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ASSESSMENT OF RAINWATER HARVESTING POTENTIAL AND APPROPRIATE TECHNOLOGIES IN ABUJA, NIGERIA

OHIAMBE ESEOGHENE

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DECLARATION

This research thesis is my original work and has not been submitted in any other university for award of a degree.

Signature:………………………………. **Date**: ....

OHIAMBE ESEOGHENE

This research thesis has been submitted for examination with our approval as University Supervisors.

Signature:………………………………. **Date**: ....

Prof. Patrick G. Home

J.K.U.A.T, Kenya

Signature:………………………………… **Date**: ....

Prof. Akinwale O. Coker

University of Ibadan, Nigeria.

Signature: ………………………………. **Date**: ....

Dr. Joseph Sang

J.K.U.A.T, Kenya

DEDICATION

I dedicate this project to the Almighty God and to my Parents Pastor Arch. A. F Ohiambe and Pastor Mrs Esther Ohiambe.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AHP – Analytical Hierarchy Process

DEM – Digital Elevation Model

LULC – Land Use/Land Cover

MCDA – Multi Criteria Decision Analysis

MCDM – Multi Criteria Decision Making

RWH – Rainwater Harvesting

SRTM – Shuttle Radar Topography Mission

WOP – Weighted Overlay Process

FCT – Federal Capital Territory

WSSD – World Summit for Sustainable Development

MDGs – Millennium Development Goals

SDGs – Sustainable Development Goals

WHO – World Health Organization

UN – United Nations

SPI – Standard Precipitation Index

GIS – Geographical Information System

FCDA – Federal Capital Development Authority

FAO – Food Agriculture Organisation

ABSTRACT

Water scarcity is vastly becoming a serious environmental problem in the world and in Nigeria, it is increasingly becoming severe and frequent. This is especially so in Abuja where; water scarcity is a major contributor to environmental problems. The rate of water consumption, urbanization and industrialization has exceeded the rate at which the available water supplies are replenished. Rainwater harvesting is one of the means with which water scarcity in Abuja State could be mitigated. The current research was therefore aimed at assessing and mapping Rainwater harvesting potential in Abuja, appropriate technologies as well as evaluating the effect of rapid urbanisation and climate change on that potential. The study applied Geographical Information System (GIS) integrated with Multi-criteria Decision Analysis (MCDA) to assess the potential for rooftop, surface and in-situ Rainwater Harvesting (RWH). Some of the factors considered during this analysis were annual rainfall, landuse/landcover, population, land slope and soil type. The spatial multi-criteria evaluation was used to classify and rank the suitable locations for rainwater harvesting while the Analytical Hierarchy Process (AHP) method was used to compute the priority weight of each criterion. Using AHP, the percentage weights derived for each criterion considered for in-situ rainwater harvesting were rainfall 24.2%, slope 24.8%, soil 20.8% and landuse/landcover 30.2%. Potential maps of different RWH systems and technologies for Abuja were generated. The total quantity of harvestable rainwater was estimated to be 5.6 billion m^3 by in-situ rainwater harvesting at minimum rainfall. Some of the appropriate technologies found are negarims, trapezoidal bunds, bench terraces and ngolo pits. The effect of urbanization leading to the lateral spread of built-up areas and climate change on the potential of rooftop and surface rainwater harvesting reflected an increase of about 120% and 18.2% respectively in the quantity of rainwater harvestable at minimum rainfall between the years 2016 and 2046. The result showed that Abuja has an excellent potential for rooftop, surface and in-situ RWH and this potential will most likely increase over time. This quantity of harvestable rainwater can be used as an additional source of water which will minimize the problem of water scarcity in the state. It is therefore recommended that RWH be adopted in Abuja.

Keywords: Abuja, Analytical Hierarchy Process, Geographical Information System, Rainwater Harvesting Potential, Water Scarcity.

CHAPTER ONE: INTRODUCTION

1.1 Background of Study

Water scarcity has been found to be one of the major problems the world is facing, to be more precise, water was significantly noted by the Secretary General of the World Summit for Sustainable Development (WSSD) as one of the five specific areas, amongst energy, Health, Agriculture and Biodiversity in which specific results are both essential and achievable. That water is a necessity in achieving solution to all the other problems highlighted previously cannot be over emphasized (Malesu et al., 2005). The proportion of people lacking potable drinking water was found according to Malesu et al. (2005) to be high with the possibility of that proportion increasing, the projection of increase in the proportion of people lacking potable drinking water would get even worse. Estimate shows that for every three persons in the world, two would live in water stressed areas by the year 2025, while the number of people without access to clean water in the continent of Africa will increase from 100 million to 400 million (Malesu et al., 2005).

In a move to eradicate poverty the United Nations set eight Millennium Development Goals (MDG) to meet the needs of the world's poorest countries by 2015. Under Goal 7 Environmental Sustainability, Target 3 was set to reduce by 2015, the proportion of people without sustainable provision of potable drinking water. Since then, it is estimated that about 1.6 billion people have been provided with potable drinking water. However, the problem of water was again highlighted in the Sustainable Development Goals (SDGs), estimates still showed that 784 million people worldwide still need to gain access to potable drinking water (WHO/UNICEF JMP, 2008).

Within Africa, according to Malesu et al. (2005) it was estimated that about one third of the population lack potable drinking water and it is projected that 25 countries will experience water scarcity by the year 2025. Therefore, the task of preventing the spread of water scarcity is an important task and would require concerted effort to resolve.

An important component towards meeting the African Water Vision is the need for managing rainwater resources to prevent drought in communities liable to regular climatic variability and instability. Rainwater Harvesting (RWH) and storage has been recognized as one way of achieving this. At the Pan-African Conference on Water in Addis Ababa in 2003 and at the African MDGs on Hunger meeting in 2004, RWH was identified as among the important interventions necessary towards meeting the MDGs in Africa (Desta et al., 2005; Lenton et al., 2005).

Currently, rainwater harvesting is an opportunity to extend water supply to rural areas where there are few other alternatives. Do-it-yourself rainwater harvesting in the Northern Region of Ghana is widespread. Finding ways to improve the quantity and quality of informal harvesting is a potential means for improving water supply for many low income households in the Northern Region of Ghana (Barnes, 2009).

RWH is an ancient practice that can be traced back 4000 years B. C. and in many different countries of the world. The reviews of RWH is as rich, vast and captivating as its history and the application of the technology around the world. New interests in RWH centres around the use of the technology for domestic drinking water supply in urban and rural settings.

Generally, rainwater harvesting can be described as any human practice that deliberately collects and conserves or stores rainwater to be used in the future. It is the precise and deliberate collection of rainwater from any surface known as catchment area and storage of the same in physical structures or within the soils profile (Mbilinyi et al., 2005). Rainwater may be harvested from rooftops, ground surfaces and from ephemeral watercourses. It can serve as an affordable water source for household use, agriculture, environmental flows and prevention of flood damage (Malesu et al., 2005). Rainwater harvesting provides natural soft water which can serve non-potable indoor usages. After appropriate treatment, rainwater provides potable drinking water for human consumption. In addition to its potential to generate considerable quantities of water, rainwater results in collection of decentralized water which makes it less expensive and beneficial when compared with deep drilling and water supplies from public taps. Rainwater is also used to minimize water losses and to augment water supply in any watershed systems (Sekar & Randhir, 2007).

Growing water scarcity in many parts of the developed and developing world, as well as lack of access to potable drinking water around the world are major problems which could potentially be remedied by the scaling up of RWH technology. Scaling up of RWH technologies would require outlining all the available technologies currently in use and bringing them to the knowledge of decision makers and thus to the public. This is why Malesu et al. (2005) came up with the research work to map the potentials of RWH technologies for the whole continent of Africa. Nigeria being a part of this continent with the largest population and one of the smaller land areas compared to countries like Algeria, Libya, Sudan, Congo, should take full advantage of these technologies to prevent becoming one of the water stressed countries expected in 2025.

Nigeria is situated in West Africa. It has a total land mass of 923,770 km^2, the land area is 910,770 km^2 and water area of 13,000 km^2. Major environmental issues in Nigeria include rapid deforestation, soil degradation and overexploitation of groundwater, water scarcity, desertification, oil pollution, erosion and improper disposal of solid waste (Ince et al., 2010). Last collected in 2015 by the National Bureau of Statistics the total population of citizens in Nigeria was around 182.2 million people (NBS, 2017). Today, it is estimated to have about 200 million indigents. The country comprises 36 states including the Federal Capital Territory (Abuja). These 36 states are grouped into geopolitical zones and about 774 local government areas. These divisions are the basis for administrative divisions of the country. The country is annually gifted with 267 billion cubic metres of surface water and about 52 billion cubic metres of groundwater. Toward the southern part of Nigeria, where the annual rainfall is quite high, surface water and springs are the most appropriate and tapped sources of water, particularly where groundwater aquifers are deep. In the north however, where rainfall is minimal, and aquifers shallow, groundwater is the major and most practical source of water leading to over exploitation of groundwater resources (Ince et al., 2010). The geology of the area is such that well yields are not predictable; often the water needs to be pumped up using a hand pump. Generally, the quality of groundwater in the country is a lot better than that of surface water with regards to health criteria (NWSSP, 2000).

Although Nigeria is generously endowed with surface and groundwater, which can easily meet the water demands, according to national sector data, the average national water supply coverage was just about 57%. Of this percentage, about 60% were urban areas, 50% for semi-urban areas, and 55% for rural areas (Ince et al., 2010). In urban areas, both surface water and groundwater are used as water sources which require distribution systems, treatment plants, piped systems, elevated tanks, house connections, yard taps and public standpipes. In semi-urban areas, water supplies are mainly based on individual mechanized boreholes and overhead tanks, also piping with yard taps and public standpipes. Each public standpipe is generally intended to serve 250 people which would mean thousands of standpipes considering the population. Rural water supplies generally involve boreholes with hand pumps, and covered wells. Although rainwater harvesting and natural springs are also used they haven't been tapped into as much as they should with respect to their potential (Barnes, 2009).

1.2 Statement of Problem

Like many developing countries, Nigeria cannot satisfy its domestic water needs and only 47% of the total population had access to water from improved sources in 2007 (WHO/UNICEF JMP, 2008). One major environmental problem Nigeria is currently facing is water scarcity. Nigeria is said to be one of the 25 African countries that will experience water scarcity or stress by 2025 (UNEP, 2002). The country is already facing water supply shortages in both urban and rural areas despite the abundant land and water resources that are available in various climatic zones (Adeboye & Alatise, 2008). The built-up areas have expanded laterally which has led to water shortages in most parts of the country (Lade & Oloke, 2015). However, the water scarcity issue in Abuja is unique because Abuja is not classified as an ASAL region. In fact, Abuja actually experiences an average annual rainfall of about 1100 mm - 1600 mm and its temperatures are not as high as in the ASAL regions. In Abuja, the rate of water consumption has exceeded the rate at which the available water supplies are replenished. This is because the population growth in Abuja has been very rapid within a short period due to urbanization. Population of 107,069 grew to be 3,564,100 within 30 years from 1996 to 2016 (NBS, 2017). First the issue of having sufficient water in the tapped sources for the population and the ability to properly distribute this water has been a challenge. In Abuja, the cost of living is quite high and with the above stated problems, water has become so scarce and expensive. It is commonly said that water is everywhere, however, potable water is not accessible by everyone (Malesu et al., 2005). The cost of transporting/distributing water from the already tapped sources to every residence in Abuja has become a major challenge. If it is not the electricity problems, it would be the distance from the source to blame. So many residents spend a lot of money just on water bills with little or no absolute certainty that they will have it whenever they need it. Also, it is quite expensive to tap into ground water resources due to the geology and hydrogeology of the region (Aladenola & Adeboye, 2010). This research therefore focused on assessing the potentials and technologies of Rainwater Harvesting in Abuja to reduce the cost of potable water as well as making water available to every individual resident in the state.

1.3 Research Objectives

1.3.1 General objective

The general objective of this research was to assess the rainwater harvesting potential and appropriate technologies in Abuja, Nigeria.

1.3.2 Specific objectives

The specific objectives were;

1) To assess the rainwater harvesting potential in Abuja, Nigeria.
2) To determine the appropriate rainwater harvesting technologies for the different land uses in Abuja, Nigeria.
3) To predict the effect of climate change and landuse/land cover change on the potential of rainwater harvesting in Abuja, Nigeria.

1.4 Research Questions

The research questions considered in this work were;

1) What is the rainwater harvesting potential in Abuja, Nigeria?
2) What rainwater harvesting technologies are appropriate in Abuja, Nigeria?
3) What would be the effect of population increase, urbanisation and climate change on rainwater harvesting potential in Abuja, Nigeria?

1.5 Justification

Nigeria has been faced with several environmental problems in the past, however the problem of water scarcity has been persistent. Over the years, many researchers have developed concepts and ideas that could improve the water situation of the country. However, this problem has never been solved. In Nigeria, there has been several research works carried out on rainwater harvesting including socio-economic aspects of rainwater harvesting and the potential in some states. However, very few have tried to assess the potential of harvesting rainwater and map these potentials along with the applicable technologies such that it becomes easy to implement. The implementation of RWH technologies will not be efficient if decision makers are not properly informed of the technologies which can be adopted in different regions to enable them harvest and store enough rainwater to meet all sorts of water needs with little effort. Effective harvesting of rainwater will reduce pressure on public water supply systems which in most cases are not functional due to logistics and inadequate infrastructure (Aladenola & Adeboye, 2010).

Hence, the findings obtained from this research would provide scientifically verified information to aid decision makers in selecting appropriate rainwater harvesting technologies. This research work was targeted at solving the problem of water scarcity on a local scale. These small cities and local government areas would be informed about easier, more efficient ways of getting water where and when it is needed after the potential of RWH is assessed and applicable technologies highlighted. Federal Capital Territory (FCT), Abuja, would be the direct beneficiary of this research as it was carried out in the state.

1.6 Scope of Study

Abuja otherwise known as the Federal Capital Territory (FCT), it is the first planned city in Nigeria and has brought a change in the economy with the creation of jobs and educational institutions. It however was not prepared for the kind of growth in population that it has been experiencing since its inception. This growth has led to its very quick expansion and over exploitation of natural resources. The massive growth of the population has had impacts on the tapped water resources of the area in the form of a rapidly growing need for water, the expansion of residential settlements which is a strain on the existing water distribution systems. Water scarcity is a major environmental problem affecting the lives of thousands in Abuja, especially those who cannot afford the cost of water from the water distribution service due to the cost of living in the city. Beside the city, there are other local government areas quite far from the city where the water distribution systems are yet to reach, these are areas where farming and other agricultural actives are carried out. These local government areas are also in dire need of water supply for continuous crop production, livestock production as well as human consumption. This study focused on Abuja, both urban and rural areas of Abuja, assessing the RWH potential in Abuja in order to reduce the strain on distribution agencies while making sure water is provided to every individual. It also focused on assessing appropriate technologies for RWH based on landuse, topography, rainfall and soil type.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

According to Osuagwu (1999), literature review shows a summary of previous research works which are related to a researcher's present study. Furthermore, it involves relating what has been done, to what extent and what is yet to be done with reference to the authors of these review papers as it concerns this research (Gojeh, 1995). The problem of water scarcity and many of the researches carried out both to understand water scarcity, its effect and preventive measures or otherwise methods which could minimize it, were reviewed. Rainwater harvesting being one of the methods highlighted to minimize water scarcity was also reviewed.

2.2 Water Scarcity

"Water! What is it good for?" Water is an essential resource in every area and aspect of living. It is essential for manufacturing, agriculture, commerce, several types of energy including electricity. Water is essential for economies, the existence of humans, animals and plants is solely dependent on water. As important as water is, it cannot be manufactured yet it can be polluted, desalinated, recycled and or treated but never lost. Water cycle is an example of a closed system, where water exists in different forms at different times. It evaporates from open water bodies like the oceans, seas, rivers and lakes due to the heat of the sun and accumulates in the clouds as vapour then returns to the earth as rain or snow. This is what makes it a closed system (Xercavins & Garrich, 2003). Water scarcity is an imbalance of supply and demand under prevailing institutional arrangements and or prices; an excess of demand over available supply; a high rate of utilization compared with available supply, especially if the remaining supply potential is difficult or costly to tap (FAO Water, 2010). Water scarcity is the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully (UN-Water, 2003).

Water scarcity in many parts of the world has resulted in the reduction of food and livestock production, population movement or shift, additional cost of living, famine, starvation, political stress, loss of good lands and properties, loss of human, plant and animal lives and many other problems (STRATFOR, 2018).

2.3 Causes of Water Scarcity

There are numerous causes of water scarcity in the world. These causes fall under two categories, artificial; that is caused by man and natural (STRATFOR, 2018). The artificial causes of water scarcity include but are not limited to;

- **Government or Policy makers**: In countries with weak political institutions or warfare, water distribution or accessibility can be challenging issues. Where conflict exists, control of water sources is a strategic advantage.

- **Public attitudes:** When the population of a region do not view water as a "common right" for the public and commercial attitudes prevail, suggesting that water is more of a commodity that can be traded or sold for profit.
- **Farming practice:** The types of crops grown for food or cash can drastically impact the amounts of water available for other uses. Whether irrigation or other RWH techniques are used to raise crops, and how water is conserved or managed, also are key factors.
- **Infrastructure:** The availability of infrastructures such as reservoirs, dams or aqueducts for storing and distributing water, or desalination plants to increase the quantity of water obtainable for consumption.

The above are very major causes of water scarcity however they cannot be compared to the natural causes, which include;

- **Geographical Terrain:** this refers to the topography of an area with features like mountains or rivers that can naturally supply or absorb freshwater supplies.
- **Climate:** this refers to factors like temperatures, annual precipitation which can affect the flora and fauna and even the culture of the peoples of any region.

2.4 Effects of Water Scarcity

The effects of water scarcity are innumerable as water stands to be one of the most important resources for the sustenance of all forms of life. Therefore, water scarcity can lead to reduced production of crops or livestock for consumption and commercial purposes

(STRATFOR, 2018; FAO Water, 2010; Kisakye et al., 2018). The reduction of agricultural product will in turn bring about a rise in the cost of these products, demand will increase massively while supply will reduce leading to increased need for imports and other logistical factors. Another effect of water scarcity is political stress, when the government is unable to meet the economic needs of citizens and residents in the region this results in political stresses (STRATFOR, 2018). When this economic pressure is prolonged, naturally many people will begin to move to better locations where they can afford all the necessary food and water supply they require to live comfortably. This is called mass migration. The others who remain might experience famine and starvation (STRATFOR, 2018).

2.5 Measures to Address Water Scarcity

Water was identified as one of the most important resources required in solving all environmental problems at the World Summit for Sustainable Development (WSSD) held in 2002. Problems like Energy, Health, Agriculture, Biodiversity and Water were highlighted in the WSSD. That water is required to address all of them need not be emphasized. The WSSD further reiterated the Millennium Development Goals (MDGs) target to reduce by half in 2015, the proportion of people lacking potable drinking water and basic sanitation. Further deliberations on water have continued to dominate international forums, as at the Third World Water Forum in Kyoto, 2003; the International Conference on Water for the Poorest in Stavanger, Norway and the annual Stockholm Water meetings. The UN General Assembly in late 2003 adopted a resolution that proclaimed the period 2005-2015 as the International Decade for Action-Water for Life. The resolution emphasized that water is critical for sustainable development, including environmental integrity and eradication of poverty and hunger, and is indispensable for human health and well-being. Water scarcity has been an environmental issue for many decades now and several methods have been recommended for both minimization and prevention of water scarcity. Some of these methods include river diversion, dams, groundwater development, desalinization, pollution control, on-farm storage, re-cycling and treatment, use of waste water and rainwater harvesting (UN, 2003).

Rainwater harvesting was identified as a very important way of meeting the African Water Vision of eradicating water scarcity in order to reduce poverty. At the Pan-African Conference on Water in Addis Ababa, 2003, and at the African MDGs on Hunger meeting in 2004, rainwater harvesting was also recognized as among the important interventions necessary towards meeting the MDGs in Africa (Malesu et al., 2005). Moreover, NEPAD's Comprehensive Africa Agriculture Programme (CAADP) recognizes land and water management as one "pillar" of three that can make the earliest and significant difference to Africa's agricultural crises. In total, 874 million hectares of land in Africa could benefit from increased agricultural production by increasing the managed use of water, which also includes rainwater harvesting and storage. Given that 40 billion working hours are lost each year in Africa carrying water, causing "water poverty" which affects mostly women, this can be reversed by supplying water close to home (Malesu et al., 2005). In areas with dispersed populations where the costs of developing surface or groundwater resources are high, rainwater harvesting, and storage have proved a more affordable and sustainable intervention. However, despite its proven uses for domestic, agricultural, commercial and environmental purposes, rainwater has not been fully utilized in Africa (WHO & UNICEF, 2008).

2.6 Rainwater Harvesting

Rainwater harvesting is not a new concept in water resources management. It has been in existence for a long period before the advent of large scale public water systems. Rainwater harvesting is being encouraged and promoted in China, Brazil, Australia, and India. In New Delhi and Chennai, India, it is mandatory to have a rainwater harvesting system for a building plan to secure approval from the local authority (UN- HABITAT, 2005). The benefits of rainwater harvesting are enormous. Expanded use of rainwater harvesting provides a source of free water with only storage and treatment costs, augment limited quantities of groundwater and reduce storm water runoff. It reduces erosion and non-point pollution in urban environment (IPCC, 2007; Flower et al., 2007).

Even though rainwater can be harvested and used for different purposes through different means, it is important to understand all the variables that are involved. Various technologies to harvest rainwater have been in use for millennia and new ones are being developed all the time with regards to the purpose and location of use. They include macro-catchment technologies that handle large runoff flows diverted from surfaces such as roads, hillsides, pastures, as well as micro-catchment technologies that collect runoff close to the growing crop and replenish the soil moisture. Rooftop harvesting structures have the advantage of collecting relatively clean water, while weirs and dams on ephemeral watercourses can store relatively larger volumes and for longer periods (Krishna, 2005).

Local building methods and techniques for rainwater harvesting are specific to location, climate and materials availability. A wealth of information exists about traditional building methods and rainwater harvesting techniques. In India for example, forty-five different traditional practices for harvesting rainwater for irrigation and domestic use have been identified (Narayanan, 2008). The history of rainwater harvesting is described in depth by Pacey & Cullis (1986), Gould & Nissen-Peterson (1999) provided a more technical discussion of system design and components, using traditional and contemporary examples from around the world. Both Pacey & Cullis (1986) and Gould & Nissen-Peterson (1999) described both technical and socio-economic considerations of implementing rainwater harvesting projects, including the design, construction and implementation.

The quantity and quality of rainwater to be harvested using different technologies and for different purposes must be carefully considered. A critical component, often the most expensive, is the means of storage. There are a wide range of tank designs, both above and below ground, designed from various materials. The movement to lower the cost of storage and promote quick adoption of RWH in the 1980's led to the hasty adoption of untried and untested construction techniques involving basket and bamboo reinforced concrete. Successful materials for constructing storage tanks both above and below ground include ferrocement, galvanized steel, plastic, brick, and stone masonry (Gould & Nissen-Peterson, 1999). Above ground storage makes access to and maintenance of the tank easier. Advantages of below-ground tanks include structural support of the soil, temperature moderation and protection from vandalism. However, it is more difficult to detect and repair leaks in these storage containers. Also, soil properties are a concern. Expansion and contraction of soil, particularly clay-rich soils, can lead to cracking, leaking and structural damage if proper reinforcement of the tank is not present. A good example of a low-cost, below-ground storage method is the one designed by Cresti (2007) in Rwanda using a cover supported by wooden poles and a plastic liner. Still the cost of this can be brought down. Therefore, according to Barnes (2009) the feasibility of lower-cost underground storage should be investigated. If the cost of storage could be lowered, rainwater harvesting could contribute in a larger way to SDGs and reach more people as is the original reason for considering rainwater harvesting.

The practice of collecting rainwater can be broadly divided into two; roof-based and land-based (Malesu et al., 2005). Rooftop rainwater harvesting at household level is most commonly used for domestic purposes. It is quite popular as household option because the water is close to where it would be utilized and therefore it requires little effort from the community or neighbours. Land-based practices includes collection of rainwater from surfaces on the ground. This could be for agricultural purposes or for human consumption.

In many regions of the world, clean water is not available especially to households. Since rainwater is free and relatively clean, with little and proper treatment it can be used as potable water source for all kinds of domestic chores. Rainwater harvesting at household level for domestic work saves the cost of high quality drinking water sources and reduces the pressure on distributors. It also reduces the consumption of potable water thus limiting the quantity of wastewater generated (UNDP & ICRAF, 2007).

2.6.1 Rainwater harvesting for gender equity

Approximately two third of the world's illiterates are women. This is because girls are supposed to collect water for domestic chores and as such are restricted from going to school. But even in the literate world, where there is a shortage or scarcity of water, the women are still left alone to the task of getting water for domestic supplies. The drudgery from fetching water have been found to affect the women's health who spend an average of 1 hour daily covering about 1 km to fetch water (Otufale & Coster, 2012). Rainwater harvesting would reduce the pressure on women to collect domestic water. When rainwater is collected, and stored in households, it will enable women and girls spend their time on education and other relevant issues making them more useful to the society and economy at large, bringing about gender equity (UNDP & ICRAF, 2007).

2.6.2 Rainwater harvesting for alleviation of poverty

The problem of poverty is undoubtedly linked to that of water. Rainwater harvesting improves access to water, brings water closer to the location where it should be used, increases the amount of water that can be available to each individual as well as improves the quality of water which some are exposed to. This in its self is a step towards reducing poverty (UNDP & ICRAF, 2007).

2.6.3 Rainwater harvesting for food security

Many farmers in Nigeria have found it difficult to cultivate their entire farm lands for lack of water, this is leading reduction in agricultural produce. This issue has contributed to the problem of food security as well as land degradation. Most of those lands remain exposed to erosion and salinization, over grazing and desertification. These lands which if water was made available could yield a whole lot of crops which would provide more food for the peoples of the world and help in poverty alleviation, food security and economic development (Aladenola & Adeboye, 2010; Coker, 2001).

2.6.4 Socio-Cultural considerations of rainwater harvesting

After having considered all the requirements and benefits of RWH, one other important consideration is the socio-cultural aspects of rainwater harvesting. From all the literatures above, the benefits of RWH are obvious. However, it cannot be imposed on people if their traditions or beliefs won’t allow it. Therefore, the need to review the socio-cultural views of the region of study is important. Residents in Barcelona and UK were interviewed concerning water harvesting structures with which they documented differences in social knowledge accumulation between single family and multifamily residential properties (Domenech & Sauri, 2011; Ward et al., 2010). Another perspective is that integrated water management (which includes rainwater harvesting) is economically efficient from a societal view point because of non-market values and an inefficient distribution of costs and benefits (Vesely et al., 2005; Kettle, 2009; Wilson et al., 2010).

