APPLICATION OF GIS TO DETERMINE SUITABLE SITES FOR SURFACE RAINWATER HARVESTING IN A SEMI-ARID CATCHMENT

A Case Study of Notwane Catchment

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A Case Study of Notwane Catchment

By

Tshegofatso Mosate

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

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a dissertation entitled: *Application of GIS to Determine Suitable Sites for Surface Rainwater Harvesting in a Semi Arid Catchment: The Case Study of Notwane Catchment* in (Partial) fulfilment of the requirements for the Degree of Master in Integrated Water Resources Management of the University of Dar es Salaam.

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Date:...

DECLARATION

AND

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

Signature...

ACKNOWLEDGEMENT

DEDICATION

I dedicate this to my beloved, wonderful family whom I spent eighteen months away from them studying, sorry for the pain I put you through. It has never been easy being away but God provided a way. I am forever grateful for his mercies that he brought upon us. He deserves the honour and glory. To my beloved husband, this is for you honey XoXo.

LIST OF ABBREVIATIONS

BNWMP	Botswana National Water Master Plan
cm	Centimetre
CN	Curve Number
CR	Consistency Ratio
DEM	Digital Elevation Map
DFRR	Department of Forestry and Range Resources
DMS	Department Meteorological Services
DSM	Department of Surveys and Mapping
DSS	Decision Support System
DWA	Department of Water Affairs
ERDAS	Earth Resources Data Analysis System
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GIS	Geographic Information System
IWRM	Integrated Water Resources Management
m	Metre
mm	Millimetre
MoA	Ministry of Agriculture
RWH	Rainwater Harvesting
SADC	Southern African Development Community
SCS-CN	Soil Conservation Services-Curve Number
SDRN	Sustainable Development Research Network

UNDP	United Nations Development Program
UNEP	United Nations Environment Program
USGS	United State Geology Survey
UTM	Universal Transverse Mercator
WGS	World Geodetic System

ABSTRACT

Assessment of potential surface runoff harvesting sites is an important undertaking in a country like Botswana, where high spatial variability in rainfall and recurrent drought and flash floods are common. Surface rainwater harvesting (RWH) is being practiced in various areas in the country however its full potential has not yet been thoroughly explored and remains untapped. This study employs the GIS-based multi criteria decision support approach in the identification of potential sites by cost-effectively integrating a number of factors in attempt to explore the full potential of surface RWH systems that takes into consideration effect of high evapotranspiration on open surfaces water bodies among other factors. The analysis, shows that of the total 15,706 km^2 of the catchment area, only 10% has potential for surface runoff harvesting and about 37% of the Notwane catchment is not suitable for macro RWH whereas only 16% of the area is moderately suitable and 65 % marginally suitable. The developed surface RWH suitability criteria were used to assess the existing water management structures in the basin. The analysis shows that 39% of existing small agricultural dams fall within suitable potential site class whilst 17% are in the marginally suitable potential sites. Moreover, using this GIS based approach, it was realised that the study area has a potential for underground water storage (sand and surface storage), though further investigations are needed which can reduce impacts of evapo-transpiration. In conclusion, it was noted that providing accurate and precise spatial representation of the physiology and land use for the analysis of runoff generation potential site within the study area is an important step in developing an integrated strategy for surface rainwater harvesting plan for any catchment and the decision support system has proved to work.

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CHAPTER ONE

INTRODUCTION

1.1   General Introduction

Integrated Water Resources Management (IWRM) recognises that water is a precious, finite and vulnerable scarce resource that has many competing uses (Scoullos *et al.,* (2002). The current global climate change/variability, rapid population growth and blooming of economic development activities is even putting more pressure on the resource and it is now becoming vulnerable and depleted especially in semi arid to arid regions where rainfall is low and erratic.

Recurrent drought and flash floods are becoming common phenomenon in these regions. Issues of increased water demand and reduced water availability for various purposes are becoming more critical in these places. The United Nations Environment Program (UNEP) estimates that over two billion people by 2050 will live under situations of high water stress, which would be a limiting factor for future development in many countries around the world (Sekar and Randhir, 2007). It is already happening to some arid to semi arid regions, including Botswana (BNWMP, 2006). Figure 1.1 below shows the climatic zones of Botswana.
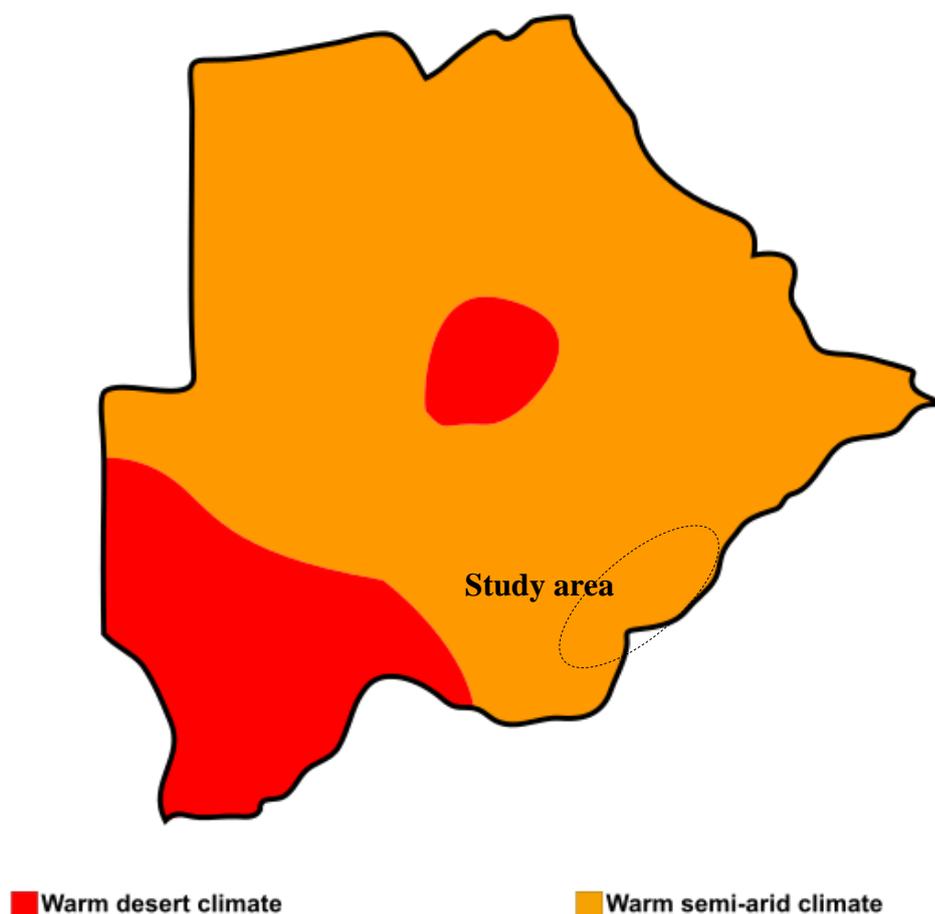
(Source: Tsheko ,2006).

Figure 1.1: **Botswana Map of Köppen Climate Classification**

Drought is the most serious natural hazard facing Botswana especially in the Limpopo river basin in terms of severity and frequency of occurrence. The most seriously affected water users in this river basin are the pastoralists and agro pastoralists whom are faced with frequent decrease in water availability or soil moisture to considerably below normal or expected amount to barely meet basic water requirements (Government of Botswana, 2013). This is even threatening the sustainability of water supply in this river basin on the Botswana side where almost

two thirds of the country's population lives (Statistics, 2014) and rain fed agriculture is the predominant farming system. Consequently the water users in this area suffer from livelihood losses, hunger, conflict and internal displacements since now the government has implemented a water allocation monitoring tools which ensures efficient water allocation based on how much is contributing to the Gross Domestic Product per capita (GDP) without neglecting the fact that water is a basic human need .

Botswana as a country, need to further look into other unconventional water sources that takes into consideration effects of high evapotranspiration rate on open surface sources. This should be done in order to improve the reliability of water supply in general and the productivity of small-scale rain fed agriculture in the South Eastern margins of the country by adopting strategies that ensure increased water quantity. Climatic uncertainty and aridity conditions are the major challenges facing water resources management in this area (Parida *et al*., 2006). These challenges are mainly connected to poor temporal and spatial rainfall distribution and high evapotranspiration rate rather than acute water shortage (BNWMP, 2006).

Semi arid to arid areas have unpredictable rainfall patterns, both in amount and time. This makes the ability to effectively manage the resulting effective runoff extremely vital (Mbilinyi *et al*., 2013). Rainwater harvesting (RWH) has been identified at a number of global platforms as one of the significant interventions necessary towards reaching the Millennium Development Goals in African continent (Rima and Hanspeter, 2013). It improves water productivity by mitigating temporal and spatial

unevenness of rainfall distribution and provides water for basic human daily needs and other small-scale productive activities (Mwenge *et al*., 2007b).

Rainwater harvesting can be described in a broad sense as all methods that ponder, stock up and collect effective runoff from rainwater, for various purposes (Rockström, 2000). These methods can be categorised into three main systems when categorised according to the type of catchment surface used, which are in-situ, ex situ and domestic RWH system. The domestic RWH system collects water from the roof tops, court yards treated surfaces and stores it storage tanks whereas ex-situ (macro) RWH system uses uncultivated areas as its catchment area and in-situ (micro) RWH system uses part of the target area as the catchment area (Falkenmark and Rockstro¨m, 2004).

Efforts have been put in place by the Government of Botswana to increase availability of water in this dry area through water importation by transfer schemes and water saving technologies to meet its demand for domestic and industrial purposes. Several techniques for harvesting rainwater such as dams and roof top rainwater harvesting have been practised. However these efforts are not bearing any fruits as there are continued challenges of aridity and climatic uncertainty where annual rainfall is of low average and its spatial distribution is highly variable in space and time (BNWMP, 2006). The study area is a water deficit area. The mean annual rainfall varies from lower than 250 mm in the extreme South West of the country to more than 650 mm in the extreme North (BNWMP, 2006).

Botswana's full potential on surface rainwater harvesting has not yet thoroughly been explored and many past researches envisage that, knowing the full potential of this intervention could improve the water scarcity issue both in space and time for various productive uses (Naidu and Gould, 2007). With rapid growing global water shortage crisis, there is an urgent desire to come up with cost effective and less time consuming techniques for determining and locating areas that are highly suitable for introducing runoff harvesting structures in those areas where such innovations are most needed.

Surface rainwater harvesting is a hydrological involvement which can best be represented through hydrological models that have the ability to show flow direction, runoff concentration and collection areas and ultimately areas of great impoundments on a large spatial extent scale. Geographical information system (GIS) has the capability to perform the above mentioned. It has the ability to extract key hydrological parameters which can be used as inputs into other hydrological models. It provides a useful approach to the above mentioned because it provides an environment for collecting, storing, analysing, transforming and displaying non spatial and spatial data for particular purposes (Coskun and Musaoglu, 2004).

1.2   Statement of the Problem

The South Eastern part of Botswana, as a semi arid area experiences periods of dry spells alleviated by low and unreliable rainfall which is unevenly distributed in space and time and faces challenges of recurrent droughts that jeopardises the success of

rain fed agriculture and general water availability in the area, coupled with high water demands (BNWMP, 2006).

As a result of this, management of water resources is faced with serious problems of water scarcity, shortage and untapped full potential of water supply strategies. This calls for urgent attention. In addition to these problems, management of water resources is faced with challenges of lack of scientific and technical decision support tools that guide effective monitoring and evaluation of existing water management policies to guide current and future integrated water resources management, development and water efficiency (Department of Water Affairs- Ministry of Minerals, Energy & Water Resources., 2013). Hence calls for a more comprehensive strategies guided by effective management tools to address this water scarcity issues such as targeting efficient use of rainfall where it falls. Rainwater harvesting appears to be one of the most promising alternatives for various purposes but there is a greater need to assess and identify its potential at a large spatial extent in order to achieve maximum efficient use of the unevenly distributed rainfall where it falls.

1.3   Research Objectives

1.3.1   Main Objective

To assess and determine potential runoff harvesting sites in a semi arid catchment using an integrated spatial Decision Support framework.

1.3.2 Specific Objectives

i. To estimate the potential runoff in Notwane sub Catchment using rainfall-runoff model.

ii. To assess and map potential surface rainwater harvesting sites in Notwane sub Catchment.

1.4 Research Questions

i. What is the potential runoff volume at each point generated by Notwane catchment?

ii. Where on Notwane catchment can surface rainwater harvesting be considered?

iii. Do the existing and water management structures fall within the vicinity of the identified rainwater potential sites.

1.5 Justification of the Study

The purpose of this study is to apply and suggest a GIS framework to determine potential rain water harvesting sites in a semi arid catchment of Notwane where surface rainwater harvesting can be a strategy towards addressing the water quantity issues especially considering the temporal and spatial distribution of the rainfall as well as high evapotranspiration rate for better understanding of water supply management options for mitigation and adaptation to fresh water scarcity.

The assessment and identification of the potential surface rainwater harvesting site is aimed at increasing the efficient use of rainfall where it falls and can help to facilitate

catchment development planning, implementation and promotion of rainwater harvesting initiatives, as well as monitoring and continual evaluation of land and water resources in interest areas. This will ensure maximisation of water availability in drought prone areas; ultimately leading to improved land productivity and the overall sustainability of catchment by informing the policy makers with scientific information, evidence and planning the impact strategies of future similar situations.

1.6   Scope of Study

Through this research, the full potential of the spatial extent of Notwane catchment to harvest rainwater based on surface catchment was assessed by the use of GIS based Decision Support Systems (DSS) and suitability of potential sites were mapped for various technologies and even explored the potential for underground water storage particularly the sand dam. At the end a GIS based decision support framework was recommended based on the results to water managers for future water development projects.

CHAPTER TWO

LITERATURE REVIEW

2.1   Water Resources Assessment

According to literature in most part of the world, population and economic development are increasing at a fast rate and adequacy in water supply to meet societal and economic needs and to ensure equitable access to the resource is one of the most pressing and significant challenges faced by decision-makers in water resources management (Rima and Hanspeter, 2013).

The Authors further mention that besides the challenges to cope with water scarcity and stress due to climatic variability, in semi arid regions, opportunities are being discovered through the increased knowledge about productive sustainable land and water management systems, particularly in areas of increase water availability through integrated assessment and identification of potential surface rainwater harvesting sites that are sustainable. It is further said that these areas have the potential to become at least self-sufficient or even net exporters of food. Hence nations have been called to come up with comprehensive strategies to address water scarcity, rain water harvesting was one of the adaptive strategies to address issues of water quantity but it has to be done is an integrated approach in order to ensure sustainability (Rockström, 2000).

Many research studies such as the one conducted by Rima and Hanspeter (2013), Munyao (2010) and Mbilinyi *et al.* (2013) have identified the use of rainwater

harvesting practices as an adaptive strategy to coping with water shortage and recurrent droughts in most semi arid regions where rainfall is highly erratic, and often associated with convective storms, that are extremely variable in space and time and have very high rainfall intensity (Lebel *et al.,* 2015)*.*

Integrated learning of runoff model, remote sensing and GIS has in recent times gained significance in targeting suitable locations for water recharging and or harvesting structures. These researchers work, aimed at prioritising the area suitable for water harvesting by taking into consideration parameters such as runoff physiographic characteristics such as soil type, land use and antecedent soil moisture, environmental and socio economic conditions The full potential for the Notwane catchment to practice rain water harvesting is not yet fully known, but efforts have been made to acknowledge and appreciate its existence (Kamutati, 2000). It was done aiming at reducing reliance on the national water supply and most people used it during times of water rationing and it is only done at household level targeting rooftop rainwater harvesting catchment.

2.2   Assessment of Potential Surface Rainwater Harvesting Site

2.2.1   Application of GIS to Identify Surface Rainwater Harvesting Sites

According to Walsh (1992), solving complex water resources challenges require both spatial representation of the water resources system and an insight into water resources problems (Walsh, 1992). Over the years, the use of GIS and remote sensing technology has gained much needed support and has closed the above mentioned gap. This has motivated many water researchers to combine GIS and DSS

to explore a range of planning and management scenarios in water resources management at basin level (Georgakakos *et al*., 2002).

Integration of the GIS and hydrological model provides unique advantages for sustainable water resources management since they provide spatial representation, comprehensive database, and modelling capability. A lot of studies have applauded it to work in most parts of the world where data is limited (Forkuob *et al.*, 2013).

Several researches using application of GIS have been employed by different researchers to identify suitable surface rainwater harvesting site in semi arid region where data availability is limited (Giupponi and Sgobbi, 2013). Similarity distinguished in most of these methods worth noting is the generation of various thematic maps from remotely sensed data (such as aerial photography and satellite images) which are overlaid in a GIS environment to assess the suitability for potential surface rainwater harvesting (Mbilinyi and Tumbo, 2013). In most of those studies, the application of GIS was used as both data management and modelling tool for spatial and non spatial data analysing. Senay and Verdin (2004) in Mwenge *et al.* (2008*)* used runoff data acquired from monthly point measurement rainfall data and used the SCS curve number model to generate baseline maps for surface rainwater harvesting potential in Africa.

In recent surface catchment rainwater harvesting studies, some authors such as Ramakrishnan *et al.* (2007) used spatial parameters like fracture patterns, runoff potential and micro catchments. They used SCS-CN method to derive the potential

runoff, which was expressed it in terms of runoff coefficient. They also included IMSD FAO specifications for recharge structures parameters such as effective storage rock mass permeability to augment effective storage. After identifying potential surface rainwater harvesting sites they conducted field survey in the study area to verify and assess the suitability and followed by implementation. Other authors such as Mati *et al.* (2006) and Mbilinyi *et al.* (2006) used baseline thematic maps such as soil depth and texture, rainfall, topographic maps, limited field surveying and population density to produce composite maps that show attributes that serves as indicators of suitability for location specific rainwater harvesting projects.

