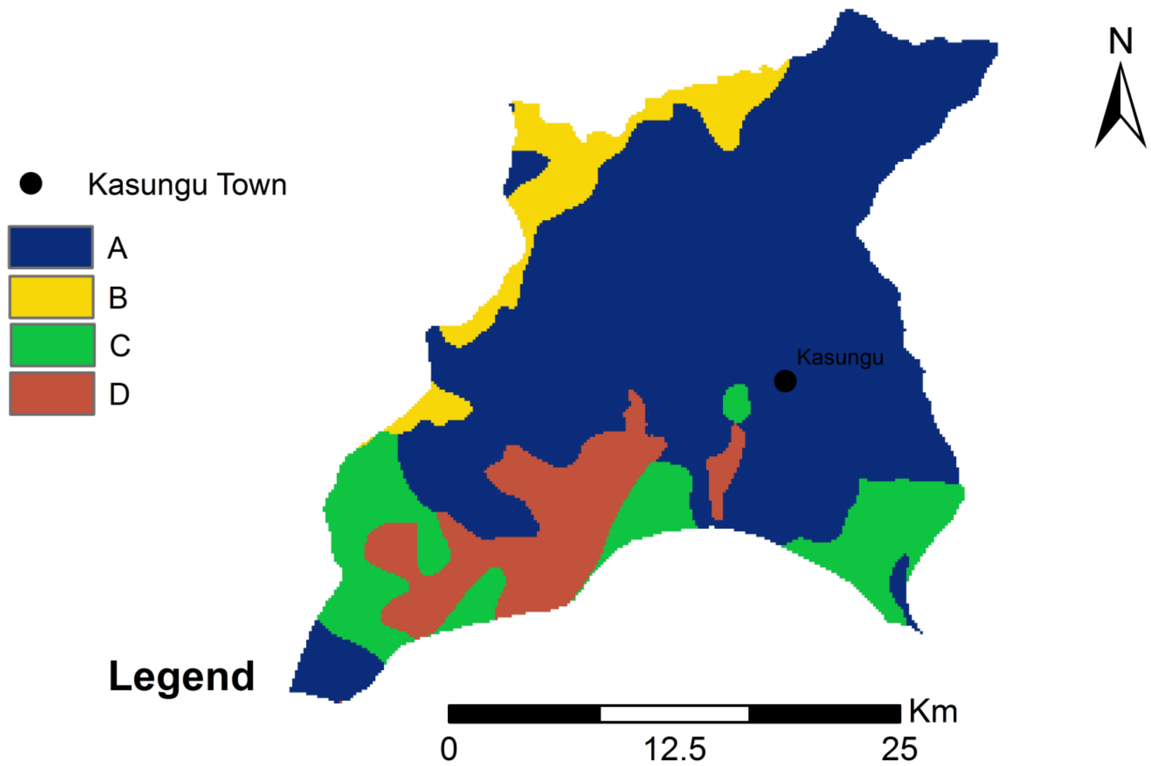


Figure 15: Hydrological Soil Groups (HSGs)

The slope of land is significant in site selection for implementation of all ground based RWH technologies, in particular ponds, pans, weirs and also in-situ RWH (Mati et al., 2006b). Critchley et al., (1991) indicated that RWH is not recommended for areas of slope more than 5 % especially, due to large quantities of earthwork required which is costly. Farm ponds are more appropriate in areas having a flatter slope but a slight slope is required for better harvesting of the runoff (Buraihi and Shariff, 2015). Msigwa et al, (2015) also considered slope as a factor in their study. The slope of an area influences recharge and infiltration hence variation in amount of runoff that is expected from the various terrains. The study area falls on slope of less than 4 % to more than 12 % as shown in figure 22. The selection of the slope boundaries for analytical purposes were based on the five groups for slope categories adopted from Critchley et al., (1991). Areas of slope less than 4 % were amounting to 33.4 % of the total land while slope of 8-12 % only amounted to 13.6 % of total land. Therefore in this study slope shown in figure 16, was considered as a factor as well for identifying suitable areas for RWH. All factors are shown in table 1.

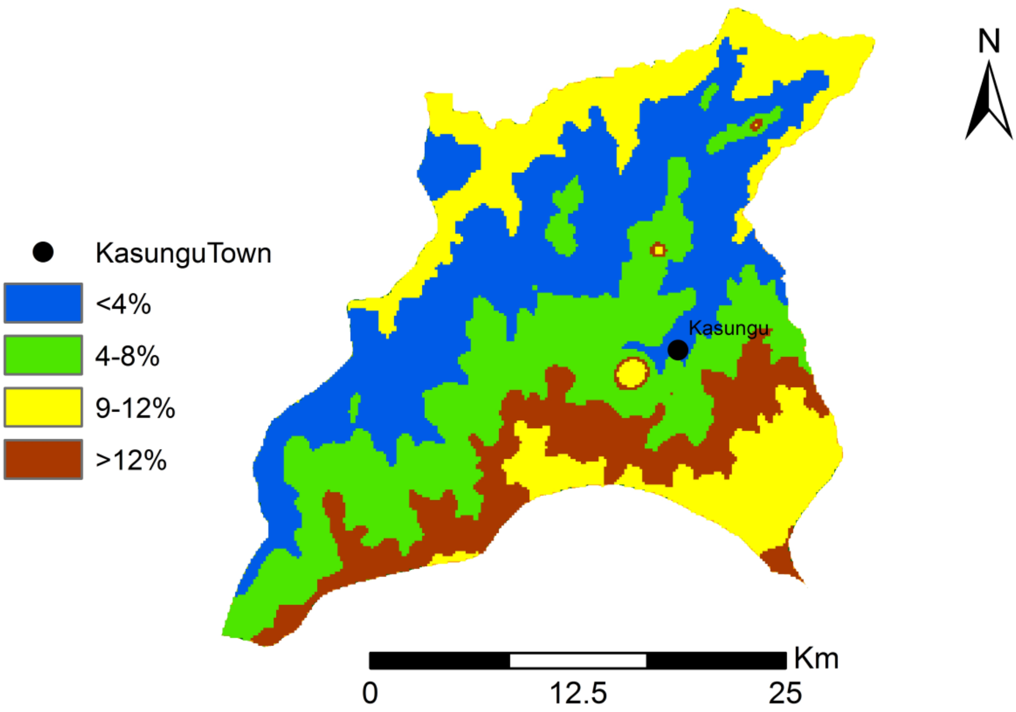


Figure 16: Slope of the study area

Table 1: Physical factors attribute

No	Factor	Attribute selected
1	Rainfall	Annual rainfall of 100 mm – 1000 mm
2	Land use	Agricultural/ cropped land
3	Soil type	High water holding capacity soils, Deep soils
4	Slope	Slopes of less than 5 %

Physical factors were combined and processed in Arc Map 10.2.2 to generate Runoff potential map as described in section 3.6.3. The amount of runoff harvested should be able to satisfy crop water requirement for a crop e.g. maize, as too much or too little runoff is considered not suitable for RWH (Winnaar et al, 2007). Using a similar approach by Winnaar et al., (2007) the amount of runoff generated in the study area was classified into five classes as shown in table 2.

Table 2: Suitability ranking for runoff potential areas

No	Runoff generated (mm)	Suitability class	Suitability score
1	<328	Very low	5
2	328-473	Low	4
3	473-617	Medium	3
4	617-761	High	2
5	>761	Very high	1

3.5.3 Selection of factors (Socio economic factors)

The socio economic conditions of the study area were considered for identifying suitable areas for RWH. In order for the technologies to be successful there is need to involve the communities right from planning stage (Prinz and Singh, 2000). Mwenge-Kahinda et al., (2009) also considered socioeconomic factors in identifying suitable areas for RWH. Hence in this study socio economic factors were considered as important factors for identifying suitable sites for RWH technologies.

The socio-economic factor of the farmers per village level was derived from National Statistical data portal generated by the National Statistical Office (NSO) of Malawi. The data integrates poverty and unemployment levels at village level to estimate household annual income level from crop sales. Any household with an annual income exceeding MK 310,250 (equivalent of USD 456) was considered above the low income group (poverty datum) (NSO, 2000) and is more like to successfully implement RWH as compared to a household whose annual income is below poverty datum (Baiyegunhi, 2015).GPS was used for capturing coordinates for each household. A socio economic map layer of the households in the village was generated using coordinates for each household and an estimated annual income level.

A socio-economic layer was derived by generating a point map of income levels from the location of farmers in villages and then interpolated using the Inverse Distance Weighting Technic of ArcGIS 10.2.2. The map was classified and assigned suitability values based on the RWH suitability criteria used by (Mwenge Kahinda et al., 2009) as shown in table 3 which considered the ranges of income levels from the poverty datum (scored as medium) and other classes being either very low/low or high/very high. A medium suitability score means that the household lives on USD 456 per annuam which is the poverty datum while very low class means very poor and very high class means rich households within the villages.

Table 3: RWH suitability ranking for socio-economic factors

No	Socio economic Class	Income level (USD/year)	Suitability score
1	Very low	Less than 365	1
2	low	365-455	2
3	Medium (Poverty datum)	455-457	3
4	High	457-547	4
5	Very high	More than 547	5

3.5.4 Selection of factors (Environmental factors)

Dry areas are generally fragile and usually limited to adjust to some changes (Oweis et al, 1999). For instance, if the use of natural resources (land and water), is suddenly changed by RWH, the environmental consequences are often far greater than foreseen. Consideration was given to the possible effects of RWH technologies on the environment. Newly introduced RWH may intercept runoff of the catchment especially at the upper stream, thus depriving downstream users of the resources. After all not all runoff should be harvested for agricultural uses; about a third of it is needed to sustain the environment (Anbazhagan et al, 2005). Implementation of RWH in the areas involved setting up integrated plans that shall improve agricultural practices, such use of healthy planting material and soil fertility practices to control soil erosion (Oweis et al., 1999).

