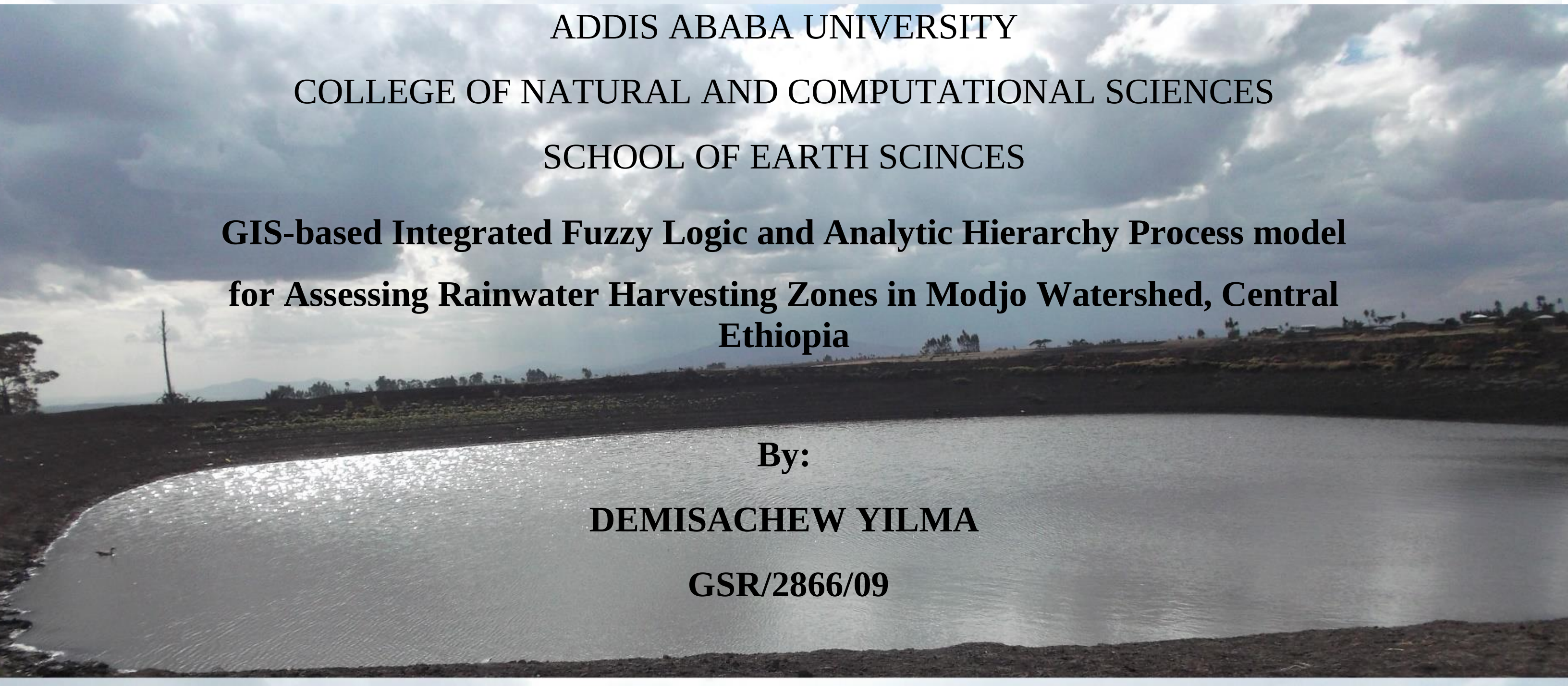

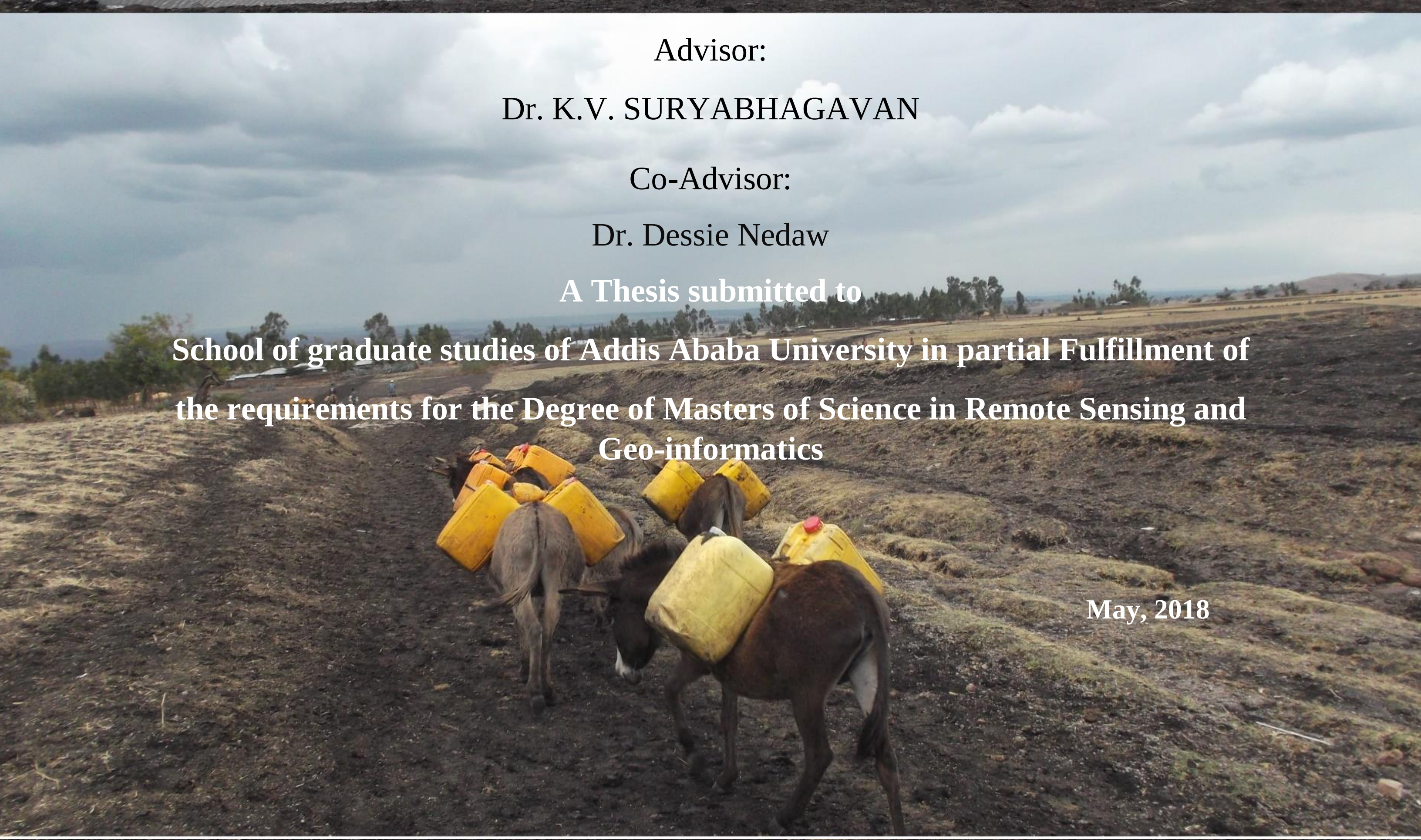

ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

SCHOOL OF EARTH SCINCES

GIS-based Integrated Fuzzy Logic and Analytic Hierarchy Process model for Assessing Rainwater Harvesting Zones in Modjo Watershed, Central Ethiopia

By:

DEMISACHEW YILMA

GSR/2866/09

Advisor:

Dr. K.V. SURYABHAGAVAN

Co-Advisor:

Dr. Dessie Nedaw

A Thesis submitted to

School of graduate studies of Addis Ababa University in partial Fulfillment of the requirements for the Degree of Masters of Science in Remote Sensing and Geo-informatics

May, 2018

ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

SCHOOL OF EARTH SCIENCES

GIS-based Integrated Fuzzy Logic and Analytic Hierarchy Process model for Assessing Rainwater Harvesting Zones in Modjo Watershed, Central Ethiopia

By:

DEMISACHEW YILMA GASHAW

GSR/2866/09

A Thesis submitted to

School of graduate studies of Addis Ababa University in partial fulfillment of

the requirements for the Degree of Masters of Science in Remote Sensing and Geo-informatics

May, 2018

Addis Ababa University

School of Graduate Studies

This is to certify that the thesis prepared by **DEMISACHEW YILMA GASHAW**, entitled: "GIS-based Integrated Fuzzy Logic and Analytic Hierarchy Process Model for Assessing Rainwater Harvesting Zones in Modjo Watershed, Central Ethiopia" and submitted in partial fulfillment of the requirements for the degree of Masters of Science in Remote sensing and Geo-informatics complies with the regulations of the University and meets the accepted standards with respect to the originality and quality.

Signed by the Examining committee:

Examiner

Dr. Tilahun Azagegn________________________ Signature___________Date _____________

Dr. Tesfaye Korme________________________Signature___________Date _____________

Advisor Dr. K.V. Suryabhagavan________Signature___________ Date _____________

Co-Advisor Dr. Dessie Nedaw___________Signature____________Date ______________

____

Chairperson

Acknowledgments

First and foremost, Glory be to the Merciful and Almighty GOD and His Mother, Saint Virgin Mary, for all things done for me in my entire life and that make all of this happen!

I am greatly indebted to my advisor **Dr. K.V. Suryabhagavan** of the Natural, Computational Sciences School of Earth Sciences Remote Sensing and Geo-Informatics at Addis Ababa University for his unfailing guidance, advice and constant encouragement helped me to complete the present research work. I honestly appreciate! I am also grateful for my advisor **Dr Dessie Nedaw** for his professional guidance, encouragement and patience during research period.

I would like to thank all the lectures of Addis Ababa University who were involved in one way or another in disseminating the knowledge, which I am now proud of.

I wish to express my genuine thanks to Arba Minch University for this higher education sponsorship, I am also thankful to Addis Ababa University.

I would also like to acknowledge Ethiopian Metrological Agency, Oromia water work design and super vision and Geological Survey of Ethiopia for their kindness in providing the necessary data and information to carry out this research.

Words cannot express my feelings which I have for my family: Yeshiwork Tefera (mom), Yilma Gashaw (dad), Woyineshet Gashaw (Emayye) and all my brothers and sisters; particularly Nigest. I am highly indebted to them for their blessing, guidance, advice, encouragement and support, I wish to offer my most heartfelt thanks to them. Wish them health and long live!

Finally, I would like to convey my special thanks to my friends: Belete, Wondifraw, Ahimed, Dagnachew, Habtamu, Tekalign, Worku, Sendu, Tegenie, Gashaw and many others for the enjoyable time spent together and their helps at the time of research work.

Table of Contents **Page**

List of Tables **page**

List of Figures **page**

List of Appendices

Acronyms

AHP	Analytical Hierarchy Process
ARC	Antecedent Runoff Condition
CI	Consistency Index
CN	Curve Number
CR	Consistency Ratio
CSA	Central Statistics Agency
DEM	Digital Elevation Model
DSS	Decision Support System
EMA	Ethiopian Mapping Authority
FAO	Food and Agriculture Organization
GPS	Global Positioning System
GIS	Geographic Information Science
HSG	Hydrological Soil Groups
IDW	Inverse Distance Weight
LU/LC	Land-use/land-cover
Masl	Meter above sea level
MCDA	Multiple Criteria Decision Analysis
MER	Main Ethiopian Rift
MoA	Ministry of Agriculture
NMA	National Metrological Agency
NRCS	Natural Resources Conservation Service
PCM	Pairwise Compression Matrix
RI	Random Index
RS	Remote Sensing
RWH	Rainwater Harvesting
SCS-CN	Soil Conservation Service Curve Number
SRTM	Shuttle Radar Topography Mission
WLC	Weighted Linear Combination

Abstract

GIS-based Integrated Fuzzy Logic and Analytic Hierarchy Process model for Assessing Rainwater Harvesting Zones in Modjo Watershed, Central Ethiopia

Demisachew Yilma Gashaw, MSc. Thesis
Addis Ababa University, May 2018.

Water is one of the basic requirements for life, economic and social developments, it is required for human beings, animals and plants. Therefore, adequate water supply and water management are critical for the development of water needs. However, in the study area lack of water for agricultural, potable and livestock consumption during the dry month of the year is one of a concern. The objective of this research was to assess the most potential sites of rainwater harvesting in Modjo watershed in central Ethiopia using an advanced geospatial-based model that combines fuzzy logic with Analytical Hierarchy Process (AHP) model. This technique helps to detect water harvesting sites in suitable places and to improve water resource management to resolve water shortage in the study area. The methodology adopted in this study was fuzzy logic modeling to standardize the input factor. Analytical Hierarchy Process modeling was used to drive the weight of each influential factor and weighted linear combination (WLC) technique was used to process and aggregate these factors together. Based on the literature reviewed and availability of data, ten significant layers of the study area such as rainfall, runoff depth, drainage, land-use and land-cover, slope, lithology, lineaments, proximity to road and urban were incorporated to develop the model. Results of this study revealed that rainwater harvesting potential suitability class coverage of study area was very highly suitable (18.1%), highly suitable (20.9%), moderately suitable (20.3%), low suitable (10.6%) and very low suitable (3.1%), while 26.9% of the area was covered by constraints. This research demonstrates that compatibilities of geospatial modeling to investigate the possibilities of selecting potential sites for rainwater harvesting in modjo watershed.

Keywords: Analytical Hierarchy Process, Fuzzy logic, Modjo watershed, Rainwater, WLC

CHAPTER ONE

1 INTRODUCTION

1.1 Background of the study

Rain Water Harvesting (RWH) is the process of collecting and storing water for future productive use, which means Rainwater is collected when water falls on the earth, stored and utilized at a later point for different purposes. It can be purified to make it into drinking water, livestock consumption, used for daily applications and even utilized in large-scale industries. In short, Rainwater harvesting is a process or technique of collecting, filtering, storing and using rainwater for irrigation and for various other purposes (Kahinda *et al.*, 2008). Other literature defined RWH as rainwater collection from runoff and catchment areas such as urban structures or roofs to meet demands for domestic, industrial, agricultural and environmental purposes when water sources are becoming scarce or low water quality (Worm and Hattum, 2006). The amount of water harvested by this method depends on the amount of the rainfall, the permeability of the surface, the area of the surface and the slope of the surface among other factors. The research is done based on this type of RWH method.

In large part of the world, surface runoff water harvesting is best known and practiced in the semi-arid areas where annual rainfall is in the range between 400 and 600 mm. The runoff irrigation facilities in the Negev Desert were built during the Israeli Babataean and Roman-Byzantine periods back in the 1,300−2,900 A.D (Evaenari *et.al.*, 1971 as cited in Tauer and Humborg, 1992), and this practice provided a livelihood for a considerable population of more than 2000 years ago and continuing until about 700 A.D (Pacey and Cullis, 1986).

The amount of water present on earth is always constant. It is transformed from one form to another in a specified manner. Though two by a third of earth or 75% is covered with water, the usable water for irrigation and drinking purpose is only two percentages of total fresh water (Belete Berhanu *et al.*, 2014). So proper management of the available water is very important for the sustainable utilization of it. The major share of usable water is present in the inner part of earth known as groundwater. Increase in the groundwater storage of a region is the direct measure of water richness. Water harvesting technique plays a vital role in increasing the groundwater recharge (Naseef and Thomas, 2015).

Rainwater harvesting (RWH) has become an increasingly important practice because of global warming and the depletion of fresh water sources. The scarcity of fresh water has resulted in the need to identify and utilize other freshwater sources that could satisfy the growing water demand (Faez and Abdul Rashid, 2015). A major factor in increasing agricultural production is the development of irrigation practices, which in turn is essential for economic development of the country.

The history of water harvesting in Ethiopia dated back as early as the pre-Axumite period (560 BC) (Fattovich, 1990). It was a time when rainwater was harvested and stored in ponds for agricultural and water supply purposes. Anthropologists have documented evidence of the remains of ponds that were once used for irrigation during this period. These techniques, though dates back in the antiquity, their importance has not been recognized until very recent time.

One of the basic requirements for life, economic and social development is water. Water is required by human beings, plants, animals and for ecosystem functions. Therefore, adequate water supply and water management are critical in the development of drinking water supply, Agricultural and industrial activities. The demand for water increases linearly as population increases. According to (World Water Organization) the Globe water consumption rate doubles in every 20 years, a rate that is twice the population growth rate. However, to satisfy the increasing demand of water, priority should be given to rainwater harvesting either for surface storage or for artificial recharge since this assist in sustainable management for water resources (Bakir and Xingnan, 2008). According to World Bank (2006), Ethiopia water resources endowment appears generous, with a mean total surface water flow of about 122 billion cubic meters per year. The country has several major rivers and lakes, and significant groundwater resources and annual rainfall. However, rainfall across much of the country is both highly seasonal with most of the rain falling in a single, short season and exceptionally variable and unpredictable, both in time and space.

For various activities, rainwater harvesting deals with many spatial data that can be easily handled using geospatial technologies such as RS and GIS, such types of technologies are widely being applied in the field of Hydrology and water resource developments (Sharma and Kujur, 2012). In Ethiopia, little has been done in the use of RS and GIS techniques to identify sites for rainwater harvesting. One area that will be benefited from such types of study will be modjo watershed and its environs.

In recent years, Geographical Information Systems (GIS) have provided a flexible, powerful platform for integrating remote sensing data and runoff model outputs to optimally situate WH structures (Mbilinyi *et al.*, 2007). Typically; by using spatial analysis tools. Delineating suitable areas for WH structures is often performed by integrating different factors using GIS overlay and index-based Multicriteria Decision Analysis (MCDA), which for GIS can provide a set of powerful techniques and procedures for making critical decisions (Gbanie, 2013).

Water harvesting structure is extremely important to conserve precious natural resources like, soil and water, which is depleting day to day by the alarming rate in the watershed (Kiflu Gudeta, 2010). Water harvesting structure is one of the important components of watershed developments. for most time there are strong links between soil conservation and water conservation measures. The reduction of surface runoff can be achieved firstly by selecting the best sites for water harvesting and constructing suitable structures or by changes in land management. In another hand, this reduction of surface runoff will increase the rate of infiltration and helps for water conservation. Appropriate sites are needed to avoid an excessive runoff, this type of activities helps in flood control in lower catchments, improving soil moisture availability and to increase the water table of the watershed (Singh *et al.,* 2008).

Harvesting is a technique which is used to effectively trap the surface runoff. In technical terms, water harvesting is a system that collects rainwater from where it falls around its margin rather than allowing it to go as runoff. By selecting best water harvesting area at appropriate sites it is possible to increase water for irrigation and drinking purposes in the study area. Although these best waters harvesting areas act as a barrier to soil erosion and preventing flooding, The Identification of potential sites for Rainwater Harvesting (RWH) is an important step towards maximizing water availability and land productivity in the areas. The traditional fragmented approach of Identification of potential sites for Rainwater Harvesting (RWH) is no longer viable and a more holistic approach to water management is essential. According to Naseef and Thomas, (2015) percolation tanks, check dams, farm ponds, bunds. are some of the types of water harvesting structures that are widely used in the world.

There are several factors influencing the selection of sites for RWH. Those factors are Slope, land-use/land-cover, soil type, runoff potential, the geology of the area, drainage, rainfall, soil clay content and other ecological and socio-economic factors. In addition to the above-listed criteria, porosity and permeability, runoff potential, stream order and catchment area were adapted as criteria to select suitable sites for various rainwater harvesting zones (Buraihi and Shariff, 2015). The appropriate method used in this research for identifying suitable RWH zones is using GIS-Based decision support system and Remote Sensing by means of Fuzzy Logic and AHP model was the best alternative.

The integration of GIS and RS technologies have several strengths to water resource research (Girish *et al.*, 2008). The overall objectives of this research studies include identification of best sites for rainwater harvesting using fuzzy and AHP model, identification of watershed segmentation, drainage divides and a network of channels, identify and delineate RWH potential zones through the integration of various thematic maps with GIS techniques. Characterization of terrain slope, rainfall distribution, catchment configuration and routing of the flow of water. The above-listed variables have been difficult to do from paper maps and aerial photographs. These traditional methods are subject to errors related to manual operations. The work using to traditional measurement methods has also provided to be time-consuming. Nevertheless, once the GIS system is developed, it is straightforward to produce needed data, make maps, and provide simple or complex displays of model results through integration of other sources of data such as historical maps and aerial photos can be of assistance, it can be concluded that suitability mapping using GIS is a flexible, time-efficient and cost-effective method to screen large areas for RWH suitability facilitating decision-making for investments in RWH (Lyon, 2003).

1.2 Statement of the problem

Ethiopia is very well known for its enormous water resource potential. It is still known as the water tower of Northeastern Africa, the source of the Blue Nile and many transboundary rivers (Getachew Alem, 1999). However, the community in modjo watershed faces lack of permanent sources of water, for livestock consumption and agricultural purposes, in addition, Crop production in Ethiopia is mainly practiced under rainfed conditions and this sector is the backbone of the country's economy. A major part of this crop production is in semi-arid areas such as in the modjo watershed. To increase crop yields and improve food security, effective planning and development of water resources in the area are critically important. Therefore, managing water resources to sustainable growth are the most critical issue in dry areas as it has impacts on the livelihood of people and the productivity of the land and the society in general. Water, one of the most essential resources in our day-to-day life is depleting faster in rural as well as urban areas of the watershed, mainly because of increase in agricultural and domestic demands. Recent time in modjo watershed as water resources become rare in many locations, the capture of rainwater for everyday use is not on the rise.

Water scarcity is a major issue in central parts of Ethiopia basically modjo watershed, dense population and seriously dependence on irrigation on modjo river recent time places immense pressure on available water resources, which have a different seasonality. New forms of management based on traditional and scientific knowledge must be introduced to solve the problem of water supply, water demand, and water quality in the watersheds. To cope up this problem one of the best alternatives and the initial stage is finding the potential zones for water harvesting and increasing water demand in water prone areas using appropriate techniques are critically important.

In the watershed due to the population increasing from time to time water resources becoming increasingly scarce. Lack of water for potable, agricultural and livestock consumption during the dry month of the year is one of concern for this study area. Especially from the month December to May most of this watershed area have scarcity of water because of no rainfall and most of the traditional water storage or ponds are becoming give out; This action forced the community in the watershed to consumes high demand of water from the upper stream of Modjo river. Here after, shortage of water is happening at downstream, due to this event most of the irrigated plants becoming shrivel and lead conflict among the upper watershed community. In recent time along the modjo river the consumption of water becoming higher and higher from time to time, this higher consumption of water leads conflicts between the downstream and upper stream community because of during dry season, the upper watershed community consumes high amount of water for irrigation and livestock consumption, such actions cause shortage of water at the downstream of the watershed. So, these activities strongly require conflict resolution for water resource management (Apipalakul *et al.,* 2014). The early stages to mitigate conflicts among upper and downstream of the watershed community can be: GIS-Based Approach for harvesting potential zones for rainwater harvesting is a meaningful for conflict resolution on any water resources in the watershed.

In modjo watershed when rainfall comes too early or too late, the entire agricultural cycle can be disrupted, because there is no sufficient water storage capacity to smooth and schedule water delivery. The area is gifted with plenty of natural resources including ample rainwater but, due to lack of sufficient water management, all waterfalls drained to lower stream. Nevertheless, all agricultural practices in the area take place depending only under rain-fed conditions and the cropping season is one time a year. It is, therefore, important that adequate supplies of surface water harvesting must be developed to improve sustainable development, by means of harvesting rainwater during the rainy season for water supply and irrigation practices in the area. However, to increase the water demands at this watershed first identification of best sites for water harvesting zone using RS and GIS is the most applicable means. Therefore, Rainwater harvesting is one of the best alternatives to mitigate the disaster harnessing as the water source to address the water scarcity problem in the regime.

Quantities of runoff have increased over the surface and causing environmental related disasters in the form of flooding and soil erosion during the rainy season. However, excessive runoff is a resource that can be harnessed for use by households, agriculture, and environmental improvement. Though rainwater harvesting has a great potential, a major knowledge gap exists concerning the choice of the most suitable areas where harvesting can be practiced. Therefore, there is a need for a robust methodology that can enable water resource managers to identify and map existing potentials for water harvesting. Most places in the watershed receive moderate to good rainfall. But this rainfall occurs in short spells of high intensity. Because of this most of the rain falling on the surface either flood the area or flows away rapidly resulting in very little or no infiltration into the soil. Consequently, one of the best ways to prevent rainwater from getting wasted is harvested it at the source. Therefore, to overcome these issues No research has been conducted to identify suitable locations for WH in the study area by using remote sensing and GIS with the integration of fuzzy logic and AHP approach. As such, the proposed approach using readily available data is expected to provide guidance for decision makers active in the region's water resource management. Thus, in the research, the integrated fuzzy and AHP modeling method using geospatial data and used to explore the potential area of RWH sites in Ethiopia in general and particularly for the study area.

1.3 Objectives

1.3.1 General objective

The main objective of this research was identifying potential sites for rainwater harvesting in the catchment using integrated fuzzy logic and analytic hierarchy process model.

1.3.2 Specific objectives

- To assess suitable sites for water storage to catch surface runoff for the agricultural development.
- To identify RWH potential zones through the integration of various thematic maps with GIS techniques.
- To identify potential areas for different types of rainwater harvesting structure in the entire watershed.
- To validate the suitability of fuzzy modeling and AHP approach for potential RWH structure sites selection in the study area.

1.4 Research questions

This research will try to find answers for the following Questions.

- How can integrate Remote Sensing, GIS, fuzzy logic, AHP and Hydrologic modeling be optimally utilized to identify suitable RWH potential site?
- What are the factors influencing rainwater harvesting site selection? How?
- How to develop a model using fuzzy and AHP integrated approach, for suitable site analysis?
- What are the criteria and methods to be followed for rainwater harvesting site selection in the watershed?

1.5 The significance of the study

Rainwater harvesting is a key technology that has the potential to address drinking, domestic and agricultural production needs. These needs are inherently linked to thematic areas that include water for health, energy, food security, and ecosystems. As a general the significance of this proposal was: For the community, who were highly vulnerable by the scarcity of water in the study area, as well as provides a supply of safe water close to homes, schools or clinics, encourages increased consumption, reduce the time women and children (students) spend on collecting water and the requirements of water for feeding the livestock can be met; For researchers, who will be doing about RWH by providing insights on the major factors that affect rainwater harvesting; It will be used as an input for government, policy makers, planners and water project managers for their decision-making process related to selecting potential zones for rainwater harvesting structures and finally, It will be used as an input for those who want to invest their economy in water supply and irrigation practices in the area.

1.6 The scope of the study

This paper was conducted on identifying sites that are best for harvesting rainwater in Modjo catchment using fuzzy logic and analytic hierarchy process model with the integration of geospatial technology, and its scope was limited to modjo watershed, central Ethiopia.

1.7 Limitation of the study

To improve the accuracy of the result a dense network rainfall station and continuously recorded rainfall data is required to investigate the spatial rainfall distribution in study area. Lack of existing WH data for validation with generated RWH potential zones.

1.8 Thesis organization

The thesis is organized into six chapters as outlined below**:** Chapter one gives an overview of RWH, study area and outlines the key problems that form the basis of this research. The research objective, research questions and highlights of significant of the study as well as the scope of the study and the thesis outline are included in this chapter. Chapter two reviews related works conducted in this field and detail description of RWH within different methods of RWH modeling and describe the model used in the research. A brief description of the study area is also highlighted in the chapter. Chapter three explain in detail about the dataset used, presents the conceptual framework used in conducting the research, the methodology used and fieldwork data collection and analysis was done in this portion. Chapter four presents the result of analysis of RWH potential using fuzzy logic and analytic hierarchy process. The suitability for farm pond, percolation tank and check dam RWH techniques also presented. Chapter five discusses the results obtained and their relevance to the study area. Finally, conclusion and recommendations are arising from chapter six.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 An overview of Rainwater harvesting

Rainwater Harvesting is when the precipitation is collected from a small/large surface area (catchment) and directed through channels to a storage facility or to a nearby field or retained at the site itself. Rainwater harvesting is the storage and accumulation of rainwater for reuse, rather than permitting it to runoff, It can be collected from drainage or roof tops, and in many places, the water collected is redirected to a deep pit (well, shaft, pond or borehole). The harvested water is used for gardens, livestock, irrigation, domestic use with proper treatment. The harvested water can also be used as drinking water, longer-term storage, and for other purposes such as groundwater recharge (https://en.wikipedia.org/wiki/Rainwater_harvesting).

Rainwater harvesting, in a broad sense, is the collection of the raindrops/runoff for domestic consumption and/or food production purposes, which will otherwise cause soil erosion. It could also be described as an act of maximizing the use of the available rainfall by applying different techniques (Getachew Alem, 1999). In fact, rainwater harvesting practices and their recognition as alternative options to supplement other water sources is not new in Ethiopia.

According to Kahinda *et al.* (2008) RWH is defined as the collection, storage and use of rainwater for small-scale productive purposes, as well as Critchley *et al.* (1991) defined it as the collection of runoff for productive use. Although, Tavakoli *et al.* (2010) defined as the concentration of rainwater through runoff into smaller target areas for beneficial use. Mati *et al.* (2006) defined RWH as the deliberate collection of rainwater from a surface known as catchment and its storage in physical structures or within the soil profile.

The practice of water and soil conservation has been in place for more than five hundred years in Konso, but this effort was not developed and duplicated elsewhere in the country, especially in areas that have similar problems with Konso. Recently, encouraging efforts have been made in Amhara and Tigray regional states to adopt bund construction for water and soil conservation through food-for-work programs. With certain modifications, it would be acceptable in other parts of the country.

2.2 The ancient and current rainwater harvesting practices in the world

The practice of harvesting rainwater is an old tradition adopted in many parts of the world, Rainwater harvesting and utilization systems have been used since ancient times and evidence of roof catchment systems date back to early Roman times. Roman villas and even whole cities were designed to take advantage of rainwater as the principal water source for drinking and domestic purposes since at least 2000 B.C. many different cultures have used this technology for agricultural purposes. The Philippines have been using rainwater for rice terraces for thousands of years; Indian history indicates that rainwater systems have been in use since 3000 BC. Usage can also be traced back 2000 years ago in Thailand and other parts of Southeast Asia, where simple gutters were used to fill jars and pots. The earth dams of ancient Egypt were used to control runoff. (Leung, 2008). In the Negev desert in Israel, tanks for storing runoff from hillsides for both domestic and agricultural purposes have allowed habitation and cultivation in areas with as little as 100 mm of rain per year. Evanari *et al.* 1971 (as cited in Critchley and Siegert, 1991).