Kadam *et al*. (2005) considered parameters such as geology and hydro geomorphology as per integrated mission for sustainable development specifications for determination of structures. They used bio physical parameters including drainage networks. Remarkable credit must be given to Kahinda *et al.* (2008) for incorporating socio economic factors into the methodology used, that enables water resources managers to assess and investigate the suitability of surface rainwater harvesting which other previous studies did not include.

Most literature recognises that omission of socio economic factors results in failure of most rainwater harvesting projects. Suitability maps for surface rainwater harvesting were developed from integration of socio economic, ecological and physical factors. Habangana and Aliwa (1993) employed the use of average rainfall data, rainfall fluctuation rate and annual rain days and combined them with

topographic factor whilst Prinz *et al.* (1998) mainly used remotely sensed data, coupled with field survey for ground truthing and thematic maps.

2.2.2 Factors Affecting the Identification of Potential Harvesting Sites

Six key factors are outlined by FAO (2003) that are considered when identifying surface rainwater harvesting sites that needs to be overlaid in GIS environment so that successful suitability model for surface rainwater harvesting can be developed. These factors include; slope (topography), land use/cover, rainfall (climate) and hydrology (rainfall-runoff relationships), soil (structure, texture and depth) and socio-economic issues (accessibility, related project implementation cost, population density, workforce, water laws, peoples priority and land use,) of the area under consideration.

2.2.2.1 Slope

Prinz *et al.* (1998) suggest that slope gradient and relief factors play a very crucial role in assessing the method of surface rainwater harvesting system especially in the context of runoff generation since it influences the recharge and infiltration of a given area. Thus different RWH technologies depend on the slope type of a particular area. Catchments with steep slope are better placed to ensure high runoff efficiency. However, according to FAO (2003), catchments with slopes greater than 5% are more susceptible to high soil erosion rates. Hence, in a study conducted by Hatibu and Mahoo (1999) recommended that steeper slopes should be considered for soil erosion control measures.

2.2.2.2 Land Use/Land Cover

Land cover/ land use is an essential factor that directly affects surface runoff. Relationship between land cover/land use and the runoff generated at a particular known area after any rainfall event has occurred (Mbilinyi and Tumbo, 2013).

2.2.2.3 Rainfall

The rainfall factor helps in determining the available soil moisture and understanding the rainfall-runoff processes. Its magnitude plays a very important task in assessing the appropriateness of surface rainwater harvesting of a particular area. In some parts of semi-arid to arid regions such as Botswana and most Southern African countries like Zimbabwe and South Africa, rainfall events are of short duration, unevenly distributed spatial and sometimes the variability is large and in some parts intensity is relatively high causing flash floods. Therefore promoting surface rainwater harvesting in areas receiving very low mean annual rainfall or very high mean annual rainfall is not recommended (FAO, 2003). Rather the FAO recommends using a design rainfall of 67% Probability of Exceedance.

2.2.2.4 Soil

According to Hudson (1987), soil acts essentially as a pervious medium that provides several passageways for water to move into the surface. Soil texture and depth are the mostly used soil physical properties when dealing with surface rainwater harvesting. The ability of the soil to pass water through a drainage channel depends on the size of the soil particle, arrangement and degree of aggregation between them hence making soil, the principal controller of the hydrological response of the

catchment (USDA, 2004). Deep and well to excessively drained soils with low clay content generally have low runoff generation potential, especially when there are no restrictions in other soil profiles such as presence of an impermeable layer. Shallow and poorly drained soils with high clay content that are susceptible to surface crusting have high potential to generation high runoff (Schmidt and Schulze, 1987). In-situ RWH system are best suited in soils with deep soil depth soils (FAO, 2003). The land cover/land use is also a crucial component in determining the amount of initial abstraction. It represents the surface conditions in a catchment

2.2.3 Surface Rainwater Harvesting Suitability Model Framework

According to literature, the combination of multi criteria decision making methods with GIS application and remote sensing have gained noticeable confidence over recent times and has very much advanced from the convectional map overlay approaches to the land use (Malczewski, 2004; Mbilinyi and Tumbo, 2013; Munyao, 2010).

Spatial decision support system provides unique advantages for sustainable water resources management, in the sense that it has capabilities to perform spatial representation, comprehensive database, and modelling capability. According to Mbilinyi and Tumbo (2013), the suitability model framework which has adopted the analytic hierarchy process is one of the spatial decision support systems that can be integrated into a GIS environment using multi criteria evaluation from expert knowledge including indigenous knowledge which combines and analyse spatial and non spatial data and produce a resultant decision. The steps involves the utilisation of

bio-physical (socio economic and hydro-geologic) data, the decision maker's preferences (assigning weights to each thematic layer) and the manipulation of the data and preferences according to specified decision rules referred to as factors and constraints (running scenarios). Process flow diagram in Figure 2.1 illustrates the model framework mentioned above.
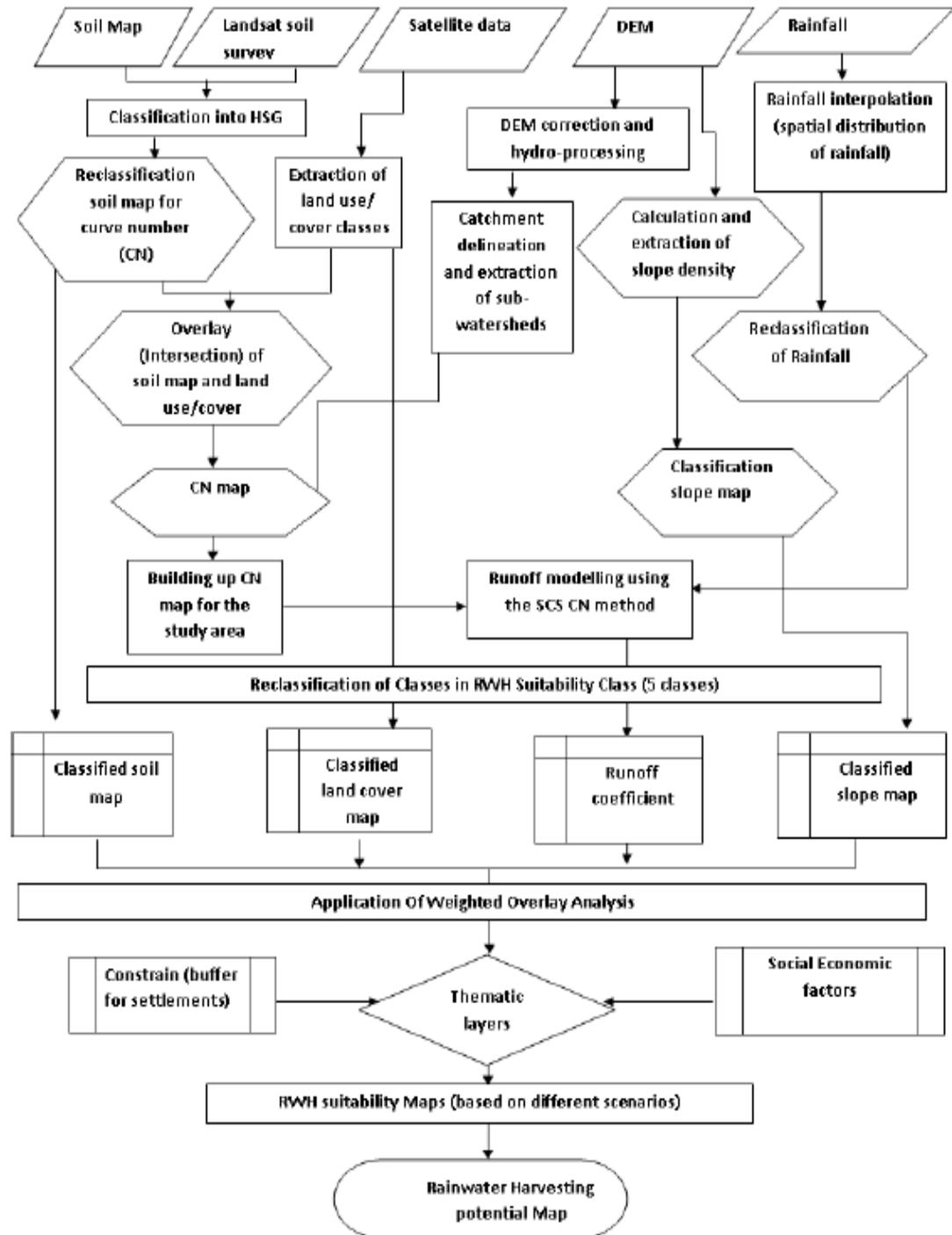
(Source: Modified after Mbilinyi and Tumbo, 2013).

Figure 2.1:   Surface Rainwater Harvesting Suitability Framework

It is worth noting that analysis of location suitability for any intended purposes makes a clear difference between the location selection problem and the location search problem. The ultimate objective in location selection analysis is to identify the best site for an intended activity from a set of potential sites. The analysis is characterised by known physical factors in a pre-identified site. But for the cause of this study, the general objective of the location search is to clearly identify the spatial extent of the best sites for surface runoff harvesting in the catchment, which will be categorised into four levels of suitability (Malczewski, 2004).

2.3   Decision Making and Selection of Potential Harvesting Sites

The use of GIS based site suitability analysis has been used over the years to identify the suitability of areas for various purposes such as in ecological approach to identify suitable habitat sites for animal and plant species, and land suitability for agricultural use.

A clear distinction is made between the site search problem and site selection problem. For the intended activity in site selection analysis, the characteristics of the potential sites are well-known and the best site is identified from a set of potential sites. The most challenging thing is to rank the alternative sites based on their characteristics so that the best site can be determined. Site search analysis is where there is no set or pre-determined set of candidate sites and the characteristics of the sites have to be set by solving the problem.

2.4 Rainfall-Runoff Coefficient Modelling in GIS Environment

Since surface rainwater harvesting technology is mainly about increasing the efficiency of rainwater by concentrating it through runoff , it is best to illustrate it through rainfall runoff models coupled with the application of GIS, since it is capability of showing the flow direction, runoff and areas of runoff concentration (Mbilinyi and Tumbo, 2013). Direct rainfall-runoff estimation is always important but in some areas is not always possible in desired time. The use of remote sensing and GIS technology has over the past been useful to overcome the problem through the use of conventional methods for estimating runoff such as the soil conservation services method (SCS-CN).

This method has been widely used by past researchers on surface rainwater harvesting studies to estimate runoff and has proven to work in most areas such as in rural areas of South Africa (de Winnar *et al*., 2007). The model uses several hydrological factors that affect runoff generation (soil type, land use, land cover and initial soil moisture condition) and has the ability to incorporating them into a single CN parameter. It creates an empirical relationship to calculate initial abstraction and runoff as a function of soil type and land use (Singh *et al*., 2015)**.** Figure 2.2 shows the SCS-CN model frame work to estimate potential runoff and its pixel based. .
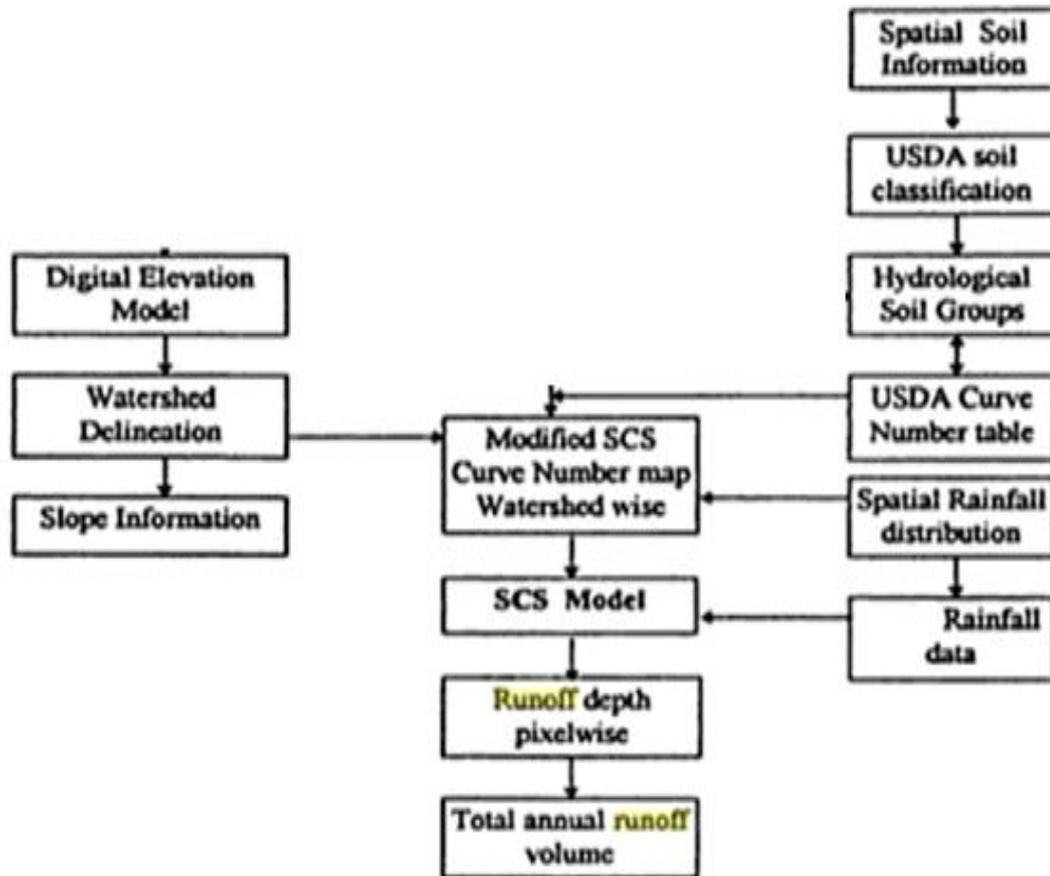
(Source: Muthu and Santhi, 2015).

Figure 2.2:   A SCS CN Method to Estimate Potential Runoff

Arnold (1986) has used this method to estimate the runoff from Wadi su'd watershed. Other authors in Mcpherson and Gould (1985) such as Hill *et al*. (1987) have used it to generate SCS curve number using raster GIS. Ngigi *et al*. (2007) used the digitised land use/cover map to derive modified SCS runoff curve numbers for Kaliaghti River Basin in India. Mcpherson and Gould (1985) investigated impacts of seasonal and monthly of effects on runoff curve number and designed the curve number for some basin in India.

CHAPTER THREE

METHODOLOGY

3.1 Description of the Study Area

3.1.1 Location and Size

The study area is situated in the South Eastern part of Botswana (Figure 3.1). It is falls within South East, Kgatleng, Kweneng districts with a total population of 715 959 (Statistics, 2014). It lies between latitude $24°S$ and $25°S$ and longitude $25°E$ and $26°E$. The study area forms part of an internationally shared Limpopo River Basin by four Southern African Development Community (SADC) countries; Botswana, Zimbabwe, Mozambique and South Africa and has a total area of 411,000 km^2 of which only 15,706 km^2 is makes up the study area.
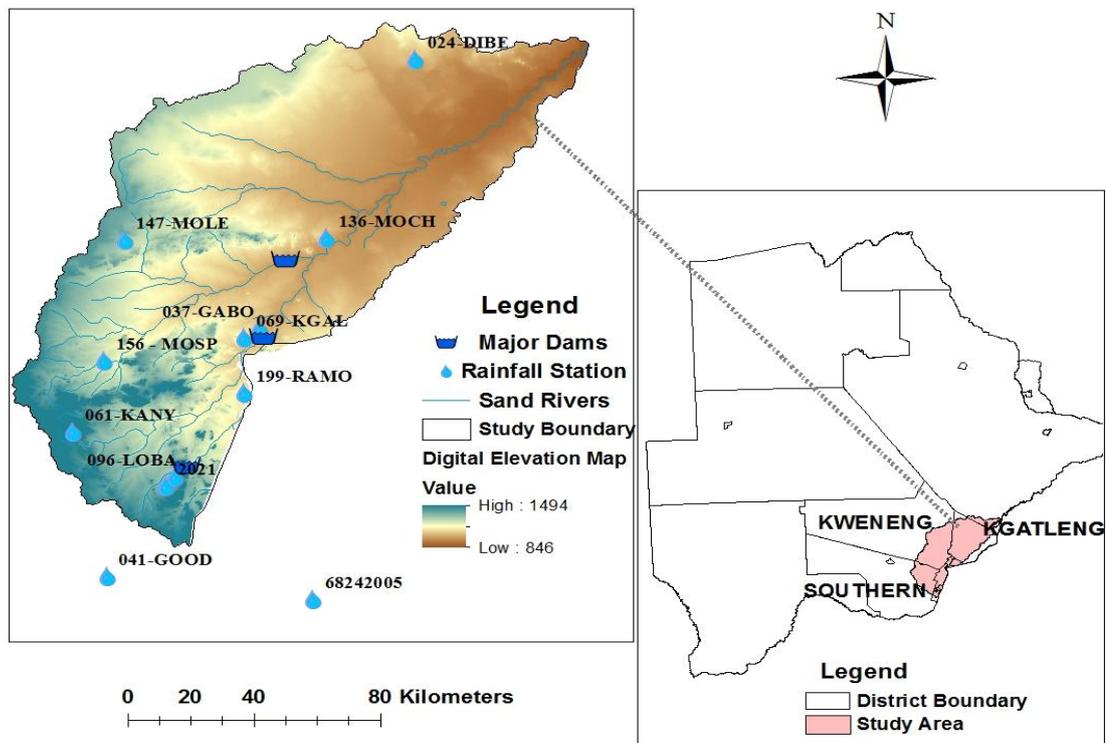
Figure 3.3: **Location of the Study Area**

3.1.2   Climate

The climate of the study area is described as semi arid. It is characterised by an average annual rainfall of between 450 mm and 800 mm with the wet season being between October and February. The synoptic year in Botswana can be sub-divided into four seasons/periods as follows, based upon sea-level pressure distribution over the African continent:

- Dry/Winter season – May to August

- Rainy/Summer season – November to March

- Spring Transition or Pre-rainy period – September to October

- Autumn Transition or Post-rainy period – April

Generally in Botswana rains are caused mainly by convectional processes resulting in thunderstorms, which typically occur as heavy localized events with a high spatial and temporal variability (BNWMP, 2006). It is influenced by tropical storms and cyclones originating from the South West Indian Ocean and moving westwards into the Mozambique corridor, where most of them short live, inducing South-Easterly subsident airflow over Botswana (EHES and SMEC, 2006).

