EXPLORATION OF GROUNDWATER POTENTIAL USING GIS AND REMOTE SENSING IN EMBU COUNTY, KENYA

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JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY

2019

Exploration of Groundwater Potential using GIS and Remote sensing in Embu County, Kenya

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A thesis submitted in Partial Fulfilment for the Degree of Master of Science in Environmental Engineering and Management in the Jomo Kenyatta University of Agriculture and Technology

2019

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

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DEDICATION

To my dear husband Felix Kipchirchir Ngetich and our children Tamara Cherotich Ngetich and Kibet Chirchir Ngetich. I am deeply grateful for your unending support and patience that has made this degree a reality.

ACKNOWLEDGEMENT

The completion of this work has been possible through the assistance of several people and institutions. I am thankful to Almighty God for his guidance. I sincerely acknowledge the support and guidance of my supervisors Dr. (Eng). James M. Raude and Dr. Joseph K. Sang throughout my research. Special thanks for your encouragement. I acknowledge Mr. Musa Githinji and Mr. Charles Mudunyi from the Ministry of Water and Sanitation for the assistance during data collection. Many thanks to my colleagues', postgraduate students, for your encouragement and support. Special thanks to Irene Jeptum for your encouragement. To the staff of the School of Biosystems and Environmental Engineering (SOBEE) I am grateful for your support throughout my research and thesis writing.

I am deeply grateful to my husband Felix Ngetich for his love, patience, financial and emotional support. My family, thank you a lot for your patience during this research. May the Almighty God abundantly bless you.

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LIST OF ABBREVIATIONS

DEM:	Digital Elevation Model
ERDAS:	Earth Resources Data Analysis System
ESRI:	Environmental Systems Research Institute
ETM:	Enhanced Thematic Mapper
GIS:	Geographical Information Systems
GPI:	Groundwater Potential Index
GSE:	Geological Society Engineering
IPCC:	Intergovernmental Panel on Climate Change
ISRIC:	International Soil Reference and Information Centre
IWMI:	International Water Management Institute
KMD:	Kenya Meteorological Department
LD:	Lineament Density
MODIS:	Moderate Resolution Imaging Spectrometer
MCE:	Multi Criteria Evaluation
MIF:	Multi Influencing Factors

PCA:	Principal Component Analysis
PCI:	Principal Component Image
RS:	Remote Sensing
SOTER:	Soil and Terrain Database
SRTM:	Shuttle Radar Topographical Mission
TIFF:	Tagged Image File Format
TM:	Thematic Mapper
UTM:	Universal Transverse Mercator
USA:	United States of America
USGS:	United States Geological Survey

ABSTRACT

Integration of Remote Sensing (RS) and the Geographical Information System (GIS) uses in groundwater resources is a major development. The RS and GIS geospatial techniques enhances the assessment, monitoring and conservation of groundwater resources. In this study, RS and GIS geospatial approaches were applied with the aim of identifying groundwater potential zones in Embu County, Kenya, based on selected multi-influencing factors. The multi- influencing factors include Drainage density, Slope, Lithology, Soil, Lineament density, Land use/ Land cover and Rainfall. Embu County, in Kenya mainly depends on groundwater for domestic use. Sadly, occurrence of conflict among the communities is frequent due to water shortages in the County. Therefore, a detailed investigation of groundwater potential is necessary for efficient and sustainable management of this scarce natural resource Lineament layer was obtained by processing Landsat 8 ETM+ image using Principal Component Analysis (PCA) in ENVI 4.7 and automatic extraction from Principal Component Image (PCI) using the LINE module in Geomatica software. All thematic layers were transformed to raster format before applying weighted overlay analysis in GIS, for mapping of potential groundwater zones in Embu County. The groundwater potential map produced showed that about 78% of the total area fell under 'high' to 'very high' zones indicating that over three quarters of the study area falls under good groundwater potential zone. About 20% showed moderate potential while only 2% fell under the low potential zone. The proposed study approach can be used as a way of modelling geospatial data for mapping of groundwater potential zones. The groundwater potential map produced along with the other thematic maps serve as resource information database which can be updated from time to time by adding new information. The study findings are useful to first-hand information planners and local authorities for assessment, planning, management and administration of groundwater water resources in Embu County and the same procedure can further be replicated in other counties

