USE OF SATELLITE PRODUCTS TO ASSESS WATER HARVESTING POTENTIAL IN REMOTE AREAS OF AFRICA

A CASE STUDY OF UNGUJA ISLAND

ZANZIBAR

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USE OF SATELLITE PRODUCTS TO ASSESS WATER HARVESTING POTENTIAL IN REMOTE AREAS OF AFRICA

by

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Abstract

This study presents a methodology that can be easily applied to identify Rain Water Harvesting (RWH) sites using freely available RS products and GIS for data scarce areas of Africa. The potential of data integration (use of historical and near real time RS data, GIS and hydrological modelling) to assess the potential of RWH in combination with analytic hierarchy process (AHP) using spatial multi-criteria evaluation (SMCE) model as the GIS platform is exploited.

The Integrated Land and Water Information System (ILWIS), a GIS software package is used to derive all the key spatial layers that are used for various analysis. Input layers derived for use in this model include rainfall, slope, soil groups, land use/cover, CN and runoff index with a spatial resolution of 30 metres. RWH maps indicating spatial extents of suitable areas for roof catchment (RC), Micro and Macro Catchment are the key outputs.

Soil Conservation Service (SCS) is used for runoff modelling at pixel scale. About 84% of the total runoff is generated within flat and undulating slope classes. Masika rains (March to June) contribute 64% while the Vuli rains (October to December) accounts for 20% of the total annual runoff.

Based on the developed model, the RWH sites identified relative to runoff generating areas produced 10.18 km^2 suitable areas for roof catchment, generating 4.6 Million Cubic Metres (MCM) which can meet 33% of the total annual water demand. 30% of the island is suitable for micro-catchment RWH and 23% suitable for macro-catchment RWH representing a total area of 44,000 and 35,000 hectares respectively.

Validation for micro-catchment RWH (based on existing and expert knowledge) shows that 10 % of the sites identified as suitable are unsuitable, 10 % in marginally suitable areas and 80 % within suitable and highly suitable areas. For macro-catchment RWH, 12% of the sites are in unsuitable areas, 20 % in marginally suitable and 68 % within suitable and highly suitable areas.

The capabilities of using RS, GIS and field data for identifying potential sites for RWH technologies for decision making on development and management of RWH programmes is well demonstrated.

The main constraint to the adoption of RWH could be associated with lack of knowledge among the decision makers and the community on existing potential for RWH for the island. RWH suitability maps developed in this study that give a clear indication of the spatial extents and the existing potential can be a starting point for creating awareness among stakeholder at the local and national scale.

Key words: Remote Sensing; GIS; AHP; SMCE; Roof catchment; Micro and Macro catchment RWH

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Abbreviations and Acronyms

AHP	Analytic Hierarchy Process
ARC	Antecedent Runoff Conditions
CI	Consistency Index
CN	Curve Number
CR	Consistency Ratio
DEM	Digital Elevation Model
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAO	Food and Agricultural Organisation of the United States
GIS	Geographic Information Systems
ICRAF	International Centre for Research in Agro-forestry
ILWIS	Integrated Land and Water Information System
KARS	Kizimbani Agricultural Research Station
MCDM	Multi-criteria Decision Making Methods
MDGs	Millennium Development Goals
MPE	Multi-sensor Precipitation Estimate
NDVI	Normalised Difference Vegetation Index
NGO	Non Governmental Organisation
RC	Roof Catchment
RI	Random Index
RS	Remote Sensing
RWH	Rainwater Harvesting
SCS	Soil Conservation Services
SMCE	Spatial Multi Criteria Evaluation
SMOLE	Sustainable Management of Land and Environment
UNEP	United Nations Environmental Programme
ZAWA	Zanzibar Water Authority

1. INTRODUCTION

“Water is at the heart of Millennium Development Goals (MDGs) numbers 1, 3 and 7, and is indirectly associated with the success or otherwise of all the other Goals. But for Africa to meet the MDGs, bold and targeted actions are required in the water sector. To address this, the African Water Vision for 2025 has set to develop the full potential of Africa’s water resources for sustainable growth in the region’s economic and social development, of which rainwater harvesting (RWH) and storage forms a major component” (ICRAF, 2005).

In general terms RWH can be defined as the harnessing of rainwater that will normally runoff for beneficial use in areas of water scarcity. Various methods exist that can be used to harness rainfall key of which that have been applied include:-

- Micro-catchment rainwater harvesting
- Macro-catchment rainwater harvesting
- Large catchment flood water harvesting with storage in dams, pans and sub-surface dams

RWH can be a measure to increase access to water for the vulnerable sections of the society in arid and semi-arid parts in countries where water resources are scarce or inaccessible.

The water harvested can be used for various purposes ranging from domestic, livestock, agricultural production, industrial and groundwater recharge. A successful implementation of RWH should integrate social-economic and environmental issues to ensure sustainability and protect fragile ecosystems.

RWH may lead to increased food production through minimizing the risk of crop failure during droughts and floods; avail more water for domestic and industrial use. At watershed level anticipated benefits include recharge to groundwater systems and improvement of environment. The results of rainwater harvesting in modification of the ecosystems is clearly demonstrated by Vohland et al., (2009).

According to a report by Millennium Development Goals - MDG Centre, Nairobi Kenya (2007) the following key issues that contribute to poor water access need to be addressed in Zanzibar.

- Poor access to and availability of water due to inadequate water harvesting infrastructure – water storage falls below 1700 m^3/capita/year (international accepted minimum).
- Extremely low agricultural production – averaging less than one ton per hectare due to intra-seasonal dry spells and drought; this has been made more critical by climate change and weather risk; these could be mitigated through supplementary irrigation and in-situ RWH
- Poor management of rainwater e.g. flooding, erosion etc.

This research seeks to address, the key contributing factor which as outlined by ICRAF and UNEP (2005) is the lack of tangible scientifically verified information that can be used to identify areas where RWH can be applied. This was achieved by developing a user friendly database with formats that can be easily updated, queried, managed and utilized based on Remote sensing (RS) and Geographic information systems (GIS).

1.1. General objectives

This study explored the potential of data integration (use of historical and near real time RS data, GIS and hydrological modelling) to assess the potential rainwater harvesting sites in remote and data scarce areas.

1.1.1. Specific objectives

The followings specific issues are addressed:-

- Identify and map out the potential rainwater harvesting sites for Unguja Island.
- Determine effectiveness of integrating RS and GIS (data preparation and model parameterization) with hydrological modelling to identify potential rainwater harvesting site
- Identify data requirements (bio-physical and socio-economic) and structure of a GIS based RWH potential identification model that can be applied locally.

1.2. Research Questions

This research will seek to answer the following questions:-

- Which historical and near real time satellite data products can be used to map out RWH potential sites?
- How can integrating remote sensing, GIS and hydrological modelling be optimally utilized to identify suitable RWH sites?
- Which is the best approach in assessing RWH potential site?
- How appropriate are the identified RWH sites for the specific technology?

1.3. Hypothesis

The validity of the following hypothesis is tested:-

- Available historical and near real time satellite data sets can be used to identify potential RWH sites.
- Runoff available for storage can appropriately be modelled using available rainfall runoff models in remote and data scarce areas.
- RWH sites and appropriate technologies can be optimally determined by integrating RS, GIS and rainfall-runoff models.

1.4. Thesis Outline

The general purpose of this research is to develop methodology that can be easily applied to identify RWH site using freely available RS data and GIS for data scarce and remote area of Africa.

This thesis is presented in six chapters as outlined below:-

Chapter 1 gives an overview of the study area and outlines the key problem that forms the basis of this research. The Research objectives, research questions, the hypothesis and the thesis outline.

Chapter 2 reviews related works conducted in this field to gain insights on key methodologies used that may be applicable to this research. A brief description of the study area is also highlighted.

Chapter 3 presents the conceptual framework used in conducting the research, the methodology used, field work data collection and analysis. It forms the basis of all the other chapters.

Chapter 4 presents the results of analysis of the RWH potential using the analytic hierarchy process (AHP). The suitability for both micro and macro catchment RWH is presented.

Chapter 5 discusses the results obtained and their relevance to the study area.

Chapter6 outlines the conclusions and recommendations arising from this research.

2. LITERATURE REVIEW

2.1. Rainwater harvesting concepts

Zanzibar has experienced an increasing water demand in all sectors since early 1980s according to Halcrow (1994). RWH can be used as a measure to increase water availability for all sectors.

RWH in various forms has been traditionally practised throughout the centuries. Diversions using spate flow from normally dry water courses (wadi) into agricultural area in the Middle East form some of the earliest examples. Other examples include the Negev desert (Evenari et al., 1971), the desert areas of Arizona and Northwest Mexico (Zaunderer et al., 1988) and Southern Tunisia (Arnold *et al.*, 1986).

The importance of traditional, small scale systems of rainwater harvesting in sub-Sahara Africa has recently been recognised (Critchley et al., 1989). Simple stone lines are used, e.g. Burkina Faso and Mali; earth bunding systems in eastern Sudan, Kenya and the central rangelands of Somalia.

Rainwater harvesting for improved crop production has received great attention in the 1970s and 1980s mainly due to the widespread variability of rainfall with the associated effects of crop failure or reduced yield and threat to livestock and human life in semi arid and arid regions of Africa (Hatibu et al., 1999)

It is advocated that RWH holds the opportunity to contribute to the equitable, efficient and sustainable use of water resources by alleviating temporal and spatial water scarcity, providing water beyond the basic human needs and, hence enabling small-scale productive activities (Kahinda et al., 2007). More emphasis is made on the importance of social, economic, and environmental considerations when planning and implementing RWH projects (Arnold *et al.*, 1986) to ensure sustainability.

RWH technologies are flexible and can be adjusted to local circumstances and should therefore be built according to the ecological characteristics of a particular region or locality (Bancy et al., 2007).

2.2. Rainwater harvesting potential assessments

2.2.1. Application of Remote sensing and GIS

Diverse research methodologies using RS and GIS have been applied by different authors to identify potential rainwater harvestings in remote and data scarce areas; in most of these methods, thematic maps are derived from remote sensing data and integrated in GIS to evaluate suitable sites for rainwater harvesting.

Remote sensing is of immense use for natural resources mapping and generating necessary spatial database required as an input for GIS analysis. GIS is a tool for collecting, storing and analyzing spatial and non - spatial data, and developing a model based on local factors can be used to evaluate appropriate natural resources development and management action plans. Both these techniques can complement each other to be used as an effective tool for selecting suitable sites for water harvesting structures (ICRAF, 2005).

In assessment of rainwater harvesting potential using GIS and RS, FAO(2003) outlines six key factors that require to be integrated into a GIS framework in order to successfully develop a suitable model for RWH. This include; rainfall, hydrology (rainfall-runoff relationships), slope, land cover, soils (texture, structure, depth) and socio-economics of the area under consideration.

Identifications of potential sites for construction of rainwater harvesting structures for recharging groundwater in Bakhar watershed of Mirzapur District, Uttar Pradesh, India, was conducted by Kumar, Agarwal and Bali (2008) through deriving various thematic maps such as Landuse/Landcover, geomorphology and lineaments, etc, using remote sensing. These layers along with geology and drainage were integrated using GIS with some weighting using expert knowledge to identify sites for rainwater harvesting.

The application of GIS as an integrating tool to store, analyse and manage spatial information and linking it to hydrological response models, to facilitate decision making by providing catchment level identification, planning and assessment of runoff harvesting sites has been applied by de Winnaar et al.,(2007).

Kahinda et al.,(2008) presented a methodology that enables water managers to assess the suitability of RWH for any given area which incorporated social economic factors which previous methodologies did not consider. These came out of the realisation that the non-integration of socio-economic factors leads to failure of rainwater harvesting projects. Using a combination of physical, ecological and socio-economic factors in-field RWH and ex-field RWH suitability maps were developed.

2.2.2. Analytic Hierarchy Process (AHP)

The integration of Multi-criteria decision making methods (MCDM) with GIS has considerably advanced the conventional map overlay approaches to the land-use suitability analysis (Malczewski, 2004).

Analytic hierarchy process (AHP) is one of a GIS-based MCDM that combines and transforms spatial data (input) into a resultant decision (output). The procedures involve the utilization of geographical data, the decision maker’s preferences and the manipulation of the data and preferences according to specified decision rules referred to as factors and constrains.

Key considerations that are of critical importance in decision making as outlined by Malczewski (2004) are; (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation and analysis, and (ii) the MCDM capabilities for combining the geographical data and the decision maker’s preferences into uni-dimensional values of alternative decisions.

AHP is a key decision making tool that was used in this study to assist in obtaining an appropriate solution over suitability assessment for RWH. The process involved the structuring of factors that are selected in a hierarchy starting from the overall goal to criteria, sub-criteria, and alternatives in successive levels (Saaty, 1990).

Four steps are outlined by Saaty (2008) that are key in undertaking AHP in an organized way in order to make a decision over alternatives. These are; definition of the problem or issue to be considered, identify the goal which is the criteria that the other elements usually the alternatives will depend on which should be at the top of the decision making tree, develop a pairwise comparison matrix, weigh priorities for each element with priorities obtained in the comparison matrix to obtain a global priority that will form the basis of decision making for the alternatives at the bottom of the hierarchy.

Kinoti et al., (2006) used expert knowledge based multi-criteria evaluation process to identify water harvesting systems in Tanzania. This study integrated various data such as meteorological, terrain parameters and remote sensing to simulate runoff generation. The runoff potential is determined by assigning weights and AHP is applied as a decision support system to arrive at the final decision.

Integrating AHP in a GIS environment can be used to make decisions based both on expert and indigenous knowledge and choose between alternatives. The weighting assigned to the thematic layer vary from one site to the other hence may not be replicated.

2.3. Rainfall-Runoff modelling

Rainwater harvesting is a hydrological intervention which can best be depicted through hydrological models that are able to show directions of flow, runoff and run-on areas and identify locations for impounding structures.

This can be achieved through appropriate extraction of the key hydrological parameters in GIS based environment. The data required for input in the hydrological models are currently obtainable through remote sensing techniques.

Gupta et al.,(1997) suggested the use of land cover information derived from remote sensing satellite data in the form of the normalized difference vegetation index (NDVI) to derive maps that are used as input to derive a modified Soil Conservation Service (SCS) runoff curve number (CN). The derived CN is then used to model rainfall- runoff relationships for a watershed/catchment.

The Soil Conservation Services (SCS) method has been widely applied to estimate the surface runoff from a given rainfall event. This method is usually acceptable where the rainfall amount from a given rainfall even exceeds 40 mm. This method has been applied by de Winnaar et al., (2007) to determine the runoff available for in determining the potential RWH potential sites for Thukela River Basin, South Africa.

The key parameters that can be used to derive the CN are the reclassified soil categories based on the soil texture units and landcover to derive the final curve number. The derived CN is then used to derived the runoff expected from a given rainfall amount and hence the runoff index is developed (Senay et al., 2004).

2.4. Study area

The study area is Unguja which is the main Island of the two that form Zanzibar. The Island has a total area of 1658 km^2 and is located 40 kilometres off mainland Tanzania; approximately bounded by co-ordinates 5 degrees and 6 degrees south latitudes and along 39 degrees east longitude. The north- south extent of Unguja is approximately 85 kilometres with the east-west extent varying from 9 kilometres in the northern end to about 35 kilometres in the south (Hettige, 1990). Figure 2.4-1 shows the extent of the study area.

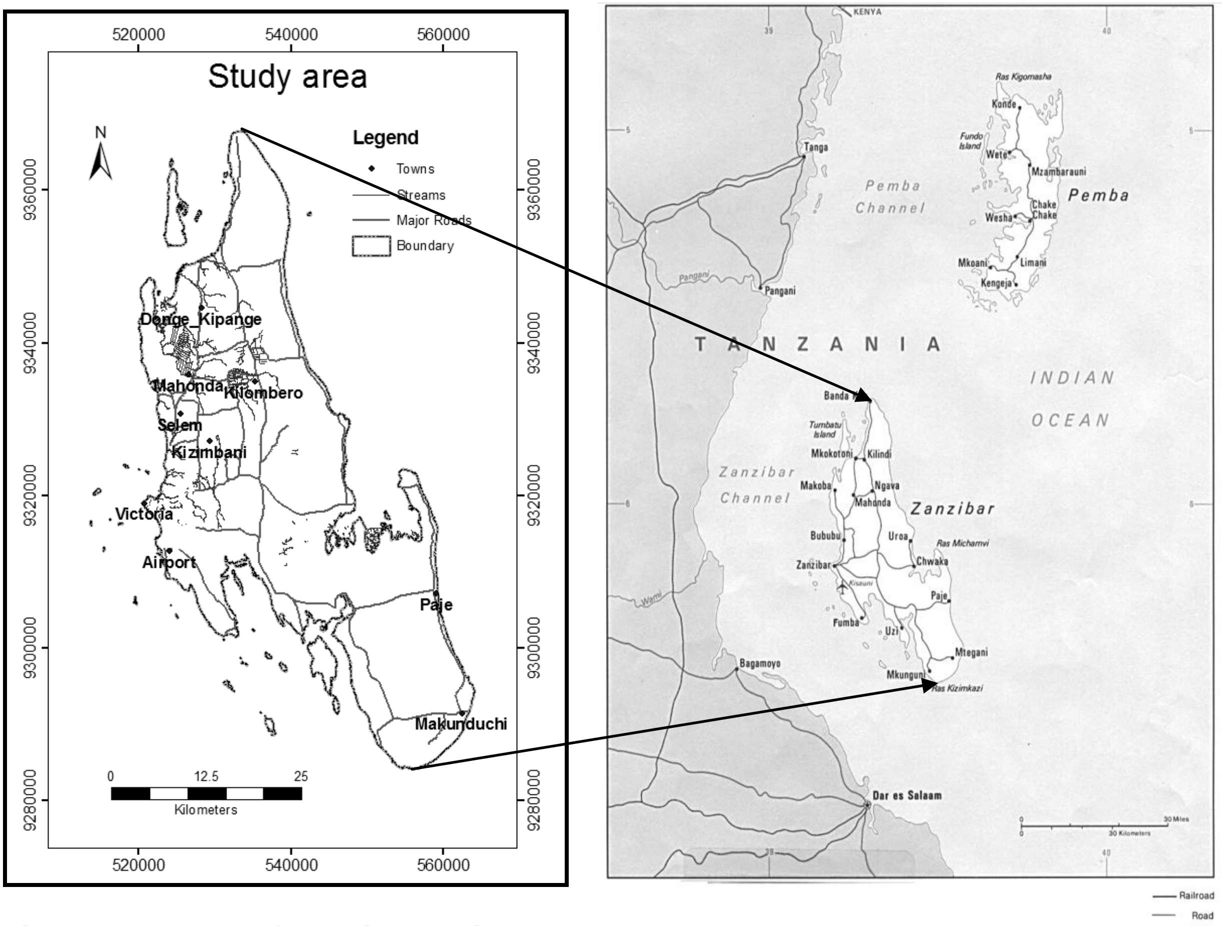


Figure 2.4-1: Map of Unguja Island

2.4.1. Climate

The Island is characterised by a bimodal rainfall pattern. The average annual rainfall of the Island varies from about 1,200 mm along the east coast to more than 2,000 mm in the central hilly part of the Island.

There are two distinct rain seasons locally known as Masika (long rains) and the Vuli (short rains). The main rainfall season (Masika) starts in March with a peak in April extending to June. The second rain period (Vuli) is between October to December. Majority of rain falls during Masika rainfall with April-May accounting for 49% of the total rainfall; the driest months known locally as Mchoo are July and August; this period though, also receive some precipitation (Hettige, 1990).

Annual average temperature of the Island is 26^{o}C, with maximum temperatures of 27^{o}C occurring in January and minimum of 24^{o}C in July. Evapotranspiration varies between 4.4 mm in May to 5.8 mm per day in February with a mean of about 5mm per day.

2.4.2. Topography

Unguja is characterised by wide valley corridors, fault structures and residual hills reaching a maximum of about 117 meters in the central parts of the Island.

Four main topographic systems are identified by Hettige M.L (1990) namely: marine, ridge, coralline reef and alluvial systems. The ridge system has a varying elevation with low elevation system ranging between 0-45 meters, low to medium (30 -70 meters) and medium (45 -117 meters). The fourth system of the ridge system is defined by isolated wedge shaped limestone outcrops in the coral rag regions.

The alluvial system is composed of open and closed corridors; plains; depressions and basins. This system can be differentiates by their drainage patterns with open corridors having unrestricted drainage while the closed corridors have a subsurface drainage. The depressions and basins are characterised by flat areas with a blocked drainage towards the sea.

2.4.3. Drainage Characteristics

Drainage is mainly westerly but predominantly subsurface apart from areas with heavy clay soils.

In the ridges system, with underlying slowly permeable clay soils drainage channels have developed with time along the slopes of Miocene limestone ridges, draining directly to the sea and some minor rivers within the corridor valleys (FINNIDA, 1991; Hettige, 1990) giving rise to dissected landscapes and a dendritic drainage pattern.

2.4.4. Soils and Geology

Surface geology of Unguja is characterised by a sequence of recent deposits (Q1); quaternary formations (Q2); early quaternary deposits and Miocene limestone. Recent deposits are found within the corridor zone and are composed of colluvial and alluvials. The quaternary system consists mainly of terraced coralline reef formation.