Rainwater harvesting has been a common practice by different civilizations for about four thousand years mainly used for drinking purposes or agricultural practices. The Egyptians built storage tanks ranging from 200 to 2000 cubic meters (some of them are still in use today); in Thailand, the practice is about 2000-year-old, and in rural areas of the world, pots and different types of methods have been used to irrigate the soil and store rainwater for centuries.

Rainwater harvesting (RWH) is a technique of collection and storage of rainwater into natural reservoirs or tanks, or the infiltration of surface water into subsurface aquifers (before it is lost as surface runoff). One method of rainwater harvesting is rooftop harvesting. With rooftop harvesting, most any surface-tiles, metal sheets, plastics, but not grass or palm leaf can be used to intercept the flow of rainwater and provide a household with high-quality drinking water and year-round storage. Other uses include water for gardens, livestock, and irrigation, (https://en.wikiversity.org/wiki/Rainwater_harvesting).

Rainwater harvesting was a significant and successful design in the past, its popularity has declined over the centuries. Urbanization demanded a more centralized water supply system. Watersheds and pipelines came into use and running water became one of the world's greatest inventions. However, due to modern day water pollution and drought, rainwater harvesting techniques have come back into practice again.

2.3 History of rainwater harvesting in Ethiopia

The history of rainwater harvesting practices in Ethiopia dates back as early as 560 BC, Anthropologist (Fattovich, 1990) have documented evidence of the remains of ponds that were once used for irrigation during this period. A roof water harvesting set up is still visible in the remains of one of the oldest palaces in Axum; during the Axumite Kingdom. In those days, rainwater was harvested and stored in ponds for agriculture and water supply purposes, which are evidenced with documented literature and visual observations on the remains of ponds that were once used for irrigation during that period. The palace of the legendary Queen of Sheba. Other evidence includes the remains for one of the old castles in Gondar, constructed in the 15−16th century, which used to have a water harvesting set up and a pool that was used for religious rituals by the kings. In the south of the country, the Konso people have had a long and well-established tradition of building level terraces to harvest rainwater to produce sorghum successfully under extremely harsh environment; low, erratic and unreliable rainfall conditions. Even these days, there are several traditional rainwater-harvesting technologies in Ethiopia, which have been used by communities in areas of water shortage. For many traditional communities in rural areas where natural sources of water are lacking, a collection of rainwater from pits on rock outcrops and excavated ponds are common practices. In many semi-arid lowland areas of Ethiopia, where rainfall is not adequate for crop growth, farmers use runoff irrigation as a source of life-saving irrigation supplies. (Getachew Alem, 1999; Girma Moges, 2009; Allen and Roberts, 2015).

2.4 Rainwater harvesting practices in Ethiopia

The practice of harvesting rainwater is an old tradition adopted in many parts of the of Ethiopia, Collection and storage of rainwater for different purposes has been a common practice since ancient times. The system was used thousand years ago in many parts of the country. There are also evidence indicating ancient churches, monasteries and castles in Ethiopia used to collect rainwater from rooftops and ground catchments. Run-off irrigation is widely used in Hararghe to produce major crops in the area; sorghum, and chat (Chat edulis). The technique is based on the use of runoff produced from the adjacent upland farms and made to be diverted for use back in the farm at a lower elevation. This technique is well adapted for crop production in the highlands of Hararghe with altitudes in the range between 1700 and 2500 m a.s.l. In these areas, crop productivity has been significantly increasing, and production is getting stabilized even at bad seasons (Getachew alem, 1999).

Traditional ponds have been used in Ethiopia for a millennium, they are used to harvest rainwater for both human and livestock watering in most rural areas, particularly in the arid and semi-arid areas where annual rainfall is less than 600 mm. Ponds are simple to construct and it can be managed by the community. Approximately 15 to 20 percent of the people and over 80% of the livestock in Ethiopia uses water from either rivers/stream and ponds. Traditional ponds that are estimated in Ethiopia are over 2000 ponds (quite a small number compared to over 2 million ponds in the United States). They are used primarily for domestic water supply and livestock watering. The size of the ponds ranges from 650 m^3 to several thousand, and they serve for 3 to 6 months only. In Dalocha alone, Silte District, Gurage Zone of Ethiopia, about 150 traditional ponds are used for human and livestock watering. The most common type of pond is the excavated type. The distribution of these ponds generally is in the arid and semi-arid areas where the Sahelian climatic condition prevails. Traditional ponds are major sources of water in the rift valley where groundwater is deep and other sources of water are not feasible (Getachew Alem, 1999).

2.5 Ethiopian water resources and challenges

Ethiopia is very well known for its enormous water resources potential. It is still known as the water tower of Northeastern Africa, the source of the Blue Nile and many transboundary rivers. Since almost all river basins originate from the highlands and high rainfall areas, they have huge amount of surface water running into river basin systems. This potential is not fully utilized and translated into development because of many factors including limited financial resources, technical challenges, and lack of good governance in the water sector (Belete Berhanu *et al.,* 2014). The total annual runoff is estimated at 110 Billion m^3, and only less than 5 percent is used in the country (Getachew Alem,1999). The remaining water leaves the country through transboundary rivers.

Ethiopia faces a range of challenges in water management, with levels of service provision for water supply and sanitation that are amongst the lowest in the world, very low levels of irrigation development and challenges in areas such as hydropower development, disaster mitigation and ecosystems management (World bank, 2006). Despite these challenges, Ethiopia has huge water resources potentials: the key issue for the future is to identify the most effective strategies to unlock these potentials to meet national development objectives (Ministry of Resources, 2001). The key focal areas for a more effective water-poverty strategy for Ethiopia are, perhaps inevitably, rural water supply and sanitation and small-scale farming, most of which is dependent upon rainfall rather than irrigation. For water supplies, the key element of a strategy is to focus on local-level systems that fit the needs and potentials of individual communities.

The potential of groundwater and of increasing local level rainwater harvesting and storage facilities are emphasized. For the agricultural sector, on which so many poor Ethiopians depend, the focus should be on improving on-farm water management, including rainwater capture and storage. This should be supported by the extensive development of small-scale irrigation where it is feasible, again based on more effective storage of rainwater and, in some parts of the country, groundwater utilization. Poverty reduction in Ethiopia will fail unless the basic issues of poor food security, inadequate nutrition and low and insecure rural incomes are addressed (). Improved water management can play a major role in meeting these challenges. Since Ethiopia is Home to several international rivers (Belete Berhanu *et al.,* 2014), the country needs to plan the development of its water resources with careful consideration of how its neighbors might react.

2.6 Benefits of Rainwater Harvesting

Rainwater harvesting is increasingly relevant in the context of growing population and its demands on water quantity; rainwater harvesting can be useful for improving water availability for crops in rainfed agricultural systems (Ghimire and Johnston, 2015). This paper presents rainwater harvesting as one of the most promising alternatives for supplying water in the face of increasing water scarcity and escalating demand in the study area. Rainwater harvesting can conserve water and reduce water bill, but these savings depend on the storage capacity of the system as well as proper use and maintenance. The other significance of rainwater harvesting is reducing flooding and erosion in small streams by reducing runoff volume.

Water harvesting structure is one of the important components of watershed development. According to Singh *et al.* (2008), there is strong links between water conservation and soil conservation measures. However, before implementing water harvesting structure in a given area first selecting appropriate sites for water harvesting using proper methods is critical, at that moment the reduction of surface runoff can be achieved by constructing suitable structures or by changes in land management. Further, this reduction of surface runoff will increase infiltration and help in water conservation. Appropriate structures are needed to avoid an excessive runoff, help in flood control in lower catchment, improving soil moisture availability and to increase the water table in the watershed.

2.7 The World Water Crisis

Freshwater scarcity has been cited as the major crisis of the 21st century, but it is surprisingly hard to describe the nature of the global water crisis (Srinivasan *et al.*, 2012). However, water and its availability and quality will be the main pressures on and issues for, societies and the environment under climate change. Climate-related impacts on water resources are already being documented. In all corners of the world, there is growing empirical evidence of increased severe weather events, flooding, and diminished ice cover, all of which can be attributed to climate change. Numerous scientific studies also show increases in the intensity, duration, and spatial extent of droughts, higher atmospheric temperatures, and warmer sea surface temperatures, changes in precipitation patterns, and diminishing glaciers and snowpack. In the future, climate change will affect water supply, quality, and demand for Increase water shortages due to changes in precipitation patterns and intensity. The subtropics and mid-latitudes, where much of the world's poorest populations live, are expected to become substantially drier. Reduced precipitation in some arid regions could trigger exponentially larger drops in groundwater tables (UNGC, 2009).

2.8 Ethiopian agriculture

Many scholars agree that Agriculture is the pillar of the Ethiopian economy and therefore this sector determines the growth of all the other sectors and consequently, the whole national economy. The sector is dominated by small scale farmers who practice the rain-fed mixed farming practices id dominated by small scale farmers employing traditional technology, adopting a low input and low output production system. In terms of livestock, the country stands at the top lists in Africa and ranks tenth in the world. However, animal husbandry has not managed to establish itself as a main contributor to the national economy, as hoped for due to the use of backward technologies. (Atsbaha Gebre-Selassie and Tessema Bekele, 2010).

2.9 Remote Sensing and GIS application on water resources

Remote Sensing and GIS technology are evolving rapidly in the field of water resource engineering to allocate the surface and subsurface water resources optimally for different purposes. These technologies have been extensively used to organize the data in a scientific manner. The remote sensing is helpful to acquire the data over a wide area regularly and GIS can be used to process the data to obtain the desired results. According to Rango, 1994; Gautam and Luketina (2000) Remote sensing and GIS data are being used operationally in precipitation estimates, soil moisture measurements for irrigation scheduling, snow water equivalent and snow cover extent assessments, seasonal and short-term snowmelt runoff forecasts, reservoir water quality assessments, identification of the extent of subsurface water resources, flood mappings and surface water inventories.

Geographical Information System is a very powerful means of managing the attributes of objects or things and the analysis of their spatial properties. Geographical Information System can also provide automated cartographic transformation and generation of graphics products. More specialized analysis functions, like finding the shortest path in a network, or calculating the areal extent of a watershed draining through a specified point given a digital elevation model, selecting best sites for different purposes are also possible. Satellite remote sensing, on the other hand, provides the necessary data in a regular sequence and on a regional, continental or global scale to measure, monitor and model complex natural, hydrological and manmade features (Gautam and Luketina, 2000).

The integration of GIS and Remote Sensing technologies has several strengths to water resource researchers. Therefore, the objective of this research studies includes identification of best sites for rainwater harvesting using Fuzzy logic and AHP model, identification of watershed segmentation, drainage divides and Network of channels, characterization of terrain, slope, rainfall distribution, catchment configuration and routing of the flow of water. Obtaining these, the above-listed variables has been difficult to do from paper maps and aerial photographs. These traditional methods are subjected to errors related to manual operations. The work using traditional measurement has also proved to be time-consuming. but once the GIS system is developed, it is strength forward to produce needed data, make maps and provide a simple or complex display of model results with the integration of another source of data such as historical maps and aerial photos can be of assistance. Therefore, GIS plays a key role in maintaining data and analyzing optimal locations. According to Al-shabeeb, (2016) GIS is a tool that reduces time and cost of the site selection and provides a digital data bank for future monitoring program of the selected sites. Multi-Criteria Decision Analysis (MCDA) in GIS environment is used to combine layers of spatial data representing the criteria and to specify how the layers are combined. The Fuzzy Logic and Analytical Hierarchy Process (AHP) is a method of MCDA that is implemented within GIS, which defines weights for criteria selected.

2.10 Principles of Fuzzy logic and AHP modeling

2.10.1 Fuzzy logic theory

Fuzzy Logic was initiated first in the 1960s and 70s, by Lotfi A. Zadeh, professor for computer science at the University of California in Berkeley (Zadeh, 1965). Basically, Fuzzy Logic is a multivalued logic, that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, zero/one. Concepts like rather tall or very fast can be formulated mathematically and processed by computers, to apply a more human way of thinking in the programming of computers (Zadeh, 1984). Logic is the study of the structure and principles of correct reasoning, and more specifically, attempts to establish the principles that guarantee the validity of deductive arguments. The central concept of validity is for logic because when affirming the validity of an argument are saying that it is impossible that its conclusion is false if its premises are true. Fuzzy logic is an intelligent technique widely used to map an input space to an output space by using a list of IF-THEN rules. According to Fuzzy Logic provides a different way to approach a control or classification problem. This method focuses on what the system should do rather than trying to model how it works. One can concentrate on solving the problem rather than trying to model the system mathematically if that is even possible. On the other hand, the fuzzy approach requires a sufficient expert knowledge for the formulation of the rule base, the combination of the sets and the defuzzification.

The fuzzy model represents the real system in a form that corresponds closely to the way humans perceive it. Thus, the model is easily understandable, and each parameter has a readily perceivable meaning. The model can be easily altered to incorporate new phenomena, and if its behavior is different than expected, it is usually easy to find which rule should be modified, and how? Furthermore, the mathematical procedures used in fuzzy modeling have been tried and tested many times, and their techniques are relatively well documented (Garrido *et al.*, 2012).

2.10.1.1 Fuzzy set theory

Fuzzy set can be defined mathematically by assigning to each possible individual in the universe address a value representing its grade of membership in the fuzzy set (Al-Abadi *et al.*, 2017). A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object grades of membership ranging between zero and one. The notions of inclusion, union, intersection, complement, relation, convexity, etc. are extended to such sets, and various properties of these notions in the context of fuzzy sets are established (Zadeh, 1965).

2.10.2 Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process is one of the most commonly MCDM techniques incorporated into GIS-based setting procedures (Mosadeghi *et al.,* 2015). The Analytic Hierarchy Process, introduced by Saaty (2008), is an effective tool for dealing with complex decision making, and may aid the decision maker to set priorities and make the best decision or else AHP helps decision makers arrive at the best decision in a case of multiple conflicting objectives (criteria). By reducing complex decisions to a series of pairwise comparisons and then synthesizing the results. The AHP helps to capture both subjective and objective aspects of a decision. In addition, AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision-making process.

Analytic hierarchy process is a flexible decision-making tool for multi-criteria problems and has been used in this study to determine the relative importance of RWH site selection criteria. This model helps decision makers to organize and evaluate the relative importance of selected objectives and the relative importance of alternative solutions. In general, the AHP method is a common decision-making technique, which can be used to analyze and support decisions with multiple objectives (Saadat *et al.,* 2017). This paper deliberates the use of Fuzzy logic and Analytic Hierarchy Process methods in combination with advanced geospatial techniques for selection of RWH site in modjo watershed. The Analytical hierarchy process can be implemented in three simple consecutive steps such as computing the vector of criteria weights, computing the matrix of option scores and ranking the options.

The AHP procedure involves six essential steps (1) define the unstructured problem, (2) develop the AHP hierarchy, (3) operate pairwise comparison, (4) estimate the relative weights, (5) check the consistency, and (6) obtain the overall rating (Cheng, 1999; Chi and Kuo, 2001; Murtaza, 2003; and Lee *et al*., 2008).

2.11 Factors used to identify potential sites for rainwater harvesting structure

The selection of potential areas depends on a multitude of factors including Hydrological, Environmental and socio-economic conditions. Different studies used different parameters. For instance, Kahinda *et al*. (2008), the six key factors to be considered when identifying RWH sites: climate (rainfall), hydrology (rainfall-runoff relationship and intermittent watercourses), topography (slope), agronomy (crop characteristics), soils (texture, structure and depth) and socioeconomic criteria (population density, workforce, people's priority, experience with RWH, land tenure, water laws, accessibility and related costs).

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Location of the study area

The study area is found in the main Ethiopian Rift valley extending up to the eastern escarpment. it is part of the upper Awash River Basin of Ethiopia and covers most part of Lome, Ada'a, Liben and Gimbichu districts in eastern Showa Zone of Oromia Regional state. However, most of the study area is found in Lomé and Ada'a districts. Geographically the study area is bounded by the latitude of 8˚24'33"−9˚ 05' 50"N and longitude of 38˚49'42"−39˚17'25" E covering a total area of 2187.43 km^2 (Fig 3.1). The area is characterized by undulating topography with hills, mountains, plateaus, plains and river valleys (Berhan Gessese *et al.*, 2014).

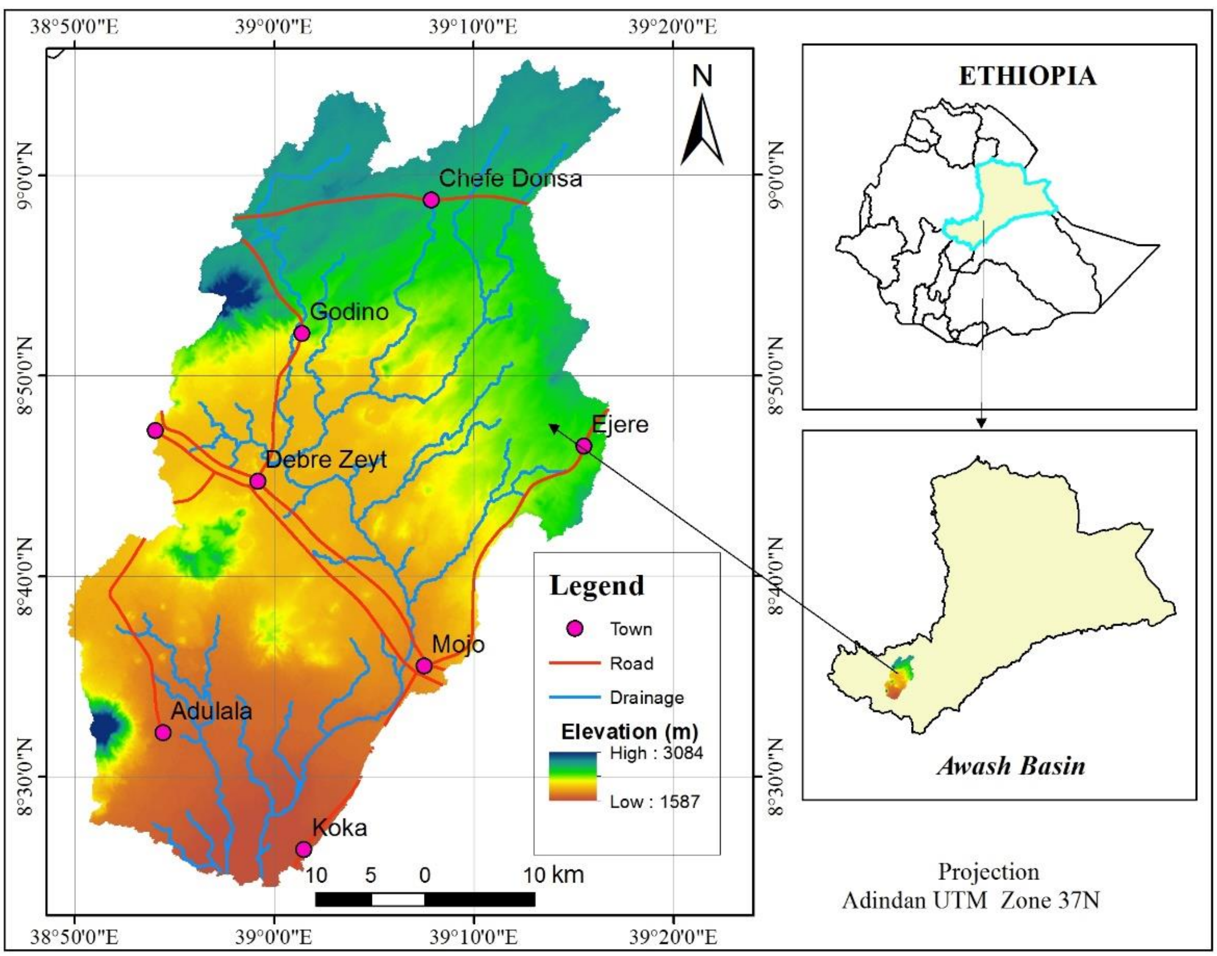

Figure 3.1: Location map of the study area.

The physiographic of the watershed discloses a distinct variation with altitude that ranges from 1587−3084 m asl. Modjo river is one of the tributaries of Awash river basin and the highest elevation in this watershed is mount Erer; while other notable mountains in the watershed include mount zukala and mount Beda gebaba are found in the watershed. Although, there are different towns in the watershed such as Debre zeit, Modjo, Ejere, Ejersa, Cheffe, Dukem, Adulala and Koka towns.

3.1.2 Population and economic activities

According to the 2014, Population and Housing Census, the population of three districts namely Gimbichu, Adaa and Lome, covering most of the study area was 547,277. Most of the population (66.6%) centers are in the rural areas and the remaining (33.4%) centers are in the urban areas. The rapidly expanding population in the area is placing increasing pressure on agricultural land and forests resulting in overgrazing, deforestation and land degradation (Kiflu Gudeta, 2010). The area is traversed by the main high way from Addis Ababa to Djibouti. Most parts of the areas are accessible from all direction by several all weathered and gravel roads.

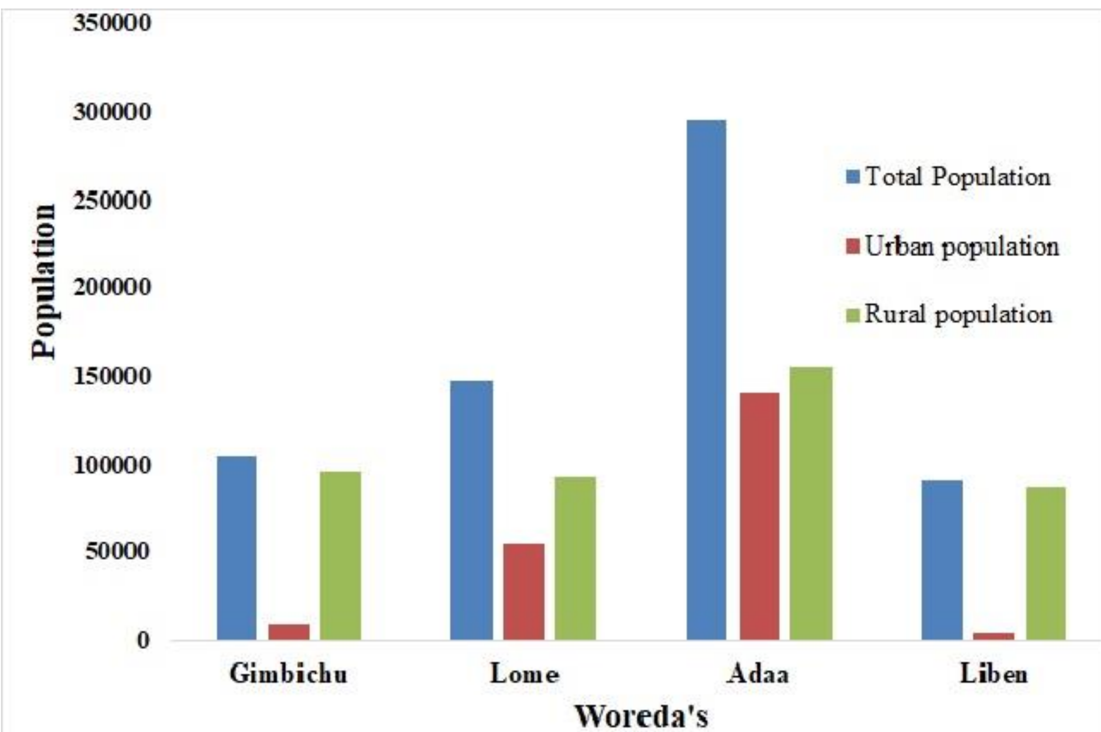

Figure 3.2: Population distribution in the watershed

3.1.3 Climate

According to Ethiopian Metrological Agency recorded data; On the basis of the 31 years' climate data (1987−2017) from six weather stations, Chefe-Donsa (upstream part), Debrezeit (relatively midstream part) and Modjo (down-stream part), and other adjacent to the river weather station such as ejere, koka, zukala and sendafa the average mean annual long-term maximum temperature varies between 23·2˚C upstream part and 27·9˚C downstream part, whereas the minimum temperature varies from 10·6°C upstream part to 11·6°C downstream part (Berhan Gessesse *et al.*, 2014). However, the mean annual temperature ranges from 16·5°C (upstream part), 19·2°C (relatively midstream part) and 22.2°C downstream part (Fig 3.3B). The climate of the study area thirty-one years' rainfall records for stations within and adjacent to the study area shows an average annual rainfall between 908 mm and 1051 mm with a mean annual value of 979.5 mm. Most rainfall occurs between June and September. Although the rainfall is bimodal, the short rains (Belg) are erratic and not sufficient for rainfed crops (Eyasu Elias, 2003). The annual temperature of the study area is 19.35ºC with average winter high of 23.9ºC in May at Koka dam and an average low of 13.9ºC in December at Chefedonsa (Kiflu Gudeta, 2010). As a conclusion, the climate of the study area is indicated in detail in (Fig 3.3).

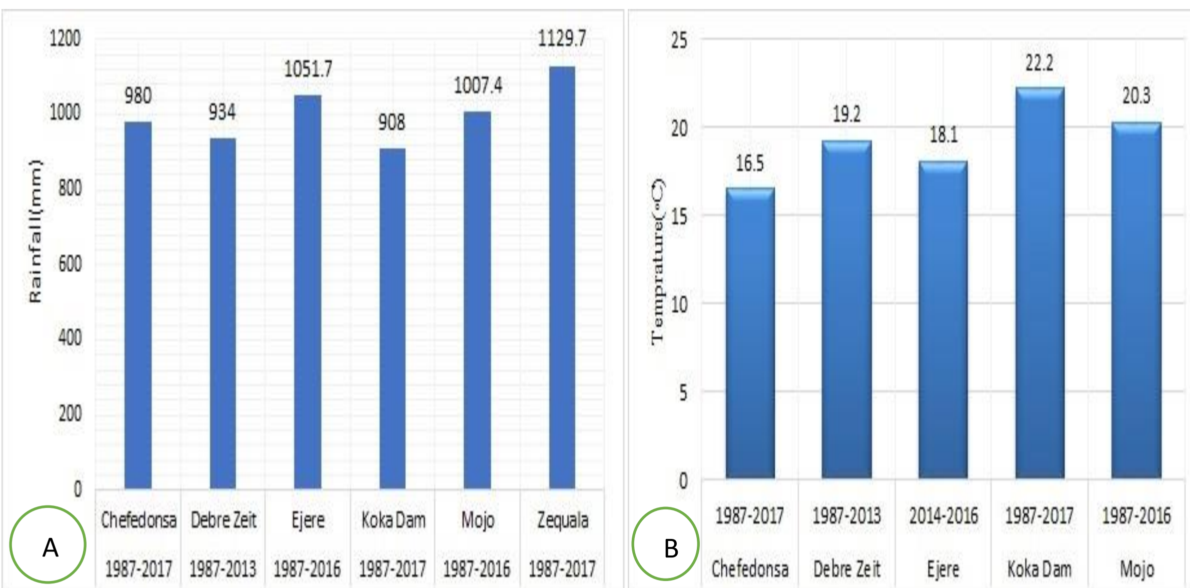

Figure 3.3: Average Rainfall (A) and Temperature (B) 1987−2017 of the study area.

3.1.4 Land-use/land-cover

The land-cover map was prepared from sentinel 2A imagery and classified into eight major classes (Fig 3.4). These are wetland, waterbody, shrubland, settlement, grassland, forest, bareland and agriculture. Agricultural, bareland and shrubland types have the higher coverage in the study area as shown in (Table 3.1).

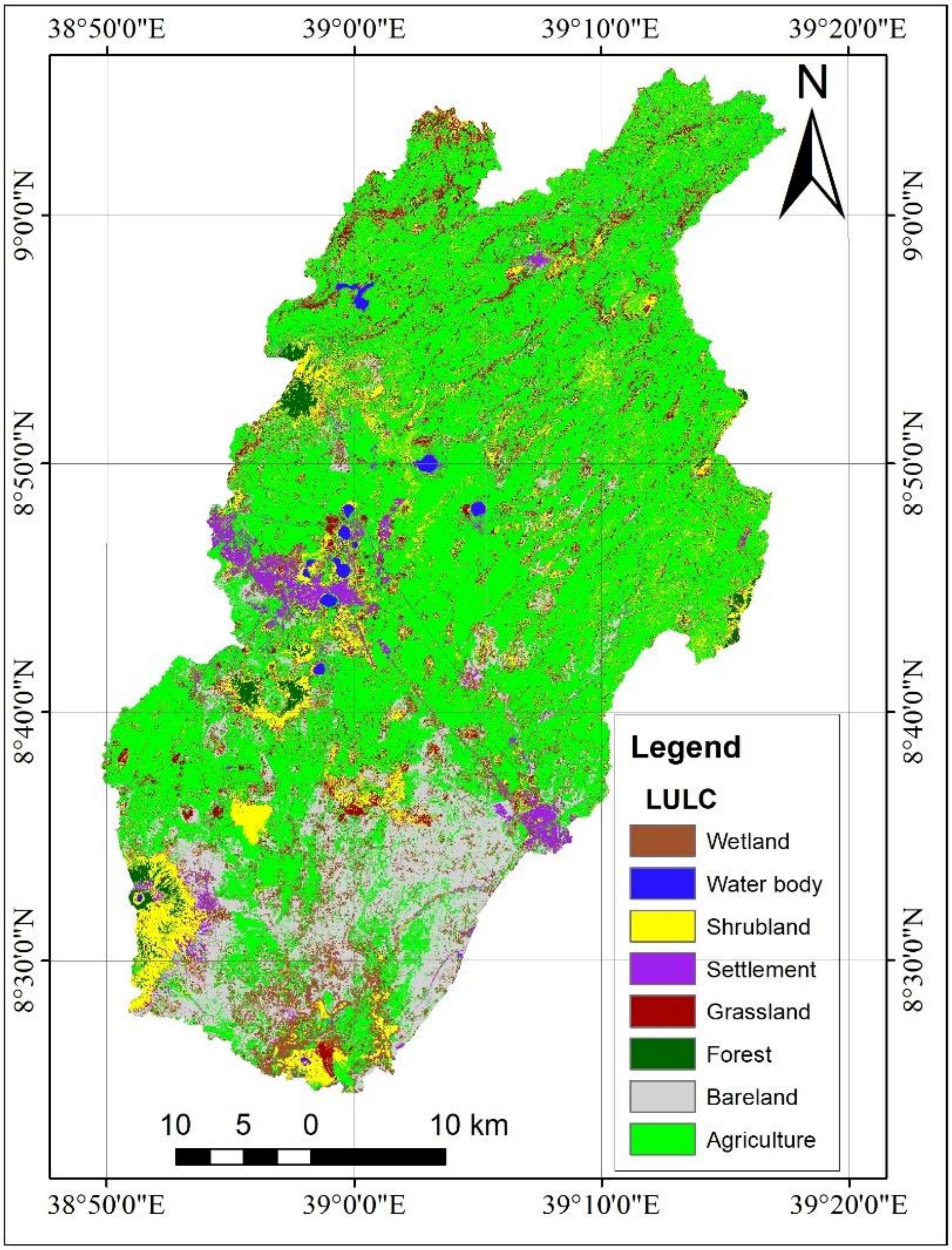

Figure 3.4: Land-use/land-cover map of the study area.