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Groundwater is a precious resource on earth. The development of groundwater plays a major role in a country's economy for both the urban and rural populations. Key amongst the rights and fundamental freedoms in the Constitution of Kenya (CoK) 2010, is the right of every person to access clean and safe water in adequate quantities (CoK, 2010). Further, in Kenya's blueprint, the vision 2030, the vision for water and sanitation is to ensure that improved availability and accessibility of water and sanitation to all, through conservation of water sources and implementation of new ways of harvesting and using rain and groundwater (Kenya Vision 2030, 2010). The prioritization of access to water is informed by the fact that over 80% of Kenya's surface area fall under semi-arid and arid agro-ecological zones (JICA, 2012). Groundwater is one of the most valuable natural resources serving as a significant source of water to communities, agricultural and industrial purposes (Rahmati et al., 2016) though currently under-exploited in Kenya (JICA, 2012). Compared to other water sources, groundwater is less vulnerable to climate fluctuations in an undisturbed aquifer system and therefore, can act as a critical buffer against drought and variations in rainfall (Balamurugan et al., 2017). Hence, the need to identify and map groundwater potential zones for groundwater development and effective water resource management (Mati et al., 2005) in water-scarce regions of Kenya is paramount.

There is no direct method to facilitate quantification of water below the surface. However, the presence or absence of groundwater can only be inferred indirectly by studying the geo-environmental parameters. Test drilling and stratigraphic analysis are the most reliable and standard methods for determining the location for drilling a borehole and the corresponding thickness of the aquifereous unit (Jha et al., 2010). The traditional approach of groundwater exploration through drilling, geological, hydro-geological, and geophysical methods are costly and time-consuming (Rahmati et al., 2016; Singh et al., 2002; Sander et al., 1996). Such methods suffers significant failure rates depending on the resources and expertise available (Lee et al., 2015). However, the failure rates can be reduced by utilising Geographic Information System (GIS) and Remote Sensing (RS) techniques (Jha et al., 2007).

GIS and RS technologies have great potential for use in groundwater potential analyses (Lee et al., 2015). Systematic integration of information about surface features related to groundwater such as landforms, land use, and lineaments is an essential aspect of GIS (Lee et al., 2015; Nampak et al., 2014). In the recent past, GIS and remote sensing have been applied extensively in groundwater-related studies (Balwant et al., 2018; Mokadem et al., 2018; Senthil, 2017; Thomas and Duraisamy 2017; Hornero et al., 2016; Mallast et al., 2011; Mogaji et al., 2011). While, it is not possible to directly understand groundwater distribution using RS and GIS technologies without field surveys, groundwater potential can be inferred from surface attributes such as geology, soil texture, land use, and drainage systems of a watershed (Lee et al., 2015; Machiwal et al., 2011; Dinesh-Kumar et al., 2007).

To understand groundwater systems, the physical characteristics of the related factors that configure the system should be identified (Lee et al., 2015). Generally, the occurrence and productivity of groundwater in a given aquifer are influenced by geo-environmental factors (Rahmati et al., 2016) such as landforms, drainage density, slope steepness, lineaments, land use and land cover (Oh et al., 2011). The information about geo-environmental factors related to groundwater can be extracted through RS data (Nampak et al., 2014) and integrated in a GIS environment followed by spatial analysis and visual interpretation (Jha et al., 2007). An integrated analysis of these geo-environmental factors can be critical in identifying and delineating the potential high yielding groundwater zones in a cost-effective manner. This can help in narrowing down the target areas for conducting detailed hydrogeological and geophysical surveys on the ground, and ultimately to locate the sites for drilling.