In 2015, a socio-economic survey was carried out in Ibadan City, Nigeria. The work showed that about 57% of the total population surveyed was willing to buy or rent properties with RWH technologies while about 18% were unsure and 25% wouldn't want it at all due to traditional beliefs and shallow knowledge of rainwater harvesting (Lade & Oloke, 2015).

In Ijebu Ode, Nigeria, it was shown that most people in that area wouldn't mind using harvested rainwater if the price of construction was subsidized. It was also stated that there were no cultural restrictions as to using rainwater in Ijebu Ode (Oke & Oyebola, 2012). Rainwater harvesting has been successfully deployed in eastern part of Nigeria such as Edo State with appreciable success and is practiced by more than 80% of the households (Tobin et al., 2013) compared to 3-6.6% households in the South Western part of Nigeria who have deployed RWH (Lade & Oloke, 2015; Gbadegesin & Olorunfemi, 2007). Also, residents in Odeda, Ogun state, Nigeria rely on RWH during the wet season because of the poor quality of the shallow wells attributed to the poor sewage construction, sewerage and open defecation prevalent in the area. However, rainwater harvesting has not spread to the northern part of Nigeria so well (Shittu et al., 2012). Sadly, literature review revealed that most of the alternative sources of water in the northern part of Nigeria like ground water or rivers are unwholesome for drinking and are contaminated by pathogens which have led to water-borne diseases such as typhoid, cholera, dysentery, hepatitis (Dahunsi et al., 2014; Otufale & Coster, 2012; Amori et al., 2013; Amakom & Jibiri, 2010).

In 2010, the drinking water quality in Nigeria was an assessed. Several sources of water were tested except the quality of rainwater. The method which Ince et al. (2010) used for the Rapid Assessment of Drinking-Water Quality (RADWQ) was based on the UNICEF Multiple Indicators Cluster Surveys which was developed as a tool for the WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply and Sanitation to monitor global access to safe drinking-water (Howard et al., 2003).

2.7 Assessing the Potential of Rainwater Harvesting

The quantity of rainwater harvested depends on monthly precipitation, roof catchment area and roof runoff coefficient (Woltersdorf et al., 2015) while the quality of rainwater harvested depends on roof type, level of atmospheric pollution, geographical location, container size, catchment characteristics, land use practices, and local climate.

Several studies have been done on different issues pertaining to the potentials of rainwater harvesting. Such studies include the quality, quantity, storage and methods of harvesting rainwater. Many have gone ahead to estimate the storage capacity which would be required for different sizes as well as different materials for roof and ground surfaces. With respect to storage, Woltersdorf et al. (2015) recommended tank size of 30 m^3 for a roof size of 100 m^2 while Ndiritu et al. (2011) recommended a storage tank size of 40 m^3

for a roof size area range between 75-150 m^2. Imteaz et al. (2012) recommended a tank size of 7 m^3 to achieve 100% reliability for toilet flushing and laundry within four months. Likewise, Biswas & Mandal (2014) observed that a 4 m^3 concrete tank installed with a roof area of 40 m^2 was adequate to take care of water demands of four-member household for five-month dry period while Mwenge et al. (2010) recommended an optimum tank size of 500 L which achieved water savings of 10-40% daily. In assessing the potentials of RWH, some studies have considered the climatic conditions (Balogun & Oyedepo, 2016; Mahmoud & Alazba, 2014; Kahinda et al., 2008). The data for rainfall and weather pattern was collected and analysed using Guhathakurta & Saji (2013) seasonality index with which they computed the mean rainfall of month, mean annual rainfall and the Standard Precipitation Index (SPI) as described by Akinsanola & Ogunjobi (2014) and Adegoke & Sojobi (2015). Rainwater harvesting potential according to Balogun & Oyedepo (2016) was calculated using the monthly balance approach. The monthly harvestable rainwater (Q_m) was calculated as a function of the product of mean monthly rainfall (R_m), roof area (A), percentage of roof area utilized for rainwater harvesting (β) and roof runoff coefficient (C) as given in the following equation (Balogun & Oyedepo, 2016).

$$Q_m = R_m \times A \times \beta \times C \qquad (1)$$

In Zanzibar, Geographical Information System (GIS) database of RWH potential was developed using ArcGIS and Arc view software, by utilizing both vector and raster (gridded) available databases. The major variables identified for prioritizing RWH in the

GIS were rainfall, topography, soils, and land suitability and population density (UNDP & ICRAF, 2007). Also, the RWH potential for the whole of Africa was done using Arc GIS and Arc view software which gave a relatively good result for the potentials of RWH in Africa except for the scale which was used due to the large area considered in the study (Malesu et al., 2005).

2.7.1. Surface runoff collection from open surfaces

This involves the collection of runoff from open surfaces, such as roads, home compounds, hillsides, open pasture lands and may also include runoff from watercourses and gullies an example of which is illustrated in Figure.2.1. It is an intervention that could be implemented almost anywhere, as long as local site conditions permit it. The potential of sand/subsurface dams in an area is a function of the availability of sand rivers, topography that allows construction of weirs, a geology that suits storage structures and the presence of a population large enough to make use of the water stored (Gould & Nissen-Peterson, 1999). However, site selection is based on availability of settlements rather than population density. The runoff coefficient for the geology of the region will enable the determination of what quantity of rainwater can be harvested using any of the above RWH structures and thus help determine the most suitable structures both for the harvesting and storage of rainwater.

Figure 2.1: Illustration of Rainwater Harvesting from Open Pasture Lands (Liaw & Chiang, 2014)

2.7.2. Multi-criteria decision making in rainwater harvesting

Decision Analysis is a set of systematic procedures for analyzing complex decision problems. These procedures include dividing the decision problems into smaller more understandable parts; analyzing each part; and integrating the parts in a logical manner to produce a meaningful solution (Malczewski, 1999). In general, Multi-Criteria Decision

Making (MCDM) problems involve six components (Keeney & Raiffa, 1976; Pitz & McKillip, 1984):

1. A goal or a set of goals the decision maker wants to achieve
2. The decision maker or a group of decision makers involved in the decision-making process with their preferences with respect to the evaluation criteria,
3. A set of evaluation criteria (objectives and/or physical attributes)
4. The set of decision alternatives,
5. The set of uncontrollable (independent) variables or states of nature (decision environment)
6. The set of outcomes or consequences associated with each alternative attribute pair.

Multi-Criteria Decision Analysis (MCDA) techniques can be used to identify a single most preferred option, to rank options, to list a limited number of options for subsequent detailed evaluation, or to distinguish acceptable from unacceptable possibilities (Dodgson et al., 2000).

There are various types of spatial MCDA (Udezo, 2017). They include simple additive weighting, analytical hierarchy process, the value/utility function method, the ideal point method, outranking method, ordered weighted average, goal programming and compromise programming.

GIS based multi-criteria decision analysis can be thought of as a process that combines and transforms spatial data into a resultant decision. The MCDM procedures are decision rules which define a relationship between the input maps and an output map. The procedures use geographical data, the decision maker's preferences, data manipulation, and preferences according to decision rules. Two considerations of critical importance for spatial MCDA are the GIS capabilities of data acquisition, storage, retrieval, manipulation and analysis, and the MCDM ability to combine the geographical data and the decision maker's preferences into one-dimensional values of alternative decisions (Malczewski, 2004).

MCDM methods have been applied in several studies since 80 per cent of data used by decision makers is related geographically (Malczewski, 1999). GIS may provide more and better information about decision making situations. GIS allows the decision maker to identify a list meeting a predefined set of criteria with the overlay process (Heywood et al., 1993) and the multi criteria decision analysis within GIS may be used to develop and evaluate alternative plans that may facilitate compromise among interested parties (Malczewski & Ogryczak, 1996).

2.7.3. Analytical hierarchy process

The Analytical Hierarchy Process (AHP) developed by Saaty (1980) is a technique for analysing and supporting decisions in which multiple and competing objectives are involved and multiple alternatives are available. The method is based on three principles: decomposition, comparative judgment and synthesis of priorities.

In the AHP, the first step is that a complex decision problem is decomposed into simpler decision problems to form a decision hierarchy (Erkut & Moran, 1991). When developing a hierarchy, the top level is the ultimate goal of the decision. The hierarchy decreases from the general to more specific until a level of attributes are reached. Each level must be linked to the next higher level. Typically, a hierarchical structure includes four levels: goal, objectives, attributes and alternatives. The alternatives are represented in GIS database. Each layer consists of the attribute values assigned to the alternatives (cell or polygon) which are related to the higher levels elements (attributes). Once decomposition is completed, cardinal rankings for objectives and alternatives are required. This is done by using pairwise comparisons which reduces the complexity of decision making since two components are considered at a time. Pairwise comparison involves 3 steps: (a) development of a comparison matrix at each level of hierarchy (b) computation of weights for each element of the hierarchy and (c) estimation of consistency ratio.

The final step is to combine the relative weights of the levels obtained in the above step to produce composite weights. This is done by means of a sequence of multiplications of the matrices of relative weights at each level of the hierarchy. First, the comparison matrix is squared, and the row sums are calculated and normalized for each row in the comparison matrix. This process is continued when the difference between the normalized weights of the iterations become smaller than a prescribed value (Saaty, 1980).

The AHP has widespread use due to its flexibility and ease to use. It is also incorporated into GIS environment (Banai-Kashani, 1989; Eastman et al., 1993; Jankowski, 1995; Siddiqui et al., 1996) and can be used in two distinctive ways within GIS to derive weights and combine them with attribute map layers and to aggregate the priority for all levels of the hierarchy structures. In addition, the AHP can even be implemented in spreadsheet environment (Kirkwood, 1997). However, ambiguity in relative importance, inconsistent judgments by decision maker and the use of 1 to 9 scale can be thought as the disadvantages of this method. The ratio scale makes sense when dealing with something like distance, or area which are natural ratio scales, but not when dealing with things like comfort, image, or quality of life, for which no clear reference levels exists. Furthermore, for large problems too many pairwise comparisons must be performed (Malczewski, 1999).

2.7.4. Pairwise comparison method

The pairwise comparison method involves pairwise comparisons to create a ratio matrix. It takes pairwise comparisons as input and produced relative weights as output. The pairwise comparison method involves three steps (Saaty, 1980):

1. Development of a pairwise comparison matrix: The method uses a scale with values ranging from 1 to 9. The possible values are presented in Table 2.1:

Table 2.1 Scale for Pairwise Comparison

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very strong to extremely strong importance
9	Very Extremely strong importance

Source: Saaty, (1980)

2. Computation of the weights: The computation of weights involves three steps. First step is the summation of the values in each column of the matrix. Then, each element in the matrix should be divided by its column total (the resulting matrix is referred to as the normalized pairwise comparison matrix). Then, computation of the average of the elements in each row of the normalized matrix should be made which includes dividing the sum of normalized scores for each row by the number of criteria. These averages provide an estimate of the relative weights of the criteria being compared.
3. Estimation of the consistency ratio: The aim of this is to determine if the comparisons are consistent or not. It involves following operations:

a) Determine the weighted sum vector by multiplying the weight for the first criterion times the first column of the original pairwise comparison matrix, then multiply the second weight times the second column, the third criterion times the third column of the original matrix, finally sum these values over the rows,

b) Determine the consistency vector by dividing the weighted sum vector by the criterion weights determined previously,

c) Compute lambda(λ) which is the average value of the consistency vector, using (n) which is the number of criteria considered and Consistency Index (CI) which provides a measure of departure from consistency and has the formula:

$$CI = (\lambda - n) / (n-1) \qquad (2)$$

d) Calculation of the consistency ratio (CR) which is defined as follows:

$$CR = CI / RI \qquad (3)$$

Where RI is the random index and depends on the number of elements being compared. If $CR < 0.10$, the ratio indicates a reasonable level of consistency in the pairwise comparison, however, if $CR \geq 0.10$, the values of the ratio indicates inconsistent judgments.

The advantages of the pairwise comparison method is that only two criteria have to be considered at a time, it can be implemented in a spreadsheet environment (Kirkwood, 1997) and it is incorporated into GIS based decision making procedures (Eastman et al., 1993; Janskowski, 1995). On the other hand, the relative importance of evaluation criteria is determined without considering the scales on which the criteria are measured. Also, if you have many criteria, the amount of pairwise comparisons that should be made will be very large.

2.7.5. Weighted overlay analysis

The Weighted Overlay tool applies one of the most used approaches for overlay analysis to solve multicriteria problems such as site selection and suitability models. In a weighted overlay analysis, each of the general overlay analysis steps are followed (Hillier, 2011).

Every overlay analysis, in such weighted overlay analysis, the problem must define, broken into sub-models, and then identify the input layers (ArcMap Help). Since the input criteria layers will be in different numbering systems with different ranges, to combine them in a single analysis, each cell for each criterion must be reclassified into a common preference scale like 1 to 5 or 1 to 10, with the highest numbers being the most favorable. An assigned preference on the common scale expresses the phenomenon's preference for the criterion. The preference values are on a relative scale. That is, a preference of 10 is twice as preferred as a preference of 5 when your scale is up to 10, otherwise your highest scale is the most preferred.

The preference values should not only be assigned relative to each other within the layer but should have the same meaning between all layers. For example, if a location for one criterion is assigned a preference of 5, it will have the same influence on the phenomenon as a 5 in a second criterion.

Each of the criteria in the weighted overlay analysis may not be equal in importance (Hillier, 2011). The important criterion can weigh more than the other criteria. The last step during an overlay analysis process is to validate the model to make sure what the model indicates at a site is the case there.

2.8 GIS Mapping of Rainwater Harvesting Technologies

There have been several approaches over the years by different authors to identify and map rainwater harvesting potentials in several regions of the world. In most of these approaches, thematic maps are derived from remote sensing (RS) data and integrated in GIS to evaluate suitable locations for harvesting rainwater. RS and GIS are aids in the determination of rainwater harvesting location. GIS has been recommended as a problem-solving, decision-making tool in rainwater harvesting. Due to the ancient practice of harvesting rainwater, different technologies and approaches have been employed. Some of these technologies have different names in different parts of the world but are the same. Others have quite similar names but are different technologies.

About six key factors have been identified to be considered when identifying a rainwater harvesting location. These include; rainfall data, topography, vegetation, soil properties, socio-economic criteria and hydrology and hydrogeology of the area considered (Kahinda et al., 2005).

The Multi-criteria technique is applied to identify locations for rainwater harvesting technologies within the GIS context. This approach has been used in several other countries but would be new to Nigeria especially in the field of rainwater harvesting. The approach was found to be reliable for the evaluation of the multiple criteria and expert opinion in an efficient and precise pattern so as to produce suitable maps and tabular data (Mahmoud & Alazba, 2014). From their work, it was obvious that the combination of Multi Criteria Evaluation MCE-GIS has the potential to identify suitable locations for rainwater harvesting technologies.

2.9 Identifying the Appropriate Rainwater Harvesting Technologies for Different Land Uses

RWH technologies range from traditional methods practiced thousands of years ago to modern methods with improved technology practiced today. They also range from impounding water in a 20 litres plastic bucket to a sophisticated domestic RWH system. Individuals make decisions on the construction and maintenance of their systems. There have been several techniques applied all over the world to harvest rainwater. These are convenient cost-benefit techniques that are suitable and effective in the regions in which they are used.

2.9.1. Rainwater harvesting technologies

Rural areas still practice traditional RWH methods till date. Some selected methods of traditional water and rainwater-harvesting include: Negarims, semi-circular and trapezoidal bonds, *Fanya juu* in Africa. For the success of RWH technologies, detailed analyses of rainfall data, catchment properties, storage facilities and maintenance, purpose of harvesting rainwater, water consumption patterns, per capita income of population have to be taken into consideration. There are many other RWH technologies like the Khadin, Shuijiao and the Zings (Mbua, 2013)**.**

a. Broad-bed and furrow

Broad-bed and furrow, these are modified contour ridges, with deliberate effort to guarantee that there is a catchment ahead of the furrow. This system is within-field micro-catchment RWH system as shown in Figure 2.2. The catchment area otherwise known as the collection area is left bare, clear of vegetation to increase runoff. Other crops can be planted along the sides of the broad-bed and on the ridges. Plants requiring more water like peas and beans, are usually planted on the top side of the furrow, while cereal crops, like millet, are usually planted on the ridges. The distance between each ridge ranges between 1 m to 2 m, this depends on the slope gradient, the catchment area and the quantity of rainfall available. The broad-bed and furrow is suitable where the annual rainfall is within the range 350 mm -700 mm or more, land is of gentle/flat slope (between 0.5-3% steepness) and soil is moderately light. They are commonly used in Kenya, Ethiopia and Tanzania, (Duveskog, 2001; Mati, 2005).

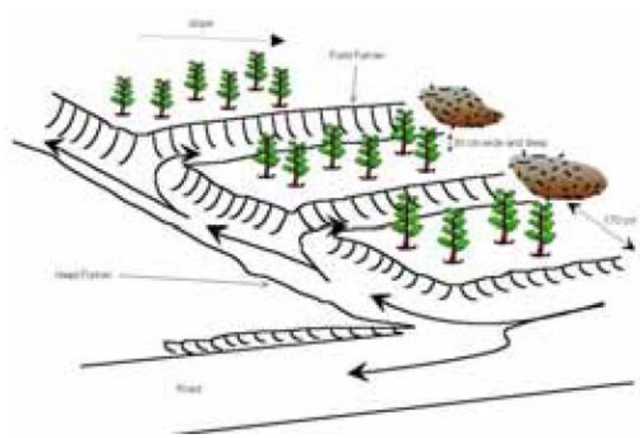

Figure 2.2 Broad-bed and Furrow (Mati, 2005)

b. Bench terraces

These are constructed by re-shaping steep slopes making them flat or almost flat beds, separated only by vertical risers. Bench terraces are made on very steep slopes, they are usually made to collect rainwater and channel it into farm lands for high-value crops like vegetables and coffee. They are usually designed with vertical breaks ranging between 1.2 m and 1.8 m. In Eastern Africa, bench terraces are hardly excavated directly rather, they are created over time from other methods of terracing such as grass strips, stone lines, trash lines or *fanya juu* terraces. Bench terraces are found in almost all countries and areas with steep slopes like Ethiopia, Kenya, Tanzania, Madagascar Rwanda, Burundi, Uganda, South Africa and Lesotho (Wenner, 1981; Mati, 2005).

c. Contour stone bunds

These are buffer strips made simply by arranging stones across the slope along the contour, forming a barrier as illustrated in Figure 2.3. The crop is planted directly ahead of the stone bund, making the other end of the bund free to be used as catchment. Since the bunds are quite permeable, they just slow down the runoff, serve as filters and spread the water all over the field, thereby enhancing water infiltration and reducing erosion. Contour stone bunds are usually practiced in areas receiving annual rainfall of about 200-750 mm and are spaced about 15-30 m apart, with smaller spacing on steeper slopes. They can be reinforced using crop or earth residues to stabilize them (Critchley & Siegert 1991; Hilhorst and Muchena 2000; Duveskog 2001).

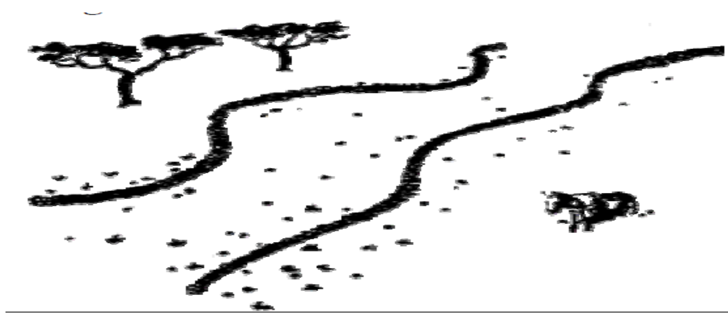

Figure 2.3: Contour Stone Bunds (Mati, 2005)

d. *Fanya juu* terraces

Fanya juu terraces are earthen embankments, constructed by digging trenches of about 60 cm width along the contour and casting the soil upslope to form a ridge (Figure 2.4). It efficiently reduces slope-length hence, prevents soil erosion from steep croplands. *Fanya juu* terraces are very suitable on moderate slopes with annual rainfall of about 500-1,000 mm. To stabilize the bunds, the planting of grass, trees and bushes along the terrace banks would do, also contributing to productivity and biodiversity. *Fanya juu* terraces are now found almost in all countries and have made productive impacts in agriculture (Thomas and Biamah, 1991; Lungren and Taylor, 1993; Tiffen et al., 1994).

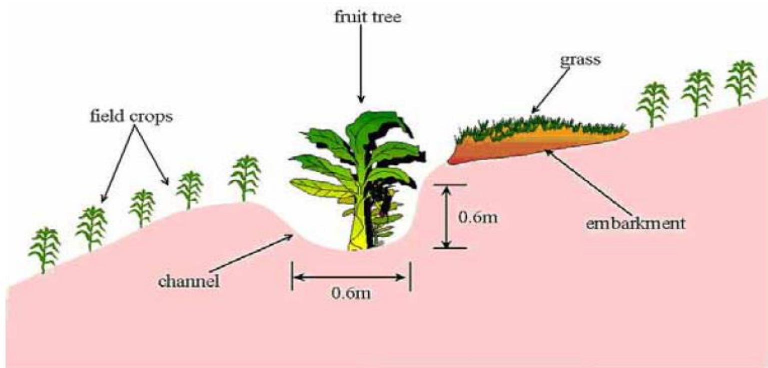

Figure 2.4: *Fanya juu* Terraces (Mati, 2005)

e. Flood water harvesting

Flood water harvesting includes a series of techniques for diverting and storing runoff in weirs, earth dams, ponds, sand dams and pans. This water can be used for supplemental irrigation or it can be harvested and directed into a cropped field to improve soil moisture directly. This is usually adopted in areas with very high rainfall and steep slopes (Mati, 2005).

f. Grass strips

Grass strips are vegetative buffers where grass is planted in thick strips, about 0.5 - 1m wide, all along the contour at intervals equal to the calculated terrace spacing. These lines are used to create blockades which reduce soil erosion and runoff, through a filtering process. Silt gradually build up in the front of the strip and over time, benches are formed. The space between each strip depends on the slope of the land. On gentle slopes, the strips are made with a wide spacing of about 20 - 30m while on steep slopes, spacing is about 10 - 15m. Grass requires regular trimming to prevent spreading to the cropped area. Grass strips are suited to areas with high rainfall (Mati, 2005; Thomas, 1997; Morgan, 1995).

g. Negarims

Negarims are a newer micro-catchment technique of designing basins, used for planting fruit trees. In their design, they are regularly shaped square earth bunds turned 45 degrees from the contour to concentrate surface runoff at the lowest corner of the square as shown in figure 2.5. They are efficient in land utilization. (Hai, 1998; Critchley & Siegert, 1991; Thomas, 1997).

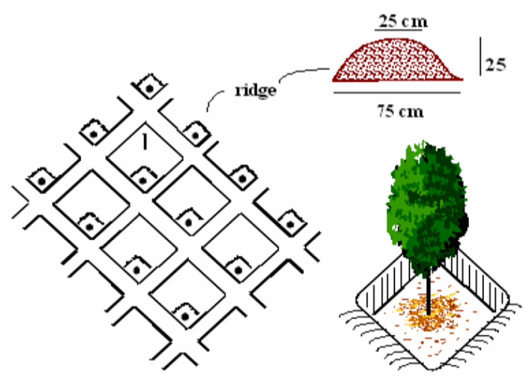

Figure 2.5: Negarims (Mati, 2005)

h. Ngolo pits

Ngolo pits otherwise known as Matengo pits, are categorized by a design of square pits and ridges, they are constructed using weeds and crop residues, on slopes about 35-60 % steepness. Ngolo technique involves a crop rotation mainly between beans and maize, with detailed activities to preserve the pits all through the season. It is quite effective in minimizing soil erosion on very steep slopes (Edje & Samoka, 1996; Mati, 2005).

i. Rock catchment

Rock catchments are a type of ground catchment techniques; however, they are characterized as a distinct category based on their difference from other ground catchment techniques like the gravity flow supplies. The runoff is collected using stone and cement gutters constructed on rock surface into concrete reservoirs or stone masonry dams as shown in Figure 2.6. Rock catchments can yield large quantities of water example; 100 mm of rain is equivalent to 1000 m^3 of water on an area of 10000 m^2. Where the rocks are at a higher elevation than the surrounding land, the water harvested can be supplied to stand pipes through a gravity-fed pipe network. Rock catchments have been popular in the Kitui and Laikipia districts of Kenya (Gould & Nissen-Peterson, 1999; Mati, 2005).

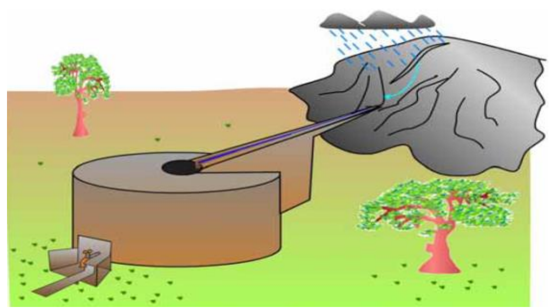

Figure 2.6: Illustration of a Rock Catchment (Mati, 2005)

j. Trapezoidal bunds

Trapezoidal bunds are large structures, about a 100 m long along the contour having wing walls turned about 135º facing upslope. These bunds are normally spaced about 20 m apart, and overflow arrangements are created in such a way that excess runoff from one bund can find its way to another bund just below it. Field crops like sorghum and millet are grown in the bunds. An example of a trapezoidal bund is the Teras system, a widespread system of large earth bunds with straight walls. It is used to cultivate drought-tolerant crops like sorghum (Critchley & Siegert, 1991).

2.10 Urbanisation and Its Effect on Rainwater Harvesting Potential

Urbanization is defined as the demographic process where an increasing share of the population of a nation lives within urban settlements." Settlements are also defined as urban only if most of their residents derive much of their livelihoods from non-farm occupations. It occurs due to the movement of people from rural to urban areas especially in developing countries. According to the UN Population Bureau (2010), Africa's population reached more than 1 billion in 2009, of whom around 40% lived in urban areas. It is expected to grow to 2.3 billion by 2050, of whom 60% will be urban (UN population Bureau, 2010). Urbanization is an important challenge for the next few decades but can be minimized since it is caused by several reasons like; lack of resources and social amenities in rural areas, the availability of public services in town and the intrinsic excitement of urban areas, poor health facilities and infrastructures in the rural areas (Mohamed et al., 2014).

Urbanization however, has some effects in both the environmental and economic aspects of every region. The effects are not always positive; air pollution results from poor mechanical and industrial practises, water pollution from poor sewage facilities and disposal of industrial wastes into waterways, traffic congestion and noise pollutions are synonymous to large cities. Urbanization would also have effect on the potentials of rainwater harvesting as more agricultural lands, uncultivated lands as well as forests and rocky areas would gradually be converted into residential areas, roads and other infrastructures. The effect of urbanization also cuts across climate and weather conditions.