Miocene limestone’s are in three classes differentiated by age and stratigraphy as M1, M2 and M3. M1 is the most recent and consist of crystalline, reef and detrital limestone. M2 is composed mainly of grey to white limestone with hard siliceous bands. M3 are greyish to bluish green limestone's consisting mainly of marls clays and sandy clays and can be found underlying the weathered M2 system (Hettige, 1990)

Soil types of the island largely depend on geological formation and variations are associated with the parent material. Sandy Mchanga (sandy soils) is mainly found in the Q1 formation. Within the M2 and M3 systems the Uwanda and Maweni kinongo soils (loamy soils) are dominant. Kinongo soils (loamy soils) are a product of M1 weathering while the Kinamo (clay soils) are formed from the M3 system.

3. METHODOLOGY

3.1. Conceptual framework

The methodology used to determine the potential RWH site for the study area using RS and GIS is as indicated in the flow chart figure 3.1-1.

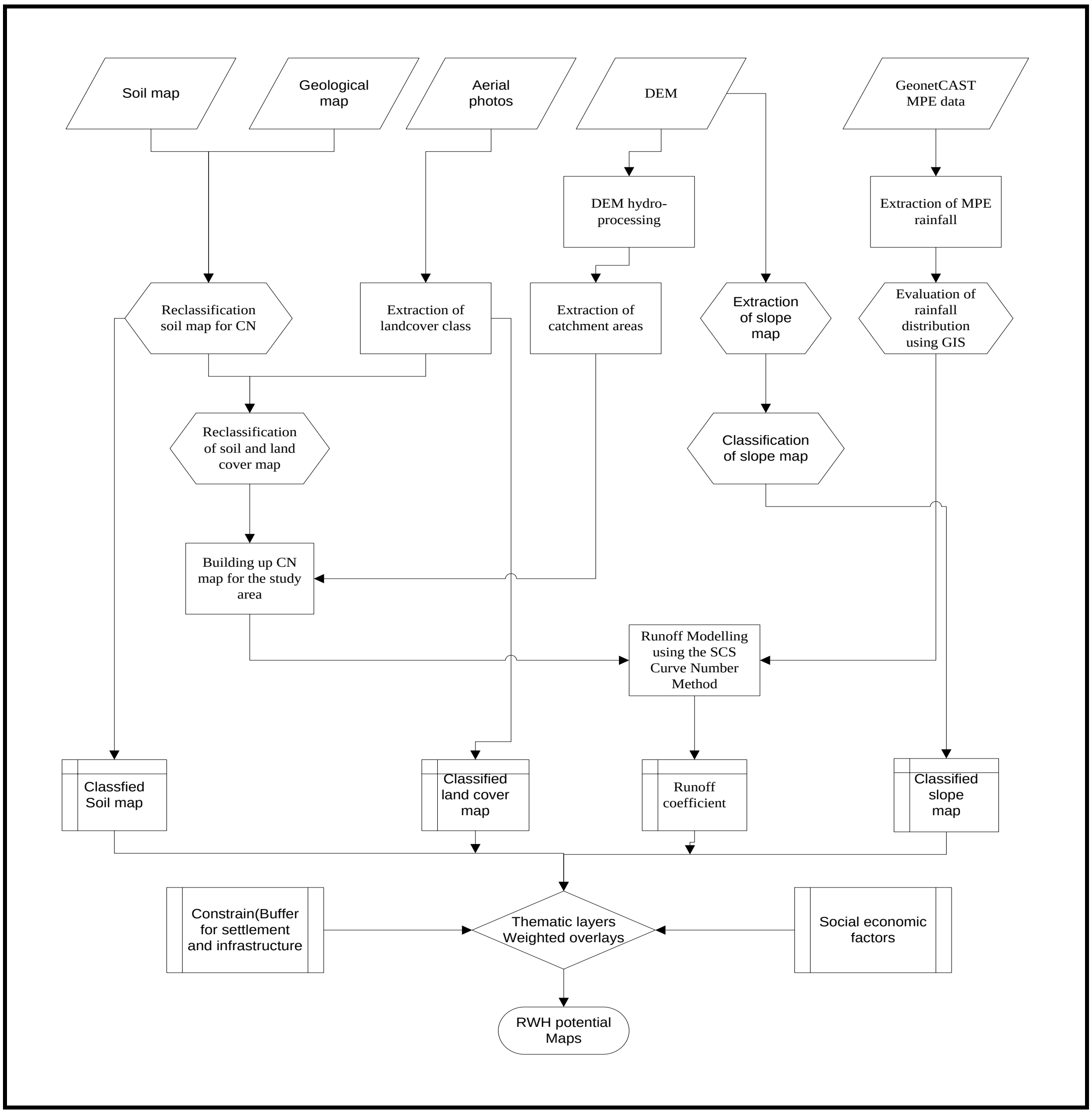


Figure 3.1-1: Conceptual framework for generating runoff coefficient and suitable RWH site

3.2. Primary data sets and field work

3.2.1. Primary data sets

The primary data sets used in this study are presented in table 3.2-1.The data giving the scale, spatial extent, data type and source of data was collected from different sources during field work.

Table 3.2-1: Primary Data sets

Data set	Year	Scale	Spatial Extent	Type	Source
Soil Map	1990	1:100000	Unguja Island	Scanned map	(Hettige, 1990)
Meteorological data	various	Point Measurements	9 weather stations on the Island	Daily totals for 2 stations and monthly average totals	Tanzania Meteorological Agency and ZAWA
Otho-rectified aerial photographs	July 2004 to may 2005	0.5 metres spatial resolution	Unguja Island	Geo-referenced	SMOLE
Layer digitized from aerial photos in vector format	2009	Varying	Unguja Island	Geo-referenced vector format layers for Roads, buildings, streams , Unguja outline and land use	SMOLE
Hydro-geological map	1987	1:125000	Unguja Island	scanned map	ZAWA

3.2.2. Field work

Field work was conducted during the months of September and October 2009. Random sampling was undertaken considering soil variability, landscape, landcover and topography to identify this relationship between the variable. Aerial photo for the study area were used to aid in sampling and enable coverage of diverse landcover and soil types.

Landcover/ land use and soil type (texture) were recorded for 191 sample points. The key issues considered were; co-ordinates, dominant landcover/ land use, soil type and texture; and the infiltration properties of the soils. Specific notes were made on sites that were considered suitable for both micro and macro catchment rainwater harvesting.

Soil types and texture were identified in the field with help from a soil scientist from Kizimabani Agricultural Research Station (KARS). Social economic information was also gathered to establish the community perception on RWH. Aerial photo used during field work and points sampled are presented in appendix 1.

3.3. Application of RS and GIS

Application of the methods explored in the literature review is tested in deriving the thematic layers that are the key inputs used to determine the potential sites for both micro-catchment and macro-catchment RWH. The layers are processed using ILWIS a freeware GIS/RS package that is accessible to most organisations.

3.3.1. Digital Elevation Model (DEM) Hydro-Processing

Aster Dem with 30m resolution tile number ASTGTM_S06E039 and ASTGTM_S06E039 were downloaded (http://www.gdem.aster.ersdac.or.jp/.) and were used for this study to derive the key hydrological parameters.

Digital image processing was performed to extract the DEM that is used for hydrological processing using Integrated Land and Water Information System (ILWIS), a GIS/RS package based on the approach developed by Maathuis et al., (2006).

Pre-processing of the DEM was performed to interpolate for undefined area using an average filter of kernel size 5 by 5 before further processing to derive the catchments, drainage and slope maps. The DEM was further analysed to remove pits (sinks) and flat areas to maintain continuity of flow to the catchment outlets .Figure 3.3-1 shows the Final Interpolated DEM, filled DEM (sinks free DEM) and the sinks area maps.

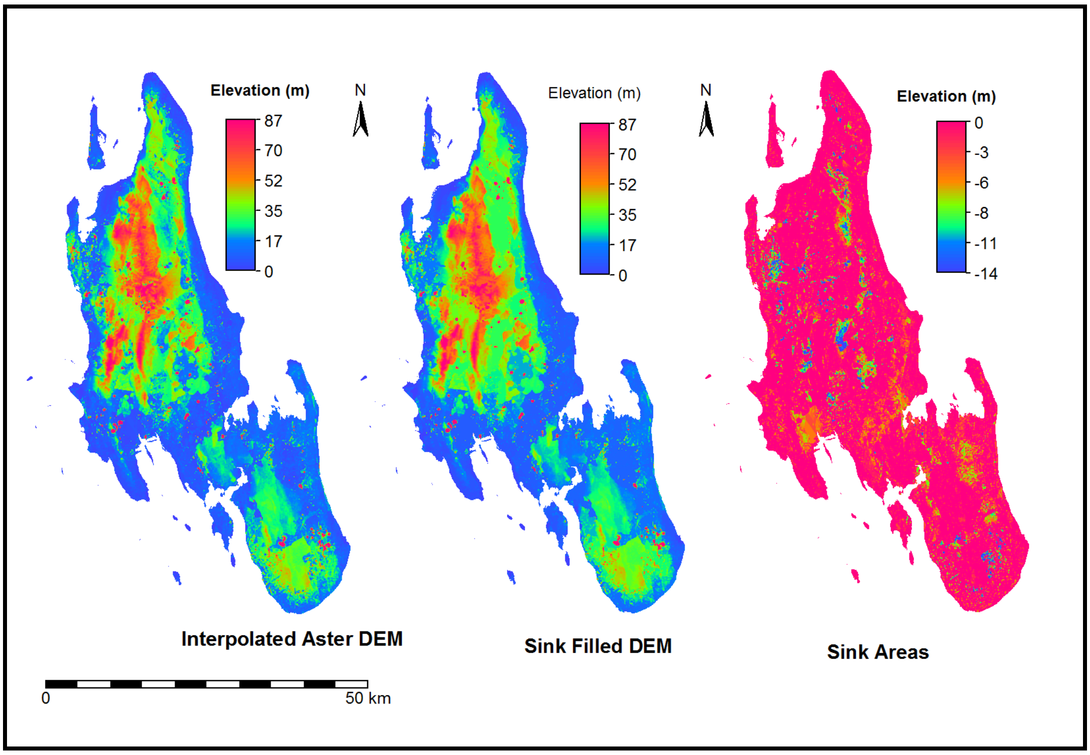


Figure 3.3-1: Interpolated DEM, Sink Filled DEM and Sink Areas

Steps used to delineate the catchment areas after the fill sinks operation are as outlined below:

- Flow direction determination using the deterministic 8 model which determines into which neighbouring pixel any water in a central pixel will flow. Parallel flow correction is achieved through increasing the elevation of the flat area cell in order to attain the desired drainage pattern (Garbrecht J et al., 1997)

- Flow accumulation to obtain the drainage pattern of the terrain which represents the number of pixels contributing water to any outlet within the basin. The outlets of the largest streams, rivers etc, acquire the highest values.
- The drainage network determined using a threshold of 750 contributing pixels; otherwise a lower number of pixels indicate overland flow.
- Catchment extraction based on the derived drainage network and the flow direction map and a minimum drainage length of 1000 metres.
- The final catchment map determined by merging the minor catchment extracted using outlet point map based on the Strahler stream ordering. This operation generates 26 catchments.

The final catchment and drainage maps generated are presented in figure 3.2-2.

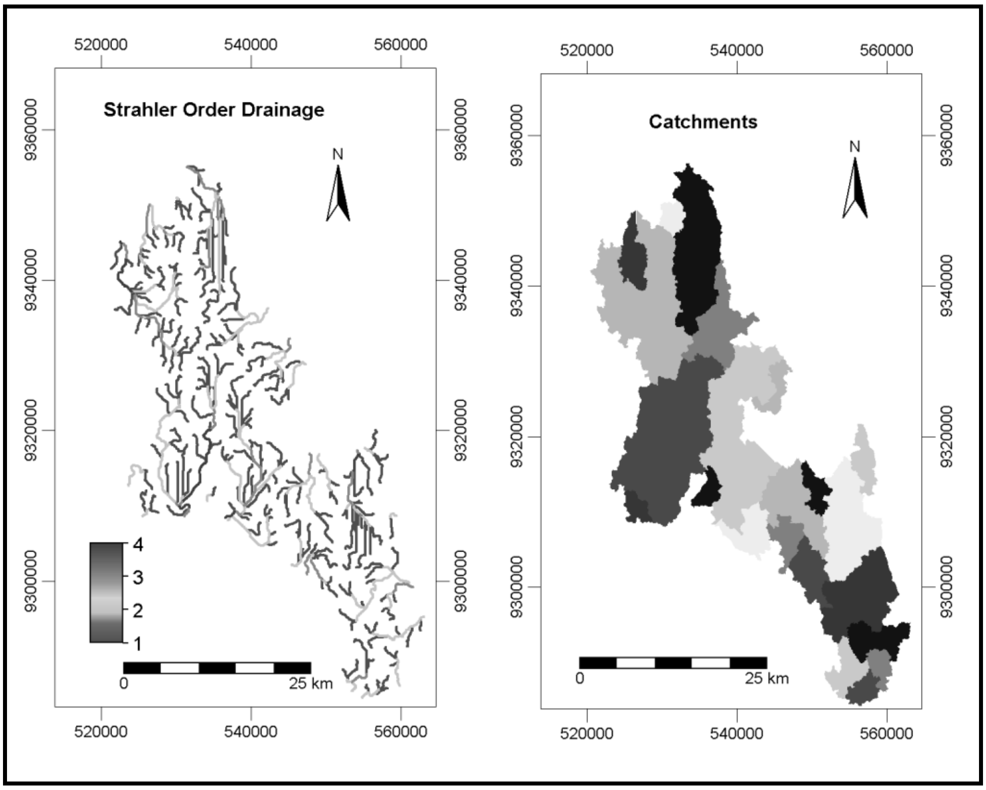


Figure 3.3-2: Drainage and catchment areas derived from DEM

In the eastern part of the island dominated by limestone outcrops (known as coral rag region), subsurface flow is dominant. This region therefore has an undefined drainage pattern due to absence of surface flow and high infiltration rates.

3.3.2. Analysis of Rainfall Distribution from rain gauges network

The rainfall gauges network in the island is sparse and has not been operational continuously over the years. Rainfall point measurements have traditionally been used to estimate rainfall for most regions in Africa. A dense network is required to estimate accurately the spatial rainfall distribution for a given area.

Interpolation of point measurement is therefore necessary to estimate rainfall for areas that are not covered by rain gauges (Goovaerts, 2000). Eight rainfall stations are used for interpolation to surrounding areas that are not covered by the network. Figure 3.3-3 shows the location and distribution of the rainfall stations used.

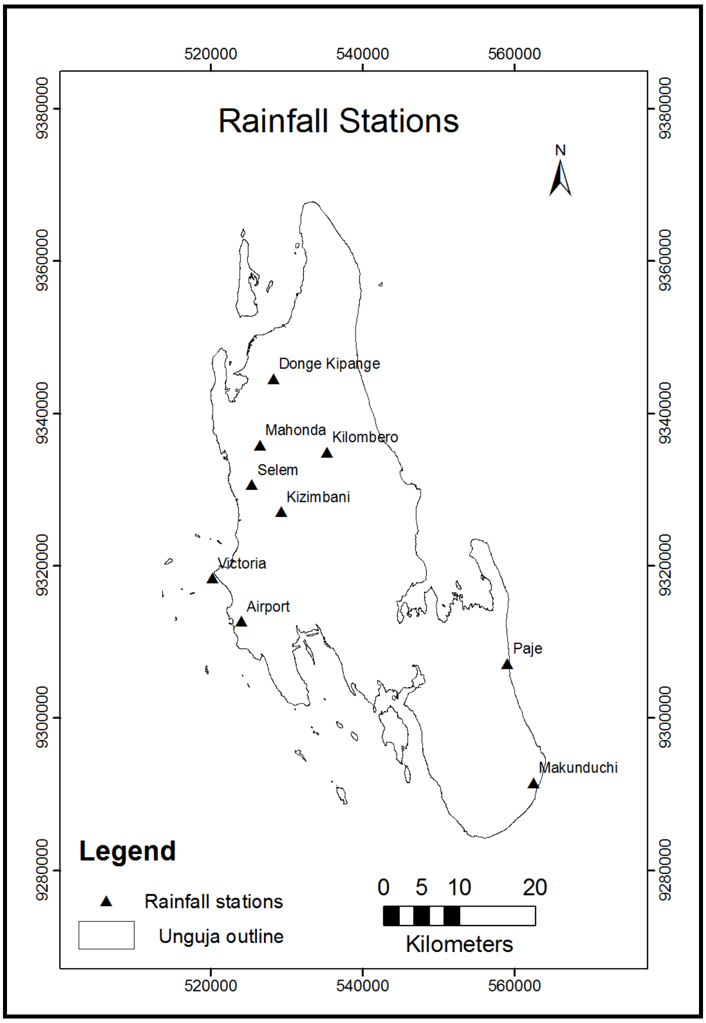


Figure 3.3-3: Spatial distribution of rainfall stations

The eight rainfall stations area assigned attributes based on the long term annual averages rainfall for interpolation using the moving average method. Due to the sparse nature of the stations and a few years of continuous data, this method is preferred over the kriging method that performs better when the data density is sufficient (Eischeid J et al., 2000).

Moving average performs a weighted averaging on point values based on a specified weight function and a limiting distance (ITC-ILWIS, 2001). The inverse distance weighting method based on equation 3-1 was used.

$$\text{Weight} = \left(\frac{1}{d^n}\right) - 1 \qquad \textbf{3-1}$$

Where:

d = $\frac{D}{D_0}$ = relative distance of point to limiting distance point.

D = Euclidean distance of point to limiting distance

D_o = Limiting distance
n = weight exponent

The weight functions ensure that points close to the measurement receive higher weight value than points which are farther away. The final rainfall map is developed using equation 3-2.

$$\text{Estimated value} = \frac{\sum_{i=1}^{n}(W_i \times Val_i)}{\sum_{i=1}^{n} Wi} \qquad \textbf{3-2}$$

Where
W_i = Weight value for point *i*
Val*i* = Point value of point *i*

The interpolated rainfall map figure 3.3-4 of the study area is based on the long term annual average measured rainfall, a limiting distance of 4 kilometres and a weighting exponent of 1 to ensure a smooth interpolation. Appendix 2 gives the rainfall data used for interpolation to spatially distribute point measurements over the entire study area.

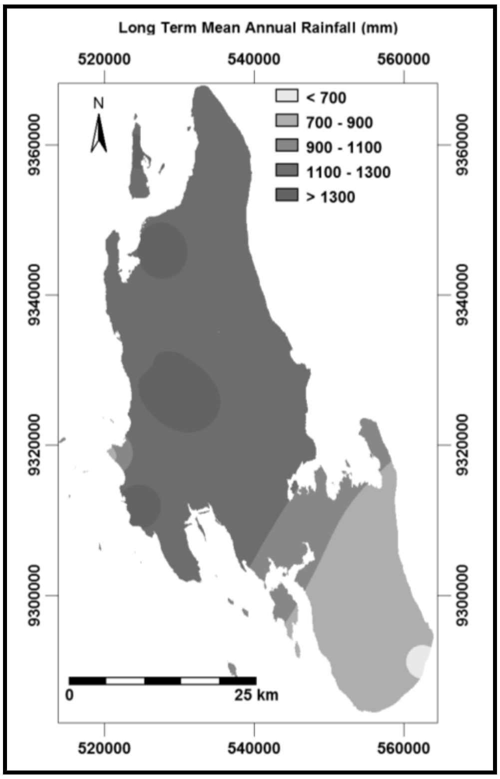


Figure 3.3-4: Spatial distribution long term mean annual rainfall

More rainfall is received in the western part of the Island characterised by high elevation than the east. There is a variation in the amount of rainfall received despite the small extent of the Island with some areas receiving rainfall amounts as low as 700 mm. A maximum of about 1600 mm per annum is received in the central part of the Island.

3.3.3. EUMETSAT MPE Rainfall Product

The Multi-sensor Precipitation Estimate (MPE) is a real-time instantaneous rain-rate product which is derived every 15 minutes from the EUMETSAT's geo-stationary satellites. The product provides real rainfall rates and daily average precipitation mostly for convective rainfall (Kidd et al., 2008). The product is suitable for use in Africa where real time rainfall information is not readily available and the rainfall monitoring gauge for meteorological and short-range hydrological applications is sparse or lacking.

MPE data with a spatial resolution of 3 kilometers for the period January 2007 to December 2009 was downloaded and resampled to match the spatial resolution of the base maps used in this study (30 meters). Bi-cubic resampling was applied since it gives more reliable results compared to other methods.

MPE data is selected for use due to its ability to retrieve rainfall intensities for remote area where no rainfall gauges exists hence enabling more representative retrievals for hydrological modeling. Figure 3.3-5 outlines the annual total rainfall as derived from MPE product for the years 2007 to 2009.