Table 3.1: Land-use/land-cover types and coverages of the study area.

Land-use/land-cover classes	Area (km^2)	Area (%)
Agriculture	1290	58.96
Bareland	272	12.43
Forest	29	1.33
Grassland	150	6.86
Settlement	72	3.29
Shrubland	226	10.33
Water	9	0.41
Wetland	140	6.30

3.1.5 Soil

Clay or Vertisols are the major soil types accounting for about 80.67% of the total land mass of the area. The two dominant vertisols in the watershed are pellic vertisols and vertic cambisols. Other soil types of minor importance are Clay loam, Silt loam and Loam which cover about 7.64% of the land mass. According to (FAO, 1998) vertic cambisols, lithic leptosols, eutric vertisols, chromic luvisols and haplic luvisols are the major soil groups in the study area given in (Table 3.2).

Table 3.2: Major Soil texture of the study area.

HSG	Soil Texture	Major soil type	Area (km^2)	Area (%)
B	Silt loam, loam	Luvisols, Leptosols	167.37	7.65
C	Clay loam	Luvisols	167.18	7.64
D	Clay	Vertisols	1765.12	80.67
		Rock and water	47.04	2.15

3.1.6 Geology

Modjo watershed area represents a transition zone between the Ethiopian Plateau and the Main Ethiopian Rift (MER). In this area, the rift escarpment is not well defined, and the MER intersects the important E-W structure (the Yerer-Tullu Wellel Volcano Tectonic Lineament; Due to its accessibility, this area was studied by several researchers (Mohr, 1961; Justin-Visentin et al., 1974; Kazmin and Berhe, 1978; Morton et al., 1979; Gasparon et al., 1993; Abebe, 1995; Wolde, 1996; Chernet *et al.,* 1998; as cited in Innocentil *et al.,* 1999). Despite these efforts, only the stratigraphical and compositional features of the volcanic products, forming most of the outcropping rocks, were essentially described. However, the emerging stratigraphic framework has still several discordant reconstructions by different authors, especially owing to the relationships between this area and the evolution of the rift.

This region is mainly covered by volcanic rocks (about the 70% of the studied area) and the sedimentary rocks consist of alluvial cover and lacustrine sequences. Volcanic activity in the area has given rise to central composite volcanoes as well as to monogenic apparata as domes, spatter cones and maars. Maars concentrate in the central trough, along with a NE-SW belt and are generally occupied by lakes. Ignimbrites, consisting of several units, form wide sub-horizontal covers that occupy the 27% of the studied area. Basaltic lavas, generally tabular, form about 28% of the outcropping rocks. Emission centers of lavas and ignimbrites are observed only for the youngest volcanic products. (Innocentil *et al.*,1999). Figure 3.5 shows the lithology of modjo watershed composes of Rhyolite Domes and flows (Qr), Bofa Basalt (NQtb), Debre Brehan and Goro Ignibrite (Ntb), Wechecha Trachytes (Nc), Pyroclastic and pumic fall deposits (Qb) and Lacustrine Sediments (Q).

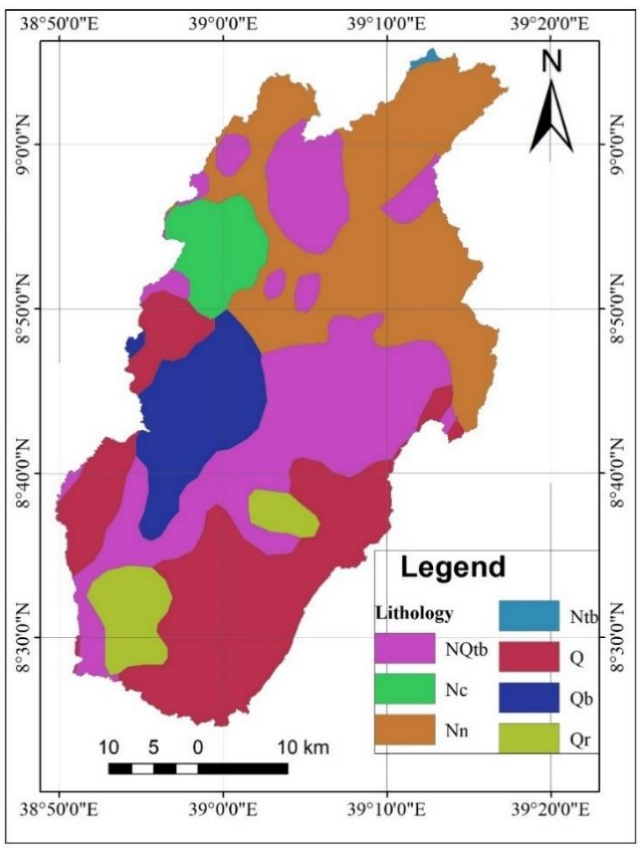

Figure 3.5: Geological map of the study area.

3.1.7 Physiographic classes

The Relief of the study area is relatively low, and the mean elevation decreases southward from about 3084 m close to Addis Ababa and northern part to about 1587 m close to the south-eastern limit of the study area, Southeast of Modjo. According to Innocentil *et al.* (1999), the general smooth morphology of the central area is interrupted by the two central volcanoes Yerer and Zikwala, that rise more than 1000 m above the plain. The overall altitude variation of the study area is 1587 to 3084 m a.s.l. The landform types in the study area were classified into five major physiographic classes such as smooth plains, irregular plains, hills, law mountains and high mountains (Fig 3.6).

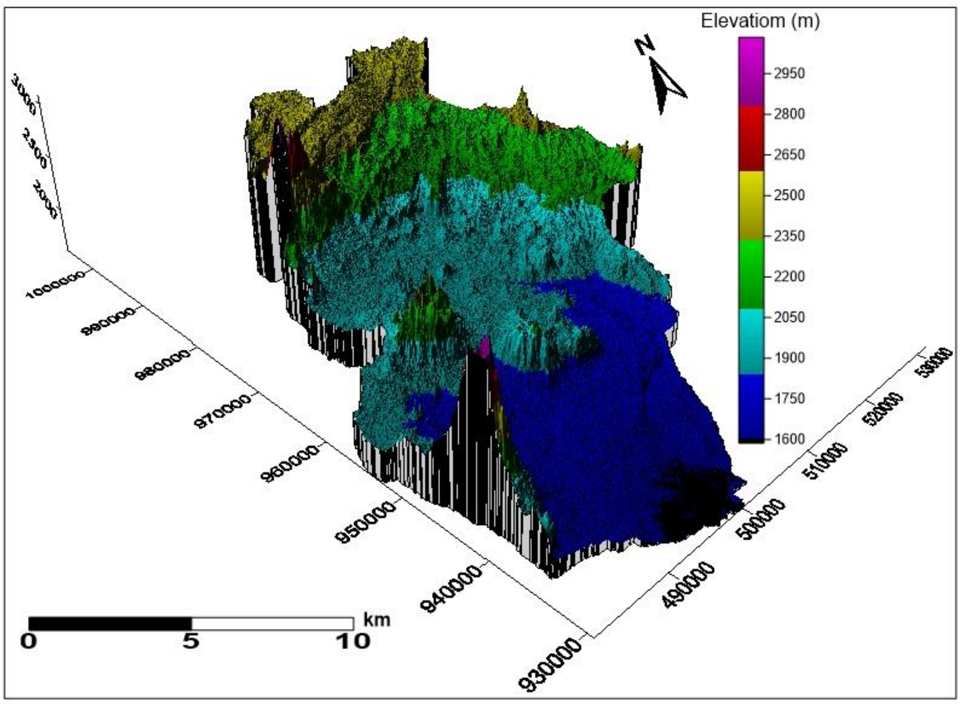

Figure 3.6: Physiography map of the study area.

3.2 Description of data and software

3.2.1 Data description

To realize the above-specified objectives, data was collected and organized from both primary and secondary data sources, the primary data includes GPS data for verification of land-use/land-cover maps of the study area that was produced from sentinel 2A images, the sentinel was without the presence of cloud (cloud-free image). In addition to this satellite, Shuttle Radar Topography

Mission (SRTM), DEM data with a spatial resolution of 30×30 m was used for extraction of Lineament, elevation, watershed delineation, drainage and slope analysis.

The secondary data used for this study were those published and unpublished documents from various Organization and institution. National meteorological agency of Ethiopia was the main sources for climate data. Geological data from a Geological Survey of Ethiopia, Topographic map from Ethiopian mapping authority (EMA) and different data related to water from the ministry of water was gathered.

3.2.2 Softwares used

To achieve the overall goal of the study the following software was used. ArcGIS 10.3 was used for storing, analyzing, Fuzzifying and managing spatial data of the study area (used as a Geodata Base) in the vector as well as raster format. IDRISI Selva 17.02 was used for calculation of criteria weight and used as a combination of criteria weight with fuzzified layers based on weighted linear combination techniques. ERDAS Imagine 2015 and Impact tool were used for Georeferencing, Image analysis like layer stacking, mosaicking, pre-processing and coordinate transformation of a given area. Geomatica 2015: was used for geological lineament extraction for the study area from DEM images and Microsoft office packages: office such as MS-excel, MS word and MS power point were used as their needs.

3.3 Research methodology

The overall methodology used to select the best site for RWH zones in modjo watershed is shown in (Fig 3.7). There are many studies concerned with the water harvesting site selection criteria using fuzzy and AHP approach. Most of these methods were used in this research to define water harvesting site selection criteria, together with the opinion of local experts and researcher. The methodology followed in the research broadly comprises three basic phases such as i) Data collection phase, ii) Data analysis or synthesis phase and iii) Interpretation and result phase.

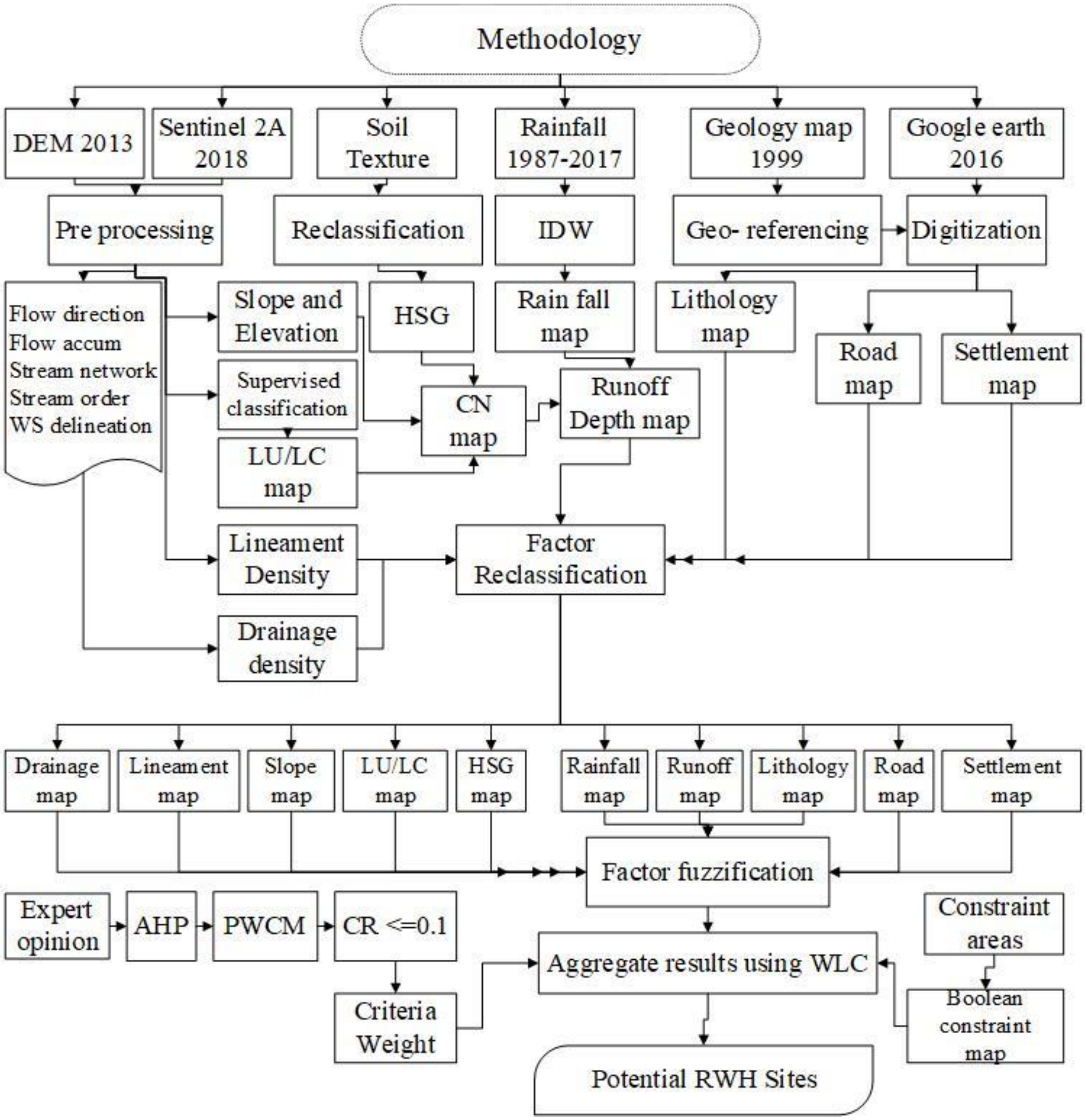

Figure 3.7: Flowchart of the methodology used in the research.

3.3.1 Data collection phase

3.3.1.1 Primary and secondary data sets.

To accomplish the above-specified objectives, different data were collected and organized from both primary and secondary sources, the primary data sets and secondary data sets used in the study were presented in (Table 3.3). These data type and source of data was collected from different sources during fieldwork. The fieldwork was conducted during the months of February to March 2018. Satellite images and maps such as GPS reference and topographic maps, google earth and world land cover images were used to identify detail of training sites for LU/LC class as well as for identification of perennial and intermittent rivers in the study area. Socio-economic information was also gathered to establish the community perception on rainwater harvesting.

Table 3.3: Primary and secondary data sets.

Datasets	Year	Scale	Type	Spatial Extent	Source
Metrological data	1987-2017	Point measurements	10 Weather stations in & adjacent the watershed	Modjo watershed	NMA
Soil map	1990	Polygon	Shapefile	Modjo watershed	Ministry of Agriculture
Satellite image	2018	10×10m	Raster format	Modjo watershed	USGS
DEM	2013	30×30m	Raster format	Modjo watershed	USGS
GPS data	2018	Point measurements	For different LULC class verification	The watershed	Field (personal)
Google Earth	2017	Point (verification)	Kmz type	Modjo watershed	Google Earth
Geology map	1999	1:250,000	Geological map	Watershed and adjacent	Geological survey

3.3.2 Data analysis phases and standardization of analyzed datasets

In data analysis phases, the techniques for identification of appropriate input criteria, data organization, data checking, data processing and editing, Exploratory (experimental) data analysis attribute table design and editing, data cleaning, field verification, digitization, data integration, data validation, data transforming, modeling and algorithms with the goal of discovering useful information, suggesting conclusions, and supporting decision-making was carried out. While in data standardization criteria such as constraints dataset and thematic layers were converted into raster data format and the converted layers were reclassified based on an elaborate literature search, endogenous and expert knowledge have been conducted. However, before analysis and standardization of the raw data, the following main activities have been carried out.

a) Criteria of thematic layer preparation

Criteria selection for RWH site search analysis is based on an elaborate literature search, indigenous and expert knowledge. The appropriate criteria used for this research were LU/LC, slope, soil texture (HSG), rainfall, runoff depth, drainage density, lithology and lineament density. In addition to these eight physical criteria; tow socio-economic factor layers were used in the research to select the optimum sites for RWH in the study area. These socio-economic factors were; urban area and major roads. The site selection process also takes consideration specific guidelines from food and agricultural organization (FAO, 1998).

b) Image preprocessing

Image pre-processing was done in the initial processing of raw data, the main aim of pre-processing of an image is to improve image data that captured by the sensor. consequently, preprocessing improves undesired distortions or enhances some image features; initial processing which was applied in this data were radiometric (Top of Atmospheric correction) and geometric correction. image pre-processing was conducted using impact tool software. As a general, since pre-processing is important for generating accurate information from an image, it has been given high consideration in this study. however, pre-processing does not increase image information content.

3.3.2.1 Digital elevation model (DEM) hydro-processing

SRTM DEM with 30 m spatial resolution were acquired from (http://www.gdem.aster. ersdac.or.jp/.) and was used for this study to drive the key Hydrological parameters. The data was used to drive the thematic map of the slope (%), drainage density km/km^2 and the watershed boundary of the study area. Before using the DEM, it was recommended that the data must be processed through three phases. According to Jenson (1991), stated that depressions in the DEM were first filled by raising the values of cells in depressions to the value of the depression's spill point. Next, the computation of the flow direction for each cell in the depressionless DEM was performed. The direction water will flow out of each cell is encoded to correspond to the orientation of one of the eight cells that surround the cell. The third conditioning step is that computation of the flow accumulation value for each cell. This is the count for each cell of how many upstream cells would contribute drainage to it based on their flow directions (Mason and

Maidment, 2000). Therefore, in DEM processing the above listed three phases were applied and slope, drainage and the watershed boundary were directly derived from filled DEM.

The purpose of filling raw DEM data is, to improve the accuracy of the data by removing peak, pits (sinks) and flat areas to maintain continuity of flow to the catchment outlet. Sinks and peaks in a DEM are often errors due to the resolution of the data or rounding of elevations to the nearest integer value. In ArcGIS, the fill tool uses to locate and fill sinks as well as remove peaks. The tool iterates until all sinks within a specified Z limit are filled and again iterates until all peaks within a specified z limit are removed. The overall hydrological modeling process is shown in (Fig 3.8)

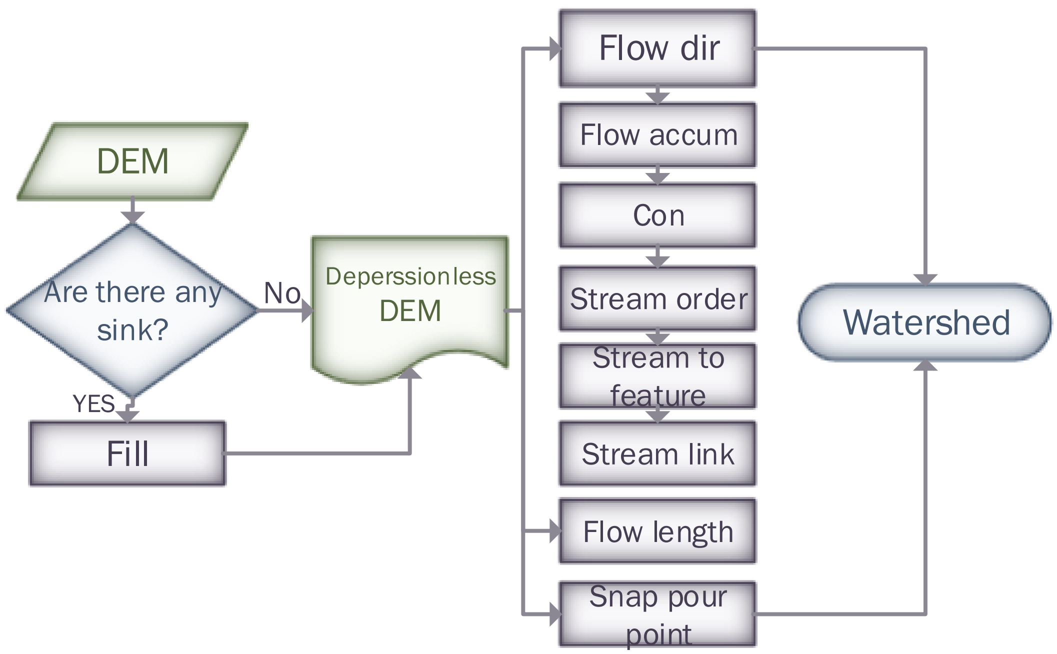

Figure 3.8: Hydrological modeling flow chart.

3.3.2.1.1 Flow direction

The flow direction is one of the key components to derive Hydrological characteristics of a surface, the flow direction request calculates the direction of flow out of each cell into one of its eight neighbors. The direction of flow is determined by finding the direction of steepest descent from each cell (ESRI, 1999). Though the flow direction of the study area was calculated using flow direction tool, this tool can determine the direction of flow from every cell in the raster. The tool creates a raster of flow direction from each cell to its steepest down slop neighbor. This operation was used for required input to create stream order raster for the next steps of drainage creation and as input for flow accumulation calculation.

3.3.2.1.2 Flow accumulation

Flow accumulation was derived for obtaining the drainage pattern of the terrain of the study area, which represents the number of pixels contributing water to any outlet within the watershed. The operation calculates accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output raster. The accumulated raster layer was derived from flow direction raster grid as an input to determine the accumulated number of raster grids.

3.3.2.1.3 Drainage density extraction

Since the drainage is an area, network or a path upon which waterfalls on a surface travels to an outlet, it is one of an important factor for rainwater harvesting site selection. By means of applying a threshold value to the results of the flow accumulation using conditional tool, a drainage of the study area was defined. Once defined the drainage network was further analyzed using the stream order (Strahler), stream link, stream to feature conversion was applied. Later, drainage density was calculated from extracted streams.

$$Dd = \frac{\sum LK}{AK} \tag{1}$$

Where, Dd = Drainage density, ΣLk = Total length of all stream segments in a given basin and Ak = Total area of the basin.

3.3.2.1.4 Watershed delineation and stream extraction

A watershed is an upslope area that contributes flow or water to a common outlet as concentrated drainage. For delineation, pour point was taken as stream gauge, and the watershed was delineated upstream of the stream gauge. After placing all pour points on the proper flow accumulation cell, the values of flow accumulation and flow length were reported and the watersheds were delineated. The delineated catchment was determining the scope of the study area. Final watershed and drainage density map generated was presented in (Fig 3.9a) and reclassified based on the suitability for RWH and reviewed literature (Table 3.4).

Table 3.4: Drainage density suitability class (Abdel Rahman, 2016).

Factor	Drainage density km/km^2	Rate	Suitability class
Drainage density	<1	1	Very low
	1 – 2	2	Low
	2 - 2.5	3	Moderate
	2.5 – 3	4	High
	>3	5	Very high

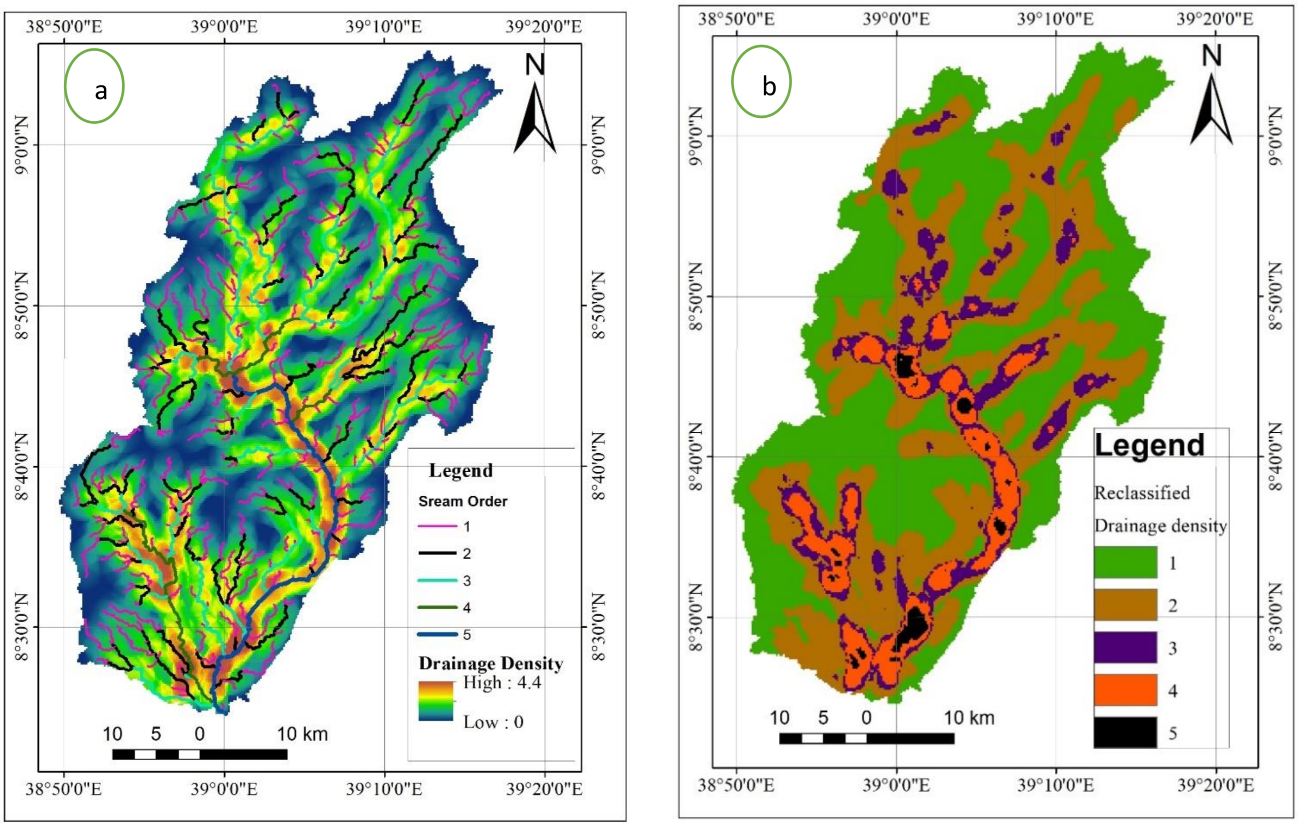

Figure 3.9: Drainage density km/km^2 map (a) and Reclassified drainage density map (b).

3.3.2.2 Slope

The slope is an important parameter for rainwater harvesting site selection since the recharge, runoff and the movement of surface water depends on the slope (Naseef and Thomas, 2015). The slope of the study area was generated from Filled DEM and represents the rate of change of elevation for each digital elevation model cell. It is done by surface option from spatial analysis tool. Slope tool calculates the maximum rate of change in value from that cell to its neighbors. Basically, the maximum change in elevation over the distance between the cell and its eight neighbors identifies the steepest downhill descent from the cell (Fig 3.10), as well as the output slope raster can be calculated in two types of unit, degree or percent.

The highest area of the slope in the catchment as presented in (Table 3. 5) was fall under flat and gently flat were 51.08% and 30.13%, respectively, gently undulating category covering 13.22%, and rolling to hilly covering an area of 4.71% followed by steeply dissected to mountainous occupying an area of 0.87%, respectively.

Table 3.5: Area coverage and suitability rank for the slope of the study area.

Factor	Slope (Degree)	Area	Area (%)	Description	Rate	Slope suitability class
Slope (SL)	>30	19	0.87	Steeply dissected to mountainous	1	Very low
	15-30	103	4.71	Rolling to hilly	2	Low
	8-15	289	13.22	Flat to gently undulating	3	Moderate
	2-8	659	30.13	Generally flat	4	High
	<2	1117	51.08	Flat	5	Very high
	Total	2187	100			

Source: (Girma Mogos, 2009; Maina and Raude, 2016; Al-shabeeb, 2016).

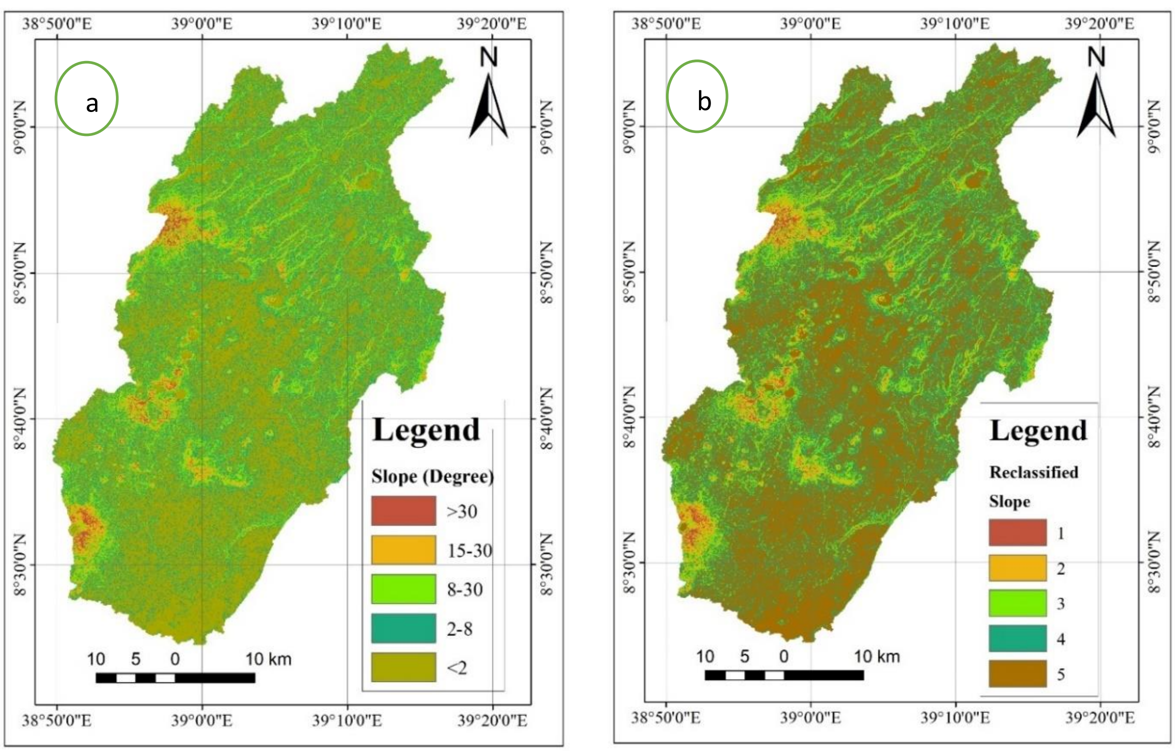

Figure 3.10: a) Slope map b) Reclassified slope map.