The arid and semi- arid land zones of Kenya, are agriculturally low-potential areas due to low and erratic rainfall (JICA, 2012). Most of these low potential areas are experiencing an increase in population pressure resulting from an influx of immigrants from the over-populated neighboring high potential areas (Ngetich et al., 2014). The immigrants are searching for greener grazing lands, and better livelihood. To worsen the situation, there has been a chronic recurrence of severe droughts leading to regular water shortage (Huho, 2010). On the other hand, the demand for groundwater which is the primary source of water in these agro-ecologies is increasing. Groundwater in ASAL's is key in providing drinking water supply and supporting irrigated agriculture. Remote sensing and GIS techniques provides an access to large coverage, including inaccessible remote areas like the study area. This study on groundwater potential mapping using RS and GIS can support exploration and exploitation thus complementing other water sources in the marginal sub-humid, semi-arid and the arid agro-ecologies.

1.2 Statement of the problem

Groundwater is gaining more popularity due to drought problems, rural water supply, and irrigation projects. The growing importance of groundwater is due to an increasing need for water which has led to over exploitation of groundwater creating a water shortage condition (Oteze, 2006). A common problem encountered during the exploration of groundwater is the production rate of dry wells. This occurs due to improper evaluation of groundwater and site selections (Abebe, 2006). Since the groundwater occurs deep in the subsurface, there is no direct method to facilitate observation of water below the surface. Its presence or absence can only be inferred indirectly by studying the groundwater occurrence and distribution of the controlling parameters (Lee et al., 2015; Machiwal et al., 2011; Dinesh-Kumar et al., 2007).

In Kenya, like in many African countries, the provision of water for the rapidly growing population is usually stated as one of the cardinal objectives of the governments' development plan. In Embu County, specifically Mbeere North and Mbeere South Sub-counties are representatives of parts of over 80% of Kenya that fall under Arid and Semi-Arid areas. The county has a human population of 577,390 people according to the projected figures from Kenya population and housing census report of 2009. The two sub-counties have a lower population density ranging from 99/km^2 to 115/km^2 that accounts for 40% of Embu County's population. The demand for groundwater which is the primary source of water in these sub-counties is increasing due to an influx of immigrants from the over-populated high population density, high-potential areas of the county. There has been a perennial water shortage in the two sub-counties (GoK, 2012). During the dry spells, locals walk kilometres to the nearest water sources; alternatively, residents are forced to buy water. Water scarcity is also the major factor limiting crop productivity in semi-arid Mbeere sub-County (Gicheru et al., 2004). This necessitates groundwater potential mapping to support exploration and exploitation thus complementing other water sources in the county.

1.3 Justification of the study

It is key to know the groundwater potential of an area before embarking on any further exploration, as these will provide information on the water potential of the area. (Kuria et al., 2012). This will lead to the prevention of sudden drying up of boreholes during dry season and prevention of minimal yield from the boreholes. The absence or lack of detailed hydrological maps in the study areas makes the use of RS and GIS important. Developers can avoid losses associated with drilling of groundwater in unsuitable areas. Also, groundwater resources can quickly and precisely be assessed by these techniques.

Mbeere North and Mbeere South sub Counties are experiencing an influx of immigrants from the over-populated high-potential areas of Embu County, in search of better opportunities to improve their lives. Sadly, occurrence of conflict is frequent due to water shortages in these sub-counties. Therefore, a detailed investigation of groundwater potential is necessary for efficient and sustainable management of this scarce natural resource. The existing methods of groundwater exploration using geophysical and geo-electrical techniques are expensive and time-consuming. Hence, there is a need to exploit new technologies that involve the use of Remote Sensing and Geographical Information System (GIS) in the exploration of groundwater (Sener et al., 2005). These techniques does not require skilled personnel while implementing them. Hence, there is overall reduction in the cost of exploration of groundwater reserves. Findings from this study will serve as a guide to the County Government, Non-Government Organizations and other stakeholders involved in water exploration.