This is a phenomenon which produces dry conditions and may sometimes lead to heat waves in the summer. A few of the tropical cyclones, however, can proceed far westward, reaching Botswana as low pressure centres, and bringing unusually heavy rainfall to the Eastern parts of the country, as happened during Cyclone Eline. Botswana has a saucer-like physiographic characteristic, which result in lack of

major barriers to the flow of moist air and orographic influences on making of clouds, leading to virtually non-existent precipitation (Moalafhi and Tsheko, 2012).

3.1.3 Physiography

The study area is characterised by more or less undulating slopes, which intersect with watercourses at some point. In general, the topography can be said to be hilly with some areas having rocky outcrops and hardveld. The altitude of the area ranges between 1494 m to 942 m above sea level. It is characterized by several groups of relatively small hills, often with flat tops at medium relief range of 200 m -400 m above the base and it is mostly dominated by sedimentary rock (Lungu and Sefe, 1988).

3.1.4 Hydrology

The flow direction of the South Eastern part of Botswana is mostly towards the North Easterly direction, coming from the Eastern part and it drains into the left bank of the Limpopo river and some flows of the drainage streams originates from South-Africa in the North West Province. It produces 19.9 million cubic meters mean annual volume and the flow is un-gauged (BNWMP, 2006). The catchment is made up of three main rivers which are Notwane, Metsimotlhabe and Thagale river systems. There are two large reservoirs in the study area that are the main water supply sources for domestic and industrial water supply to Gaborone and surroundings areas. About 200 small agricultural earth dams have been constructed in the area to argument agricultural water demand.

3.1.5   Soils

The study area falls within the hardveld region and has more diverse and hard geological base. The soils are mostly of the parent luvisols with field soil moisture capacity averaging about 90 mm. Ferralsols and acrisols occur as traces in the South Eastern Botswana and North Western province in South Africa (Joshua, 1991). There is also an extensive occurrence of Arenosols and Regosols which are dominant on sandstone and sandy surface deposits. Van Der Merwe *et al*. (1999) suggest soils especially those with vertic like properties are prone to suffer from crusting, runoff, erosion and other forms of land degradation.

3.1.6   Socio-Economic

Some of the socio economic activities in the basin include sand and quarry mining, tourism and agriculture. Most agricultural operations in the South Eastern part of Botswana are at the subsistence level. There are a number of game reserves and sanctuaries located in the catchment which include Mokolodi Game Reserve and Gaborone Game Reserve, and a number of private game farms (BNWMP, 2006).

3.1.7   Land Cover

Vegetation occurrence is dominated by *croton gratissimus* woodland on rocky outcrops and hills. The Taung and Nnywane rivers are dominated by the hardveld and the occurring vegetation is *rhus leptodictya* tree savannah.

3.2   Data Collection

3.2.1   Description of Available Data and Field Observations

Since the general objective of this study is to identify potential surface rainwater harvesting sites, the results are based on the use of representation of spatial variations in landscape characteristics such as soil, slope, land use/land cover and rainfall which were collected from different Governmental Departments.

The methodology employed for this study is illustrated in Figure 2.1 in section 2.2.3 of chapter 2. It consisted of three stages thus; the pre-processing, main processing and mapping of potential harvesting sites. The pre-processing involved the collection of primary data such as coordinates of major features in the study area and onsite soil analysis. The secondary data involved collection of observed meteorological data (rainfall) from the Department of Meteorology Services and several shape files from different Governmental Departments, (Table 3.1) for the data collected.

Table 3.1:   Data Collected for the Study

DATA	TYPE	CHARACTERISTIC	SOURCE	USE
30*30 DEM	Spatial (raster format) Datum: WGS 84	DEM 30m*30m	(http://gdex.cr.usgs.gov/gdex/).	Delineation of the catchment
Shape files	Spatial	• Soil (1:250 000) • Land use/cover (1:250000) • 5m Contours(1:5000) • Croplands (coordinates points) • Existing water management structures(dams)	MoA, DWA, DFRR, DSM.	• Input into RWH potential site suitability framework and SCS CN for runoff computation) • Constraints for socio economic factor • DWA and MoA
Rainfall (mm)-15 stations	Point measurement	1966-2015	DMS	• Input into the SCS CN model to estimate potential runoff.

Surface rainwater harvesting technologies considered for this study was grouped into two broad categorise thus macro and micro rainwater harvesting systems. The results were then statistically analyzed using spatial statistically analyst tool in Arc GIS 10.1 to see percentage area coverage of land suitability for different on ground rainwater harvesting technologies in the study area.

3.3   Data Preparation and Pre-Processing Analysis

Five criteria were chosen for the determination of potential rainwater i.e. runoff coefficient, slope, drainage, soil texture and land use/land cover factors (Mkiramwinyi, 2007).

The soil texture and soil depth map was created from the soil data shapefile and the limited field survey conducted during data collection. A slope map expressed in percentage was created using ArcGIS 10.1 from a hydrological correct DEM. The recent land use/land cover map was downloaded from Landsat ETM+ and through the help of personnel from the Department of Surveys and Mapping; several land cover classes were identified. After creating all the necessary thematic layers, each thematic layer was re-classified and rasterised into four classes of level one to four according to their level of suitability (Table 3.2).

Table 3.2:   Reclassification of each Thematic Layer into Level of Suitability (Source: Modified after Ritung et al., 2007).

Class Group	Suitability Level	Description
Class 1	Suitable	Land having no limitation to sustain a given land utilisation type.
Class 2	Moderately suitable	Land with minor limitations which when combined together is less severe to sustain the intended activity.
Class 3	Marginally suitable	Land having limitations which when combined together are moderate to sustained the intended activity and will so reduce productivity
Class 4	Not suitable	Not Suitable as the range of inputs required is beyond the set requirements.

Since the datasets were collected from different sources and different organisations at different scales, to account for the different resolution, a cell size of 100 m by 100 m was adopted when rasterising the re-classified vector layers into a raster format for further analysis. The suitability of surface rainwater harvesting technology was done by overlaying a set of criterion affecting individual surface rainwater harvesting technology. This criterion was based on filed observation conducted during data collection (appendix A) and extensive existing literature review based on the past experience of implementing, lesson learnt of such technologies.

3.3.1   Land Use/Land Cover

Limited field survey was conducted in the study area to familiarize with the land use/ land cover and identify land use/cover in the area which was used as control points Landsat ETM+ data were acquired from FAO-SDRN and the Regional Remote Sensing Unit. Channels 1, 3 and 4 of the Landsat ETM+ (Path172 Row 077 2015) images were used to create the land-use/land-cover map. Manual and semi-automatic classification was carried out using ERDAS software. The study area land use/ land cover database was extracted using the study area boundary, edited and projected to UTM Zone 35 South, in ArcGIS 10.1 for further analysis

3.3.2   Digital Elevation Map

The hydrological parameters such as flow accumulation, stream network and slope were acquired from the hydrological corrected Digital Elevation Model (DEM). The corrected DEM was created from the 5 m by 5 m contour shape-file acquired from Department of Surveys and Mapping, river network shape-file and 30 m by 30 m

downloaded DEM using Arc GIS 10.1 package. It was done so as to improve the course resolution of the 30 m by 30 m downloaded DEM.

This plays the same role as the 5 m contours and relief shading but it has an additional advantage of providing a powerful analytical perspective. Arc GIS 10.1 was used to extract hydrological parameters. All sinks were filled before estimating any parameters in order to ensure continuity of flow to the catchment outlet. Figure 3.2 shows the DEM for the study area. The topography ranges from high 1494 masl to 843 masl with most high lands in the western part of the study area. The low lands are on the North East of the catchment.
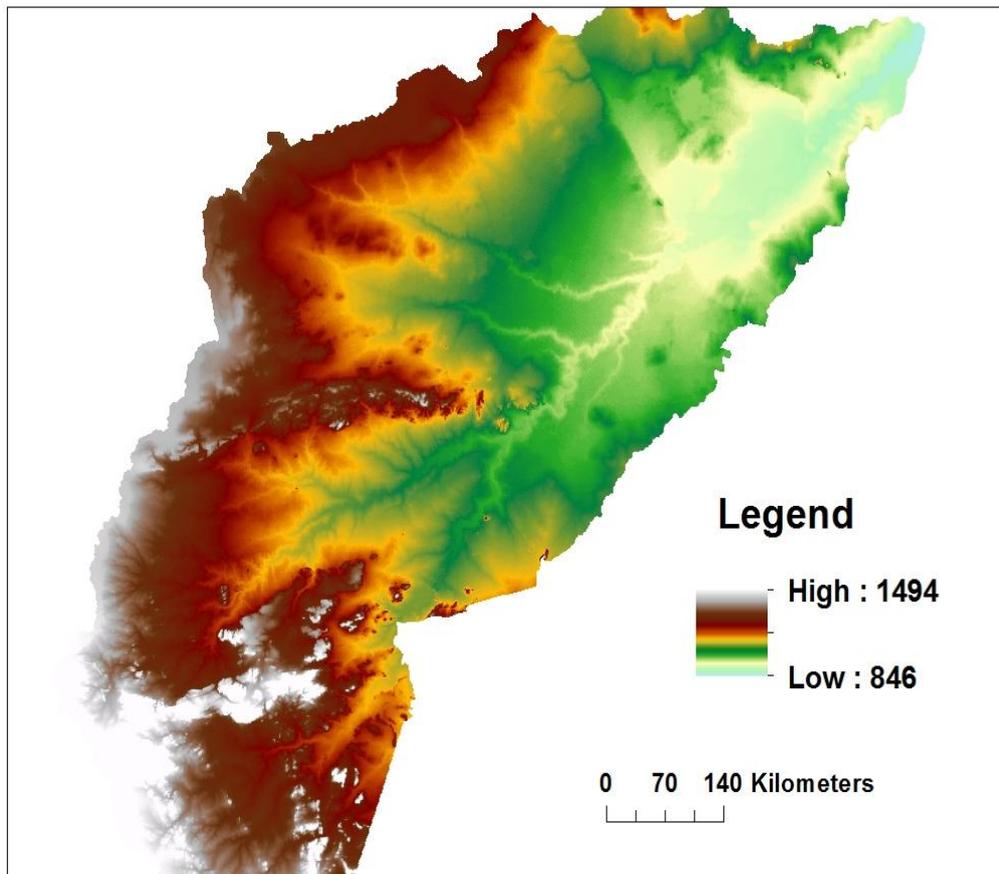
Figure 3.4:   Digital Elevation Map of the Study Area.

3.3.3 Slope Density Analysis

Slope is defined as the ratio of the elevation difference between two points to the horizontal straight distance between the two points (FAO, 1994). It is calculated from a relief ratio. In surface rain water harvesting assessment, it is an important factor, combined with other factors for site location and implementation of all ground based rain water harvesting technologies since it depicts areas with preferable high proportion of surface runoff.

A hydrological improved DEM was used to create slope density, expressed in percentages in a GIS environment. The slope steepness helps in understanding the nature of terrain of the study area which affects the runoff characteristics thus recharge and infiltration capacity. It helps to locate area of maximum water or storage collection areas. Steep areas with high rainfall are usually considered as suitable sites for generating significant runoff (de Winnaar *et al.*, 2007). The calculated slope density was then re-classified according to FAO slope classification guidelines (Table 3.3).

Table 3.3:   Slope Classification (Source: de Winnaar et al., 2007).

No.	Relief	Slope %
1	Flat	<3%
2	Undulating/gently sloping	3 – 8 %
3	Sloping	8 – 15 %
4	Hilly	15 – 30 %
5	Mountainous to steep mountainous	>30 %

3.3.4 Soil Map Analysis

A digital soil data together with its metadata was obtained from the Botswana Ministry of Agriculture at a scale of 1:100 000. The study area was clipped out of the whole country data using ArcGIS and projected to UTM Zone 35 South for further analysis.

3.3.5 Rainfall Analysis

Pre-processing of the rainfall data included quality check using double mass curve technique. The mean annual rainfall values were interpolated to estimate rainfall for areas not having rainfall point measurements.

Rainfall gauge stations i.e. ground monitoring point data was used to generate rainfall map in a GIS environment through spatial interpolation, and thereby generating data in areas with no data. A theissen polygon was used to see how much each gauging station contribute to the catchmemt. Figure 3.3 shows the spatial distribution of rain-gages in the study area.
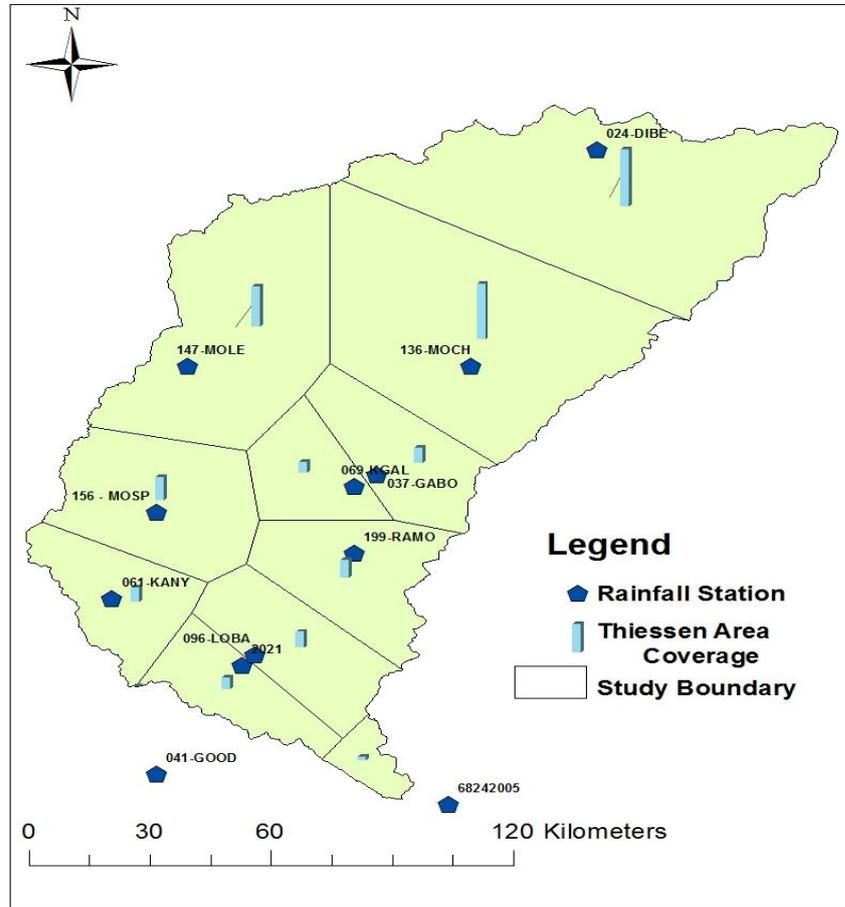
Figure 3.5:   Distribution of Rainfall Stations in the Study Area

Kriging interpolation method was used. This method is commonly used to estimate

values at unmeasured locations and to also get the spatial variability of the rainfall

across an area or a catchment (Longley, 2011). The key interpolation of this

technique relies on the possibility to estimate values based on observed z values of

neighbouring 18 data points, which are weighted with regard to spatial covariance

values. The technique relies on both the geographic location and the distance of

known data points when estimating values in unknown locations. However this does

not only depend on the distance but rather on the overall spatial arrangement of the

measure points. The technique uses the following general formula for interpolation;

$$Z(So) = \sum_{j=1}^{n} \lambda_j Z_j (S_j) \qquad (3.1)$$

Where:

Z (sj) is the measured value at the jth site.

j is unknown weight for the measured value at the ith site.

n is the number of measured values.

Z (So) is the predicted value.

3.4   Estimation of Runoff Depth Using SCS CN Model

Since harvesting of runoff is a hydrological intervention, it can best be explained by

hydrological models which have the capability to show flow direction, point of

runoff collection areas and ultimately areas of great impoundments on a large spatial

extent scale. GIS has the capability to perform the above mentioned. It has the ability

to extract key hydrological parameters which can be used as inputs into other

hydrological models.

The SCS CN method has widely been used to estimate the surface runoff from a

given rainfall event. de Winnar *et al.* (2007) have used this method to determine

runoff available for assessing the potential of Thukela River Basin to harvest

rainwater. Hence the SCS CN method has been adopted for this study to estimate the

runoff depth. Land cover/land use map and soil texture map (which was reclassified

into hydrological soil group using the United States Department Agriculture

classification system, were used to derive curve numbers that were used to estimate

runoff depth of the study area. The runoff depth has been calculated using the output

of the Soil Conversation Service model to plan for rainwater water harvesting (Gupta and Deelstra, 1997). This equation can be expressed as the following

$$Q = \frac{(P-la)^2}{(P-la)+S} \qquad (3.2)$$

Where:

Q is runoff depth (mm)

P is rainfall (mm)

S is potential maximum retention after runoff starts (mm)

I_a is initial abstraction (mm)

Initial abstraction (l_a) refers to the losses before runoff is generated thus; infiltration, evaporation and water intercepted by vegetation (Melesse *et al*., 2002). I_a recommended for the study area by Joshua (1991) is 0.3S based on the reason that Arenosols are the major dominating soil group in the area and have are somewhat excessively drained with initial rates being much higher. Therefore, referring to Equation 3.2, the SCS equation can be expressed as:

$$Q = \frac{(P-30)^2}{(P-70)+S} \qquad (3.3)$$

Where

S is potential maximum retention after runoff starts (mm)

Q is runoff depth (mm)

The model relies on the runoff Curve Number (CN) which is calculated via the effect of soil and land cover on the rainfall-runoff processes. It ranges between 1 (where there is 100% rainfall infiltration and no effective runoff produced) to 100 (where there is 0% rainfall infiltration and high effective runoff is produced). Curve Number with low values indicates low runoff potential, whereas curve number with high values represents high runoff potential (Melesse *et al.*, 2002).