When RWH technology has been introduced in an area there is an effect that is imparted on the environment (Mati et al., 2006b). The environmental sensitivity map for Kasungu district which indicates how sensitive an area is likely to be affected by any environmental activity in terms of the amount of runoff generated, was sourced from the district forestry office. The map which had five classes: very high, high, moderate, low and marginal was clipped to the study area boundary map. Forestry office allocates a class to a piece of land basing on the anticipated negative effects per $500m^2$ land due to agricultural activities on the biodiversity in terms of deprivation of required amount of water for survival. A very high ecological class indicates that the biodiversity of the ecology is very sensitive to environmental modifications, hence least suited for RWH as shown in table 4. Suitability scores were assigned to each class following a criteria used by Mwenge-Kahinda et al., (2008) where very high sensitive areas were assigned 1 and marginal areas were assigned 5.

Table 4: RWH suitability ranking for environmental factors

No	Environmental sensitivity	Suitability score
1	Marginal	5
2	Low	4
3	Moderate	3
4	High	2
5	Very High	1

3.5.5 Assignment of weights to the factors

The weighted overlay also known as a multi-criteria evaluation (MCE) was used to create an output layer (final RWH suitability map) by combining different factors. In order to make a decision based on set priorities and to enable selecting among available alternatives , weights were assigned to the factors by applying the pair-wise ranking known as the Analytical Hierarchy Process (AHP) and rank sum methods that were developed by Saaty, (2008).

The following steps are involved in AHP; (i) Defining the decision making goal, which was to retain moisture as much as possible (ii) Selecting, organizing, and weighting factor, which included physical, socio economical and environmental factors (iii) applying factor to alternatives and rank alternatives, in this study alternatives were various RWH technologies, and (iv) conduct sensitivity analysis. A generic AHP model is displayed in figure 17 adopted from Aragon et al, (2013). In pairs, each factor is compared to each another: factor A vs. factor B, factor A vs. factor C, and factor B vs. factor C.

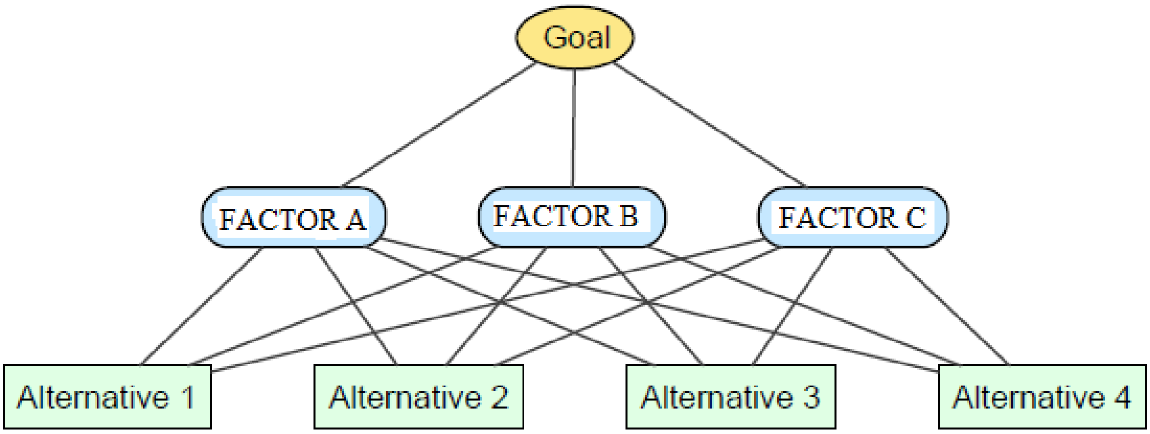


Figure 17: Generic analytic hierarchy process model

Following the steps from Saaty, (2008), for every pair wise comparison, we ask if one factor is more important (or effective, likely, preferred) than the other? If yes, by how much more? To determine the relative "how much more," we use the basic scale a qualitative, ordinal scale with ratio properties adopted from Saaty (2008). The judgment of "how much more" is based on the qualitative description (moderate, strong, very strong, and extreme) and not on the quantitative intensity of the associated values (1, 2 . . ., 9) as shown in table 5. It is the interpretation of the relative importance of one factor compared to another. If possible, the interpretation should be guided by the review of evidence (data or testimony). If two factors are equal, then these the two factors contribute equally to the objective. If a factor is moderate over another, then experience and judgment slightly favour [this] activity over another. If a factor is strong over another, then experience and judgment strongly favour [this] activity over another. If a factor is very strong over another, then [this] activity is favoured very strongly over another; its dominance demonstrated in practice. If a factor is extremely over another, then evidence favouring [this] activity over another is of the highest possible order of affirmation. The intensity score (*i*) is a ratio with valid reciprocal values (1/*i*). For example, if factor A, compared to factor B, is scored with intensity value *i*, then factor B, compared to factor A, has the reciprocal intensity value 1/*i*.

Table 5: The fundamentals of scale for pair wise comparisons

Intensity (*i*)	**Definition**	**Explanation**
1	**Equal** importance (likelihood or preference)	Two activities contribute equally to the objective
3	**Moderate** importance	Experience and judgment slightly favour one activity over another
5	**Strong** Importance	Experience and judgment strongly favour one activity over another
7	**Very** strong importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	**Extreme** importance	Evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8 1/*i*	For compromise between above values Reciprocals of above intensities	

The measurement tool for the pair wise comparisons of all selected parameters for in situ RWH was done by assignment of weights to each parameter as shown in table 6. Next, a comparison matrix was created using the results from AHP. This was done by incrementally in a rank-order (starting with the most important factor) and numerical weights were computed using the rank sum value method. Starting with the diagonal values which are always **1s**. Priority vector is also called normalized principal Eigen vector/ weight (Saaty, 2008). To normalize the values, the cell value was divided by its column total (table 7). And to calculate the priority weight, the mean value of the rows was determined.

Table 6: Pair-wise comparison matrix for in situ RWH

	Runoff	**Socioeconomic**	**environmental**
Runoff	1	9	2
Socioeconomic	1/9	1	1/5
Environmental	1/3	5	1
Total	**1.4**	**15.0**	**3.2**

Table 7: Normalisation and weighting for in situ RWH

	Runoff	**Socioeconomic**	**environmental**	**Weights**
Runoff	0.6923	0.6000	0.6250	0.6391
Socioeconomic	0.0769	0.0667	0.0625	0.0687
Environmental	0.2308	0.3333	0.3125	0.2922

3.5.6 Consistency of judgement

Decisions makers' judgments still cannot be measured with absolute certainty and therefore can be inconsistent with their valuations. It is for this reason that consistency of judgments for multiple pair wise comparisons improves accuracy of judgement. For example, if a decision maker prefers criterion A to B, and then B to C, we can expect A to be preferred to C. However, inconsistency arises when the decision maker prefers C to A. Inconsistency is measured by the consistency ratio (CR) shown in equation 3.3 and it is generally acceptable if CR < 0:10 (Saaty, 2008). When CR becomes relatively large (> 0:10), then its reasons should be explored hence some pair wise values needs to be reconsidered and the process is repeated until the desired value of CR < 0.10 is reached. Perfect consistency means that CR must be Zero but may not be attainable because of bias and inconsistencies that arise when making subjective judgments. Inconsistencies can result from unintentional errors, lack of concentration during the comparison process, or even misunderstandings. An advantage of the AHP is that it allows us to identify, explore, and correct these inconsistencies.

Thus the accuracy of pair wise comparison in this study was validated by calculation of the consistency index (CI). This establishes the inconsistent in the pair wise judgments to allow for re-evaluation of comparisons. The consistency index which is a measure of deviation from consistency basing on the comparison matrix is expressed as;

$$\mathrm{CI} = (\lambda - \mathrm{n}) \,/\, (\mathrm{n} - 1) \qquad \text{Equation 3.2}$$

Where λ is average value of consistency vector and n is the total number of columns in the matrix (Saaty, 2008). Then the consistence ration (CR) was calculated using the formula;

$$\mathrm{CR} = \mathrm{CI}/\,\mathrm{RI} \qquad \text{Equation 3.3}$$

Where random index (RI) is an index that depends on the number of elements that are being compared Saaty, (2008). The table of the random indexes of matrices of order 1-10 as derived by Saaty, (2008) is presented in appendix 7.6.

3.5.7 A GIS model for generating RWH suitability map

Generating suitability map was done in a suitability model builder of ArcGIS 10.2.2. The model produces RWH suitability maps by incorporating various factor maps layers using a Multi-Criteria Evaluation (MCE). Several tools of ArcGIS were built-in the model to solve various spatial challenges that included reclassifying values, reprojecting, and overlaying. All vector type format maps were converted into raster datasets to enable the ArcGIS weighted overlay.

A weighted linear combination (WLC) of MCE is standardized to a common numeric range, and then summed by means of a weighted average. All factors were combined by using a weight to each factors followed by a summation of the results to generate a suitability map calculated using by equation 3.4 by Malczewski (2004),

$$s = \sum WiXi \qquad \text{Equation 3.4}$$

Where S = suitability output level per pixel i

W_i = weight of factor i

X_i = criterion score of factor i

Therefore the higher the suitability value, S of a given site (pixel) i, the more suitable the pixel is for RWH technologies. S is based on the established suitability ranking of 1-5 where 1 denotes the sites (pixels) that are not suitable and 5 indicates areas (pixels) that are very highly suitable for RWH adopted from (De Winnaar et al., 2007) shown in table 8;

Table 8: Suitability ranking for *S*- value per pixel

No	Suitability class	Suitability score
1	Very low	1
2	Low	2
3	Medium	3
4	High	4
5	Very high	5

3.6 Rainfall runoff modelling

This section covers the method that was used for rainfall runoff modelling in this study. Runoff modelling simulates the volume of runoff that can be generated in the field and from external catchments and application directly into the soil profile for moisture retention or storage for supplementary irrigation to the crops during dry spells. The SCS curve number method was used to estimate the amount of runoff generated in the area. Lastly a runoff potential map was generated and incorporated into the GIS model for identification of suitable sites for RWH.

3.6.1 Determination of curve numbers

Land use and soil shape files were converted from vector format to raster using the conversion tools in ArcGIS10.2.2 software which is a GIS computer software. The soil map was reclassified into the Hydrological Soils Groups (HSG) of A, B, C, and D as illustrated by Schulze et al., (1992) in order to conform to the Natural Resources Conservation Curve Numbers Table of Runoff (NRCS TR- 55) (Benimana et al, 2014) basing on values shown in a look up table 9 adopted from Soil Conservation Service (1964). Assigned soil groups were as follows; Group A: sand, loamy sand and sandy loam types of soils, Group B: silt, silt loam and loam soils, Group C: sandy clay loam soils and Group D: clay loam, silty clay loam, sandy clay, silty clay and clay soils. Concepts used for deriving Curve Number (CN) by SCS method provided the basis for generating CN for this study. Thus based on the HSG land use output map CN values were assigned to each combination following the procedures illustrated by Soil Conservation Service, (1964). The chart in figure 18 shows the overall methodology for the GIS-based SCS-CN method which was adopted from (Shadeed and Almasri, 2010).