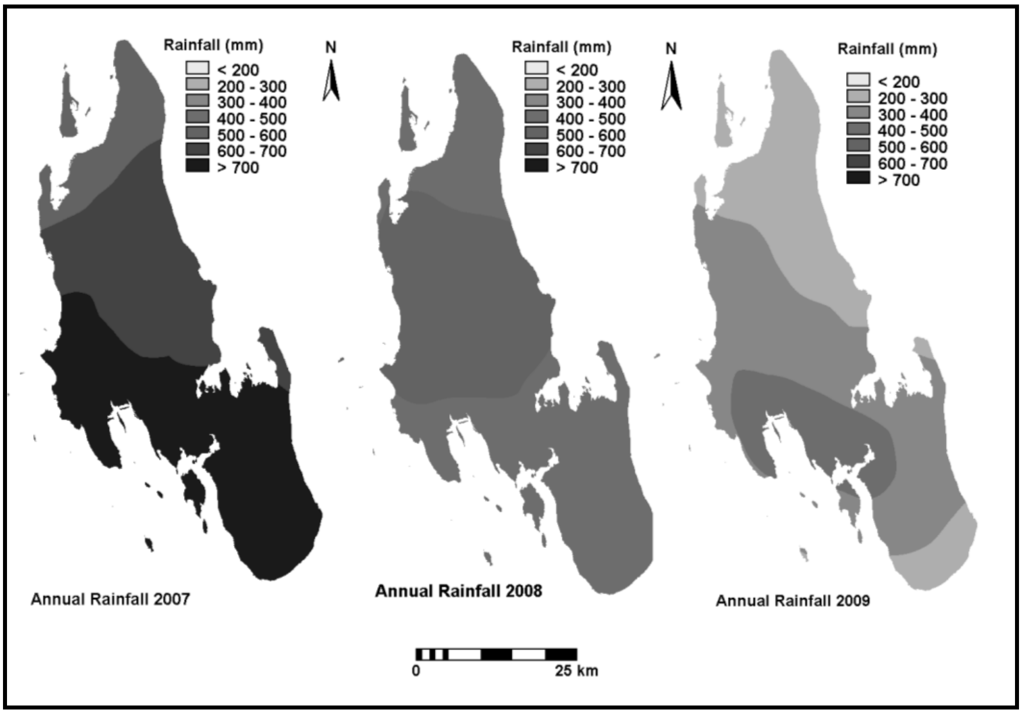


Figure 3.3-5: MPE Annual Rainfall Totals

3.3.4. Thematic maps

3.3.4.1. Land use/Landcover

Landcover/land use map was derived from aerial photos taken between March 2004 and May 2005 with a spatial resolution of 0.5 metres. Thematic mapping of the different land cover/ land use classes was achieved through unsupervised classification and visual interpretation owing to the high resolution of the RS data used. Automated classification resulted to a high number of mixed pixels hence the choice of the two methods applied.

Landcover class were determined based on land use and landcover classification system for remote sensed data by James et al., (2001).This system was selected since it uses the features of existing widely used classification systems that are amenable to data derived from RS sources. To enhance the accuracy of classification 98 GCPs (ground control points) are used. The accuracy of classification tested using 93 reference points collected during the field work survey.

Accuracy assessment of classification was performed using a confusion matrix which compares the classification results with ground truth information. This is a simple cross-tabulation of the mapped class label against what is observed on the ground or reference data for a sample of cases at specified locations (Canters, 1997). Accuracy or the degree of correctness of a map classification is considered unbiased if it gives a accurate representation of the landcover (Foody, 2002) indicating the degree to which the derived image classification agrees with reality.

This comparison gave a user accuracy of 82%, reliability accuracy of 85% and an overall accuracy of 80%. The results of accuracy assessment are presented in the appendix 3.

The classified landcover/use map figure 3.2.3 was resampled to 30 metres resolution using the nearest neighbour algorithm to match all the other layers.

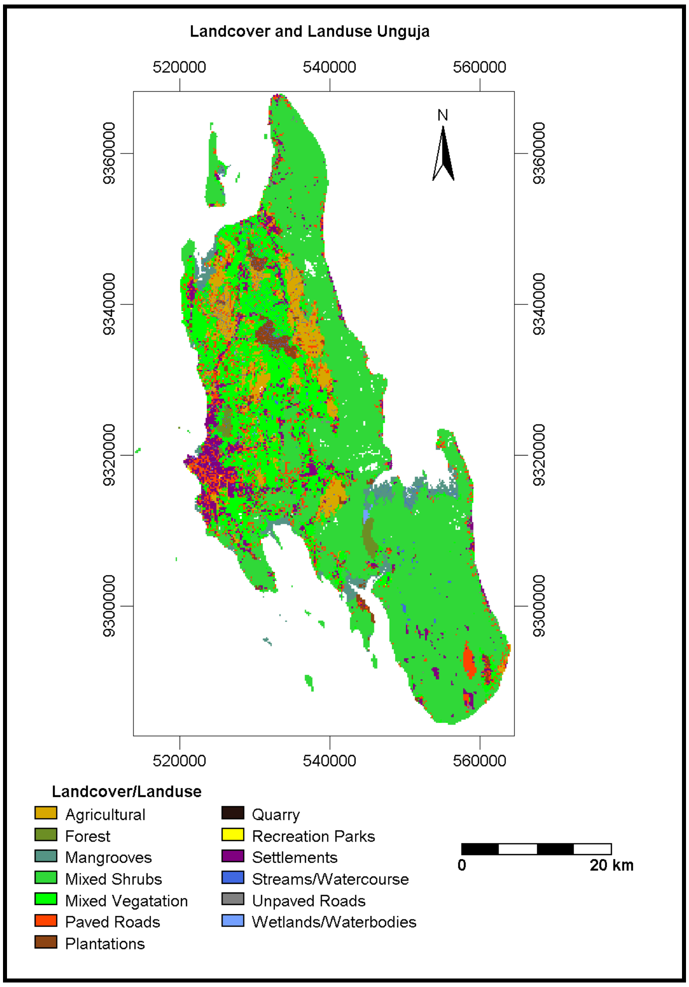


Figure 3.3-6: Classified Land cover/land use

Mixed shrubs is the dominant land cover class covering mostly the eastern part of the Island which is mainly under flat coralline limestone referred to as the Coral rag region. The western and central parts are occupied by different landcover classes and is characterised by undulating terrain; it also represents different land use practices.

3.3.4.2. Soil map

The study area lacks an elaborate soil map that shows the variability of soil properties among different land use systems and scales. The soil map of the study area was digitised from national level soil map produced by Carton W.E,(1955) and improved using the soil studies carried out by Hettige (1990) coupled with extensive sampling during the field work.

Soil map figure 3.3-7 classified is based on the works by Carton (1955) and explained Hettige (1990). They are the Kinongo soils which are mainly loamy soils; Mchanga soils mainly sandy soils and Kinamo soils that are clayey soils. The eastern part of the Island referred to as coral rag region is mainly covered by Uwanda and Maweni soils that overlay the porous coralline limestone and are a sub-group of the Kinongo soils (Hettige, 1990).

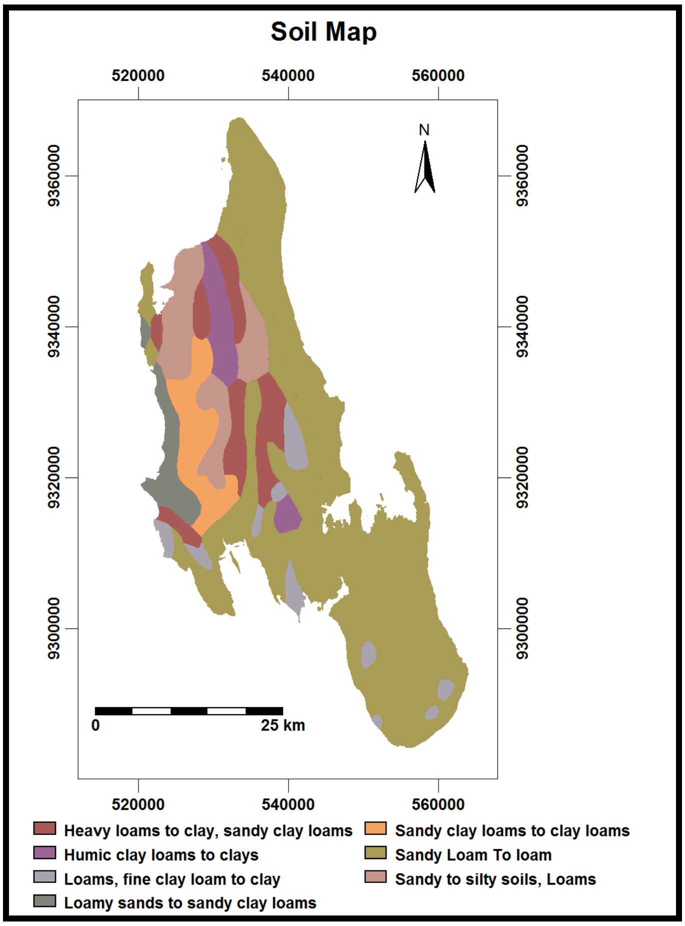


Figure 3.3-7: Soil texture map of the study area

The area covered by each soil class based on texture is presented in table 3.3.1.

Table 3.3-1: Areas covered by different soil classes

Local Class Name	FAO classification	Texture	Area (Km2)	% of total Area
Shallow Kinongo	Haplic and humic ferralsols	Loams, fine clay loam to clay	67	4
Deep Kinongo	Rhodic ferralsols	Heavy loams to clay, sandy clay loams	139	9
Uwanda	Mollic and Rendzic Leptosols	Sandy Loam To loam	310	20
Kinamo	Eutric and calcic vertisols,cambisol	Humic clay loams to clays	64	4
Reddish Mchanga	Rhodic nitisols and Haplic Acrisols	Sandy clay loams to clay loams	99	6
Gleyish Mchanga	Ferric and Gleyic acrisols, gleysol and Fluvisols	Sandy to silty soils, Loams	142	9
Sandy Mchanga	Dystric Cambisols and cambic Arenosols	Loamy sands to sandy clay loams	59	4
Maweni	Rendzic Leptosol	Sandy Loam To loam	681	44
Total			**1561**	**100**

Maweni and Uwanda soils types cover about 60% of the total area and are characterised by high infiltration rate since the overlay the parent coralline limestone formation. Kinamo soils mainly derived from M3 geological formation and composed of marls clays and sandy clays represent areas that are expected to generate more runoff.

3.3.4.3. Slope map

The slope of a given area influences recharge and infiltration hence the amount of runoff that is expected from the terrain. Technology suitability for different RWH options highly depends on the slope of a given area.

Slope map was derived based on 30 metres pixel size Aster-DEM. A linear 5 by 5 gradient filter (DFDX and DFDY) was applied in the X and Y direction with a gain factor of 0.083 (ITC-ILWIS, 2001). Filtering to resolve for undefined area was performed using a 5 by 5 majority filter.

The derived slope map figure 3.3-8 is classified into 5 slope percentage classes based on the FAO slope classification following guidelines by Allen et al., (1998). The FAO slope class indicates the dominant relief or slope of a soil association.

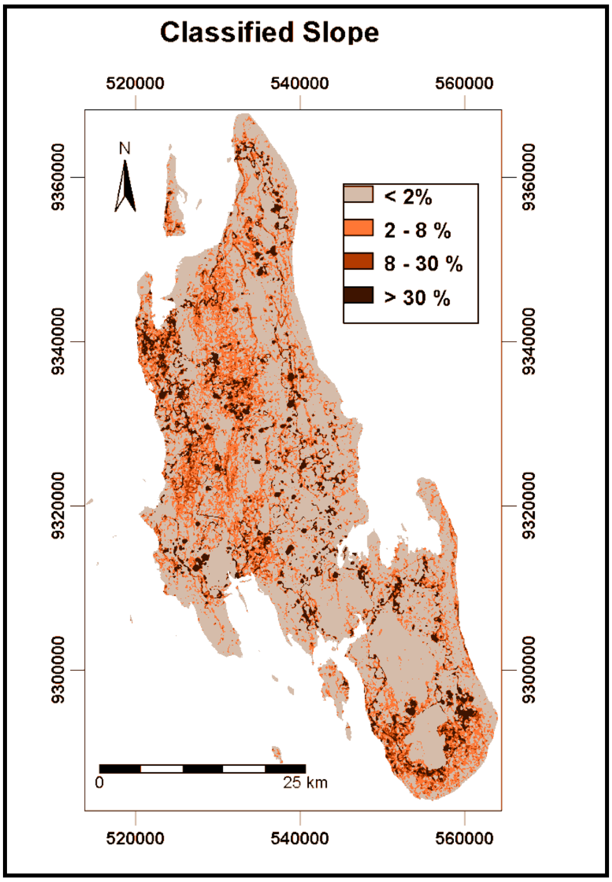


Figure 3.3-8: Classified slope map of the study area

Areas under different slope classes are presented in table 3.3-2. The Island is mainly covered by flat and flat to gently undulating slope classes representing 86.2 % of the total area. For analysis of RWH harvesting potential the dominant slope percentage is used which is based on FAO slope classification guidelines

Table 3.3-2: Extents of land area under different terrain classes

Slope Definition	Dominant Slope Percentage	Area (km^2)	Fraction of Total area %
Generally Flat	0 - 2 %	996	65.0
Flat to Gently Undulating	2 - 8 %	325	21.2
Rolling to hilly	8 - 30 %	83	5.4
Steeply dissected to Mountainous	> 30 %	129	8.4
Total		**1532**	**100**

3.4. Rainfall-runoff modeling

Rainfall runoff relationships for the basin are considered using the SCS curve number method. In undertaking hydrological modelling using remote sensing data in GIS environment the SCS curve runoff model is largely suitable due to its reliance on land cover parameters which can be extracted from RS (Senay et al., 2004).

This method has several advantages mostly based on its simplicity to apply and acceptability; however the method is also associated with several disadvantages. This method nevertheless is found to be more appropriate in the absence of accurate hydrological and topographical data that is essential for runoff estimation (Senay et al., 2004).

3.4.1. SCS Curve Number Method Description

SCS runoff curve number is a conceptual model whose main objective is to estimate runoff depth from a rainfall storm based on the Curve Number parameter. The method holds several advantages due to it's; simplicity, predictability, stability, dependence on one parameter and responsiveness to runoff producing watershed properties. Associated disadvantages are; its marked sensitivity to CN, unclear description on how to vary antecedent conditions, varying accuracy due to variation in biomass, lack of provisions to account for spatial scale effects and the fixed initial abstraction ratio at 0.2 (Victor et al., 1996).

Runoff generation from a watershed is mainly due to both surface and near sub-surface flow process key of which include ; Horton overland flow, overland flow, through-flow processes, partial-area runoff direct channel interception. The curve number method estimates direct runoff that combines channel runoff, surface runoff, and subsurface flow (USDA, 2004).

Runoff curve number equation estimates total storm runoff from total storm rainfall and this relationship excludes time as a variable and rainfall intensity. Its stability is ensured by the fact that runoff depth (Q) is bounded between 0 and the maximum rainfall depth (P). This implies that as rainfall amount increase the actual retention (P-Q) approaches a constant value; the maximum potential retention (USDA, 2004; Victor et al., 1996)

The runoff equation relates runoff (Q) to precipitation (P) and the Curve Number (CN) which is in turn related to storage (S). CN is based on the following parameters; hydrologic soil group, land use and treatment classes, hydrologic surface conditions and the antecedent moisture conditions.

Equation 3-3 known as the runoff curve number gives the relationship between the parameters described above.

$$Q = \frac{(P-I_a)^2}{(P-Ia+S)} \qquad \textbf{3-3}$$

Where:
Q = depth of runoff, in inches
P = depth of rainfall, in inches
I_a = initial abstraction, in inches
S = maximum potential retention, in inches

$$S = \frac{1000}{CN} - 10 \qquad \textbf{3-4}$$

Initial abstraction consists mainly of interception, infiltration during early parts of the storm, and surface depression storage. Its determination is not easy due to the variability of infiltration during the early parts of the storm since it depends on conditions of the watershed at the start of a storm such as the land cover, surface conditions and rainfall intensity; thus it is assumed to be a function of the maximum potential retention as related in equation 3-5 (USDA, 2004)

$$Ia = 0.2S \qquad \textbf{3-5}$$

Causes of variability of the CN are collectively called the Antecedent Runoff Condition (ARC) and are divided into three classes: II for average conditions, I for dry conditions, and III for wetter conditions. These are mainly due to rainfall intensity and duration, total rainfall, soil moisture conditions, cover density, stage of growth, and temperature. Attempts to explain the variability have been focused on antecedent soil moisture, usually as indicated by 5-day antecedent precipitation (USDA, 2004).

Various studies have shown that there exists no relationship between the antecedent precipitation and the CN hence it should be treated as random variable (Cronshey, 1983; Hjelmfelt, 1987, 1991; Van Mullem, 1992).

3.4.2. Evaluating Curve Number for the study area

CN is evaluated for the study area on pixel basis using the landcover/land use and soil map that are reclassified to hydrologic conditions and hydrologic soil group.

3.4.2.1. Reclassification of landcover and soli map to hydrologic conditions

Land cover or land use represents the surface conditions in a watershed and plays key role in determination on the amount of initial abstraction. The landcover/land use map was reclassified to hydrologic conditions based on the USGS land use and land cover classification system. The table of runoff curve number (SCS, 1986) following Chow et al.,(1988) appendix 4 is used to assign codes to the various land cover/land use classes. Table 3.4-1 gives CN for hydrological soil cover complexes for ARC II and I_a=0.2s for the study area.

Table 3.4-1: Curve Number for hydrological soil cover complexes

	Hydrological soil group			
	A	**B**	**C**	**D**
Agricultural	72	81	88	91
Coastal Sand	50	50	50	0
Forest	36	60	73	79
Mangroves	0	0	0	0
Mixed Shrubs	30	48	65	73
Mixed Vegetation	39	61	74	80
Paved Roads	98	98	98	98
Plantations	36	60	73	79
Quarry	77	86	91	94
Recreation Parks	49	69	79	84
Settlements	61	75	83	87
Streams/Watercourse	0	0	0	0
Unpaved Roads	76	85	89	91
Wetlands/Water bodies	0	0	0	0

3.4.2.2. Reclassification of Soil map to Soil Group

Application of the CN method requires that the soils for the study area are reclassified to fit in one of four categories (A, B, C, and D). The condition to fit the soils classes to certain categories is subjective but depends highly on the infiltration rates and the textural soil composition. These factors for the different soil classes were approximated during the field work and are used to classify the soils of the study area following the generic conditions for soil classification table 3.4-2.

Table 3.4-2: Generic conditions for soil classification (according to the CN method).

A	Low overland-flow potential. Minimum infiltration capacity when wetted > 0.76 cm/hour. Deep well to excessively drained sands and gravels
B	Moderate minimum infiltration capacity when wetted 0.38 to 0.76 cm/hour. Moderately deep to deep, moderately to well drained, moderately fine to moderately coarse grained (e.g. sandy loam)
C	Low minimum infiltration capacity when thoroughly wetted 0.13 to 0.38 cm/hour. Or soils with impeding layer fragipan.
D	High-overland flow potential. Very low minimum infiltration when wetted < 0.13 cm/hour. Clay soils with swelling potential, soils with permanent high water table, soils with clay near the surface, or shallow soils over impervious bedrock.

Based on the conditions set above the soils for the study area are assigned groups has shown in table 3.4-3. The final soil groups map figure 3.4-1 is based on table 3.4-3.

Table 3.4-3: Reclassification of soils to soil groups

Local class Name	Lithology	FAO Classification	Texture	Depth	Infiltration	Runoff	Soil Group
Shallow Kinongo	Crystalline, reef and detrital Limestone	Haplic and Humic Ferralsols	Loams, fine clay loam to clay	Shallow to thick	Medium to High	Low	B
Deep Kinongo	Crystalline, reef and detrital Limestone	Rhodic Ferralsol	Heavy loams to clay, sandy clay loams	Shallow to Medium	Medium to High	Medium	C
Kinamo	Marls, Sandy clays and clayey sands	Eutric and calcic vertisols, cambisol	Humic clay loams to clays	Thick	Low	High	D
Uwanda	Coralline and reef limestone	Mollic and Rendzic Leptosols	Sandy Loam To loam	Shallow	High	Low	A
Reddish Mchanga	Marls, sandy clays and clayey sands	Rhodic nitisols and Haplic Acrisols	Sandy clay loams to clay loams	Thick	Medium to High	Low	A
Sandy Mchanga	Marls, Sandy clays and clayey sands, sands and sandstones	Dystric Cambisols and cambic Arenosols	Loamy sands to sandy clay loams	Medium to thick	Medium to Low	Medium	B
Maweni	Sands and sandstones, marls, sandy clays and clayey sands	Rendzic Leptosol	Sandy Loam To loam	Shallow	High	Low	A

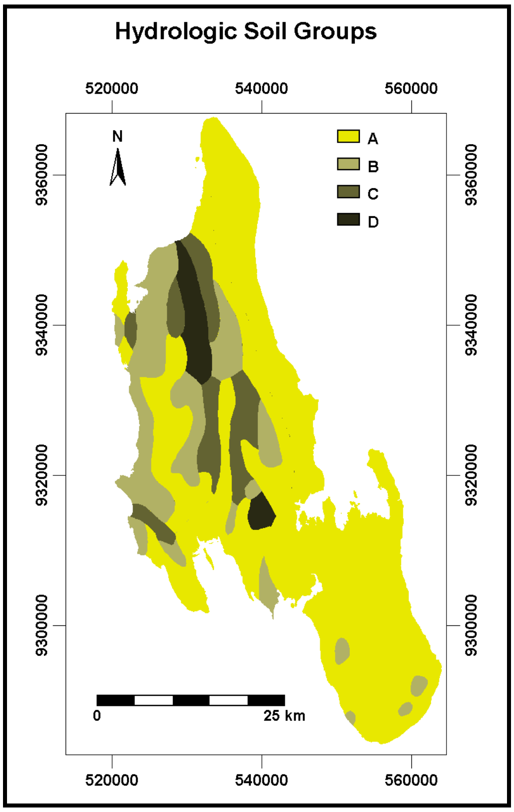


Figure 3.4-1: Reclassified soil map to soil groups

Evaluation of area covered by different soil groups is presented in Table 3.4-4. Areas under hydrologic soil group A are expected to generate less runoff and only about 32% of the study area is expected to produces considerable prior runoff before the landcover type is taken into consideration.