The S which is the potential maximum storage can be estimated by using the curve number as shown in Equation 3.4;

$$S = \frac{25400}{CN} - 254 \qquad\qquad (3.4)$$

Where;

   S is potential maximum retention after runoff starts (mm)

   CN is curve number

3.4.1   Evaluating Curve Number for the Study Area

The curve number is calculated per each pixel using the combined land cover and soil maps as input factors. This curve number characterizes the runoff properties of these two layers combined.

It is used as input variable in the SCS CN model (Singh *et al.*, 2015). The model groups all soils textural classes into four Hydrologic Soil Groups using the United State Geology Survey (USGS) land use and land cover classification system (Maidment, 1993). The reclassification of Notwane catchment soil into hydrological soil groups was created based on the infiltration capacity, soil form, family and the

soil textural class of different soils based on AG: BOT/85/011 Field Document Number 33 (Joshua, 1991).

Table 3.4, describes how soil textural classes are grouped into the Hydrologic Soil Groups. All the hydrologic soil groups were found in the study area thus A, B, C and D groups.

Table 3.4:   Soil Groups and Corresponding Soil Texture

(Source: Maidment, 1993).

Hydrological Soil Group	Description	Textural Class
A	Low overland flow potential. Minimum infiltration capacity when wetted. Deep to excessively drained sand and gravel	Sandy loam, loamy sand
B	Moderate minimum infiltration capacity when wetted. Moderately deep to deep, moderately to well drained,	Silty loam and loamy
C	Low infiltration rate, high/moderate runoff potential	Sandy clay loam
D	High runoff potential with low infiltration rate	Sandy clay, clay

The land cover/ land use map was re-classified into hydrologic conditions according to USGS land use and land cover classification system. The re-classified land cover/ land use map and the hydrological soil group map were intersected together to generate CN map, which was represented by codes from runoff CN (SCS, 1986; Chow *et al.*, 1998). Table 3.5 shows CN for hydrological soil cover complexes for antecedent runoff condition for average conditions (class II) and $I_a = 0.3S$ for the study area.

Table 3.5: **CN for Hydrological Soil Cover Complexes**

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

	Hydrologic Soil Group			
	A	**B**	**C**	**D**
Mixed shrubs	30	48	65	73
Arable fields	72	81	88	91
Open water bodies	0	0	0	0
Urban areas	61	75	83	87
Open grass				

3.4.2 Determination of Runoff Depth Using Curve Numbers

The maximum potential retention (S) and initial abstraction (l_a) were used in this study to determine the rainfall-runoff relationship using the calculated pixel based on the CN analysis. To derive an annual runoff coefficient (K) per pixel, annual runoff depth map prepared using Equation 3.3. This annual runoff coefficient gave an idea of the percentage rainfall that was converted into effective runoff. Equation 3.5 was used to derive K.

$$K=\frac{\text{Yearly (seasonal total runoff (mm)}}{\text{Yearly (seasonal)total rainfall (mm)}}$$

(3.5)

3.5 Decision Making and Selection of Potential Harvesting Sites

The use of GIS based site suitability analysis has been used over the years to identify the suitability of areas for various purposes such as in ecological approach to identify suitable habitat sites for animal and plant species and land suitability for agricultural use. For this study, the focus was on location search analysis using various spatial representative thematic layers. Not all factors are regarded equally the same in considering sites for surface rainwater harvesting. Multi criteria decision making

process was adopted and the weighted linear combination method was employed to overlay the weighted criteria in a GIS environment. It is embedded with good extensions to support planning and decision making process to decide and select suitable sites. This method follows the analytical hierarchy process known as the pair- wise comparison. Section 3.5.1 elaborates this further.

3.5.1 Criteria for Potential Harvesting Sites Search Analysis

In general, site selection relies on availability of good spatial data at fine spatial resolution. The runoff, land use/ land cover, drainage network, soil type, rainfall spatial distribution, geology and slope density were used for this study. The criteria for site search analysis are based on an intensive literature review, use of indigenous knowledge and expert knowledge. Specific guidelines from FAO were also taken into consideration regarding some of the conditions that must be followed to sustainably implement surface rainwater harvesting project. Table 3.6 and Table 3.7 illustrate the criteria list considered for both micro and macro rainwater harvesting system.

Table 3.6: **General Criteria and Constraints for Micro RWH**

(Source: Modified after FAO, 2003).

Spatial factors	Thematic layer for evaluation	Group of factors
Distance to cropland not more than 1km	• Land Use/ land Cover	Socio Economic
Runoff coefficient not less than 0.5	• Runoff coefficient • Rainfall	Hydro-Meteorological
Soil with high water capacity. Slope not less than 0.5% and not more than 16 %	• Soil texture • Slope density	Geomorphologic

Table 3.7: **General** **Criteria** **and** **Constraints** **for** **Macro** **RWH** **(Source: Modified after FAO, 2003**).

Spatial Constrains And Factors	Thematic Layer For Evaluation	Group of Factors
Distance to cropland not more than 1km	• Land Use/ land Cover	Socio Economic
Runoff coefficient not less than 05. High drainage density with suitable rainfall.	• Runoff coefficient • Rainfall • Drainage density	Hydro-Meteorological
Soil with coarse to gravel texture. Slope not more than 16 percent	• Soil texture • Slope density	Geomorphologic

3.5.2 Calculation of Relative Weights

Relative importance weight of each criterion is very vital for decision makers, since each factor has a varying significance. Decisions made on multi criteria analysis is based on relative importance weight of each criterion (factor). Several methods are available for the determination of these weights. A pair wise comparison method, commonly known as Analytic Hierarchy Process is the mostly used and hence has been adopted for this study. It involves the evaluation of each criterion against each other criteria and this is done in pairs to decide which criterion is more significant than the other for a given aim (Drobne *et al.,* 2009). Table 3.8 shows the rating used to compare the two criteria on a 9 point continuous scale.

Table 3.8:   The Scale of Pairwise Comparison (Source: Saaty, 2008).

Intensity of significance	Description
1	Equally importance
2	Equally to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance
Reciprocals of above	If an activity i has one of the above non zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.

According to Mkiramwinyi (2007), to fill a table matrix (Table 3.9); the values from pair wise comparison are written on the diagonal top right box. Then, the cells on the lower diagonal left box are the inverse values of the top diagonal box. This is done so as to convert the qualitative terms of to what an extent, a factor is more significant than the other into quantitative terms, thus giving it a rating weights. Table 3.9 and Table 3.10 represent the quantitative terms of how each factor affect the selection of site search analysis.

Table 3.9: **The Summation of Values for Macro RWH System.**

	Drainage	Runoff Coefficient	Slope	Soil Texture	Soil Depth	Rainfall	Land Use
Drainage	1	2	3	4	5	6	7
Runoff Coefficient	0.5	1	2	3	4	5	6
Slope	0.3	0.5	1	2	3	4	5
Soil Texture	0.3	0.3	0.5	1	2	3	4
Soil Depth	0.2	0.3	0.3	0.5	1	2	3
Rainfall	0.2	0.2	0.3	0.3	0.5	1	2
Land Use	0.1	0.2	0.2	0.3	0.3	0.5	1
Summation	2.59	4.45	7.28	11.08	15.83	21.50	28.00

Table 3.10: **The Summation of Values for Micro RWH System.**

	Rainfall	Runoff Coefficient	Slope	Soil Texture	Soil Depth	Land Use
Rainfall	1	2	3	4	5	6
Runoff Coefficient	0.50	1	2	3	4	5
Slope	0.33	**0.5**	1	2	3	4
Soil Texture	0.25	0.33	**0.50**	1	2	3
Soil Depth	0.20	0.25	0.33	0.50	1	2
Land Use	0.17	0.20	0.25	0.33	0.50	1
Summation	2.45	4.28	7.08	10.83	15.50	21.00

After filling the pairwise comparison table matrix in Table 3.9 and Table 3.10 relative weights of the factors were calculated (Table 3.11 and Table 3.12) for macro and micro RWH system respectively.

Table 3.11: **Pairwise Comparison for Macro RWH System.**

	Drainage	Runoff Depth	Slope	Soil Texture	Soil Depth	Rainfall	Land Use	Weight %
Drainage	0.386	0.449	0.412	0.361	0.316	0.279	0.250	**0.350**
Runoff Depth	0.193	0.225	0.275	0.271	0.253	0.233	0.214	**0.237**
Slope	0.129	0.112	0.137	0.180	0.189	0.186	0.179	**0.159**
Soil Texture	0.096	0.075	0.069	0.090	0.126	0.140	0.143	**0.106**
Soil Depth	0.077	0.056	0.046	0.045	0.063	0.093	0.107	**0.070**
Rainfall	0.064	0.045	0.034	0.030	0.032	0.047	0.071	**0.046**
Land Use	0.055	0.037	0.027	0.023	0.021	0.023	0.036	**0.032**

Table 3.12: **Pairwise Comparison for Micro RWH System**

	Rainfall	Runoff Depth	Slope	Soil Texture	Soil Depth	Land Use	Weight %
Rainfall	0.408	0.467	0.424	0.369	0.323	0.286	**0.379**
Runoff Coefficient	0.204	0.233	0.282	0.277	0.258	0.238	**0.249**
Slope	0.136	0.117	0.141	0.185	0.194	0.190	**0.160**
Soil Texture	0.102	0.078	0.071	0.092	0.129	0.143	**0.102**
Soil Depth	0.082	0.058	0.047	0.046	0.065	0.095	**0.065**
Land Use	0.068	0.047	0.035	0.031	0.032	0.048	**0.043**

The consistency of the calculated pairwise comparison was then evaluated using consistency ratio (CR) to check if the evaluation between the chosen factors falls within the acceptable limits. The CR should be below10%. Thus, if the CR is less than 10% then evaluation between factors is satisfactory else calls for re-evaluation of comparing the factors again. CR was calculated using the following equation,

$$CR = \frac{CI}{RI} \qquad (3.6)$$

Where;

    CI is the consistency Index

    RI is the Random Index

RI is given (Table 3.13), the value used for this study was adopted from Saaty (2008) and it depends on the order of the matrix. The criteria for macro rainwater harvesting system had 7 criteria and the micro rainwater harvesting system had 6 criteria.

Table 3.13:   **Random Indices (RI) n=1, 2.....15 (Source: Saaty, 2008).**

N	RI
1	0.00
2	0.00
3	0.58
4	0.90
5	1.01
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

3.6   Suitability Model

Surface rainwater harvesting technologies are highly site-specific, and rely on various factors such as physiographic, environmental, socio economic and technical factors (de Winnaar *et al.*, 2007). Most of the rainwater harvesting technologies in the South Eastern part of Botswana is mostly surface water storage system such as small agricultural reservoirs mainly for livestock drinking purposes and other three big dams used for domestic and industrial water consumption.

The methods adopted for this study are relevant for any type of harvesting that uses small reservoirs, stone terraces and underground water storage (sand and subsurface dam). Due to data limitation, other underground water storages such as ground water recharge pits and trench are not discussed in detail but potential sides will be identified based on presence of homesteads especially in urban area of Gaborone where large quantities of roof water or surface runoff is available within a very short period of heavy rainfall.

3.6.1   Criteria for Determining the Suitability of the Harvesting Site

Site search and selection analysis is the first and most important steps in planning and implementing a successful strategy for surface rainwater harvesting initiative. It should be appropriate on both physical and social grounds. Since surface rainwater harvesting is a hydrological intervention, determination of criteria to support a strategy for determining suitable rainwater harvesting sites needs a biophysical approach.

This approach utilises information based on physically acquired catchment characteristics for better understanding of the catchment hydrological response. This saves a lot of time and resources needed to determine runoff harvesting sites manually and it is dependent on good data availability. The socio economic factors should also be considered in order to ensure project sustainability. In this study arable land has been considered as a socio economic factor.

Many authors have came up with several biophysical factors that are of use when selecting potential runoff harvesting sites such as suitability of the soil, slope, land use, and the harvesting potential of the upstream catchment. Ziadat *et al.* (2006) regard the steepness of the area as an important criterion for determining and implementing any runoff harvesting interventions especially in the context of rainfall runoff generation whilst Schmidt and Schulze (1987) suggest the soil as the prime controller of the hydrological response of any catchment due to its capacity to soak up, store and discharges water.

The following tables represent the suitability level for each factor affecting individual rain water harvesting technology considered in this study. The suitability level was selected based on literature search, expert and indigenous knowledge.

This site search analysis approach takes into consideration certain guidelines from FAO regarding conditions that must be satisfied both social economics and bio-physical in order to sustainably implement successful RWH projects.

Table 3.14:   Suitability Levels of Each Factor for Small Dams
(Source: Mbilinyi and Tumbo, 2013).

	Suitability Level			
	Suitable	**Moderately Suitable**	**Marginal Suitable**	**Not suitable**
Corresponding Suitability Values				
Suitability Values	**4**	**3**	**2**	**1**
Slope (%)	10-30	5-10	2-5	>30<2
Drainage density	98-131	65.8-98	32.9-65.8	0-32.9
Soil texture	clay	Sandy clay loam	Loamy	Sandy loam
Runoff Coefficient	>0.89	0.78-0.89	0.52-0.77	0-0.51
Rainfall (mm)	500-600	300-400	200-300	< 100
Land use	arable	Open shrub	Open grass	Built up area/open water

Table 3.15:   Suitability Levels for each Factor for Stone Terraces

(Source: Mbilinyi and Tumbo, 2013).

	Suitability Level			
	Suitable	**Moderately Suitable**	**Marginally suitable**	**Not Suitable**
Corresponding Suitability Values				
Suitability Values	4	3	2	1
Slope (%)	18-30	5-10	2-5	<2
Runoff coefficient	0.78-0.85	>0.85	0.52-0.77	0-0.51
Soil texture	Sandy loam	Sandy clay loam	Loamy sand	Loamy
Land Use	Arable	Open shrubs	Open grass	Built up areas/open water
Rainfall	500-600	300-400	200-300	<200
Soil Depth (cm)	>50	30-50	10-30	< 10

To finally identify potential suitable sites, the re-classified thematic layers from a

scale of one to five (not suitable, marginally suitable, moderately suitable and

suitable) were overlaid using weighted overlay sum in Arc GIS 10.1. The aim of the weighted overlay analysis was to use a common scale of values to standardise the diverse and dissimilar data input for easy integrated analysis. The following general formula was applied (Malczewsk, 1999).

$$S_{si=} \sum(RIW_{factor} * S_{factor\ layer}) \tag{3.7}$$

Where;

S_{si} is suitability level for cell i

RIW_{factor} is relative importance weight for each factor layer i

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physiographic Characteristics Analysis

a) Land Use/ Land Cover Map

Results from data analysis, shows that the study area comprises of five major land cover/land use units with open grass taking a large portion of 36% of the study area, followed by the mixed shrub. The built up areas and open water bodies units cover a small portion of the study area (figure 4.1).
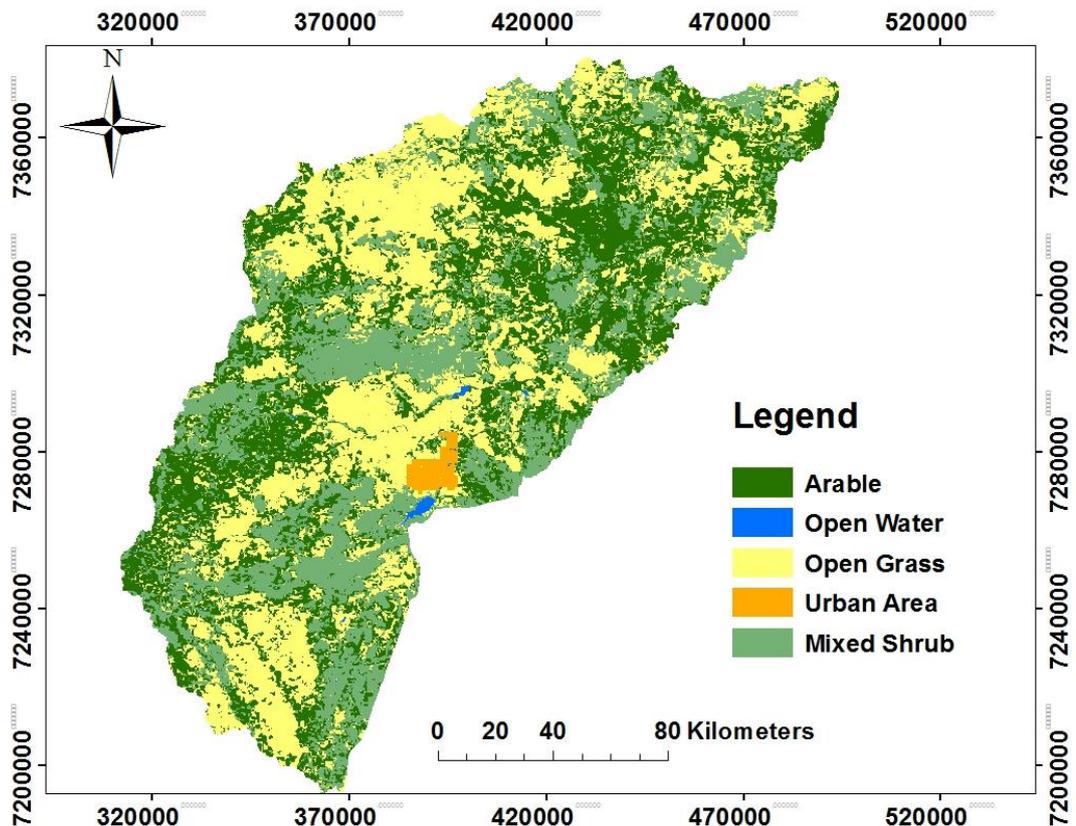

Figure 4.1: Land Use/ Land Cover of the Study Area

Majority of the study area is cover with mixed shrub and open grass. This is very important since the vegetation cover plays a very important role on the infiltration capacity. Soil porosity is increased by the presence of this vegetation rooting system which results in increased infiltration capacity of the soil. Sparsely scattered vegetation cover causes rapid runoff on undulating slopes since the surface flow takes less time to infiltrate through the soil, whereas on bare land such as cultivated or arable fields, runoff is more compared to areas covered by vegetation (Moges, 2004). Table 4.1 shows the land area covered by each land unit.