Table 9: Curve Number table for various land uses

Land Cover	Description of land cover	Hydrologic condition[2*]	Number for Hydrologic Soil Group A	B	C	D
Cultivation	Contour tied ridges(C)	Poor	70	79	84	88
		Good	65	75	82	86
	Mulching[1*]	Poor	71	80	87	90
		Good	64	75	82	85
Fallow	Bare soil	-	77	86	91	94
Developed areas (Towns)	Open spaces e.g. cemeteries and golf courts	Grass cover < 50%	68	78	87	89
		Fair condition (grass cover 50%-75%)	49	68	79	85
		Good condition (grass cover >75%)	38	62	74	80
	Impervious areas: paved parking, driveways and roofs, etc		98	98	98	98
Grasslands		Fair	49	69	79	84
Forestry	Savannah tree	Fair	43	53	78	82
Mountainous	Mountain bush mixture with trees	Fair	48	57	63	74
Water bodies	Wetlands		0	0	0	0

Note: [1*]Crop residue cover applies when at least 5 % of the ground surface throughout the year. [2*]Hydraulic condition is based on factors that affect infiltration and runoff, including (a) density of vegetative areas, (b) amount of year-round cover, (c) amount of grass, (d) % of residue cover on the land surface (good≥ 20%), and (e) degree of surface roughness. Poor: Factors impair infiltration and increase runoff. Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Source: Soil Conservation Service, (1964)

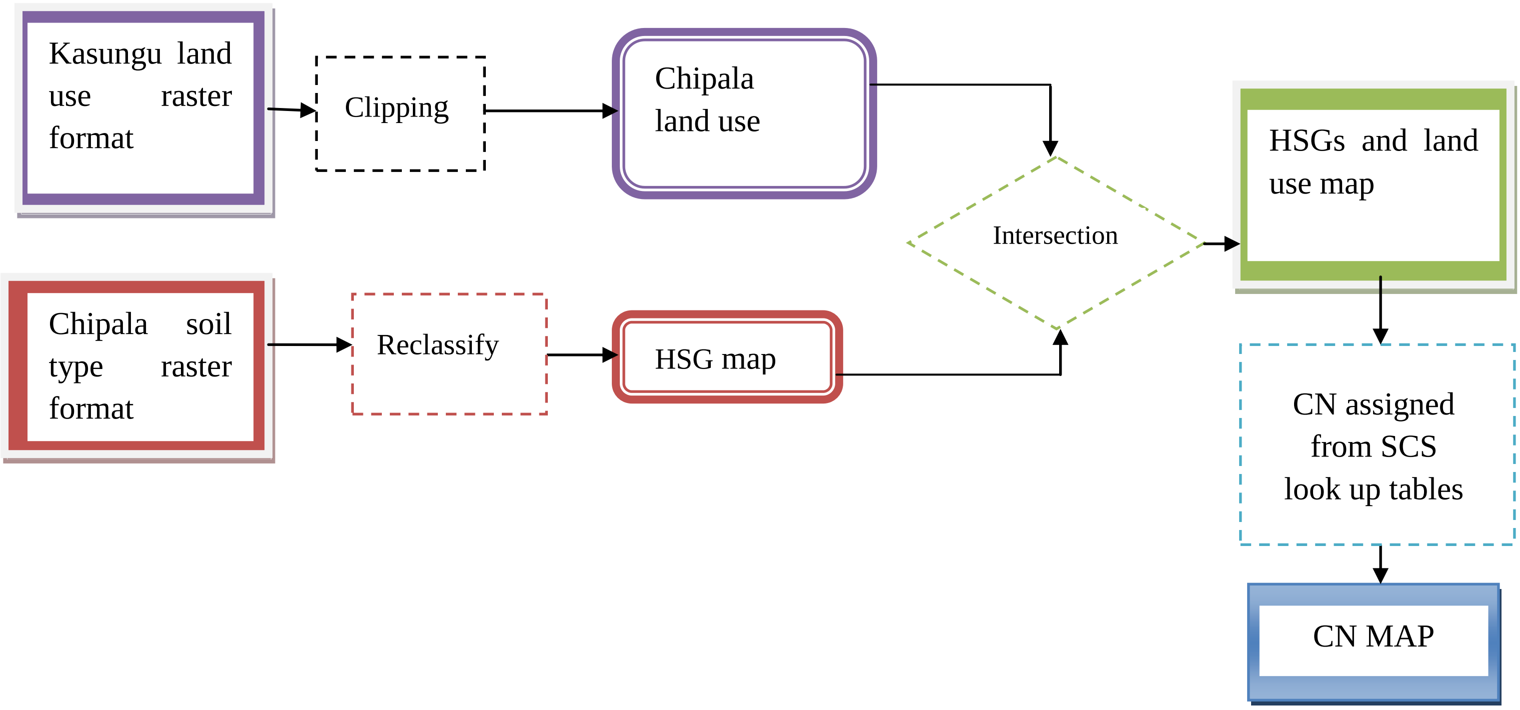


Figure 18: Methodology for deriving CN adopted from (Shadeed & Almasri, 2010)

3.6.2 Runoff estimation

Runoff was estimated using CN map that was processed in a spatial analyst tool box of ArcGIS10.2.2 that used the equations (3.5-3.7). The hydrologic relationship among rainfall (P), soil storage (S) and direct runoff (Q) is given by:

$$Q=\left\{\frac{(P-I)^2}{P-I+S}\right\} \quad \text{Equation 3.5}$$

The initial abstraction defined by the SCS mainly consists of interception, depression storage, evaporation and infiltration occurring prior to runoff. To eliminate the necessity of estimating both parameters *I* and *S* in the above equation, the relation between *I* and *S* was estimated by analyzing rainfall-runoff data for many small watersheds. The empirical relationship was established as; *I*= 0.2S (Schiariti, 2012).

Hence;

$$Q = \left\{\frac{(P-0.2)^2}{P-0.8S}\right\} \quad (p > 0.2S) \quad \text{Equation 3.6}$$

This is the rainfall-runoff equation used by the SCS for estimating depth of direct runoff from storm rainfall. The equation has one variable *P* and one parameter *S.*

But *S* is related to curve number (CN) by;

$$S = \left(\frac{25{,}400}{CN}\right) - 254 \quad \text{Equation 3.7}$$

A weighted CN for each catchment was computed using the formula:

$$CN = \sum (CN_i * A_i)/A \quad \text{Equation 3.8}$$

Where CN = weighted curve number; CN_i = curve number for land cover type; A_i = area with curve number CN_i and A = the total area of the catchment.

To estimate rainfall runoff in the study area CHIRPS raster data was selected to be used in the runoff calculations. CHIRPS data covered a long period of time of 34 years from 1981-2015 and large area hence was presumed to be more accurate to work in estimating runoff unlike the collected rain gauge data which was for 10 years from 2005 to 2015 shown in table 10 and figure 19. Using ArcGIS10.2.2 CHIRPS global raster map was resized from 25 km^2 to 1 km^2 pixel sizes since the study area was much smaller as compared to the global scale. CHIRPS rainfall data was reprojected to enable overlay of the study area boundary map which were further processed to clip the study area boundary map.

Table 10: Average annual rainfall from various rain gauge stations

Station	Annual average rainfall 2005-2015 (mm)
Chamama	896
Chipala	643
Chulu	812
Kaluluma	751
Lisasadzi	852
Mkanakhoti	891
Mtunthama	896
Santhe	989

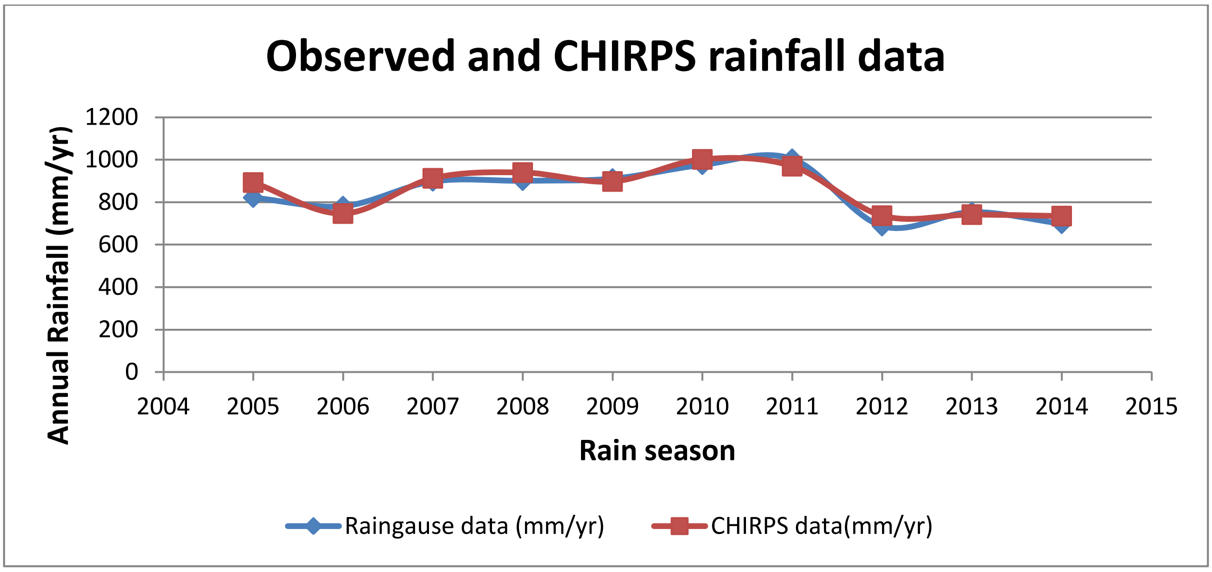


Figure 19: Observed and CHIRPS rainfall data for Chipala EPA

3.6.3 Generation of runoff potential map

In order to generate a runoff potential map several thematic layers were overlaid such as land use, soil map and slope map. The overlaid thematic maps were assigned CN values of each specific soil type and land use polygon with values from the look up tables. The overlaid maps were processed into CN thematic map that was intersected with the slope map. Using the Spatial Analyst tools of ArcGIS10.2.2, equation 3.6 was entered in the Map algebra task bar that utilized the precipitation (P) and initial abstraction (S) thematic maps to produce the runoff potential (Q) map.