Table 3.4-4: Percentage of areas under different soil groups

Soil Group	Area (Km^2)	% of total area
A	1016	68.2
B	271	18.2
C	139	9.3
D	64	4.3
	1490	**100**

3.4.2.3. Building up CN map

CN map was generated using the reclassified landcover to hydrologic conditions and the soil groups obtained earlier. The Values assigned to the landcover as hydrologic conditions and the soil groups are reclassified to generate CN map using all the possible combinations of the input classes. This procedure is performed in ILWIS using the 2-Dimensional table operation.

Figure 3.4-2- shows the generated CN map per pixels for the study area. The map gives an impression of the area that can generate more runoff based on the landcover and soils in the study area.

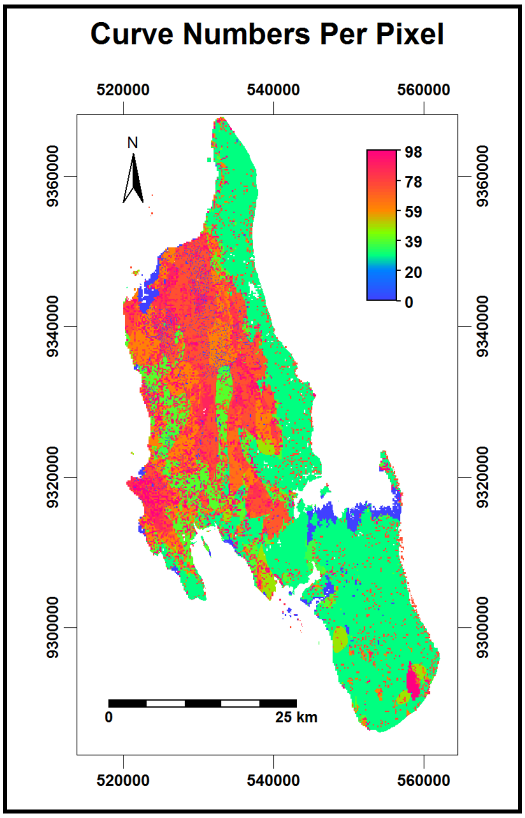


Figure 3.4-2: Curve Numbers per 30 meters pixel size

High CN values indicate areas that have the lowest infiltration and more runoff is expected from this areas since the initial abstraction and storage area minimal.

3.4.3. Determination of Runoff using Curve Numbers (CN)

Rainfall runoff relationships in this study are determined using pixel based curve numbers and following the SCS curve number method. The formulation in equation 3-3 requires the determination of the initial abstraction (I_a) and the maximum potential storage (S).

These are derived as input maps using equation 3-4 and 3-5 before the runoff can be calculated. The maximum potential storage map is converted to mm from inches by replacing 1000 and 10 with 25400 and 254 in equation 3-4 since the rainfall depth is expressed in mm. Figure 3.4-3 shows the derived initial maximum storage per pixel.

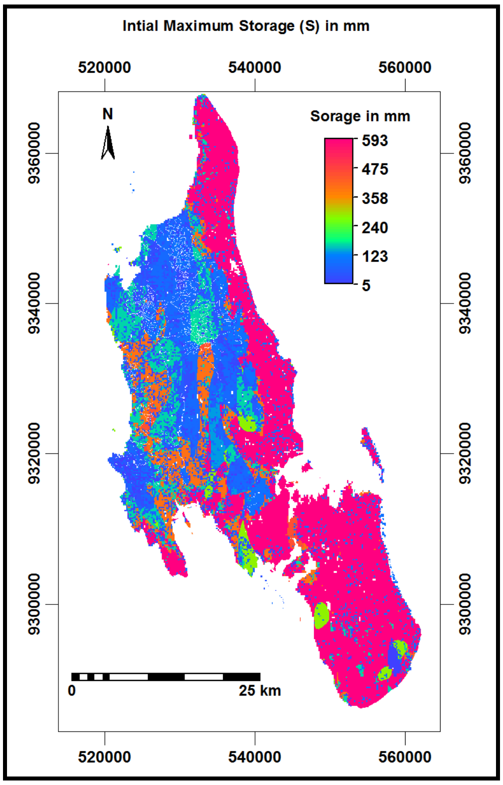


Figure 3.4-3: Initial maximum storage values per 30 meters pixel size

The Initial storage is low in areas expected to generate more runoff which mainly depends on the CN values as derived from the landcover and soils map. The coral rag area covering mainly the eastern part of the Island and dominated by the limestone and mixed shrubs have the highest initial storage and initial abstraction hence the least runoff.

The runoff coefficient can be derived as either an event runoff coefficient or annual runoff coefficient. Event runoff coefficient is defined as the portion of rainfall that becomes direct runoff during an event. In hydrological modelling it represents the lumped effect of a number of processes in a catchment which may include; interception, evaporation, rainfall intensity, initial abstraction and hence runoff (Viglione et al., 2009).

Annual runoff coefficient per pixel is derived for this study as opposed to event runoff coefficient for individual storms since to establish the runoff amount that is available for agricultural production this method takes into account rainfall events that do not significantly contribute to any runoff (Zhu et al.).

Annual runoff depth is derived using the MPE data following equation 3-3: Annual runoff coefficient per pixel is then derived using the formulation equation 3-5 which gives an indication of the percentage rainfall that is transformed to runoff.

$$K = \frac{Yearly\ (seasonal)\ total\ runoff\ (mm)}{Yearly\ (seasonal)\ total\ rainfall\ (mm)} \qquad \textbf{3-6}$$

The annual runoff coefficient is based on runoff calculated using antecedent runoff conditions II (ARCII); which in the median value, motivated by the fact that the probability of occurrence of higher and lower values of the runoff coefficient would be equal (Pilgrim et al., 1975, 1993).

3.5. Decision making and RWH site selection

GIS-based site suitability analysis has been applied in a wide variety of situations including ecological approaches for defining land suitability/habitant for animal and plant species (Pereira et al., 1993), land suitability for agricultural use (Cambell et al., 1992); environmental impact assessment (Moreno et al., 1988), site selection for public and private sector facilities (Church, 2002.; Eastman et al., 1993).

Site suitability analysis makes a distinction between the site selection problem and the site search problem. The aim of site selection analysis is to identify the best site for an activity from a set of potential (feasible) sites. In this type of analysis all the characteristics (such as location, size, relevant attributes, etc.) of the candidate sites are know. The problem is to rank or rate the alternative sites based on their characteristics so that the best site can be identified. If there is not a pre-determined set of candidate sites, the problem is referred to as site search analysis. The characteristics of the sites (their boundaries) have to be defined by solving the problem. The aim of the site search analysis is to explicitly identify the areal extent of the best site (Malczewski, 2004).

The focus of this research was on site search analysis using thematic layers generated in form of spatial raster layers and applies the analytical hierarchy process which takes into account the spatial variability of all the input layers.

Analytic Hierarchy Process (AHP) to arrive at a decision on best sites RWH is implemented using the spatial multi-criteria evaluation (SMCE) module embedded in ILWIS. SMCE has been shown to support planning and decision making due to its capability to perform spatial data analysis and is demonstrated to work appropriately for waste disposal and park sites selection by Sharifi et al.,(2004) and Zucca et al.,(2008).

Biophysical and socio-economic criteria are considered in form of raster thematic layers and integrated as either constrains or factors in RWH potential site search process.

The process is performed in two phases as documented by Sharifi et al.,(2004); the identification (design) and comparison/evaluation (choice of solution). To achieve this goal four steps as documented by Garfi et al., (2009) are implemented; problem definition; criteria identification and selection; calculation of the relative weights; and evaluation of results.

3.5.1. Problem definition

Currently, RWH is not practiced in most parts of the study area. Though RWH is recognised to hold the potential to increase water availability for both domestic and agricultural production, it is also considered core to achieving full potential of Africa water resources for sustainable social and economic growth (ICRAF, 2005).

The problem is thus defined as the evaluation of appropriate sites that Micro and Macro RWH can applied in the island in order to improve water availability for enhanced agricultural production while preserving environmental integrity.

3.5.2. Criteria identification and selection

Criteria selection for site search analysis is based on an elaborate literature search, indigenous and expert knowledge. The site selection process also takes into account specific guidelines from Food and Agricultural Organisation (FAO) on conditions that must be fulfilled both bio-physical and social economic to sustainably implement RWH projects.

The criteria list considered for Micro and Macro RWH are outlined in tables 3.5-1 and 3.5-2.

Table 3.5-1: General criteria and constrains for Micro RWH

Group of Factors/ Constrains	Spatial constrains and factors	Thematic layer for evaluation
Constrains	Distance to roads not less than 30 metres	Distance to roads layer
	Distance to buildings not less than 15 metres	Distance to buildings layer
Environmental	Not within natural forests and protected areas or areas of ecological importance	Landcover / land use
	Not within water bodies, swamps and streams	Landcover/land use
Geomorphologic	Soils with high water holding capacity	Soil texture
	Slope not more than 30 percent	Slope classes
Socio-economic	Recreational and historical sites unsuitable	Landcover/ land use
Hydrological	Runoff index not less than 0.5	Runoff index layer

Table 3.5-2: General criteria and constrains for Macro RWH

Group of Factors/ Constrains	**Spatial constrains and factors**	**Thematic layer for evaluation**
Constrains	Distance to roads not less than 30 metres	Distance to roads layer
	Distance to buildings not less than 50 metres	Distance to buildings layer
Environmental	Not within natural forests and protected areas or areas of ecological importance	Landcover / land use
Geomorphologic	Soils with high water holding capacity	Soil texture
	Slope not less than 5 percent	Slope classes
Socio- economic	Recreational and historical sites unsuitable	Landcover/ land use
Hydrological	Runoff index not less than 0.5	Runoff index layer

Constraints are criterion that determine in arriving at the main goal areas that should be considered as absolutely not suitable and as opposed to the factors, a poor performance of a constraint cannot be compensated by good performance of another factor or constraint.

Factors are criteria that contribute to a certain degree towards the output and can be in form of a benefit or cost. A benefit contributes positively while a cost contributes negatively to the overall goal. As opposed to constraints, poor performance of a factor can be compensated by good performance of another factor. This can still lead to good overall performance towards the final goal (Sharifi et al., 2004; Zucca et al., 2008).

3.5.3. Calculation of the relative weights

Weighting of the factors and groups of factors is an important step since this determines the relative contribution that a factor or group of factors will have towards attaining the sub-goals and the overall goal. Three options that are available in ILWIS SMCE module for assigning weights are; direct method, pair-wise comparison and rank ordering. Use is made of the pair-wise comparison and the rank order methods in this study.

In the pairwise comparison method, also known as the Analytical Hierarchy Process (AHP) (Saaty, 1990, 2008), for each pair of factors an indication is made to which factor is the most important using the fundamental scale of absolute numbers; Table 3.5-3. Computation of weights in AHP for each decision element based on the pairwise comparisons makes use of the eigenvalue technique (Saaty, 1980).

Table 3.5-3: The fundamental scale of absolute numbers (Saaty, 2008)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If 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*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities

The qualitative terms to what extent a factor is more important than another is subsequently indicated which is then used to convert these comparisons of all pairs of factors to quantitative weights for all factors (Saaty, 2008).

In the rank order method, all factors and optional sub goals are placed in a rank-order (most important item at the top) and numerical weights are calculated using either the expected value method or the rank sum method.

The expected value method assumes equal probability for each set of weights that fits the rank order of criteria. The weight vector is calculated as the expected value of the feasible set and the result is a unique weight vector. The expected value method calculates the weight, w_k, for criterion k according to equation 3-7 (Janssen et al., 1994)

$$W_k = \sum_{i=1}^{n+1-k} \frac{1}{n(n+1-i)} \qquad \textbf{3-7}$$

Where n = the number of criteria
k = criterion

The rank sum method calculates the weight, W_k, for criterion k according to equation 3-8. This method combined with a multi-criteria method, always leads to complete ranking (Janssen et al., 1994).

$$W_k = \frac{n+1-k}{\sum_{i=1}^{n}(n+1-i)} \qquad \textbf{3-8}$$

Where n = the number of criteria
k = criterion

The weights assigned to the criteria's by applying the pairwise ranking and rank sum methods are presented in tables 3.5-4 and 3.5-5 for micro and macro RWH respectively.

Slope plays a key role in determination of technological choice for both micro and macro catchment RWH. The limit of application in the site analysis is set through standardization which is set as a cost or benefits depending of the type of RWH system analysed. Figures 3.5-1 and 3.5-2 show the standardization applied for both micro and macro catchment RWH.

Table 3.5-4: Weighting for Micro-Catchment RWH

Weight	Group of factors	Weight	Spatial factors
0.17	**Environmental**	0.67	Not within natural forests and protected areas or areas of ecological importance
		0.33	Not within water bodies, swamps and streams
0.37	**Geomorphologic**	0.67	Soils with high water holding capacity
		0.33	Slope not more than 30 percent
0.10	**Socio- economic**	1.00	Recreational and historical sites unsuitable
0.37	**Hydrological**	1.00	Runoff Index greater than 0.5

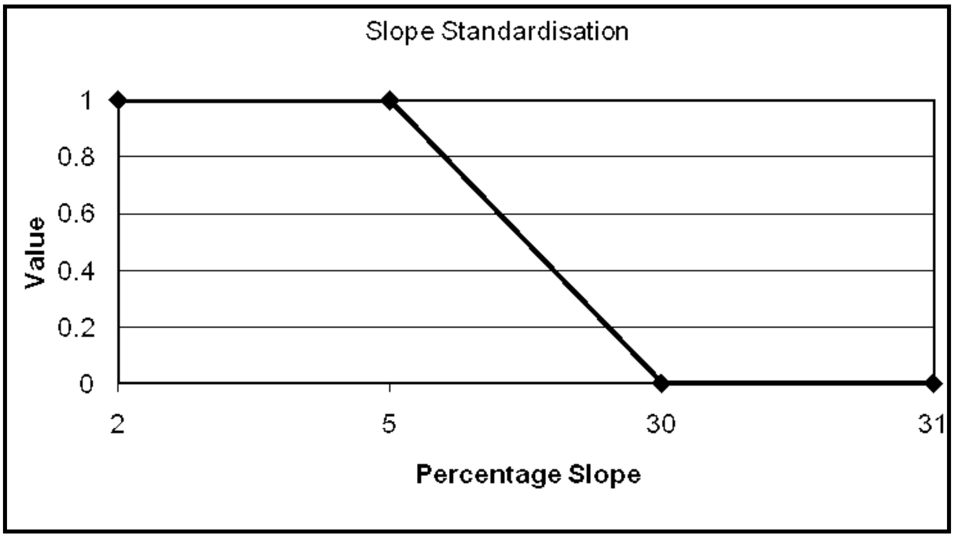


Figure 3.5-1: Slope Standardization (Cost Function) for Micro-Catchment RWH

A cost function with goal of 5% is applied for micro-catchment RWH. The implication is that as the slope increases beyond the set goal the suitability decreases.

A similar standardisation is used for the runoff coefficient for both micro and macro-catchment RWH. A benefit function with a goal of 0.40 is used to ensure that only those areas that 40% of the rainfall is transformed to runoff under natural conditions attain maximum suitability values in the final site selection process. Figure 3.5-2 below show the standardisation applied.

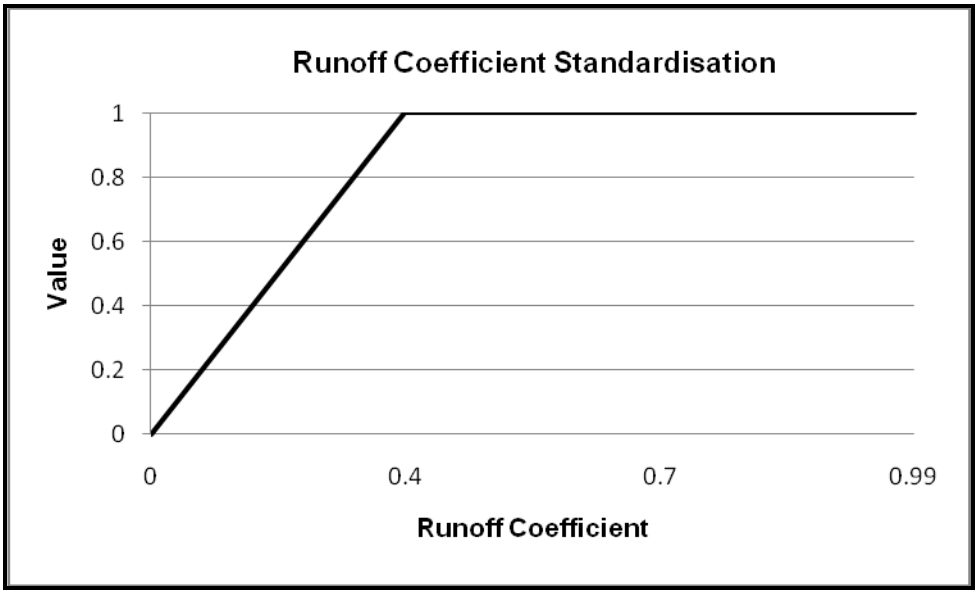


Figure 3.5-2: Runoff Coefficient Standardization (Benefit function)

Table 3.5-5: Weighting for Macro-Catchment RWH

Weight	Group of factors	Weight	Spatial factors
0.17	**Environmental**	1.00	Not within natural forests and protected areas or areas of ecological importance
0.37	**Geomorphologic**	0.67	Soils with high water holding capacity
		0.33	Slope not less than 5 percent
0.10	**Socio-economic**	1.00	Recreational and historical sites unsuitable
0.37	**Hydrological**	1.00	Runoff index greater than 0.5

For macro-catchment RWH the slope is standardised using a benefit function whose implication is that as the slope increases suitability increases and attains a maximum value at 30% slope.

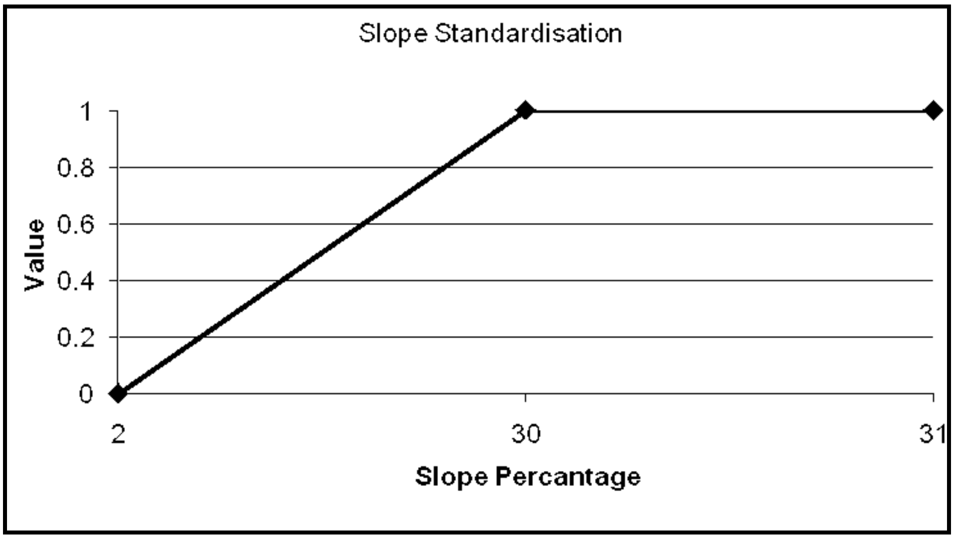


Figure 3.5-3: Slope Standardization (Benefit function) for Macro-RWH

3.5.4. Assessing Consistency of Pairwise comparison

The accuracy of pairwise comparison is assessed through the computation of the consistency index (CI). This determines the inconsistent in the pairwise judgments hence allows for re-evaluation of comparisons.

The consistency index which is a measure of departure from consistency based on the comparison matrices is expressed as

$$CI= (\lambda-n) / (n-1) \qquad 3\text{-}9$$

Where λ is the average value of consistency vector and n are the number of columns in the matrix (Garfì et al., 2009; Saaty, 1990; Vahidnia et al., 2008)

The consistency ratio (CR) is the calculated as

$$CR=CI/RI \qquad 3\text{-}10$$

The random index (RI) is an index that depends on the number of elements that are being compared (Garfì et al., 2009).The table of the random indexes of matrices of order 1-15 as derived by Saaty,(1980) is presented in appendix 8.

Perfect consistency implies a value of zero for CR which may not be attainable due to bias and inconsistencies in subjective judgments. Pairwise judgement is considered acceptable if $CR \leq 0.1$ otherwise the pairwise judgments may be revised before the weights can be applied (Saaty, 1980).

3.5.5. Evaluation of Results

The areas identified for both Micro and Macro RWH must have the highest suitability index that is derived based on the weight assigned to the factors and group of factors. This study though, focuses mainly on site search analysis which is to explicitly identify the boundary of the best sites for RWH.

The results of analysis are evaluated based on areas deemed suitable on the basis of soil characteristics and key land use practices. This is depicted through areas that the generated composite index maps show maximum suitability.

3.6. Sensitivity Analysis

Sensitivity analysis was performed to assess how a change in criteria weighting affects the RWH potential site selection.

Parameter sensitivity evaluation was achieved by applying different weighting to the main criteria in the SMCE decision making tree. The sensitivity of a factor or a group of factors is shown by the change in the spatial extent of RWH suitability. The process was used to determine:-

- The importance of a factor or group of factors is in the site selection process for RWH.
- Establish the levels of uncertainties of the different thematic layers and identify parameters that need to be more accurately determined to ensure more accuracy of the RWH model.