Table 4.1:   Land Cover Unit per Areal Coverage of the Study Area

Type of land cover		Area (km^2)	% of the Total Area
Deciduous Forest	Mixed shrub	4404.70	28
Open Shrub			
Range Land			
Arable	Arable	5489.36	35
Open Water bodies	Open Water bodies	30.07	0.19
Urban Area	Urban Area	122.20	0.78
Open Grass	Open Grass	5660.17	36

b)   Slope Density Map

Figure 4.2 shows the slope of the study area. The entire study area is relatively flat especially in the Northern part of the catchment. This is characterised by a slope percentage less than 3. The topography in the Southern part is mostly made up of undulating to generally gentle slopes. There are few areas that have hilly to steep mountainous slopes. These areas make a small percentage of the study area.
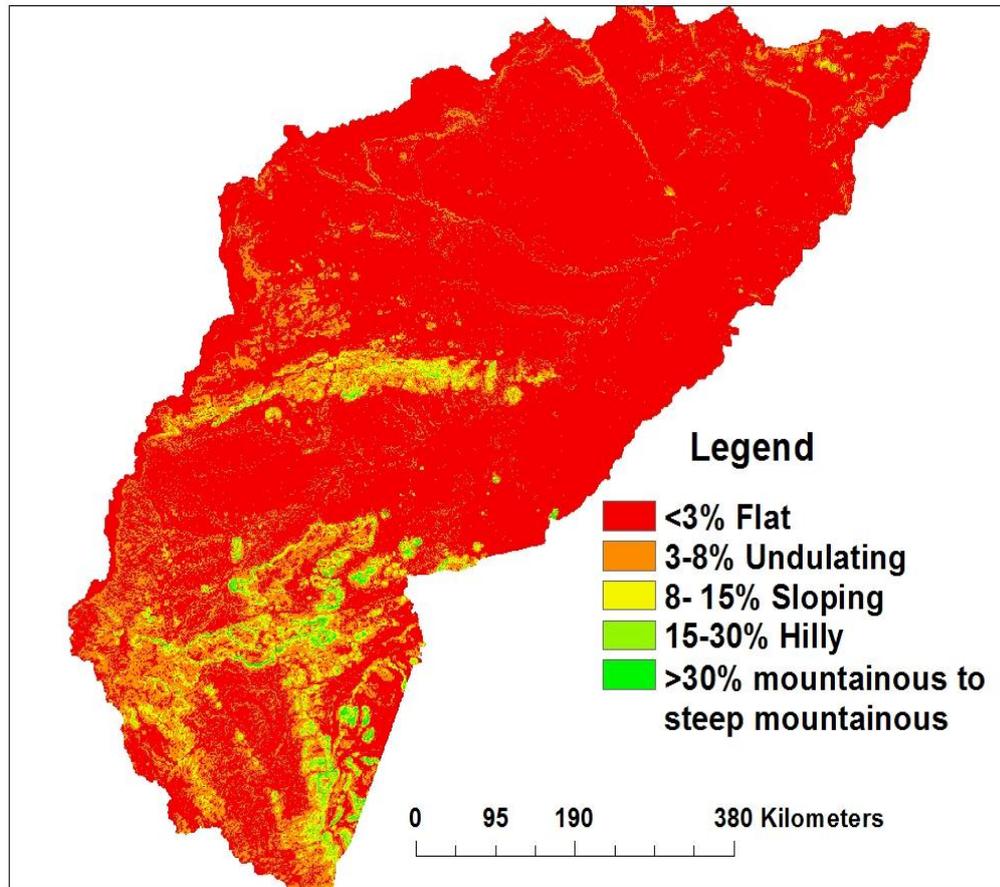
Figure 4.2:   Slope Classification Map of Study Area

From the analysis, the study area has a flat topography with slope percentage less than 3% in majority of the areas, followed by undulating and sloping areas and few mountainous slopes of more than 30%. The slope steepness plays a crucial role in depicting areas of preferable runoff, thus steep to sloping areas have high runoff potential.

Four textural classes were identified with the sandy loam being the dominating textural class covering 63% of the study area. There were few spots of clay which only covered an area of 12 km^2.

c)   **Soil Map**
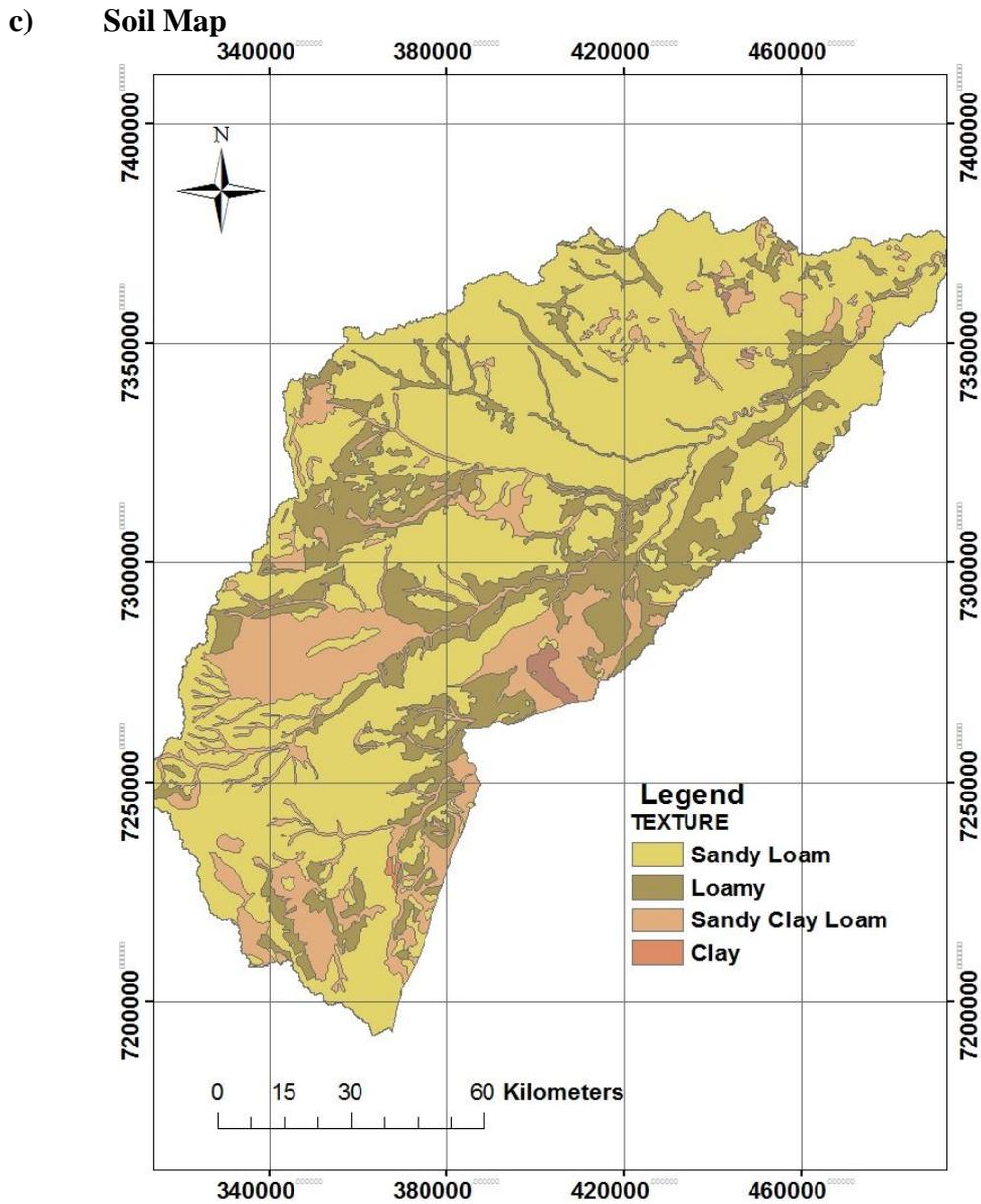
Figure 4.3:   Soil Texture in the Study Area

The major dominating soil in the study area is the Arenosols which are developed from the sand deposits which is derived from the weathering of coarse grained rocks. This is depicted in figure 4.3. These soils tend to be coarse sandy soils which are relatively deep and can be grouped collectively as sandy loam soils. Although the textural class suggest low soil moisture holding capacity, most moisture is available

after it rains at a depth of 10m (Joshua, 1991). They are generally considered excessively to moderately drained with high porosity of about 40% and have low surface runoff from a rainfall event. They are distributed all over the study area with majority of it occurring in the North Eastern part of the study area. Figure 4.4 shows the percentage distribution of the four textural classes found in the study area.
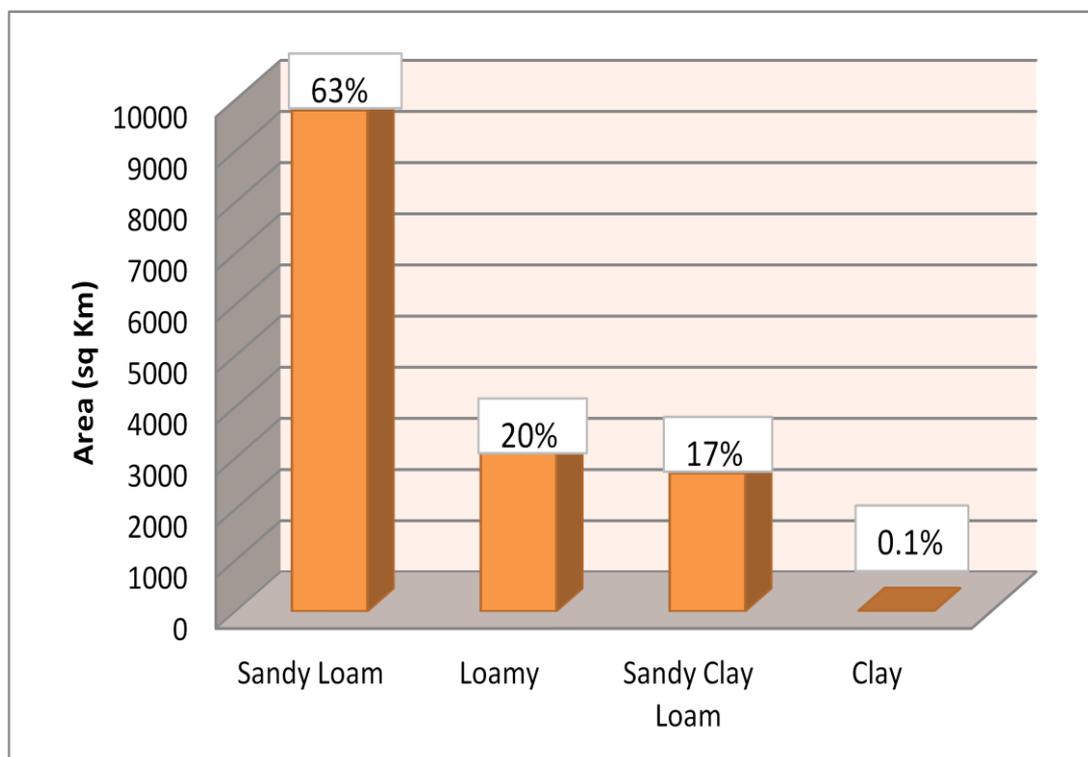
Figure 4.4: **Percentage of Land Area per Soil Textural Class**

The sandy loam covers 63% of the study area. Another soil type that covers most of the study area is the loamy and sandy clay loam, this form the Regosols and Luvisols respectively. They cover 20% and 17% of the study area respectively (Figure 4.4). The loamy soils are characterised by medium texture and are well drained. These soils are very stony and underlain by unconsolidated gravely material. They are also

very shallow depth. The sandy clay loam has a bit of clay bulge in the sub soil; the soil depth is very deep to deep and is well drained. The clay soils have a pronounced clay accumulation and they appear similar to luvisols.

d)   Rainfall Distribution

Rainfall amount across the study area is highly variable in space with the Northern part area receiving twice lower amounts of rainfall than in the Southern part. The maximum amount of mean annual rainfall ranges between 360 mm/year-400 mm/year and the low range mean annual rainfall is between 260 mm/year-350 mm/year. This range occurs in most parts of the study area. Figure 4.5 shows the mentioned spatial variability.
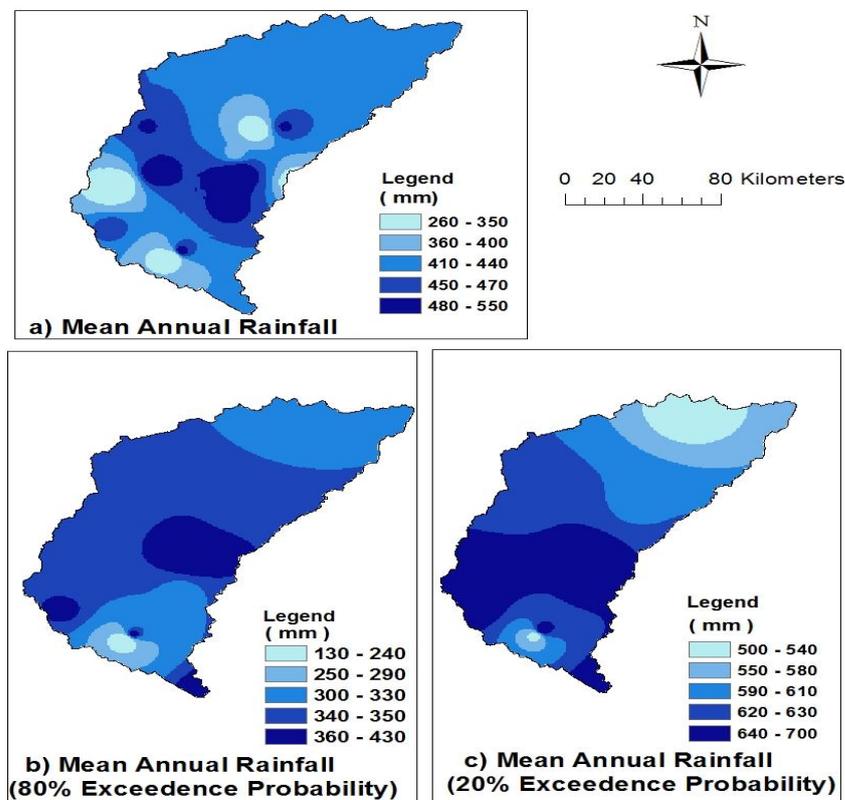

Figure 4.5:   Spatial Distribution of Average Yearly Rainfall in the Study Area

The mean annual rainfall that has 20% exceedence probability is mostly high in the middle part of the study area with mean annual value of 640 mm/year-700 mm/year. There are some areas that receive low rainfall in the Southern region of about 500 mm/year-540 mm/year. This rainfall is unreliable and has low chances of occurrence and many at times causes flash floods on the downstream of the catchment, in the Northern part of the study area (refer to Figure 4.5c).

The mean annual rainfall that has 80% occurrence probability is highly variable in space with some parts in the upstream receiving low mean annual rainfall of about 130 mm/year-240 mm/year and the downstream catchment receiving upper ranges of 300 mm/year-330 mm/year of rainfall. Majority of the study area receives rainfall amount ranging from 340 mm/year-350 mm/year. It is important to note that this rainfall occurs during the summer months around October to early April.