The slope classification categories offer favorable rain/runoff potential collection sites. Such flat areas allow water to collect and not to flow away and therefore, naturally help in concentrating the rainfall runoff from a given storm. On the other hand, steep slopes favor runoff generation and were ranked high for runoff generation sites while for rainwater harvesting flat slope was ranked higher.

3.3.2.3 Land-use/land-cover map

The raw satellite image of the study area was acquired on January 24, 2018 using the platform Earth Explorer (http://earthexplorer.usgs.gov/). Six bands of the image were combined to create a mosaic raster of the study area and enhanced using the radiometric algorithm. Supervised maximum likelihood classification was used to produce the land cover map of the study area, for which training samples were collected using google earth and field surveys to create a spectral signature file, supervised classification was performed to the image using spectral signatures collected from training samples (polygons that represent distinct sample areas of the different land cover types to be classified). After preparing the signature file, Maximum likelihood classifier then attached labels to all the image pixels according to the trained parameters to generate a land cover map of the study area. Land-use/land-cover layer map of the study area was analyzed, classified and standardized based on their suitability rank for RWH structure (Table 3.6) and (Fig 3.11).

Table 3.6: Suitability rank for land cover (Girma Moges, 2009; Maina and Raude, 2016).

Factor	Land-cover type	Rate	Suitability class	Area (%)
LU/LC	Waterbody, wetland and settlement	1	Very low	10
	Grass and Forest	2	Low	8.19
	Shrubland	3	Moderate	10.33
	Agriculture	4	High	58.96
	Bareland	5	Very high	12.43

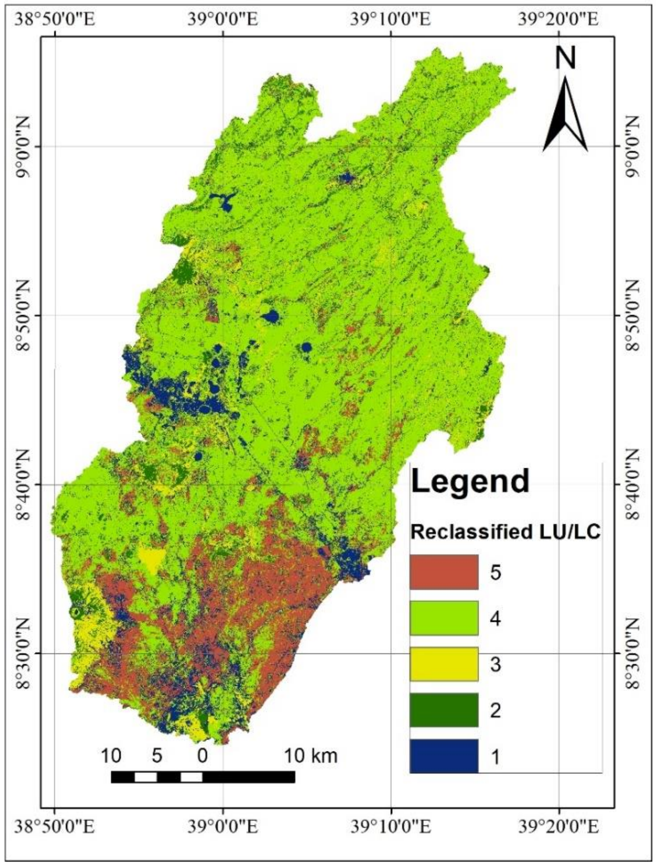

Figure 3.11: Reclassified land-use/land-cover map.

3.3.2.4 Soil texture

The soil map of study area was obtained from Ministry of Agriculture, Ethiopia and used as an input for soil mapping analysis. Each type of soil was assigned to the proper hydrological soil group that developed by US Soil Conservation Service (NRCS, 1986). According to SCS, all the soil, based on their permeability and infiltration are divided into 4 groups A, B, C and D. Hydrological Soil Group of A has the lowest runoff potential while group D has the highest. A study conducted by Khalil (2017) the soil map was classified into Hydrological Soil Groups (HSGs) based on the characteristics of soil infiltration and runoff as shown in (Table 3.7).

According to Soil Conservation Service (SCS) 3000 soil types were classified into four Hydrological Soil Groups (HSG) depending on the infiltration, soil composition and other criteria, these classified soil groups are. A, B, C and D known as Hydrologic Soil groups(HSG), HSG is highly useful in estimating the runoff in a watershed since soil heavily influences runoff generation (Al-Abadi *et al.,* 2017). The soils of group A indicate that low runoff potential, high infiltration rate, deep sand and deep loess aggregate silts. The soils of group B indicates that moderate infiltration rate, moderately deep sand; shallow loess and sandy loams. The soils classified under group C pointed to moderately fine to moderately rough textures, clay loams; shallow sandy loams; low organic content; soil with high clay content and moderate rate of water transmission. Finally, the soils classified under group D pointed to slow infiltration and high runoff potential; swells when wet clay pan/clay layer (Maina and Raude, 2016).

In the other way Soils can be classified as one of four major textural classes: (1) sands, (2) silts, (3) loams, and (4) clays (Fig 3.12A). Soil texture (which affects permeability) and soil profile influence water movement. Soil's textural class is determined by the sizes of the inorganic particles (sand, silt and clay) it contains and the percentage of each size particle (Table 3.8). Sands have very coarse particles, while silty or clay soils have very fine particles. Sandy soils are permeable, which means that water moves through them rapidly. Soils with lots of clay or silt restrict the movement of water. Acceptable soils for a soil storage and infiltration system include sand, loamy sand, sandy loam and loam; all others are considered impermeable (Elhakim, 2016).

When choosing a location for a soil infiltration system, considering geography (since geography determines the climate and rainfall patterns), topography, vegetative cover, separation distances, water movement and soil characteristics is more important, as well as the rate of infiltration is determined by soil characteristics including ease of entry, storage capacity and transmission rate through the soil, therefore identifying soil textural class that covers the study area and soil type that is suitable for RWH structure in the study area is significant tasks; (https://en.wikipedia.org/wiki/Infiltration hydrology). The study area has HSG of B, C and D types and reclassed based on the clay contents contain (Fig 3.12B).

Table 3.7: Hydrologic Soil Groups and soil texture.

Group	Soil type	Characteristics
A	Sand, Loamy Sandy, Sandy Loam	Low Runoff, High Infiltration
B	Silt loam, loam	Moderate infiltration rates
C	Sandy clay loam	Low infiltration rate
D	Clay, silty clay loam, sandy clay, silty clay.	High runoff potential, very low infiltration

Source: Maina and Raude (2016).

Table 3.8: Hydrologic Soil groups and Clay contents of the study area.

Group	Soil type	Clay content (%)	Rate	Soil clay content class	Area (km^2)	Area (%)
B	Loam, silt loam	10−20	2	Low	207.86	9.50
C	Sandy clay loam, clay loam	20−40	4	High	201.46	9.21
D	Clay	>40	5	Very high	1771.06	80.98
	Water	<10	1		6.64	0.30
Total					**2187**	**100**

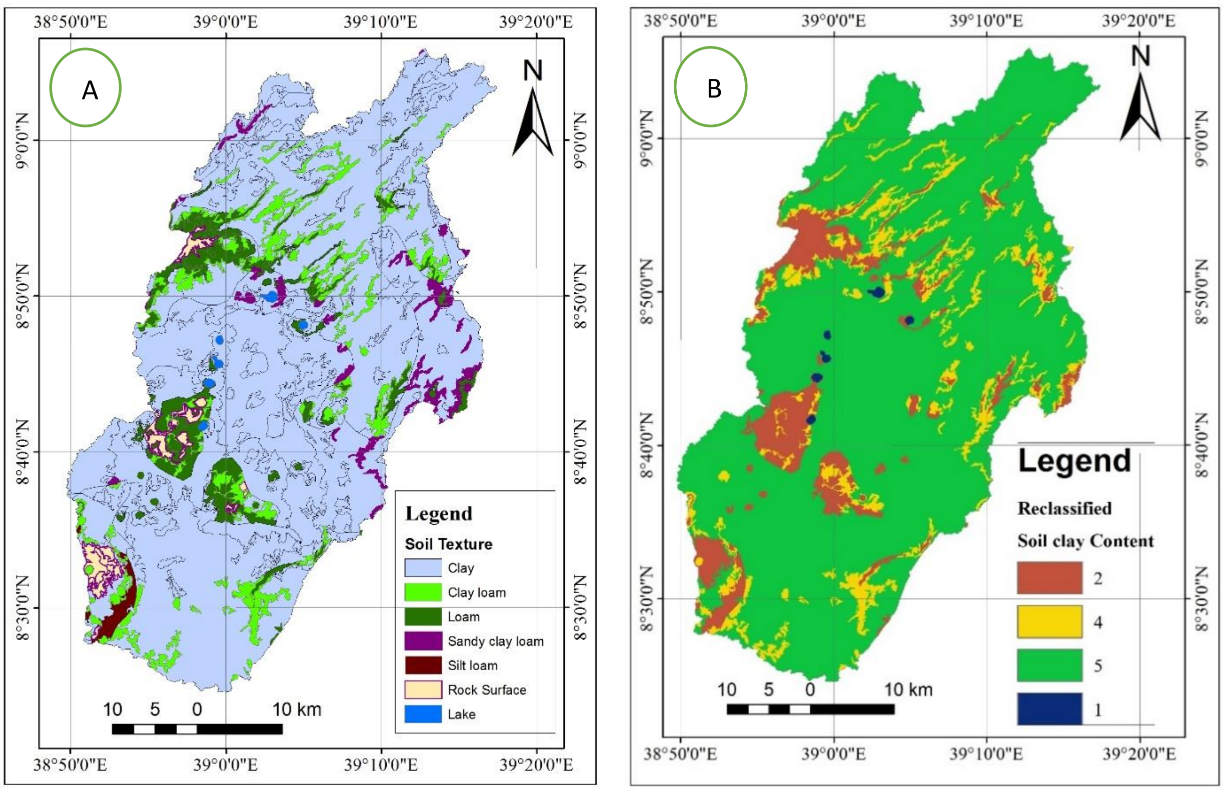

Figure 3.12: Soil Texture map A) and Reclassified soil map (B).

3.3.2.5 Rainfall

The rainfall is one of the most factors which play an important role in potential RWH suitability, therefore, evaluating rainfall distribution in the study area is critical because changing in rainfall pattern is serious factors in determining RWH site selection. Nevertheless, the rainfall gauges network in the watershed are sparse. However, A dense network and continuously recording rainfall is required to estimate accurately the spatial rainfall distribution for a given area. To predict the rainfall in overall the study IDW interpolation techniques was used.

Interpolation predicts values for cells in a raster from a limited number of sample data points. This analysis can be predicting unknown values for any Geographic point data. The assumption that makes interpolation feasible option is that spatially distributed objects are spatially correlated; in other word things that are close together tend to have similar characteristics. for example, if it is raining on one side of the street, it is possible to predict with a high level of confidence that it is raining on the other side of the street. As a conclusion values of points close to sampled points are more likely to be similar than those that are farther apart, this is the basis of interpolation. In the study estimating and evaluating a recognized value of Rainfall at unsampled points were generated based on the values of 7 rain gauge station records inside and adjacent to the watershed. According to Ly *et al.* (2012), for annual and monthly rainfall, geostatistical interpolation methods seem preferable to deterministic methods. The use of multivariate geostatistical methods in combination with elevation data has generally yielded more accurate interpolations; for daily rainfall, geostatistical methods and IDW have proved to be comparable approaches, for hydrological modeling. The unknown values are predicted with a mathematical formula that uses the value of nearby known points.

$$Zg = \sum_{i=1}^{ns} \lambda i Zsi \qquad (2)$$

Where Zg is the new estimated value at the required points, Zsi is the recorded known value at point i, ns is the total number of observed points and λ = (λi) is the weight contributing to the interpolation (Fig 3.13a and b) and the interpolated rainfall map was reclassified based on the suitability for RWH sites (Table 3.9). Finally, spatially explicit models require that the rainfall data must be resampled to a 30m spatial resolution than the source data to match the resolution of the other relevant datasets.

Table 3.9: Rainfall suitability class.

Factor	Values (mm)	Rate	Suitability class	Area %
Rainfall	926−960	1	Very low	22.54
	960−989	2	Low	30.95
	989−1022	3	Moderate	29.53
	1022−1064	4	High	13.17
	1064−1122.5	5	Very high	3.81

Source: (Al−shabeeb, 2016).

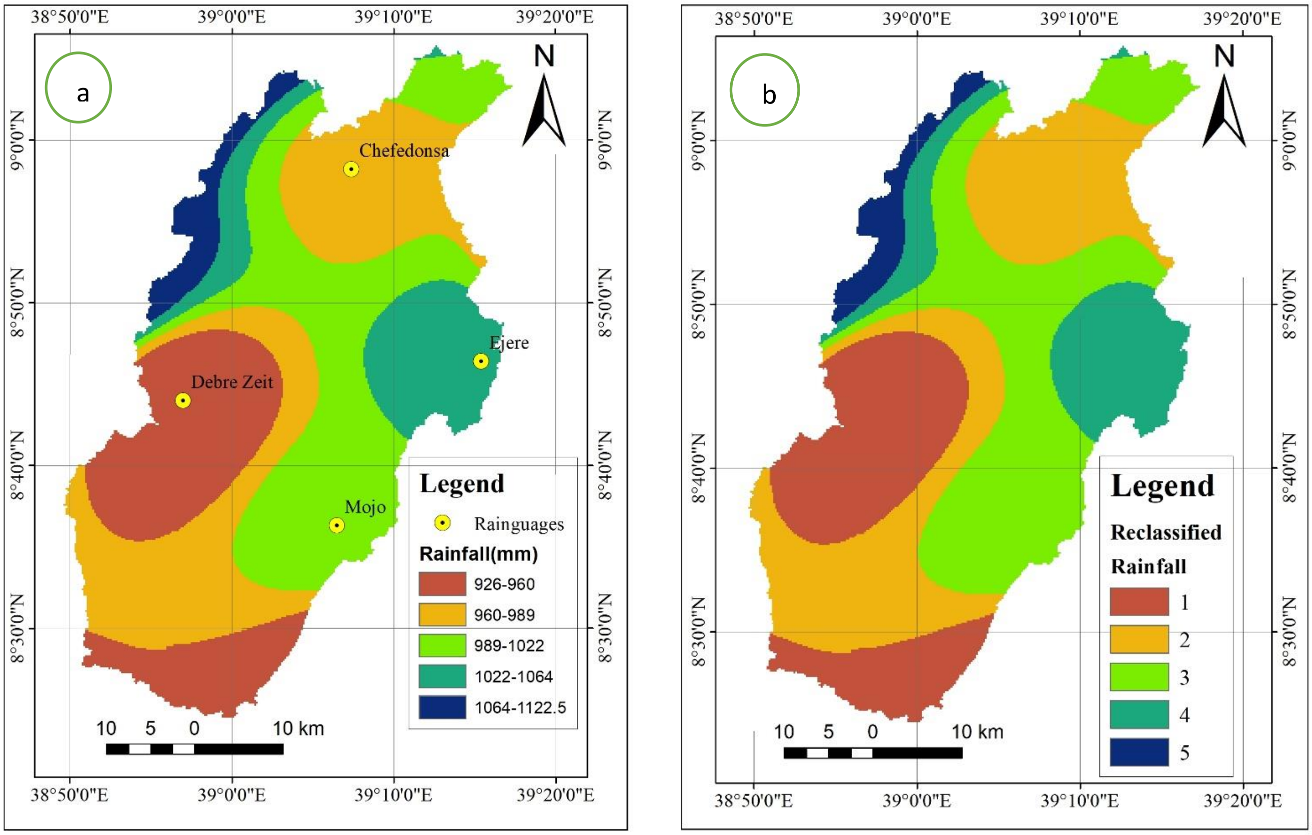

Figure 3.13: a) Rainfall map and b) Reclassified rainfall map.

3.3.2.6 Curve number

The curve number also called a runoff curve number is an empirical approach used in hydrology to estimate or predict the direct runoff or infiltration from the relationship between rainfall, land cover types, Hydrologic Soil Groups and antecedent moisture condition (USDA−NRSCS, 1986). The CN method was developed by the U.S. Department of Agriculture Soil Conservation Service (USDA−SCS), now Natural Resources Conservation Service (USDA−NRCS, 1986, and Jae *et al.*, 2006). Soil conservation service runoff curve number is a conceptual model; its main objective is to estimate runoff depth from a rainfall storm based on the curve number parameter (Munyao *et al.*, 2010). In this paper the key parameters or components that were used to drive CN are the reclassified soil group categories based on the soil texture units and land cover categories of the study area as well as since the study area has a slope >5% slope calculation was incorporated. According to Chaudhary *et al*. (2013) proposed the following equation for NRCS method to incorporate slope more than 5% in the calculation.

$$\mathrm{CN2a} = \mathrm{CN2}\frac{322.79+15.63(a)}{a+323.52} - 240 \tag{3}$$

The same equation has been used in raster calculator for slope correction using the following condition; "CN Map" *((322.79 + (15.63 * "Slope mpm")) / ("Slope mpm" + 323.52)).

$$Slope\ mpm = \frac{Slope\ map(\%)}{100} \tag{4}$$

Curve number is a dimensionless number ranging from 0 to 100 that represent the ability of the land surfaces to capture water (Mason and Maidment, 2000; Al−Abadi *et al.*, 2017). A low curve number means that water easily infiltrates into the soil, leaving less for a runoff. A high curve number means that water is not captured by the land surface, but instead turns into a run-off (Fig 3.14A and B). The derived curve number is then used to model rainfall-runoff relationship for a given catchment as well as the derived CN was used to drive the runoff depth expected from a given rainfall amount and hence the runoff map was developed (senay *et al.*, 20004 and Rajbanshi, 2016).

In the study to calculate CN corresponding to land-use/land-cover and Hydrologic soil groups by combining the attributes of each layers using spatial join or union tools and assigning a number based on their standard weight criteria was applied (Table 3.10).

Table 3.10: Weighted runoff curve numbers for LULC of the study area.

LULC	Hydrologic Soil Groups		
	B	C	D
Agriculture	78	85	89
Breland	79	86	89
Forest	63	75	82
Grassland	61	74	80
Settlement	85	90	92
Shrubland	65	75	80
Waterbody	100	100	100
Wetland	100	100	100

Source: (USDA NRCS,1986; Satheeshkumar *et al.*, 2017).

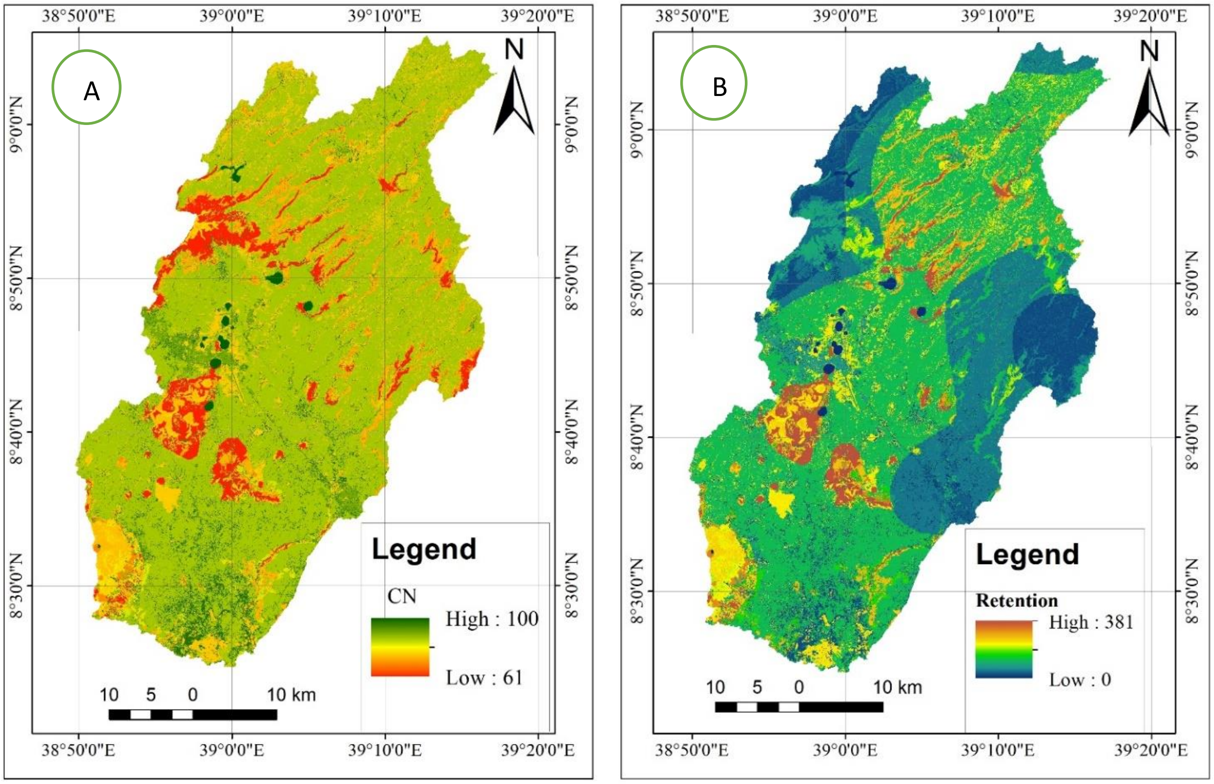

Figure 3.14: Curve Number (A) and Runoff Retention (B) map of the study area.

3.3.2.7 Runoff depth

In the study runoff depth was developed from a combination of Curve Number and rainfall, this method is usually acceptable where the rainfall amount from a given rainfall exceeds 40 mm (Maina and Raude, 2016). The method was developed by the USDA−Soil Conservation Service (Mishra and Singh, 2003) is widely used for the estimation of direct runoff for a given rainfall event from small agricultural watersheds (Al−Abadi *et al.*, 2017). Most of the watershed's runoff producing characteristics such as soil type, land-use, hydrologic condition and antecedent moisture condition. The thematic maps corresponding to each parameter were generated and stored in the common spatial geo-databases.

The major factors that determine CN are the hydrologic soil group (HSG), land cover type, treatment, hydrologic condition, and antecedent runoff condition (USDA, 1986). The hypothesis of the USDA−SCS CN method is that the ratio of actual retention in the watershed to the potential maximum retention is the same as the ratio of actual direct runoff to the potential maximum runoff (Boughton, 1989).

$$\frac{Fa}{S} = \frac{Pe}{P-Ia} \quad (5)$$

where Fa is the actual retention in the watershed, excluding Ia (mm); P is the precipitation (mm); Pe is the actual direct runoff (mm), S is the storage determined by Equation (1), and Ia is the initial abstraction before ponding. The total precipitation (P) equals the sum of the actual direct runoff (Pe), the initial abstraction before ponding (Ia), and the actual retention in the watershed (Fa). Thus, the runoff equation is:

$$Q = \frac{(P-Ia)^2}{(P-Ia)+S} \quad (6)$$

Where Q is a runoff (mm), P is Rainfall (mm), S is potential maximum retention after runoff begins (mm). Ia is an initial abstraction (mm); all losses of water before the beginning of runoff; It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Initial abstraction is highly variable but generally is correlated with soil and land cover parameters. Through varies studies of small agricultural watersheds, Ia was found to be approximated by the following empirical equation.

$$Ia = 0.2 * S \quad (7)$$

By removing Ia as an independent parameter, this approximation allows the use of a combination of S and P to produce a unique runoff amount. Substituting equation 7 into equation 6 gives;

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad p > 0.2S \quad (8)$$

Con ("rainfall map >= "I map", Power (("rainfall map" -"I map"),2) / ("rainfall map" + "S map" - where S map is related to the land cover type and soil conditions of the watershed through the curve number (CN). This number has a range of 0 to 100 and was derived using the following equation.

$$S = \frac{25400}{CN} - 254 \quad (9)$$

"I map"),0), condition was used to map the runoff depth for the study area (Fig 3.15A) and the generated runoff depth map was reclassified based on the suitability class for RWH site selection (Table 3.11, Fig 3.15B).

Table 3.11: Runoff depth classification of the study area.

Factor	Runoff depth (mm)	Rate	Suitability class
Runoff (R)	R<628	1	Very low
	628<R≤740	2	Low
	740<R≤818	3	Moderate
	818<R≤889	4	High
	R>889	5	Very high

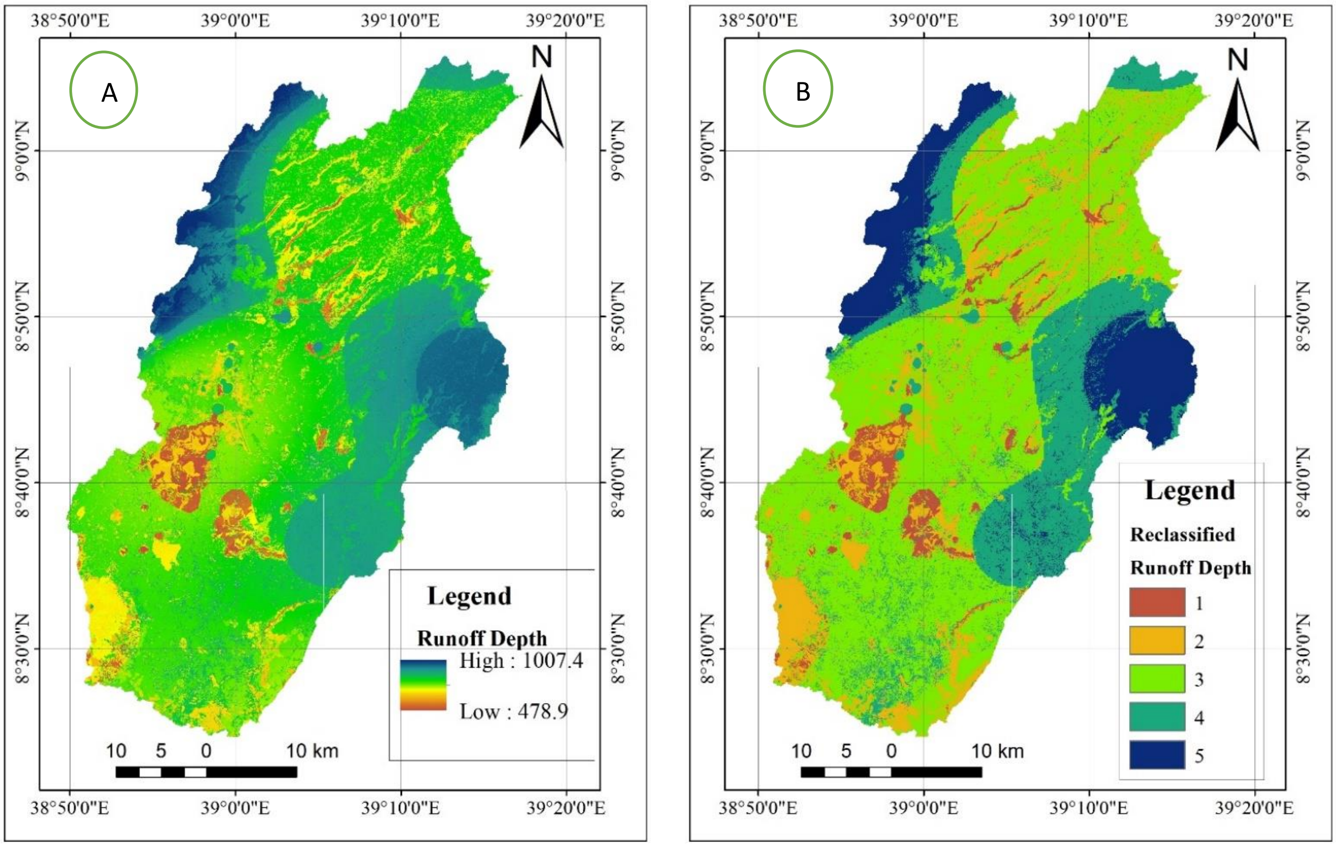

Figure 3.15: Annual Runoff depth map (A) and Reclassified runoff depth map (B).