3.7. Selection of technological choices

RWH technologies location and distribution can be identified using spatial mapping based on biophysical characteristics (Ngigi et al., 2007). A number of factors may be considered, however the key spatial factors considered for identification of the suitable RWH systems are the percentage slope, the soil characteristics and to some extent the annual runoff coefficient based on FAO recommendations.

The classification of RWH techniques as outlined in FAO (1994) is mainly adopted with minor adjustments. Table 3.7.1 and appendix 7 outline the classification system used in this research to derive areas that are suitable for application of different RWH techniques.

Table 3.7-1: Micro-catchment RWH systems

RWH system	Criteria	Reference
Roof Catchment	Presence of settlements Runoff coefficient > 0.8	(Arnold *et al.*, 1986) (Zhu et al.)
Ponds and pans	Runoff Coefficient > 0.5 Slope > 5%	(FAO, 1994; Hatibu et al., 1999; Hudson, 1987; Mbilinyi et al., 2007)
Strip catchment tillage	CBAR = 2:1 Agricultural lands	(FAO, 1994; Hatibu et al., 1999)
Contour bunds	CBAR of less than 3:1. slope < 5%	(FAO, 1994; Hatibu et al., 1999; Hudson, 1987; Mbilinyi et al., 2007)
Semi-circular bunds	Slope < 3% CBAR of at least 3:1	(FAO, 1994; Hatibu et al., 1999; Hudson, 1987; Mbilinyi et al., 2007)
Water storage structure for crop production (ndiva)	Clay soils Sloping terrain > 8% Near water sources e.g. stream	(FAO, 1994; Hatibu et al., 1999; Hudson, 1987; Mbilinyi et al., 2007)
Conservation Bench terraces	Slope < 2 % Deep soils CBAR 2:1	(FAO, 1994; Hatibu et al., 1999; Hudson, 1987; Mbilinyi et al., 2007)
Borders	Slope < 8% Clays, silt clays and sandy clays	(FAO, 1994; Hatibu et al., 1999; Hudson, 1987; Mbilinyi et al., 2007)
Stone terraces	Slope > 30% Unstable soils	(FAO, 1994; Hatibu et al., 1999; Hudson, 1987; Mbilinyi et al., 2007)

The main micro catchment RWH currently practiced in the island is the level bunds mainly for rice production (Plate 1). These have not been widely adapted but present a window of expansion since the community has some experience on their implementation and management.

Plate 1: Level Bunds for Rice Farming (Paddy Rice)

Assessment of the amount of runoff that can be harvested to meet the water requirement for rice farming to enhance production and reduce risk of crop failure is based on this system though other harvesting methods can still be adopted.

Consumptive water use for rice production is estimated to range between 1000 mm to 2000 mm depending on the efficiency of the systems applied by the farmers (Tuong et al., 2003). Table 3.7-2 outlines the seasonal amount of water required for various purposes during the entire growing period for rice.

Table 3.7-2: Typical daily rates of water outflows and seasonal water input in lowland rice: Adopted from (Tuong et al., 2003)

	Daily (mm day^{-1})	Duration (days)	Season (mm)
Land preparation			
Land soaking			100 - 500
Evaporation	4 - 6	7 to 30	28 - 180
Seepage and percolation	5-30	7 to 30	35 - 900
Total land preparation			160 - 1580
Crop growth period			
Evapotranspiration			
Wet season	4 - 5	100	400-500
Dry season	6 -7	100	600-700
Seepage and percolation			
Heavy clays	1- 5	100	100-500
Loamy/sandy soils	15-30	100	1500-300
Total crop growth			500-3700
Total seasonal water input			660-5280
Typical range of values for total seasonal water input			1000-2000

The extra water required for seasonal rice production during the long and short rains is based on the potential area for rice production estimated at 8240 hectares by JICA (2002). The current area utilised is 5400 Ha under rain-fed rice production and 400 hectares under irrigations which implies that the full potential is not exploited.

An average amount of 1500 mm is used to calculate the extra water required during for the two rain seasons. Based on a design rainfall of 820 mm (long) and 340 mm (short) rains for a normal year, the run-on and runoff areas ratios and the amount of water to be harvested are determined based on equations 3-11 and 3-12 (Zhu et al.).

$$\begin{gathered}\mathit{Extra\ water\ required} = \\ \mathit{Cultivated\ area} \times (\mathit{Crop\ water\ requirement} - \mathit{Design\ Rainfall})\end{gathered} \qquad \textbf{3-11}$$

$$\frac{\mathit{Catchment\ Area}}{\mathit{Cultivated\ Area}} = \frac{\mathit{CWR} - \mathit{Design\ rainfall}}{\mathit{Design\ Rainfall} \times \mathit{RC} \times \mathit{EF}} \qquad \textbf{3-12}$$

Where CWR – Crop water Requirement
RC – Runoff Coefficient
EF – Efficiency Factor

The adaption of runoff harvesting and storage in earth dams, ponds and small weirs is slowly picking up in the study area due to the need for irrigation during the dry periods when surface water resources are inadequate to meet irrigation water demands (Plate 2 and 3)

Plate 2: In-stream water harvesting using a storage weir

Plate 3: Earth pan to harvest runoff for dry season irrigation

Runoff harvesting and storage (Macro-Catchment RWH) viability is assessed through selection of 15 possible impoundment sites aided by the use of aerial photos of the study area. The potential runoff expected at impoundment site based on the suitability criteria's derived using AHP is applied. The water demand per hectare as determined in Zanzibar irrigation master plan (JICA, 2002) of 11,000 m^3/ha over the dry period is used to determine the storage required. Evaporation and seepage loss are accounted for in the above estimates since it is based on the analysis of dam operations which also include inflow and withdraws.

4. RESULTS

4.1. Rainfall Analysis

The core purpose of this research is not to validate MPE product but to explore how best it can be applied to derive the runoff index in data scarce areas where the spatial distribution of rain gauge network is inadequate or lacking.

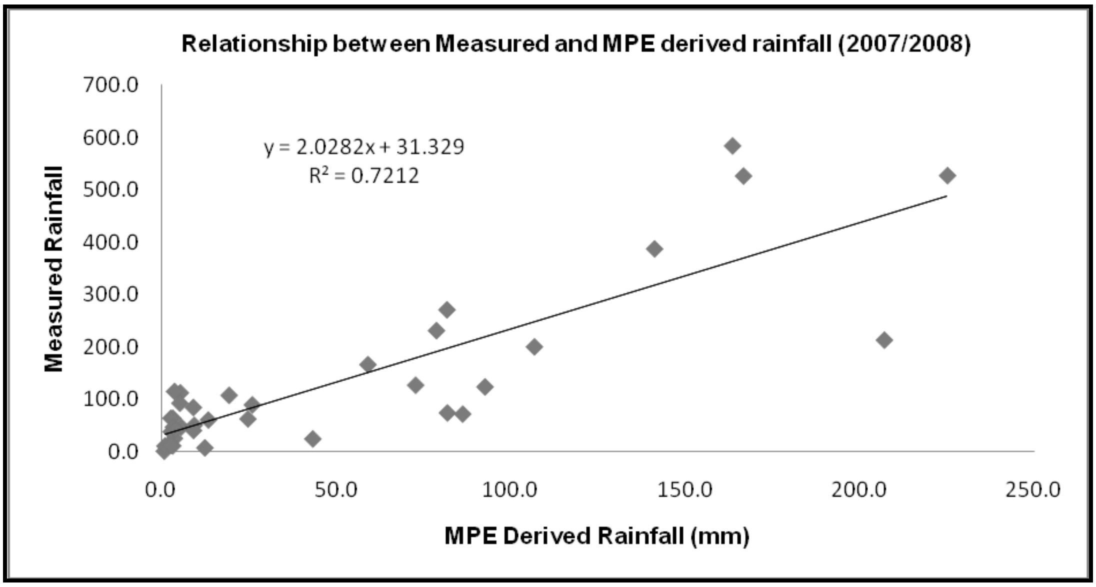
The comparison is based on total annual rainfall measured from two rainfall stations that data was available for the years 2007 and 2008. The correlation coefficient (r) and the coefficient of determination (r^2) are determined for the two data sets. The correlation coefficient is used to measure the strength of the relationship between the two data sets while r^2 is to test how well the MPE rainfall amounts can be used to predict the actual measured rainfall. Table 4.1-1 gives the correlation values obtained and figures 4.1-1 shows coefficient of determination obtained.

Table 4.1-1: Correlation of measured rainfall and MPE product

	Airport 2007	**Kizimbani 2007**	**Airport 2008**	**Kzimbani 2008**
MPE Airport 2007	0.87			
MPE Kizimbani 2007		0.24		
MPE Airport 2008			0.86	
MPE Kizimbani 2008				0.86

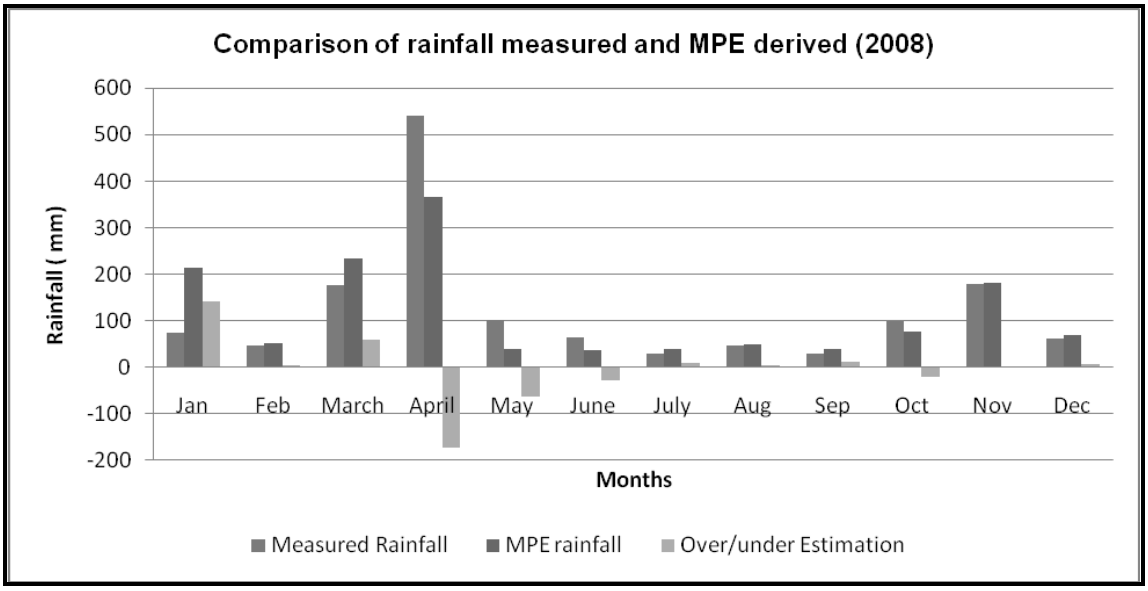
The measured and MPE derived rainfall are highly correlated in both the year except for Kizimbani in 2007. A similar result is obtained for the coefficient of determination. Based on the result obtained, the MPE product for the year 2008 is used in all further rainfall runoff modelling.

Figure 4.1-1: Plot of measured and MPE derived rainfall



MPE rainfall despite the high correlations obtained under or over estimates the rainfall amounts (figures 3.3-5 and 4.1-2) in most cases. The retrieval trends and the error in estimation of the rainfall amounts is as shown in figure 4.1-2. MPE though captures appropriately all the daily rainfall events recorded over the period of analysis.

Figure 4.1-2: Comparison of MPE rainfall retrieval and gauge data



Underestimations are more during the wet season with an average underestimation of 18 % over these periods (March to June and October to December) and a 43 % average overestimation over the dry months. The total measured rainfall over the period of analysis is 1440 mm with the MPE retrieval being 1399 mm showing a total average underestimation of 3 %.

Based on these results, and in order to exploit the MPE strength of its ability to derive rainfall with a high temporal and spatial resolution, the MPE derived rainfall amounts were adjusted based on the obtained linear regression relationships (figure 4.1-1) before it is further utilised for rainfall runoff analysis.

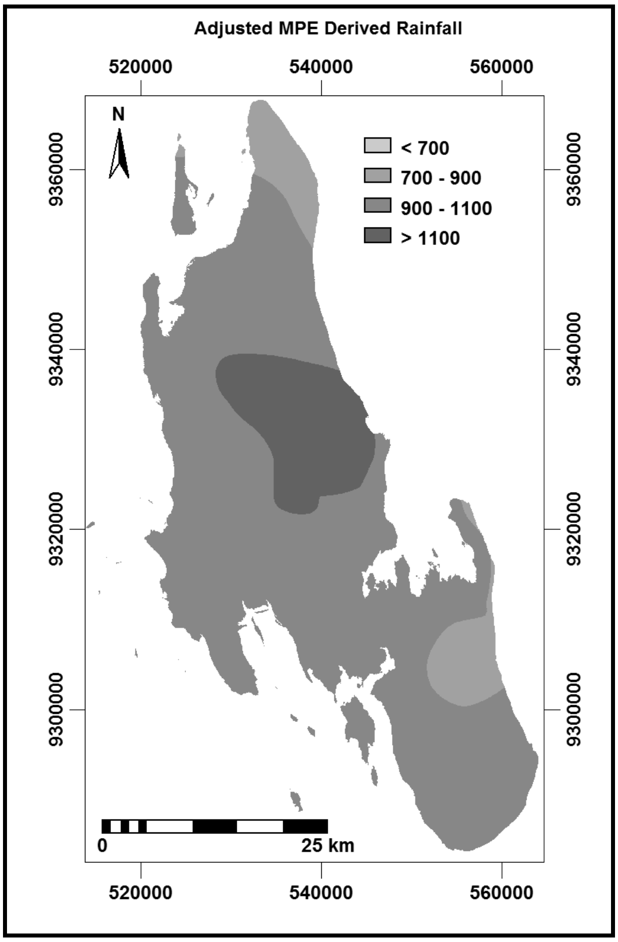


Figure 4.1-3: Adjusted MPE derived rainfall

The adjusted rainfall amounts depict the spatial-temporal rainfall distribution depth more appropriately and thus can be adequately applied to derive the runoff depth.

4.2. Rainfall Runoff modelling

4.2.1. Annual Runoff and Runoff Coefficient

Results of spatial distributions of modelled annual runoff depth in mm are shown in figure 4.2-1. Daily runoff maps were aggregated to prepare expected annual runoff map. A variation from as low as 97 mm in the coral rag region with an increase westwards to a maximum of 542 mm was observed.

The pixel based runoff index which is the ratio of modelled runoff depth to the annual rainfall, shows a wide variation over the Island. It ranges from 0 - 0.99 (99%) figure 4.2-2.

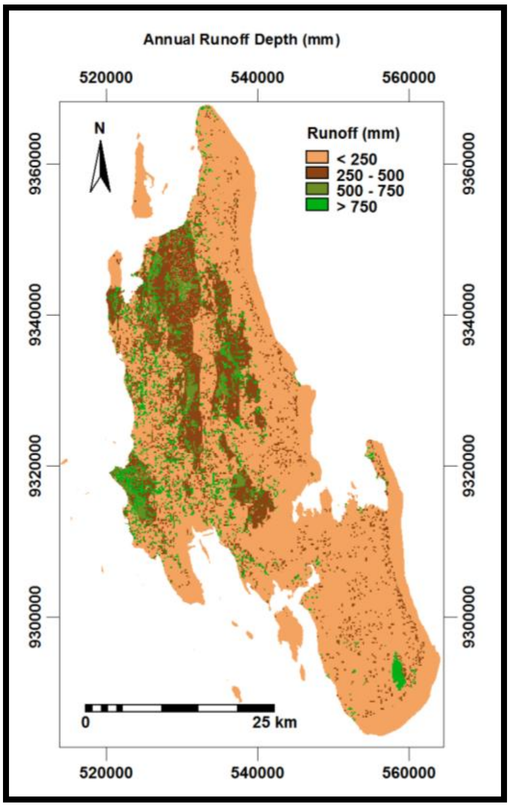


Figure 4.2-1: Annual runoff Depth (mm/year)

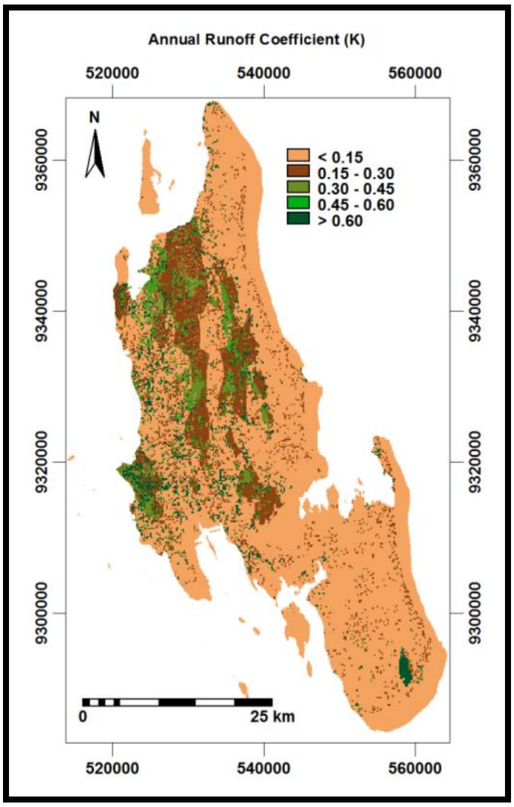


Figure 4.2-2: Annual Runoff coefficient

The main agricultural areas in the Island fall within the range of 360 mm and 450 mm of annual runoff. These are areas that require supplementary irrigation to mitigate inter-seasonal crop failures and increase the crop yields.

Monthly runoff volume generated compared to the rainfall volume is presented in figure 4.2-3. The main rainfall season (March to May) contributes 64 % of the total annual runoff while the short rain season (October to December) account for 21% of the annual runoff volume. The dry months produce only 15% of the total runoff even though about 20% of the total rainfall is received within this period.

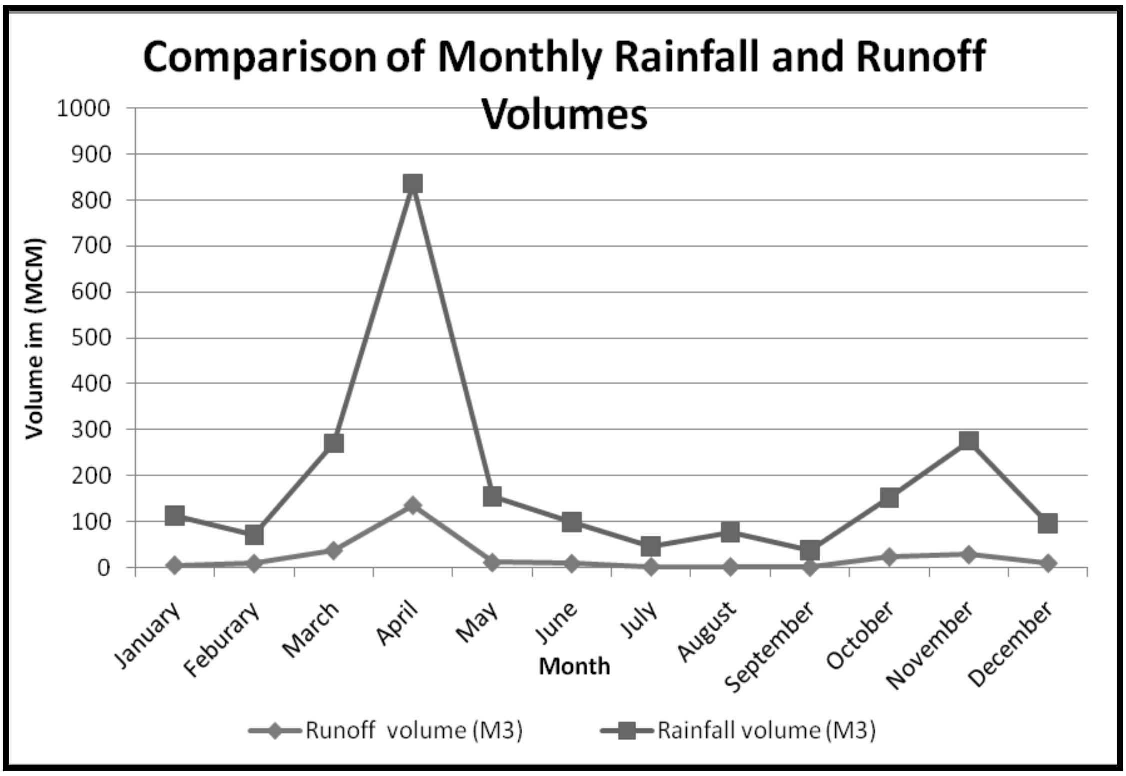


Figure 4.2-3: Comparison of monthly rainfall and runoff volumes (MCM)

4.3. Rainwater harvesting potential

4.3.1. Roof catchment

Roof catchment (RC) rainwater harvesting can be implemented in all regions of Island since the annual rainfall amount is above 200 mm. The roof catchment RWH potential is determined based on the presence of suitable roofing system. Figure 4.3-1 shows the areal extents of roof catchment RWH suitability for the Island.