4.2   Estimation of Runoff Depth Using SCS CN Model

SCS CN method has been adopted for this study, to estimate the runoff depth. Land cover/land use map and soil texture map (which was reclassified into hydrological soil group using the United States Department Agriculture classification system), were used to derive the curve numbers which were used to estimate runoff depth of the study area. The resultant Hydrological Soil Group map is shown as Figure 4.6. The dominant soil group appears to be group A, which may not be as suitable for certain RWH technologies such as small dams but rather be suitable for technologies such as sand dams. Figure 4.7 depicting the curve numbers, shows similar results
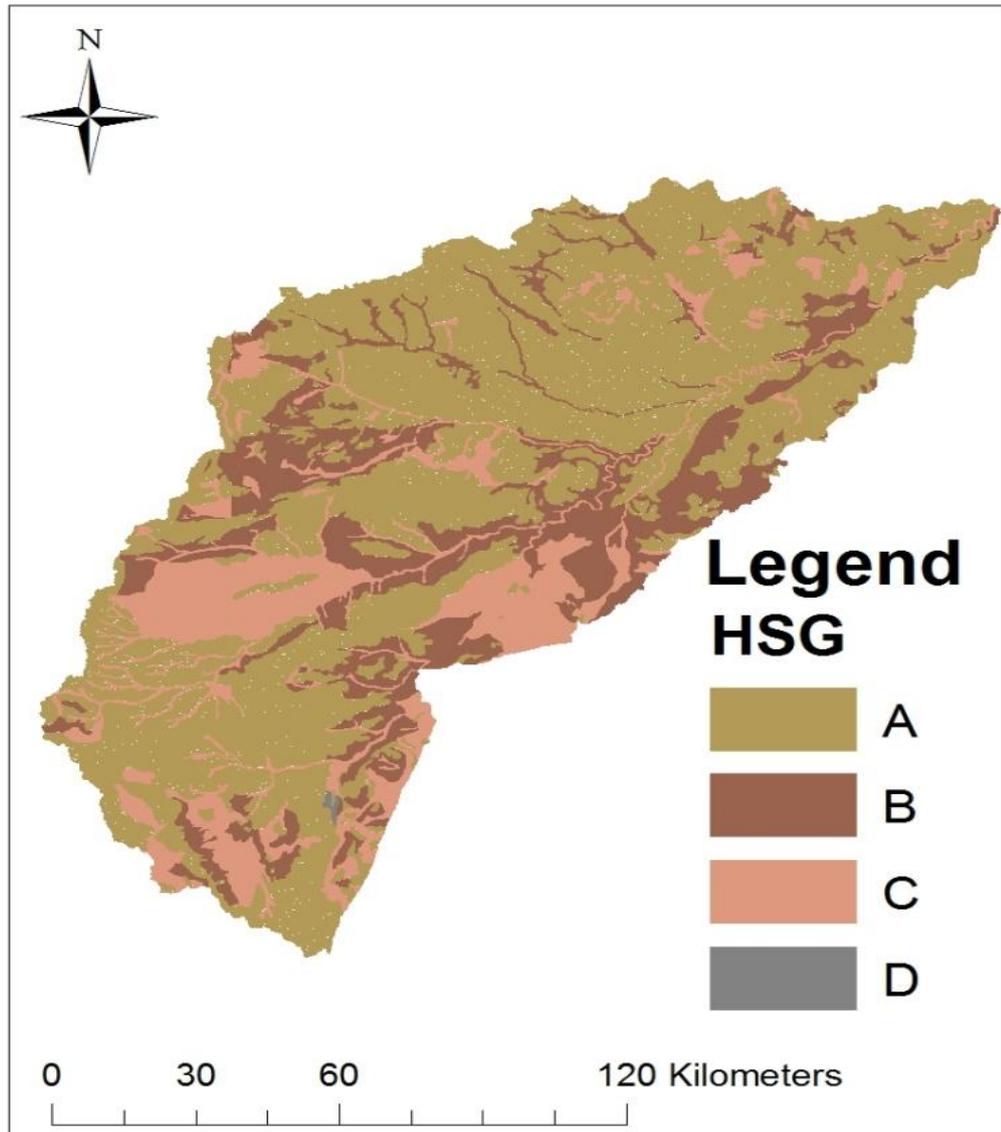
Figure 4.6: **Hydrologic Soil Group in the Study Area**

It shows the generated CN map per pixel after possible intersection of land cover/ land use map and the hydrological soil group map. This figure gives an indication of areas that have a potential to generate more runoff based on the two input factors. High CN values represent areas that have high runoff potential and low infiltration. This is due to the fact that initial abstraction and storage are minimal. There is high runoff potential in the upstream of the catchment as indicated in Figure 4.6, since this

area is mostly covered with group C and B soils which have moderate to low infiltration rates and they are made of sandy clay loam and loamy textural classes respectively.
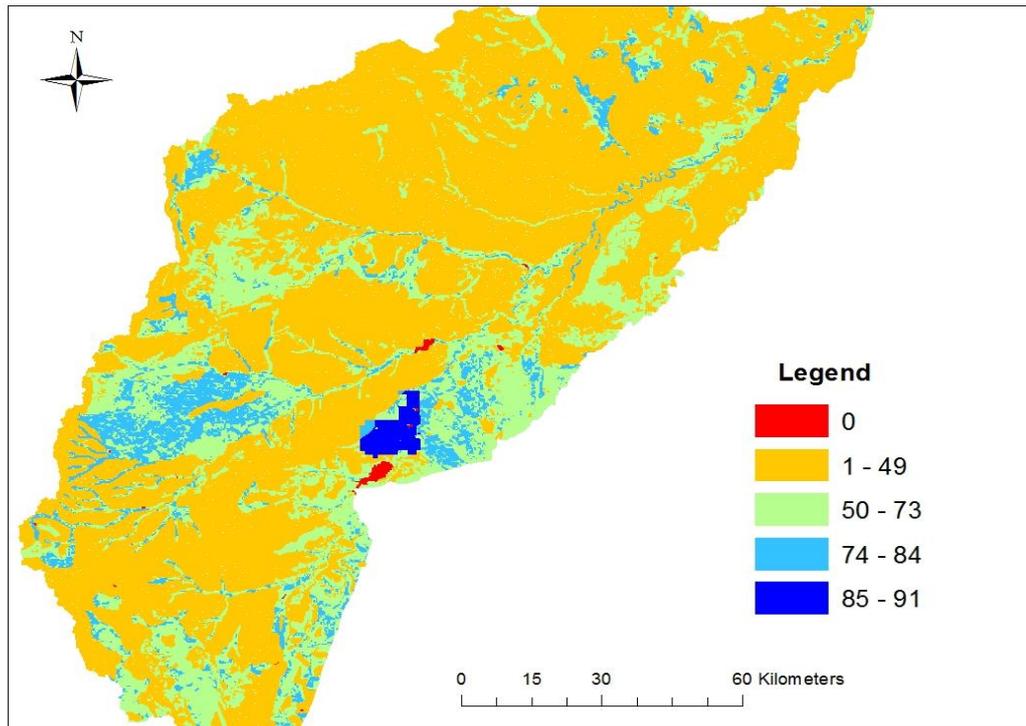
Figure 4.7:   Curve Number in the Study Area

On the downstream of the catchment majority of the area is covered with group A soil, which has high infiltration rate and low runoff potential due to their coarse textural characteristics. The dominating soil textural class in this area is the sandy loam. However, there are some areas downstream of the study area that has high runoff potential which is represented by high CN. These are areas with group C soil and have high curve number ranges of 84-91 and the dominating land use is build up areas.

Equation 3.3 was used to calculate runoff depth. This followed the SCS CN method.

The resultant runoff depth that was calculated is shown in Figure 4.8.
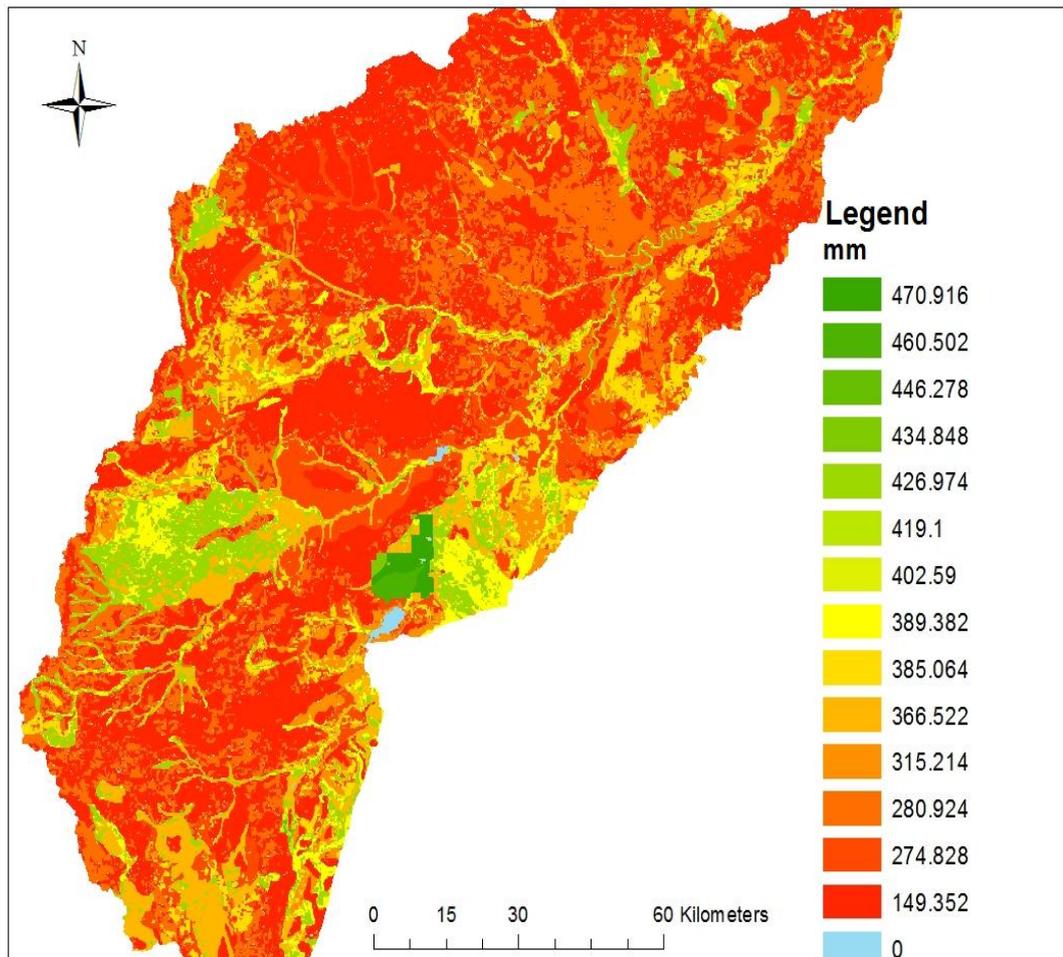
Figure 4.8:   Runoff Depth in mm per Annum for the Study Area

Figure 4.8 shows the generated runoff depth expressed in mm per annum. Majority

of the areas in Notwane catchment have low values of runoff depth, these areas are

covered with group A soil and are dominated by arable fields. The topography is

relatively flat hence less runoff potential, as most rain water where it falls is lost

through infiltration. Areas around build up areas have high runoff depth which indicates high runoff potential.

## 4.3   Determination of Potential Site for Surface Rainwater Harvesting

In this study, the input layers/factors were rainfall, soil texture, soil depth, drainage density, slope, runoff coefficient and land use/cover. These thematic layers were used to identify the spatial extent of potential surface rainwater harvesting site for both macro and micro rainwater harvesting systems and identify potential sites for different surface rainwater harvesting technologies in the Notwane catchment. Since determination of the suitability of the land for potential runoff harvesting is site specific and requires quantitative data and Ziadat *et al.* (2006) suggest integration of specific factors, a multi criteria analysis commonly known as Analytical Hierarchy Process which uses a pair wise comparison was employed to determine which criterion is more significant than the other.

Table 4.2 shows different weighting factors assigned to each thematic layer for both micro and macro rainwater harvesting systems. These weights were used to identify and map suitable sites for various surface rainwater harvesting.CR for both rain water harvesting systems was calculated to evaluate if the pair wise comparison fall within the acceptable limits and the results shows that the CR for micro rainwater harvesting system was 3% and for macro rainwater harvesting system was 3.5% and it can be said that it falls within the acceptable limit of less than 10%. Hence the weights are adopted.

Table 4.2:   Different Weighting Factor for each Thematic Layer.

Thematic Layers	Weight factor	
	Micro Harvesting System	**Macro Harvesting System**
Drainage		0.350
Rainfall	0.379	0.046
Runoff coefficient	0.249	0.237
Slope	0.160	0.159
Soil texture	0.102	0.106
Soil depth	0.065	0.070
Land use	0.043	0.032
	CR: 0.03	**CR: 0.035**

4.3.1   Potential Sites for Macro Catchment Surface RWH System

The spatial extent of potential suitable sites in Notwane catchment for macro rainwater harvesting has considered the following physiographic factors; the drainage density, runoff coefficient, slope density, soil (texture and depth), rainfall and land use which have been integrated using different assigned weights (Table 4.2) to produce four suitability classes. The following Figure 4.9 shows the results of this spatial extent.
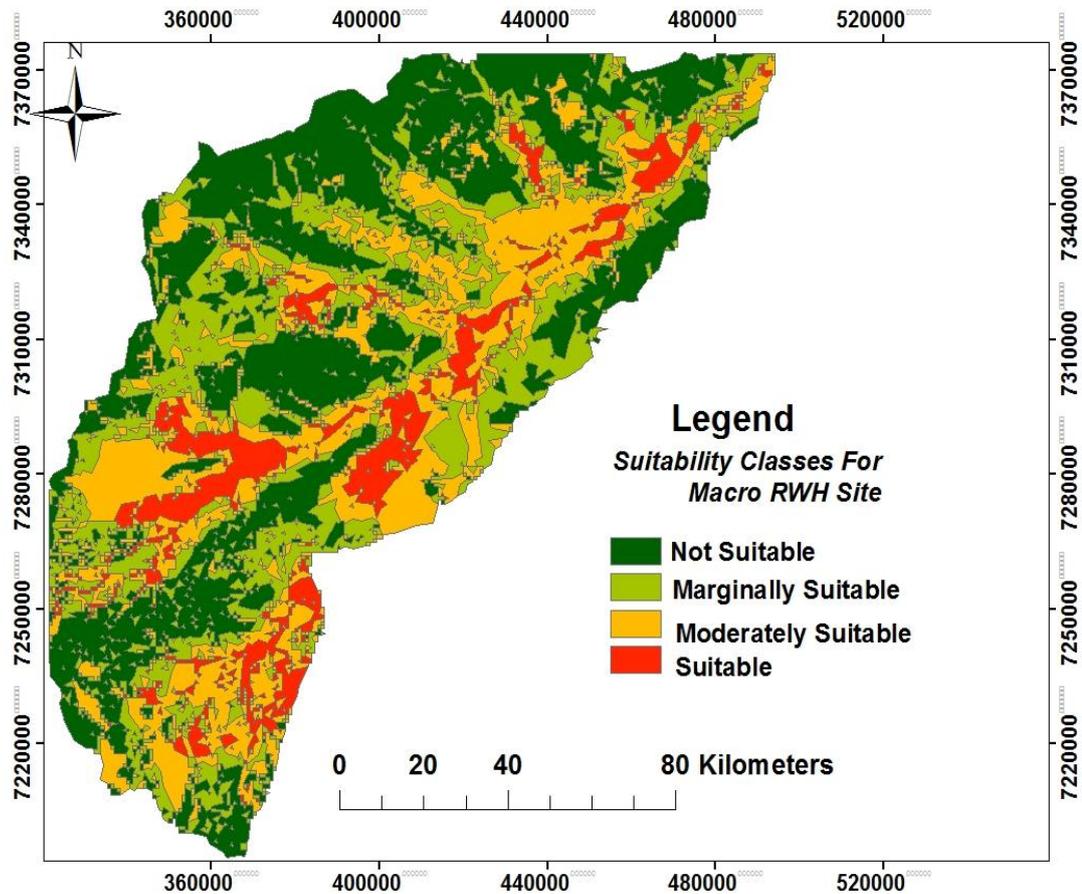
Figure 4.9:   Potential Site for Macro Rainwater Harvesting System

From the total study area of 15,706 km^2, only 10% is suitable for macro rainwater

harvesting systems. These are sites that have no limitation to sustain the intended

purpose. Majority of these areas are found in locations that have relatively high

runoff depth of about 366 mm/annum or more with high annual runoff coefficient,

ranging between 0.78 and 0.85 and are located in high drainage density areas. Most

of these suitable sites are located on undulating to sloping landscape with a slope

percentage of less than 3%-15% and are surrounded by areas with higher elevation of

about 1200 masl. The soils are loamy to sandy clay loam and they have vertic like

properties that make them vulnerable to surface crusting. These types of soils are suitable for most macro RWH systems due to the fact that they have high water retention capacity, which is associated with low seepage and percolation. The results analysis matches with Mbilinyi *et al.* (2005) where the authors found out that indiva (small dams) were constructed on locations closer to the streams with a slopping topography. The authors further describe that, this factor is suitable, since runoff water can easily enter and leave the rainwater storage medium by gravitational force. From the results, areas with high elevation are the sites that have been analysed to have a marginally suitable potential for RWH and occupy 26% of the study area (Figure 4.10). These results correspond to the observed data in the field where few small dams were observed in areas of high elevation.
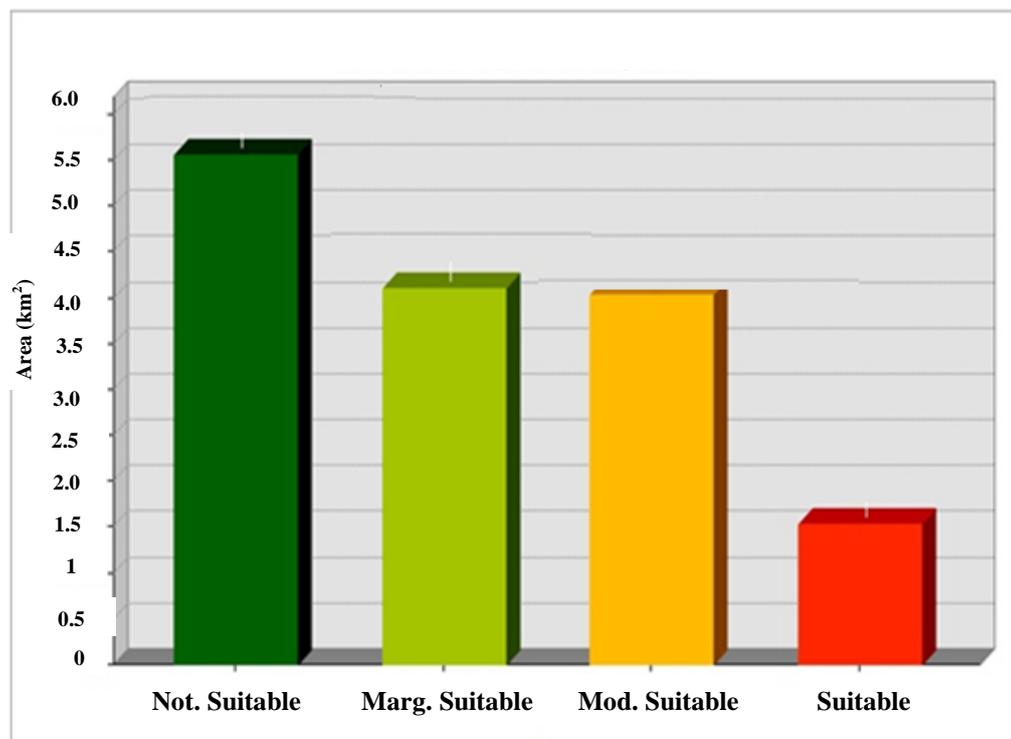

Figure 4.10:   Land Area per Suitability Class for Macro RWH System

Areas that are classified as not suitable are found mostly in steep mountainous to hilly topography and are located far from the drainage network. This analysis corresponds to the results by Prinz *et al.* (1998) where the authors found that locations with high drainage network are ranked higher in suitability, as compared to areas with fewer networks of drainage channels. This is due to the fact that as you move away from the river there is higher potential of water losses as a result of seepage and evaporation.