3.3.2.8 Runoff coefficient (C)

The runoff coefficient is a dimensionless coefficient relating to the amount of runoff to the amount of precipitation received. It has a larger value for areas with low infiltration and high runoff (pavement, steep gradient), and lower for permeable, well‒vegetated areas (forest, flat land). A high runoff coefficient (C) value may indicate flash flooding areas during storms as water moves fast overland on its way to a river channel or a valley floor. The larger values correspond to higher runoff and lower infiltration. Larger areas with permeable soils, flat slopes and dense vegetation should have the lowest "C" values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation or bare-lands should assign the highest coefficient values (Fig 3.16). Runoff coefficient was derived based on the following equation.

$$C = \frac{Q}{P} \tag{10}$$

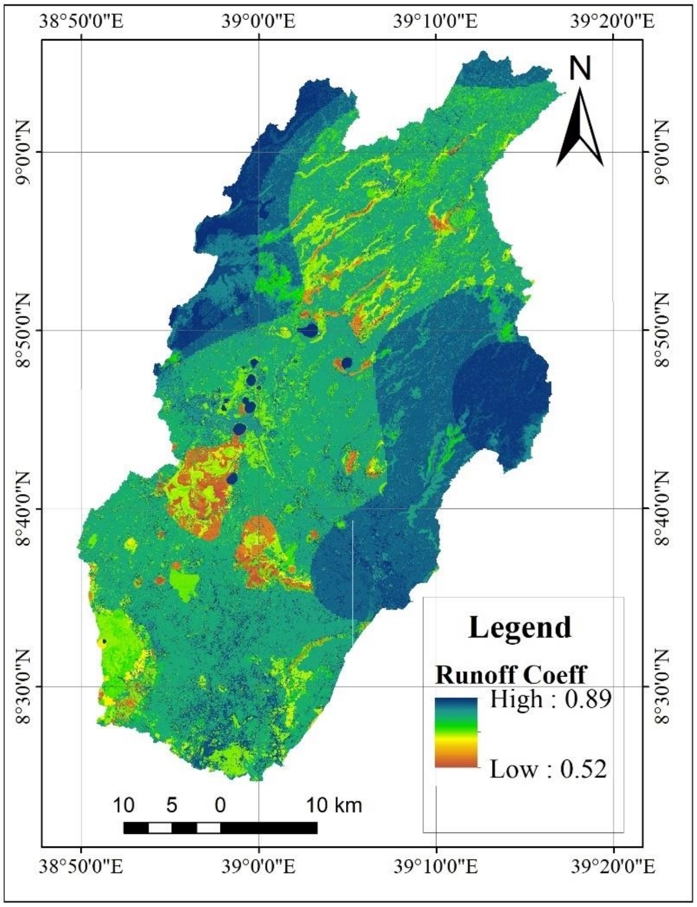

Figure 3.16: Runoff coefficient map.

3.3.2.9 Lithology

In order to understand the lithology of the study area a general lithological map has been digitized in ArcGIS, Rhyolite domes and flows, Basalt, Ignimbrite, Trachyte, pyroclastic and pumice fall deposits and Lacustrine sediments are some of the lithological units in the study area (Fig 3.17), therefore the above mentioned lithological units in the study area was reclassified based on their permeability, fracture and nature of lithological structure (Table 3.12), since lithology can determine the infiltration of water. However, the lithology of the study area does not have extreme permeable bedrock characteristics.

Table 3.12: Lithology classification of the study area.

Factor	Type	Rate	Suitability Class
Lithology	Pyroclastic and pumice fall deposit	5	Very high
	Lacustrine sediments	4	High
	Rhyolite, ignimbrite and Trachyte	2	Low
	Basalt	1	Very low

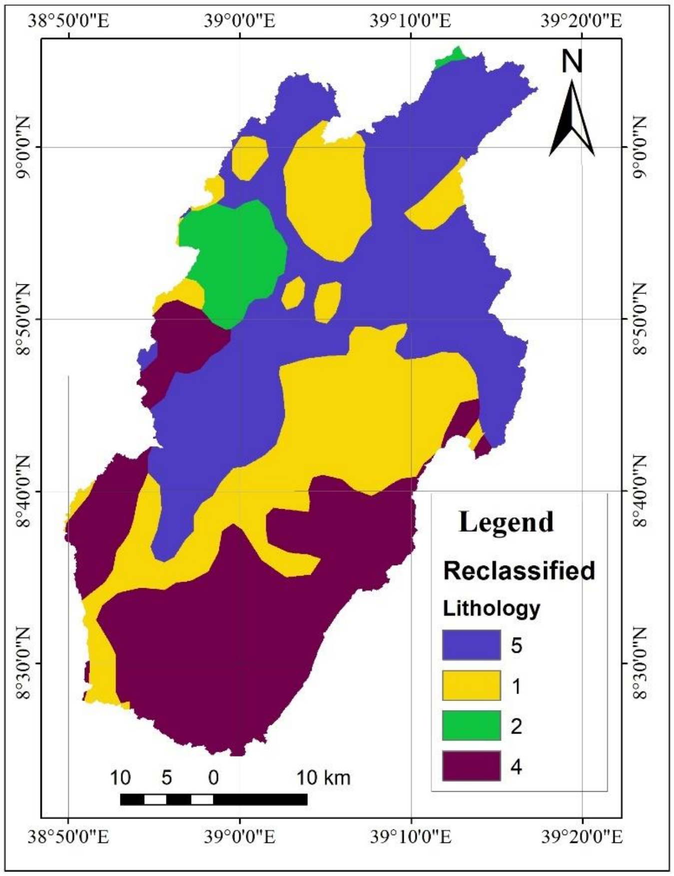

Figure 3.17: Reclassified lithological map of the study area.

3.3.2.10 Lineament

Lineaments were generated from SRTM DEM to give more information on potential sites of the rainwater harvesting structures depending on whether the sites are best for surface water storage or groundwater. Thus, in the study lineaments were manually digitized from DEM as well as extracted using Geomatica software and lastly cross-checking was applied. In conclusion, the extracted lineament was buffered since it represents spatial influence that would lead to leakage or seepage for the surface water storage (Maina and Raude, 2016). Lineaments would be highly suitable when groundwater recharge is to be conducted and least suitable for surface water harvesting since it would encourage leakage or infiltration. For surface runoff harvesting a land unit present in higher lineament density rated lower and a land unit located in no lineaments or less lineament density area rated higher as shown in (Table 3.13 and Fig 3.18b).

Table 3.13: Lineament classification of the study area.

Factor	Lineament density km/km^2	Rate	Suitability class
Lineament	<0.14	5	Very high
	0.14−0.30	4	High
	0.30−0.45	3	Moderate
	0.45−0.60	2	Low
	0.60−0.75	1	Very low

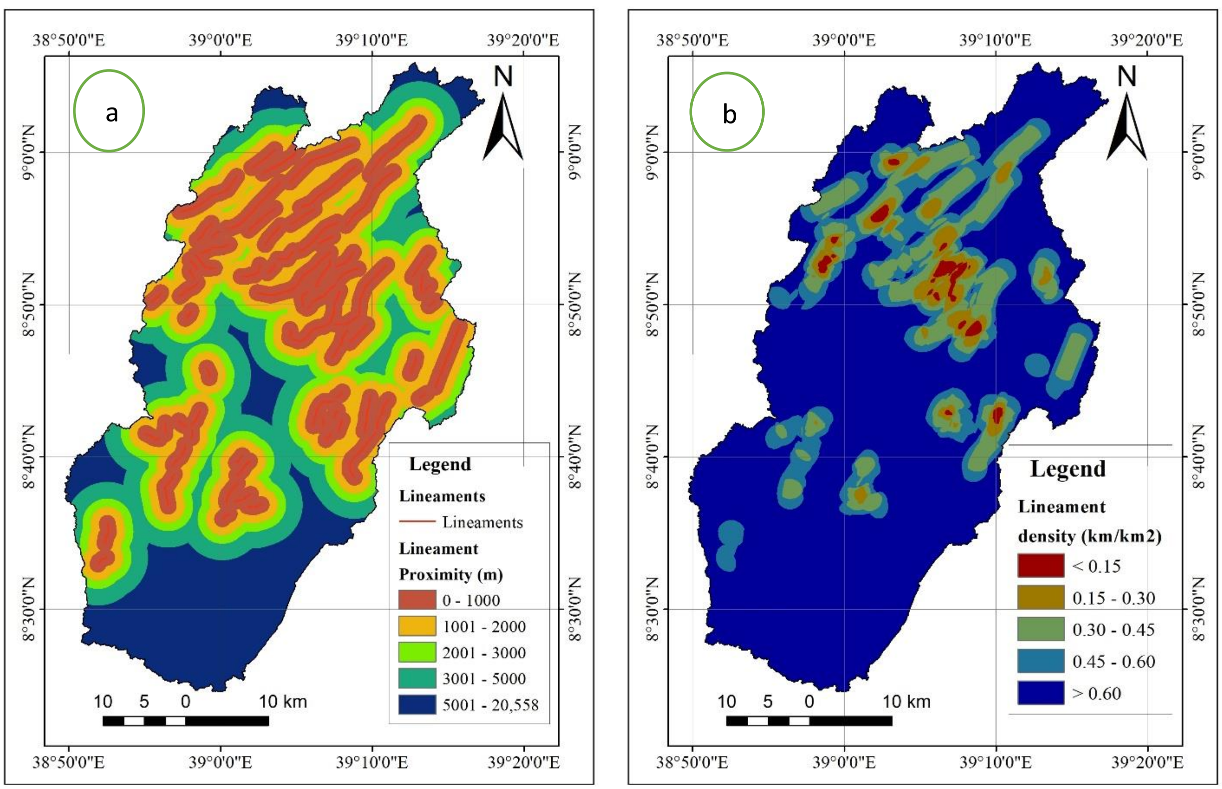

Figure 3.18: Lineament proximity map (a) and Lineament density map (b).

3.3.2.11 Distance to Road

Road layer which is found in the watershed were input as polyline shapefile, then using Euclidean distance function, the road distance layer has been produced, the distance from roads varying between 0−14000 m, as the land units close to the roads the suitability of the land for RWH become lower, as well as the suitability was higher if it was far from road (Fig 3.19) due to most of the people in the watershed was settled and constructed their village following the segments of the road. Thus, RWH sites must be far from roads since the RWH reservoir may generate a high level of the flood to the nearby area as well as the journeyer and the farmer may prone to water born disease such as Malaria. Consequently, to overcome the above listed complications RWH site would be far from the road. To standardize this layer and linear decreasing equation was used (Table 3.14).

Table 3.14: Standardize Euclidean distance from Road layer.

Factor	Road proximity(m)	Rate	Suitability class
Road	<500	1	Very low
	500−1000	2	Low
	1000−1500	3	Moderate
	1500−4000	4	High
	>4000	5	Very high

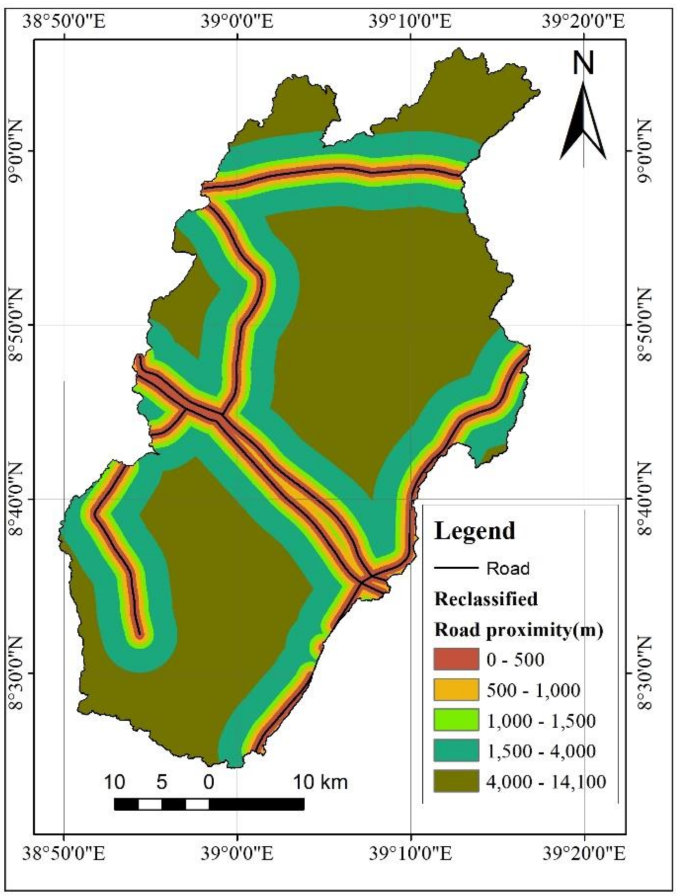

Figure 3.19: Distance to road proximity map.

3.3.2.12 Distance to urban

Urban area is a human settlement with high population density and infrastructure of built-up environment and urban are the main creators of economic wealth in the study area as well as Urban economy is focused on promoting urban strategies and policies that strengthen the capacity of cities, to realize their full potential as drivers of economic development, wealth and employment creation. Therefore, selecting a site away from the urban area is preferable to overcome the economic crisis of the urban during the implementation of RWH Stricture.

Table 3.15: Standardize Euclidean distance for the Urban layer.

Factor	Urban proximity(m)	Rate	Suitability class
Urban	<4000	1	Very low
	4000−6000	2	Low
	6000−8000	3	Moderate
	8000−10000	4	High
	>10000	5	Very high

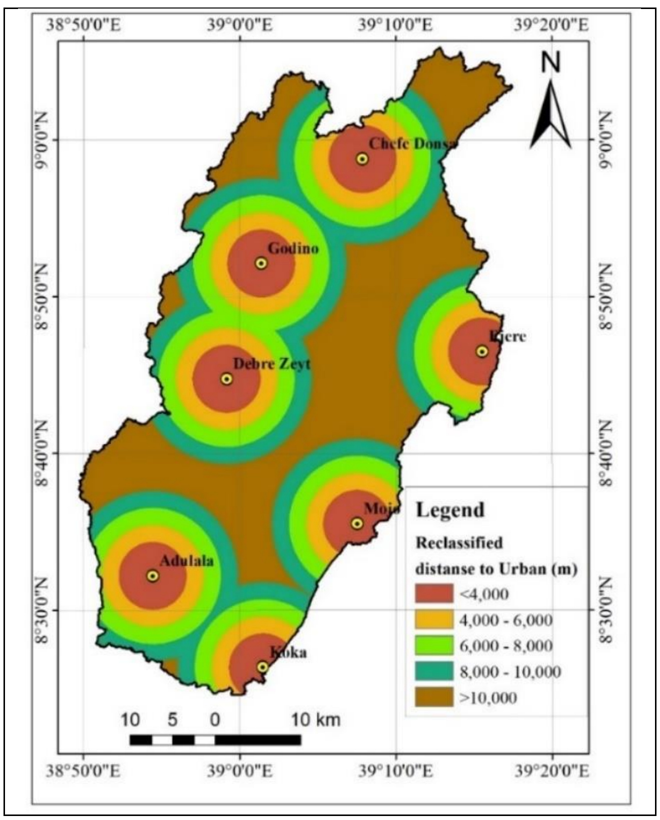

Figure 3.20: Distance to urban proximity map.

The standardized reclassification of this layer was done based on the distance of each land parcel to the nearby urban (Table 3.15). As the land unit closes to the urban area the rate of the land unit become lower, as well as the land unit was rated higher if it is far from urban (Fig 3.20).

3.4 Modeling Fuzzy Logic and assigning AHP weights

In the paper fuzzy logic-based approach was used to standardize the factors of each criterion, and AHP was used to derive weights of each factor. The total score for WH suitability area in the watershed was obtained from a linear aggregation of the products of fuzzy standard criteria and AHP-derived weights. As a Fuzzy logic was used to standardize factors for identifying locations suitable for WH, whereas AHP was used to infer the weight of each influential factor. Ultimately, the factors were aggregated using Weighted Linear Combination (WLC) technique. The objective of using AHP is to differentiate the influential factors from relative importance of multiple paired criteria. Composite weights are then dictated by aggregating the weights according to the hierarchy.

The classical theory of crisp sets can describe only the membership or non-membership of an item to a set 0 or 1 nevertheless, fuzzy Logic transforms the input raster into a 0 to 1 scale, indicating the strength of a membership in a set, based on a specified fuzzification algorithm.

$$\mu A\ (x) : X \rightarrow [0, 1] \tag{11}$$

in which, X refers to the universal set defined in a specific problem and $\mu A\ (x)$ the grade of membership for element x in fuzzy set A. in the study to build a fuzzy logic-based model, the proper types of membership function and its parameters were carefully selected which means the two main steps in fuzzy logic for overlay analysis; fuzzification, or the fuzzy membership process, and fuzzy overlay analysis was applied. These two steps correlate to the reclassify/transform and the add/combine steps, respectively, in the general overlay process. The process of decomposing a given system input and/or output into fuzzy sets is called fuzzification, therefore, Fuzzification was applied in all the above-listed criteria factors to get the fuzzified membership based on (Table 3.16). In the study the ‘large’ and ‘small’ Fuzzification algorithm was used; Small fuzzy algorithm was Used to indicate that small values of the input raster have high membership in the fuzzy set, while the large fuzzy algorithm Used to indicate that large values of the input raster have high membership in the fuzzy set. The large fuzzification algorithm is written mathematically:

$$\mu(X) = \frac{1}{1+(\frac{X}{f2})^{-f1}} \tag{12}$$

Whereas, the small fuzzification algorithm is written as

$$\mu(X) = \frac{1}{1+(\frac{X}{f2})^{f1}} \tag{13}$$

Where, $\mu(X)$ is large and small fuzzification algorithms; f^1 is the spread of the transition from a membership value of 0 to 1 and f^2 is the midpoint. Therefore, by considering the above algorithm, the fuzzy logic approach was used in the study to standardized factors in the range of 0 to 1. The fuzzy membership function tool in ArcGIS 10.3 was used to derive membership functions for factors used to derive spatial suitability levels.

Table 3.16: Fuzzy standardized attribute values for RWH suitability.

Factors	Very low	Low	Moderate	High	Very high
Fuzzy weight	**≈0**	**≈0.2**	**≈0.5**	**≈0.8**	**≈1**
Slope (˚)	>30	15−30	8−15	2−8	<2
Drainage density(km/km^2)	<1	1−2	2−2.5	2.5−3	>3
Land−use/land−cover	Water, wetland and settlement	Grass and Forest	Shrubland	Agriculture	Bareland
Soil texture clay content (%)	<10	10−20	----	20−40	>40
Rainfall(mm)	926−960	960−989	989−1022	1022−1064	> 1064
Runoff (mm)	R<740	740<R≤850	850<R≤930	930<R≤1000	>1000
Lineament density(km/km^2)	>0.47	0.31−0.47	0.18−0.31	0.6−0.18	<0.06
Settlement proximity(km)	< 1.5	1.5−1.7	1.7−1.8	1.8 −2	> 2
Road proximity(m)	< 500	500−1000	1000−1500	1500−4000	>4000

3.5 Developing Analytical Hierarchy Process (AHP) Model

Analytical Hierarchy Process (AHP) is an excellent and well−known weight evaluation method (Malczewski, 2006). A study conducted by Jankowski (1995) method of AHP is depend on three ideologies: decomposition (establishing decision hierarchy), comparative judgment and synthesis of priorities. In the first step of AHP, a complex decision problem is decomposed into simpler decision problems to form a decision hierarchy. Once decomposition is completed, an expert would be asked to make pair-wise comparisons between two factors at a time to decide which factor is more important, this doesn't mean that the least weight has no factor. The final step is to combine the relative weights of the levels obtained in the previous step to produce composite weights.

3.5.1 Establishing Decision Hierarchy

To establish the AHP Model for RWH site selection; the initial stage is to build a hierarchy for the decision as hierarchical structure; also called decision modeling and it simply consists of building a hierarchy to analyze the decision. Analytical hierarchy process shapes the problem as a hierarchy; which presents an effective method for regulating complex decisions and has an application in group decision making around the world in a wide variety of decision situations. Once a hierarchy is developed, a prioritization technique was used to determine the relative importance of elements, all compared as pairs with respect to their importance in making the decision, at every level of the hierarchy (Fig 3.21). Decomposed analytical hierarchy structure of RWH sites. The importance of decomposition a structure hierarchically is that structuring the problem in this way is better to understand the decision to be achieved, the criteria to be used and the alternative to be evaluated. This step is crucial in solving complex problems.

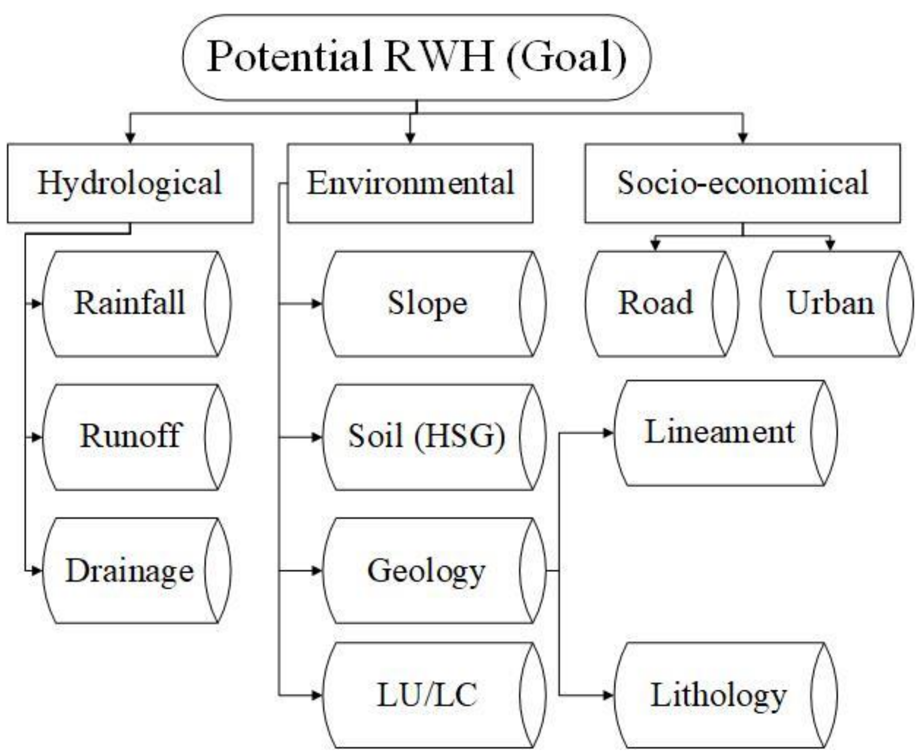

Figure 3.21: Established decision hierarchy For RWH site selection.

3.5.2 Driving weights for the criteria using Pairwise Comparison

According to Saaty,1980 suggests a scale from 1 to 9 (Table 3.17) for pairwise comparison matrix (PCM) elements, where the value of 1 indicates that the criteria are equally important and a value of 9 indicates that the criterion under consideration is extremely important compared to the other criteria; which means all the criteria not equal important in a given factor; as the value of criteria approaches to 9 its importance becoming higher and higher. clearly, the weight of each criterion is different and due to this, it is required to drive by pairwise compressions the relative priority(weight) of each criterion with respect to each of the others using a numerical scale for comparison developed by saaty (2008) as shown in (Table 3.17). Each alternative, criterion and the goal collectively referred as model elements. Pairwise Comparison Matrix includes a consistency check where judgment errors are identified and a consistency ratio is calculated (Hameed, 2013).

Table 3.17: Scales for the pairwise comparisons methods (Satty, 1980 and 2008).

Intensity of importance	Verbal judgment	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	Judgment and Experience slightly favor one criterion over another
5	Strong importance	Judgment and Experience strongly favor one criterion over another
7	Very strong importance	Judgment and Experience very strongly favor one criterion over Another
9	Extreme importance	The evidence choosing one criterion over another is of highest possible validity
2, 4, 6, 8	Intermediate value	If a compromise is needed these values can be used
Reciprocals	Values for inverse comparison	If criterion had one of the above numbers assigned to it when compared with criterion j, then j has the reciprocal value when compared with i.
1.1–1.9	If the factors or layers 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.

As part of the AHP, a verbal scale, or Saaty's scale (Table 3.17), is used in the study to empower decision makers to consolidate subjective experience and knowledge in an instinctive, normalized way. Once the comparison matrix is made, the relative weights of the different components against components in the adjacent upper level are figured as parts of the normalized eigenvector that is connected to the eigenvalue of their comparison matrix (Mustafa, 1991).

To achieve the pairwise comparison of RWH site selection it needs create a comparison matrix of the criteria involved in the decision Hierarchy, Cells in comparison matrices have a value from a numeric scale shown in (Table 3.18) To reflect the intensity judgment in each of the compared pairs. Example if we consider that Hydrologic factor is important than the Environmental factor, the Hydrologic−Environment comparison cell (the intersection of the row 'Hydrologic' and column 'Environment') contains the value 1.5 as shown in (Table 3.18). Mathematically this means that the ratio of the importance of Hydrologic versus the importance of Environment is one and a half (Hydrologic/Environment = 1.5). Because of this, the opposite comparison, the importance of Environment relative to the importance of Hydrologic, produce the reciprocal of this value (Environment/Hydrologic = 0.665) as shown in the Environment−Hydrologic cell in the comparison matrix in (Table 3.18). Similarly, if Hydrologic is importance than Socio-economic factor (Hydrologic/Socio-economic=2), and the Socio Economic−Hydrologic cell will contain the reciprocal 1/2. Finally, if Environment is importance than Socio-economic factor than, the Environment−Socio-economic cell contain the value 1.5 and the Socio-economic Environment cell can have the reciprocal 1/1.5. However, in comparison matrix when the importance of criterion compared with itself; the diagonal input value is always 1 which corresponds to the intensity of equal importance and the lowest triangular matrix is filled using formula;

$$A = [a_{ij}] = \begin{bmatrix} a11 & a12 \cdots a1n \\ a21 & a22 \cdots a2n \\ \vdots & \vdots \quad\quad \vdots \\ an1 & an2 \cdots ann \end{bmatrix} \tag{14}$$

$$[a_{ji}] = \frac{1}{[a_{ij}]} \tag{15}$$

Such that $[a_{ij}]$ is >0

The pair-wise comparison matrix was made from the comparison factors listed on each criterion. The diagonal elements of the square matrix always 1 because comparing the same factors have the same weight, therefore the upper and lower triangular matrix was generated by comparing the factors with each other as decided by the expert.

Table 3.18: Pair-wise comparison matrix of factors with intensive judgments.

RWH(Goal)	Hydrologic	Environmental	Socio-economic
Hydrologic	1	1.5	2
Environmental	0.667	1	1.5
Socio-economic	0.5	0.667	1

CR=0.002; 1= equal importance, 1.5= intermediate value (when compromises is needed); 2=weak importance.

Now each element of a column of the matrix was summed up (Table 3.19) and again each element of the column was divided with the sum of its column (Table 3.20) to get the normalized relative weight using equation (16).

$$W'=\frac{aij}{\sum_{i=1}^{n} aij} \qquad \text{for all } j=1, 2, \ldots n \tag{16}$$

Where, n=number of factors in a column, the normalized relative weight of each factor is shown in (Table 3.19).

Table 3.19: Column Addition.

RWH(Goal)	Hydrologic	Environmental	Socio-economic
Hydrologic	1	1.5	2
Environmental	0.667	1	1.5
Socio-economic	0.5	0.667	1
Sum	2.167	3.167	4.5

Table 3.20: Normalized matrix.

RWH(Goal)	Hydrologic	Environmental	Socio-economic
Hydrologic	0.461	0.474	0.444
Environmental	0.308	0.316	0.333
Socio-economic	0.231	0.211	0.222

After normalized matrix was calculated the weights of the pairwise matrix was calculated by considering an average of the normalized relative weights in a row for each class within a factor as given in Equation 17. Overall priorities or weights of the criteria was obtained by simply calculating the average value of each row (Table 3. 21).

$$w = \frac{\sum_{j=1}^{n} (w')ij}{n} \qquad \text{for all i=1, 2…n} \qquad (17)$$

Table 3.21: Calculation of weights: row averages.

RWH(Goal)	Hydrologic	Environmental	Socio-economic	Weight
Hydrologic	0.461	0.474	0.444	0.460
Environmental	0.308	0.316	0.333	0.319
Socio-economic	0.231	0.211	0.222	0.221
CR				**0.002**

According to the results in (Table 3.21), the calculated weights give more importance to the Hydrologic criterion 0.460, followed by Environment 0.319 and The Socio-economic factor has a minimum weight 0.221 in RWH site selection decision. From this outcome, it can be interpreted that Hydrologic factors has 46 % of the overall importance of the criteria, followed by Environment with 31.9% and Socio-economic 22.1%, respectively.

3.5.3 Consistency ratio

After the judgment has been developed, it is necessary to check that whether the judgment is consistency or inconsistency. However, some inconsistency is expected and allowed in AHP analysis and it is impossible to avoid some inconsistency in the final matrix of judgment. A consistency ratio tells us how much present the decision has been consistent or inconsistent; inconsistency ratio results, a higher number means the judgment has been less consistent whereas a lower number means a judgment has been more consistent. However, in AHP the consistency ratio (CR) of less than 0.1 or 10% is acceptable to continue the AHP analysis. If the consistency ratio is greater than 0.10 or 10%, it is necessary to revise the judgments to locate the cause of the inconsistency and correct it. Finally, the consistency of the rating for each factor was tested by the calculation if random consistency index (RI) (Table 3.25) and consistency index (CI) as given in (Table 3.22, 3.23 and 3.24), respectively and equation 18.

$$\mathrm{CI} = \frac{\lambda_{\max-n}}{n-1} \tag{18}$$

Where, λ_{max} is the largest eigen value of the comparison matrix and n is the number of factors in the matrix.

Table 3.22: Prioritization results.

RWH	Hydrologic	Environmental	Socio-economic
Weight	0.460	0.319	0.221
Hydrologic	1	1.5	2
Environmental	0.667	1	1.5
Socio-economic	0.5	0.667	1

Table 3.23: Weights as factor and calculation of weighted column.

RWH	Hydrologic	Environmental	Socio-economic	Weighted Sum
Weight	0.460	0.319	0.221	
Hydrologic	0.460	0.479	0.442	1.381
Environmental	0.307	0.319	0.332	0.957
Socio-economic	0.230	0.213	0.221	0.664

Table 3.24: Calculation of λ_{max}.

	Weighted Sum	Weights	Result
Hydrology	1.381/	0.460	3.002
Environmental	0.957/	0.319	3
Socio-economic	0.664/	0.221	3.005
		Total	9.007
	Divide the total by 3 to obtain λ_{max}		3.002

λ_{max} = (3.002+3+3.005)/3=3.002

now consistency index (CI) can be calculated using equation 19

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} \tag{19}$$

Where, n is the order of the comparison square matrix; which n=3

Therefore; CI=3.002-3/3-1=0.002/2= 0.001; now it is possible to calculate consistency ratio (CR) Define as:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{20}$$

Where, RI is random consistency index to the different number of criteria; which is obtained from (Table 3.25)

Table 3.25: Random Indices for consistency/inconsistency check.