CHAPTER 4

4 Results and Discussion

4.1 Existing RWH technologies

This section presents results from the survey on the current RWH technologies implemented in the study area and how farmers perceive rainwater harvesting technologies in terms of performance and investment cost.

4.1.1 Characteristics of sampled households

Among the sampled households, males were 74 % whilst the remaining 26 % were females. The average family size of the sampled households was 6; the largest family size was 12 and the smallest being 2. The largest group (41 %) of the respondents was in the age group of 35-45 years while just a few (3 %) were above 65 years old. The study revealed that 13 % of the sample was illiterate while the remaining 87 % were literate. The largest group (42.6 %) of the farmers land size under RWH ranged from 0.5-1.0 ha while a few (7.4 %) had more than 1.5 ha of land. In 2012 it was reported that 55% of smallholder farmers in Malawi have less than 1ha of cultivable land (GOM, 2012). Among the sampled farmers 68.5 % indicated that land belonged to them while 10 % rented and 5.6 % borrowed it from either friends or families.

4.1.2 RWH technologies practiced

The field study showed various types of RWH technologies were implemented in the study area with the most commonly implemented technology being soil mulching (50 %), others were contour tied ridges (39 %), planting pits (7 %) and infiltration pits (4 %) as shown in figure 20. It was observed that soil mulching was the most preferred technology by farmers because it is cheaper in terms of investments costs and demands less labour as compared to other technologies. Infiltration pits were the least implemented technology because of high labour demand in terms of excavation of the pits.

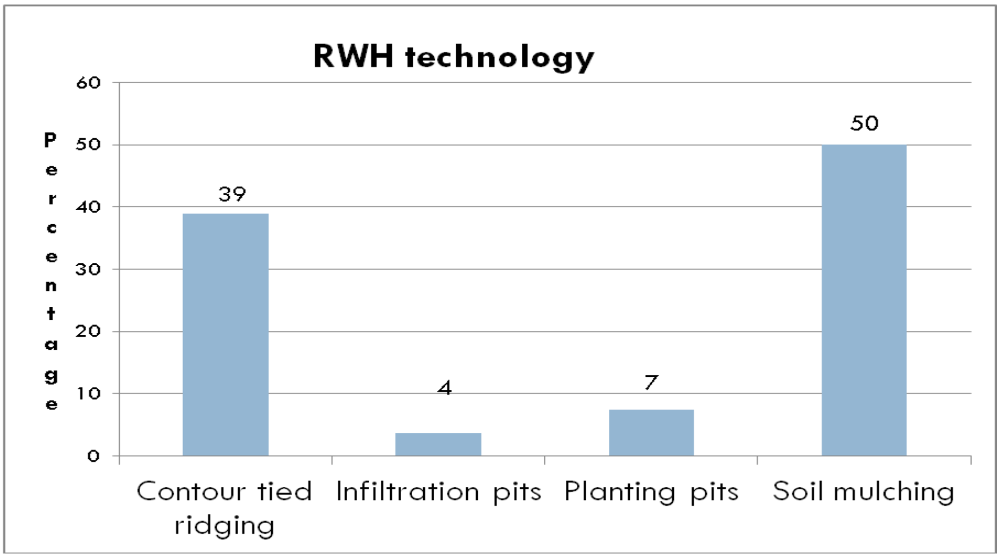


Figure 20: Rainwater harvesting technologies implemented

From the sampled farmers 38.9 % indicated that they started implementing RWH technologies from 2001-2010 period, 37 % started implementing RWH from 1991- 2000, 20.4 % started implementing RWH after 2011 whilst 3.7 % started implementing RWH technologies from 1981-1990. The highest implementation percentages for periods 2001-2010 and 1991-2000 coincides with the 1991-1992 and 2000-2002 severe drought periods in Southern Africa in which Malawi was equally affected. This was caused by global warming which resulted in climate variability (Minot, 2012). As a way of coping up with the situation most farmers started implementing RWH technologies.

Farmers indicated that mulching of the soil in the study area is done soon after harvesting the previous crop. Soil mulching sometimes called mulch tillage system, also called stubble mulch farming, is based on the principle of causing least soil disturbance and leaving the maximum of crop residue on the soil surface (30 % or more) and at the same time obtaining a quick seed germination (FAO, 1993). The mainly used mulching materials in the area are maize crop and groundnuts residues because of their abundant availability (figure 21a &b). Most farmers (51 %) indicated that they started implementing soil mulching after having experienced permanent crop wilting from prolonged dry spells of the preceding rain seasons while others (39 %) reported food insecurity and 10 % of farmers having received farm inputs as the main reason for starting rainwater harvesting. Farmers indicated that they benefitted from the technology through protection of the soil against raindrop impact, decrease in flow velocity by imparting roughness, and improved infiltration capacity. This was similar to what Ibraimo and Munguambe, (2007) found out in their study. However in some cases farmers indicated that they face challenges of livestock damaging their mulches (Figure 21c).

a: Soil mulching

b: Maize field under soil mulching

c: Livestock feeding on the mulch

Figure 21: Soil mulching

Contour tied ridging was another RWH technology commonly implemented in the study area. Most of the visited contour tied ridges fields (87 %) were built by farmers' own capital and labour and only a few (11.1 %) was constructed with help from government supported programmes which had been able to provide incentives to RWH farmers in form of 2 kg maize seed and 10 kg bag of fertilizers per RWH farmer while only 1.9 % indicated that they were assisted by relatives to start implementing the technology. The contour tied ridges in the study area are spaced at 0.75 m apart and earth cross ties are at 2 m and staggered. The ridges are 0.3 m in height while cross-ties are at 0.2 m high. These measurements were also recommended by Wiyo and Feyen, (1999), since contour ridges likely to be overtopped if too much rainwater is harvested in the furrows. Sometimes they also may collapse at low points where large volumes of runoff accumulate (Shaxson and Barber, 2003). Therefore to reduce these risks sampled farmers carefully lay out and maintain the tie ridges and furrows to ensure there are no low points and in order to prevent lateral movement of water along the furrows as shown in figure 22. This was a similar observation for contour tied ridges that was made by Shaxson & Barber, (2003).

Figure 22: Contour tied ridging with maize

4.1.3 Farmer perception of RWH technologies

Most sampled farmers (55.6 %) perceived RWH as good technology in terms of soil moisture retention for crops during dry spells with 31.5 % perceiving the technology as very good as shown in table 11. However 13 % of the sampled farmers indicated that they perceived the technology to be poor as they could not retain the adequate soil moisture for crops during dry spells. Farmers indicated that the low moisture retention was mainly caused by high water losses through evaporation and seepage.

Table 11: Farmers perceptions of RWH technologies

	Frequency	Percentage
Good technology	30	55.6
Very Good technology	17	31.5
Poor technology	7	13.0
Total	**54**	**100.0**

In order to minimize seepage losses, 56 % of the sampled farmers indicated to have located their RWH technologies on dense textured soils in order to hold more water as compared to soils that are coarse textured where harvested water was lost almost after the rains while 44 % agreed that they never considered any factor for locating the technology. The farmers suggested that water losses could be reduced by proper location of the technology. On the other hand farmers pointed out during focus group discussion that the high labour demand for RWH technology during implementation contributed to other farmers' reluctance to adopt the technology.

4.1.4 Productive purpose of RWH

All the sampled farmers indicated that RWH technologies were used for moisture retention in crop production with 81.5 % maize, 16.7 % tobacco and 1.9 % soy beans field. However farmers reported that the harvested water was generally not sufficient as compared to the crop water requirements for mitigating the dry spells. Farmers with contour tied ridges indicated that most of the harvested water is lost through evaporation, while farmers with soil mulching indicated that most of the water loses were as a result of seepages. The poor performance of the RWH technologies resulted in disappointment and eventually abandonment of technology by farmers.

4.2 Performance of RWH technologies in terms of soil moisture retention

Meteorological data for the sampling area the period of the study (December 2015- April 2016) sourced from the Malawi Meteorological Services department indicated the statistics shown in table 12. These statistics are important in helping understand the weather conditions of the study area at the time of soil sampling. The highest temperature and rainfall were recorded in the month of January at 31.9 ^{o}C and 291 mm respectively.

Table 12: Meteorological data for the growing season 2015/2016

Data		Dec 2015	Jan 2016	Feb 2016	Mar 2016	20 Apr 2016
Relative humidity (%)	Mean	50	77	71	73	70
Air temperature (^{o}C)	Max	31.7	31.9	30.4	30.7	28.4
	Min	19.0	13.9	19.5	18.3	17.1
Open evaporation (mm/day)	Max	7.2	6.6	6.7	6.2	5.9
	Min	5.7	5.3	5.3	4.8	4.7
Rainfall (mm)	-	63.5	291	202	154	15,9
No. of rainy days ≥ 0.3mm	-	6	13	11	8	7
No of dry days		25	18	18	23	23
Average wind speed (Km/day)	2m	6.3	5.8	4.7	2.2	4.3

From figure 23, it was noted that rainfall received in the area varied with time. After rains had started in December 2015, the amount received increased significantly in the month of January then started to decline steadily up to the month of April 2016.