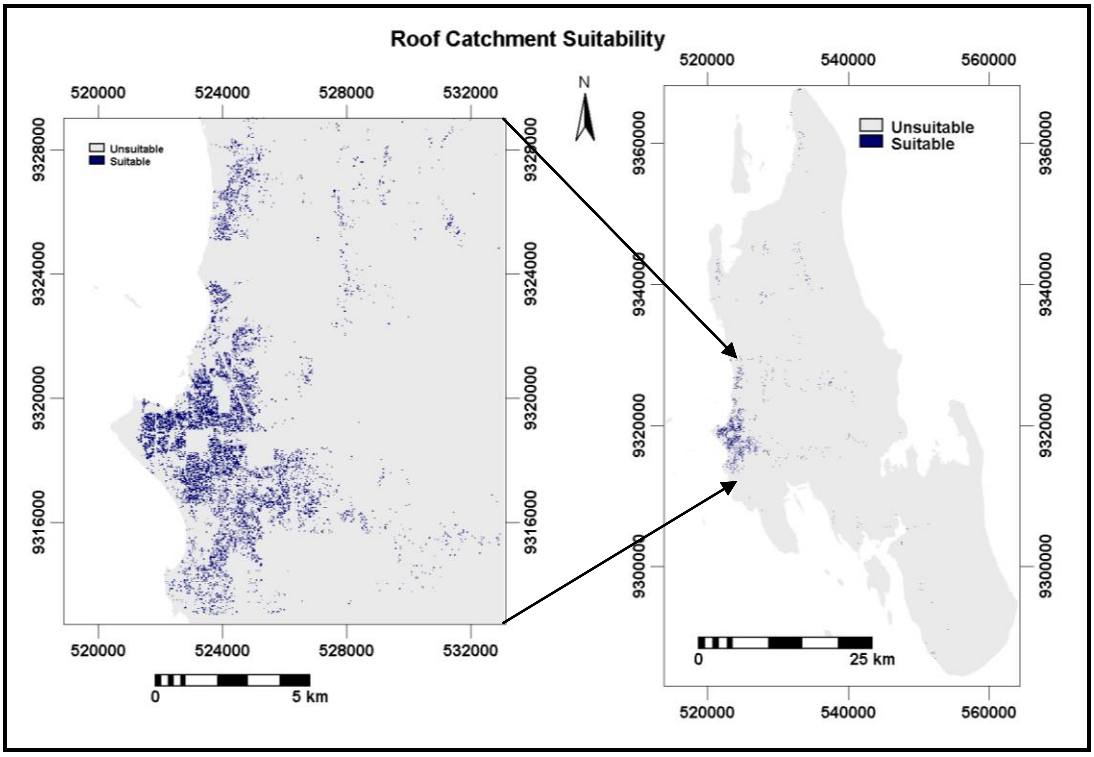


Figure 4.3-1: Roof Catchments suitability Map

Currently only 10.18 km^2 is built up with suitable roofing systems that can be used for RWH and are depicted as the suitable areas in figure 4.3-1.This area can generate a total annual runoff volume of 4.6 million cubic meters. Areas shown as unsuitable are an indication of the absence of suitable roofing systems associated mainly with lack of settlements. Despite the existing roof catchment RWH potential has identified, RC rainwater harvesting has not been adopted and exploited to its full potential.

The runoff available for storage was further analysed to determine the proportion of domestic water demand that it can meet. Analysis assumes the basic water requirements for domestic use as recommended by Gleick (1996). Table 4.3-1 outlines the different water uses that account for 50 litres/capita/day required to meet the basic needs.

Table 4.3-1: Recommended basic water requirements for human needs (Gleick, 1996)

Purpose	Recommended minimum (litres per person per day)	Range (litres per person per day)
Drinking Water	5	2 to 5
Sanitation Services	35	5 to 145
Cooking and Kitchen	10	10 t0 50
Total	**50**	

Daily water requirements of 0.05 m^3/day translates to annual domestic water demand of 18.25 m^3 per capita. The runoff generated can meet an annual domestic water demand of 252,000 persons which represents about 33% of the total population of the island estimated at 0.76 million persons currently.

4.3.2. Micro Catchment Rainwater Harvesting

Based on AHP analysis that took in to account various physical layers, the spatial extents of micro-catchment RWH suitability areas are identified. All the factors and group of factors are integrated to produces five suitability classes figures 4.3-2 and 4.3-3. The potential sites for Micro-catchment RWH as identified reflect specific suitability levels of parameters and weight of factors applied in the analysis.

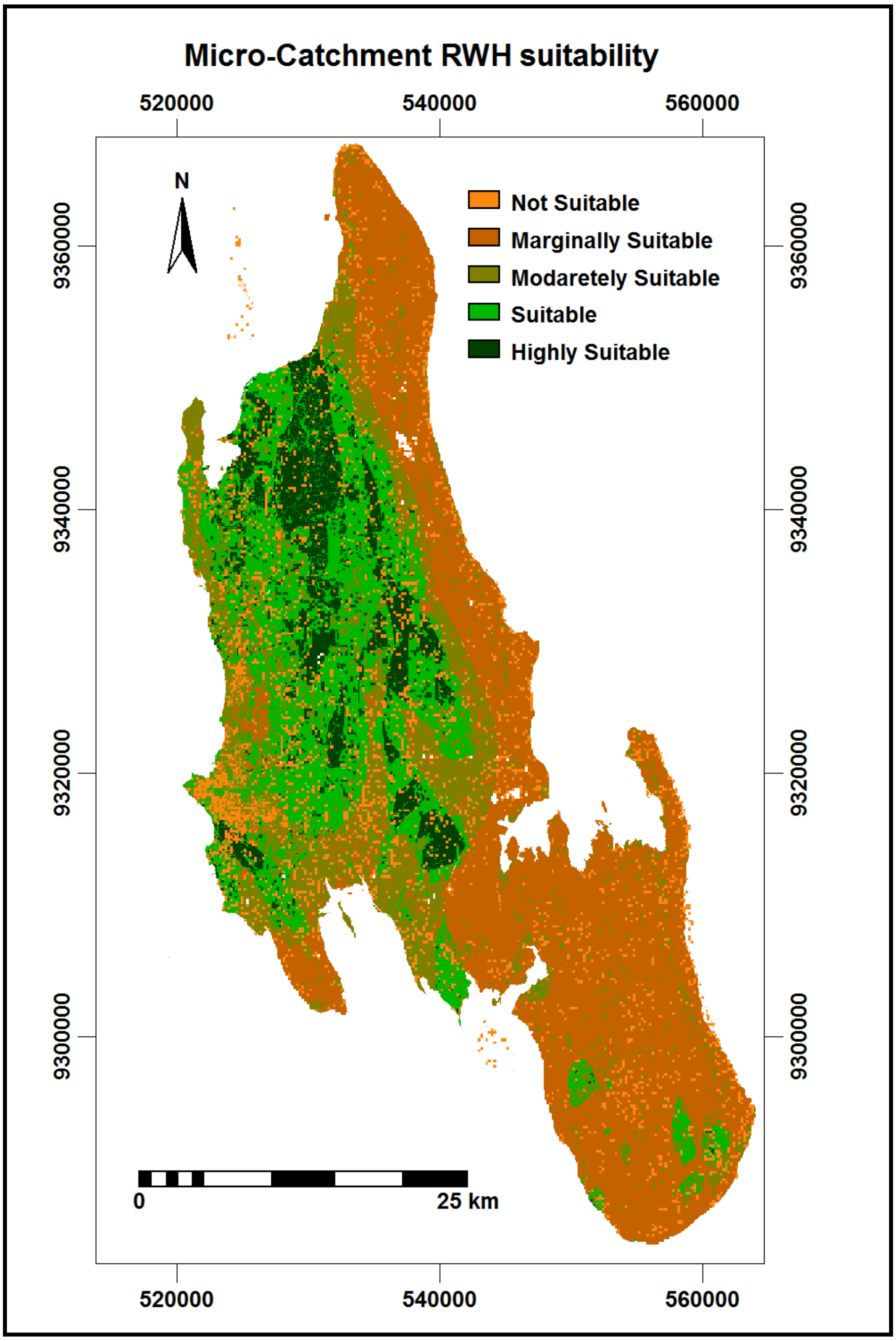


Figure 4.3-2: Micro-Catchment RWH Suitability

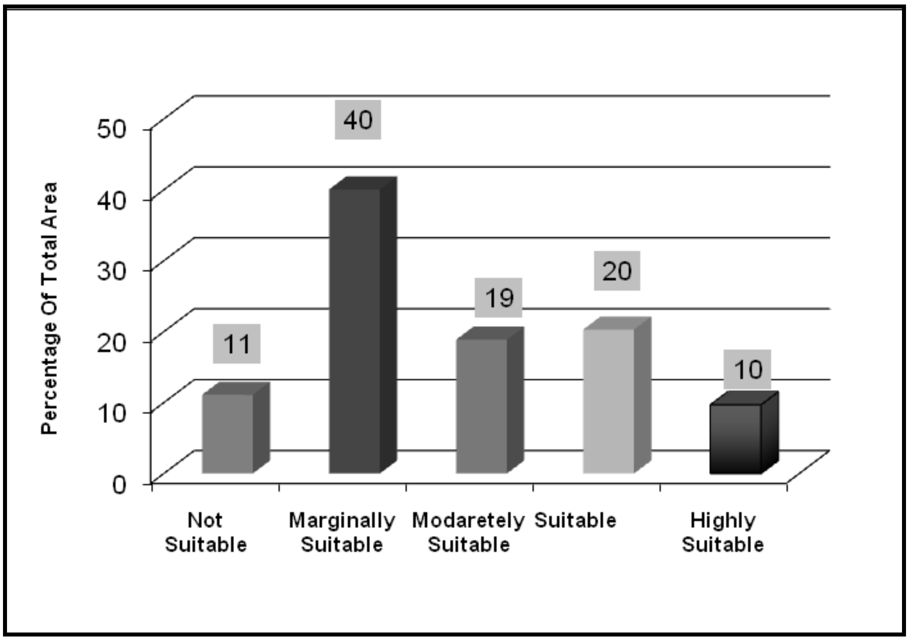


Figure 4.3-3: Percentage area under different suitability classes

Area considered suitable (suitable and highly suitable classes) cover a total of about 44,000 hectares' that represent 30 % of the Island. Suitable areas are mainly located in agricultural areas and in area with soils having high water holding capacities. Areas dominated by limestone's in the coral rag region; eastern part of the Island are least suitable.

The most suitable RWH methods for different area are evaluated based on table 3.7-1 and appendix 7. Accordingly areas suitable for different harvesting techniques are shown in table 4.3-1 below.

Table 4.3-2: Areas suitable for different Micro-catchment RWH technologies

Technology	Percentage Slope	Area (Ha)
Conservation Bench terraces, Stone terraces, Semi-circular bunds	0-2	24179
Contour bunds, Borders	2-8	11902
Strip catchment tillage	8-16	2048
Stone terraces	16-30	367
Water storage structure for crop production (ndiva[1])	> 30	3260

Most of the technologies options for micro-catchment RWH can be practised since the landscape is mainly within flat to undulating slope classes in areas identified as

---

[1] Small water reservoirs

suitable. The results indicate that integration of multiple RWH systems is possible for the study area.

Analysis of rainfall trends indicate that in a normal year 815 mm of rainfall is received during the main rain season (Masika[2]) and 340 mm in the short rain (Vuli[3]) period representing 61% and 24% of the total rainfall. Over the same period a runoff volume of 40 MCM (69%) and 11.7 MCM (20%) respectively is produced by the suitable areas for micro catchment RWH.

The additional water depth (mm) required seasonally based on design rainfall depth of 815 mm and 340 mm in a normal year is 685 mm and 1160 mm for the main and short rain season respectively. Based on equations 3-11 and 3-12; an average runoff coefficient of 0.2 as derived from figures 4.2-2 and 4.3-2, efficiency factor of 0.5 and the current area under rain-fed rice production of 5400 hectares, the extra water required; run-on and runoff ratios for level bunds was determined.

The extra water required in main season is 36. 6 MCM while in the short rains is 62.6 MCM. Catchment area and cultivated area ratios for the seasons are 1:2 and 3:1 which represents a minimum catchment area of 4,500 ha and 18,200 ha for the both seasons respectively.

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[2] Long rains

[3] Short rains

4.3.3. Macro Catchment Rainwater Harvesting

The macro-catchment suitability map indicated that 23% of the study area is suitable (with suitable and high suitable classes) for RWH Figures 4.3-4 and 4.3-5. Suitability areas cover a total area of about 35,000 hectares.

Determination of suitability is based on natural catchments with no treatment hence areas with soils with high water holding capacity present the more suitable area. Unsuitable areas are dominated by limestone areas were the amount of runoff generated is minimal and impoundment may not be feasible.

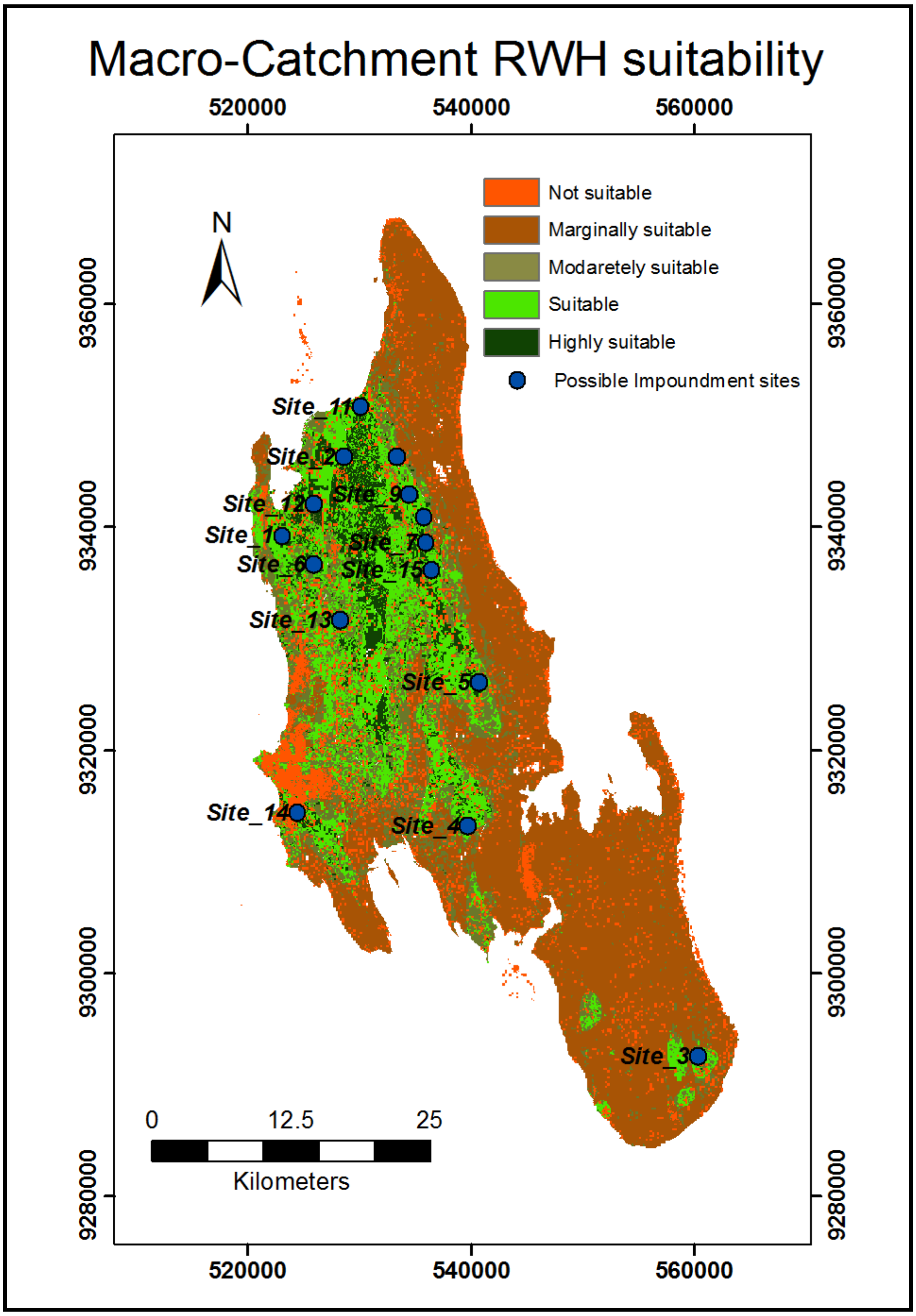


Figure 4.3-4: Macro Catchment RWH suitability

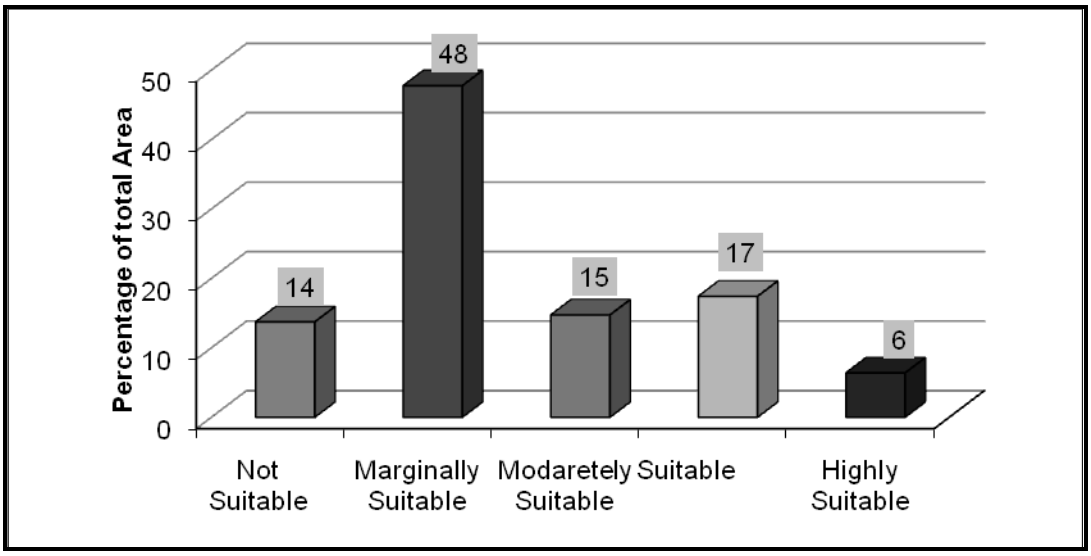


Figure 4.3-5: Percentage of area covered by different suitability

Possible impoundment sites were selected (figure 4.3-5) to evaluate the possible runoff that can be captured and stored based on the catchment contributing area. The sites are selected based on the derived drainage pattern figure 3.3.2 and are as presented in table 4.3-1 showing the annual runoff volume that can be harvested at the point of impoundment.

Table 4.3-3: Possible Impoundment site and contributing catchment areas

Proposed Point of Impoundment	Catchment Area (Ha)	Drainage Density (m/km2)	Longest Flow Path Length (m)	Annual runoff volume (MCM)
1	161	1612	4469	0.3
2	148	398	2521	0.2
3	176	284	2132	0.1
4	169	747	2928	0.5
5	1314	690	9182	1.6
6	597	717	4044	2.2
7	1528	818	10417	5.0
8	1220	738	6667	3.0
9	411	840	3870	0.9
10	988	742	6236	1.6
11	1892	732	8170	3.7
12	1125	827	5091	2.5
13	2834	749	12368	5.1
14	3104	895	11122	6.4
15	5221	977	14639	11.2

These sites are selected for analysis purposes and do not represent all the possible harvesting sites. The amount of water harvested and the size of the impounding structure need to be considered based on maximum water demand and demand fluctuation over the year, losses through evaporation and seepages must be taken into consideration.

Downstream irrigable area based on land suitability for irrigation and location of the impoundment site was determined to evaluate the storage required to meet dry season irrigation water demand. The limiting factor to the possible irrigable area is the runoff generated that can be harvested for storage at impoundment site. Table 4.3-4 show the required storage volume to meet the dry period irrigation demand and the possible maximum irrigable area.

Table 4.3-4: Storage required covering the dry season irrigation water demand and maximum irrigable area (based of available runoff)

Proposed Point of Impoundment	Catchment Area (Ha)	Annual runoff volume generated (MCM)	Target Irrigable area (Ha)	Storage required to cover dry Season (MCM)	% of water requirement met by runoff	Maximum Irrigable area (Ha) (based on runoff generated)
1	161	0.3	12	0.1	227	12
2	148	0.2	15	0.2	121	15
3	176	0.1	10	0.1	91	9
4	169	0.5	800	8.8	6	45
5	1314	1.6	85	0.9	171	85
6	597	2.2	1400	15.4	14	200
7	1528	5	940	10.3	48	455
8	1220	3	560	6.2	49	273
9	411	0.9	200	2.2	41	82
10	988	1.6	125	1.4	116	125
11	1892	3.7	360	4.0	93	336
12	1125	2.5	540	5.9	42	227
13	2834	5.1	360	4.0	129	360
14	3104	6.4	115	1.3	506	115
15	5221	11.2	1360	15.0	75	1018
Total		**44.3**	**6882**	**75.7**	**59**	**3357**

The selected impoundment site can only be able to meet 48% of the dry season irrigation water demand based on the target irrigable area. This clearly indicates the need to develop other water sources to meet the supplementary irrigation water demand in the area.

4.4. Validation of results

In order to validate the results of analysis 21 and 24 locations of existing and areas considered suitable for both Micro and Macro catchment respectively are used. The points were selected based on indigenous knowledge and expert assessment during the field work survey assisted by personnel from the department of irrigation-Zanzibar. The selected point’s appendix 5 and 6 are used to test and check the quality of performance and reliability of the developed RWH assessment model.

Testing for Micro-catchment rainwater harvesting show that 10 % of the sites identified suitable are unsuitable, 10 % marginally suitable and 80 % within suitable and highly suitable areas. Validation for Macro catchment RWH indicates that 12 % of the points are in unsuitable areas, 20 % in marginally suitable and 68 % within suitable and highly suitable areas.