Materials like concrete, asphalt, bricks etc absorb and reflect energy differently than vegetation and soil. Cities remain warm in the night when the countryside has already cooled. Cities often receive more rain than the surrounding countryside since dust can provoke the condensation of water vapour into rain droplets (Bhuvandas, 2014).

2.11 Climate Change and Its Effect on Rainwater Harvesting Potential

Climate change is a change in the statistical distribution of weather patterns when the change lasts for a longer period of time, usually a minimum of 30 years (AAS, 2018). It is a change in global or regional climate patterns, especially a change starting from the mid to late 20th century till now and attributed largely to the increased levels of atmospheric carbon dioxide produced by the use of fossil fuels. Climate change maybe an effect of natural processes example the sun's radiation or volcanoes, it can also be artificial for example, human activities such as use of fossil fuels or land use.

Most importantly as it concerns this study is the effect of climate change on rainfall variabilities. Rainfall variability will become more of the sign for climate change, different regions of the world will experience this differently (Kisakye et al., 2018). Some will experience droughts while others will experience excessive rainfall which might lead to flooding except if properly prepared for.

2.12 Knowledge Gap

In Nigeria, the recognition and application of RWH as a means of water supply is still in the research phase. The public as well as decision makers are yet to acknowledge rainwater harvesting as a major source of water (Lade & Oloke, 2015; Aladenola &Adeboye, 2010). Even when they come to this realization, there still would be a gap between the application of traditional/ancient rainwater harvesting techniques and the modern technologies allowing for more effective harvesting and use of rainwater. There have been many research works carried out in Nigeria on rainwater harvesting including Lade & Oloke (2015), Aladenola & Adeboye (2010), Adeboye & Alatise (2008), Ince et al. (2010) and Balogun & Oyedepo (2016). However, there is still so much more to be done. The quantity of rainwater which can be harvested is yet to be estimated. The different water needs which can be met by RWH in Abuja is yet to be defined, and most importantly the applicable technologies for effective/efficient rainwater harvesting are still unknown. The effect of landuse/land cover change and climate change on the potentials of rainwater harvesting as the region moves from rural to urban, has not been evaluated.

CHAPTER THREE: METHODOLOGY

3.1. Description of The Study Area

This research focussed on Abuja, also known as the Federal Capital Territory (FCT). Abuja is situated in the North Central zone. It is in the centre of Nigeria just north of the confluence of the Niger River and Benue River. Abuja lies between coordinates: 8°50’ N 7°10’ E/ 8.833° N 7.167° E, it has a total land mass of 7,315 km^2 (FCDA, 2015). Abuja municipal itself is one of the local government areas in Abuja, a well-planned city, built up mainly in the 1980s to replace the overcrowded coastal city of Lagos. It is approximately 480 km northeast of Lagos, the former capital of Nigeria until 12 December 1991. It was chosen as the new capital because of its central location, easy accessibility, salubrious climate, low population density and the availability of land for future expansion. It was the first planned city to be built in Nigeria. The position of Abuja and its local government areas in Nigeria are shown in Figure 3.1.

Abuja lies at 300 – 760 m above sea level and has a cooler climate and less humidity than is found in Lagos. Abuja has three weather conditions per annum; a warm, rainy season and a hot dry season. Just between the rainy season and the dry season, there is a short period of harmattan, with a major feature of dust haze, intensified coldness and some dryness. The rainy season begins in April till October, with daytime temperatures reaching about 28° - 30° C and night time temperatures range around 22° - 23° C. During the dry season, daytime temperatures can increase up to 40° C and night temperatures sometimes drop to 12° C. The high altitudes and rolling terrain of Abuja acts as a moderation on the weather of the territory. The annual total rainfall is in the region of 1100 mm to 1600 mm, making it a potentially good region for rainwater harvesting (CyBlug, 2018).

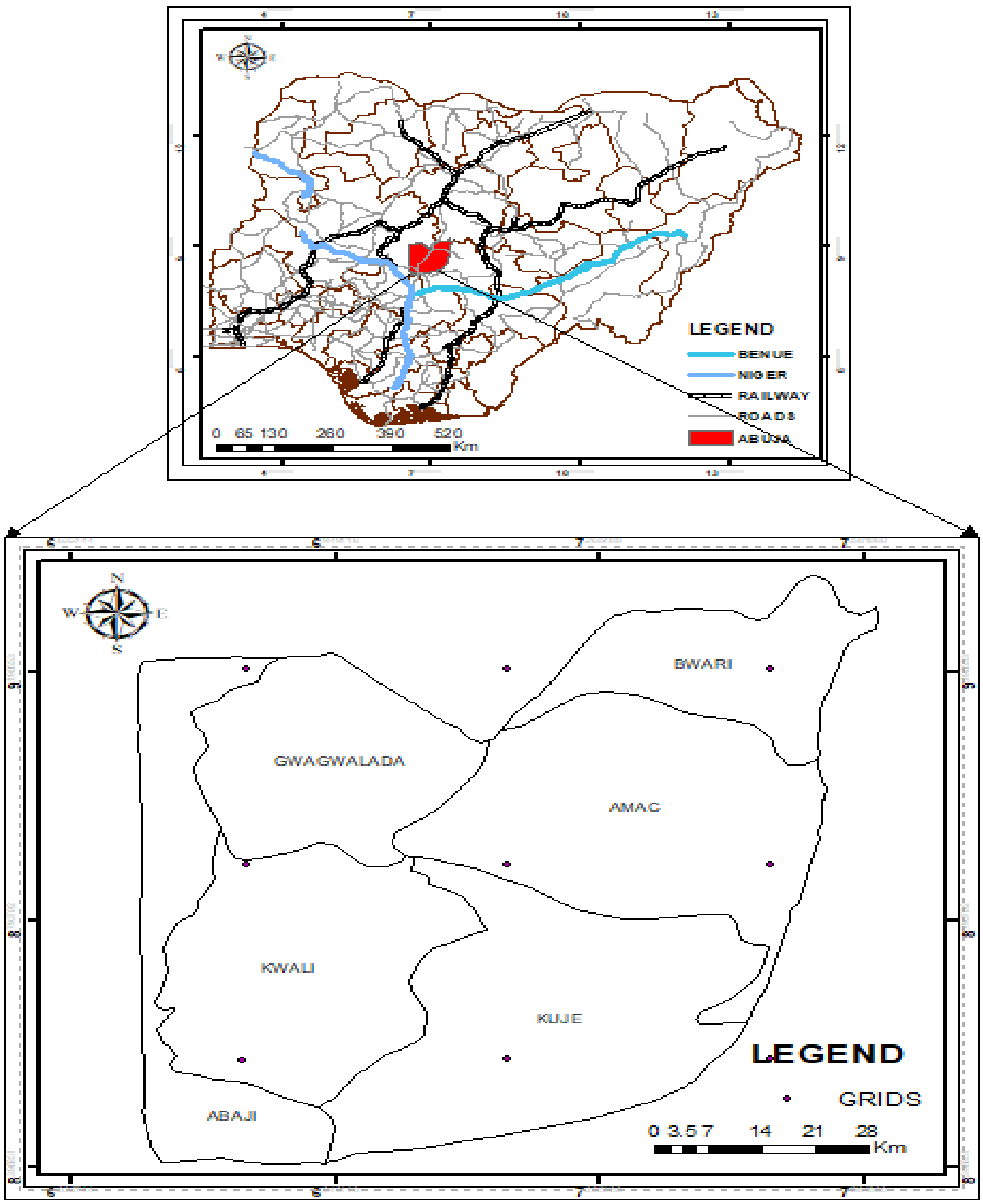

Figure 3.1: Location of Abuja in Nigeria (inset)

The population of Abuja as at 1991 was 107,069 which grew to 776, 298 in 2006 putting it among the first ten most populous cities in Nigeria. From then, Abuja grew at the rate of 139.7%. Between 2000 to 2010, it became the fastest growing city in the world (NBS, 2017). The population census done in 2011 gave an estimated population of 2,238,800. If the population growth rate would remain the same as in the period 1991-2015 (+13.91%/5year), Abuja population in 2017 has been estimated to be 3,166,506 which still makes it the fastest growing city in Africa and one of the fastest-growing cities in the world. Due to a huge influx of people into the city, there emerged satellite towns and smaller settlements towards which the planned city is sprawling. The shift from rural to urban in this region is very rampant and obvious yet it still depends on the previously existing resources to meet the needs of every resident.

Abuja is currently made up of six local councils, comprising of Abuja Municipal otherwise known as AMAC and five other Local Government Areas namely: Abaji, Gwagwalada, Kuje, Bwari and Kwali. All these local government areas have rural areas, villages in which water scarcity has become a major problem. And due to the cost of living in the city, life for them has also become too expensive and thus the need for another water source.

The lowest elevation in Abuja is found in the extreme southwest where the floor plains of the river Guraja is at an elevation of about 300 m above sea level. From there the land rises irregularly eastward, northward and north westwards. The highest part of Abuja is in the northeast where there are major peaks of over 760 m above sea level and hills occurring either in clusters or in the form of long ranges. The most prominent of these include the Guafata range southwest of suleja, the Bwari-Aso range in the Northeast, the Idon-Ka range north-west of Kuje and the Wuna range north of Gwagalada. Elsewhere in the territory, there are major rather roundish isolated hills often called iselbergs between the major plains and the ru-bock plains. Indeed, about 50% of Abuja consists of plains.

Peasant farming in Abuja aims chiefly at food crop production for domestic consumption and internal exchange. The most preferred areas for farming are the top hills and the bottom slopes. Two systems of crop production are commonly practiced i.e. bush fallowing and permanent cultivation. The crops which are commonly produced during the rainy season are rice, sugar cane, banana and plantain. Some of those produced through small-scale irrigation during the dry season are tomatoes, okra, maize and pepper. After this, the land is either utilized to grow vegetables or left to fallow for about six months (Agbo, Englama, & Philip-ogoh, 2014). Being the Federal Capital Territory of Nigeria, Abuja has its well planned residential areas, administration areas with roads, houses, offices, industries but it also has cultivated lands like every other state in Nigeria.

Abuja is almost predominantly underlain with high grade metamorphic and igneous rocks. The rocks consist of gneiss, migmatites, granites along the eastern margin of the area. The bed broadens towards the south and reaches a maximum development to the south-eastern part of the area where the topography is rugged, and the relief is high. In general, the rocks can be divided into five major types namely; metamorphosed Supra Crustal, Exogenic, Migmatitic Complex, Minor Intrusions and other formations like Quartzite, pegmatite etc. (Kogbe, 1976). The soils of the territory are generally dry in November due to the harmattan, the high sandy content makes the soils highly erodible. The shallow depth is a reflection of the presence of the lower horizons. However, on the famous Gwagwa plains there are deep and clayey soils, perhaps reflecting the presence of parent materials like gabbro and fine to medium textured biotite granite. Therefore, the soils of the Gwagwa plains are the most fertile and productive (Kogbe, 1976). The dominant vegetation of the territory is classified into three namely; park or grassy savannah – about 53%, savannah woodland – about 12.85% and shrub savannah – about 12.9% (Agbelade et al., 2017).

The conceptual framework of the adopted methodology is presented in Figure 3.2. It highlights the three objectives, the data utilized in each objective, the various analysis carried out on these data and the actives adopted to produce the results obtained. The objectives required very similar data; rainfall, landsat images which was used to create the landuse/landcover for abuja, SRTM DEM data for slope and then soil data. These data were collected and from different sources analyses using methods highlighted in the text.

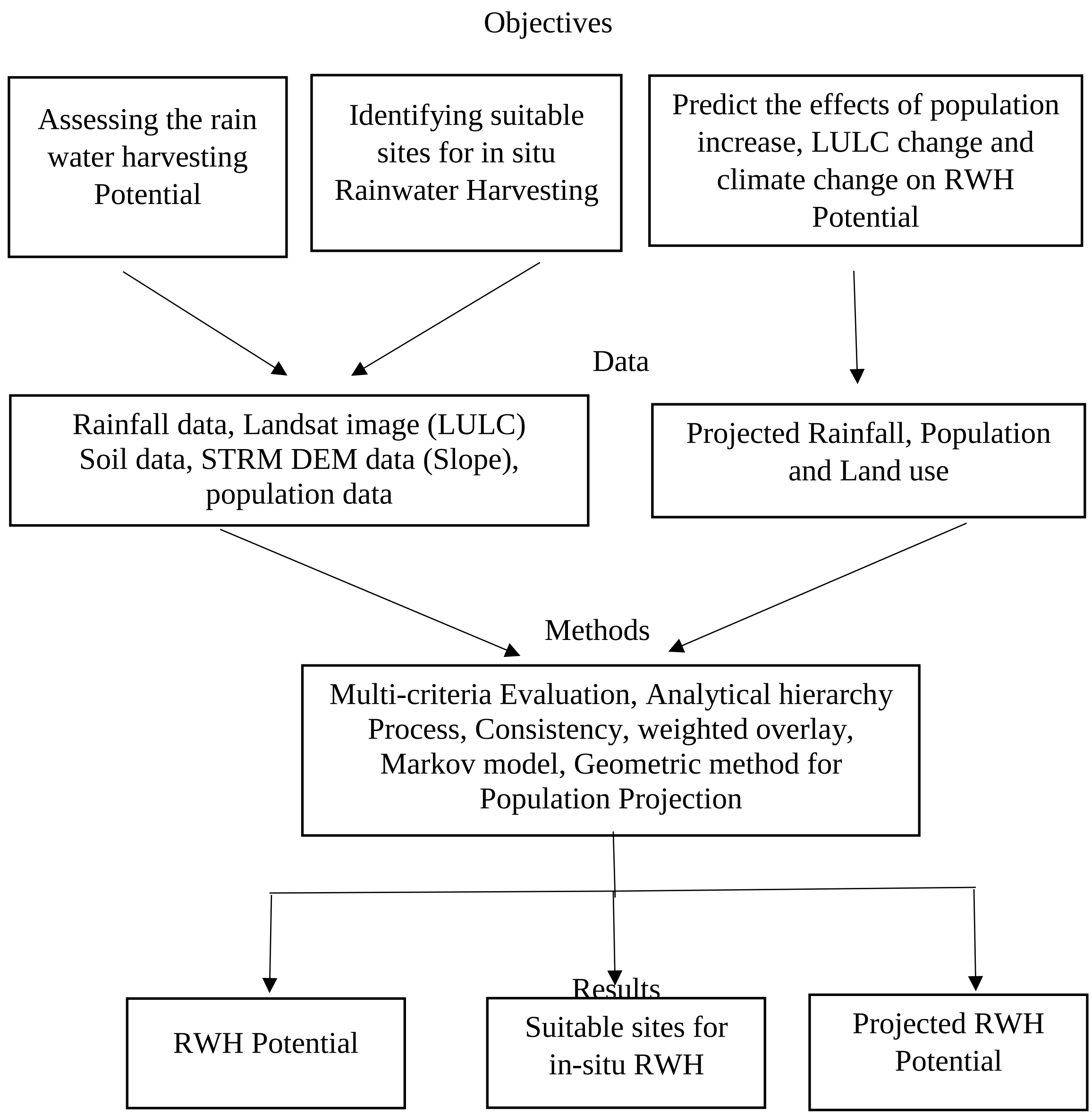

Figure 3.2: Summary of Specific Objectives, Data and Methods

3.2. Assessing the potential of rainwater harvesting

The relevant information in assessing the potential of RWH are; rainfall data, population data, land use maps, elevation maps and soil maps (Malesu et al., 2005). To collect actual data for rainfall, there are several ministries where this can be obtained from including the airport, meteorological agency, Ministry of Environment and Ministry of Agriculture. However, the rainfall data was collected from the meteorological agency in Abuja because it is the source from which other ministries collect data. After which, the total annual rainfall for the year 2016 was estimated and then the rainwater harvesting potential was determined using the total annual rainfall estimated.

3.2.1. Rainfall data and weather patterns

This is one of the important data relevant for RWH, without which there would be nothing to harvest. To assess the rainfall variability over the study area for the period 1991-2016, daily data was collected from the ground-based station of the Nigeria Meteorological Agency (NIMET) stationed at the Abuja International airport, while the satellite-observed data were obtained from the Tropical Rainfall Measuring Mission (TRMM). The ground-based data was compared with the satellite data for consistency as shown in Figure 3.3 and Table 3.1

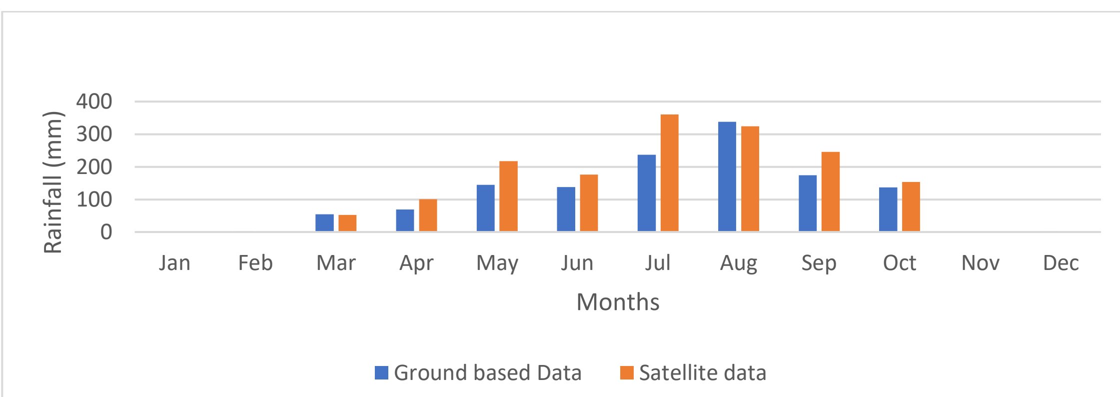

Figure 3.3: Comparison of Ground-based Data for Abuja and TRMM Satellite Data

Figure 3.3 shows the comparison of mean monthly rainfall. From the comparison, it was deduced that the satellite data is not very different from the ground-based data. The differences which was estimated to be about 8.5% might have been caused by some differences such as wind direction and temperatures which are not captured by the satellite stations (Harikumar et al., 2008).

Table 3.1: Ground-based/Satellite data

Month	Rainfall (mm)	
	Ground based Data	Satellite data
Jan	1.2	0
Feb	2.0	0
Mar	54.6	52.7
Apr	69.4	100.7
May	144.5	216.9
Jun	137.7	175.8
Jul	237.4	360.5
Aug	338.4	324.2
Sep	174.3	245.8
Oct	136.5	154
Nov	1.7	0
Dec	2.3	0

3.2.2. Population data

The last population census of Abuja was carried out in 2015 by the National Bureau of Statistics (NBS) and the percentage growth rate was estimated to be +13.91%/5year. Therefore, it was estimated that the population of Abuja would be 3,564,100 in 2016 using the same growth rate. Although this was for the whole state, the census is usually carried out with respect to local government areas before they are compiled. Therefore, the population of each local government area was obtained from the records of NBS.

Population density is the determination of the number of persons per area, either in square meters or square kilometres depending on the area studied and choice of units. According to the United States of America's National Geographic Society (USANGS, 2018), population density is estimated by dividing the population by the area enclosed.

3.2.3. Slope data

The Shuttle Radar Topography Mission (SRTM) 30 m DEM of the study area was obtained from United State Geological Survey/National Aeronautics and Space Administration/Shuttle Radar Topography Mission (USGS/NASA SRTM) through the USGS Earth explorer website www.usgsearthexplorer.org. The slope map was generated using the slope tool on ArcGIS after which the slope of the study area was reclassified into four categories as done by Mahmoud & Alazba (2014). The classification gave a view of the flat, moderate, steep and hilly regions in the study area.

3.2.4. Landsat data and land use/land cover

In this study the Landsat imagery was used to create the land use/land cover (LULC) map for the study area. The spatial resolution of Landsat imagery described in Table 3.2 was adequate for vegetative analysis particularly, to identify all kinds of vegetative cover (Fisher et al., 2017). Three scenes of Landsat images from the Landsat5, Landsat7 and Landsat8 were acquired for the land use/land cover of the years 1987, 2001 and 2016 respectively. These were all obtained online from the data archive of Global Land Cover Facility (GLCF) under the United States Geological Survey (USGS). The images acquired for the use of this study were all cloud free. These were modified and projected using Universal Transverse Mercator UTM 32N. World Geodetic System WGS 1984 Coordinate system of earth model by GLCF was used to create the maps. Table 3.2 shows a list of Landsat images acquired and their dates.

Landsat images are generally known to be efficient, simple and first choice when it comes to mapping on GIS. Three Landsat Imageries were downloaded from USGS. The LULC were classified into nine classes; water bodies, wetlands, cultivated lands, sparse vegetation, dense vegetation, forested areas, built-up areas, rock outcrops and bare surfaces. Adopting the LULC classification done by Udezo (2017) as well as Mahmoud & Alazba (2014), the classification was done by first loading the landsat images on Erdas Imagine 2014, then creating a false composite with bands 4,3 and 2. Training samples for the supervised image classification using maximum likelihood algorithm were created. With these samples the LULC classification was done.

Table 3.2: Summary of Images Used for the Research

Sensor	Reference System/ Path/Row	Spatial Resolution	Acquisition Date	Sources
Landsat 5ETM+	WRS/189/054	30 m	22-12-1987	http://earthexplorer.usgs.gov/
Landsat 7ETM+	WRS/189/054	30 m	28-11-2001	http://earthexplorer.usgs.gov/
Landsat 8 OLI and TIRS	WRS/189/054	30 m	22-12-2016	http://earthexplorer.usgs.gov/

3.2.5. Soil data

The soil data for Abuja was extracted from Harmonised World Soil (HWS) database. There exist five soil types in Abuja which are loam, sand, loamy sand, sandy clay and sandy loam (Kogbe 1976). With the soil types known, the composite runoff coefficient in relations to slope and LULC was calculated using the information for runoff coefficient given by Mohamed et al. (2014) as shown in Table 3.3.

Table 3.3: Relative Runoff Coefficient for Different Soil Types, Slope and Landuse

Land use	Slope (%)	Sand	Loamy sand	Sandy loam	Loam	Silt loam	Silt	Sandy clay loam	Clay loam	Silty clay loam	Sandy clay	Silty Clay	Clay
Forest	<0,5	0.03	0.07	0.10	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40
	0,5–5	0.07	0.11	0.14	0.17	0.21	0.24	0.27	0.31	0.34	0.37	0.41	0.44
	5–10	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50
	>10	0.25	0.29	0.32	0.35	0.39	0.42	0.45	0.49	0.52	0.55	0.59	0.62
Grass	<0,5	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50
	0,5–5	0.17	0.21	0.24	0.27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54
	5–10	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60
	>10	0.35	0.39	0.42	0.45	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.72
Crop	<0,5	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60
	0,5–5	0.27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.61	0.64
	5–10	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70
	>10	0.45	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82
Bare soil	<0,5	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70
	0,5–5	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.61	0.64	0.67	0.71	0.74
	5–10	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70	0.73	0.77	0.80
	>10	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85	0.89	0.92
IMP		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

From the Table 3.3, the composite runoff coefficient was estimated using the equation given by ODOT (2018):

$$C = \frac{C_1A_1 + C_2A_2 + \cdots C_nA_n}{A_{total}} \quad (4)$$

Where C is the composite runoff coefficient

C_1 to C_n are the corresponding runoff coefficients for different landuses, soil type or slope

A_1 to A_n are corresponding areas of different landuses, soil types or slopes

A_{total} is the sum of the areas considered from A_1 to A_n

3.2.6. Summary of Data Sources and Description

All data collected, their sources, description and scale/resolutions are summarized in the Table 3.4.

Table 3.4: Data Sources and Description

SN	DATA	Acquisition Date(s)	Data format	Scale/Resolution	Data Sources	DESCRIPTION
1	Landsat	(1987-2016)	Digital	30 m	www.glovis.org	Image Classification; LULC analysis
2	Soil Texture Map	2008	Digital	1:250,000	HWSD	Soil texture & classification
3	Shapefile	1994	Digital Map		NASRDA	To delineate the extent of the study area
4	SRTM (DEM)	2014	Digital Map	30 m	Digital web	The Digital Elevation was derived from it.
5	TRMM	2016	Numerical		www.pmm.nasa.gov	Rainfall
6	WBCCP	2018	Numerical		www.wbccp.org	Projected Rainfall
7	Population	1991-2016	Numerical		NBS	Population density, dynamics & Projection

3.2.7. Model building

With the data collected, the rainfall, slope, soil and the land use/land cover maps were created and overlaid on GIS database giving a model of the distribution of rainwater harvesting potentials. After the overlay operation, the classifications were in three and four categories depending on the result obtained. Theses classifications were termed excellent, very good, good and moderate in the case of four categories. Malesu et al. (2005) and Mahmoud & Alazba (2014) used similar method for assessing the rainwater harvesting potentials as illustrated in Figure 3.4.

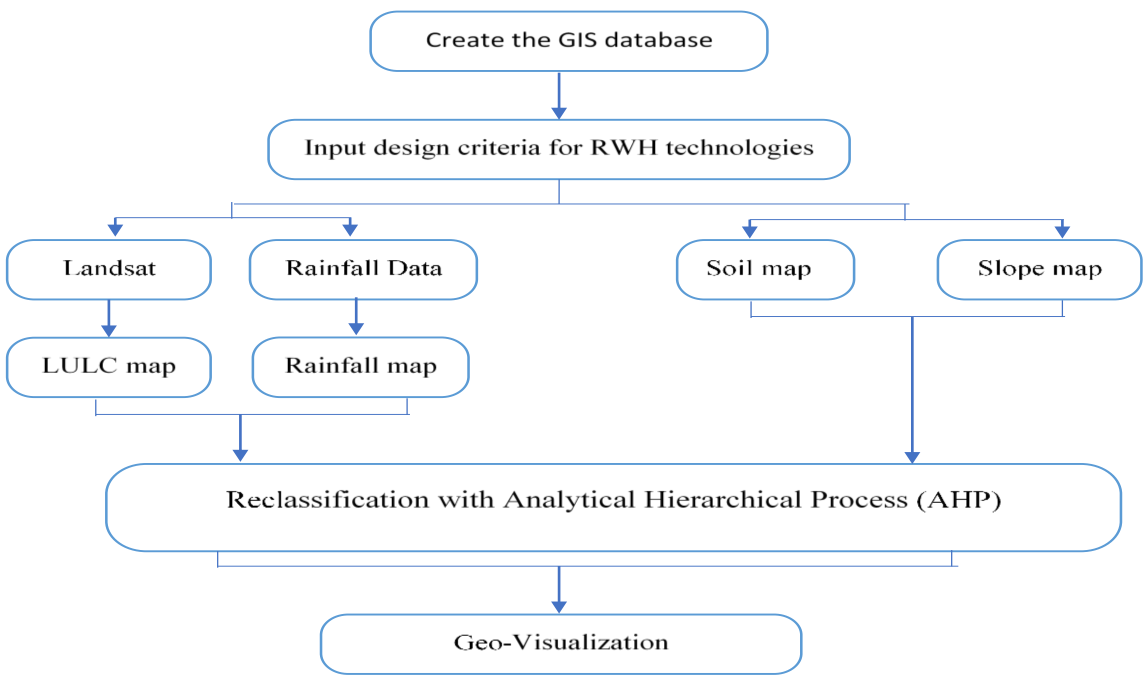

Figure 3.4: Model Design for Assessing Potential of RWH

The GIS database contains baseline thematic maps which capture the major physical and hydrological factors associated with rainwater harvesting such as rainfall, topography, soils and socioeconomic prevailing conditions such as population density and land use. This stage involved using map analysis tools and calculations on GIS, by combining two or more baseline maps. The final map obtained showed all areas which are suitable for in-situ RWH and their potential suitability. The AHP tool and Weighted overlay tool on GIS was used to determine the RWH potential (Malesu et al., 2005).