1.4 Objectives

1.4.1 Main objective

The main objective of this research was to identify groundwater potential zones using a combination of GIS and Remote Sensing techniques in Embu County.

1.4.2 Specific objectives

The specific objectives of the study were to:

i) Evaluate importance and relationships between a set of hydrological, geological and topographical parameters that influences the natural occurrence of groundwater in Embu County.

ii) Determine groundwater potential zones in Embu County through integration of thematic maps by applying weighted overlay in a GIS environment.
iii) Verify the GIS model groundwater potential zones in Embu County using existing groundwater borehole distribution data.

1.5 Research questions

This study sought to answer the following research questions.

i) What is the importance of rainfall, lithology, lineaments, soil, Land use/land cover, drainage density and slope on ground water availability in Embu County?
ii) How does the ground water potential zones in Embu County vary?
iii) How are the results of potential groundwater availability comparable to existing borehole distribution data?

1.6 Scope and limitation of study

The study area which is Embu County, comprises of three sub- counties; Mbeere North, Mbeere South and Embu Sub –Counties. This study focuses on the assessment of groundwater potential zones using Remote Sensing and Geographic Information System. The factors to be considered in the study includes lineament density, lithology, land-use/land-cover, drainage density, rainfall, soil, and slope. The lack of the whole groundwater inventory data and unevenly distribution of data point are the major limitation of this study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Groundwater is one of the earth's most important resource which plays an important role in any country's development. It becomes a usable resource when the water-bearing formations are permeable enough to allow water to infiltrate through them, to yield an adequate quantity of good quality water for use through boreholes, hand dug-well and springs (Kuria et al., 2012). Groundwater can be replenished from recharge sources to permit continued exploitation. Various techniques are used to provide information on the occurrence of groundwater since it cannot be seen directly from the earth's surface (Kuria et al., 2012).

Mapping of groundwater potential zones within each geological unit has become an appropriate procedure with the advent of Remote Sensing and Geographic Information System (GIS) technologies. This study involved identifying groundwater potential areas in a GIS environment. This required a clear understanding of the various aspects of groundwater, GIS, and modelling involved. This chapter reviews existing literature on groundwater and GIS that was relevant for the study. These include groundwater occurrence, groundwater exploration techniques, aquifer properties, GIS and Remote sensing use in finding groundwater, GIS modelling and its application in groundwater.

2.2 Conceptual framework

2.2.1 Groundwater Occurrence

Groundwater is stored in the open spaces and fractures within geologic formations beneath the earth's surface known as aquifers (Lehr et al., 2005). An aquifer is a saturated bed, or formation which not only stores water but yields it in sufficient quantity to be of consequence as a source of supply. Aquifers may be made of consolidated or unconsolidated rock (Lehr et al., 2005). Consolidated rock occurs in the form of rocks of such materials as sandstone, tuffs, limestone, and granite. The main properties of an aquifer are its capacity to release the water held in its pores and its ability to transmit the flow easily (Lehr et al., 2005). These properties essentially depend upon the composition of the aquifer and they include the porosity, specific yield, hydraulic conductivity, permeability and coefficient of storage. Groundwater potential means having a latent possibility or likelihood of occurrence of groundwater in an area. Areas or zones of abundant groundwater available for use are referred to as areas of good groundwater potential. Productive water bearing zones are referred to as good groundwater potential aquifers, which when correctly sited yields sufficient quantities. Knowledge of groundwater potential acts as a guide and therefore, makes it easy for exploitation. (Madan et al., 2010).

2.2.2 Groundwater Exploration

The search for groundwater has intensified in human history. This is due to the fact that many governments are unable to meet the ever increasing water demand; inhabitants have had to search for alternative sources such as surface streams, shallow wells and boreholes (Trimmer, 2000). Groundwater exploration is carried out in many ways ranging from traditional to modern methods. Groundwater exploration is developing everyday through new means and devices. Meijirik (2007) reports that exploration for groundwater using photo geology was a major field of interest in the past and present in areas covered inadequately by geological maps. Several techniques can be used to explore groundwater resources. Test drilling and stratigraphy analysis are the most reliable and standard methods for determining the location of a borehole and the thickness of the aquifereous unit (Madan et al., 2010). However, these methods of groundwater investigation are not time and cost-effective, and also often require skilled personnel (Roscoe, 1990; Fetter, 1994).