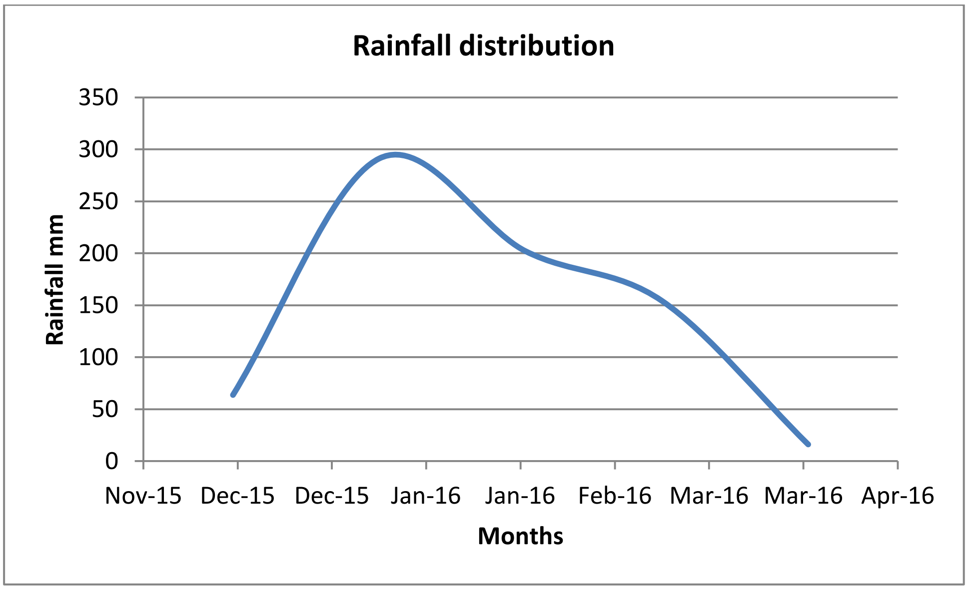


Figure 23: Temporal distribution of rainfall during the study period

Soil sampling was done nine times in the season thus once in December (before the rains started), twice in January (when rains had started and crops planted), thrice in February, twice in March and once in April (soon after crop harvest), sampled one-day after each of four rain events, during the season, which corresponded to four stages as suggested by Doorenbos and Pruitt, (1977). Results were recorded and for each zone (cluster) average soil moistures as percentage of dry mass basis were entered in a table 13.

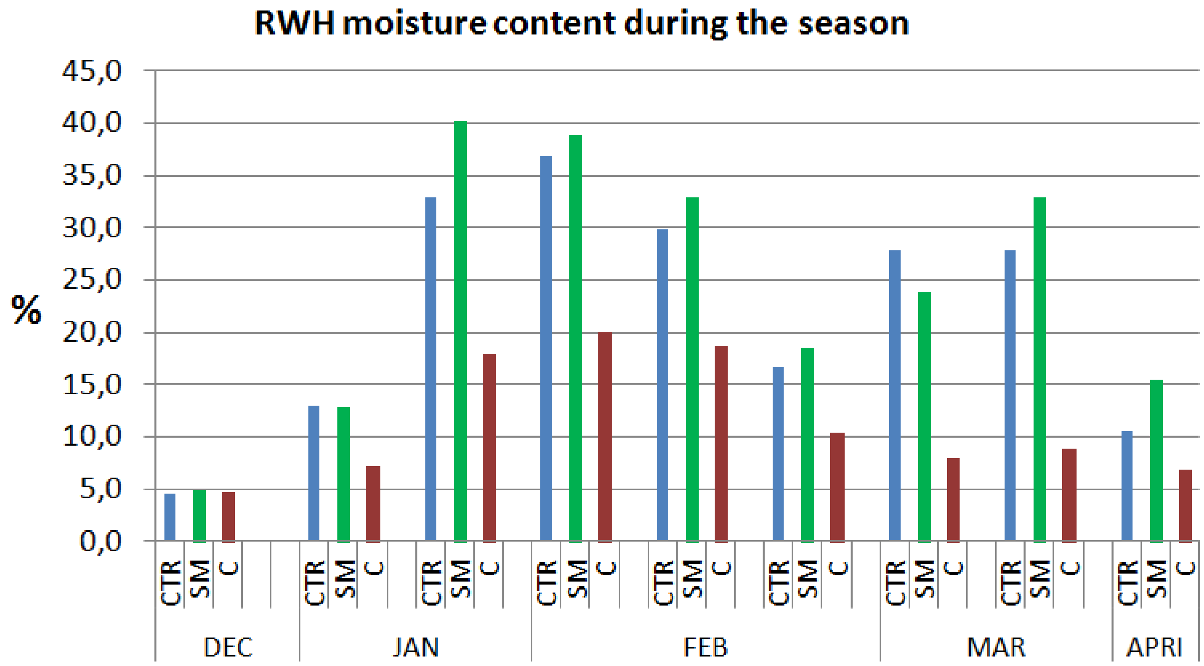
From table 13, it was observed that the average soil moisture content expressed on dry mass in fields with contour tied ridges was 4.5 %, mulching was 4.9 % while control fields had 4.7 % from all the zones before rains started in December. However after receiving rainfall in excess of 60mm/day, moisture content started increasing in all the technologies from January to February when more rainfall was received till March when moisture content started to decline in all the technologies. Data from table 13 is presented in the bar graph in figure 19.

Table 13: Average percentage value of soil moisture per technology

Sample	DEC		JAN				FEB						MAR				APR	
	1		2		3		4		5		6		7		8		9	
Tech. name/ %moisture	CTR	4,5	CTR	13,0	CTR	22,1	CTR	36,9	CTR	31,5	CTR	16,6	CTR	27,8	CTR	27,8	CTR	10,5
	SM	4,9	SM	12,8	SM	25,5	SM	38,8	SM	32,8	SM	18,4	SM	23,8	SM	32,9	SM	15,4
	C	4,7	C	7,2	C	17,9	C	20,0	C	18,7	C	10,3	C	7,9	C	8,8	C	6,8

CTR= Contour tied ridging; SM= Soil mulching and C= Control field (No RWH)

From figure 24, soil moisture under soil mulching recorded the highest moisture content (42 %), the same day contour tied ridging recorded 32.8 % while control field recorded 17.9 %. Similarly, the average amount of soil moisture for all the fields during the season recorded highest under soil mulching (24.4 %), contour tied ridging (22.2 %) and control field (11.4 %). It was found out that there was variation in the moisture content for the three technologies since Coefficient of Variance (CV) was greater than zero, Pallant, (2013) shown in table 14. Using the one way Analysis of Variance (ANOVA) to test for the significance difference (α=0.05) of amount of moisture measured in the technologies. The ANOVA results showed that there was a statistically significant difference in the moisture measurements for the three technologies (P< 0.05).



CTR= Contour tied ridging; SM= Soil mulching and C= Control field (No RWH)

Figure 24: Soil moisture content under different RWH technologies

Table 14: Variation in moisture content among technologies

Technology	Number	Mean (%)	Std. Deviation	Coefficient of Variance (CV)	P_values
Soil Mulching	9	22,196	11,2616	0,5074	0.028
Contour tied ridging	9	21,448	12,4127	0,5077	0.035
Control fields	9	11,385	5,8487	0,5137	0.080
Total	**27**	**19,343**	**10,3152**		

The results agree with studies by (Mhizha and Ndiritu, 2013; Mupangwa et al, 2011) in Zimbabwe which reported that contour ridging improves soil moisture. Therefore contour tied ridging and soil mulching performed much better in terms of soil moisture retention as compared to fields without RWH technologies which are in line with the field survey results on farmers' perceived RWH technologies but fail to agree that mulching was a better technology than contour tied ridging in terms of moisture retention.

4.3 Rainfall runoff modelling

4.3.1 Land use

The land use maps of 2015 in vector formats were converted into thematic maps (as shown in figure 20) and the land use area has already been delineated into: built up, seasonal wetlands, forestry, fallow and shrubs, and agricultural areas by the Land Resources Conservation Department. The highest percentage (62 %) of the area is covered by crop land and the least area (2 %) is covered by built up area as presented in table 15 and figure 20.

Table 15: Land uses in the study area

No	Land use	Area (km^2)	Area percentage
1	Forest	147,82	19
2	Seasonal wetlands	46,68	6
3	Agricultural lands	482,36	62
4	Grassland and shrubs	85,58	11
5	Built up area	15,56	2
	Total	**787,0**	**100**

4.3.2 Soil hydrological group

The soil types in the study area were grouped into four hydrological soil groups. The soil groups were as follows; Group A: sand, loamy sand and sandy loam types of soils, Group B: silt, silt loam and loam soils, Group C: sandy clay loam soils and Group D: clay loam, silty clay loam, sandy clay, silty clay and clay soils as shown in table 16 indication the area percentage of each HSG.

Table 16: Hydrological soil groups

Hydrological Soil Group	Area (km^2)	Area percentage
A	601,4	77,3
B	24,9	3,2
C	80,9	10,4
D	70,8	9,1
	778,0	**100.0**

4.3.3 Deriving Curve Number map

The curve number values were assigned to the respective combined attribute generated from the overlaid maps (land use and hydrological soil groups) from TR55 of USDA look up tables. The derived CN map for the area is shown in figure 25.

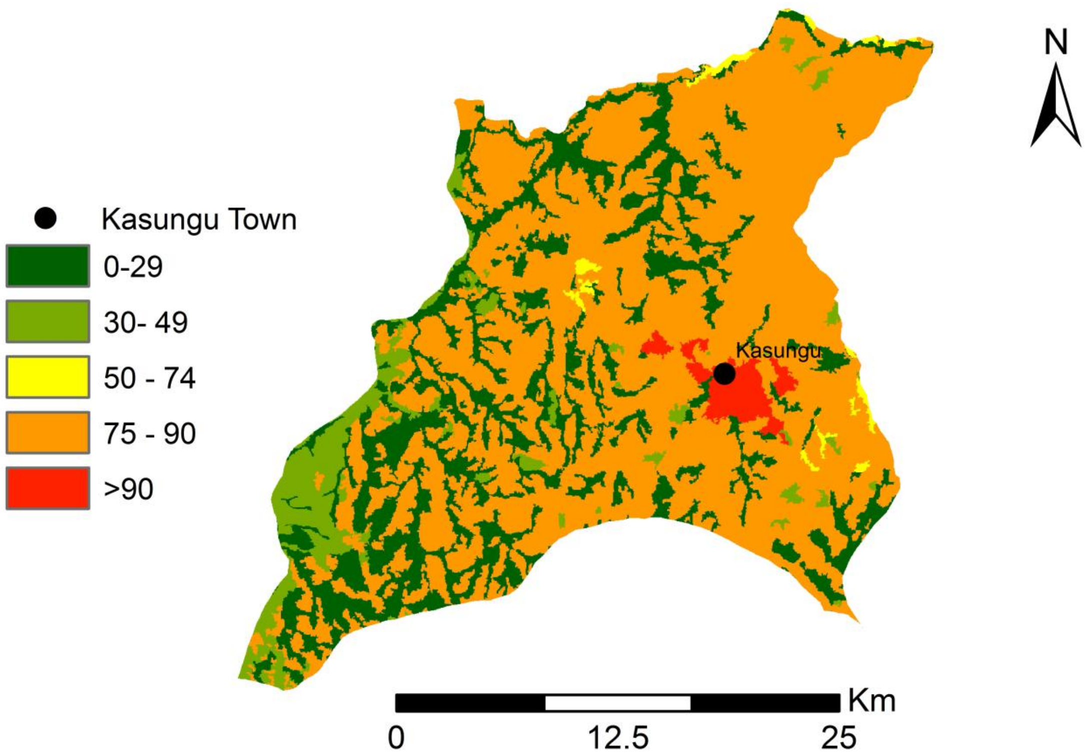


Figure 25: CN values

4.3.4 Estimated runoff

The runoff depths for the different places of the study area were determined using CHIRPS rainfall data that generated the runoff potential map. CHIRPS rainwater data used in this calculation showed that the annual rainfall for the study area ranges from 734 mm to 942 mm. The results of spatial variation of modelled annual runoff depth in mm are shown in figure 26. A direct annual runoff depth variation from 328 mm in areas near the Kasungu national park with an increase eastwards to a maximum of 761 mm was observed especially in built-up areas.