I. Image Pre-processing

Image pre-processing consists of those operations that prepared the data set for subsequent analysis. One of the analyses deals with compensating for systematic errors, which are errors that come as a result of the effects of numerous atmospheric and radiometric factors, such as sensor spectral properties, atmospheric scattering, and change in illumination. These parameters can cause difficulty in comparing more than one image of the same scene which are taken under different conditions (Schott et al., 1988). Removal of these effects from the digital data leads to the restoration of the images to their correct or original condition. Image restoration can be broken down into two; radiometric restoration and geometric restoration. Radiometric restoration is the removal of shadows from an image using finer resolution panchromatic images while geometric restoration involves fixing projection details of an image onto another image to make that image planimetric. Both of these meethods are employed to remove both systematic and non-systematic errors.

II. Imagine Processing

The images were loaded into Erdas Imagine 2013 interface and a false colour composite was formed using bands 4, 3, 2, that is, the infrared, red and blue bands respectively. The supervised image classification of the images was carried out using the Maximum

Likelihood algorithm. This was based on the data obtained for the training areas in the ground truthing. The classification of the image provided the aerial extent of each land cover type which was used to assess the changes in land cover over the 30 years period (1987-2016).

III. Analysis of Land Use/Land Cover of the Study Area

On a global and even local scale, the various factors of RWH vary in both space and time. This study therefore tried to represent all by Presentation of GIS maps that showed the distribution and aerial extents of land use systems and classes, to show the great advantage of the satellite remote sensing and GIS technologies over the conventional land use survey techniques. Each land use feature was identified and mapped using supervised classification method. The description of the landuse/land cover classes was based on the description given by Mahmoud & Alazba (2014) and Udezo (2017) as shown in Table 3.5.

Table 3.5: Description of LandUse/Land-Cover

S/N	Land-Use/Land-Cover	Descriptions
1	Built-Up	Residential, industrial and commercial units, road railway networks and other associated lands
2	Vegetation	Natural and manmade forests, natural grasslands, woodland, shrubs, sparsely planted trees
3	Bare Surface	All empty spaces, sands
4	Water Body	Streams, rivers, dams and ponds
5	Rock	Rocky areas

IV. Reclassification of Slope Map

The slope map was created using the slope tool on ArcGIS which produced 10 classes which were reclassified into 4 classes in order to have a common value. The slope map classification was achieved using symbology under the diagram properties in the model. The reclassification of the slope map helped in grouping different slope range in different slope classes during criteria evaluation and as such provided a proximity surface for rainwater harvesting technologies.

V. AHP and Weighted Overlay Process

In this study, the pairwise comparison scale by Saaty (1980) was adopted. The hierarchy is the final goal which is to determine potential for RWH. The next stage in the hierarchy is the criteria needed to determine the potential. For example, surface RWH potential, the criteria used were rainfall, soil, slope and LULC. The ranking in this stage helps to reclassify each of the criteria maps into their different ranks. The advantage of this hierarchical decomposition is simply to clearly understand the decisions as well as results to be obtained, the criteria to be used and the alternatives present (Decision Lens, 2015).

a. Determining Priorities Weight for each Criteria

The criteria in this study are of different importance, for example, in-situ RWH, rainfall is very important followed by the LULC, slope and soil respectively. The second step in the AHP process is to determine the relative weight of each criteria. This is called relative because the derived criteria priorities are measured with respect to each other.

I) Pairwise comparison for surface RWH.

Table 3.6 shows the pairwise comparison matrix of the criteria for surface RWH as employed in this study.

Table 3.6 Pairwise Comparison Matrix

Surface RWH	soil class	slope class	LULC class	rain class
soil class	1	0.5	0.33	0.25
slope class	2	1	0.33	0.2
LULC class	3	3	1	0.33
rain class	4	5	3	1

For a pairwise comparison to be carried out, the pairwise comparison matrix of the criteria to be considered must be prepared, an example of which is shown in Table 3.6. All cells in the matrix must have numeric values to express the relative preference (also known as intensity judgement) in every compared pair. Pairwise comparison matrix with importance judgement shows the importance or relevance placed on each criterion. Assuming we consider the rain class to be very strongly more important than soil class, the rain class-soil class comparison cell will contain the value 7 as shown in Table 3.7. It does not matter how many criteria are involved in the decision making, the AHP method simply compares a pair of elements per time. The comparison matrix in Table 3.7 shows the pairwise relative judgment for the criteria involved in Surface RWH.

Table 3.7 Pairwise Relative Judgment

Surface RWH	soil class	slope class	LULC class	rain class
soil class	1	0.33	0.2	0.14
slope class	3	1	0.33	0.2
lulc class	5	3	1	0.33
rain class	7	5	3	1

II) Column Addition

This is the second stage in the calculation of the weight of each criterion used in the pairwise comparison. It is simply summing up the values in each column as shown in Table 3.8.

Table 3.8 Summation of Values in Columns

Surface RWH	soil class	slope class	lulc class	rain class
soil class	1	0.33	0.2	0.14
slope class	3	1	0.33	0.2
lulc class	5	3	1	0.33
rain class	7	5	3	1
Sum	16	9.33	4.53	1.67

III) Normalized Matrix

Normalized matrix is done using an excel spreadsheet or AHP-based software or tool. It involves dividing each value in the pairwise comparison matrix by the total of its column. For example, the first column in Table 3.9 is divided by 16 to produce the first column in Table 3.9. That is repeated for all for columns in this example.

Table 3.9 Normalized Matrix

Surface RWH	soil class	slope class	lulc class	rain class
soil class	0.0625	0.0354	0.0442	0.0838
slopeclass	0.1875	0.1072	0.0728	0.1198
lulc class	0.3125	0.3215	0.2208	0.1976
rain class	0.4375	0.5359	0.6623	0.5988

IV) Weight of each criterion

The weight of each criteria is obtained using the normalized matrix as illustrated in Table 3.10. This is done by calculating the average value of each row in the normalized matrix.

Table 3.10: Normalized Matrix and Weight of Each Criteria

surface RWH	**soil class**	**slope class**	**lulc class**	**rain class**	**Weight**
soil class	0.0625	0.0354	0.0442	0.0838	0.0565
slopeclass	0.1875	0.1072	0.0728	0.1198	0.1218
lulc class	0.3125	0.3215	0.2208	0.1976	0.2631
rain class	0.4375	0.5359	0.6623	0.5988	0.5586

V) Weight and the original pairwise matrix is shown in Table 3.11. It is the original pairwise judgment matrix and the weight of each criterion.

Table 3.11 Pairwise Judgement Matrix and Weight

surface RWH	soil class	slope class	lulc class	rain class	Weight
soil class	1	0.33	0.2	0.14	0.0565
slope class	3	1	0.33	0.2	0.1218
lulc class	5	3	1	0.33	0.2631
rain class	7	5	3	1	0.5586

b. Consistency

Once judgement is made, it is important to verify the consistency of the judgement made. This is illustrated in the following example.

I) Start with the matrix showing the judgment comparisons and derived weights which is presented in Table 3.11.

II) Use the weights as factors (priority) for each column as shown in Table 3.12.

III) Multiply each value in the first column of the comparison matrix in Table 3.12 by the first criterion weight (i.e., 1 x 0.0564 = 0.0564; 3 x 0.0564 = 0.1694; 5 x 0.0564 = 0.2823; 7 x 0.0564 = 0.3952) as shown in the first column of Table 3.13; multiply each value in the second column with the second weight; continue this process for all the columns of the comparison matrix (in our example, we have four columns). Table 3.13 shows the resulting matrix after this process has been completed.

Table 3.12: Weight as Factors

surface RWH	**soil class**	**slope class**	**lulc class**	**rain class**
weight	*0.05645*	*0.1218*	*0.2631*	*0.5586*
soil class	1	0.33	0.2	0.14
slope class	3	1	0.33	0.2
lulc class	5	3	1	0.33
rain class	7	5	3	1

Table 3.13: Calculation of Weighted Column

surface RWH	**soil class**	**slope class**	**lulc class**	**rain class**
soil class	0.0564	0.0402	0.0526	0.0782
slope class	0.1693	0.1218	0.0868	0.1117
lulc class	0.2823	0.3654	0.2630	0.1843
rain class	0.3952	0.6091	0.7892	0.5586

IV) Add the values in each row to obtain a set of values called weighted sum as shown in Table 3.14

V) Divide the elements of the weighted sum vector (obtained in the previous step) by the corresponding weight of each criterion as shown in Table 3.15. Calculate the average of the values from the previous step; this value is called λ_{max}.

$$\lambda_{max} = (4.0290 + 4.0202 + \ldots 4.2108)/4 = 4.1057.$$

VI) Then we calculate the consistency index (CI) as follows:

$$CI = (\lambda_{max} - n) / (n-1) \qquad (2)$$

Where n is the number of compared elements (in this example n =4).

Consistency index is therefore,

$$CI = (\lambda_{max} - n) / (n-1) = (4.1057-4) / (4-1) = 0.0352$$

Table 3.14: Calculation of Weighted Sum

surface RWH	**soil class**	**slope class**	**lulc class**	**rain class**	**Weighted sum**
soil class	0.0564	0.0402	0.0526	0.0782	0.2274
slope class	0.1693	0.1218	0.0868	0.1117	0.48975
lulc class	0.2823	0.3654	0.2630	0.1843	1.09522
rain class	0.3952	0.6091	0.7892	0.5586	2.35226

Table 3.15: Calculation of Lambda(λ)

weighted sum	**weight**	**Lambda λ**
0.2274	0.0564	4.0290
0.4897	0.1218	4.0202
1.0952	0.2630	4.1627
2.3522	0.5586	4.2108
	Total	16.4229
Divide Total by 4 to get λmax		4.1057

VII) Now, the consistency ratio can be calculated thus:

$$CR = CI/RI \qquad (3)$$

$$CR = 0.0352/0.89 = 0.0396$$

Since this value of 0.0396 for the proportion of inconsistency CR is less than 0.10, assuming that our judgments matrix is reasonably consistent, so we may continue the process of decision-making using AHP.

c. Carrying out Weighted Overlay Process

The Weighted Overlay Process (WOP) allows the implementation of several steps in the general overlay analysis process all in one tool. It combines the following steps

I) It reclassifies values in all input raster layers into a common evaluation scale of suitability or preference, similarities or risks, as the case may be.
II) It multiplies the values of the cells in each input raster file by the raster's weight of importance.
III) It then sums the resulting values of each cell to produce the final raster file which is the suitability raster file.

Generally, the values of continuous raster files are grouped into ranges, example; slope. Each range must be given a single value before it can be introduced to the weighted overlay tool. There are other tools which allow reclassification of such raster files like; the 'reclassify tool' on GIS. In our example from the AHP, each raster file had already been reclassified and assigned values. Since the layers from the previous example have been reclassified, they can now be loaded into the weighted overlay tool along with their weights. The cells in the layer were ranked, then the output raster produced a range of potential. In the output raster, higher values indicate that a location has a higher potential than the areas with lesser values.

d. Determining the RWH potential on GIS after the weighted overlay

With the weights obtained from the AHP process for surface RWH above, the weighted overlay on GIS is carried out. This overlay produces a suitability map which shows the potential of RWH and categorizes or ranks it to explain which areas are most suitable. Higher values indicate that a location is more suitable. The suitability from the weighted overlay is explained as follows:

Assuming Point A in the study area of the four criteria maps used in the AHP example above have a ranking of 5 in all four maps, (i.e., the rain class is 5, LULC class is 5, slope class is 5 and soil class is also 5) the overlay result would show that exact point to have a potential of 5 as illustrated in Table 3.16; which means it has a high potential for Surface RWH.

Table 3.16: Potential for Point A

Point A	**Cell Value**	**Weight**	**Resulting Cell Value**
soil	5	0.0564	0.2823
slope	5	0.1218	0.6091
lulc	5	0.2630	1.3154
rain	5	0.5586	2.7930
		Potential	5

The values are the classifications of each layer at Point A, this means that at point A, rainfall is classified as 5, LULC is also classified as 5 as well as slope and soil. The weights of each criteria are the same as the ones from Table 3.10 and Table 3.11. The resulting cell values is the multiplication of the cell values at Point A with the weight of each criteria (i.e., soil – 5 x 0.05646306 = 0.282315276… rain – 5 x 0.55861493 = 2.793074664) as shown in Table 3.16. The final suitability value is the sum of the resulting cell values for all criteria. In our example the suitability of Point A is 5.

Take another example of Point B in Table 3.17, having a variation in the cell values where soil is classified as 5 but slope is classified as 3 and LULC is classified as 1 but rainfall is classified as 5.

Table 3.17: Potential for Point B

Point B	**Cell Value**	**Weight**	**Resulting Cell Value**
soil	5	0.0564	0.2823
slope	3	0.1218	0.3654
lulc	1	0.2630	0.2630
rain	5	0.5586	2.7930
		Potential	3.7039

Now the suitability for Point B has reduced to 3.7039 as shown in Table 3.17. This is because the cell values which indicates its position in slope map to be moderate and on the LULC map to be low. The variations of the individual cell values for Point B resulted in the potential result.

3.3. Identifying Appropriate Rainwater Harvesting Technologies

There are several rainwater harvesting interventions in existence. However not all of these interventions/technologies are applicable in every location. According Gould & Nissen-

Peterson (1999), Malesu et al. (2005), Kahinda et al. (2008) and Mahmoud & Alazba (2014), all rainwater harvesting technologies can be generally classified under three major categories.

2.7.6. Rooftop rainwater harvesting

Rooftop RWH is one of the easiest ways of providing drinking water at household level and all that is required is a roof which would serve as the catchment area as illustrated in Fig.3.4. In countries where settlements have been mapped such as Nigeria, it is possible to show where rooftop RWH can be targeted. By applying mapping masks (a mask hides unwanted information), it is possible to prioritize where rooftop RWH would be most appropriate (Malesu et al., 2005). GIS was used as a platform for estimating the roof-area of residential areas in the region with the use of attribute and spatial data from the land use classification database. The roof-areas of buildings in residential areas were estimated by multiplying the residential area by its BCR (building coverage ratios). BCRs are defined by Liaw & Chiang (2014) as the ratio of the building area to the construction site area. After assessing the runoff of several roofs to more precisely determine the runoff coefficients (C), the most commonly used roofs are the inverted-V (iron sheet and frame), level cement, parabolic, and saw tooth roof as shown in Figure 3.6. Table 3.18 shows the characteristics of the runoff coefficients for these roof types. According to Liaw & Chiang (2014), the runoff coefficient increases as the amount of rainfall increases. However, it becomes a constant value after a certain rainfall value for all roof types. All the roof types shown in Figure 3.5 exhibited similar average C values. Therefore, a single value of C (0.82) was used and adopted here as well (Liaw & Chiang, 2014).

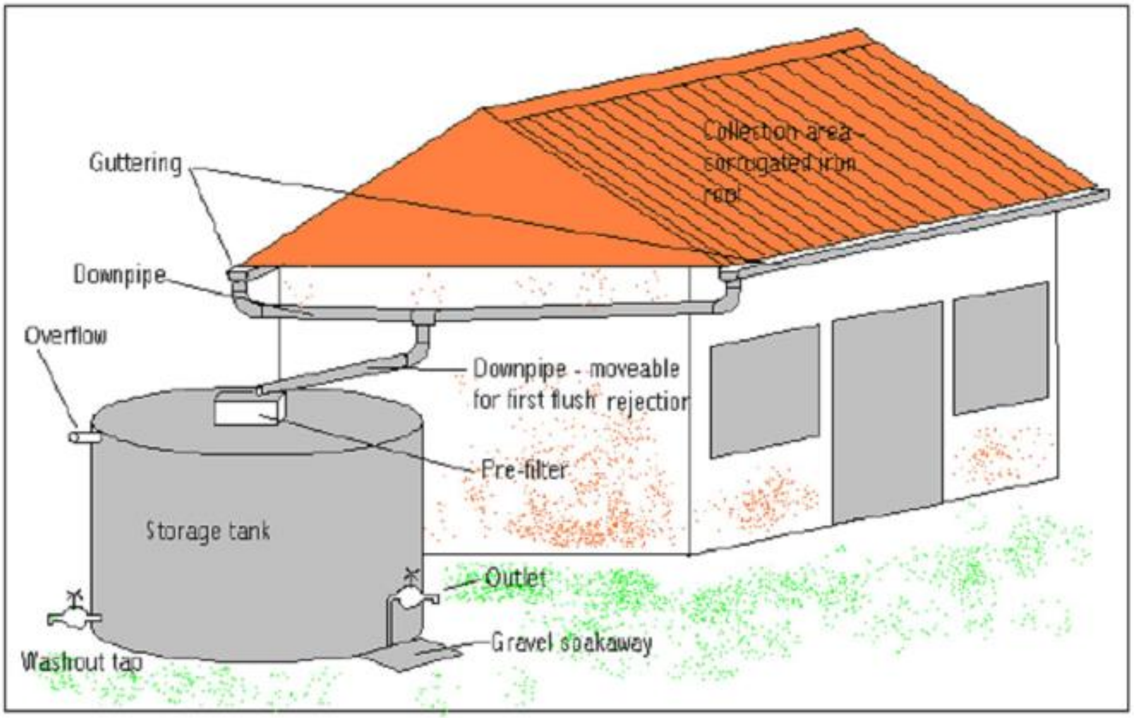

Figure 3.5: Illustration of Rooftop Rainwater Harvesting

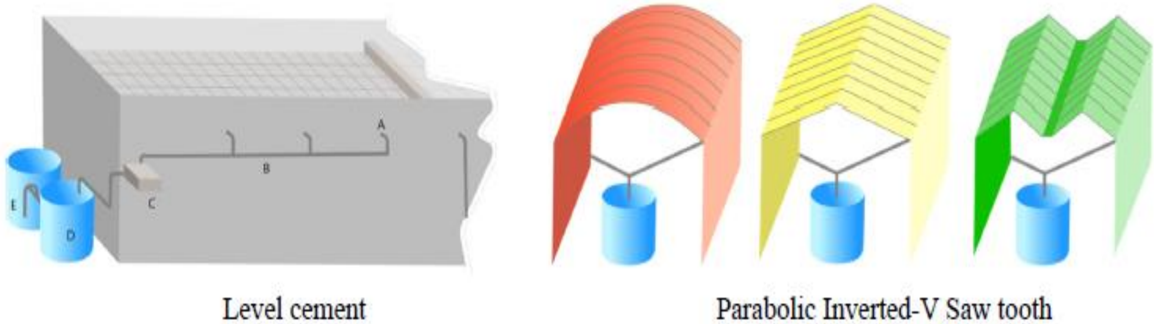

Figure 3.6: Four Different Roof Types

Table 3.18: Variation of C Values for These Four Types of Roof

Roof Types	Inverted-V	Level Cement	Saw Tooth	Parabolic
N	84	90	79	87
$\bar{C}$	0.82	0.81	0.83	0.81
${\sigma_C}^2$	0.076	0.068	0.095	0.066

Source: (Liaw & Chiang, 2014)

Notes:

N: No. of samples of rainfall events from the same roof;

$\bar{C}$: Average C value;

${\sigma_C}^2$: Standard deviation of C value.

2.7.7. Surface runoff collection from open surfaces

This involved considering all open surfaces in the study area, such as roads, home compounds, hillsides, open pasture lands and runoff from watercourses and gullies. Every of such surfaces on the LULC map were classified based on an assumed possibility to allow the low of water based on the soil texture or surface material and slope. Surface runoff collection can be implemented almost anywhere (Gould & Nissen-Peterson, 1999). However, site selection is based on availability of settlements rather than population density. The runoff coefficient for the soil texture and slope of the region will enable the determination of what quantity of rainwater can be harvested.

2.7.8. In-situ rainwater harvesting

All 100 in-situ RWH technologies recorded in Mati (2005) were considered using their design criteria as a base of analysis on the GIS platform. Some of these criteria include; size of catchment area, purpose of harvest (that is type of crop), the quantity of rainfall required per annum, quantity of rainwater that can be harvested due to the evapotranspiration of that region, land slope, land use. Therefore, in order to accurately select the types of rainwater harvesting technologies which can be adopted in the region, each technology and their criteria was analysed on the GIS platform. All the individual maps for appropriate technologies were combined to produce one map of the area showing all the appropriate technologies and the class of potential they fall under.

3.4. Assessing the Effects of Climate Change and Urbanisation on The RWH Potential of Abuja

In assessing the effects of urbanisation, past data of the local government area showing the population and the direction in which it has shifted to over the years was determined. Depending on the data collected and using approximately the same growth rate and shift rate the projection into the future can be determined easily and the effect on RWH potentials estimated. Adopting the method used in Jimme et al. (2015), the land use projection as well as the shift from rural to urban was determined.

The three main change detection methods which have been previously applied by several researchers like Adeniyi & Omojola (1999) and Ikusemoran (2009a) were employed. They included three steps;

I. The calculation of the magnitude of change, which was derived by subtracting the observed change of each period of the years from the previous period of years.
II. Calculating the trends that is the percentage change of each the land uses, by subtracting previous land use from most recent land use and dividing by the previous land use multiplied by 100.
III. Calculating the annual rate of change by dividing the percentage change by 100 and multiplied by the number of the study years.

The data collection, analysis and methods adopted for the projection and assessment of RWH potential is illustrated in Figure 3.7. The objective is to project rainfall, LULC and population with which the potential for RWH will be assessed.

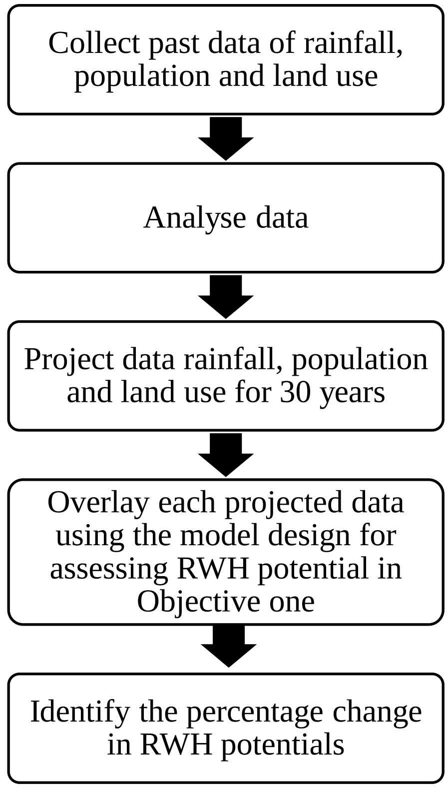

Figure 3.7: Model Design for Assessing the Effect of Climate Change and Urbanisation on RWH Potential

3.4.1. Population projection

The population of Abuja has been on a constant increasing side making it one of the fastest growing states in Nigeria. Its five-year growth rate was recorded by the National Bureau of Statistics to be about 13.19%. This growth rate was used to project the population for 2046 to have a futuristic overview of the RWH potential in Abuja. The geometric method under the simplistic model was adopted for population projection, this method uses historical data and growth rate and it is used in most local government population projection. The simplistic model for population projection assumes that past trends will continue and no major legislative or tax change is expected, according to the United States Census Bureau (2018). The geometric method is shown in equation 5.

$$P_t = P_0(1 + k)^n \qquad (5)$$

Where P_t is the population at some time in the future, P_o is the present or initial population, t is the period of the projection in decades and k is the average population increase (geometric mean) and n is the period of projection.

A time gap of (n) equal to 30 years was chosen to prevent excessive estimations either upwards or downwards but still understand what the potential might be like in the future. The population density was determined from the projected population and the map for 2046 was created with the projected population density.

3.4.2. Rainfall forecast

The rainfall data is a relevant component in estimating the rainwater harvesting potential for Abuja, however, in order to estimate the rainwater harvesting potential for the year 2046, there must be a forecast of the climatic conditions expected at that time. In this study, the rainfall forecasted data was directly collected from the World Bank Climate Change Portal where they had already done the forecasting.

3.4.3. Land use/land cover projection

Land use/land cover is an important component of the study of rainwater harvesting as already stated, the need to understand and estimate the LULC change is essential for this study as different RWH technologies are dependent on the different land use classifications. However, to project the LULC there must be past data to base the projection on. In this study, the LULC of the years 2001 and 2016 was done to aid the projection of the LULC for the year 2046. After running the supervised classification using Maximum-likelihood method for 2001 and 2016 landsat imageries, the Markov model in LULC change was adopted.

Markov model is a reliable tool for simulating LULC change in situations where changes and processes in the LULC prove to be complex to describe (Logsdon et al., 1996). A Markov process is a process where the later state of a system can be defined simply by the immediately preceding state. Markov model simulates LULC changes from one time to another using this as the basis to explain future changes. This is done by creating a transition probability matrix for LULC change from one time to the next time, this shows the characteristics of the change as well as serves as the foundation for projecting to a future time-period. Markov model gives a simple methodology with which a dynamic system can be dissected and explained (Dongjie et al., 2008; Zhang et al., 2011; Huang et al., 2008; Muller & Middleton, 1994). Several researches have attested to the efficiency of the Markov model (Zhang et al., 2011; Jianping et al., 2005). The formula simulated by Markov model is explained thus;

To Convert one state to a new state of a system is known as state transition. For example, when P is the transition probability, also known as the probability of converting present state to a new state in later time. It is expressed as follows:

$$P = P_{ij} = \begin{matrix} P_{11} & P_{12} \ldots & P_{n1} \\ P_{21} & P_{22} \ldots & P_{n2} \\ P_{1n} & P_{2n} \ldots & P_{nn} \end{matrix} \qquad (6)$$

Where P is the probability from state *a* to state *b* (Jianping et al. 2005; Dongjie et al. 2008). The major step in the Markov model is in getting the primary matrix and the matrix for transition probability (P_{ij}) which relates P_{i1j1} P_{i2j2} P_{i3j3}….P_{injn}.