Geophysical prospecting techniques have also been used by various researchers to explore groundwater resource in different types of geologic terrain (Ako et al., 1989; Amadi et al., 1990; Olorunfemi et al., 1995; Olayinka et al., 2001 and Adiat et al., 2009). However, due to lack of precision of an onsite analysis, results and interpretations of geophysical surveys always require validation with borehole data (Adiat, 2012).

The advent of Remote Sensing (RS) and the Geographic Information System (GIS) has also provided another cost and time effective means of assessing and managing groundwater resources (Jha et al., 2007; Meijerink, 2007). Locating promising groundwater locations for exploration and exploitation is based on evaluating a set of hydrological, geologic and topographical parameters that influence its availability using GIS and Remote Sensing.

2.2.3 Factors Affecting Groundwater Occurrence

Groundwater occurrence depends on rate of water movement, aquifer characteristics, and recharge of the aquifers. Groundwater movement like surface water is affected by the nature of slope. Thomas and Duraisamy, (2017) states that groundwater moves from steep slopes to gentle slopes and from higher pressure locations to lower pressure locations. The study states that the science of groundwater movement is described as groundwater hydraulics, in which, it is the hydraulic head that determines groundwater movement (Darcy’s law). Groundwater movement is rapid in gravels and sands and slow in clay or in tiny rock features.

Buddemeir and Schloss (2000) states that groundwater development potential yield depends on aquifer characteristics such as hydraulic conductivity, aquifer thickness, storability, aerial extent, groundwater levels, available drawdown and recharge. This indicates that nature of soil, lithology; climate and properties of aquifer are the major factors controlling movement and storage of groundwater in any part of the world. Groundwater recharge and storage in shallow unconfined aquifer is complex. It is dependent upon the occurrence, intensity and duration of precipitation, temperature, humidity, wind velocity as well as character and thickness of soil and rock above the water table and the surface topography, vegetation and land use (Arnold et al., 2000). Groundwater occurrence also depends on climatic conditions, as well as soil type, soil-moisture status, vegetation cover and condition, slope, cultivation practices and most of all, on evapotranspiration, which is a function of the other factors (Yeh et al, 2016). Several factors including slope, drainage density, lithology, soil, lineament density, land cover and rainfall are described here and their influence on groundwater occurrence is discussed.

2.2.3.1 Slope

Yeh et al. (2016) states that slope is one of the factors controlling infiltration of water to the ground and the indicator of groundwater potential suitability. The study found that areas with steep slopes caused more runoff, less infiltration and have low groundwater prospects compared to the areas with gentle slope. Gentle slope areas caused less runoff, high infiltration rate and have good ground water prospects. Fashae et al. (2013) illustrated that slope is a good proxy for groundwater potential analyses. The study demonstrates that slope highly influences groundwater infiltration and recharge. Where steep slopes are present, groundwater potential is low because there is more surface runoff than infiltration. Areas characterized by flatlands groundwater potential was discovered to be high because it is easier for the water to form pools and infiltrate than to runoff on the surface.

2.2.3.2 Drainage density

The drainage system of an area is determined by the slope, nature and attitude of the bedrock and also by the regional and local fracture pattern (Adiat, 2012). Drainage density is the ratio of the sum of lengths of streams to the size of area of the grid under consideration (Greenbaum, 1989). It is an inverse function of permeability. The less permeable a rock is, the less the infiltration of rainfall, which conversely tends to be concentrated in surface runoff (Magesh et al., 2012). It is a measure of surface water, sub-surface water and groundwater (Nampak et al., 2014). They reflect the lithology and structure of a given area and can be of great value for groundwater resources evaluation (Godebo, 2005).