The results give an indication of the reliability of the developed rainwater harvesting assessment (RWHA) models and owing to the fact that most of the sites are appropriately located the accuracy of the model is found satisfactory.

4.5. Sensitivity analysis

Sensitivity analysis was performed to help identify the spatial layers that are critical in accurately determining the spatial extents of RWH suitability. This was achieved by assessing the effects of the spatial extent variability by changing the weights assigned to the group of factors in the criteria tree.

The degree of suitability and areal extent was examined through variation of the weights assigned to the group of factors starting with an equal weight assignment. A variation of weights using the pairwise comparison method, (Saaty, 1990, 2008), was then performed for each pair of factors to examine which factor was the most important.

The results of this analysis revealed that the geo-morphological factors are more important followed by the hydrological factors. The soils, landcover and slope layers were the most sensitive layers and inaccuracies in this layer can lead to errors in RWH site suitability assessment. This assessment also played a major role in deriving the appropriate weights for the group of factors and individual factors (*tables 3.5-4 and 3-5-5*) that are used in suitability assessment.

5. Discussions

5.1. Rainfall

There exists strong rainfall dependence, in Sub-Saharan Africa mainly for agricultural production but the region ranks among the lowest in the world in the density of rainfall monitoring stations. The reliability of the data collected is a major issue since even where rainfall data are available, weeks can elapse between collection and accessibility to users is poor (Bowden et al., 2007). Arising from the above, the need to explore the possibility of using satellite derive rainfall is explored. The MPE product is preferred due to its high temporal and spatial reliability within the tropics.

Rainfall is a major deriving force in the runoff generation in any watershed. An accurate rainfall data input is therefore required in order to derive accurately the amount of runoff. Owing to this fact, a comparison is made between the measured rainfall and the MPE derived rainfall amounts through determination of the correlation coefficients (r) and the coefficient of determination (r^2) table 4.1-1 and figure 4.1-1. To ensure that the MPE derived rainfall accurately fits to the measured rainfall, adjustments are made to correct for time lag in between the measured and simulated rainfall. Correction for underestimation and overestimation is based on the empirical relationships derived in determination of r^2. This reduced the overall underestimation of the annual rainfall depth to 3 %.

A low correlation coefficient of r=0.24 is obtained at Kizimbani station for the year 2007 which maybe an indication of an error in the measured rainfall since all the other period have a high agreement.

Results obtained give an indication of how the MPE derived rainfall amounts fit to the gauge measured rainfall. An indication that in absence of reliable ground measurements the MPE rainfall product can satisfactorily be applied to estimate the spatial rainfall distribution based on values of r and r^2 (0.721) obtained. Despite the high correlations obtained, one of the key problems may be the accuracy of the measured rainfall and its reliability.

With adjustments to correct for time lag between the measured and the derived rainfall amounts the MPE product is well suited for the tropical and convection rainfall simulation. Correction for underestimation and overestimation of the total rainfall amount is necessary before the derived rainfall amounts can be applied to model rainfall runoff relations or design of water infrastructure.

5.2. Rainfall Runoff Modelling

Analysis of rainfall–runoff relationships determines how much of the net precipitation is partitioned into runoff after all the initial losses. The SCS curve number method as applied to model the runoff has been show to adequately give accurate results by different authors.

The main cause of uncertainties in runoff modelling using satellite derived rainfall as identified by Senay et al.,(2004) may arise from inaccuracies of the derived satellite rainfall which require to be quantified. Annual runoff depth as derived from the MPE product is lower than the amount derived using the actual measured rainfall due to the overall underestimation of the rainfall depth by 3 % (*section 4.1*). It is therefore necessary to make adjustments to the MPE derived rainfall before it is applied to model runoff.

Rainfall–runoff relationships results obtained in a spatial scale give a clear indication the amount of runoff generated by various land uses in the study area. An indication of the variation of runoff coefficient for different soil types and land slopes is demonstrated by Ngigi et al.,(2007). This correctly agrees with the results obtained in this study as depicted by figure 4.2-2.

Application of the spatially distributed MPE derived rainfall and the pixel based CN for runoff modelling represents one of the key strengths of this study. In application of SCS curve number method more reliable results are expected if rainfall runoff relationships are determined for a small area instead of averaging over the entire watershed (USDA, 2004).

Monthly runoff generation from the study area ranged from 2% to 16% of the total rainfall and is highly reliant on the ARC. This relationship is shown in figure 5.2-1. This is greatly dependent of the soils and landcover conditions of the study area.

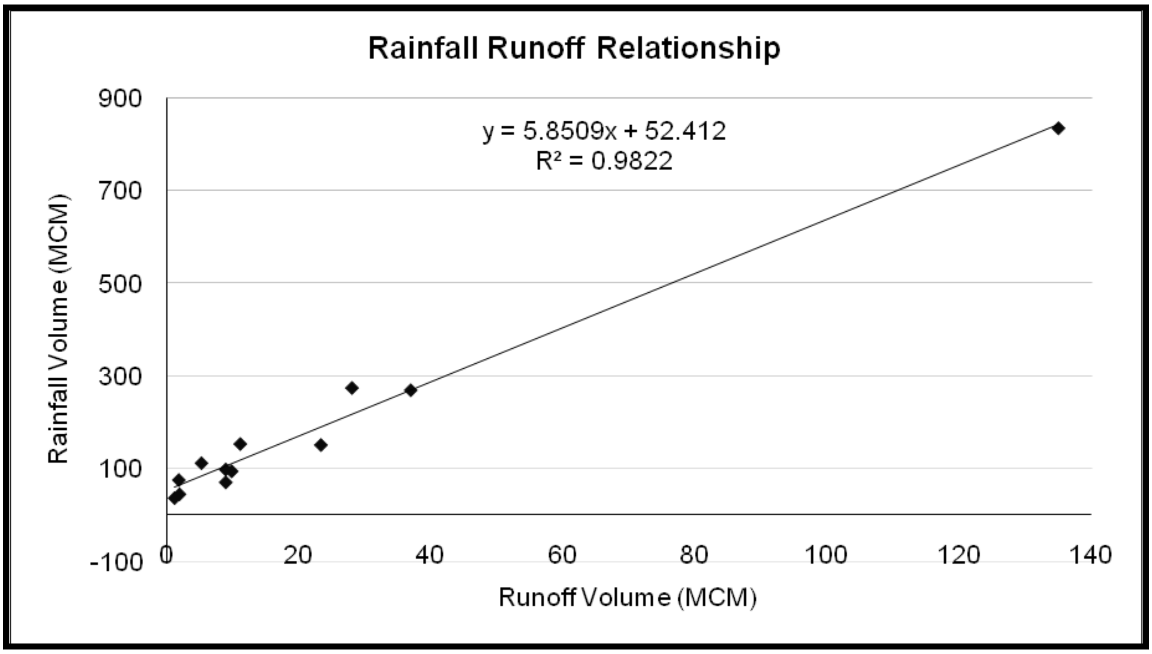


Figure 5.2-1: Monthly Rainfall runoff relationships

In the study area 84% of the total runoff is generated within flat and undulating slope classes. Deep kinango, shallow kinango and Kinamo soil type areas produce 30.3 % of the total runoff though they only cover 18.2 % of the total area of the island. Mawani soils with the highest coverage of 46.2% produce only 11.3 % of the total runoff. The built up areas generates 50.2% of the total runoff with the agricultural, mixed vegetation areas contributing 38.6 %. This is an indication that only a small area of the island is viable for rainwater harvesting due to the minimal extent of the runoff generating areas.

The total annual runoff estimated for the island of 531.5 million cubic metres JICA (2002) agrees reasonably with the modelled runoff of 415.7 million cubic metres.

Runoff volumes generated in this study may also be underestimated mainly due to the coarse nature of the soil map used to derive the CN values which plays a role in determining the amount of rainfall that will translated to runoff and the MPE underestimation of the rainfall amounts.

5.3. Rainwater Harvesting

Rainwater harvesting has a potential of addressing spatial and temporal water scarcity for domestic, crop production, livestock development, environmental management and overall water resources management (Ngigi *et al.*, 2007). Despite this realisation the existing potential for RWH in the study area has not been exploited.

Rainwater harvesting potential assessment requires accurate information on the spatial-temporal information on run-off potential area. This study provides an integrated approach to model the spatial-temporal pattern of run-off potential areas using the SCS CN model with remote sensing-derived inputs and ancillary data in GIS.

To asses RWH potential sites for the study area an annual runoff coefficient (figure 4.2-2) is derived and thresholds (figure 3.5-2) set for use in spatial modelling of suitable RWH. A threshold value of 0.8 is used to assess suitable area for roof catchment RWH while a value of 0.2 is used for both micro and macro RWH.

The cost of implementing RWH can be evaluated using general basic cost per cubic metre of water harvested that are based on published sources, expert consultations and experiences by SEARNET in East Africa (ICRAF, 2005). This can enable assessment of the best and most economically viable option since the areas identified for different harvesting methods overlap.

5.3.1. Roof Catchment

Roof catchment (RC) harvesting is not currently practised in the island mainly based on the perceived low water quality of rainwater and cultural background of the community. The low adoption rates may also be attributed to the long standing policy that assumed water has a social good and hence provided free for all the citizens. With a policy swift towards attaching an economic value to water supplied the rate of adoption is expected to increase.

Roof catchment (RC) is considered in this study based on a runoff coefficient of 0.8 mainly for corrugated roof systems. Rural household though may have lower runoff coefficients (0.5) since they may have grass thatched roofs hence not considered.

This study shows that rainwater harvesting can supplement other water sources by supplying about 49 million cubic metres of water annually if full potential (all roofs) are used. This water can satisfy an annual domestic demand of 33% of the current population.

RC rainwater harvesting can provide adequate water supply for households to cover for times of water shortage and also reduce expenditure on water. The main required intervention and challenge is to produce a system within the means of every household that can meet their demands.

During the field work survey it was established that most of the residents have interest in harvesting rainwater but were concerned with its taste and perceived low quality. It was also established that there exists adequate capacity for construction of the RWH system chosen using local skills, materials and equipment.

In order to achieve and exploit the full potential, the implementation and adoption of RC rainwater harvesting requires extensive advocacy for the community by the government, private sector and NGO to educate the community on its benefits.

5.3.2. Micro-Catchment RWH

The total annual rainfall received in region may be enough to sustain crop production, but its distribution and occurrence of intra-season dry spells and off-season dry spells may affect crop production. Mitigation of the effects of reduced crop production can be achieved through implementation of RWH systems (Ngigi et al., 2005)

Poor agricultural production can be associated with poor rainfall partitioning which implies that only a small fraction of rainfall reaches the root zone and mid season dry spells that result into to poor soil water availability during the growing season (Rockstro¨m, 2000).

Micro-catchment rainwater harvesting is currently under implementation in the study area following the development of the Zanzibar Irrigation Master plan (JICA, 2002). An indication of increased cropping intensity with adoption of RWH harvesting from the current 14% to 64% during the dry season is implied

The identified suitable sites for macro-catchment RWH covering an area of 44,000 Ha can greatly enhance agricultural production. To mitigate water shortages during the cropping period and especially during the short rain period when a shortfall of about 62.6 MCM is evident for the main crop grown (rice), level bunds with a CBAR of 3:1 are considered appropriate *(section 4.3.2 Para: 6)*. This technology will be possible to implement since most of the runoff generating area fall within flat and undulating slope classes *(section 5.2, Para: 6*) which are most suited for in-situ RWH. The soil associated with this slope classes are also well suited for agricultural production.

Most of the harvesting techniques identified *(table 4.3-2)* are relatively cheap and can therefore be a viable alternative where irrigation water from other sources is not readily available or too costly. RWH has been shown to be more viable than pumping water since it saves energy and maintenance costs (Prinz et al., 2000).

Use of rainwater harvesting is envisaged to reduce over reliance on groundwater for irrigation which according to JICA (2002) is not performing well due to the high operation and maintenance costs involved.

5.3.3. Macro-Catchment RWH

Macro-Catchment RWH is considered based on the available runoff that can be stored for use during the dry season. Most of the rivers in the study area have high peak discharges during the rainy season with no flows or very low flows during the dry season.

The ability to successfully manage this runoff is an important aspect towards sustainable agricultural production for the Island. RWH systems that can be implemented in the area considered suitable are mainly in-stream weirs, ponds and water pans. These systems have an advantage in that no major loss of agricultural land will occur and can be implemented by individual farmers or by the community use *(Plates 2 and 3).*

Studies carried out in the island in the past (Halcrow, 1994; ICRAF, 2007; JICA, 2002) show a considerable amount of surface runoff about 24% of the total rainfall is lost each year. The potential for runoff harvesting exists as identified in *figure 4.3-4* that can be utilised through construction of runoff harvesting structures.

In-Stream weirs or check dams could be constructed across the small streams that cover the landscape of Unguja and used to increase the retention time of runoff flows during flash floods. The stored water could then be harnessed by gravity through buried pipe collectors laid at the bottom or adjacent to the streambed or drawn through canals to feed agricultural field crops or domestic and livestock water supply systems.

Runoff harvested can be used for irrigation during the dry period covering the months of July to September, and January to February that are generally drier than the rest of the year. The main wet period March to April contributes about 69% of the total runoff with the short rain period producing about 20%. This gives a clear indication of the intra seasonal variation of water availability in the island.

In total, 35,000 hectares of land in the study area could benefit from increased agricultural production through increasing the management of surface runoff generated through rainwater harvesting and storage.

This is demonstrated through selection of 15 possible impoundment sites within the macro-catchment RWH suitable areas and analysis made on the required storage volumes and possible irrigable area that can be adequately irrigated over the dry period. Based on these sites, this study clearly demonstrates that a considerable amount of dry season irrigation demand (*table 4.3-4*) i.e. up to 50% can be met through RWH.

The storage volumes analysed are based on the assumption that the storage structures will have one filling during the main rain season and the extracted amounts can be replenished by the short rains.

6. Conclusions and Reccommendations

The objective of this study was to explore potential of data integration (use of historical and near real time RS data, GIS and hydrological modelling) to assess the potential rainwater harvesting sites in remote and data scarce areas in GIS environment. The developed GIS-based rainwater harvesting models combines through AHP using SMCE process physical, ecological, socio-economic and constrains layers as derived from remote sensing to generate RWH suitability maps.

This study presents a contribution to site search analysis for RWH potential using satellite products with minimal field data.

The MPE rainfall product can be used to determine the potential site for RWH due to its highly reliable temporal and spatial variability with correction for time lag and over/under-estimations. Despite its strength it is recommended that in designing of water harvesting structure accurate rainfall measurement should be used since MPE underestimates amount rainfall. Use of spatial rainfall data (satellite-derived) for 2008 as compared to the long term mean rainfall (derived from stations) showed that there was a large difference in the amount of runoff amounts generated.

Results of sensitivity analysis revealed that the most sensitivity layers were the soils, landcover and the runoff index. The soil layer used for this study was very coarse due to lack of detailed work on soil mapping for the study area. A more detailed soil map for this area would greatly improve the results obtained. A detailed soil mapping of the island is recommended.

The CN is shown to vary with land cover changes and its application should be considered alongside the changes that are taking place in Island due to changes in land tenure and social economic development. The evaluation of the impacts of land use change on the overall hydrology of the Island is therefore necessary.

Despite the fact that the potential use of the AHP as decision making tool in this study is well demonstrated in coming up with site suitability for RWH the thematic layers need to be more accurately determined. The methodology developed can be applied to assess most of the parameters important for water harvesting systems in GIS environment with limited ground data.

Currently utilisation of rainwater in Zanzibar is too low (1%). It will take great effort and investment on the part of the government, private sector and general public to fully utilize the existing potential. Adoption and implementation of RWH should be considered with knowledge that the assessment of the associated impacts to the overall water balance at the local and national scales is necessary. Linkages between surface and groundwater need to be fully investigated before decisions are made on key water resource development options.

The nature of the soil in the study area and mainly in the coral rag regions of the island point to close relationship between sub-surface flow and surface runoff hence a more elaborate water balance approach is required in order to understand this linkage which cannot be explained by the SCS curve number method applied in this study.

The capabilities of using RS, GIS and field data for identifying potential sites for RWH technologies for decision making on development and management of rainwater harvesting programmes is will demonstrated in this research.

RWH suitability maps generated can be the first step in determination of the most viable water resources management options that is feasible for different areas of the island since the spatial perspective is well captured.

Arising from the results of validation, the application of the developed models shows that it works effectively to identify potential sites for RWH technologies. Due to its flexibility, its application can be adjusted based on changing scenarios in the study area. This means that the subjective numbers in the suitability levels and weights of the criteria can be changed according to characteristic changes of the study area.

The main constraint to the adoption of RWH could be associated with lack of knowledge among the decision makers and the community on existing potential for RWH for the island. RWH suitability maps developed in this study that give a clear indication of the spatial extents and the existing potential can be a starting point for creating awareness among stakeholder at the local and national scale

References

Allen R.G, Pereira, L., Raes D and Smith, M., 1998. Crop Evapotransipiration guidelines for computing crop water requirements, Food and Agricultural Organisation of the United Nations.

Arnold, P. and C, A., 1986. Rainwater Harvesting: The collection of rainfall and run-off in rural areas. London: Intermediate Technology Publications.

Bancy, M. *et al.*, 2007. Mapping the Potential of Rainwater HarvestingTechnologies in Africa.

Bowden, J.H. and F. H.M. Semazzi, 2007. Empirical analysis of intraseasonal climate variability over the Greater Horn of Africa. Journal of Climate, 20: 5715-5731.

Calton W.E, 1955. A study of the more important soils of the Zanzibar protectorate. European Journal of Science, 10(2): 169-176.

Cambell, J.C., Radke, J., Gless, J.T. and Whirtshafter, R.M., 1992. An application of linear programming and geographic information systems: cropland allocation in antigue. Environment and Planning, A(24): 535–549.

Canters, F., 1997. Evaluating the uncertainty of area estimates derived from fuzzy land-cover classification. Photogrammetric Engineering and Remote Sensing, 63: 403-414.

Chow, V.T., Maidment D.R and Mays L. W, 1988. Applied Hydrology. McGraw Hill Higher Education, 588 pp.

Church, R.L., 2002. Geographical information systems and location science. Computers and Operations Research, 29(6): 541-562.

Critchley, W.R.S. and Reij, C., 1989. Water harvesting for plant production, Part 2. Case studies and conclusions from Sub Sahara Africa.

Cronshey, R.G., 1983. Antecedent moisture condition probabilities. Irrigation and Drainage Enginnering, Vol. 109(No. 2): 296–298.

de Winnaar, G., Jewitt, G.P.W. and Horan, M., 2007. A GIS-based approach for identifying potential runoff harvesting sites in the Thukela River basin, South Africa. Physics and Chemistry of the Earth, Parts A/B/C, 32(15-18): 1058-1067.

Eastman, J.R., Kyem, P.A.K., Toledano, J. and Jin, W., 1993. GIS and Decision Making. UNITAR, Geneva.

Eischeid J, Pasteris P.A, Diaz H.F, Plantico M.S and Lott N.J, 2000. Creating a serially complete, national daily time series of temperature and precipitation for the Western United states. Journal of Meteorology, 39: 1580-1591.

Evenari, M., Shana, L. and Tadmor, N.H., 1971. The Neger, the challenges of a desert. Havard University Press,Cambridge, Mass.

FAO, 1994. Water Harvesting For Improved Agricultural Production. In: FAO (Editor), Proceedings of the FAO expert consultation, Cairo, Egypt, pp. 424.

FAO, 2003. Land and Water Digital Media Series, 26. Training Course on RWH (CDROM).Planning of Water Harvesting Schemes, Unit 22. Food and Agriculture Organization of the United Nations, Rome, FAO.

FINNIDA, 1991. Zanzibar Urban Water Supply Development Plan. ZB/REP/4.

Foody, G.M., 2002. Status of land cover classification accuracy assessment. Remote Sensing of Environment, 80(1): 185-201.

Garbrecht J and Martz L.W, 1997. The assignment of drainage direction over flat surfaces in raster digital elevation models. Journal of Hydrology 193: 204-213.

Garfì, M., Tondelli, S. and Bonoli, A., 2009. Multi-criteria decision analysis for waste management in Saharawi refugee camps. Waste Management, In Press, Corrected Proof.

Gleick, P.H., 1996. Basic water requirements for human activities: Meeting basic needs. Water International, 21(2): 83-92.

Goovaerts, P., 2000. Geostatistical approachs for incorparating elevation into spatial interpolation of rainfall. Journal of hydrology 228, 1: 113-129.

Gupta, K.K., Deelstra, J. and Sharma, K.D., 1997. Estimation of water harvesting potential for a semiarid area using GIS and remote sensing. Remote sensing and geographic information systems for design and operation of water resources systems. Proc. international symposium, Rabat, Morocco, 1997(242): 53-62.

Halcrow, W., 1994. The development of Water Resources in Zanzibar, pp. 92.

Hatibu, N. and H. Mahoo, 1999. Rainwater harvesting technologies for agricultural production: A case for Dodoma, Tanzania. Kaumbutho P G and Simalenga T E (eds)(Conservation tillage with animal traction): 161-171.

Hettige, M.L., 1990. Land evaluation and land sustainability classification: Unguja and Pemba Islands.

Hjelmfelt, A.T., 1987. Curve numbers in urban hydrology. Topics in Urban Hydraulics and Hydrology. In: I.t.A.f.H. Research (Editor), pp. 73–78.

Hjelmfelt, A.T., 1991. Investigation of curve number procedure. Journal of Hydrological Engineering, Vol. 117(No. 6): 725–737.