The probability matrix for the year 2046 on IDIRISI by extracting the trend between 2001 and 2016 (15 years) was obtained using the Markov probability matrix. A stochastic choice analysis was done to generate a map for the LULC projection for the year 2046.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Precipitation Analysis

The ground and remotely sensed satellite derived precipitation data for Abuja were acquired and the average annual precipitation calculated. The average rainfall for Abuja for this study after considering 16 stations is shown in Figure 4.1 ranged from 1170 mm to 1470 mm per annum.

The results of the rainfall map show 5 different range of annual rainfall quantity all around Abuja. This was based on the data collected from TRMM for the year 2016. The range includes 1170 – 1230 mm as the lowest annual rainfall and 1410 – 1470 mm as the highest annual rainfall in Abuja for the year 2016. This rainfall range for 2016 falls within the range (1100 – 1600 mm) stated by CyBlug, (2018). About a quarter of the state's area falls within the range of the lowest annual rainfall (1170 mm), though a smaller area in Abuja experiences the highest annual rainfall all other areas fall within the range of 1230 – 1410 mm making the total area of Abuja very well rain fed.

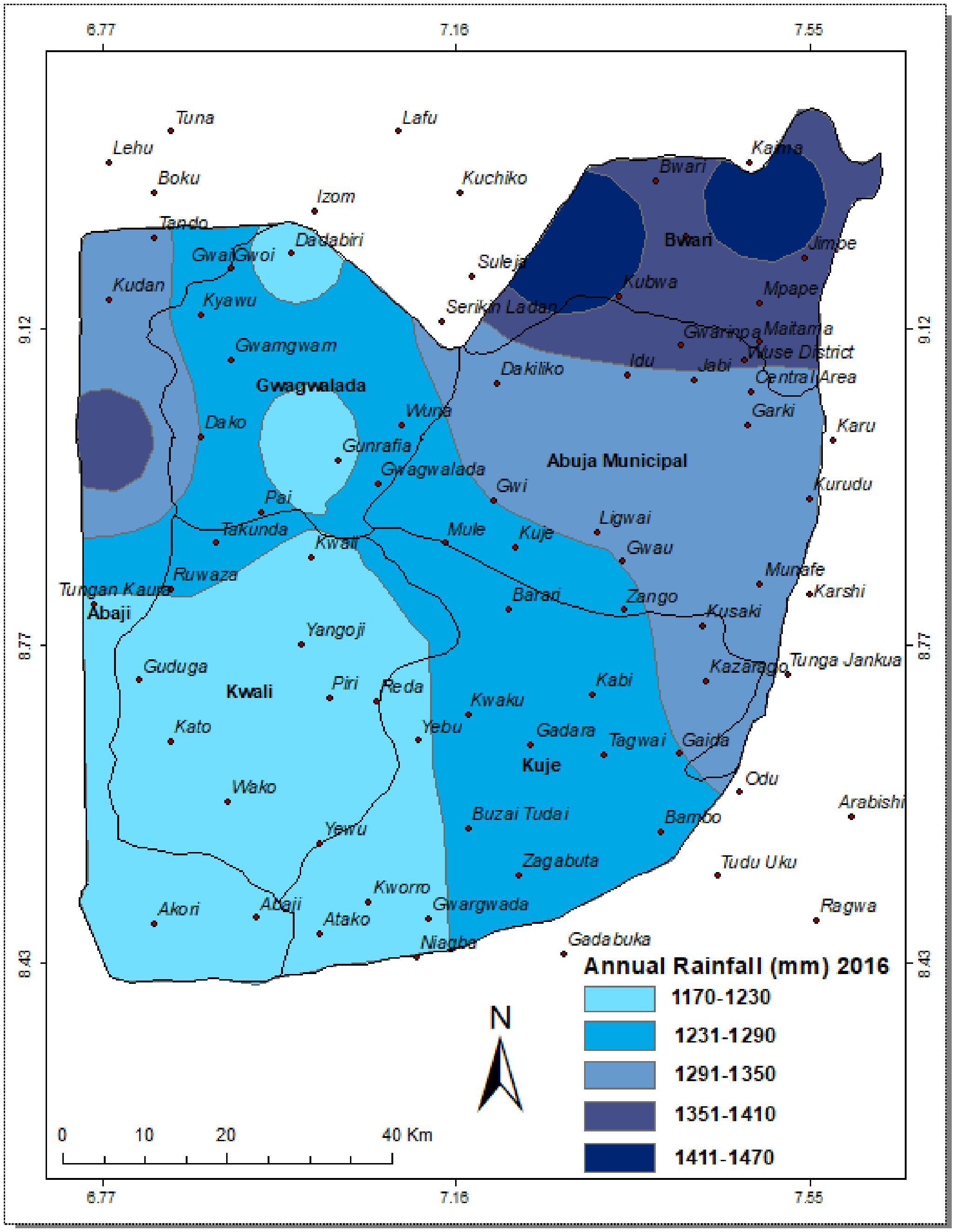

Figure 4.1: Abuja Rainfall Map for 2016

The criteria used by Malesu et al. (2005) for all types of RWH stated that any annual rainfall more than 1200 mm is considered high and their classification was divided into just three categories. Low being the least ranging from 200 mm – 400 mm, Medium ranging from 400 mm – 1200 mm and High which is above 1200 mm. It can therefore be concluded that Abuja experiences a high rainfall annually which is suitable for RWH.

4.2 Slope Analysis

The slope map for Abuja is presented in Figure 4.2. The slope map gives an impression for the steepness of the terrain. The slope distribution for the study area ranges from 0º – 71.86º. This means that there are areas with steepness as low as 0º or flat and hilly areas with steepness as high as 71.86º (305%). Areas with higher slope degree would allow water flow along the path while water would gather at areas with smaller slope degrees.

The slope maps were classified into 0° – 5°, 5° – 10°, 10° – 19° and 19° – 72° as shown in Figure 4.2. The slope of the area explains how swiftly water will move during the event of rains. Steep areas will generate runoff more quickly which will increase the potential for RWH compared to a flat area which will allow water to move slowly which will in turn increase the potential for in-situ RWH depending on the soil texture of the area (Mahmoud & Alazba, 2014). Therefore, classification of the slope made it possible to understand which areas will be suitable for in-situ or surface RWH technologies (Udezo, 2017; Mahmoud & Alazba, 2014).

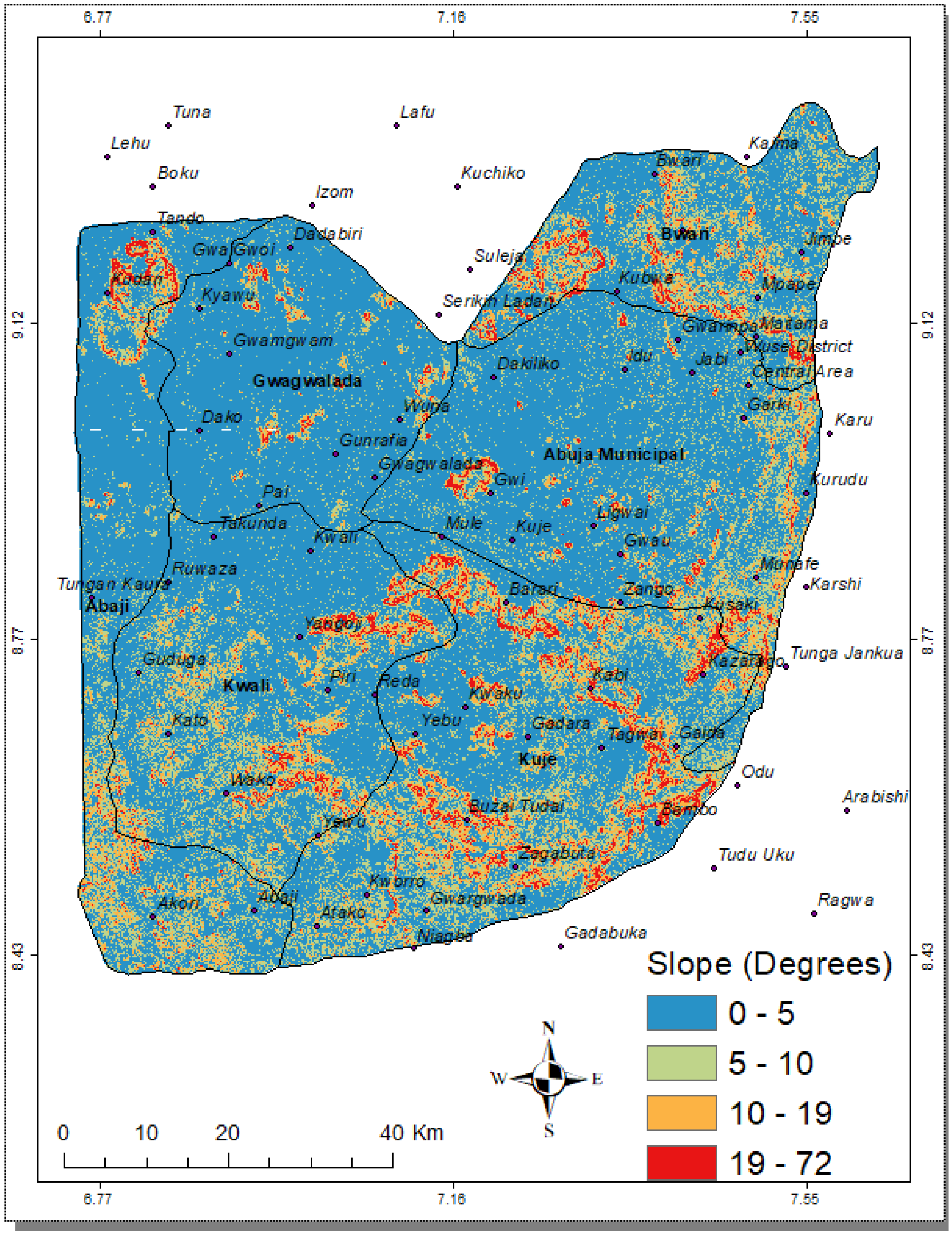

Figure 4.2: Slope Map for Identifying Rainwater Harvesting Potential

4.3. Soil Type

There are five major soil texture types in the study area which are clay loam, sand, loamy sand, sandy clay and Sandy loam as shown in Figure 4.3. The soil type with more percentage of sand allows infiltration therefore has less runoff (Mahmoud & Alazba, 2014). Soil classification helps to understand what areas would encourage in-situ and surface RWH however slow or fast depending on the slope of the area.

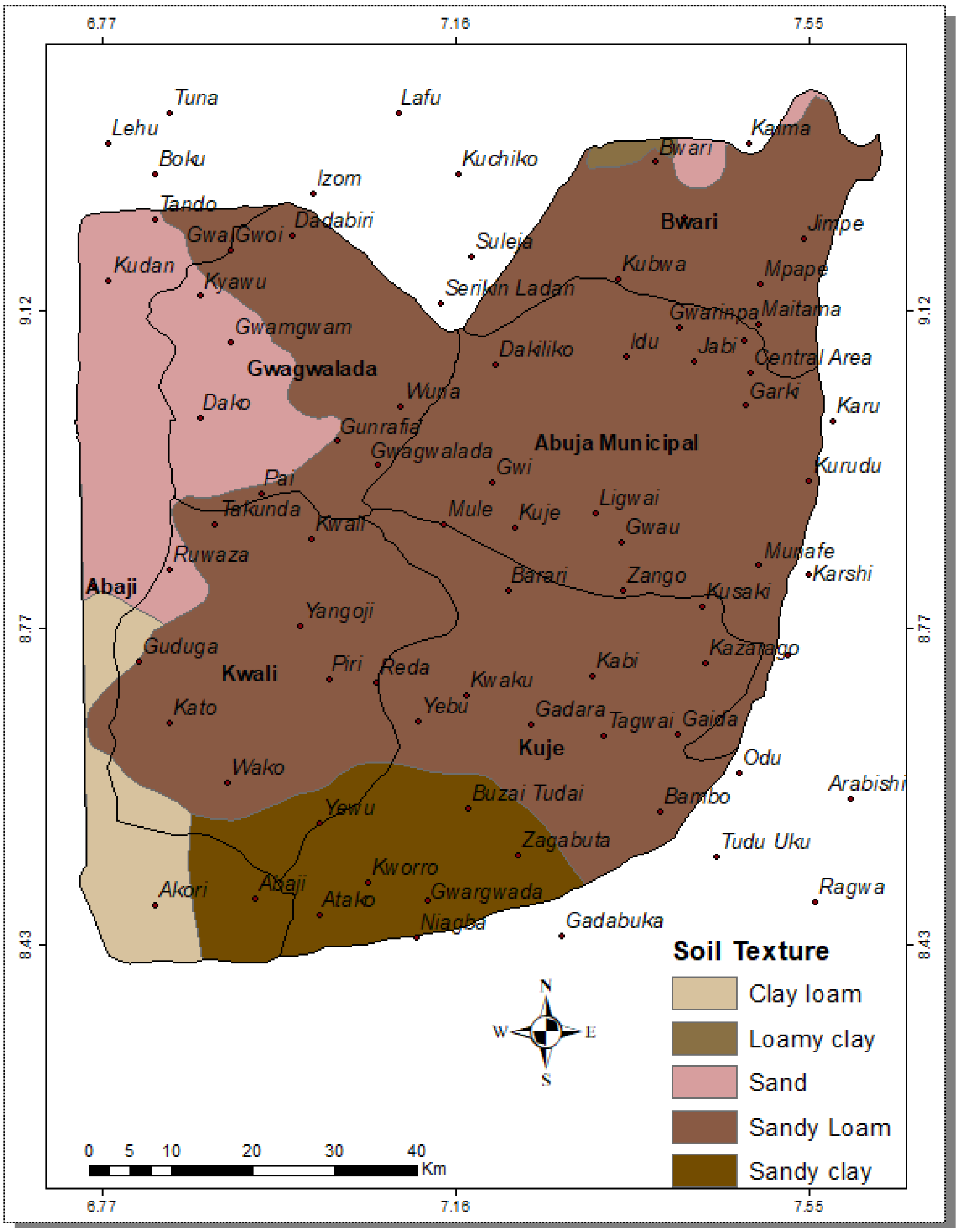

Figure 4.3: Soil Texture Map for Abuja

4.4. Land Use/Land Cover Analysis

The landsat image was classified into eight land use/land cover classes; built up, sparse vegetation, wetlands, cultivated lands, forested areas, bare surfaces, rock outcrops and waterbodies as shown in Figure 4.4.

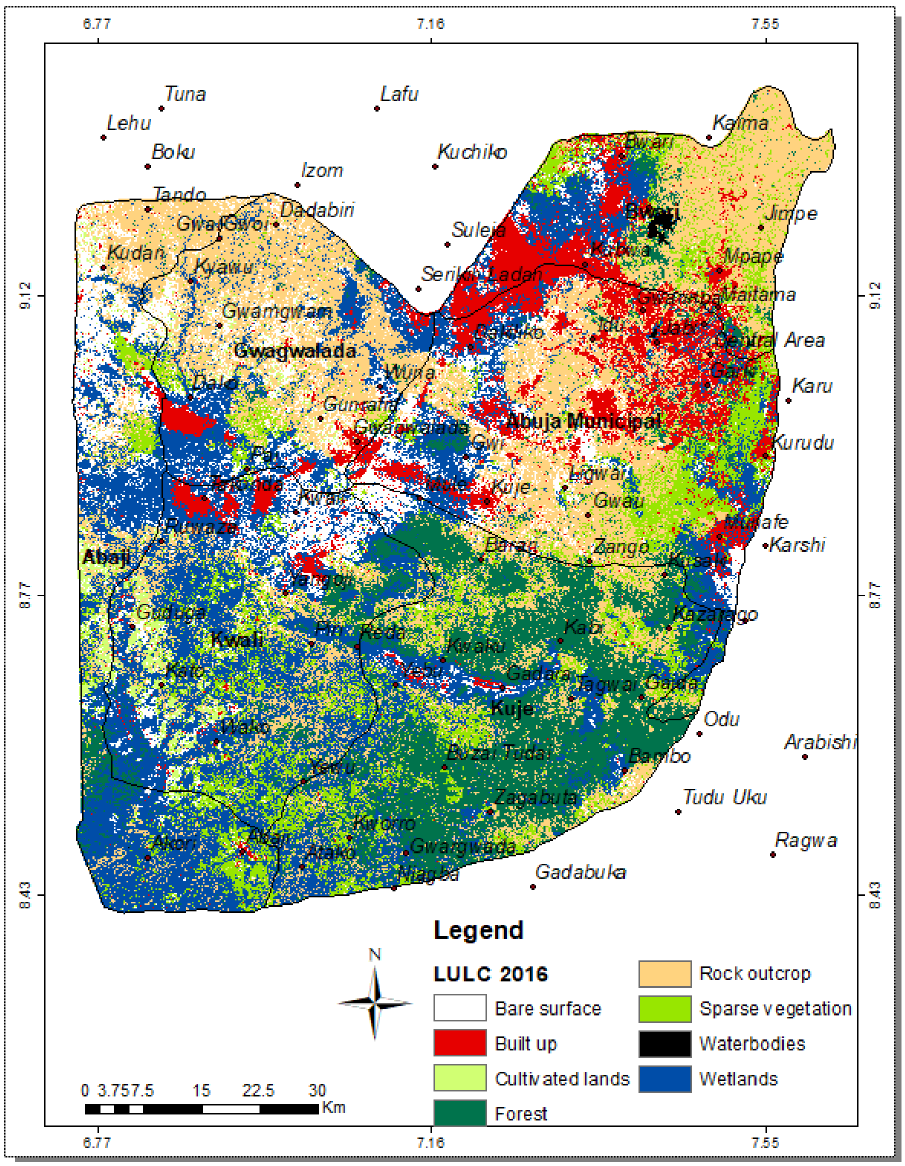

Figure 4.4: Abuja Land use/Land cover Map for 2016

The area covered by each LULC class in 1987, 2001, 2016 and 2046 is shown in Figure 4.5 where sparse vegetation represented the largest ratio of the area occupying 1997.73 km^2 which is about 27.31% of the total area followed by rock outcrops, wetlands and built-up area covering 1168.94, 1050.43 and 972.9 km^2 which is about 15.98, 14.36 and 13.3% respectively. This was found closely related to what Agbo et al. (2014) discussed in their research about the effect of high population density on rural landuse in Abuja.

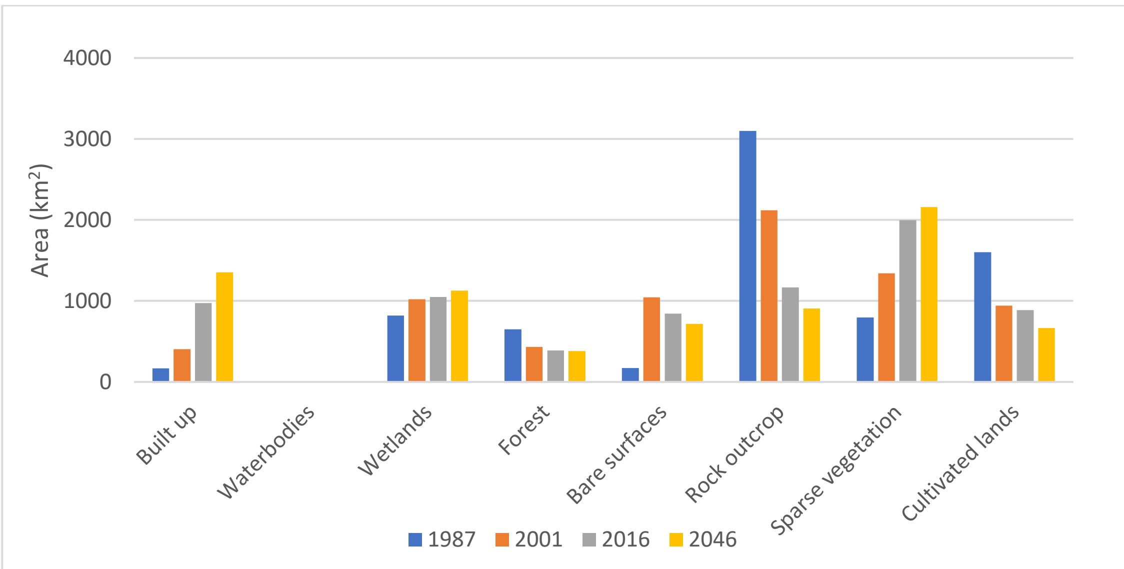

Figure 4.5: Area Occupied by each LULC Class

4.5. Population

The last population census was carried out in 2015 and the percentage growth rate was estimated to be +13.91/5years. With which the population of Abuja was estimated by NBS to be 3,564,100 using the same growth rate. Although this was for the whole state, the census is usually carried out with respect to local government (districts) areas before they are compiled. The population of each local government area was obtained from the records of the National Bureau of Statistics (NBS, 2017). With the population data, the estimated population density (persons/km^2) was generated using the area enclosed by each district as shown in Figure 4.6.

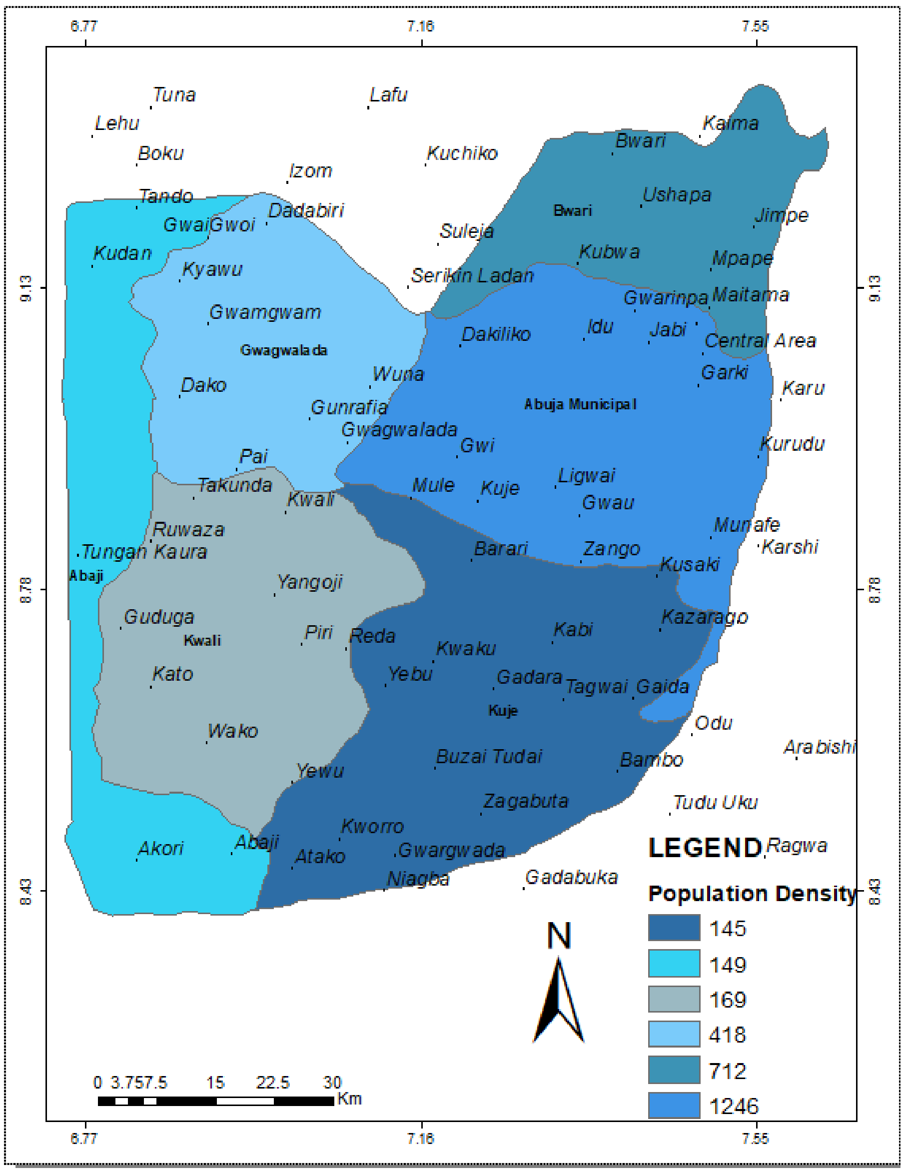

Figure 4.6: Abuja Population Density Map for 2016

The population is such that for example, Abuja Municipal (AMAC) which is major City in the study area has the highest population which is 1.97 million people. Though the area enclosed by AMAC is equally high 1579 km^2, the population density still resulted as the highest in Abuja with a value of 1246 persons/km^2. The population density was used to estimate average household size and total roof area per district. These values helped to determine the total rooftop area and thereby the quantity of rainwater harvestable using rooftop RWH technology.

4.6. Assessing the Potential of Rain Water Harvesting

The maps for LULC, slope, soil and rainfall for Abuja were overlaid as described in the methodology and the following are the results obtained for rooftop, surface and in-situ RWH.

4.6.1. Rooftop rainwater harvesting

Rooftop RWH can only be possible in built-up areas since the presence of a roof is the requirement for the necessary catchments and most especially in scattered settlements where water pipe networks installations would not be economically viable. Malesu et al. (2005) and Kahinda et al. (2008) both stated that areas receiving at least 200 mm of annual rainfall are potential locations for rooftop RWH. Abuja receives an average of 1,170 - 1,470 mm of rainfall annually, hence the ranking for rainfall in Table 4.1. Thus, settlements in Abuja have the required rainfall capacity for rooftop RWH. The population ranking is all 5 based on the assumption that every person lives under a roof, however small the roof might be. This means that the total annual rainfall, the population and built-up areas in all the districts of Abuja are suitable for rooftop RWH. Every district, person and building in Abuja can implement rooftop RWH technolgy and harvest rainwater.

During the course of the study, it was observed that the built-up area from the LULC map generated on GIS might be small as shown in Figure 4.4 since small rooftops were not detectable from the landsat image making it difficult to capture all built-up areas. Therefore the need to determine rooftop RWH through other means arose. The population data was used to determine the rooftop RWH potential by estimating an average roof size for the study area using Google-earth. This was estimated to be 180 m^2 average roof area and considering the average household size to be 4.5 persons/household (NBS, 2017). Table 4.1 shows the ranking of rainfall and population while Table 4.3 shows the estimated average roof area for each district and the quantity of rainwater harvestable from rooftops.