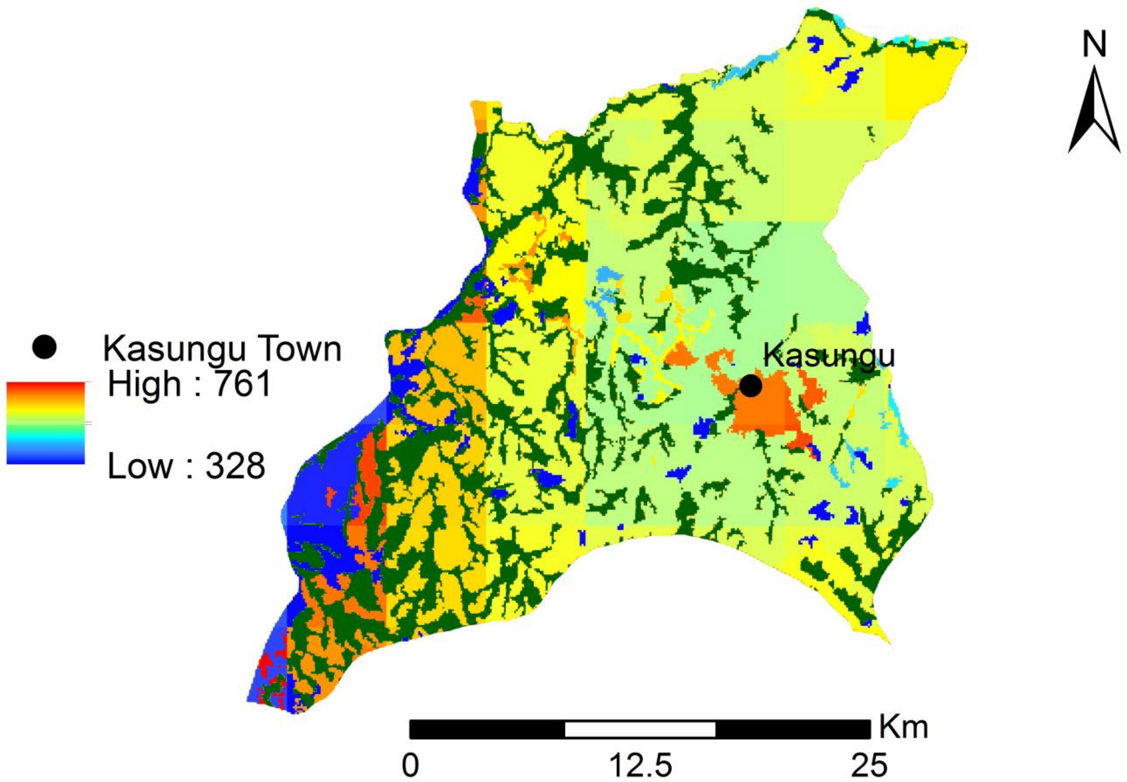


Figure 26: Runoff potential for study area

Table 17 shows the sub catchments, surface area (A*i*) and corresponding curve numbers (CN*i*), for each sub catchment. Taking the average antecedent moisture condition AMC II (Artan et al, 2001), using equation 3.6 the average annual runoff that is generated from Chipala EPA is equal to 3.86 x10^8 m^3.

Table 17: Runoff estimation through the SCS- Curve number method

Catchment	Surface area (A*i*) km^2	AMCII Curve Number (CN*i*)
A	601,4	53
B	24,9	51
C	80,9	77
D	70,8	71

4.4 Areas suitable for RWH in Kasungu district

The RWH suitability map was produced from a weighted overlay of the runoff potential map, socio economic map shown in figure 27 and environmental map in figure 28. The model had incorporated results from the field survey and literature review that showed that most in field RWH technologies experienced problems of high rate of water loss through runoff, evaporation and seepage. Thus it was concluded that slope was being responsible for water losses through high rates of runoff water on the surface ground and soil texture was being responsible for seepage, this indicates that these factors were more important than the other factors hence resulted in a higher weight for slope and soil texture embedded in the runoff potential map. This is the reason for the high weight being assigned to runoff potential map as compared to socio economic and environmental factors indicated in table 6.

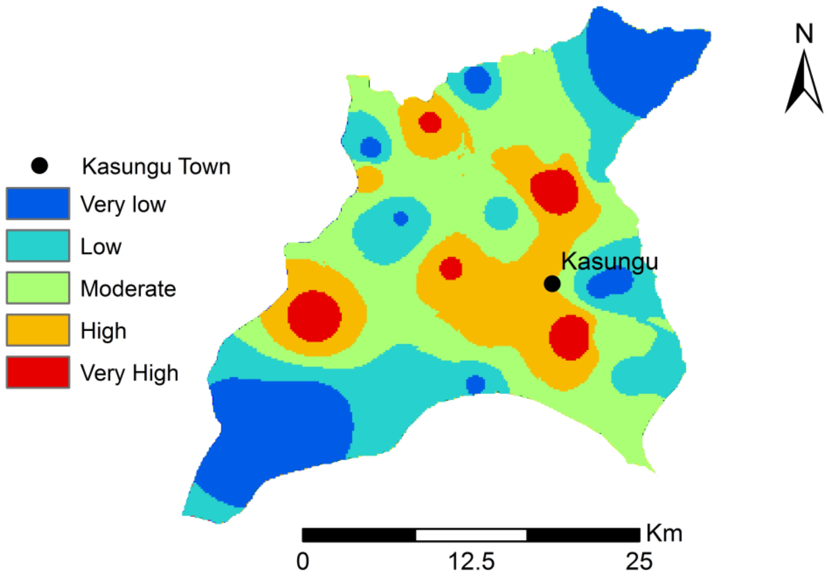


Figure 27: Socio economic factors

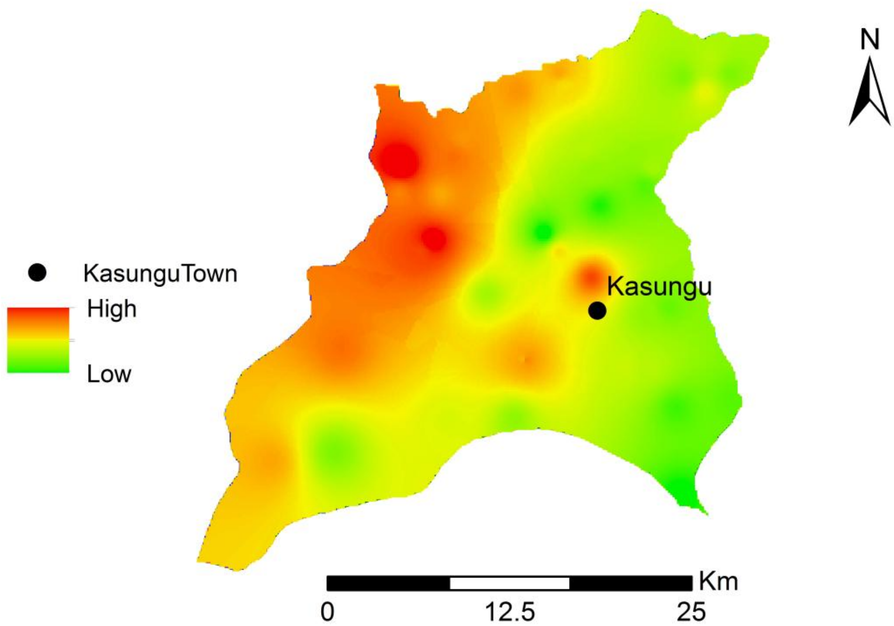


Figure 28: Spatial variation of environmental sensitivity

The generated suitability map in figure 29 indicated five classes of suitability thus; Very high, highly, moderately, marginally and not suitable. From the generated suitability map for the study area it was found out that 1.6 km^2, 260.6 km^2, 434.9 km^2, 78.6 km^2 and 2.3 km^2 of land were very high, high, moderate, marginally and not suitable respectively for in field RWH as shown in table 18. From the suitability map it can be noted that most suitable area for RWH technologies lies to the north eastern and south western part of the study area which receives annual rainfall in the ranges of 700-900 mm and characterised with patches of sandy loam soils, gentle slopes of 2-8 % and areas of crop production.