The drainage density with respect to groundwater potential is determined by analyzing the drainage length within grid area (Ozdemir, 2011). When the drainage density of an area is high, it is indicative of high runoff and consequently low infiltration rate whereas low drainage density in an area implies low runoff and high infiltration (Prasad et al., 2008). Since the drainage density can indirectly indicate the suitability for groundwater recharge of an area because of its relation with surface runoff and permeability, it is mostly considered as one of the factors that is used to identify recharge potential zones. Drainage density can be derived from the drainage pattern by adopting steps similar to those of (Greenbaum, 1989; Edet et al., 1998; Sener et al., 2005; Al Saud, 2008).

2.2.3.3 Lithology

Lithology is the description of rock composition and texture. Its investigations include the delineation and mapping of various landform and drainage characteristics that could have a direct control on the occurrence and flow of groundwater. The different types of lithology that are exposed to the surface highly affect groundwater recharge by controlling the percolation and flow of water to the ground (Shaban et al., 2005). Hence, lithology plays a great role in the occurrence and distribution of groundwater potentials zone.

2.2.3.4 Soil

Infiltration of water is highly dependent on the type of soil and soil texture. Sandy soils has large particle constituents, which makes it have high transmissivity and high infiltration values. On the other hand, clay soils have small particle constituents, resulting in low infiltration rates. In terms of groundwater potential, sandy soils are assigned higher weights, clay soils are assigned lower weights and loamy soils are assigned medium weights (Jha et al., 2010; Magesh et al., 2012; Avinash et al., 2011; Fashae et al., 2013.

2.2.3.5 Lineament density

Lineaments are structurally controlled linear or curvilinear features, which are identified from the satellite imagery by their relatively linear alignments (Magesh et al., 2012). These features express the surface topography of the underlying structural features. Lineaments represent the zones of faulting and fracturing resulting in increased secondary porosity and permeability. Lineaments provide important information on surface and subsurface features that may control the movement and storage of groundwater (Adiat et al., 2012). They are features with secondary permeability. Potential sites for productive water wells are usually located around these features

(Travaglia et.al, 2003). They are responsible for infiltration of surface runoff into subsurface and also for movement and storage of groundwater (Rao et al., 2001). The lineament density (L_d) is a measurable quantity which is the total length of all recorded lineaments divided by the area under consideration as shown in Equation 2.1 (Edet et al., 1997).

$$L_d = \sum_{i-1}^{i=n} \frac{L_i}{A}\left(km^{-1}\right) \qquad (2.1)$$

Where:

L_d = Lineament density (km/km^2)

L_i = Total length of all lineaments (km)

A = Area of the grid (km^2)

A high lineament-length density is indicative of areas of out-cropping bedrock and thin regolith whereas low lineament-length density implies buried bedrock and thick regolith. (Edet et al., 1994). Areas with high lineament density are good for groundwater potential zones (Haridas et al., 1998). These factors are hydro geologically important as they provide the path ways for groundwater movement. Lineament density of an area can indirectly reveal the groundwater potential, since the presence of lineaments usually denotes a permeable zone (Magesh et al., 2012).

Lineament analysis from remote sensing data constitutes an important part of studies related to tectonics, engineering, geomorphology and in the exploration of natural resources such as groundwater, petroleum and minerals (Koopmans, 1986; Kar, 1994; and Philip 1996). Mapping of lineaments from various remote Sensing imagery is a commonly used step in groundwater exploration. In relation to groundwater exploration, lineaments are the results of faults and fractures which infer that they are the zone of increased porosity and permeability. Hence lineaments have greater significance in groundwater studies, occurrence and distribution. (Magesh et al., 2012)

2.2.3.6 Land cover and land use

One of the parameters that influence the occurrence of sub-surface groundwater is the land cover and land use of the area. The effect of land cover is manifested either by reduced runoff or by trapped water on their leaf. Water droplets trapped in this way go down to recharge groundwater. Vegetal cover increases infiltration as compared with barren soil because it retards surface flow giving the water additional time to enter the soil. Also the root system makes the soil more pervious and the foliage shields the soil from raindrop impact thus reducing rain packing of surface soil.