Table 4.1: Ranking Criteria for Rooftop RWH Based on Population

Criteria	Values	Ranking
Rainfall	1,171.4 – 1,230.3	5
	1,230.4 – 1,289.2	5
	1,289.3 – 1,348.1	5
	1,348.2 – 1,407	5
	1,407.1 – 1,465.9	5
Population density	1 – 145	5
	146 – 149	5
	150 – 169	5
	170 – 418	5
	419 – 712	5
	713 – 1,246	5
	Average roof area per household is 180 m^2 as shown in Table 4.4	

Since according to the assumption that every person lives under a roof and the trend that every Nigerian wants their own home (Lade & Coker, 2012) makes it more understandable the reason why built-up areas are increasing laterally.

The average rooftop area was obtained from Google earth, several roofs were sampled taking their areas and geographical location (i.e. latitude and longitude locations). About two houses were sampled from each district as shown in Figure 4.7 and Table 4.2 making a total of 12 roof samples. The sampling was done randomly, just zooming into the districts and selecting rooftops with reasonable distance from each other within the same district. The average roof area was estimated as shown in Table 4.2 to help determine the total average roof area used in Table 4.3.

Table 4.2 Sampled Rooftops and Area Enclosed

Number	**Latitude**	**Longitude**	**Area m^2**
1	9.335	7.305	189
2	9.342	7.303	150
3	9.178	7.224	233
4	9.182	7.234	205
5	8.564	7.454	182
6	8.574	7.417	94.7
7	9.115	6.475	52.6
8	8.412	6.495	40.9
9	8.534	7.152	550
10	8.532	7.132	151
11	8.282	6.575	206
12	8.276	6.591	107
Average Area			180.1

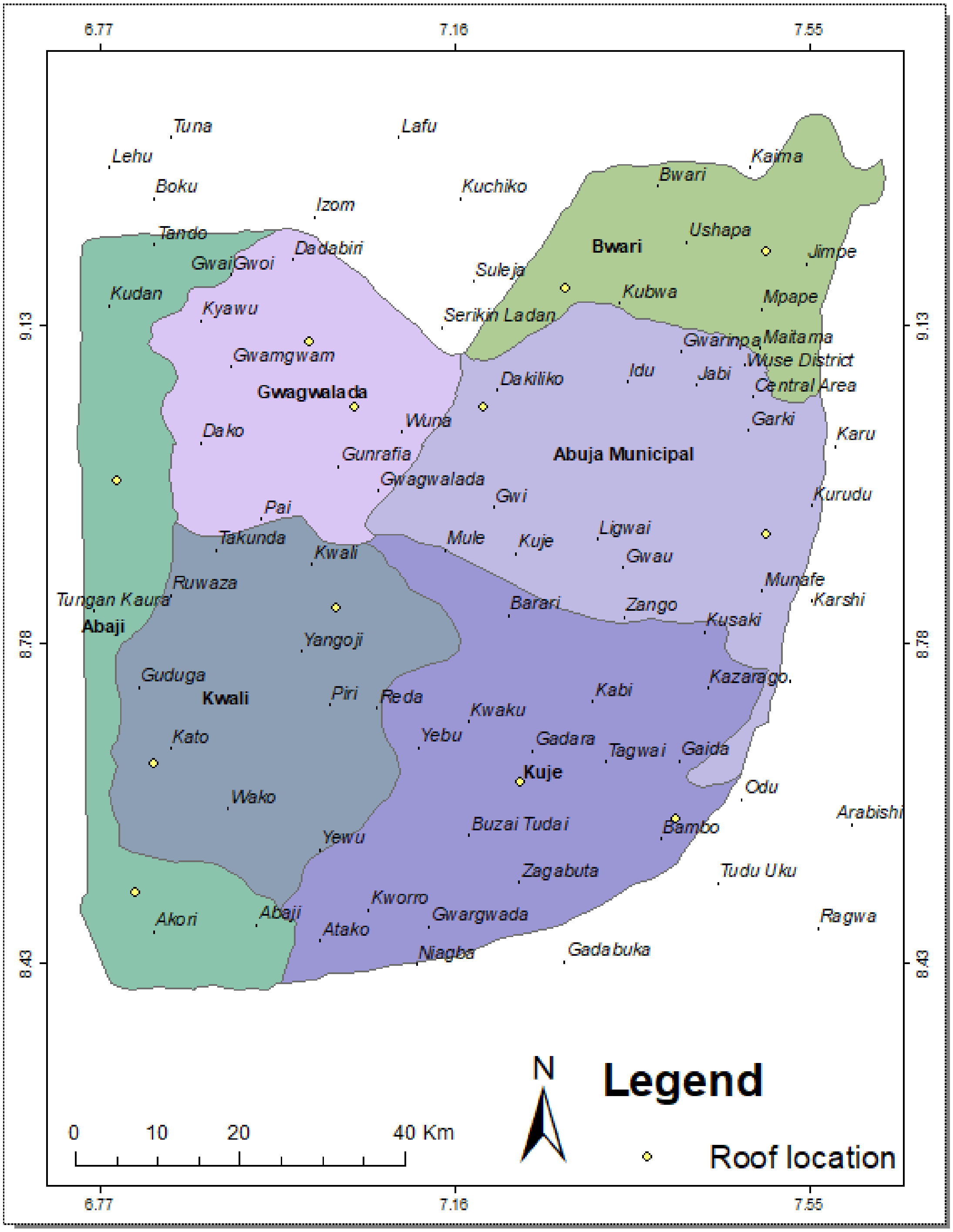

Figure 4.7 Map Showing the Random Sampling of Rooftops from Google-earth

The estimate for the total household size for each district was done by dividing each district's population by the average household size given by (NBS, 2017) is 4.5 persons/household. The runoff coefficient used was 0.8 which was the average estimate for rooftop RWH given by Laiw & Chaing (2014) and the annual rainfall range for 2016 was 1200 mm to 1500 mm. The quantity of rainwater harvestable based on projected population is shown in Table 4.3.

Table 4.3: Quantity of Rainwater Harvestable Based on Population

Abuja districts	**2016 Population**	**Total Household**	**Total roof area (m^2)**	**Volume min (m^3)**	**Volume max (m^3)**
Abaji	148623	33027	5944860	5707065.6	7133832
AMAC	1967383	437196	78695280	75547469	94434336
Bwari	580949	129100	23238000	22308480	27885600
Gwagwalada	402743	89499	16109820	15465427	19331784
Kuje	245923	54650	9837000	9443520	11804400
Kwali	218479	48551	8739180	8389612.8	10487016
Total	3564100	792023	142564140	136861574	171076968

The quantity of rainwater harvestable in each district was classified as shown in Figure 4.8. The total rainwater harvestable in Abuja based on population is therefore the sum of the total volume of rainwater harvestable in each district.

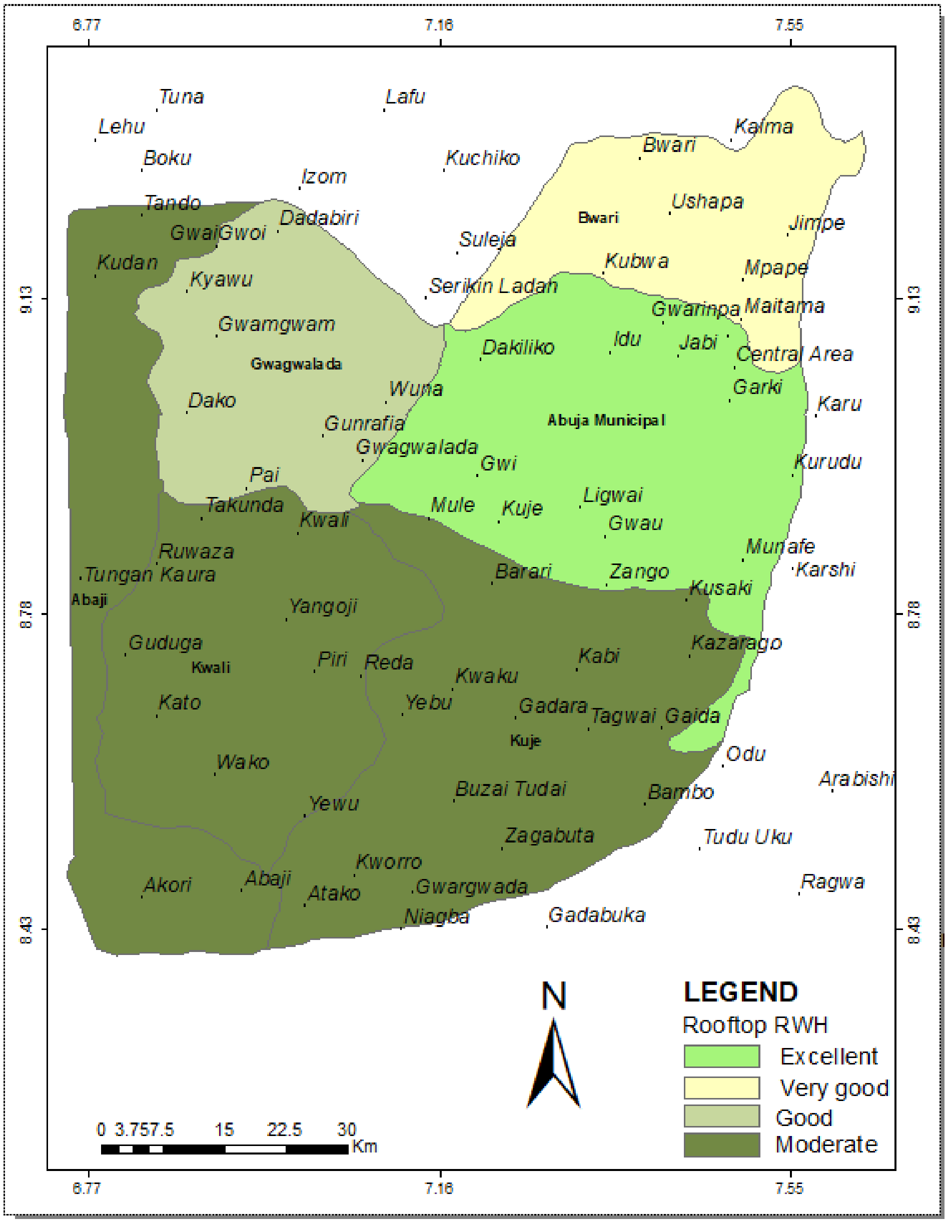

Figure 4.8: Rooftop Rainwater Harvesting Potential for Population

The ranking RWH potential for the population of each district was found to be high because they each have a population which implies they have roofs. However, from Table 4.3, different districts had different average roof sizes due to their individual populations and therefore resulted in varying volume of water harvestable, leading to the classification in Figure 4.8. The districts with moderate RWH potential which are Abaji, Kwali and Kuje were estimated to harvest less than 10,000,000 m^3 and less than 12,000,000 m^3 of water. However, further look into the results showed that every district will produce the same amount of water which is at minimum rainfall 105.2 lit/cap/day and at maximum rainfall 131.5 lit/cap/day. This is because the population was the determining factor for the number of households which is used to estimate the average roof area and ultimately the volume of rainwater harvestable. Since the average household size and average roof area for every district was the same, the result came down to the same amount of water per person. This amount is more than the demand which ranges between 50 - 100 lit/cap/day according to the State Water Agency in Nigeria (SWAN, 2018), giving Abuja the RWH potential of about 104%. However, it is important to note that although the average rooftop area used for the work is 180 m^2 based on our sampling on Google-earth, there are many other rooftops larger than this size especially in the city.

4.6.2. Surface rainwater harvesting

Surface RWH refers to the collection of runoff from surfaces such as roads, pavements, hillsides, bare lands and waterbodies into ponds, drainages and collection pans (Malesu et al., 2005). Water tends to flow from steep slopes to flat areas. Therefore, steep slopes are favourable for surface RWH (Mahmoud & Alazba, 2014). Fairly or moderately steep slopes are preferable as water gathers in these areas. Abuja has some areas with moderately steep slopes and a high amount of rainfall for surface runoff to be stored. Water could be stored in wetlands, water bodies and open bare surfaces for irrigation and domestic purposes. Assessment of Surface RWH potential also requires information on soil types in order to determine the infiltration properties as well as the runoff coefficient. For surface RWH, the soil should have low infiltration capacity. Impermeable surfaces like concrete pavements and rock outcrops also support runoff harvesting for surface RWH. Table 4.4 shows the ranking for each criterion, while Figure 4.9 shows the potential for surface RWH.

The ranking of the LULC in Table 4.4 was done considering areas that are suitable for runoff harvesting. The land use/land cover classes which are most likely to support surface RWH like rock outcrops, bare surfaces, sparse vegetation and cultivated lands were ranked highest which is 5. The areas which are moderately likely to allow surface RWH like built-up areas and forest ranked 3 while wetlands and waterbodies which don't allow for surface RWH except in rare cases of excesive rainfall were ranked lowest at 1. This ranking is in accordance with the work done by Kahinda et al. (2008).

The ranking of both soil and slope were done considering the depth, texture and runoff coefficient of each soil type which explains the rate of infiltration and thus the time required for the soil to be saturated before it begins to runoff as well as slope percentages as classified which determine how quickly water will move (Mahmoud & Alazba, 2014). The resulting map in Figure 4.9 shows the potential for surface RWH.

Table 4.4: Ranking Criteria for Surface RWH

Criteria	Values	Ranking
Rainfall	1,171.4 – 1,230.3	5
	1,230.4 – 1,289.2	5
	1,289.3 – 1,348.1	5
	1,348.2 – 1,407	5
	1,407.1 – 1,465.9	5
Land use/cover	Wetlands	1
	Water Bodies	1
	Sparse Vegetations	5
	Rock Outcrops	5
	Forest	3
	Cultivated Lands	5
	Built-Up Areas	3
	Bare Surfaces	5
Soil	Sand	3
	Clay loam	5
	Loamy sand	3
	Sandy clay	5
	Sandy loam	5
Slope	0 – 5	1
	5 – 10	3
	10 – 19	5
	19 -71.86	5

Abuja fell within the area of high RWH potential according the maps generated by Malesu et al. (2005). In this research, it is apparent that Abuja has an excellent potential for RWH, where excellent in this case is the highest rank 5. The RWH potential map shows the ranking for every part of the state.

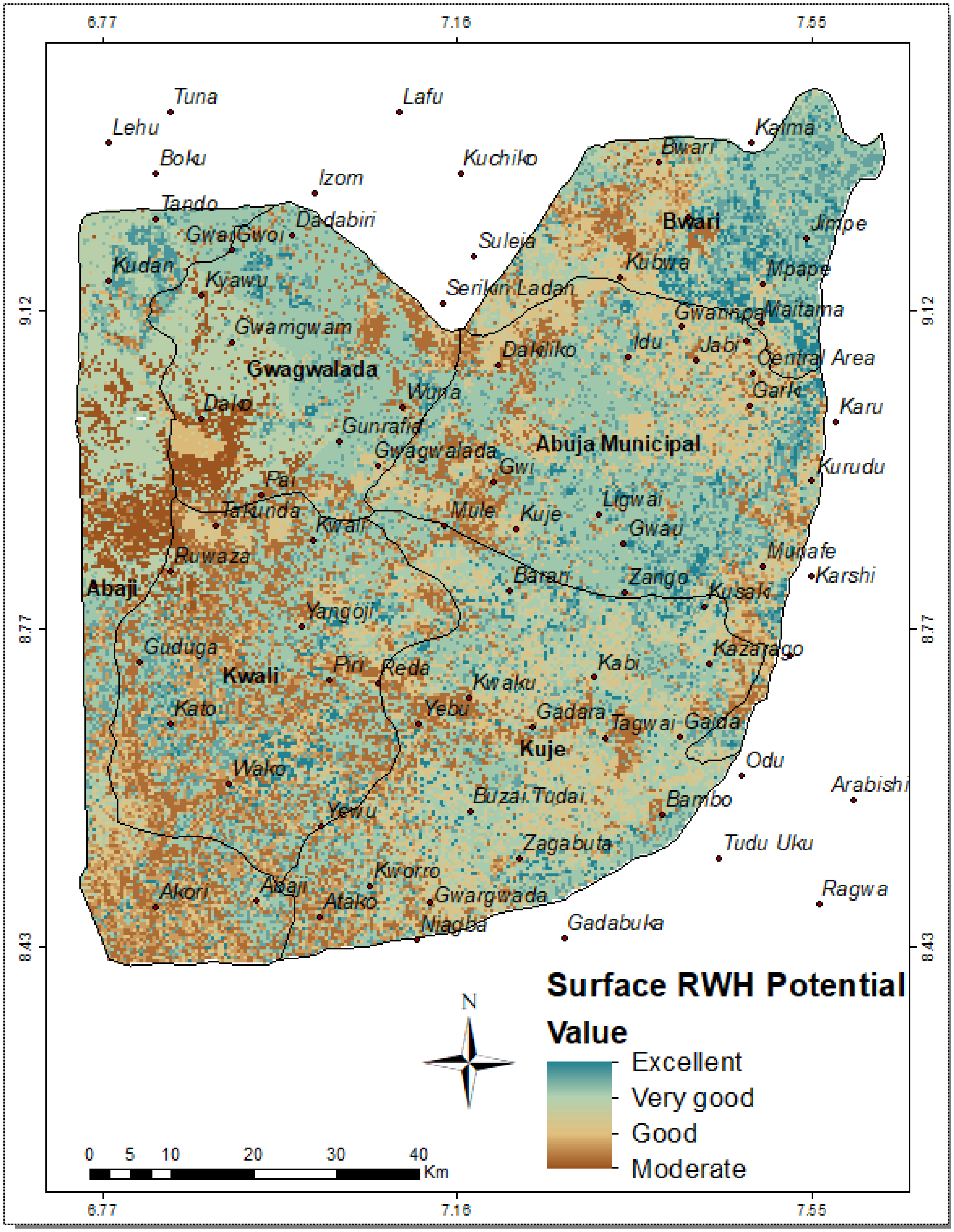

Figure 4.9: Surface Rainwater Harvesting Potential Sites for Abuja

The areas which were found to be excellent are areas with sparse vegetations and rock outcrops steep slopes, shallow well drained soils and a minimum rainfall of 1170 mm. The very good areas included some bare surfaces on steep slopes, built-up areas having maybe paved surfaces, roads and drainages and some rock outcrops with steep slopes, and of course, high rainfall. The good areas includes areas of dense vegetation, forested lands, medium to flat slopes, mostly deep poorly drained soils and rainfall. The moderate areas for surface RWH included wetlands and waterbodies which reduces its suitability for surface RWH.

4.6.3. In-situ rainwater harvesting system

In-situ RWH refers to all the farm methods used to collect rainwater directly into the soil profile on farmlands for the sole purpose of plant/crop growth. In this case, rainwater is harvested to enhance soil moisture for crop production. The average rainfall in the study area meets the requirement for in-situ RWH according to the classification method adopted by Malesu et al. (2005). Their rainfall criteria fell within the range of 200 mm – 750 mm for all crops and soil types, which the average rainfall in Abuja exceeds. Areas that need soil moisture replenishment are given priority and well-drained soils were also prioritised as they would allow water infiltrate into the soil and store within the soil profile. Table 4.5 shows the ranking of each criterion while Figure 4.10 shows the potential for in-situ RWH..

Table 4.5: Ranking Criteria for In-Situ RWH

Criteria	Values	Ranking
Rainfall	1,171.4 – 1,230.3	5
	1,230.4 – 1,289.2	5
	1,289.3 – 1,348.1	5
	1,348.2 – 1,407	5
	1,407.1 – 1,465.9	5
Land use/cover	Wetlands	1
	Water Bodies	3
	Sparse vegetation	5
	Rock Outcrops	5
	Forest	3
	Cultivated Lands	5
	Built-Up Areas	1
	Bare Surfaces	5
Soil	Sand	3
	Clay loam	5
	Loamy sand	3
	Sandy clay	5
	Sandy loam	5
Slope	0 – 5	3
	5 – 10	3
	10 – 19	5
	19 – 71.86	5

The ranking of LULC was done considering areas best for harvesting rainwater solely for the purpose of crop production which included considering the distance from the land, quantity of water needed, the slopes to avoid erosion, etc. Therefore, cultivated lands, sparse vegetations, bare surfaces and rock outcrops were ranked highest as some farmers divert water from roads, compounds and surrounding bare grounds for their crop production, built-up areas and wetlands ranked low while the others were ranked medium.

The ranking of both soil and slope were also done considering the depth, texture and runoff coefficient of each soil type as well as slope percentages as classified. The potential ranking as shown in Figure 4.10 was generated after the overlay of the criteria maps. This map shows areas with moderate to good potential, which are areas with steep slopes, loamy clay soil texture, water bodies and wetlands, some rock out crops, and a generally high rainfall which according to Mahmoud & Alazba (2014) is consistent and acceptable. The areas with very good potential included moderate slopes, very high rainfall, cultivated lands, sparse vegetation, bare surfaces, built-up areas and deep moderately drained soil types. The areas with excellent potential included medium to steep slopes, sparse and dense vegetation, forested area, some other rock outcrops which fall in areas with excellent soil textures and cultivated lands. It has the shallow to deep well drained soil and high rainfall, thus it was considered the most suitable for In-Situ RWH which accoding to Ladow (2007) is accepted.

In summary, the rainwater harvesting potential for Abuja, considering several means of harvesting rainwater, the different uses of rainwater and the population is very high. From this study, it has been shown that the potential for rainwater in Abuja is very good with an average of 4.3 for the ranking.

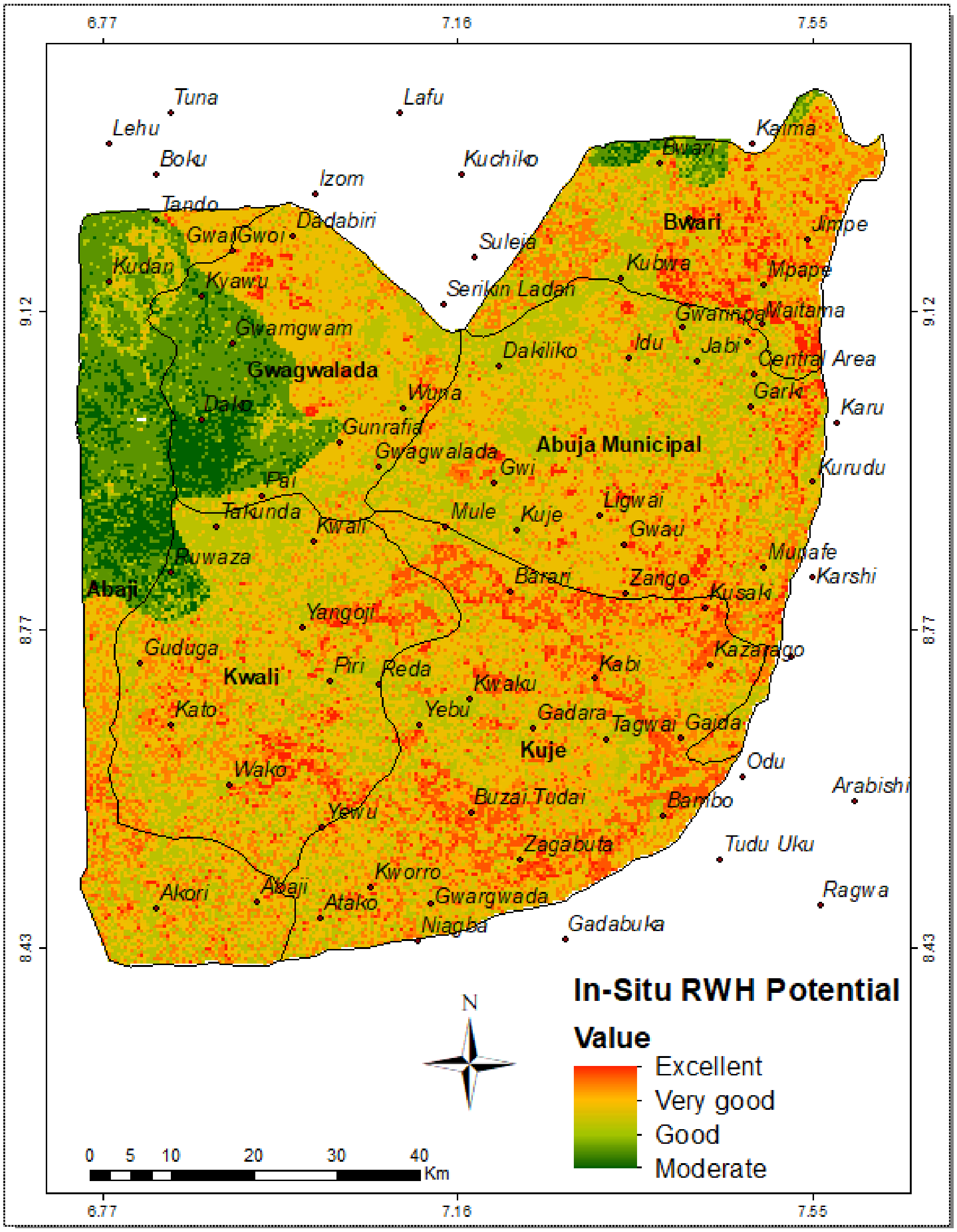

Figure 4.10: In-Situ Rainwater Harvesting Potential Sites for Abuja

Table 4.6 shows a compilation of the rainwater harvesting potential of Abuja for rooftop, surface and in-situ rainwater harvesting. From Table 4.6 it was estimated that at the minimum expected rainfall, about 920,678,400 m^3 volume of rainwater is harvestable by surface RWH from areas with excellent potentials.

Table 4.6: Quantity of Rainwater Harvestable in Abuja

Area of Abuja	Surface RWH				In-situ RWH			
	Moderate	Good	Very Good	Excellent	Moderate	Good	Very good	Excellent
In km	1059.21	1359.86	3726.993	1168.937	682.54	2023.33	2209.083	2400.047
RO coefficient	0.24	0.53	0.62	0.72	0.38	0.58	0.65	0.76
Rainfall min (mm)	1200	1200	1200	1200	1200	1200	1200	1200
Rainfall max (mm)	1500	1500	1500	1500	1500	1500	1500	1500
Volume min (m^3)	305052480	864870960	2772882792	1009961568	311238240	1408237680	1723084740	2188842864
Volume max (m^3)	381315600	1081088700	3466103490	1262451960	389047800	1760297100	2153855925	2736053580

Table 4.6 also shows that Abuja does not have low rainfall or medium rainfall. According to the classification of rainfall in Table 4.5, Abuja has a high rainfall and therefore its potential for RWH is high (Malesu et al., 2005). The runoff coefficients used in generating Table 4.6 were the composite runoff coefficients for the different LULC, soil types and slopes. Table 4.6 shows the quantity of rainwater harvestable by surface and In-Situ RWH technologies based on GIS classification and overlay operations. This is as a result of the ranking and thus classification of LULC, the quantity of rainwater harvestable both with

surface and in-situ technology is very high. In total, if all three major RWH technologies were employed, the quantity of rainwater harvestable is very high. Therefore, it is correct to say that the potential of RWH in Abuja, Nigeria, for human, animal and plant consumption using rooftop, surface and in-situ RWH is very high.