The soils around this area are mostly sandy soils and this type of textural class is not suitable for location of surface open dams since the soil is characterised by excessively to somewhat drained and many at times are deep, so most of the harvested water will be lost through a process called percolation and hence recharging the water table. The marginally suitable sites are found in areas that area covered by loamy sand and the main dominating land use/land cover is the open grass which has a CN of ranges between 1-59 and a low runoff depth per year. Figure 4.11 shows percentage land area per suitability class for macro RWH system.
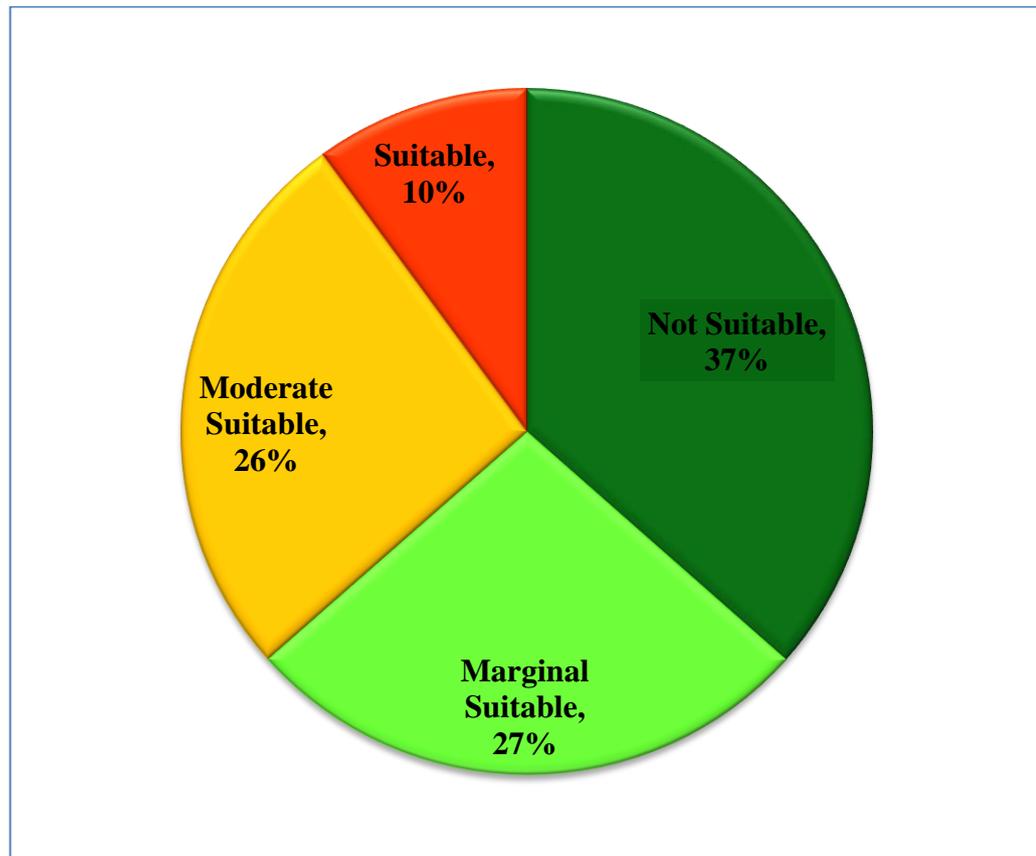
Figure 4.11: **Percentage Land Area per Suitability Class for Macro RWH System**

4.3.2 Potential Sites for Micro Catchment RWH System

The spatial extent of potential sites for micro rainwater harvesting in the study area has considered all the factors that have been discussed earlier except for the drainage density, due to the fact that these technologies are somewhat in-situ and uses only part of the target area as the rainwater harvesting catchment area, in this case arable fields were the targeted catchment area. Hence the drainage density parameter was not given much priority for this type of RWH system but was scored high when determining the macro RWH system since water has to travel short distance to avoid water loss.

Figure 4.12 show the suitability of the study area to carry out micro RWH. Due to the unavailability of the existing micro RWH structures in the study area, stone terraces were used to determine the potential of such technologies in catchment like Notwane where about 35% of the total land is arable land.
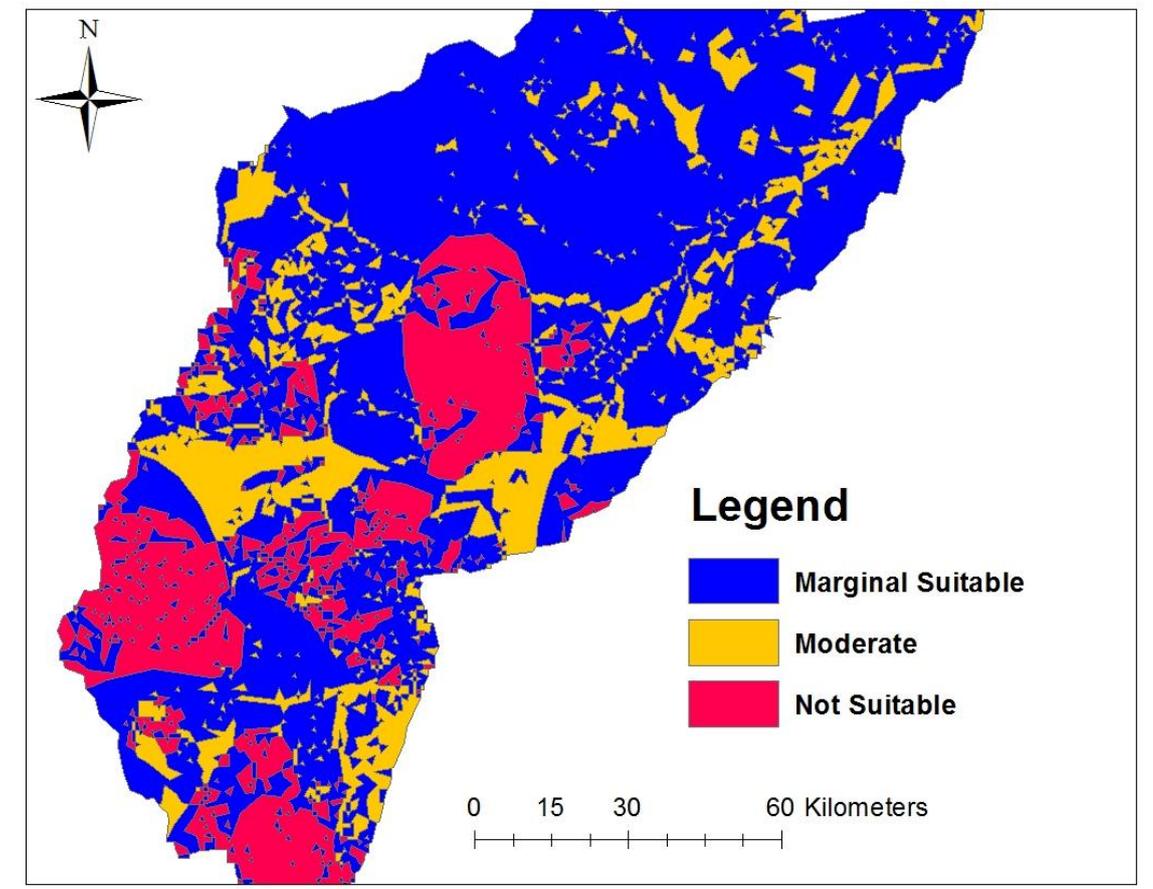
Figure 4.12:   Potential Site for Micro RWH System.

The analysis using weighted overlay in GIS environment depict that 65% of the total study area is classified to have a marginally suitable potential for micro RWH system. These sites are characterised by deep to very deep soils with depth greater than 50cm and a flat topography. Moderately suitable sites cover 16% of the study

area, where soils depth is shallow to very shallow and the topography is gently undulating to sloping steepness with a slope percentage of 3% to 18%. The same results match with Mbilinyi and Tumbo (2013) and Hudson (1987).

The not suitable sites were found in areas that have low annual average rainfall of a range between 200 mm to 300 mm and a slope percentage of greater than 15% which when classified using the FAO slope classification system, fall witin the steep to mountainous relief class. The uderlaying soil texture found in these sites is mostly sandy loam to laomy. Figure 4.13 shows land area per suitability class for micro RWH system discussed above while Figure 4.14 shows the percentage land area coverage per class suitability.
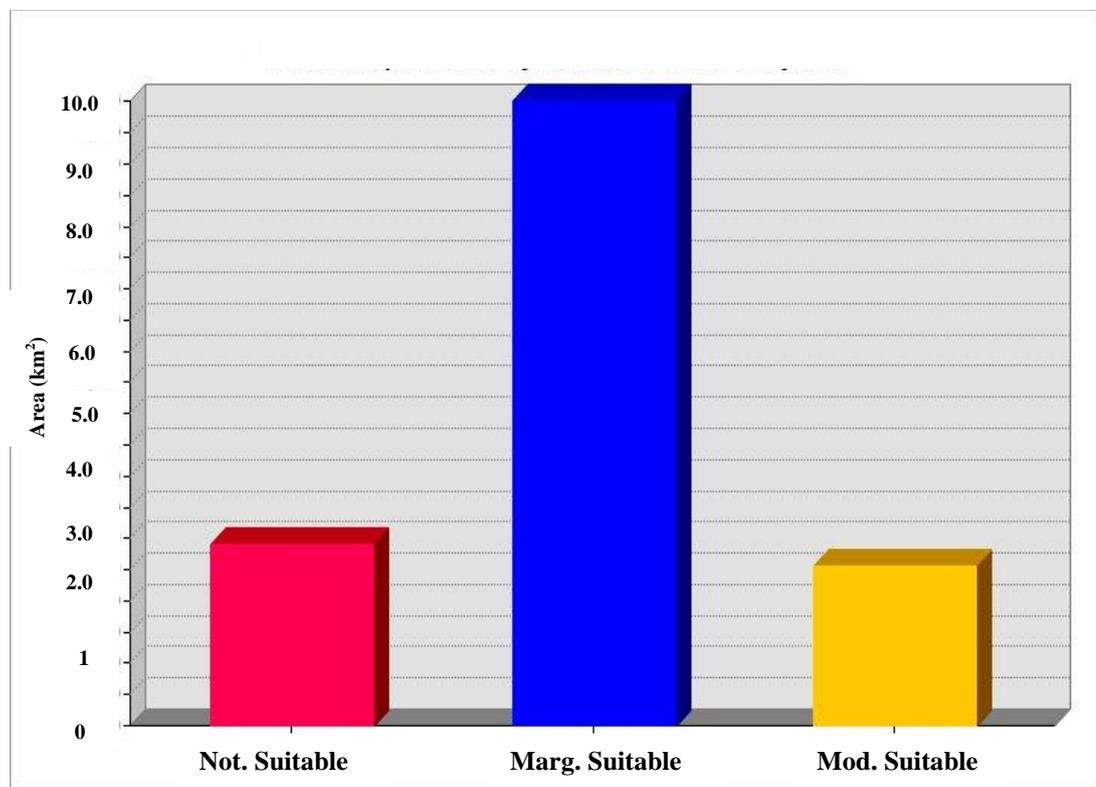
Figure 4.13:   Land Area per Suitability Class for Micro RWH System
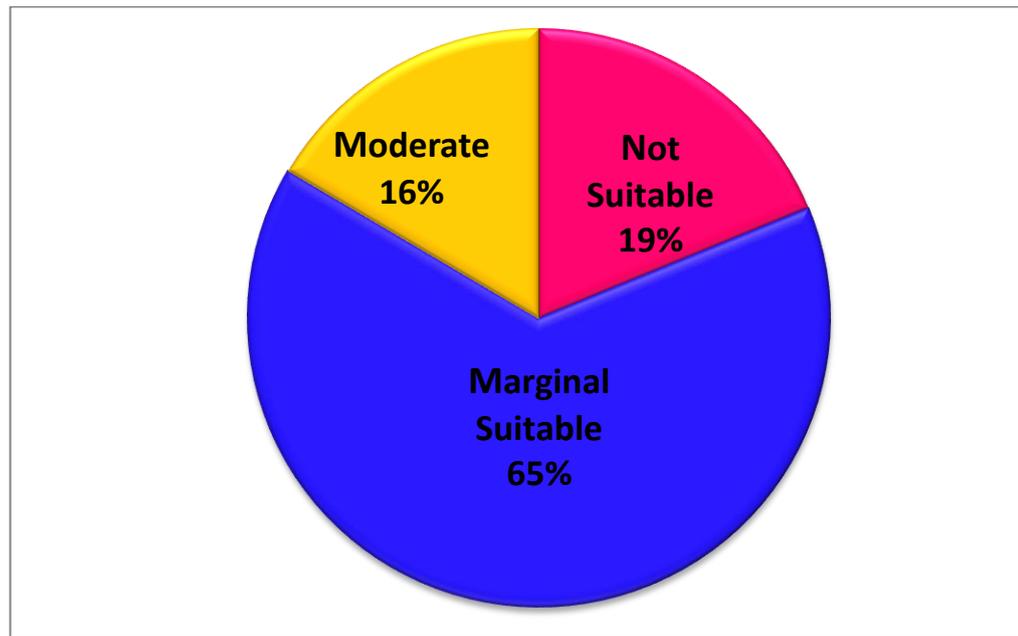
Figure 4.14: **Percentage Land Area per Suitability Class for Micro RWH System**

4.4   Exploring the Potential of Underground Water Storage System (sand dam)

According to BNWMP (2006) and EHES and SMEC (2006), the study area is susceptible to high evapotranspiration rate due to its unfavourable and unsuitable climatic condition (high temperature and low erratic rainfall), so it was necessary to explore the full potential of underground water RWH storage using the suggested DSS framework., with particular emphasis on the sand dam since most of the study area is covered with deep to shallow sandy soils and is dominated by seasonal sand rivers which are relatively wide such as Metsimotlhabe and Kolobeng rivers and these are the factors favourable for such technology.

Based on the extensive literature review and past learnt experience from countries such as Kenya, the following criteria were used to explore the potential for underground water storage particularly sand dams, in the study area since it has a potential to combat effects of high evapo-transpiration.

Table 4.3:   Suitability Levels for each Factor for Sand Dam

	Suitability Level		
	Highly Suitable	**Moderate Suitable**	**Not Suitable**
Corresponding Suitability Values			
Suitability Values	3	2	1
Topographic Zones	Transition Zones	Low Lands	High lands
Slope (%)	1.5-8	8-15	15-60
Soil texture	sandy	loamy Sand Sandy Loam	Loam
Geology	Crystalline rocks	-	Volcanic rocks
Drainage density	98-131	65-98	0-39
Runoff coefficient	>0.89	0.78-0.89	0.52-0.77
Rainfall	500-600	200-400	<200-
Land use	Arable	Open shrub/open grass	build up area
Soil depth (cm)	>150	50-150	<25-

Due to data limitation the spatial extent for potential of sub-surface dams was not explored. However a criteria was set for future reference and is depicted in Table 4.4

Table 4.4:   Suitability Levels for each Factor for Sub-Surface Dam

	Suitability Level		
	Suitable	Mod. Suitable	Not Suitable
Corresponding Suitability Values			
Suitability Values	3	2	1
Topographic Zones	Transition Zones	Low Lands	High lands
Slope (%)	0.3-4	4-15	>30-
Soil texture	sandy	loamy Sand Sandy Loam	Loam
Geology	Crystalline rocks	Any other rock type	Volcanic rocks
Drainage density	98-131	65-98	0-39
Rainfall (mm)	400-600	200-400	< 200
Runoff Coefficient	>0.89	0.78-0.89	0.52-0.77
Soil depth (cm)	>150	50-150-	<25
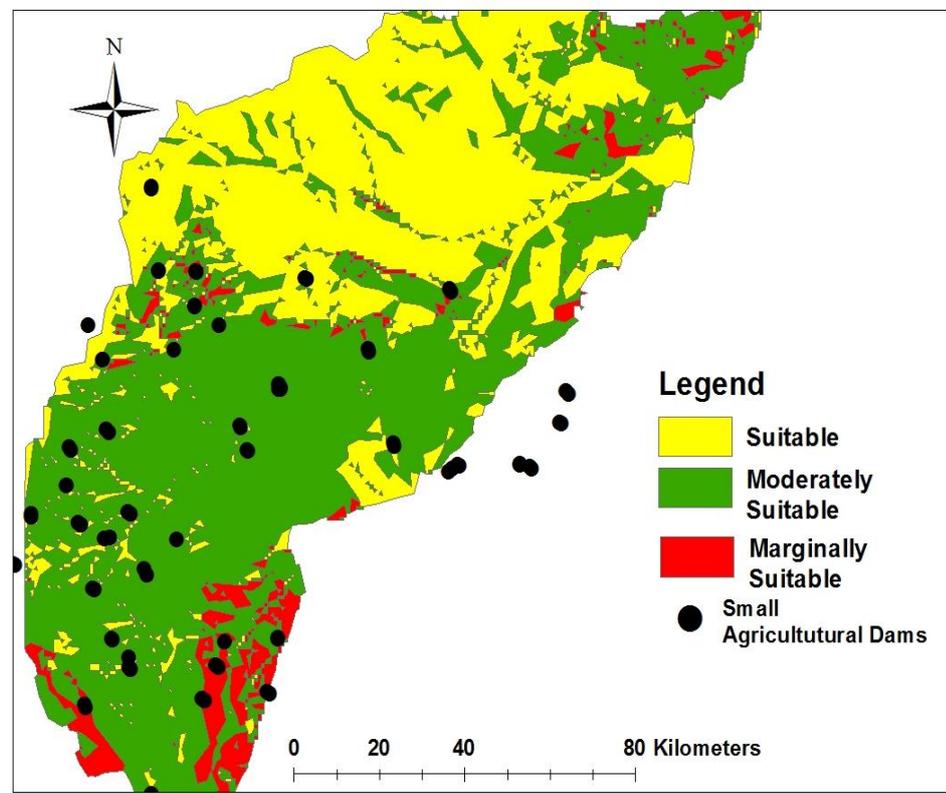
Figure 4.15:   Exploring Potential of Underground Water Storage (Sand Dam)