Hudson, N., 1987. Soil and water conservation in semi-arid areas. FAO, Bedford, United Kingdom.

ICRAF, 2005. Potential for Rainwater Harvesting in Africa.A GIS overview, ICRAF and UNEP.

ICRAF, 2007. An Assessment of Rainwater harvesting Potential in Zanzibar, pp. 86.

ITC-ILWIS, 2001. ILWIS 3.0 Academic: User's Guide, Volume 3, 530 pp.

James, R.A., Ernest E. H, John T. R and Richard E.W, 2001. A Land Use And Land Cover Classification System For Use With Remote Sensor Data. In: G. Survey (Editor). A revision of the land use classification system as presented in U.S. Geological Survey Circular 671. United States Government Printing Office, Washington, pp. 41.

Janssen, R. and Van Herwijnen, M., 1994. Multiobjective decision support for environmental management. Kluwer Academic Publishers, Dordrecht (Netherlands), 232 pp.

JICA, 2002. The Study on the Zanzibar Irrigation Master Plan, The United Republic Of Tanzania.

Kahinda, J.M., Lillie, E.S.B., Taigbenu, A.E., Taute, M. and Boroto, R.J., 2008. Developing suitability maps for rainwater harvesting in South Africa. Physics and Chemistry of the Earth, 33(8-13): 788-799.

Kahinda, J.M., R.J. Boroto, R. Dube and Taigbenu, A.E., 2007. Preliminary Conceptual Model of the GIS based Rainwater Harvesting Decision Support System.

Kidd, C., Heinemann T, Levizzani V and D.R., K., 2008. International Precipitation Working Group (IPWG): Inter-comparison of regional precipitation products.

Kinoti Mutiga, J., Woldai, T. and Su, Z., 2006. Application of expert knowledge based multi - criteria evaluation MCE process to select suitable areas for water harvesting systems in Sub-Saharan Africa, a case study of Tanzania. In: AARSE 2006 : Proceeding of the 6th AARSE international conference on earth observation and geoinformation sciences in support of Africa's development, 30 October - 2 November 2006, Cairo, Egypt. Cairo : The National Authority for Remote Sensing and Space Science (NARSS), 2006. ISBN 1-920-01710-0. 5 p.

Kumar, M., Agarwal, A. and Bali, R., 2008. Delineation of potential sites for water harvesting structures using remote sensing and GIS. Journal of the Indian Society of Remote Sensing, 36(4): 323-334.

Maathuis B.H.P and Wang L, 2006. Digital Elevation Model based Hydro-processing. Geocarto-International, Vol 21(No. 1): 15.

Malczewski, J., 2004. GIS-based land-use suitability analysis: a critical overview. Progress in Planning, 62(1): 3-65.

Mbilinyi, B.P., Tumbo, S.D., Mahoo, H.F. and Mkiramwinyi, F.O., 2007. GIS-based decision support system for identifying potential sites for rainwater harvesting. Physics and Chemistry of the Earth, Parts A/B/C, 32(15-18): 1074-1081.

Moreno, D. and Seigel, M., 1988. A GIS approach for corridor siting and environmental impact analysis, Proceedings from the third annual international conference,, San Antonio, Texas 2, pp. 507–514.

Ngigi, S.N., Savenije, H.H.G. and Gichuki, F.N., 2007. Land use changes and hydrological impacts related to up-scaling of rainwater harvesting and management in upper Ewaso Ng'iro river basin, Kenya, pp. 129-140.

Ngigi, S.N., Savenije, H.H.G., Thome, J.N., Rockström, J. and de Vries, F.W.T.P., 2005. Agro-hydrological evaluation of on-farm rainwater storage systems for supplemental irrigation in Laikipia district, Kenya. Agricultural Water Management, 73(1): 21-41.

Pereira, J.M.C. and Duckstein, L., 1993. A multiple criteria decision-making approach to GIS-based land suitability evaluation. International Journal of Geographical Information Systems, 7(5): 407–424.

Pilgrim, D.H. and Cordery, I., 1975. Rainfall temporal patterns for design floods. Journal of Hydrology, 101: 81-91.

Pilgrim, D.H. and Cordery, I., 1993. Flood Runoff. In: D.R. Maidment (Editor), HandBook of Hydrology. McGraw-Hill Companies,, pp. 42.

Prinz, D. and Anupam S, 2000. Technological Potential for Improvements of Water Harvesting.

Rockstro¨m, J., 2000. Water resources management in smallholder farms in Eastern and Southern Africa: An overview. Physics and Chemistry of the Earth 25(3): 275-283.

Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York, NY. USA.

Saaty, T.L., 1990. How to make a decision: The Analytic Hierarchy Process. European Journal of Operational Research (48): 9-26.

Saaty, T.L., 2008. Decision making with analytic hierarchy process. *Int. J. services Sciences*, Vol. 1, No. 1: 16.

Senay, G.B. and Verdin, J.P., 2004. Developing Index Maps of Water-Harvest Potential in Africa. Vol. 20(6): 789-799: 12.

Sharifi, M.A. and Retsios, V., 2004. Site selection for waste disposal through spatial multiple creteria decision analysis. Journal of Telecommunications and Information Technology: 11.

Tuong, T.P. and B.A.M. Bouman, 2003. Rice Production in Water-scarce Environments. In: J.W. Kijne, R. Barker and D. Molden (Editors), Water Productivity in Agriculture: Limits and Opportunities for Improvement pp. 53-64.

USDA, 2004. Estimation of Direct Runoff from Storm Rainfall, National Engineering Handbook, pp. 79.

Vahidnia, M.H., A. Alesheikh, A. Alimohammadi and A. Bassiri, 2008. Fuzzy analytical hierarchy process in GIS application. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. , Vol. XXXVII. Part B2.

Van Mullem, J., 1992. Soil moisture and runoff- another look. Irrigation and Drainage Enginnering(Proceedings for Water Forum): 372–377.

Victor, M.P. and H.W, R., 1996. Runoff Curve Number: Has it reached Maturity. Journal of Hydrologic Engineering, 1(1): 9.

Viglione, A., R. Merz and G. Bl¨oschl, 2009. On the role of the runoff coefficient in the mapping of rainfall to flood return periods. Hydrology and Earth System Sciences, 13.

Vohland, K. and Barry, B., 2009. A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. Agriculture, Ecosystems & Environment, 131(3-4): 119-127.

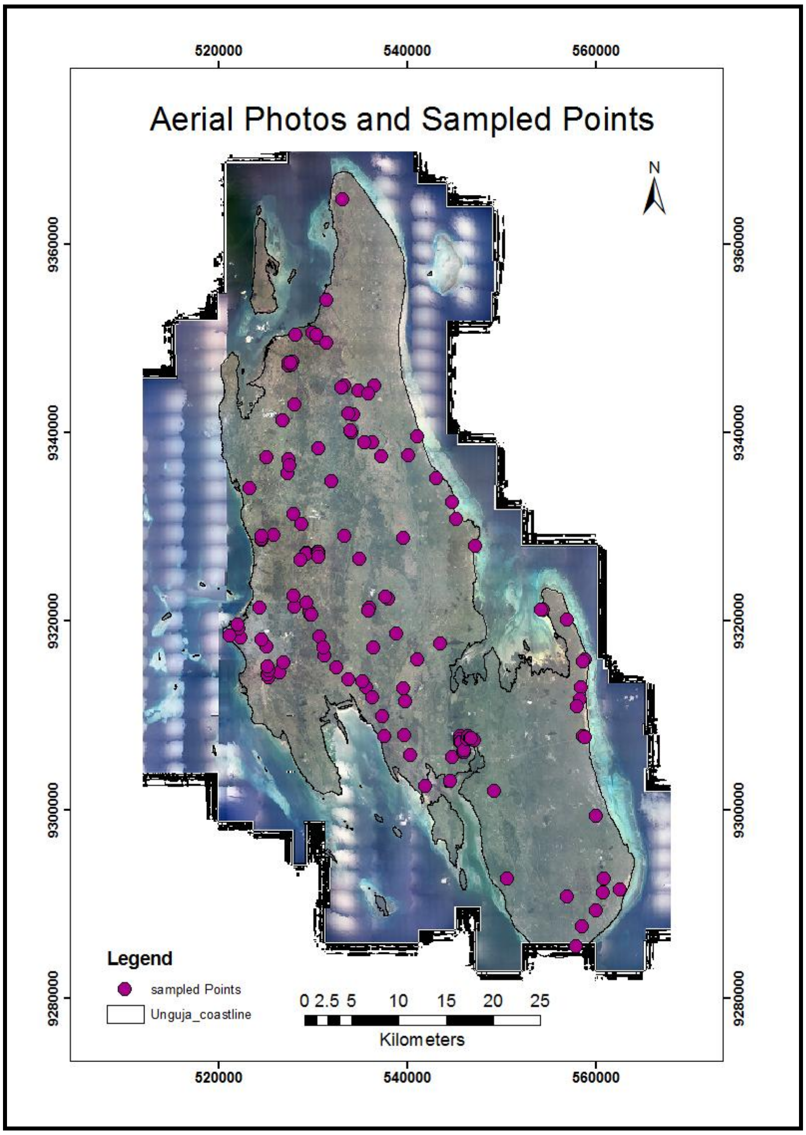
Zaunderer, J. and Hutchinson, C.F., 1988. A review of water harvesting techniques of the Arid Southwestern US and North Mexico ,Working paper for the World Bank’s Sub-Sahara Water Harvesting Study.

Zhu, Q., Li Yuanhong and Ma Chengxiang, Rainwater Harvesting experience from international community. In: T. Xiaojuan (Editor), Rainwater Harvesting, pp. 423.

Zucca, A., Sharifi, A.M. and Fabbri, A.G., 2008. Application of spatial multi-criteria analysis to site selection for a local park: A case study in the Bergamo Province, Italy. Journal of Environmental Management, 88(4): 752-769.

Appendencies

Appendix 1: Aerial photos of study area and points sampled during field work



Appendix 2: Accuracy assessments of land cover classification

	AG	MG	MS	MV	PR	Pl	Sett	ST/WC	UR	Totals	UA %
AG	13	0	2	5	0	0	1	0	0	21	**62**
MG	0	2	0	0	0	0	0	0	0	2	**100**
MS	0	0	17	0	0	0	0	0	0	17	**100**
MV	0	0	2	12	0	0	0	1	1	16	**75**
PR	0	0	0	0	9	0	0	0	0	9	**100**
PL	0	0	2	0	0	6	0	0	0	8	**75**
Sett	0	0	0	1	0	0	8	0	0	9	**89**
ST/WC	1	0	0	2	0	0	0	2	0	5	**40**
UR	0	0	0	0	0	0	0	0	4	4	**100**
Totals	14	2	23	20	9	6	9	3	5	**91**	**82**
RA %	**93**	**100**	**74**	**60**	**100**	**100**	**89**	**67**	**80**	**85**	

Abbreviations: *AG-Agricultural, MG-mangroves, MS- Mixed shrubs, MV- Mixed vegetation, PR- Paved roads, PL- Plantations, Sett- Settlements, ST/WC- Streams/Watercourses, RA%- Reliability accuracy, UA%- User accuracy*

Appendix 3: Long term mean monthly rainfall

	Airport	Kizimbani	Kilombero	Mahonda	Selem	Victoria	Paje	Makunduchi	Donge Kipange
JAN	72.0	70.6	42.3	63.6	47.4	31.0	74.2	63.2	25.3
FEB	37.6	35.1	10.2	12.7	27.3	20.0	22.8	29.6	79.1
MAR	204.5	186.3	144.1	136.3	138.6	91.4	65.4	112.5	189.3
APR	347.8	352.4	304.5	317.2	288.1	266.3	289.8	370.8	306.8
MAY	197.3	241.2	323.5	246.3	224.2	189.9	197.8	215.8	194.9
JUN	48.7	74.9	27.0	48.5	50.6	37.6	95.9	78.6	93.4
JUL	26.4	69.2	48.9	54.4	49.4	25.4	24.4	92.0	52.9
AUG	26.1	50.4	28.2	37.9	40.8	17.0	15.8	3.7	128.5
SEP	22.3	51.9	25.1	52.2	46.1	20.1	4.7	4.2	87.2
OCT	102.5	104.5	39.7	100.3	100.8	121.0	72.6	6.5	87.2
NOV	222.7	187.1	50.0	156.3	140.5	71.2	43.7	28.5	155.0
DEC	171.7	170.3	45.8	129.8	131.3	143.5	155.0	113.3	165.7
Total	**1479.6**	**1593.9**	**1089.3**	**1355.5**	**1285.1**	**1034.4**	**1062.1**	**1118.7**	**1565.3**

Appendix 4: Table of Runoff Curve Numbers (SCS, 1986)

Description of Land Use	**Hydrologic Soil Group**			
	A	**B**	**C**	**D**
Paved parking lots, roofs, driveways	98	98	98	98
Streets and Roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Cultivated (Agricultural Crop) Land*:				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, contours)	62	71	78	81
Pasture or Range Land:				
Poor (<50% ground cover or heavily grazed)	68	79	86	89
Good (50-75% ground cover; not heavily grazed)	39	61	74	80
Meadow (grass, no grazing, mowed for hay)	30	58	71	78
Brush (good, >75% ground cover)	30	48	65	73
Woods and Forests:				
Poor (small trees/brush destroyed by over-grazing or burning)	45	66	77	83
Fair (grazing but not burned; some brush)	36	60	73	79
Good (no grazing; brush covers ground)	30	55	70	77
Open Spaces (lawns, parks, golf courses, cemeteries, etc.):				
Fair (grass covers 50-75% of area)	49	69	79	84
Good (grass covers >75% of area)	39	61	74	80
Commercial and Business Districts (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential Areas:				
1/8 Acre lots, about 65% impervious	77	85	90	92
1/4 Acre lots, about 38% impervious	61	75	83	87
1/2 Acre lots, about 25% impervious	54	70	80	85
1 Acre lots, about 20% impervious	51	68	79	84

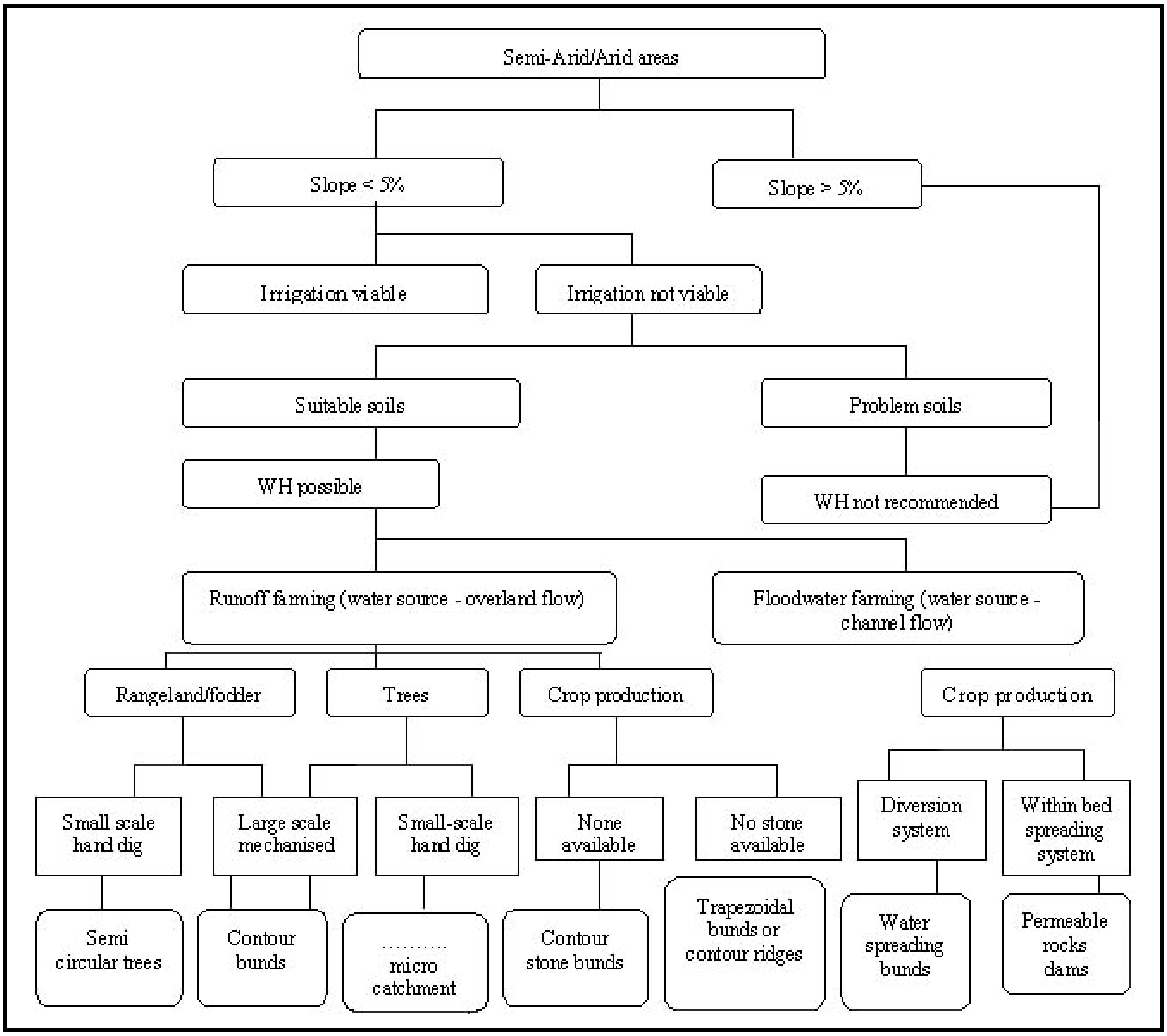
Appendix 5: Validation points Micro-Catchment RWH

Point	Easting	Northing	Land use	Landcover	Soil type
1	558525	9287536	Agricultural	Dry swamp area	Clays
2	539665	9312805	Seasonal stream	Riverine vegetation and Guavas	Clays and sand
3	537372	9309859	Agricultural	Sweet potatoes and bananas	Clays
4	534360	9341992	stream valley	Reverine vegetation and water	Clay loam soils
5	536560	9345009	Dam site Embankment	Embankment of earth dam	Sandy Clays
6	533391	9345009	Agricultural	Weeds and grass (uncultivated)	Sandy soils
7	534824	9344541	Agricultural	Weeds and grass (uncultivated)	Clays
8	531196	9317153	Agricultural (irrigated)	Uncultivated (grass and weeds)	Sandy clays
9	527515	9347213	Riparian area	Reverine vegetation and water	Sandy clays
10	523300	9334086	Agricultural	Sweet potatoes within the river valley	Sandy clays
11	528776	9330284	Irrigated agriculture	Rice on planted area and weed and grass on unplanted areas	Sandy clays
12	541062	9315940	Agricultural	Rice farming	Clays
13	534968	9326626	Abandoned quarry	Swampy area	Limestone and silt
14	528060	9321552	Irrigated agriculture	Rice farms with mangos and palms in the surrounding area	Clays and loams
15	538064	9322338	Irrigated agriculture	Rice farms with and palms in the surrounding area	Clay and loams
16	537338	9337468	Agricultural	Rain fed rice and cassavas	Sandy loams to clay
17	533094	9344754	River		clay
18	529989	9350588	River not flowing		sandy clay
19	524568	9329083	mash, ditch		sandy clay
20	531434	9349608	River		clay
21	528187	9350393	River		sandy clay

Appendix 6: Validation Points Macro-catchment RWH

Point	Easting	Northing	Land use	Landcover	Soil type
1	529790	9320640	Agricultural	Irrigated rice and bananas	Clays
2	558525	9287536	Agricultural	Dry swamp area	Clays
3	525128	9317295	Water pond	Water	Sandy clays
4	539665	9312805	Seasonal stream	Riverine vegetation and Guavas	Clays and sand
5	535750	9312974	Road	Paved tarmac	Tar
6	537372	9309859	Agricultural	Sweet potatoes and bananas	Clays
7	534360	9341992	stream valley	Reverine vegetation and water	Clay loam soils
8	536560	9345009	Dam site Embankment	Embankment of earth dam	Sandy Clays
9	534824	9344541	Agricultural	Weeds and grass (uncultivated)	Clays
10	530410	9350371	River riparian area	Riverine vegetation and palms	Sandy silt soils
11	527515	9347213	Riparian area	Reverine vegetation and water	Sandy clays
12	527494	9347117	Riparian area	Reverine vegetation and water	Sandy clays
13	528193	9350393	Riparian area	Reverine vegetation and water	Sandy clays
14	525121	9337389	Riparian area	Mixed reverine vegetation	Sandy bottoms and clays along the banks
15	523300	9334086	Agricultural	Sweet potatoes within the river valley	Sandy clays
16	528776	9330284	Irrigated agriculture	Rice on planted area and weed and grass on unplanted areas	Sandy clays
17	541062	9315940	Agricultural	Rice farming	Clays
18	533129	9364770	Bush land	Mixed shrubs	silty loams
19	536050	9321377	Agricultural	Oranges, Palms and Mangos	Loam soils
20	527770	9347195	River riparian area	Reverine vegetation and water	
21	528060	9321552	Irrigated agriculture	Rice farms with mangos and palms in the surrounding area	Clays and loams
22	538064	9322338	Irrigated agriculture	Rice farms with and palms in the surrounding area	Clay and loams
23	537338	9337468	Agricultural	Rain fed rice and cassavas	Sandy loams to clay
24	530417	9350370	River		sandy clay

Appendix 7: Macro-Catchment RWH System selection (FAO, 1994)



Appendix 8: Random Indices (RI) for n = 1, 2... 15 (Saaty, 1980)

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