4.7 Identifying Suitable Sites for In-Situ RWH Technologies

This classification as shown in Figure 4.10 was based on the slope, rainfall, soil type and LULC. After having considered the expected annual rainfall to be more than enough for crop production, different classifications of slope, flat, medium and steep were used to determine what areas are best suited with some RWH technologies. The technologies considered for the different slope classes are shown in Table 4.7.

These technologies were selected from hundreds of other in-situ RWH technologies highlighted by Mati (2005). The selection was based on their compatibility with slope, total annual rainfall, soil types, type of crops produced and ease of construction.

Malesu et al. (2005) had done the continent-based overlay of rainfall, slope, crops and soil. Comparing the results shown in Table 4.7 to that of Malesu et al. (2005), it is safe to say that they are very consistent though our results are more precise considering that they are state based. Table 4.7 shows the technologies best suitable for different slopes in the study area as illustrated in Figure 4.11.

Table 4.7: In-situ RWH Technologies and Appropriate Slopes

Slope	**In-situ RWH Technologies**
Flat	Negarims Trapezoidal bunds Grass Strips Broad Bed and Furrow
Medium	*Fanya juu* terraces Flood Water Harvesting Contour Stone Bunds Bench Terraces
Steep	Ngolo Pits Rock Catchment

The map shown in Figure 4.11 is a classification of in-situ sites based on the slope such that it is possible to select in-situ RWH technologies for different areas. About 70% of the cultivated lands from the LULC class are found in the region of medium to steep slopes, however, the flat slope has quite an area occupied by cultivated lands and lands with great potential for agriculture and crop production. These areas on GIS are consistent with the areas shown in the slope map.

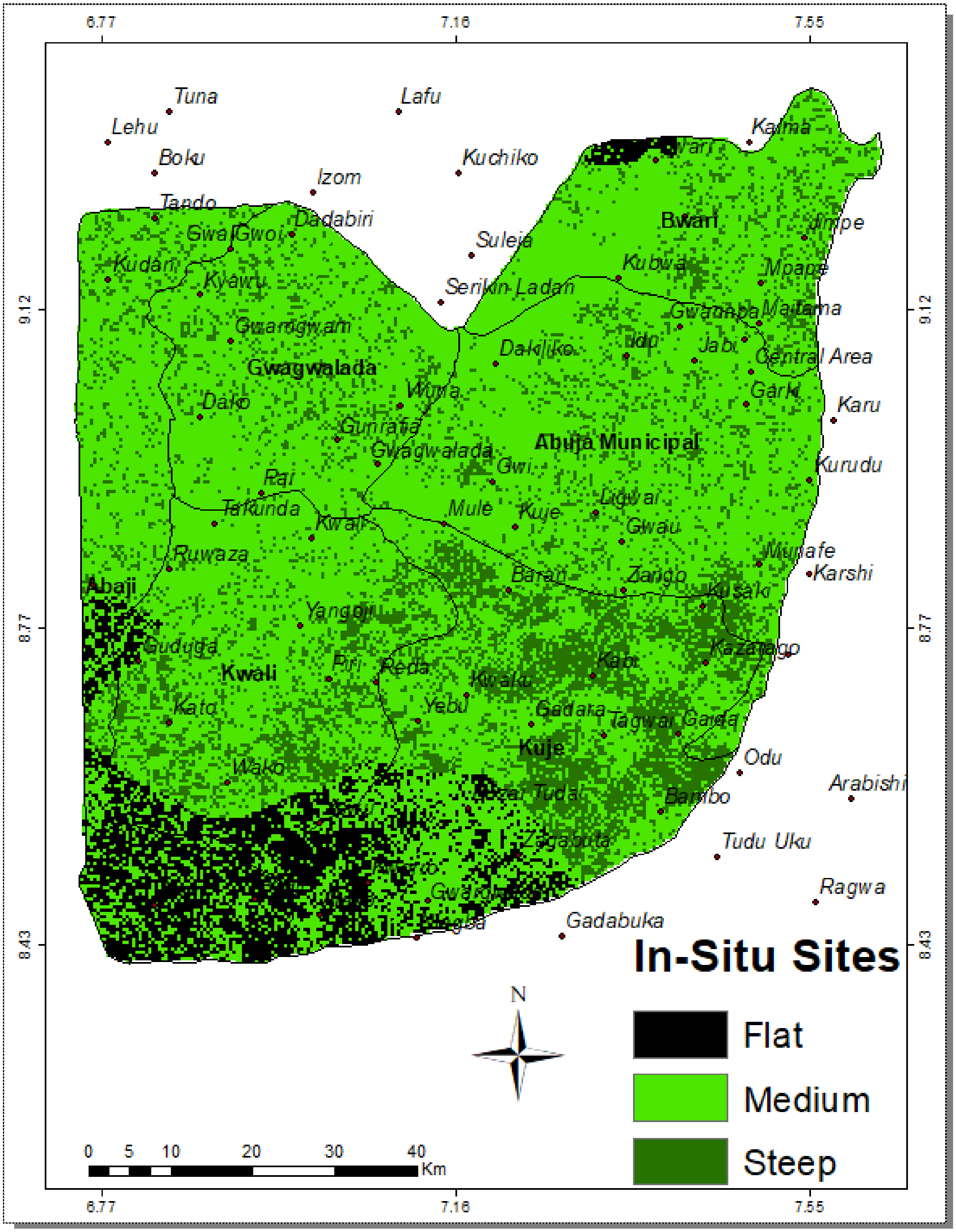

Figure 4.11: Sites for In-Situ RWH Technologies

4.8 Assessing the Effect of Climate Change and Urbanization on RWH potential

The population, rainfall and LULC data collected were projected to future years to enable the assessment of the RWH potential in years to come.

4.8.1. Population projection

The population was projection using a percentage of 13.91%/5years as recorded by NBS (2017). Since the NBS (2017) reviews were mainly for the city, Abuja municipal popularly known as AMAC, it was assumed that the same growth rate for the entire state. This was due to lack of more information about the individual districts. The population projection is shown in Table 4.8.

Table 4.8: Abuja Population and Projected population for 2046

Districts	**1991**	**1996**	**2001**	**2006**	**2011**	**2016**	**2046**
Abaji	4465	15499	32372	58640	93358	148623	338333
AMAC	59102	205164	428516	776244	1235818	1967383	4478652
Bwari	17452	60583	126537	229217	364924	580948	1322501
Gwagwalada	12099	41999	87722	158905	252984	402743	916826
Kuje	7388	25646	53565	97030	154477	245923	559832
Kwali	6563	22784	47587	86202	137238	218479	497358
Total	107069	371674	776298	1406239	2238800	3564100	8113501

The population projection for each district for the year 2046 was estimated using the geometric method for population projection. The total population for the year 2046 is estimated to be 8,113,501 people, making it a little over twice its population in 2016.

According to the predictions for AMAC by the 'World Urbanisation Prospects, 2018' this projected population for the entire state is very close to the predicted population for 2046 (UN, DESA/Population Division, 2018).

The 2046 population density was estimated using the projected population data and the district areas. This population density is shown in Figure 4.12. Three districts namely Abaji, Kuje and Kwali have same range of population density. Abaji had a population density of 339 persons/km^2, Kwali had a population density of 329 persons/km^2 and Kuje had a population density of 384 persons/km^2. The next classes were far apart, Gwagwalada, with its population density as 1000 persons/km^2, Bwari with 1621 persons/km^2 and AMAC was the highest with 2836 persons/km^2.

4.8.2. Projected rainfall

The rainfall map in Figure 4.13 was created with the projected rainfall data collected from World Bank Climate Change Portal (WBCCP). In 2016, the minimum rainfall was 1170 mm/annum and maximum were 1470 mm/annum. In 2046, according to the WBCCP (2018) rainfall projection, the minimum rainfall would be about 1225 mm/annum and the maximum would be 1908 mm/annum for the spatial extent of Abuja.

The projected rainfall map in Figure 4.13 shows five different ranges of total annual rainfall for 2046 in Abuja. This shows a precise spatial view of the rainfall interpolation in the study area which is better than the rainfall map created by Malesu et al. (2005).

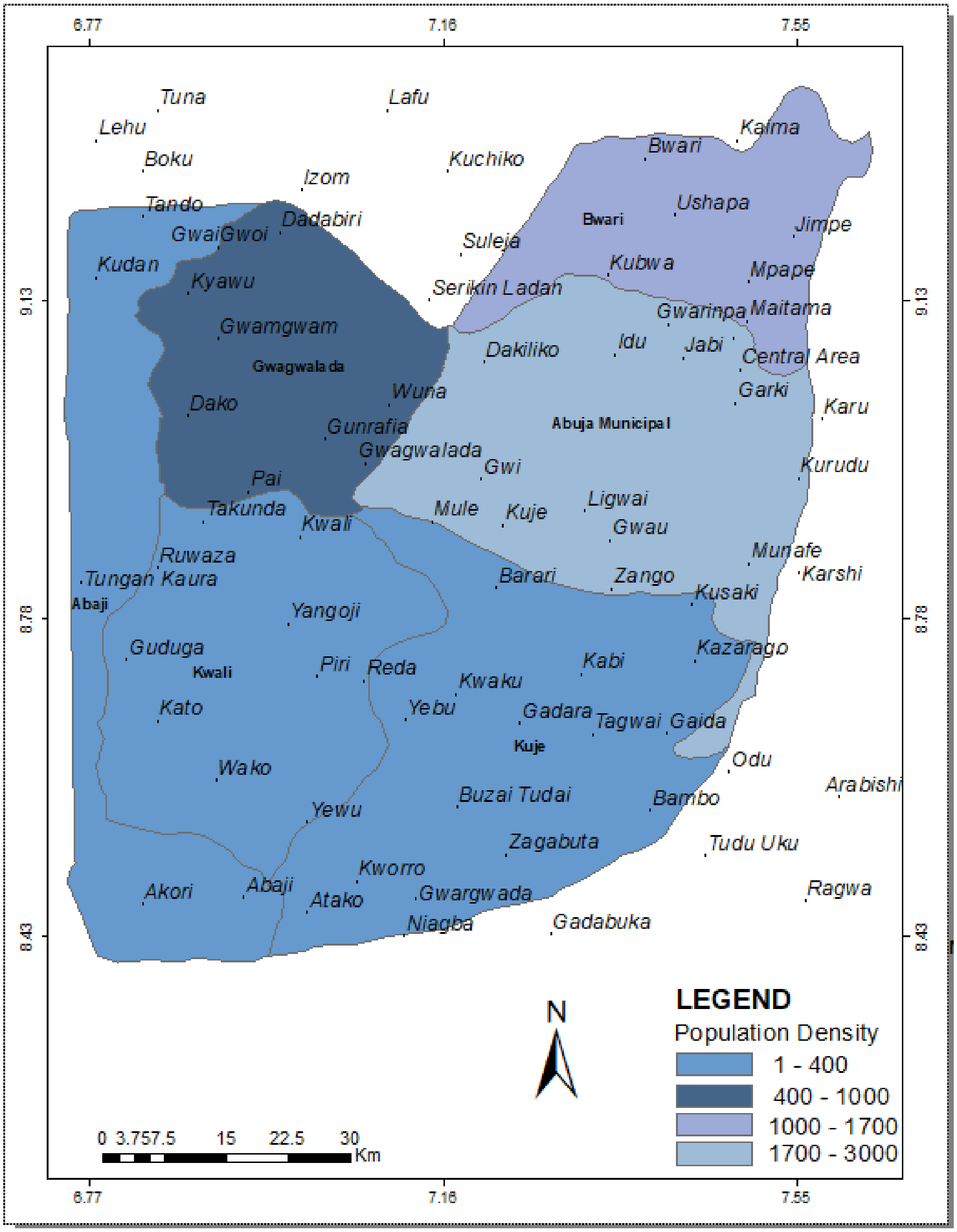

Figure 4.12: Projected Population Density for Abuja in 2046

The lowest range of the rainfall for 2046 was 1225 mm – 1362 mm while the highest range was 1772 mm -1908 mm. Still, the area with the highest rainfall is quite small, however, the area with the lowest rainfall has reduced a lot compared to 2016. From the rainfall map, it is obvious that in total (of the minimum and maximum rainfall for 2046) there would most likely be an increase of about 23% in the annual rainfall. This will definitely affect the RWH potential positively.

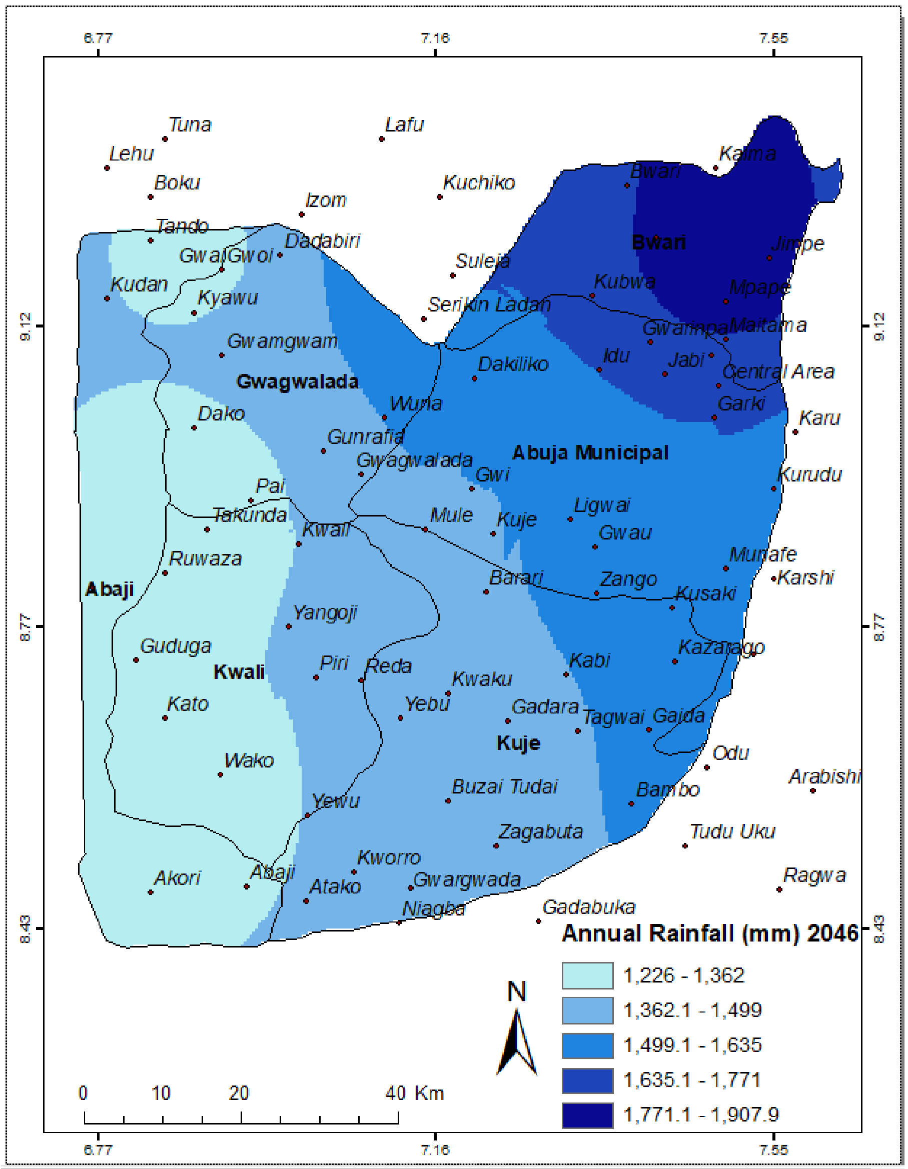

Figure 4.13: Projected Annual Rainfall Map for 2046

4.8.3. Landuse/land cover projection

LULC map for the year 2046 was generated using the Markov Projection Matrix and the LULC raster for 2001 and 2016. The difference between these 2 years became the basis for the Markov Projection Matrix. With each map having nine classifications as the LULC map for 2016, and from the maps of 2001 and 2016, there are distinct changes in the areas occupied by each LULC classification as shown in Table 4.9.

Table 4.9: Area Occupied by Different Classes in 1987, 2001, 2016 and 2046 in km^2

LULC Classes	**1987**	**2001**	**2016**	**2046**
Built up	167.13	403.36	972.9	1351.99
Waterbodies	5.85	8.05	8.78	8.95
Wetlands	821.48	1021.17	1050.43	1126.51
Forest	651.04	433.78	386.96	380.307
Bare surfaces	170.44	1043.55	844.15	715.407
Rock outcrop	3100.24	2118.42	1168.94	907.06
Sparse vegetation	797.34	1343.03	1997.73	2157.93
Cultivated lands	1601.99	943.63	885.12	667.421
Total	7315	7315	7315	7315

The areas occupied by each LULC class differ in size from one year to another, some continuously increasing for example waterbodies, built-up areas, sparse vegetation and wetlands. Some others like forests, cultivated lands and rock outcrops were continuously decreasing while bare surfaces varied especially between 1987 and 2001 but continued to decrease through to the projected year. For LULC classes like built-up areas which were seen to be continuously increasing, this is reasonable considering that the population is increasing which cannot be only as a result of birth rate, urbanisation is another reason why the built-up areas are increasing. The forested areas were decreasing as a result of the problem of deforestation in Nigeria especially Abuja (Mongabay.com, 2018). Rock outcrops are decreasing as well probably due to the use of rocks for constructions and the expansion of built-up areas which has spread into forests and some of the rock outcrops. So, the rock outcrops are no longer captured as rocks but as built-up areas. As for the increase in bare surfaces between the years 1987 and 2001, it can be as a result of reduction in rock outcrops, deforestation and then it starts reducing again as built-up areas increase and water makes its own course through the disintegrated rock paths leading to increased wetlands.

The 2046 LULC map showed increase and decrease in the areas of the classes based on the projection carried out using Markov model. Classes like waterbodies and built-up areas continued to increase while areas like forested lands continued to decrease as shown in Table 4.9. Cultivated land decreased, sparse vegetation increased, rock outcrops decreased, bare surfaces decreased while wetlands increased. The changes in these classes were based on the fact that Markov model does the projection based on 2 years, which is a good thing since it shows the changes in LULC based on a previous occurrence not just an assumption of change in LULC (Zhang et al. 2011; Jianping et al. 2005). The LULC classes for 1987, 2001, 2016 and 2046 is shown in Figure 4.14, Figure 4.15, Figure 4.16 and Figure 4.17 respectively.