Majority of the potential sites with suitable class are located on the downstream of the study area where is mostly covered with deep to shallow sandy loam to sandy soils and the topography is undulating to a flat relief. This location is mostly at the runoff receiving site of the study area, which is coming from high elevation areas in the upstream and mostly suffers from flash floods due to high rainfall intensities on the upstream. This class covers 37% of the study area and has a potential annual runoff depth of 389.38 mm/annum to 149 mm/annum. The moderately suitable sites are located in the upstream of the catchment area. This is where most of the hill ranges are found with a slope percentage ranging from 15% to more than 30% and covers about 42% of the study area. The percentage land area per suitability class discussed above is shown in Figure 4.16.
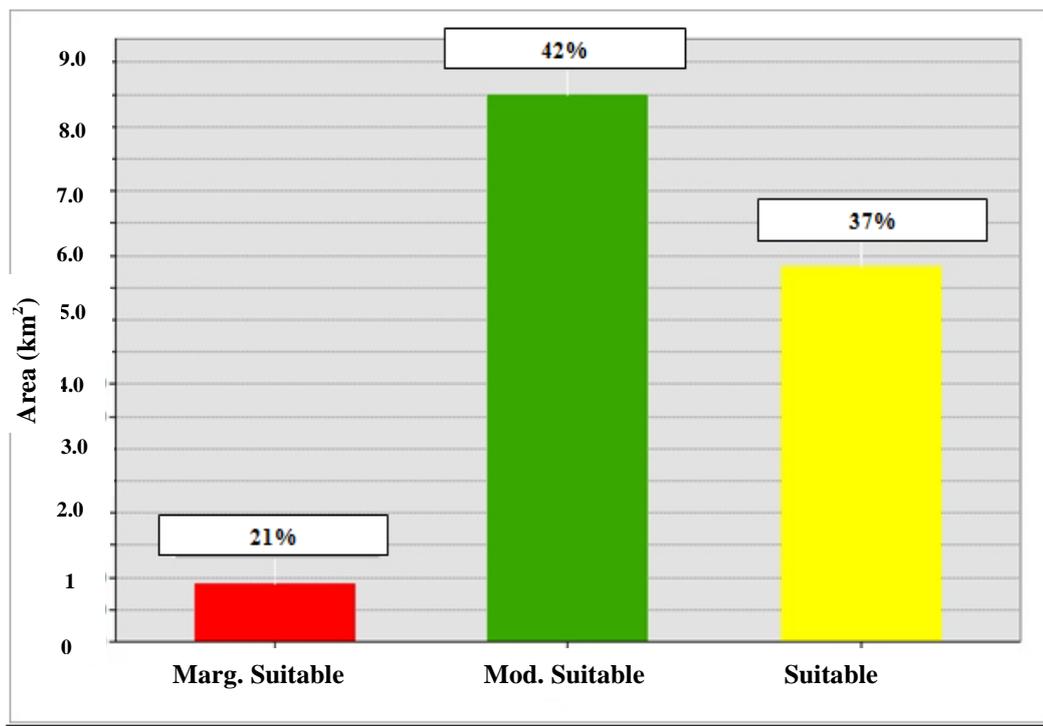
Figure 4.16:   Percentage Land Area per Suitability Class for Sand Dams

4.5 Validation and Testing

For testing and validating the accuracy of the identified potential surface rainwater harvesting sites in the catchment, existing water management structures on upper Notwane catchment were overlaid over the suitability maps for the identified potential site for surface dams which was developed using the decision support system (Figure 4.17). The testing focused on checking the reliability and quality performance of the criteria used.
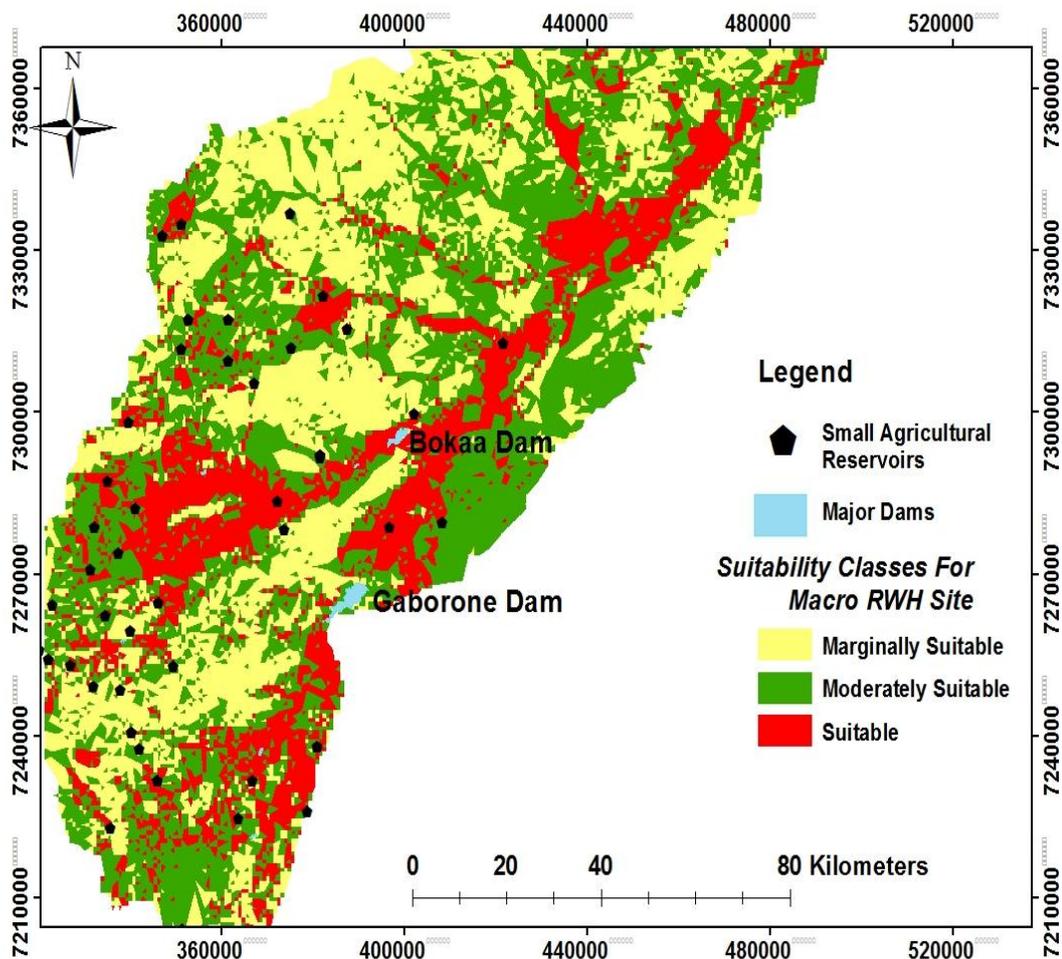
Figure 4.17: **Comparison of Predicted Potential Sites with Existing Water Management Structures.**

The small agricultural dams represented by black symbols in Figure 4.17, represent existing structures in the upper catchment of the study area which have recently been rehabilitated by the MoA. The percentage overlap was calculated to determine how many dams fall within a certain suitability class level. The findings of the testing are summarized in Table 4.5 and Figure 4.18.

Table 4.5: **Comparison of Existing Small Agricultural Dams with Predicted Locations**

Suitability class level.	Potential site	Number of Dams	Land Area (km^2) per Suitability Class	Suitability Class % LandArea Coverage
2	Marginal suitable	8	5681.8	17
3	Moderately suitable	20	6365.3	43
4	Suitable	18	3151.2	39
Total		**46**		**100**

About 20 small agricultural dams (44% of the total rehabilitated dams) were found within the sites identified to have moderately suitable potential class, followed by 39% which is about 18 dams on sites identified to have a suitable class. The sites identified to have a marginally suitable potential had 17% of the existing dams in it. Figure 4.18 shows the spatial distribution of the existing reservoirs on each suitability class.
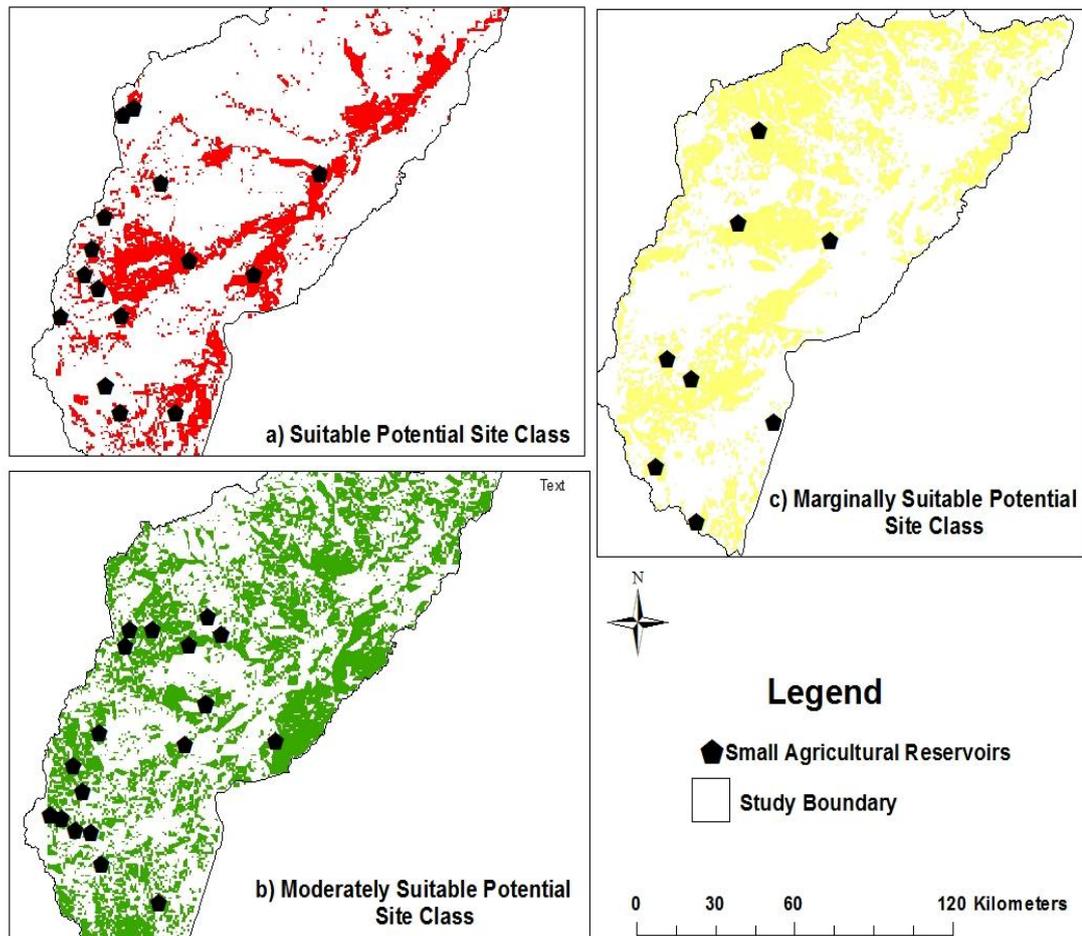
Figure 4.18: Spatial Distribution of the Existing Reservoirs per each Suitability Class.

These findings suggest the fact that, the used DSS framework to identify potential suitable sites for macro rainwater systems is reliable and can be employed to predict potential sites for surface rain water harvesting technologies in a semi arid environment. Due to data unavailability on existing stone terraces in the study area, the testing of the micro rainwater harvesting was not done.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1   Conclusion

It can be concluded that, the utilisation of GIS-based multi criteria decision support approach as a spatial analyst tool coupled with the use of rainfall runoff model to determine rain water harvesting sites, has proved to increase the level of accuracy for nailing areas of concentrated runoff collection. This is achieved through, the integration of several catchment physical characteristics, including rainfall in a GIS environment to come up with the best site that fulfil all the determining factors. The SCS CN model has proved to be applicable for the study area as it was able to identify areas of high runoff depth. Hence this methodology can be employed to earmark the potential surface runoff harvesting sites.

This is due to the fact that GIS has the ability to use spatial information in an integrated way and to show the modelling output through maps thus showing the spatial extent that can easily be interpreted and understood by anyone. Hence the framework applied works and can be used to identify this potential harvesting sites in another area with similar characteristics and this saves a lot of financial resources and time.

It also gives another opportunity for further analysis to determine the hydrological and ecological impact associated with such proposed implementation on both upstream and downstream even before those initiatives are implemented on ground

through the use of this study output results as input data in other hydrological models. The study results give a very important step towards considering an implementation of runoff harvesting strategy to the catchment since it gives planners an opportunity to target runoff collecting areas that retain high amount. With further analysis can help determine how often an on ground rainwater harvesting container fill within a rainy season and determine number of days of dry spell that can be augmented by the collected water.

The about aforementioned facts have been tried and tested by, testing the suitability map of potential sites for small dams with the existing water management structures data collected during field survey and from Department of Water Affairs and Ministry of Agriculture. The result analysis shows that of the 49 of the existing rehabilitated dams, 18 and 20 dams fall with the suitable and moderately suitable classes respectively and only 8 dams fall within the marginally suitable sites.

Since the full potential of surface rainwater harvesting in the Notwane catchment has not been fully explored and hence remains untapped, it can be through adopting this strategy towards addressing the water quantity issues especially considering the temporal and spatial distribution of the rainfall as well as high evapotranspiration rate for drought prone catchment and argument the high unmet water demands especially for the poor performing agricultural sector. All this can be accomplished if and only if the resultant effective rainwater and the in situ soil moisture where it rains can be treated as having a valuable potential and seen as a water resource and be managed correctly and efficiently.

Through this study, potential surface rainwater harvesting sites have been identified and the following can be concluded; the proportion of Notwane area that is found suitable for macro rainwater harvesting was found to be 10% of the whole catchment, thus an area about 1,524 km^2 out of the total area of 15,706 km^2 and has a runoff depth potential of between 389.38 mm/annum and 470 mm/annum. This is followed by 26% of moderately suitable with runoff depth potential of range between 366.522 mm/annum and 315.214 mm/annum. Lastly a larger percentage of 37% of the study area for not suitable which is about 5,551 km^2 with a low runoff of 274.828 mm/annum to 149.352 mm/annum. For micro rainwater most of the catchment is marginally suitable for in-situ rainwater harvesting, this means that most of the areas in the catchment have some limitations which collectively are moderate to sustain the intended activity for the given land. These areas have relatively low annum runoff depth of ranges between 366.522 mm/annum to as low as 274.828 mm/annum. However, because of their vertic properties they retain soil moisture.

5.2   Recommendations

Based on the outcomes of the results, it is recommended that;

- ➢ For better, accurate and precise identification of potential surface runoff harvesting sites, spatial data with fine scale should be used.
- ➢ The framework could be adopted by the Department of Water Affairs and Water Resources development Unit under Ministry of Agriculture to plan and manage future water development projects as it shows the full potential areas of high runoff generation.

➢ The findings of this study be linked closely with Natural Capital Accounting tool, since the outcomes provides information missing in national economic accounts (such as accounting for potential stocks from harvested rainwater) and also provide information required by Botswana Government for optimal use and management of its natural capital.

➢ The framework output maps can be used by researchers and scholars for further hydrological analysis assess impact associated with the planned water development even before the project is implemented.

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APPENDICES

Appendix A: List of Rehabilitated Small Dams

No.	Dam Name	Latitude	Longitude
1	Mpechane	-25.271944	25.525278
2	Lekgopha	-25.099444	25.371944
3	Kgomokasitwa	-25.0875	25.648333
4	Mmameno	-25.077	25.799167
5	Rankoramane	-25.024444	25.68
6	Masinyetse	-25.0222	25.473633
7	Masinyetse	-25.0222	25.473633
8	Masinyetse	-25.0222	25.473633
9	Kutlwano	-24.967778	25.435278
10	Letsetleng	-24.968889	25.820556
11	Kwafu	-24.940444	25.419667
12	Kwafu	-24.940444	25.419667
13	Ditsobotlana	-24.870278	25.395278
14	Tlhokwane	-24.861972	25.337306
15	Zambia	-24.831683	25.5099
16	Masoboloko	-24.827583	25.28825
17	Gamokalaka	-24.819167	25.212222
18	Taushele	-24.815611	25.242
19	Kgolomo	-24.801306	25.222667
20	Moshupa	-24.771064	25.419231
21	Mmamorolong	-24.744167	25.366111
22	Tshwaane	-24.726389	25.251389
23	Sephatlhaphatlha	-24.723333	25.48
24	Kubung	-24.666667	25.333333
25	Sehatlane 2	-24.64025	25.394861
26	Rakola	-24.604444	25.753889
27	Sehatlane	-24.5975	25.343889

28	Glen Valley	-24.603	25.980028
29	3-Kopi	-24.595833	26.094167
30	Dam No. 18	-24.565167	25.433083
31	Kamenakwe	-24.5575	25.7375
32	Mmaphoroka	-24.520139	25.371778
33	Gakutwe 2	-24.483889	25.831111
34	Gakutwe	-24.481111	25.831111
35	Gakutwe	-24.481	25.831222
36	Mmofu	-24.422283	25.41955
37	Longaneng	-24.413056	26.035278
38	Serale	-24.359167	25.690278
39	Dithupe	-24.321667	25.634444
40	Molepolole Prs.	-24.3	25.5336
41	Ditshoso	-24.300528	25.770139
42	Somanka	-24.296111	26.2275
43	Manyelanong	-24.269444	25.8925
44	Mahetwe	-24.252967	25.636917
45	Mogonono	-24.251111	25.550833
46	Mmadikgomo	-24.213778	25.841389
47	Botlhapatlou/Maphalelwane	-24.111944	25.496139
48	Moleleme	-24.091389	25.536389
49	Ngwanche	-24.075417	25.771972