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

Therefore, RI=0.58; CI=0.001

CR=CI/RI from equation (20) =0.001/0.58= 0.002

Since the value which means 0.002 for the proposition of inconsistency CR is less than 0.1 the judgments matrix is consistent so that AHP decision making process continued on other local priorities criteria. Following and using the above procedures and equations, the other local priorities were calculated on the study.

Table 3.26: Pair-wise comparison matrix for Hydrologic factors.

Hydrologic factor	Rainfall	Runoff	Drainage
Rainfall	1	2	3
Runoff	0.5	1	2
Drainage	0.333	0.5	1
Sum	1.833	3.5	6

Table 3.27: Calculation of weights row average.

Hydrologic factor	Rainfall	Runoff	Drainage	Weight
Rainfall	0.546	0.571	0.500	0.539
Runoff	0.273	0.286	0.333	0.297
Drainage	0.182	0.143	0.167	0.164
CR				**0.008**

Table 3.28: Weighted sum for Hydrologic factors.

Hydrologic factor	Rainfall	Runoff	Drainage	Weighted Sum
Weight	0.539	0.297	0.164	
Rainfall	0.539	0.594	0.492	1.625
Runoff	0.270	0.297	0.328	0.895
Drainage	0.179	0.149	0.164	0.492

Table 3.29: Weighted sum and λ_{max} for Hydrologic factors.

	Weighted Sum	Weights(priority)	Result
Rainfall	1.625/	0.539	3.015
Runoff	0.895/	0.297	3.012
Drainage	0.492/	0.164	2.999
		Total	9.027
	Divide the total by 3 to obtain λ_{max}		3.009

Therefore; CI= (3.009-3)/2=0.009/2; CI=0.0045

CR=0.0045/0.58=0.008; <0.1(acceptable)

Table 3.30: Pairwise comparison for environmental factors.

Environmental factors	HSG	LU/LC	Slope	Geology	Weight
HSG	1	2	2	3	0.423
LU/LC	0.5	1	1	2	0.223
Slope	0.5	1	1	2	0.223
Geology	0.333	0.5	0.5	1	0.122
Sum	2.333	4.5	4.5	8	
CR				**0.003**	

Table 3.31: Calculation of weights row average.

Environmental factors	HSG	LU/LC	Slope	Geology	Weight
HSG	0.429	0.444	0.444	0.375	0.423
LU/LC	0.214	0.222	0.222	0.25	0.227
Slope	0.214	0.222	0.222	0.25	0.227
Geology	0.143	0.111	0.111	0.125	0.122

Table 3.32: Weighted sum λ_{max} for environmental factor.

Environmental Factor	HSG	LU/LC	Slope	Geology	Weighted sum	Weight	Result
Weight	0.423	0.227	0.227	0.122			
HSG	0.423	0.454	0.454	0.366	1.697/	0.423	4.012
LU/LC	0.212	0.227	0.227	0.244	0.910/	0.227	4.007
Slope	0.212	0.227	0.227	0.244	0.910/	0.227	4.007
Geology	0.141	0.114	0.114	0.122	0.490/	0.122	4.015
Total							**16.040**
λ_{max}							**4.010**
CR							**0.003**

Therefore CI= (4.010-4)/3=0.01/3=0.003

CR=CI/RI=0.003/0.90=0.003<0.1(acceptable).

Table 3.33: Pair-wise comparison matrix and weights for Geological factors.

Geology factors	Lineament	Lithology	Weight
Lineament	1	4	0.8
Lithology	0.25	1	0.2
Sum	1.25	5	
CR			0.00

Table 3.34: Pair-wise comparison matrix and weights for socio-economic factors.

Socio economic factors	Urban	Road	Weight
Urban	1	5	0.833
Road	0.2	1	0.167
Sum	1.2	6	
CR			0.00

3.6 Water harvesting site selection based on WLC techniques

Weighted linear combination is a simple additive weighting technique in which continuous criteria are standardized and aggregated according to a weighted average concept. In the technique, the subjectively or objectively specified weights are used along with corresponding individual standardized criteria as input. The total score is obtained based on [equation.21].

$$S = \sum_{i=1}^{n} wixi \quad (21)$$

Where, S is the suitability sites, wi is the weight of criteria layer i, and xi is the membership value of criteria layer i, this equation can be used in raster calculation by rephrased as:

Si=(RW.Rr)+(SLW.SLr)+(SCW.SCr)+(LDw.LDr)+(DDW.DDr)+(LIW.LIr)+(LUW.LUr)+(RO W.ROr)+(DRW.DRr)+(DUW.Dur).

where, “r” represents the rating of each criterion namely: rainfall (R), slope (SL), lineament density (LD), soil clay contents (SC), drainage density (DD), lithology (LI), LU/LC (LU), runoff (RO), distance to urban (DU) and distance to road (DR) while “Si” is Rainwater harvesting Suitability index, which is a dimensionless number that identifies the suitable sites for the water harvesting in the study area.

3.7 Constraints

To ensure constraint, the suitability rating for each assessment criteria was falling within one of the following; either very high, high, moderate, low or very low. A poor rating represents a development constraint that prevents a site from being suitable for RWH. however, In the study lineaments, urban and major roads were considered as some constraints; these criteria have very low water hold capacity (lineament), and the major roads and urban place are preferable for socio-economic benefits than RWH sites. After the constraints were considered in the suitability analysis; the final potential RWH suitability map was generated using equation (22).

$$S = \left(\sum_{i=1}^{n} wi * xi\right) * \prod C_i \tag{22}$$

Where C_i is constraints, $\prod$ is the product and $\sum$ is Somme.

3.8 Proposing sites for rainwater harvesting structures

One of the specific objectives of this research which plays an important role in potential RWH suitability was identifying potential areas for different types of RWH techniques in the watershed; Check dam, Farm pond and Percolation tank were selected based on the reviewed literature criteria and status of the watershed (Table 3.35).

Table 3.35: Most common techniques and criteria that have been used for RWH site selection.

RWH technique	Rainfall(mm)	Slope%	Soil type	LU/LC	Drainage
Check Dams	<1000	<15	Sandy clay loam, Silt Loam	Barren, shrub and scrubland	Fifth and sixth order
Percolation tank	<1000	<10	Silt loam and clay loam	Barren or scrub land	$2^{nd,}$ 3^{rd} or 4^{th} order
Farm pond	>200	<5	Sandy clay loam, silty loam	Moderately cultivated, shrubland	2^{nd} and 3^{rd} order stream

Source: (Singh *et al.*, 2008; Adham *et al.*, 2016).

CHAPTER FOUR

4 RESULTS

4.1 Rainfall and runoff modeling

Analysis of rainfall-runoff relationship determines how much of the precipitation is partitioned into runoff as well as how much of the precipitation is infiltrated after all the initial losses. The result found in spatial scale give a clear indication of rainfall-runoff relationship, the amount of runoff coefficient generated was highly dependent on various land−use/land−cover class, soil clay content and slope of the study area. Comparison made between rainfall and runoff depth through coefficient of determination R^2 is 0.84. This indicates the two criteria have a high positive relation and 84% of runoff generated was dependent due to the increased rainfall in the study area. Annual runoff generated compared to the annual rainfall is presented in (Fig 4.1). The main rainfall season in the study area (June to September) contributes 72.64% of the total annual runoff while the short rain season (March to May) accounts for 18.58% annual runoff volume and the dry months produce only 8.78 % of the total runoff.

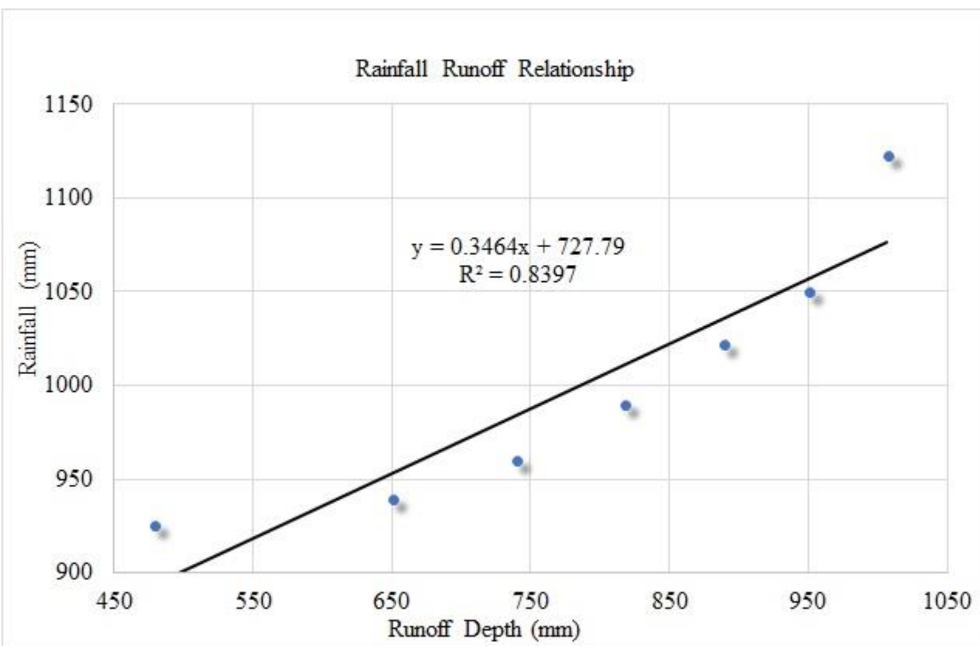

Figure 4.1: Mean annual Rainfall-Runoff relationships.

4.2 Standardized Fuzzy membership results

The fuzzy membership function transforms the standardize input data to a 0.0 to 1.0 scale based on the possibility of being a member of a specified set, which indicating a continuous increase from non−membership to complete membership of a pixel in given layer categories. The basic premise of fuzzification is that to address inaccuracies in attribute and spatial data, 0.0 is assigned to the lowest input value and 1.0 or closer to 1.0 assigned to the largest input value. all contributing factor for RWH suitability map was standardized using fuzzy set membership function in ArcGIS environment. The fuzzified results of each criteria layer of rainfall, runoff depth, drainage density, HSG, land−use/land−cover, slope, lineament, lithology, proximity to road and proximity to urban were presented based on the suitability rating score of each factor for generating potential RWH site selection (Table 3.16) in section three. Each fuzzified input layers for RWH suitability site selection results were listed below.

Rainfall

Rainfall layer map was generated from weather station data and the rainfall layer value was between 926−1022.5 mm. Standardized pixel value of the rainfall map was fuzzified using the large fuzzification algorithm method since a location with high rainfall is more suitable for RWH. The fuzzification results of reclassified rainfall (Fig 4.2a) were found to be very high in the east and western parts and central parts of the area have moderate rainfall distribution while gradually decreases in both south-west and some parts of northern direction.

Runoff depth

The standardized runoff depth was fuzzified using large fuzzification algorithm method. The fuzzified runoff depth layer map shows that the high runoff is mainly seen in the upper parts of the watershed. Especially, on the east and north−west side of the study area and to gradually decreases in south−western direction. Runoff potential in the study area is classified into five zones such as a) very high (> 889mm), b) high (818−889 mm), c) moderate (740−818 mm), d) low (628−740 mm), and e) very low (<628 mm). About 47.2% of the study area has moderate runoff potential. high (21.4%) and low (15%) runoff potential zones. Small portion of the study area falls under class of very high and very low with runoff potential zone of (12.4%) and (4%) respectively (Fig 4.2b). The amount of runoff generated was highly correlated with the distribution of rainfall in a given area. It was found that from the rainfall amount of 1122.5 mm the runoff generated ranges between 478.9 mm and 1007.4 mm. where the lowest value of runoff was recorded within the grassland and forested area and 1007.4 mm was within the agricultural land, built-up area and with higher rainfall area.

Drainage density

The drainage pattern of modjo watershed is formed by varies tributaries and sub−tributaries of modjo river and the drainage density varies between 0.0−4.4 km/km^2 and is grouped into five classes. Very low (<1 km/km^2), low (1−2 km/km^2), modrate (2−2.5 km/km^2), high (2.5−3 km/km^2) and very high (>3 km/km^2). Drainage density of very low and low catagories are dominante in the study area; encompasses an area of 46.5% and 36.7%, respectivly. Modrate drainage density covers an area of 8.8% while the drainage density of high and very high covers a small portion of the study area. The result of fuzzified drainage density reveal that most of the central parts of the watershed are very highly suitable for RWH whereas, the water divide areas and an area which contains less stream network are less suitable (Fig 4.2c).

Land-use/land-cover distribution

The majority portion of land-use/land-cover class of the study area is: agricultural land (58.9%) followed by bareland (12.4%) while water body, wetland and settlement cover an area of 10%. About 10.3% of an area was covered by shrubland whereas forest and grassland cover 8.2% portion of the study area. The fuzzification results of land-use/land-cover map tells that most central parts of the study area were covered by agriculture and some parts of southern direction covered by bare land. Which is suitable for RWH. An area of urban, water body and wetland were considered as not suitable for RWH (Fig 4.2d).

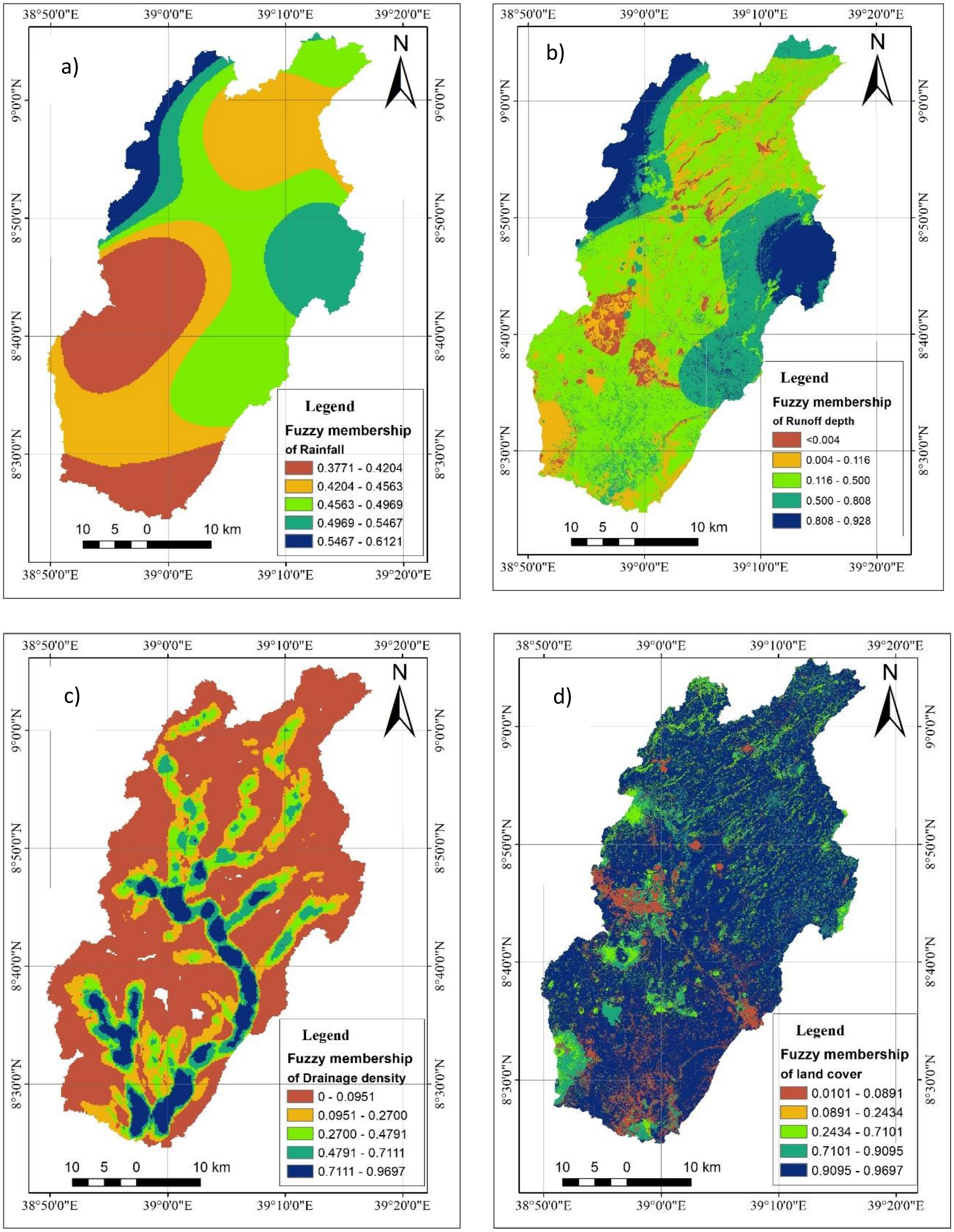

Figure 4.2: Rainfall a), Runoff b), Drainage density c) and Land-use/land-cover d), Suitability map.

Hydrologic soil group in the study area

Major portion of the study area, except some parts of central, south-west and western portion is covered with HSG D (80.9%) while HSG B and C occupies 9.5%, 9.2%, of the study area respectively. Hydrologic soil groups were fuzzified and the result revealed that 80.9% of the total area is under very high suitable class for RWH, except in fracture and mountainous area (Fig 4.3e). This indicates that most of the study area was covered by clay soil which is grouped under hydrologic soil group of D type. Since soil group of D type contains high contents of clay soils.

Slope

The result of reclassified and fuzzified slope result reveals that most of the study area is covered with flat topography that makes the study area suitable for RWH. Most parts of central and southern parts of the study areas are very suitable whereas the high-altitude places such as Yerer, Zequala and Beda gebaba mountainous area are low suitable for RWH (Fig 4.3f). Topographic slope in the study area ranges from 0 to 67^o and is categorized into five classes: steep level (>30^o), hilly (15−30^o), flat to gentle (8−15^o), nearly flat (2−8^o) and flat <2^o. Nearly flat and flat slope categories are considered most suitable for RWH and their spatial extents are 30.13% and 51.1%, respectively. The area under flat to gentle slope is 13.2% while hilly and steep slope is note suitable for RWH and occupy an area of 4.7% and 0.87%, respectively.

Lithology

Large fuzzification algorithm process applied on reclassified lithology (Fig 3.18) result revealed that most parts of central and northern parts of the study area which is covered by Basaltic rock type were very suitable whereas some parts of western and southeastern part were moderate suitable for RWH as shown in Fig 4.3g.

Lineament

Small fuzzification algorithm used on reclassified lineament density result show that, some parts of the study area are exposed to nearby lineaments which is not suitable for RWH. Especially, some central parts of the study area have dens lineaments (Fig 4.3h) that is not advisable for water harvesting. However, most parts of the area other than dens lineaments location are very suitable for RWH structure.

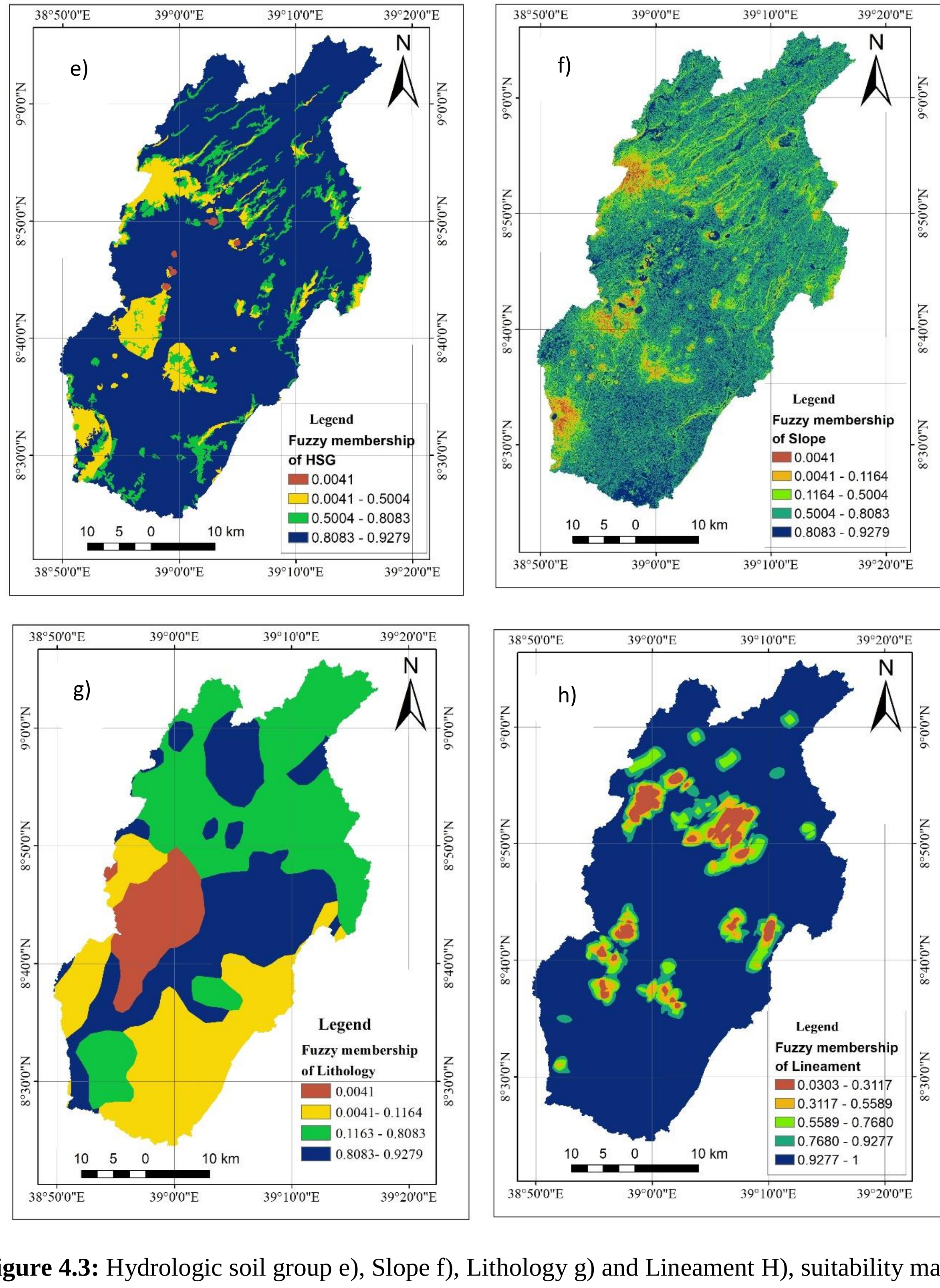

Figure 4.3: Hydrologic soil group e), Slope f), Lithology g) and Lineament H), suitability maps.

Urban proximity

The major urban area found in the watershed were buffered and reclassed based on their suitability class for RWH and fuzzified. The result of fuzzified urban proximity tells that, due to considerable economic and health risk problem with related to RWH implementation most of the locations which are far from urban were considered as very suitable while the place those are near and around the urban were considered as low suitable for RWH (Fig 4.4i).

Road proximity

The result of fuzzified major road proximity map reveals that vast portion of the study area is very suitable, scoring fuzzification value of greater than 0.80. while the adjacent areas towards the road ≤ 1 km were considered as low suitable (Fig 4.4j).

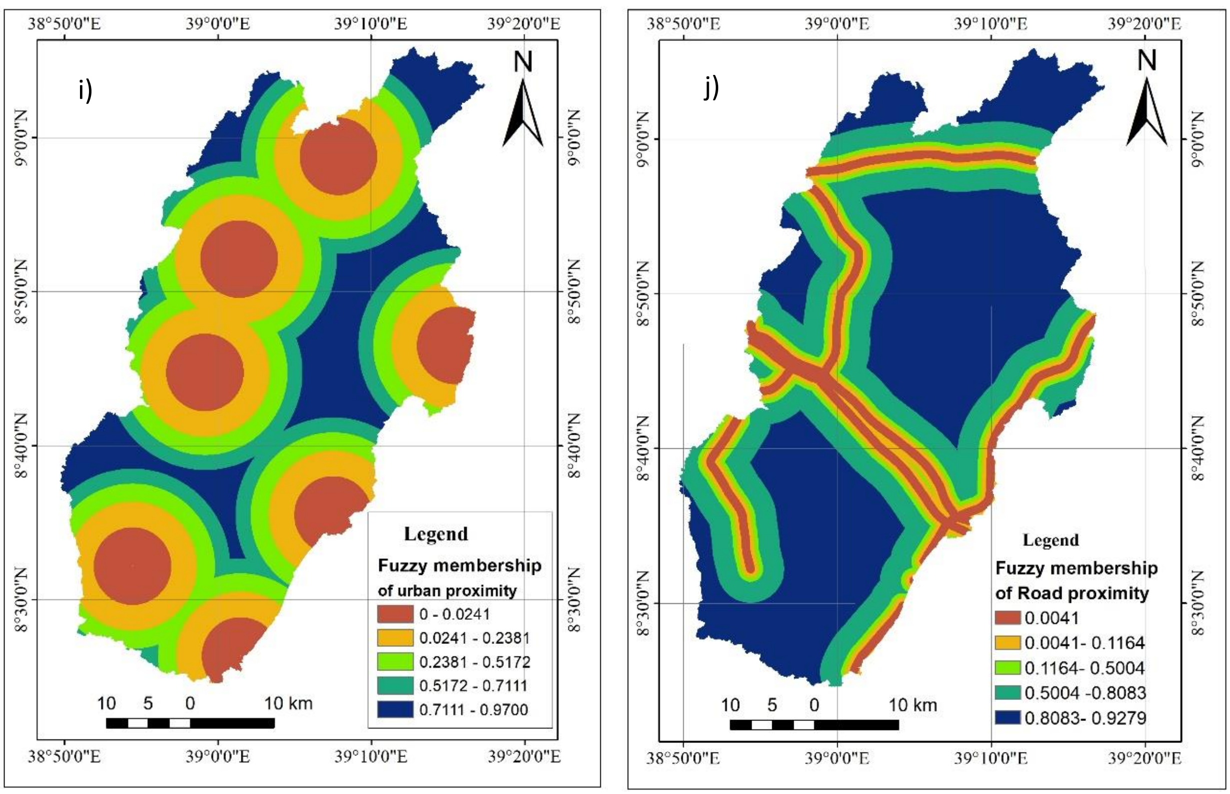

Figure 4.4: Urban proximity (i), and road proximity (j), suitability maps.

4.3 Computed layers weights

The results of each calculated criteria weight were used in the study for selecting suitable zones for RWH structures. The final calculated criteria layers weight shows that; rainfall is the dominant factor which incorporates 24.8% followed by runoff, HSG, distance to urban, distance to road, drainage density, slope, land-use/land-cover, lineament proximity and lithology, respectively. Final weights and consistency ratio was given for each individual criterion (Table 4.1), WLC techniques were then used to aggregate each layer, constraints and final weights of criterion layers to generate potential RWH zones.

Table 4.1: Final weights of main criteria, criteria and sub-criteria with consistency ratio.

Main criteria	Weight	CR	Criteria	Weight	CR	Sub-criteria	Weight	CR	Final weight
Hydrology	0.46	0.002	Rainfall	0.539	0.008				0.24794
			Runoff	0.297					0.13662
			Drainage	0.164					0.07544
Environment	0.319		HSG	0.423	0.021				0.13494
			LU/LC	0.223					0.07114
			Slope	0.223					0.07114
			Geology	0.122		Lithology	0.20	0.0	0.00778
						Lineament	0.80		0.03113
Socio-econ	0.221		Urban	0.833	0.0				0.18409
			Road	0.167					0.03691
Total									**1**

4.4 Generation of Potential RWH Suitability Map

The suitability map for RWH was generated by integrating the result of fuzzified raster maps of the layers and each thematic map weighted using AHP model were combined through WLC techniques to yield the RW suitability map (Fig 4.5). All factors and group of factors were integrated to produces five suitability zones such as very low, low, moderate, high and very high. Out of 2187.43 km^2 of the study area about 173.3 km^2 (7.9%) of the study area was very low suitable for RWH structures, 423.4 km^2 (19.4%) low suitable, 589.6 km^2 (27%) moderately suitable, 573.8 km^2 (26.2%) highly suitable and 427.3 km^2 (19.5%) is very highly suitable for RWH structure.

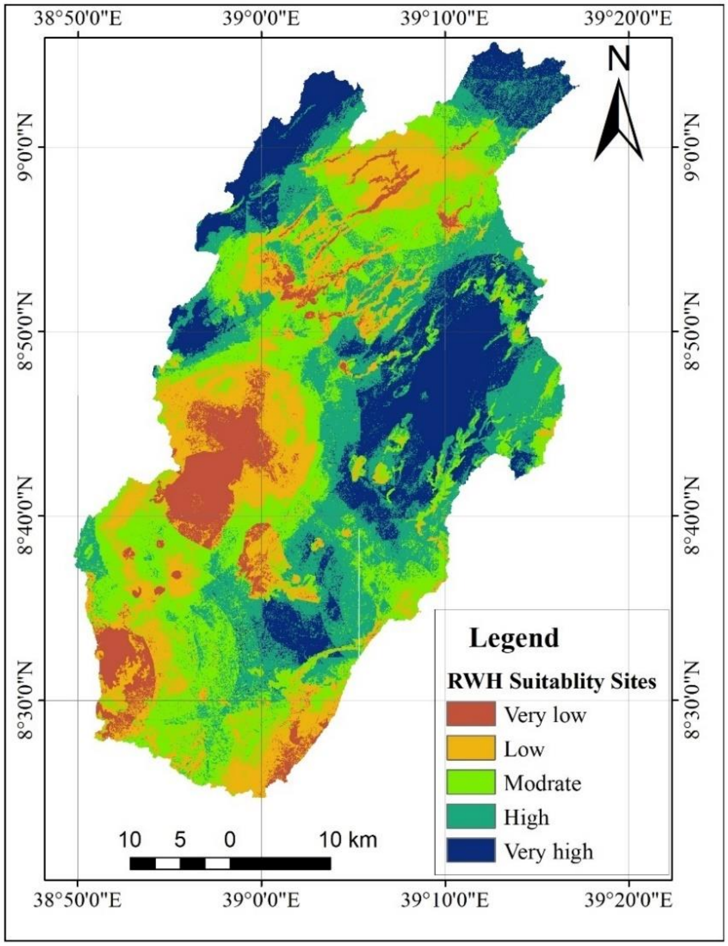

Figure 4.5: Rainwater harvesting suitability zone of the study area.