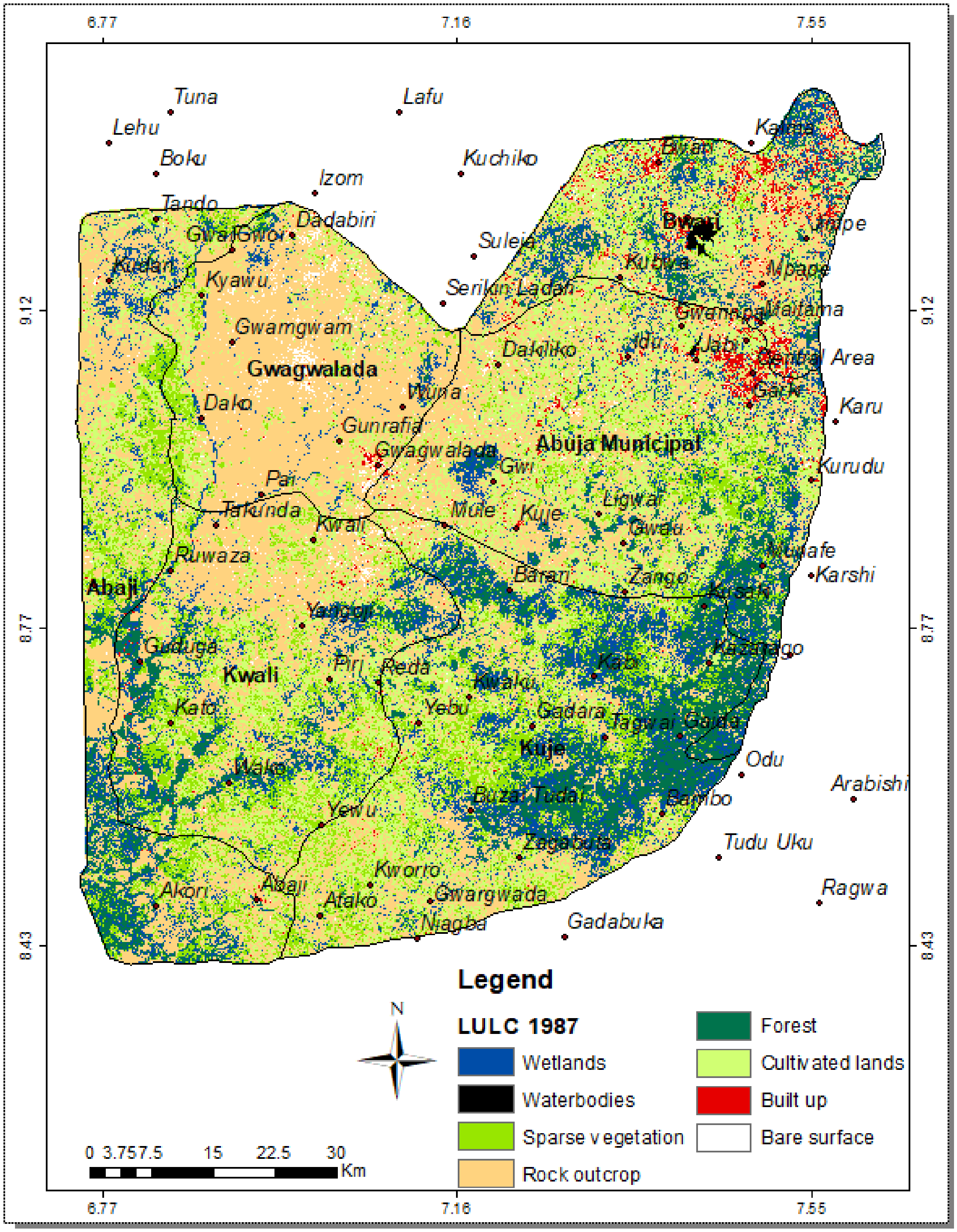

Figure 4.14: Abuja Landuse/Landcover Map for 1987

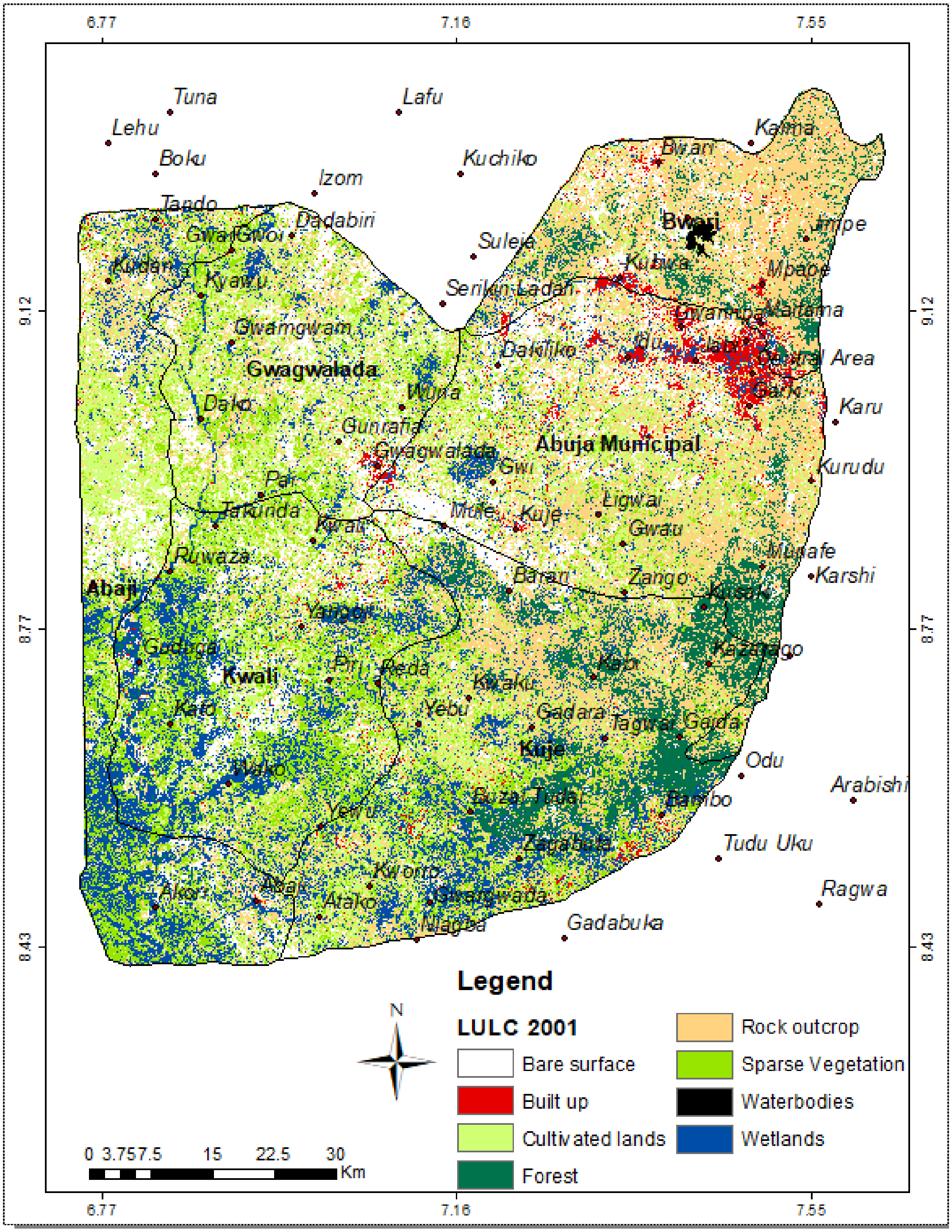

Figure 4.15: Abuja Landuse/Landcover Map for 2001

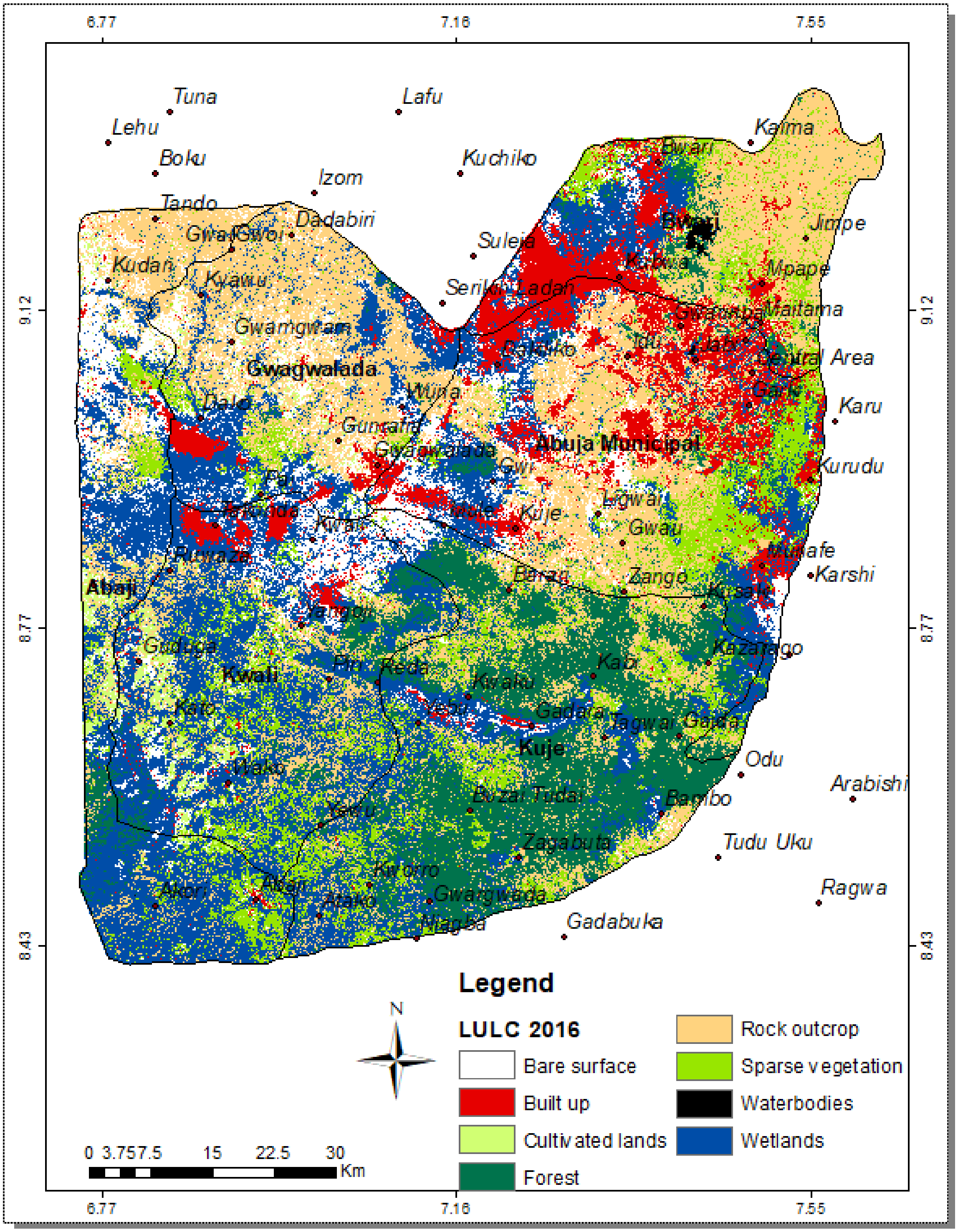

Figure 4.16: Abuja Landuse/Landcover Map for 2016

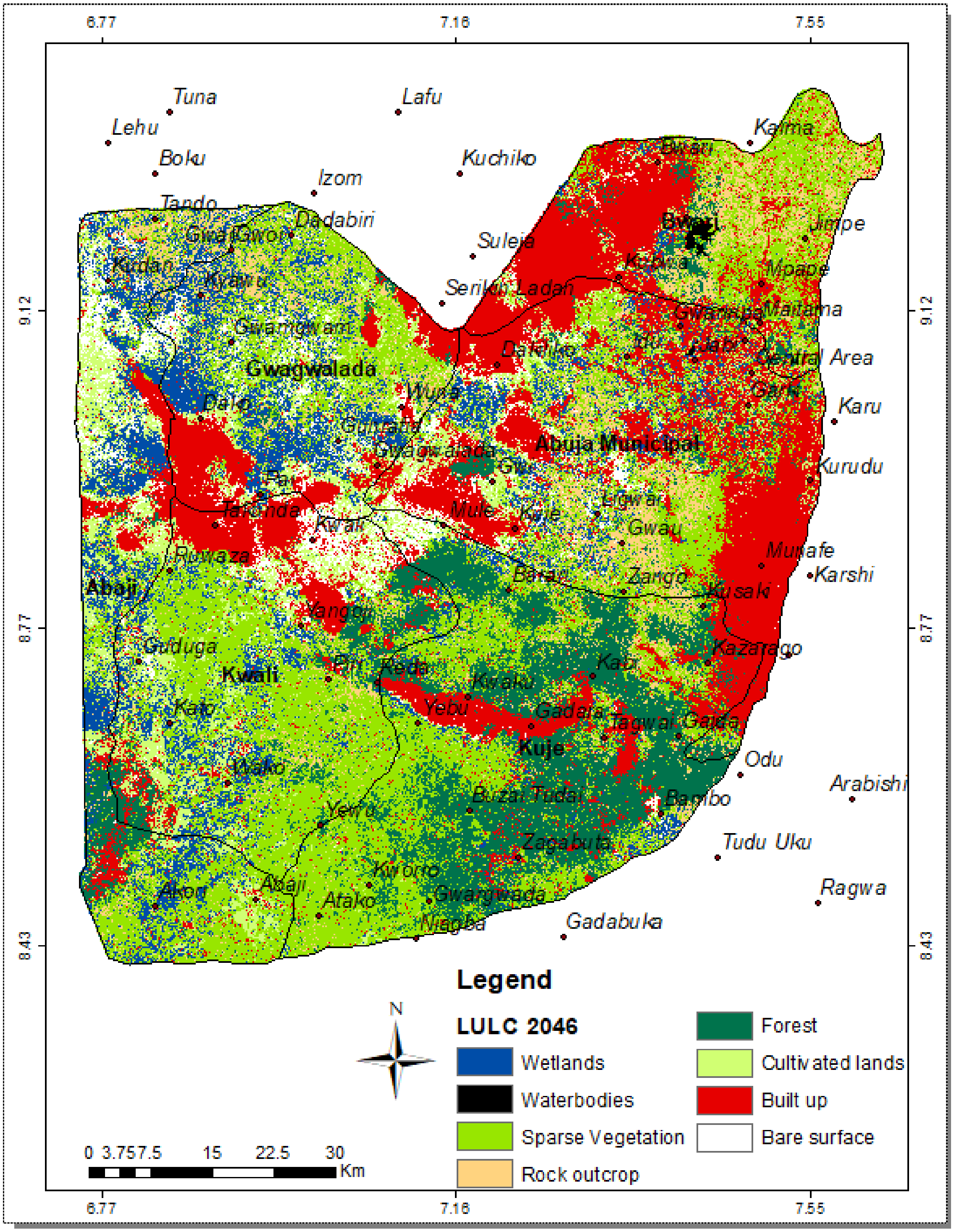

Figure 4.17: Projected Landuse/Landcover Map for 2046

4.8.4. Rooftop rainwater harvesting for 2046

Based on the population projection, an estimate of the quantity of rainwater harvestable was done using the rainfall forecast, the same average household size and average roof area as in section 4.6.1. Table 4.10 shows in summary the estimated quantity of rainwater harvestable in each district for the year 2046.

Table 4.10: Quantity of Rainwater Harvestable Based on Projected Population

Districts	**Population**	**Total Household**	**Total roof Area (m^2)**	**Volume min (m^3)**	**Volume max (m^3)**
Abaji	338333	75185	13533300	12991968	20570616
AMAC	4478652	995256	179146080	171980236.8	272302042
Bwari	1322501	293889	52900020	50784019	80408030
Gwagwalada	916826	203739	36673020	35206099	35206099
Kuje	559832	124407	22393260	21497530	34037755
Kwali	497358	110524	19894320	10998547	30239366
Total	8113501	1803000	324540000	303458399.8	472763908

The annual rainfall for 2046 ranged from 1200 mm to 1900 mm, Kisakye et al. (2018) had highlighted that some places will experience drought in the nearest future while others will experience more rainfall due to climate change. From the rainfall projections, Abuja is one of those areas most likely to experience more rainfall in 2046. The rooftop RWH potential based on the estimates above remained the same at minimum rainfall but increased from 131.5 to 166.6 lit/cap/day at maximum rainfall. This is because the projected rainfall increased. Therefore, in 2046, at minimum rainfall, every individual could have 105.2 lit/cap/day and at maximum rainfall 166.6 lit/cap/day.

Figure 4.18 shows the ranking of districts based on the quantity of rainwater harvestable. Abaji and Kwali having moderate rooftop RWH potential, Gwagwalada and Kuje having good rooftop RWH potential, Bwari with very good rooftop RWH potential and AMAC with the excellent rooftop RWH potential. The districts with the lowest potential falling within 30 million m^3 at maximum rainfall and those with the highest potential of above 260 million m^3 of water, medium and high fell between the range of 31 to 80 million m^3 of water. The various rooftop RWH potential areas based on population for Abuja in the year 2046 is shown in Figure 4.18.

The rooftop RWH potential changed a lot in 2046 compared to that of 2016 as the population projections indicated an increase which is double what it was in 2016 and the LULC maps also indicate increase in the built-up areas in Abuja. This affected the rooftop RWH potential positively considering the expected area which should be built-up in the year 2046. According to the projections, the built-up area would be about 1352 km^2 which is about 39% increase on the 2016 built-up areas and 27.7% of the total area enclosed by the state.

Considering that the population projected is also about two times the population in 2016, we can say that the predictions of a 221% increase in the rooftop RWH potential is quite consistent. Therefore, every district, person and building in Abuja can implement rooftop RWH technolgy and harvest rainwater.

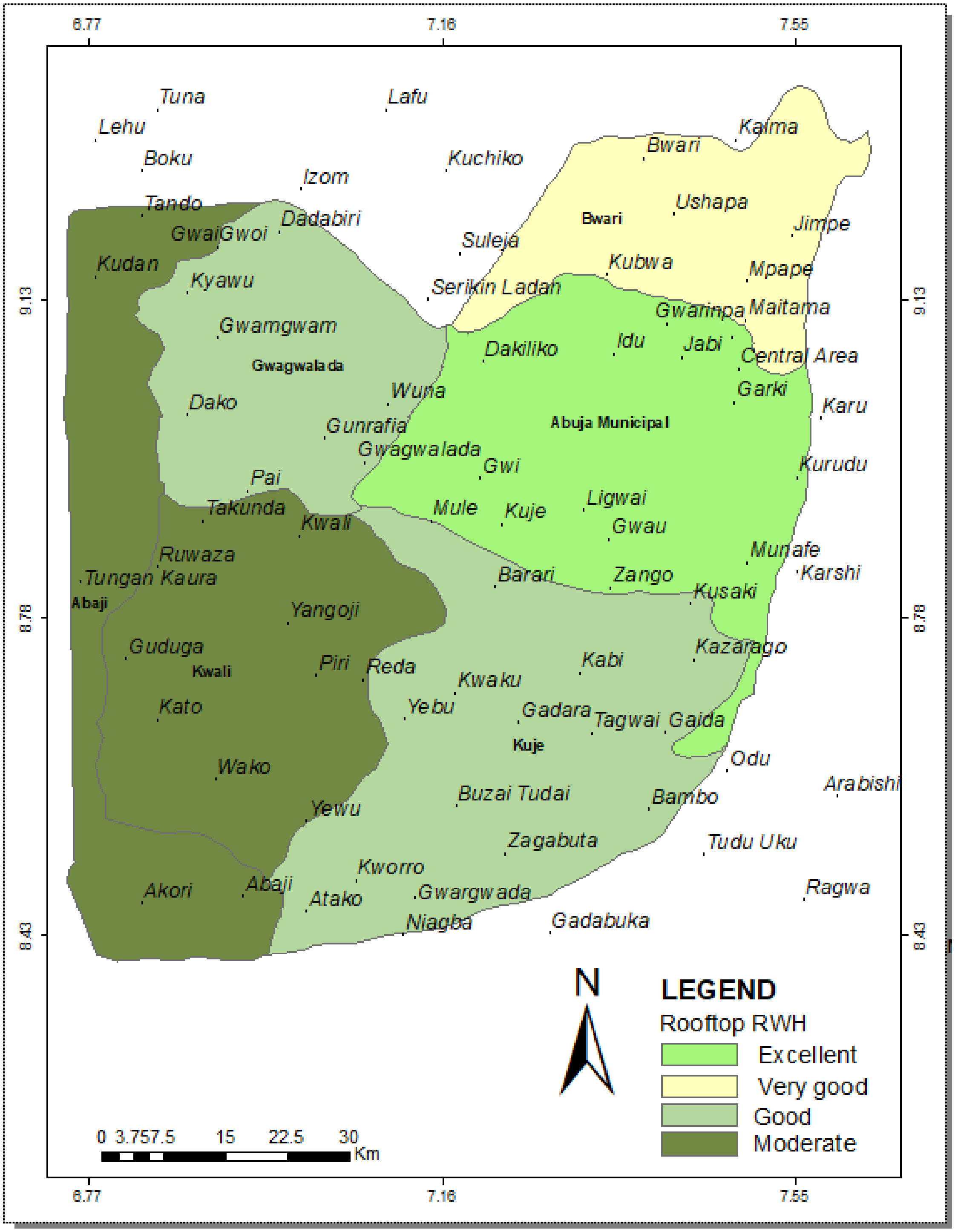

Figure 4.18 Rooftop Rainwater Harvesting Potential for 2046 Population

4.8.5. Surface rainwater harvesting for 2046

Using the same ranking criteria for the surface rainwater harvesting as in section 4.6.2, the 2046 LULC map was reclassified and the overlay operation on GIS carried out, producing the suitable sites for surface RWH as shown in Figure 4.19. In the year 2046, three categories were obtained in the surface RWH potential map: moderate, good and excellent. These categories were based on the overlay of rainfall, population, LULC, slope and soil maps. The slope and soil maps were the same used in section 4.6.2. However, all other maps overlaid were the projections of population, LULC and rainfall. The result showed that this time the area enclosed by most suitable sites for surface RWH increased compared to that in the 2016.

Therefore, the quantity of rainwater harvestable in these sites increased as well, which means that over time, the surface RWH potential increased by about 7% compared to the estimate for 2016. Table 4.11 shows the increment in the quantity of rainwater harvestable in 2046. Different runoff coefficients were used based on the difference in LULC, but the soil textures and the slope of the region remained constant. However, the areas found for surface RWH potential changed as a result of the changes in LULC which is in accordance with what Jianping et al. (2005) described. Also, the annual rainfall increased bringing about an increase in the total quantity of rainwater harvestable compared to that of 2016.

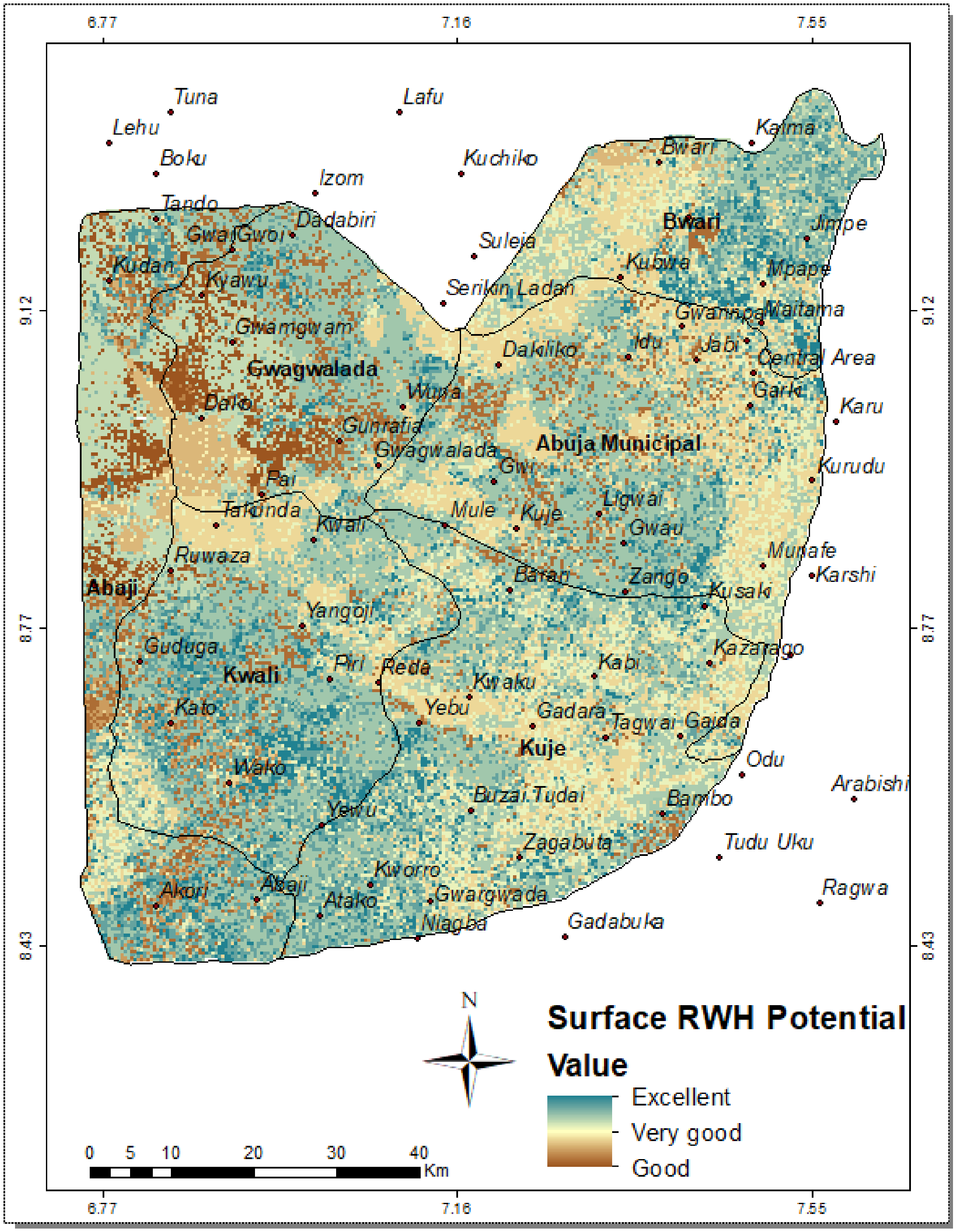

Figure 4.19: Surface Rainwater Harvesting Potential Sites in Abuja for 2046

4.8.6. In-Situ rainwater harvesting for 2046

Using the same ranking criteria for the surface rainwater harvesting as in section 4.6.3, the 2046 LULC map was reclassified and the overlay operation on GIS carried out, producing the potential sites for surface RWH as shown in Figure 4.20. In this year, three categories were obtained, good, very good and excellent potential. These categories were based on the overlay of rainfall, population, LULC, slope and soil maps. However, all other maps overlaid were the projections of population, LULC and rainfall. The result showed this time that the area enclosed by excellent sites for In-Situ RWH increased compared to that in 2016. Therefore, the quantity of rainwater harvestable in these sites increased by 7%. When compared to the in-situ RWH potential assessment for Saudi society done by Mahmoud & Alazba (2014), the in-situ RWH potential for Abuja in 2046 corresponds with what is obtainable based on the projected rainfall, LULC and population data. The individual cell rank for each criterion considered matched the resulting potential map after the overlay operation.

After estimating the area occupied by each surface and in-situ rainwater harvesting site, the total quantity of rainwater harvestable was calculated based on the areas enclosed by each rank in all 3 of them. Table 4.11 shows the quantity of rainwater harvestable. The same runoff coefficient was used for rooftop rainwater harvesting but the runoff coefficients for surface and in-situ rainwater harvesting sites changed a little due to changes in the areas of the LULC enclosed in these sites. Comparing the changes in LULC for 2046 to what was estimated by Jimme et al. (2015) for Kuje area, these changes are consistent.

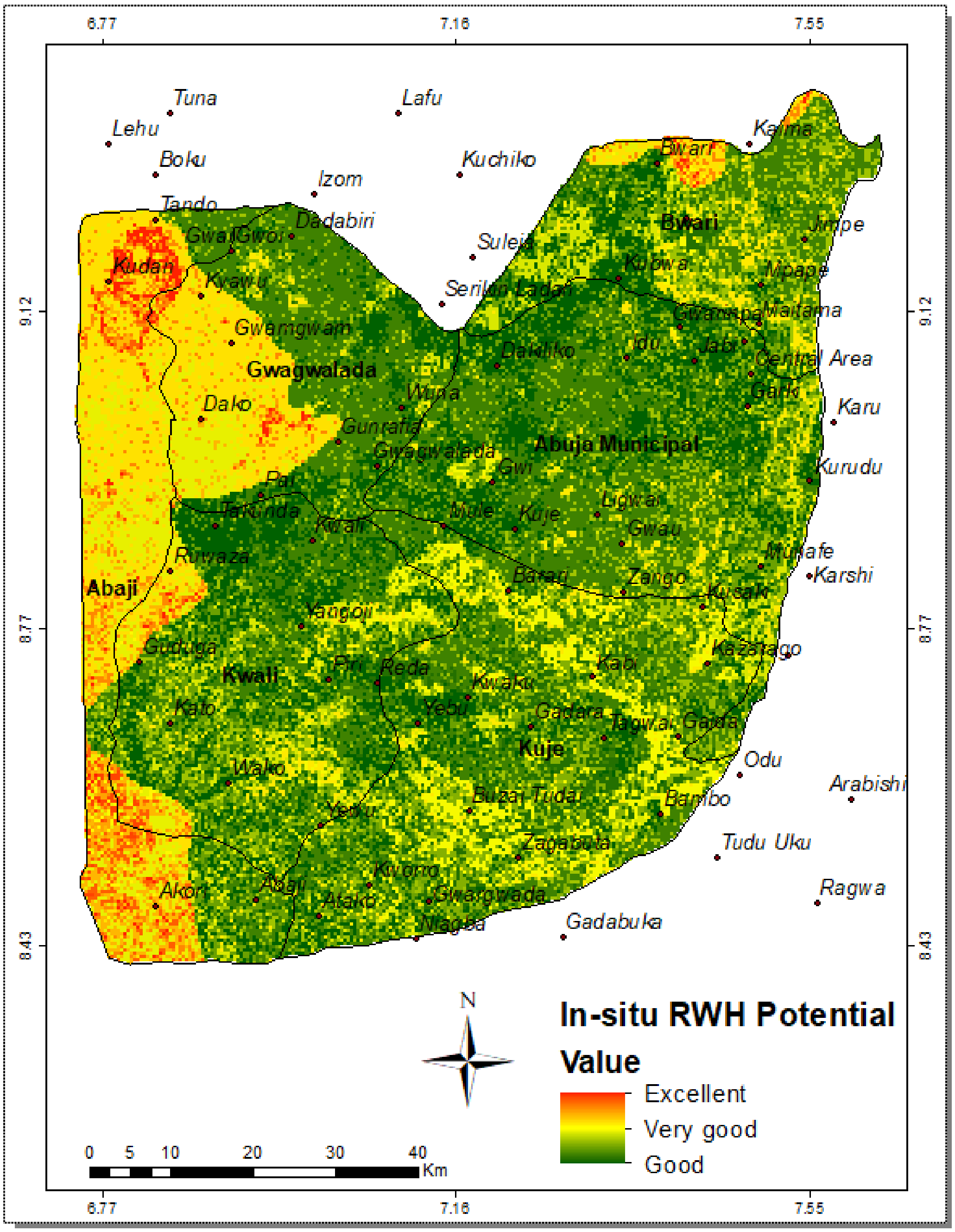

Figure 4.20: In-Situ Rainwater Harvesting Potential Sites for 2046

Table 4.11: Quantity of Rainwater Harvestable in Abuja for 2046

Area of Abuja	**Surface RWH**			**In-situ RWH**		
	Good	**Very Good**	**Excellent**	**Good**	**Very good**	**Excellent**
In km	1135.46	1732.295	4447.245	3926.89	2862.32	525.79
RO coefficient	0.53	0.62	0.72	0.58	0.65	0.76
Rainfall min (mm)	1200	1200	1200	1200	1200	1200
Rainfall max (mm)	1500	1500	1500	1500	1500	1500
Volume min (m^3)	722152560	1288827480	3842419680	2733115440	2232609600	479520480
Volume max (m^3)	902690700	1611034350	4803024600	3416394300	2790762000	599400600

From the calculations, the total rainwater harvestable in Abuja with minimum rainfall is about 11.2 billion m^3 and at maximum rainfall is 14.1 billion m^3 of rainwater. This quantity of water makes Abuja a place with very high potential for rainwater harvesting. The excellent areas for surface RWH changed drastically this time, the soil and slope classification were same and rainfall class was still in total of 5, so the only things which changed was the LULC. Having more built-up areas and cultivated lands with sparse vegetation and a reduction in forested areas and wetlands must have turned the overlay results for the better.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

With regards to the results obtained from this research, the following conclusions can be drawn;

1. Abuja had about 104% RWH potential at minimum rainfall using the rooftop RWH based on the assumption of average household size and average roof area, in comparison with the estimated average quantity of water required by every individual which was stated to be a maximum of 100 lit/cap/day. For in-situ and surface RWH, Abuja has a potential to harvest about 10.6 billion m^3 at minimum.
2. . Ten appropriate in-situ RWH technologies were identified based on the slope of the area. For steep slopes; ngolo pits and rock catchment were highlighted, for medium slopes; *fanya juu* terraces and bench terraces were highlighted and for flat slopes negarims and grass strips.
3. The effect of climate change and LULC change on RWH potential showed an increase especially for rooftop RWH. In the year 2046, the rooftop RWH potential might increase from 136.9 million m^3 to 303.5 million m^3 at minimum rainfall and from 171.1 million m^3 to 472.8 million m^3 at maximum rainfall, an increase of 160%. For in-situ and surface RWH potential in 2046 the potential increased by 7% compared to that of 2016.

5.2 Recommendations

Abuja is growing rapidly both in population and built-up areas. This is associated with the infrastructural development of the state making it highly susceptible to more complex environmental problems caused by water scarcity than it is already experiencing. From this research, it is known now that RWH is a sure means of meeting the water needs of the population in Abuja.

Therefore, the following recommendations are made:

1. Rooftop rainwater harvesting is recommended for every building in Abuja.
2. Plans for new dams and surface ponds large enough to hold the expected harvestable rainwater are suggested since the potential is most likely going to increase.
3. The in-situ RWH technologies identified as appropriate in this research are recommended for better crop production.

Furthermore, as additional recommendations, the following should be considered for further research on the subject of RWH;

1. The quality of rainwater could be studied in order to properly distinguish the specific water needs which can be met using rainwater and possibly, what measures could be taken to purify rainwater such that it can be used as potable water in Abuja.
2. The cost of installing rooftop RWH systems for different roof sizes and types and storage facilities for different capacity should be studied as well.

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