Types of land cover/ land use include forest plantations, crop farms, bare denuded soils surfaces, water bodies and settlements. Each type of land use/ land cover has a certain influence on groundwater potential indirectly through infiltration, runoff and evaporation (Fashae et al., 2013). Vegetation cover reduces evaporation and runoff hence increases infiltration. Vegetation increases chances of groundwater recharge and can be an indication of high groundwater potential (Leduc et al., 2001). Forest plantations require large amounts of water, which they absorb from the vadose zone and in other cases from beneath the water table.. In settlements and built up areas, infiltration is low because of roads, pavements and buildings covering the soil surface and consequently, low groundwater potentials are expected (Fashae et al., 2013).

2.2.3.7 Rainfall

Groundwater recharge is dominantly from rainfall (Stute et al., 2007). Rainfall determines the amount of water that would be available to percolate into the groundwater system, therefore, rainfall is an important hydrologic element (Adiat, 2012). High rainfall is favorable for high groundwater potential; hence during the weighting it is assigned a higher priority. Rainfall is one of the primary sources of groundwater and is expressed as the depth of precipitated water millimeters, measured by rain gauge for selected periods of time. Groundwater recharge to the superficial aquifer occurs via direct rainfall infiltration and thus is highly dependent on rainfall variability (Meredith et al., 2012).

2.2.4 Role of GIS and RS in the determination of Groundwater potential

Test drilling and stratigraphic analysis are the most reliable and standard methods for determining the location of a borehole and the thickness of the aquifereous unit (Madan et al., 2010). However, these methods of groundwater investigation are not time and cost effective and also, they often require skilled personnel (Roscoe, 1990; Fetter, 1994). Geophysical prospecting techniques have also been used by various researchers to explore groundwater resource in different types of geologic terrain (Ako et.al, 1989; Amadi et.al, 1990; Olorunfemi et al., 1995; Olayinka et al., 2001, Adiat et al., 2009). However due to lack of precision of an in-situ analysis, the results and interpretations of geophysical surveys can be validated by the use of borehole data.

The advent of RS and GIS has also provided a cost and time effective means of assessing and managing groundwater resources (Jha et al., 2007; Meijerink, 2007). The Geographic Information System offers spatial data management and analysis tools that can assist users in organising, storing, editing, analysing, and displaying positional and attribute information about geographical data (Burrough, 1986). In recent years, digital techniques are being used to integrate various data to solve problems related to groundwater including delineating groundwater potential zones. These various data are prepared in the form of a thematic map using GIS software tools. These thematic maps are then integrated using “Spatial Analyst” tool. The “Spatial Analyst” tool with mathematical and Boolean operators is then used to develop a model depending on the objective of the problem at hand, such as delineation of groundwater potential zones.

Various types of information of hydrogeologic significance can be extracted from remote sensing data (Adiat et al., 2012). Analysis of remotely sensed data for drainage, geology, geomorphologic, and lineament characteristics of the terrain is an integrated way facilitates effective evaluation of groundwater potential zones (Pothiraj, 2012). Several attempts have been made in the generation of thematic maps for the identification of groundwater potential zones in different regions. Kuria et al. (2012) mapped groundwater potential in Kitui area using geospatial technologies. In their work, the utility of geospatial technologies in estimating the groundwater potential in Kitui district was demonstrated. The study found out that the most suitable areas for groundwater prospecting were shown to be those in the central and eastern areas of the sub-county. However, the authors did not fully validate their study since they only indicated that existing water points were found in the identified potential region without showing a map of the existing boreholes and relationship with the map produced.