Table 18: RWH Suitability

Suitability Class	Area (km^2)	Area percentage
Very highly suitable	1,6	0,2
Highly suitable	260,6	33,5
Moderately suitable	434,9	55,9
Marginally suitable	78,6	10,1
Not suitable	2,3	0,3
Total	**778,0**	**100**

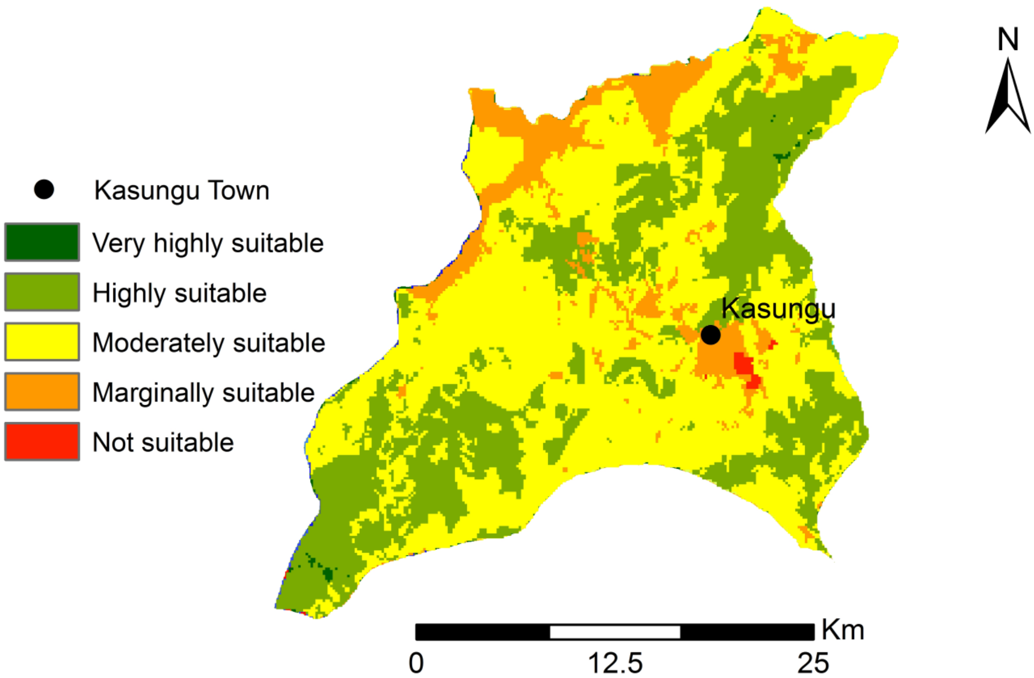


Figure 29: Rainwater harvesting suitability for the study area

4.5 Validation of the suitability levels

In order to check for applicability of the suitability ranks that were developed, the locations of the existing RWH technologies were compared with locations obtained after running the Multi-Criteria Analysis (MCE) tool in Arc Map 10.2.2. The results shown in table 19 and in figure 30 indicate that 55 % RWH technologies were located in the areas of high suitability and with 24 % located in the areas of moderate suitability whilst 17 % were located in low suitable areas and only 4 % were located in not suitable areas. Thus the established suitability ranks agree with the experiences and local knowledge by the farmers. This method of validating a model for identifying suitable RHW areas has been used by other researchers elsewhere (Ketsela, 2009; Mbilinyi et al., 2014).

Table 19: Comparisons of RWH technologies actual locations and suitability levels

	Level of suitability				
RWH technologies	**Very high**	**High**	**Moderate**	**Low**	**Very low**
Contour tied ridging	0	13	4	2	2
Soil mulching	0	14	7	6	0
Total	**0**	**26**	**11**	**8**	**2**
Percentage	**0**	**55**	**24**	**17**	**4**

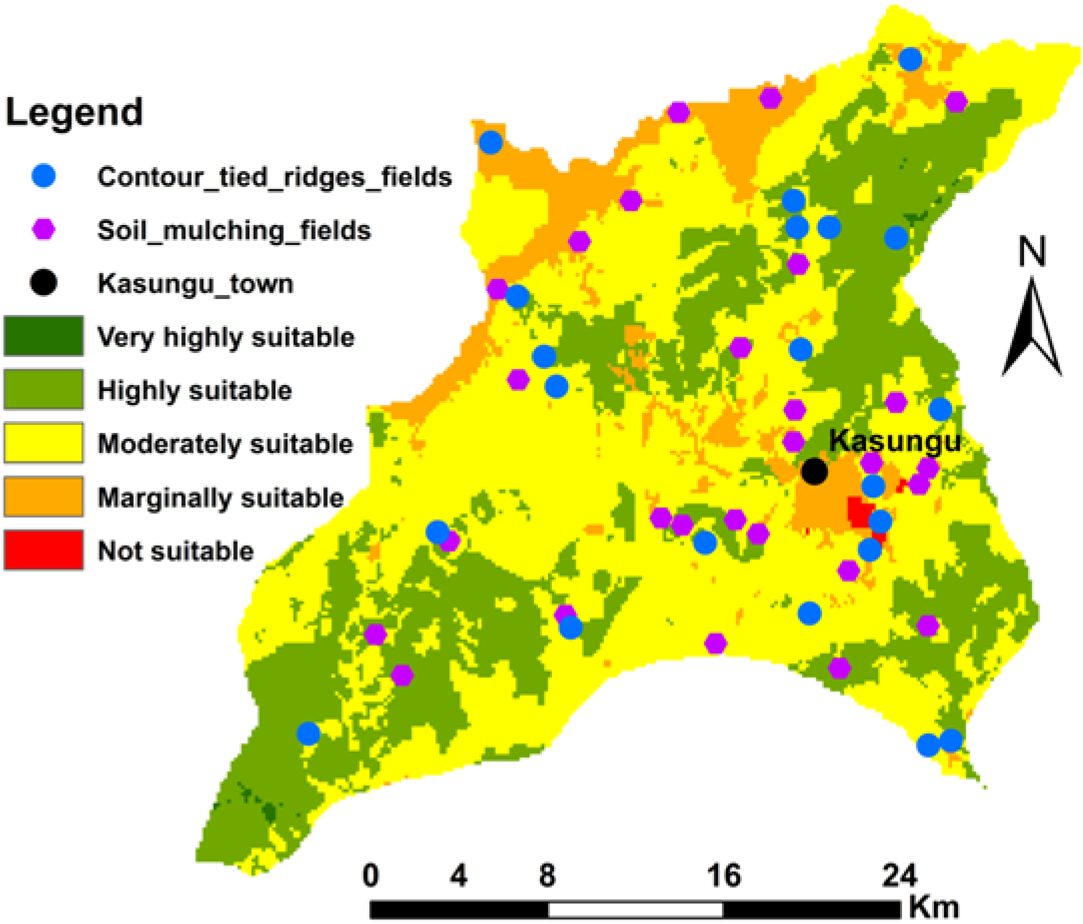


Figure 30: Location of existing RWH technologies under established suitability rank

CHAPTER 5

5 Conclusion and Recommendations

5.1 Conclusion

In this study contour tied ridges and mulching were found to be the most commonly implemented RWH harvesting technologies in the study area. The adoption of these technologies is attributed to their simplicity and low cost associated with them when compared to other RWH technologies. The performance of these technologies has been satisfactory in terms of water retention to the plants during periods of persistent dry spells with fields that have RWH performing better than fields without RWH technologies.

Annual rainfall, soil texture, soil depth, slope, land use, socioeconomic and environmental parameters were established to be the factors for locating potential RWH sites. Knowledge of these factors contribution to suitability of sites to RWH can be used by the extension workers to guide location of the RWH technologies.

The integration of factors for locating suitable areas of RWH technologies was done in a GIS based platform in order to generate suitability maps by using the Arc GIS 10.2.2 model builder. This model used a multi-criteria evaluation that combines different factors such rainfall, soil texture, soil depth, slope, land use/cover, population density and ecological parameters through a weighted overlaying process. The model generated a suitability map for in-field RWH technologies. The results from the model indicated that the majority of the land was moderately suitable (56 %) and highly suitable (34 %). These results were validated using information that was obtained from the field survey which showed that 55 % RWH technologies were located in the areas of high suitability and with 24 % located in the areas of moderate suitability whilst 17 % were located in low suitable areas and only 4 % were located in not suitable areas. These results show the reliability of the developed RWH model because most of the sites are appropriately located. Therefore the accuracy of the model is found to be satisfactory.

5.2 Recommendations

In order to enhance better performance of the RWH technologies in the study area there is need to use more mulch on ground surface even where other RWH technologies such as contour ridges have been implemented, to minimize water losses through evaporation. The use of more mulches helps to conserve more moisture in the soil.

There is need for Government through the District Agricultural Development Office (DADO) to help in creating awareness of existing potential and investing in the implementation of RWH technologies in the area.

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7 Appendices

7.1 Farmer questionnaire

UNIVERSITY OF ZIMBABWE

DEPARTMENT OF CIVIL ENGINEERING

A GIS-BASED APPROACH FOR IDENTIFYING SUITABLE SITES FOR RAINWATER HARVESTING TECHNOLOGIES IN KASUNGU DISTRICT, MALAWI

By

Fred Nyirenda

I am a student doing MSc in Integrated Water Resource Management (IWRM) at The University of Zimbabwe. I am carrying out a research on a GIS-based approach for identifying suitable sites for rainwater harvesting technologies in Kasungu District, Malawi. The questionnaire outcome will be used only for the research purpose and there is respondent confidentiality and no names will be published. This is academic research and there is no monetary value realised in participating in answering the questionnaire.