4.5 Generation of constraint layer maps

Three layers were identified as a constraint as major road, lineament and urban area found in the watershed was considered as a constraint (Table 3.36) in section three and converted into binary maps. A value of 1 assigned as suitable area while a value of 0 was assigned as a restricted (Unsuitable) area for RWH potential zones (Fig 4.6a). The restricted area means never used for RWH structures since those areas are more valuable for economic activities than harvesting water on them. Nevertheless, from those criteria lineaments cannot used for economic activities rather disuse for WH structures, because since a lineament is a fracture area, can facilitate infiltration rate of harvested water and rather used for groundwater recharge, since, the aim of this study was harvesting surface water for water supply in modjo watershed; lineament is considered as a constraint. Finally, the constraint and rainwater harvesting suitability map was aggregated (Fig 4.6b).

Table 4.2: Restricted area factors.

Constraints	Condition (m)	Value	Suitability
Distance to road	≤1000	0	Unsuitable
	>1000	1	Suitable
Distance to urban	≤5000	0	Unsuitable
	>5000	1	Suitable
Distance from lineament	≤1000	0	Unsuitable
	>1000	1	Suitable

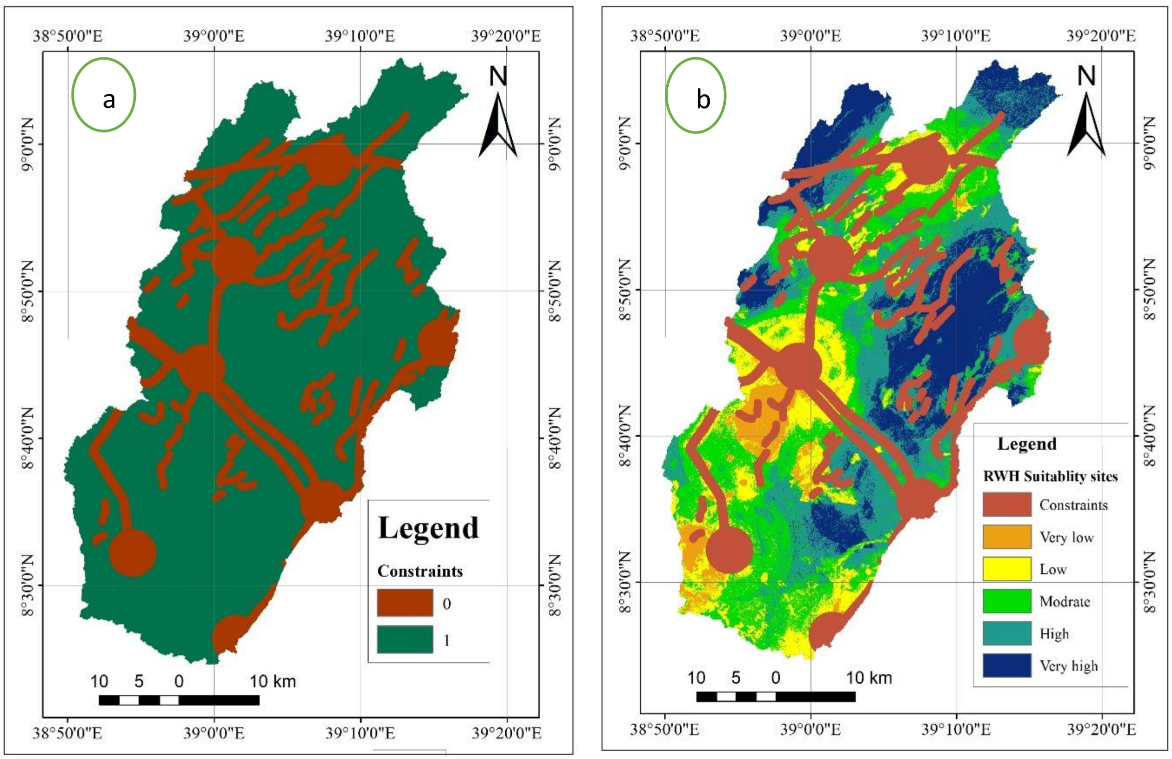

Figure 4.6: Combined constraints a) and Potential rainwater harvesting zones b) map.

Eastern, western, some parts of northern and central portion of the study areas 396.8 km^2 (18.1%) have very high potential for rainwater harvesting. The zone having moderate rainwater harvesting potential covers 444.4 km^2 (20.3%) in most parts of central and south western portions of the study area. High category of rain water harvesting potential zone 459.1 km^2 (21%) is spread in small covering all over the study area. On the other hand, the low and very low potential zones for rainwater harvesting covers 232.7 km^2 (10.6%) and 65.8 km^2 (3%), respectively. In urban, road and lineament area of the study were considered as constraints covering the total area of 588.6 km^2 (27%).

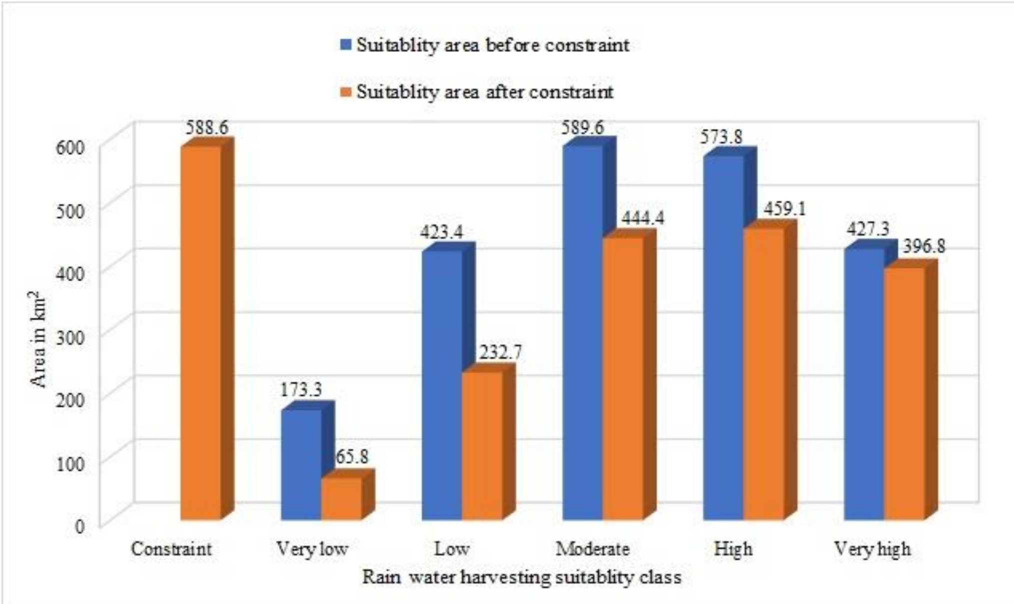

Figure 4.7: Potential rainwater harvesting suitability class of the study area.

4.6 Suitability sites for RWH structure techniques

To increase the availability of water in the study area, different types of RWH techniques were performed to resolve the shortage of water in the watershed. The most common RWH techniques that have been developed and used in most parts of the world are: Farm pond, Check dam, Percolation tanks, Nala bunds, Micro-dam and Terracing (Adham *et al*., 2016). From these listed RWH techniques: Check dam, Farm pond and percolation tanks suitability analysis were performed in the study area. The results of RWH techniques of this study reveals that 13.2% of the study area is highly suitable for check dam while 39.2% and 8.4% are highly suitable for farm pond and percolation tank, respectively (Fig 4.9, 4.10 and 4.11). In the study most of the proposed sites for different types of RWH structures are laid in very high suitability area with integration of stream order of RWH techniques.

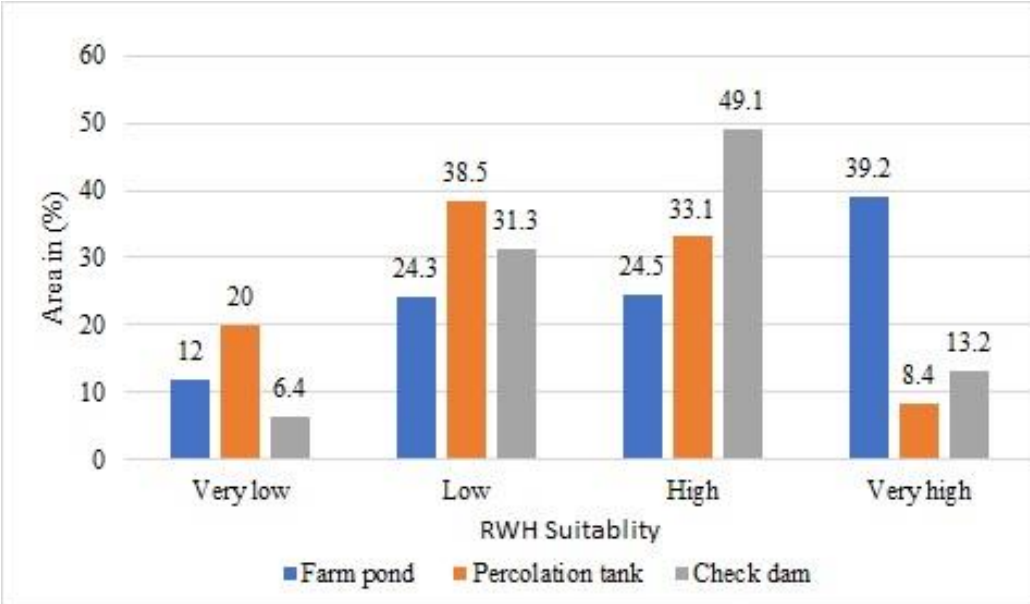

Figure 4.8: Techniques of rainwater harvesting type and area coverage.

4.6.1 Suitable sites for percolation tanks

The suitability sites for percolation tanks in the study area was identified based on the standard criteria. Sites for Percolation thanks should be constructed preferably on 2nd and 3rd order streams, this is used to save percolation tanks from damage due to high runoff; rainfall <1000 mm, slope <10% and silt and clay loam soils were considered as suitable area for construction of percolation tanks, as well as percolation tanks can be located on fractured and permeable rocks. From the total area of the watershed 183.8 km^2 area was found to be very highly suitable for the construction of percolation tanks in the study area and 12 places were proposed for the structure of percolation tanks (Fig 4.9).

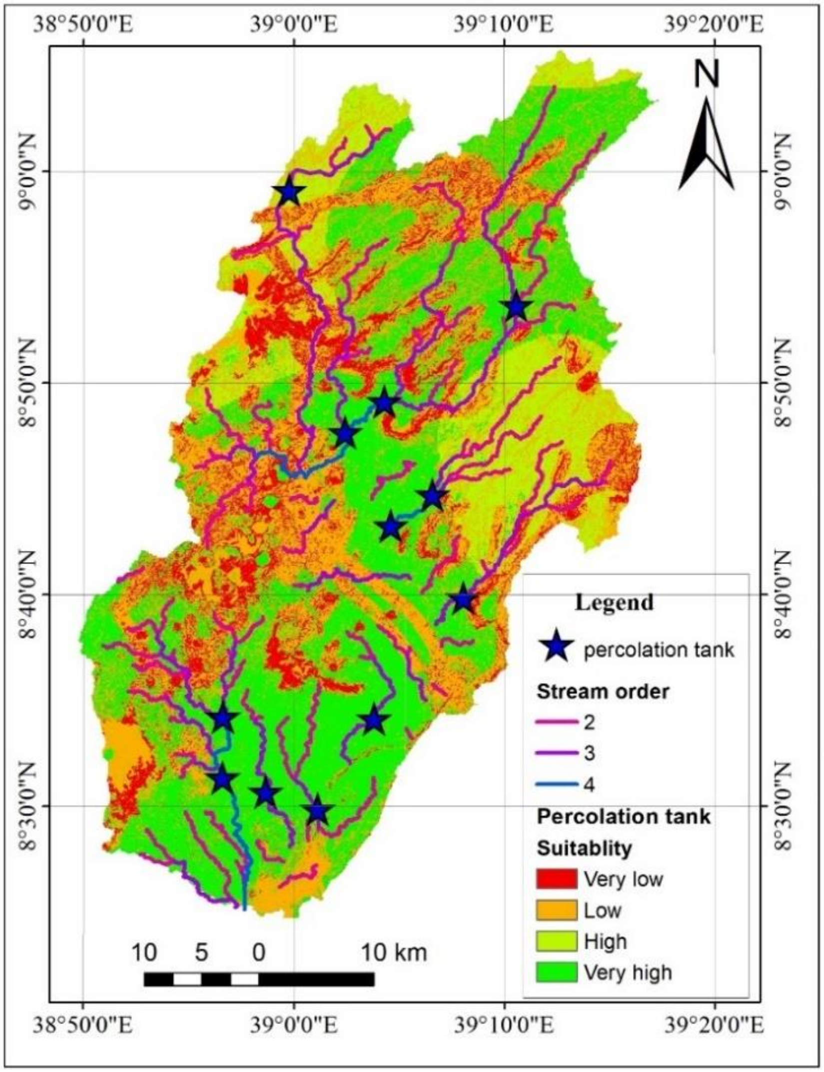

Figure 4.9: Proposed sites for Percolation tank suitability map.

4.6.2 Suitable sites for check dams

A suitability site selection for check dam construction have a stream 5th and 6th order, having a gentle slope <15%, the availability of Rainfall in the area have been approximately 1000 mm, the land cover of the area was bareland, shrubland, and scrubland and the soil type of the area was covered by sandy clay loam. Most of the sites in the watershed were found to be suitable for check dam, nevertheless, from the total area of the watershed 289.4 km^2 area of land is very highly suitable for construction of check dam. As per experience and ground truth, four suitable sites were proposed to construct check dam (Fig 4.10), these proposed check dams can be very useful as supplementing irrigation during the dry season and water conservation, as well as it may use as a water supply for livestock, Industry and municipal consumption.

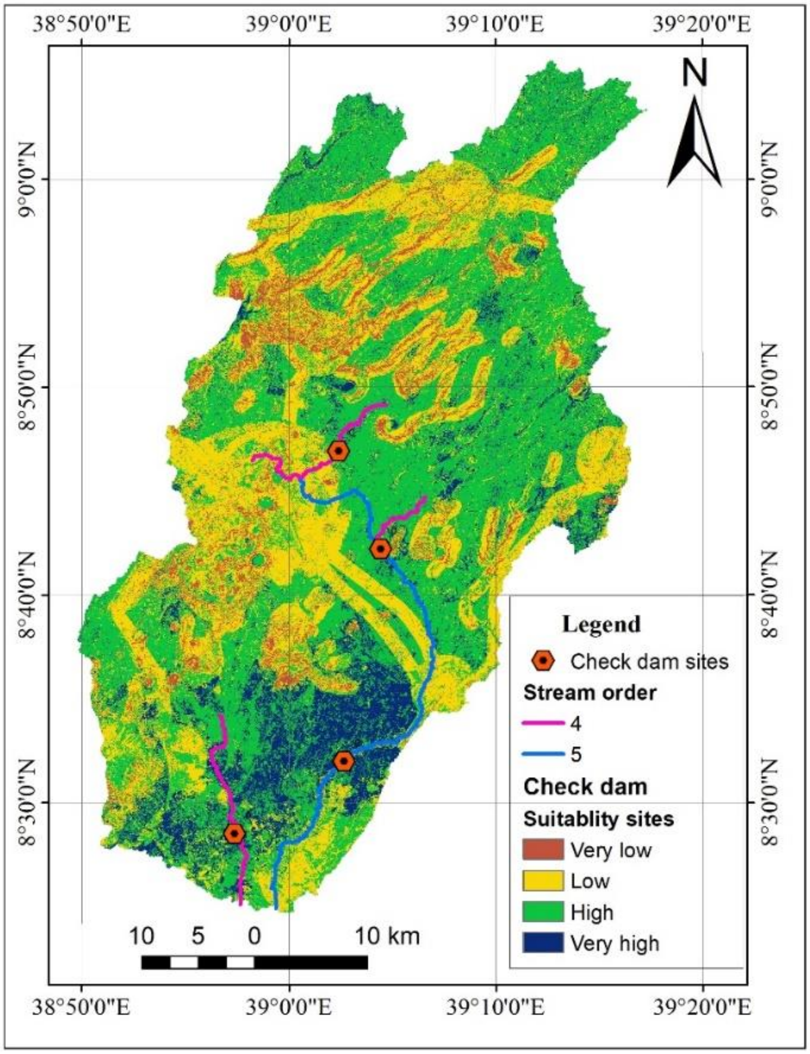

Figure 4.10: Proposed sites for Check dam suitability map.

4.6.3 Suitability sites for Farm ponds

Selecting a suitability area for farm ponds in Modjo watershed was performed to ensure long-term success and provide the best opportunity for irrigation and livestock consumption. In the watershed most of the area has stable and suitable soil types for pond construction, 80.67 % of the study area was covered by clay soils (Table 3.2), 30.13 % (Table 3.5) in section three of the area covered with slope less than 8 % and have a drainage 2nd and 3rd order above the ponds are large enough to fill the ponds in 4 or 5 spells of good rainfall, with >200mm annual rainfalls are proposed for harvesting water in the catchment. From the total area of modjo watershed 858.4 km^2 area of land is highly suitable for farm ponds, of this 47 farm pond sites were proposed (Fig 4.11) which are mainly distributed in the central parts of the watershed, where most of the area is agricultural land.

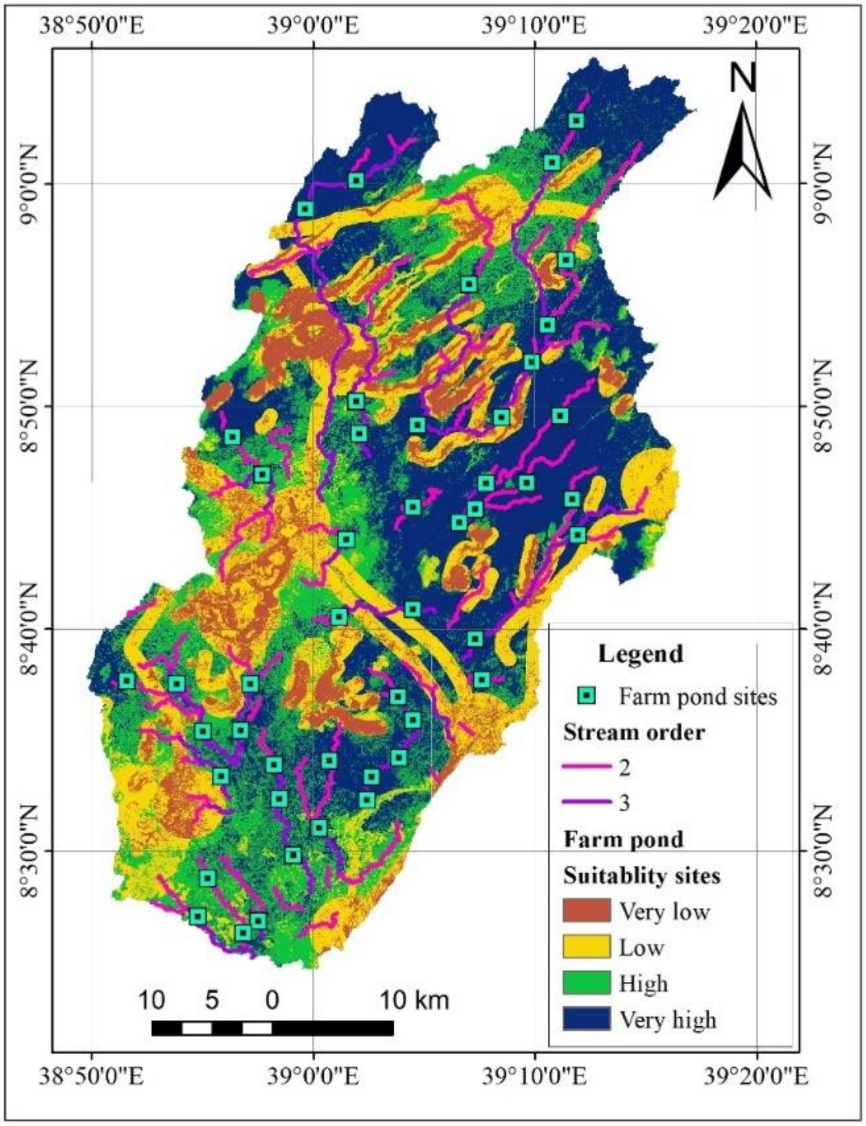

Figure 4.11: Proposed sites for Farm pond suitability map.

4.7 Validation of potential sites

To check the applicability of suitability for rainwater harvesting sites, the locations of potential RWH identified for constructing different types of RWH need to be validated with existing RWH technologies for their suitability. The ground truth relating to the location of existing RWH structures (latitudes and longitudes) was collected during the survey and was exported to ArcGIS for further validation. The proposed suitability map for potential rainwater harvesting techniques identified in (Fig 4.9, 4.10 and 4.11) was converted to kml file, exported to Google Earth and validated with the locations of existing structures by visual interpretation. The result in (Fig 4.12) indicates that 71% of existing RWH sites were in very high suitability and 13% located in highly suitable whereas only 16% were in the very low suitable area. Therefore, accuracy assessment taken into consideration by overlaying the locations of existing RWH ponds identified and the potential rainwater harvesting zones which were developed by the model were agreed with the experiences and local knowledge by the farmers. The capacity of existing ponds to hold water in a given area is very low, and due to this most of the ponds were vulnerable to runoff damage.

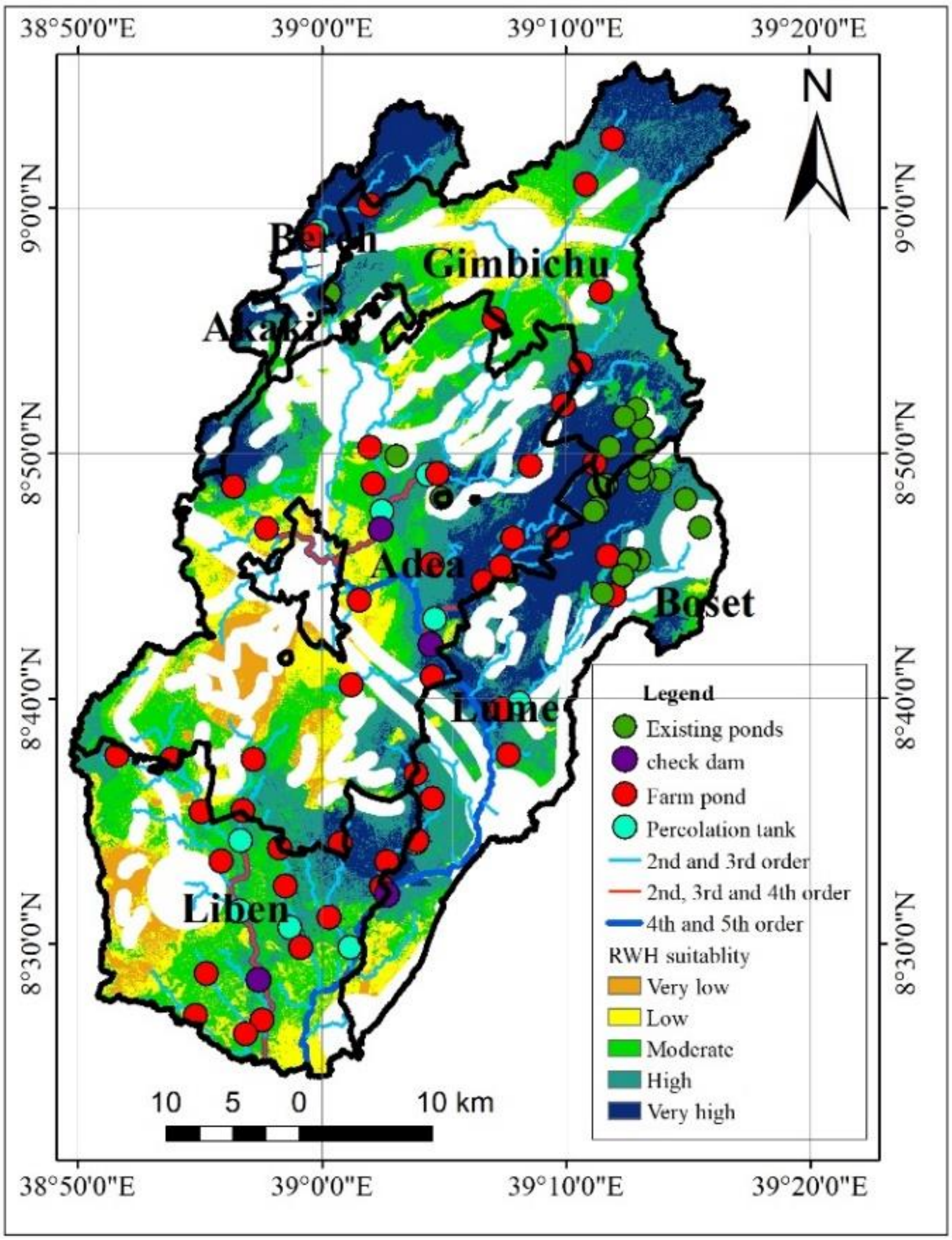

Figure 4.12: Potential rainwater harvesting class for each woreda in the watershed.

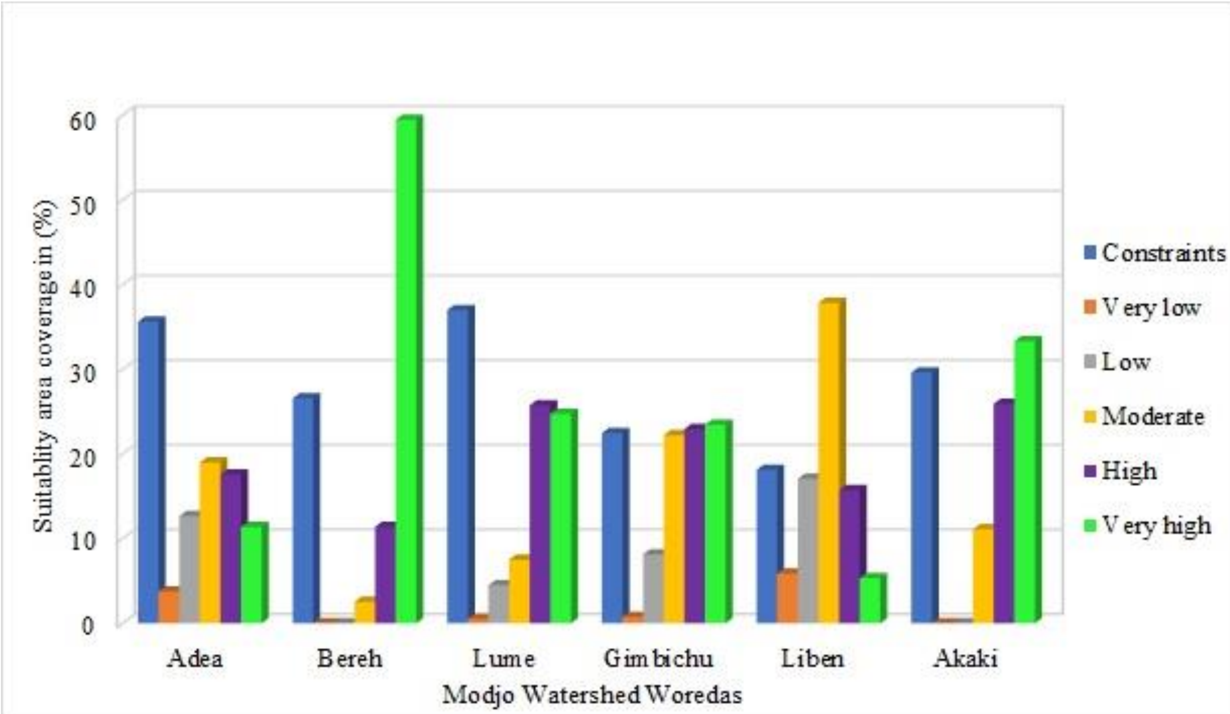

Figure 4.13: Area coverage for Rainwater harvesting suitability class for each woreda.

Potential rainwater harvesting performed in the study indicate that: Bereh, Akaki, Lume and Gimbichu district were found under very high and high suitability class covering 56 km^2 (70.9%), 16 km^2 (59.3%), 202 km^2 (50.6%) and 188 km^2 (46.5%), respectively. However, detail constraints considered in this research results some variation against referred works.

CHAPTER FIVE

5 DISCUSSION

Water is the center of economic and social development and vital to maintain health, grow food, generate energy, manage the environment and create jobs (Girish *et al.,* 2008). However, in modjo watershed most of the community are facing water scarcity during the dry season for livestock consumption and drinking purposes, this shortage of water forced the community to travel far from their village to search the water for their needs. Clean drinking water is essential to the realization of all human rights. When people do not have access to safe drinking water, the impact on the population is devastating, leading to a global crisis. Therefore, implementing RWH technology in very highly suitable locations is critical to minimize the scarcity of water in the study area.

Criteria layer analysis

From different literature, it is believed several criteria need to be considered while selecting potential sites for RWH (Munyao, 2010 and Al-Abadi, *et al*., 2016). Most of these criteria have been discussed in the literature review and methodology chapter. In this research, the criteria layers were selected based on availability and applicability of the data. The criteria layers identified for the analysis were not equally significant to select potential RWH sites of the study area. This difference was managed by AHP model (Ahmed *et al.,* 2013), the model was used to calculate the relative importance of multiple paired criteria to accomplish an expressed objective. By assigning weights it is possible to make important criteria have a greater impact on the outcome than other criteria (Siddayao *et al.,* 2014). In this study, the most influential criteria are rainfall, runoff and hydrologic soil groups which scores 24.8%, 13.7% and 13.5%, respectively, this result agrees with findings obtained by Al-shabeeb (2016) and Al-Abadi *et al.* (2017).