Date of interview_____________________ Village name_________________________

Enumerator name_____________________ Location (Coordinate):________________

A GIS-Based approach for identifying suitable sites for rainwater harvesting technologies in Kasungu District, Malawi

1.0 Demographic Information

1.1 Sex of the household head

Male		Female	

1.2 What is the age of the household head?

< 25 yrs		25-35 yrs		35-45 yrs		45-55 yrs		55-65 yrs		>65 yrs	

1.3 What is the size of household?

1.4 What is the main source of income?

Farming	Employed by govt.	Remittance	Other (Specify)

1.5 What is the level of education completed?

Never attended	Primary	Secondary	A-Level	Tertiary

1.6 What is the total farm size___________?

<0.5ha	0.5- 1.0 ha	1.0-1.5 ha	> 1.5 ha

1.7 What is the land tenure system of your field?

a.	Own	b	Family	c	Rent	d	Borrowed	e	Other (Specify)

1.8 Does land ownership affect implementation of RWH technologies?

Yes	No

1.9 If yes in what way?

____

2.0 Water harvesting practices and status

2.1 Do you practice RWH technologies?

Yes	No

2.2 If yes, which RWH technologies do you practice?

a.	Contour tied ridges	d	Terraces (fanya juu and chini)
b.	Infiltration pits	e	Soil Mulching
c.	Planting Pit	f	Others (Specify)

2.3 When did you start implementing RWH technologies?

a.	Before 1980	b.	1981-1990	c.	1991-2000	d.	2001-2010	e.	After 2011

2.4 Did you know about RWH before you started implementing the technology?

Yes	No

2.5 If yes, what was the motivation to start implementing RWH technologies?

a.	Farm inputs	b	Cash	c	Benefits of RWH	d	Food insecurity	e	Other (Specify)

2.6 If No, how did you know about RWH?

a.	Extension worker	b	Friend	c	Radio	d.	Newspaper	e	Other (Specify)

2.7 What was the Initial investment cost of RWH? MK----------------------

2.8 What was the source of the money for investment?

2.9 Have you ever made any maintenance work?

Yes	No

2.10 If yes, what was the maintenance cost you incurred?
____

2.11 Did you decide on the location of RWH technology?

Yes	No

2.12 If yes, what factors did you consider in locating RWH in your field?

____

2.13 If no, how did you manage to locate RWH in your field?
____

2.14 What are the types of crops planted in RWH fields?

a.	Maize	b	Groundnuts	c	Tobacco	d	Soybeans	e	Other (Specify)

2.15 How do you compare yield from RWH fields to those without RWH technologies?
____

2.16 Did you sell part of your crop yield?

Yes	No

2.17 If yes, what was the proportion of crops sold out of the total yield?

a.	Less than quarter	b	Quarter	c	Half	d	Three quarters	e	Other (Specify)

2.18 How do you perceive RWH technologies in terms of performance?

2.19 How do you perceive RWH technologies in terms of cost?

2.20 Did you encounter any challenges during the implementation of RWH technologies?

Yes or No

2.21 If yes? Mention the challenges?
____
____
2.22 What is your general remark of RWH technologies?
____

THE END! THANK YOU SO MUCH

7.2 Key informant checklist

UNIVERSITY OF ZIMBABWE

DEPARTMENT OF CIVIL ENGINEERING

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Name of institution…………………………………………….

Date of Interview……………………..……………………….

1. What duties do you carry out in the area?
....
....
....

2. How long have you been working in the area?..

3. Do you implement RWH technologies in the area?
....

4. If yes, did you know the crop situation in the area before you started implementing RWH technologies?..

5. Why do you promote RWH technologies for the communities?
....
....
....

6. What were the factors that you considered when advising for the type of RWH technologies?..
....
....

6. What role did the community play in the implementation process?
....
....
....

7. What are your general views on the performance of RWH technologies?
....
....

8. How do you perceive the already implemented RWH technologies in the areas in terms of sustainable or reliable in times of seasonal discrepancies?
....
....

9. What lessons have you learned from RWH technologies implemented in the areas?
....
....
....

10. What is your general comment on the RWH technologies implemented in the area?
....
....
....

THE END! THANK YOU SO MUCH

7.3 Focus group discussion checklist

UNIVERSITY OF ZIMBABWE

DEPARTMENT OF CIVIL ENGINEERING

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Name of Village…………………………………………….

Date of interview……..…………………………………….

1. State the crops that you grow in your area?

....

....

2. What are the challenges that you face in crop production?

....

....

3. Do you implement RWH technologies in your community?

....

....

4. If yes when did you start implementing the RWH technologies?...

....

5. Did you know anything about the RWH before you started implementing RWH technologies in the area?

………...

……………………………………………………………………..

6. How did the RWH idea arise in the community?

....

....

7. How are RWH technologies perceived in your communities?

....

....

8. When implementing RWH technologies, does the community decide on the location of the RWH technologies?

....

....

9. What is the criterion that you use in locating RWH technologies in various fields?

....

....

10. How do you perceive the performance of RWH technologies in your fields?

....

....

11. What challenges are you facing during the implementation of RWH?

....

....

....

THE END! THANK YOU SO MUCH

7.4 Summary of interviewed farmers

	NAME OF FARMER	VILLAGE	AREA (HA)	RWH TECHNOLOGY	CROP	LATITUDE	LONGITUDE
1	Lemekezani Banda	Gaga	0.39	Contour tied ridges	Maize	540944	8563171
2	Gilbert M. Banda	Gaga	1.8	Contour tied ridges	Tobacco	540396	8564501
3	Aswel Mwale	Gaga	0.03	Planting Pit	Maize	541101	8564423
4	Godfrey Nkhata	Chimwendo	3.3	Contour tied ridges	Tobacco	551433	8571390
5	Stonard Suwira	Chimwendo	0.6	Contour tied ridges	Maize	551590	8570216
6	Masauko Banda	Kaswamchinji	0.8	Contour tied ridges	Maize	535699	8556752
7	Antony Yezi	Changaluwa	0.1	Contour tied ridges	Maize	529985	8547828
8	Moses Kanyenda	Tena	1.4	Infiltration pits	Maize	535073	8548611
9	Wyson Chavula	Tena	2.2	Soil Mulching	Maize	532959	8552212
10	Steven Phiri	Msokera	0.3	Soil Mulching	Maize	545563	8557378
11	Nasimati Tambala	Kapyela	0.6	Contour tied ridges	Maize	539222	8567163
12	Dorothy Mwale	Chikwesa	0.01	Soil Mulching	Maize	546345	8575303
13	Dailess Zimba	Kwengwele	0.1	Soil Mulching	Maize	550416	8575930
14	Tabeti Banda	Mndume	0.2	Soil Mulching	Maize	551433	8560724
15	Matias Kamanga	Mndume	0.2	Soil Mulching	Tobacco	551492	8562133
16	Mike Banda	Chipembere	0.4	Soil Mulching	Maize	554878	8559805
17	Chancy Thyolani	Chibisa	0.2	Soil Mulching	Maize	549085	8564893
18	Dorothy Kalemba	Chiwale	0.4	Soil Mulching	Maize	544232	8571390
19	Salome Mazengera	Kanyenda	0.2	Planting Pit	Maize	543058	8570293
20	Emas Chizalo	Kanyenda	0.02	Soil Mulching	Maize	541962	8569589
21	Willi Chimwendo	Mphungu	0.1	Soil Mulching	Maize	547989	8551820
22	Noel Mvula	Chipembere	0.4	Soil Mulching	Tobacco	556991	8558865
23	Isaac Banda	Kabapha	0.7	Soil Mulching	Maize	541336	8553073
24	Christopher Banda	Kapawala	0.1	Soil Mulching	Maize	553469	8550725
25	Richard Soko	nduka	0.1	Soil Mulching	Maize	558635	8575773

26	Moses Kwindangawo	Msosula	0.02	Planting Pit	Maize	549711	8563092
27	Eneless Kamwendo	Chinkhombwe	0.02	Soil Mulching	Maize	555973	8562466
28	Tilasi Banda	Bondo	0.01	Contour tied ridges	Tobacco	558399	8547515
29	Nelo Kampira	Madzaela	0.8	Contour tied ridges	Maize	557930	8562153
30	Samson Phiri	M'biya	0.4	Contour tied ridges	Maize	555269	8557221
31	Alex Banda	M'biya	0.4	Contour tied ridges	Maize	554799	8555969
32	Ellias Banda	Chiphaso	0.6	Contour tied ridges	Maize	552138	8553151
33	Ome Zimba	Dawa	0.5	Contour tied ridges	Maize	555973	8569745
34	Cecilia Nkhoma	Yasenya	0.4	Planting Pit	Maize	549242	8555578
35	Wupe Mseko	Yasenya	0.5	Soil Mulching	Maize	549868	8556674
36	John Mbewe	Linga	0.7	Contour tied ridges	Maize	547519	8556282
37	John Bema	Nduka	0.3	Contour tied ridges	Maize	556 599	8577652
38	Josoya Kuchilumba	Chiwelera	0.8	Contour tied ridges	Maize	552999	8570216
39	Tonny Banda	Chipembere	0.4	Contour tied ridges	Tobacco	538048	8573973
40	Makaka Banda	Chindevu	0.3	Contour tied ridges	Soybeans	551746	8564814
41	Veronica Kaunda	Chiwale	0.8	Infiltration pits	Maize	542823	8571546
42	Jessy Khumbanyiwa	Kapyela	0.6	Soil Mulching	Maize	538361	8567476
43	Laston Kamwana	Madziaela	0.3	Soil Mulching	Maize	557382	8559570
44	Yalenga Kaunda	Chiwengu	0.85	Soil Mulching	Maize	557382	8552603
45	Chikondi Kudakwawo	Kabapha	0.25	Contour tied ridges	Maize	541570	8552525
46	Rashid Moffat	Tena	0.7	Soil Mulching	Tobacco	534134	8550411
47	Padziko Kamoyo	Msokera	0.28	Soil Mulching	Maize	546502	8557065
48	Hilda Zakumtima	Linga	0.54	Soil Mulching	Maize	548850	8557300
49	Desmoni Mhango	Chipembere	0.45	Contour tied ridges	Maize	554956	8558787
50	John Zinaumaleka	Gaga	0.8	Soil Mulching	Maize	539276	8563474
51	Vest Chisale	Kabuluzi	0.75	Soil Mulching	Maize	553874	8555044
52	Okondeka Vitsitsi	Bondo	1.3	Contour tied ridges	Maize	557393	8547313
53	Ulemu Zidana	Kaswamchinji	0.43	Soil Mulching	Tobacco	536199	8556355

54	Willy Mkandawire	Suza	0.9	Soil Mulching	Maize	551639	8568579

7.5 Soil moisture sampling fields

No	Name of farmer	Treatment	Village	Area of field (Ha)	Latitude	Longitude
	Zone A					
1	Josoya Kuchilumba	Contour tied ridging	Suza	0.78	551283	8568286
2	Willy Mkandawire	Mulching	Kanyenda	1.23	544205	8569742
3	Mike Banda	Control	Dawa	0.8	555913	8569940
	Zone B					
1	Antony Yezi	Contour tied ridging	Changalawa	1.3	530248	8549832
2	Rashid Moffat	Mulching	Tena	1.6	536003	8550493
3	John Ngoleka	Control	Kabapha	1.2	541493	8557505
	Zone C					
1	Tilasi Banda	Contour tied ridging	Chimwala	1.7	552076	8555443
2	Yalenga Kaunda	Mulching	Chiwengo	0.8	559022	8552874
3	Mizeki Mwale	Control	Madziela	1.7	557037	8558960

7.6 Random Consistency Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49