Fuzzy logic and AHP modeling

The study adopted fuzzy logic membership and AHP modeling method to identify potential RWH zones in modjo watershed. The basic concept behind fuzzy work is that, replaces all layer value having the fuzzy set of degree of membership between 0.0 and 1.0, where 0.0 means very low and 1.0 means very high suitable (Al-Abadi *et al.,* 2017) and there are inaccuracies in attribute and in the geometry of spatial data. The logic provides techniques to address both types of inaccuracies, all values between 0.0 and 1.0 represent a transition of 0.0 and 1.0, small and large fuzzification algorithm were used in ArcGIS environment to standardize all layers (Saggaf, 2003). Standardization of these layers requires using specific criteria (Table 3.16) of section three. While, Analytic Hierarchy Process was used to order informational layers in GIS and weighting each of the criteria. The model was developed by incorporating a useful technique for checking the consistency ratio less than 0.1 (10%) (Table 4.1) using equation 20 of the decision maker's evaluations, thus reducing the bias in the decision-making process and the weight was acceptable (Siddayao *et al.,* 2014). The final weight of each criteria layers which was calculated using AHP model was; weight of rainfall is the most dominant which scores 24.5%, runoff depth 13.7%, HSG 13.5%, urban 18.5%, road 3.7%, drainage 7.5% LULC 7.2%, slope 7.2%, lineament 3.1% and lithology 0.8%, respectively.

Rainfall-runoff modeling

Rainfall is a major driving force in runoff generation in any watershed. The total annual runoff estimated in the watershed ranges 478.9 mm within a land cover type of vegetated area and HSG of B type and a low annual rainfall area. While 1007.4 mm runoff generated was within flat and undulating slope classes and HSG of D type which contain >40% clay content soil type, built-up area as well as high rainfall and bareland area have a high runoff in the study area (Fig 4.2b). This is an indication that most of the watershed area is feasible for RWH due to the maximal extent of the runoff generation (Munyao, 2010). The variation of runoff depth for different soil types and land slopes is demonstrated by Nigigi *et al.* (2007). This correctly agrees with the results obtained in the study as shown in Fig 4.2b.

Potential rainwater harvesting zones

The total score for RWH suitability area was obtained from a weighted linear aggregation of standardized fuzzy products, AHP derived weights and constraint layers (Al-shabeeb, 2016). Weighted Linear Combination (WLC) technique is most used and preferable technique for better decision-making processes and for constraint aggregation (Baban and WanYusof, 2003; Destiny, 2015). Finally, all factors and group of factors were integrated to produce five suitability classes: Out of 2187.43 km^2 of the total study area coverage, 7.9% of the study area is very low suitable for RWH, 19.4% low suitable, 27% moderately suitable, 26.2% highly suitable and 19.5% is very suitable for RWH structure. Therefore, it can be concluded that most of the study area is suitable for harvesting water. The research also suggests and identifies suitable sites for most commonly used RWH techniques (farm pond, Percolation tank and Check dam); based on reviewed literature and common criteria of each structure types (Getachew Haile, 2017).

Rainwater harvesting techniques

Identification of potential sites for RWH and storage technologies reflects the specific suitability levels for individual factors and relative weights. Proposed farm ponds are significant for irrigation, livestock consumption, maybe for fish production and different agricultural practices. These sites are in a place with flat to medium slope 0–5% and agricultural areas within a soil type of high water holding capacity such as: clay, sandy clay loam, and silt clay together with drainage of 2nd and 3rd stream order (Rejani *et al.,* 2017). The evidence of locations where farm ponds already exist agrees with model results (Fig 4.11).

A proposed percolation tank sites were also identified downstream of runoff zone with a drainage stream order of 2nd, 3rd and 4th together with a land slope gradient of less than 10%, which allows water to percolate (or seep) through layers, relatively fine soils such as clay and silt have a high-water storage capacity together with land cover of barland and shrubland of the study area, therefore these characteristics agree with findings obtained by Schneider *et al.,* (2011).

A proposed check dam sites were selected across a drainage channel of 4th and 5th order, to lower the speed of concentrated runoff flow for a certain design range of rainy events and located on a steep gently undulating slope ranging to 15%, with clay, sandy clay loam and silt loam soils. The criteria agree with criteria of Singh *et al.,* (2008); Ferrand and Cecunjanin (2014), check dams are mostly built on steep slopes with unstable soil texture, low organic matter contents and high shares of small clay and silt particle soils with drainage greater than 3rd order.

CHAPTER SIX

6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The objective of this research was to develop a GIS-based RWH potential zones using fuzzy and AHP model that combines through WLC techniques. The research demonstrated the powerful capabilities of GIS using fuzzy logic and AHP modeling with the integration of RS data to investigate the possibility of selecting potential sites of RWH in modjo watershed. The results of this research found that using fuzzy and AHP modeling was valid and useful to select the potential water harvesting sites in the study area. The study area was classified into five classes in terms of suitability for rainwater harvesting such as very low, low, moderate, high and very high suitability for rainwater harvesting. Although, Boolean technique was used to eliminate those sites that are not suitable (constraints) for water harvesting within the study area including the lineaments, roads and urban areas, this operation resulted in classifying the study area into two classes, suitable 1 and not suitable 0 for water harvesting site, where the specified site's categories that are not suitable (0) for water harvesting are erased. To identify the optimal sites for water harvesting in the study area, the results of the WLC analysis and the results of the Boolean technique were integrated using raster calculator to generate a final water harvesting suitability map of the study area. Then the result of the study area was classified into constraints 26.9%, very low suitability 3.01%, low suitability 10.64%, moderate suitability 20.32%, high suitability 20.99%, and very high suitability 18.14% of the study area have a potential to harvest rainwater.

Most of the input criteria used as a layer for generating of potential RWH zones in the study area were highly suitable for RWH. Hydrological Soil Group within the study area was covered mostly by HSG of D type covering about 80.98% portion of the total area. Since hydrologic soil type of group D have a high clay content, the infiltration becomes too low while the runoff generated on this type of HSG is too high. The mean annual rainfall for the year (1987−2017) within modjo watershed ranges from 926−1122.5 mm which means the area receives an excess amount of rainfall; these enough amounts of water give agreement with the proposed sites to fill the reservoir in the rainy season. Although, the result of interpolated rainfall indicates that there is high rainfall variation among eastern, western, and central parts of the area, the maximum rainfall greater than 1022 mm was estimated in eastern and western parts of the study area while the land-use/land-cover of the study area was dominantly covered by agricultural land covering the area of 58.96%, whereas bare land covers 12.43% of the study area.

The integration of land-use/land-cover and HSG generates a Curve number which ranges from 61-100 and used to predict the direct runoff or infiltration in the study area. A lower value indicates the low runoff potential while the higher value indicates the high runoff potential. The produced map of CN indicates that some parts of western, central parts of the watershed and vegetation mountainous areas have low CN which is not recommended for RWH in such areas. The integration of CN with rainfall generates runoff depth ranged between 478.9–1007.4 mm where the lowest value was recorded within the Grassland and Forest area and higher runoff (1007.4 mm) was created within the Agricultural land, built up area and bare land. This agreed with the curve numbers generated earlier. The result also indicates that there was a large difference on the quantity of runoff among the central, eastern and western parts of the study area.

For assessing suitable locations for different water conservation interventions in the study area, different thematic layers of rainfall, runoff depth, drainages, soil characteristics, lithology, slope, land-use/land-cover, lineaments, distance from road and distance from urban were combined and set of criteria was applied in three stages. The specific locations and number of RWH structures were determined based on preliminary criteria, Suitable locations for 4 check dams, 47 farm ponds and 12 percolation tanks were identified, the derived sites were validated using Google Earth and investigated for their suitability with the ground truth collected data. The methodology adopted in this research is less time consuming, more precise and can be utilized for the planning of large watersheds.

6.2 Recommendations

To implement the sustainable RWH structure in the proposed area and for future studies, its recommended that the following should be addressed.

- Environmental Impact Assessment (EIA) and social economic condition must be studied in detail, to prevent accidental impact on water resources.
- It is important to take soil samples from the proposed sites to determine structural stability and soil permeability.
- It is recommended to conduct a fieldwork to investigate the selected sites to test the suitability of soil and the sub-surface layers for water harvesting purposes.

- Involving the community as part of the practical implementation for RWH structure need to be considered.
- Instead of assigning weight using random intervals for MCE, it is important to calculate the weight of each datasets by professional judgments using pair-wise comparison matrix (AHP), to avoid confusions, individual biases and to produce better results.

References

Adham A., Wesselinga, J. G., Riksen, M., Ouessar, M. and Ritsema, C. (2016). A waterharvesting model for optimizing rainwater harvesting in the wadi Oum Zessar watershed,Tunisia. *Agricultural Water Management* **176:** 191–202.

Ahmed, C.I., WanYusof, K. B., Balogun, A., and Umer, D. L. (2013). GIS-based analytic hierarchy process as a multicriteria decision analysis instrument: a review. *Arab J Geosci* **6:** 3059–3066.

Al-abadi, A.M., shamsuddinshahid, H. S., Ghalib, b., and Handhal, A. M. (2017). A GIS-based integrated fuzzy logic and analytic hierarchy process model for assessing water harvesting zones in northeastern maysan governorate, Iraq. *Arabian journal for science and engineering*, **42**(6): 2487–2499.

Allen, M. and Roberts, J. (2015). Harvesting water in Ethiopia. *Horizon research and innovation magazine*.

Al-shabeeb, A.R. (2016). The Use of AHP within GIS in Selecting Potential Sites for Water Harvesting Sites in the Azraq Basin, Jordan. *Journal of Geographic Information System*, **8** (2):73–88.

Apipalakul, C., Wirojangud, W., and Ngang, T. K. (2014). Development of Community Participation on Water Resource Conflict Management. **In:** 5th World Conference on Learning, Teaching and Educational Leadership, *Social and Behavioral Sciences,* **186** (2015): 325–330.

Atsbaha Gebre-Selassie and Tessema Bekele (2010). A Review of Ethiopian Agriculture: Roles, Policy and Small-scale Farming Systems. *Koperazzjoni Internazzjonali (KOPIN) and Emmanuel Development Association (EDA)*: 36-65.

Baban, S.M.J. & Wan-Yusof, K. (2003). Modelling optimum sites for locating reservoirs in tropical environments, Kluwer Academic publisher, Netherlands, *Water Resource Management*, **17:** 1–17.

Bakir, M., and Xingnan, Z. (2008). GIS-based hydrological modeling: A comparative study of hec-hms and the xinanjiang model. **In:** *Twelfth International Water Technology Conference*. pp. 855−865. Alexandria, Egypt.

Belete Berhanu.,Yilma Seleshi., and Assefa Melesse (2014). SurfaceWater and Groundwater Resources of Ethiopia: Potentials and Challenges of Water Resources Development. *Springer International Publishing Switzerland*. 702 pp.

Berhan Gessesse., Woldeamlak Bewket., and Bräuning, A. (2014). Model-based characterization and monitoring of runoff and soil erosion in response to land use/land cover changes in the modjo watershed, Ethiopia. *journal of land degradation and development*, **26**(7): 711–724.

Boughton, W.C. (1989). A Review of the USDA SCS Curve Number Method. *Aust. J. Soil Res.*, **27:** 511−23.

Buraihi, B.F., and Shariff, A.R.M. (2015). selection of rainwater harvesting sites by using Remote sensing and GIS techniques: a case study of kirkuk, Iraq. *Jurnal Technoloji*, **76**(15): 75−81.

Chaudhary, A., Mishra, S.K. and Pandey, A. (2013). Experimental verification of the effect of slope on runoff and curve numbers. *Journal of Indian Water Resources Society,* **33**(1): 40−46.

Cheng, C.H. (1999). Evaluating weapon systems using ranking fuzzy numbers. Fuzzy Sets and Systems, **107** (1): 25−35.

Chi, S. C. and Kuo, R. J. (2001). Examination of the influence of fuzzy analytic hierarchy process in the development of an intelligent location selection support system of convenience store. Paper presented at the *IFSA World Congress and 20th NAFIPS International Conference.* 17 pp.

Critchley, W., Siegert, K., and Chapman, C. (1991). A manual for the design and construction of water harvesting schemes for plant production. food and agriculture organization of the united nations, Rome, Italy. 154 pp.

Destiny Ugo, P. (2015). A Multi-Criteria Decision Making for Location Selection in the Niger Delta Using Fuzzy TOPSIS Approach. International Journal of Management and Business Research, **5**(3): 215−224.

Elhakim, A.F. (2016). Estimation of soil permeability. *ScienceDirect*, **55**(3): 2631−2638.

ESRI (Environmental System Research Institute) (1999). ESRI Data & Maps. unpublished report, united states of America.

Faez Hussein Buraihi, Abdul Rashid Mohamed Shariff (2015)., selection of rainwater harvesting sites by using remote sensing and GIS techniques: A case study of Kirkuk, IRAQ. *Jurnaleknologi*, **76**:15 (15) 75–81.

FAO (1998). The state of food and agriculture. The united nation, David Lubin Memorial Library, Rome, Italy, 389 pp.

FAO, (1998). World Reference Base for Soil Resources (WRB). *International Union of Soil Sciences.*

Fattovich, R. (1990). The Development of Ancient States in the Northern Horn of Africa, c. 3000 BC–AD 1000: An Archaeological Outline. *Journal of World Prehistory*, **23**(3): 145−175.

Ferrand, E. A. and Cecunjanin, F. (2014). Potential of Rainwater Harvesting in a Thirsty World: A Survey of Ancient and Traditional Rainwater Harvesting Applications. Geography Compass **8/6**: 395–413.

Garrido, J.A. (2012). A Brief History of Fuzzy Logic. Brain broad research in artificial intelligence and nuero Science, **3** (1): 71−77.

Gautam, R.K. and Luketina, D. A. (2000). Application of GIS and Remote Sensing in water resource, *Twelfth Congress of the APD-IAHR*, November 13-16, 2000, pp 21. Bangkok, Thailand.

Gbanie, S.P., Tengbe, P.B., Momoh, J.S., Kabba, V.T.S. (2013). Modelling landfill location using Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA): Case study Bo, Southern Sierra Leone. *Journal of Applied Geography*, **36**: 3–12.

Getachew Alem (1999). Water Harvesting: A Water Security Strategy for Mitigating the Impact of Drought in Ethiopia. Addis Ababa, Ethiopia.

Getachew Haile (2017). Modeling approach for identification of potential rainwater harvesting sites in Arsi zone, eastern Ethiopia. Unpublished MSc Thesis, Addis Ababa University, Ethiopia, 117 pp.

Ghimire, S.R., and Johnston, J.M. (2015). Impacts of domestic and agricultural rainwater harvesting systems on watershed hydrology: A case study in the Albemarle-Pamlico river basins (USA). ECOHYDROLOGY AND HYDROBIOLOGY. Foreign Trade Enterprise Ars Polona, Warsaw, Poland, **13**(2): 159−171.

Girish, M.K., Agarwal, Rameshwar Bali, R. (2008). Delineation of Potential Sites for Water Harvesting Structures using Remote Sensing and GIS. *J. Indian Soc. Remote Sens*. **36**: 323–334.

Girma Moges Ketsela (2015). Identification of potential rainwater harvesting areas in the Central Rift Valley of Ethiopia using a GIS-based approach. Unpublished MSc Thesis, Wageningen university, Wageningen, Netherland, 87 pp.

Hameed, H. (2013). Water harvesting in Erbil Governorate, Kurdistan region, Iraq: detection of suitable sites using geographic information system and remote sensing. Unpublished MSc Thesis, Kurdistan, Iran, 87 pp.

https://en.wikipedia.org/wiki/Infiltration_(hydrology,accessed on February 19.2018.

https://en.wikipedia.org/wiki/Rainwaterharvesting Rainwater harvesting by freshwater-flooded forests: accessed on 07.2.2018.

https://en.wikiversity.org/wiki/Rainwater harvesting, accessed on 1.31.2018.

Innocentil, F., P. F. Mazzarini, P.F., Abebe,T., Manetti, M.T., Pareschi, (1999). Geology of the Debre Zeyt area (Ethiopia) (with a geological map at scale 1:100,000), *Ethiopian Institute of Geological Survey, Acta Vulcanologica,* **11** (I): l31−141.

Jae, K.L., Engel, B.A., Muthukrishnan, S., and Harbor, J. (2006). Effects of initial abstraction and urbanization on estimated runoff using CN technology, *Journal of the American water resources association*, **42**(3): 629−643.

Janette Worm, J. and Hattum, T.V. (2006). *Rainwater harvesting for domestic use*, 1st edition., Agromisa Foundation and CTA, Wageningen, Netherland, 84 pp.

Jankowski, P. (1995). Integrating geographical information systems and multiple criteria decision-making methods, *International Journal of Geographical Information Systems*, 9(3): 251−273.

Jenson, S.K. (1991). Applications of hydrologic information automatically extracted from digital elevation models. Wiley researcher academy, **5**(1): 31−44.

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

Khalil, R. (2017). Determination of Potential Runoff Coefficient Using GIS and Remote Sensing, Journal of Geographic Information System, **09** (06): 752−762.

Kiflu Gudeta, (2010). GIS-Based Conservation Priority Area Identification in Mojo River Watershed on the Basis of Erosion Risk. Unpublished MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia, 80 pp.

Lee, A. H. I., Chen, W.-C. and Chang, C.-J. (2008). A fuzzy AHP and BSC approach for evaluating the performance of IT department in the manufacturing industry in Taiwan. Expert Systems with Applications, **34**(1): 96−107.

Ly, S., Charles, C. and Degree, A. (2012). Different methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at the watershed scale. *Biotechnol. Agron. Soc. Environ,* **17**(2): 392−406.

Lyon, J. G., and John G. (2003). GIS for water resources and watershed management. Taylor & Francis, London, 351 pp.

Maina, C.W. and Raude, J.M. (2016). Assessing Land Suitability for Rainwater Harvesting Using Geospatial Techniques: A Case Study of Njoro Catchment, Kenya, *Applied and Environmental Soil Science*: **16**: 1−9.

Malczewski, J. (2006). GIS-based multicriteria decision analysis: a survey of the literature. International Journal of Geographical Information Science, **20**(7): 703–726.

Mason, D., and Maidment, D.R. (2000). An Analysis of a Methodology for Generating Watershed Parameters using GIS. Unpublished MSc Thesis, University of Texas at Austin, 202 pp.

Mati, B., Bock, T., Malesu, M., Khaka, E., Oduor, A., Nyabenge, M., and Oduor, V. (2006). Mapping the Potential of Rainwater Harvesting Technologies in Africa A GIS overview on development domains for the continent and ten selected countries. Unpublished technical report, world agro forestry center, 128 pp.

Mbilinyi, B.P., Tumbo, S., Maho, h.f., Mkiramwinyi, F.O. (2007). GIS-based decision support system for identifying potential sites for rainwater harvesting. Journal of Physics and Chemistry of the Earth Parts, **32(**15-18): 1074−1081.

Ministry of water resources (2001). Ethiopian water sector strategy. Unpublished, Addis Ababa, Ethiopia. 37 pp.

Mishra, S.K. and Singh, V.P. (2003). Soil Conservation Service Curve Number (SCS-CN) Methodology. Springer Science Business Media Dordrecht. **42**:84−146.

Mosadeghi, R., Warnken, J., Tomlinson, R. and Mirfenderesk, H. (2015). Comparison of Fuzzy-AHP and AHP in a spatial multi-criteria decision-making model for urban land-use planning. *Computers, Environment and urban systems*, **49**:54−65.

Murtaza, M. B. (2003). Fuzzy-AHP application to country risk assessment. *American Business Review,* **21**(2): 109-116.

Mustafa, M., and Al-Bahar, J.F. (1991). Project risk assessment using the analytic hierarchy process. *IEEE Trans. Eng. Manag*, **38**(1): 46−52.

Naseef, A.U., Thomas, R. (2015). Identification of Suitable Sites for Water Harvesting Structures in Kecheri River Basin. International Conference on Emerging Trends in Engineering, Science and Technology (ICETEST- 2015). *Procedia Technology*, **24**: 7−14.

Nigigi, S.N., Savenije, H.H.G. and Gichuki, F.N. (2007). Land use change and hydrological impact related to up-scaling of rain water harvesting and management in upper Ewaso Ng'iro river basin, Kenya, 129−140 pp.

NRCS (Natural Resource Conservation Service) (1986). Urban Hydrology for Small Watersheds, 2nd ed., Technical Release 55; on Conservation Engineering Division, United states, 164 pp.

Pacey, A. and Cullis, A (1986). Rainwater Harvesting: The collection of rainfall and runoff in rural areas.5th edition, *Integrated Technology Development group (ITDG*), Southampton, London,103−105.

Rajbanshi, J. (2016). Estimation of Runoff Depth and Volume Using NRCS CN Method in Konar Catchment Jharkhand, India. *Journal of Civil Environ Eng*. **6**(236).

Rango, A. (1994). Application of remote sensing methods to hydrology and water resources. *Hydrological Sciences Journal*, **39**(4): 309−320.

Rejani, R., Rao, K.V., Srinivasa Rao, C.H., Osman, M., Sammi reddy, K., George, B., Kranthi, P., Chary, G.S., Swamy, M.V. and Rao, P. J. (2017). Identification of potential rainwater-harvesting sites for the sustainable management of a semi-arid watershed. *Indian Council of Agricultural Research (ICAR)*; *Irrig. and Drain.* **66**: 227–237.

Saadat, M.F., Karimi, S., Jafari, H., and Ghorbaninia, Z. (2017). Using Boolean and fuzzy logic combined with analytic hierarchy process for hazardous waste landfill site selection: A casestudy from Hormozgan province, Iran. *Advances in Environmental Technology***,** **1**: 11−25.

Saaty, T. L., (1980). The analytic hierarchy processes. *American Journal of Industrial Engineering*. **4**(1): 7−13.

Saaty, T.L. (2008). Decision making with the analytic hierarchy process. *International Journal Services Sciences*, **1** (1), 83−98.

Saggaf, M.; Nebrija, L. (2003). A fuzzy logic approach for the estimation of facies from wire-line logs. *AAPGBull.* **87**(7),1223–1240.

Satheeshkumar, S., Venkateswaran, S., and Kannan, R. (2017). Rainfall-runoff estimation using SCS–CN and GIS approach in the Pappiredipatti watershed of the Vaniyar sub-basin, South India. Modeling Earth Systems and Environment **3**(1):155−161.

Senay, G. B., Bohms, S., Singh, R. K., Gowda, P. H., Velpuri, N. M., Alemu, Henok and Verdin, J. P. (2013). Operational Evapotranspiration Mapping Using Remote Sensing and Weather Datasets: A New Parameterization for the SSEB Approach. *USGS Staff-Published Research*. **49**(3): 577−591.

Sharma, M. P., and Kujur, A. (2012). Identification of groundwater prospecting zones using Remote Sensing and GIS techniques in and around Gola block, Ramgargh district, Jharkhand India. *International Journal of Scientific & Engineering Research.* **3**(3): 2229−5518.

Siddayao, G.P., Valdez, S.E., and Fernandez, P.L. (2014). Analytic Hierarchy Process (AHP) in Spatial Modeling for Floodplain Risk Assessment. *International Journal of Machine Learning and Computing,* **4**(5): 450−457.

Singh,J.P; Singh, D., and Litoria, P.K. (2008). Selection of suitable site for water harvesting structures in Soankhad watershed, Punjab using Remote Sensing and Geographical Information System (RS & GIS) Approach a case study. *J.Indian Soc.Remote Sens.* **37:** 21−35.

Srinivasan, V. E. F., Lambin, S. M., Gorelick, B. H., Thompson., and Rozelle, S. (2012). The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. *Water resources research,* **48**(10): 16 pp.

Tauer, W and Humborg, G. (1992). Runoff irrigation in the Sahel zone: remote sensing and geographical information systems for determining potential sites, food and agricultural of united nation.

Tavakoli, A.R., Oweis, T., Farahani, H., Ashrafi, S., Asadi, H., Siadat, H., and Liaghat, A. (2010). Improving Rainwater Productivity with Supplemental Irrigation in Upper Karkheh River Basin of Iran. International Center for Agricultural Research in the Dry Areas. Unpublished technical report, Iran, 102 pp.

United Nation Global Compact (UNGC) (2009). Climate Change and the Global Water Crisis: What Businesses Need to Know and Do, Pacific Institute.12 PP.

USDA, (1986). Urban Hydrology for Small Watersheds, Natural Resources Conservation Service.

World Bank (2006). Managing Water Resources to Maximize Sustainable Growth in Ethiopia. The International Bank for Reconstruction and Development. Unpublished technical report No 36000-ET, Washington, DC, U.S.A, 119 pp.

Zadah, A.Z. (1984). Making computers think like people (fuzzy set theory). IEEE Spectrum: **21** (8):26−32.

Zadeh, L. A. (1965). Fuzzy sets. Information and control, **8**(3): 338−353.

Appendices

Appendix I: Validation points for percolation, check dam and farm pond for RWH sites.

S.No	GPS Points	Name	Easting	Northing	Land-use	Soil type
1	Point	Pond	39.25821	8.783307	Agriculture	Clay
2	Point	Pond	39.24823	8.802354	Agriculture	Clay
3	Point	Pond	39.23099	8.815735	Agriculture	Clay
4	Point	Pond	39.21959	8.818384	Agriculture	Clay
5	Point	Pond	39.21602	8.815025	Agriculture	Clay
6	Point	Pond	39.21685	8.823965	Agriculture	Clay
7	Point	Pond	39.2207	8.8364	Agriculture	Clay
8	Point	Pond	39.21879	8.850983	Agriculture	Clay
9	Point	Pond	39.2149	8.863889	Grass land	Clay
10	Point	Pond	39.20659	8.858098	Agriculture	Clay
11	Point	Pond	39.19632	8.837794	Agriculture	Clay
12	Point	Pond	39.19441	8.812009	Agriculture	Clay
13	Point	Pond	39.19211	8.809777	Agriculture	Clay
14	Point	Pond	39.18865	8.811113	Agriculture	Clay
15	Point	Pond	39.18796	8.796396	Bareland	Clay
16	Point	Pond	39.18548	8.793844	Agriculture	Clay
17	Point	Pond	39.21658	8.761109	Agriculture	Clay
18	Point	Pond	39.21018	8.762074	Agriculture	Clay loam
19	Point	Pond	39.20958	8.760312	Agriculture	Clay
20	Point	Pond	39.20516	8.750564	Agriculture	Clay
21	Point	Pond	39.19162	8.738414	Agriculture	Clay
22	Point	Pond	39.08163	8.803142	Water body	Clay
23	Point	Pond	39.05071	8.831823	Water body	Clay
24	Point	Pond	39.00508	8.942447	Agriculture	Clay

Appendix II: Mean annual rainfall for the last 31 years of the study area (1987−2017).

Station	Elev	Easting	Northing	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Addis Ababa Bole	**2354**	**38.75**	**9.03333**	1987-2017	10.3	27.2	54.5	86.6	74.1	108.9	222.7	246.3	124.5	30.1	4.7	6.5	996.1
Cheffe donsa	**2392**	**39.1232**	**8.97**	**1987-2017**	9.3	29.8	41.4	65.2	56.1	96.5	209.7	243.0	202.1	16.0	6.6	4.1	980.0
Debre Zeit(AF)	**1900**	**38.95**	**8.73333**	**1987-2013**	9.8	16.3	52.6	55.2	43.8	99.5	210.4	212.6	191.2	30.8	6.7	5.0	934.0
Ejere	**2254**	**39.2568**	**8.7733**	**1987-2016**	11.5	27.2	48.5	58.3	91.4	80.8	240.3	333.3	119.7	23.7	9.2	8	1051.7
Koka Dam	**1618**	**39.1542**	**8.46933**	**1987-2017**	15.0	25.3	46.3	59.1	66.1	70.0	239.9	249.1	117.5	23.8	9.2	5.4	926.7
Mojo	**1763**	**39.1082**	**8.60533**	**1987-2016**	10.7	21.1	48.5	73.4	61.4	101	289.5	234	125.5	30.3	9.16	1.8	1007.4
Sendafa	**2569**	**39.0215**	**9.15217**	**1987-2016**	17.2	22.6	41.3	72.7	55.21	118.7	315.9	337.3	113.7	19.4	4.2	4.3	1122.4

Appendix III: Runoff curve numbers for different land-classes (SCS, 1986).

Land-cover type		A	B	C	D
Open space (lawns, parks, golf courses, cemeteries, etc.):					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Commercial and business		89	92	94	95
Industrial area		81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)		77	85	90	92
1/4 acre		61	75	83	87
1/3 acre		57	72	81	86
1/2 acre		54	70	80	85
1 acre		51	68	79	84
2 acres		46	65	77	82
Bare soil	poor	77	86	91	94
Crop residue cover (CR).	Fair	76	85	90	93
	Good	74	83	88	90
Small grain		65	76	84	88
Close-seeded		66	77	85	89
Pasture, grassland, or range—continuous forage for grazing		68	79	86	89
Meadow—continuous grass, protected from grazing and generally mowed for hay.		30	58	71	78
Brush—brush-weed-grass mixture with brush		48	67	77	83
Woods—grass combination (orchard		57	73	82	86
Woods. 6/ Poor 45 66 77 83		45	66	77	83
Herbaceous—mixture of grass, weeds, and		Poor	80	87	93
low-growing brush, with brush the		Fair	71	81	89
minor element.		Good	62	74	85
Water		100	100	100	100

Appendix IV: Accuracy assessments of land-cover classification.

Accuracy assessment										
	Agriculture	wetland	waterbody	shrubland	Settlement	Grassland	Bareland	Forest	Total	UA %
Agriculture	95	1	0	3	1	4	5	1	110	86.4
wetland	2	14	0	0	0	3	0	1	20	70
water body	0	0	42	0	0	0	0	0	42	100
shrubland	2	0	0	52	1	2	5	2	64	81.3
Settlement	1	1	0	2	73	0	2	1	80	91.3
Grassland	5	2	0	1	1	64	0	2	75	85.3
Bareland	3	0	0	1	1	2	78	0	85	91.8
Forest	1	1	0	1	0	0	0	45	48	93.8
Total	109	19	42	60	77	75	90	52	**524**	
PA %	87.2	73.7	100	86.7	94.8	88.2	86.6	86.5		**463**

Hint: UA -user accuracy, PA- producer accuracy overall accuracy = $\frac{463}{524}$ *100 =88.4%

Number of samples = 524

Sum of Correctly classified = 463

Kappa coefficient = $\frac{(463*524)-39873}{(524*524)-39873}$ = 0.86, this indicates the classification is more accurate.

Appendix V: Advantages of harvested water in Modjo watershed