Ganapuram et al. (2009) mapped groundwater potential zones in the Musi basin, India using Remote Sensing data and GIS. The authors successfully delineated and showed the prospective zones of groundwater in the basin. Krishnamurthy et al. (1996) used remote sensing and GIS for demarcating groundwater potential areas in the Marudaiyar basin of Tamil Nadu, India. The authors prepared the maps of Lithology, landforms, lineaments and surface water bodies from the remotely sensed data, and those of drainage density and slope from Survey of India (SOI) toposheets. These thematic maps were integrated and analysed using a GIS-based model developed with logical conditions in a GIS environment. Finally, the groundwater potential zone map thus developed was verified with borehole well logs, which indicated a good agreement. Hence the study showed the effectiveness of using GIS and Remote Sensing in groundwater potential zones determination. However, the study incorporated only six thematic maps which could have been better if they had used more factors.

Groundwater potential can be spatially predicted by making use of various factors of hydrogeologic importance that can be obtained from these data. However, the degree of influence of a factor on groundwater occurrence varies among factors, and this may also be space dependent. Apart from the fact that groundwater potential prediction involves consideration of many factors obtainable from different sources, the process also requires inputs from many experts (Adiat et al., 2012). The groundwater prospecting in the study area has not been extensively undertaken hence a resource information database needs to be developed which can be updated from time to time by adding new information. This study was tailored to fill such gap by providing part of the required database.

2.2.5 Weighting

To apply multi-criteria evaluation (MCE), a set of relative weights is assigned for each map using weights. The weights that are calculated for each factor map are the results weighted Index Overly analysis and are based on their relative importance to groundwater accumulation. Weighted overlay analysis is one of the most widely used methods in spatial multi-criteria decision analysis. It is a simple and straightforward method for a combined analysis of multi-class maps. Human judgment can be incorporated into the analysis, and this improves the efficacy of this method. This method takes into consideration the relative importance of the parameters and the classes belonging to each parameter. There is no standard scale for a simple weighted overlay method. For this purpose, the criteria for the analysis should be defined, and each parameter should be assigned importance (Saraf and Chowdhury, 1998; Nag, 2005). Determination of weight of each class is the most crucial in the integrated analysis, as the output is mostly dependent on the assignment of appropriate weight

(Chowdhury, 1999). During the process of groundwater potential determination, the factors considered do not have the same influence, and not every factor was independent. When calculating potential groundwater, these factors were used for evaluation, and weight accumulation was applied to determine a groundwater potential score.

2.3 Literature review critique

Prasad et al. (2008) used ban integrated approach of Remote Sensing and Geographical Information System (GIS) to delineate groundwater potential zones in hard rock terrain. The remotely sensed data at the scale of 1:50,000 and topographical information from available maps, had been used for the preparation of ground water prospective map by integrating geology, geomorphology, slope, drainage-density and lineaments map of the study area. Further, the data on yield of aquifer, as observed from existing bore wells in the area, had been used to validate the groundwater potential map. The final result depicted the favorable prospective zones in the study area and could be helpful in better planning and management of groundwater resources especially in hard rock terrains. In order to validate classification the authors collected data on the yield of existing wells. About 438 wells were monitored and the yield of these wells had been found to vary from 31 to 1,426 m^3/day. These data were superimposed on the groundwater potential map and number of wells with different yield ranges was classified for different zones of potential map. Frequency distribution of various yields in different zones was also calculated. Occurrence of a number of wells with yield range of 100–500 m^3/day was more in the zones which were described as ‘‘good’’ as well as ‘‘very good’’ in comparison to the occurrence of wells with these yields in other zones. Another remarkable feature was that as one moves from ‘‘good’’ to ‘‘poor’’ zone the number of occurrence of these better yielding wells decreased suggesting that the possibility of getting better yields was decreasing. Hence, the most favorable zones for high yielding groundwater were concluded as ‘‘good’’ and ‘‘very good’’ zones as derived from the application of GIS. One limitation of this study was only incorporating five factors that influence the occurrence of groundwater. The more the factors the greater the accuracy of the result.

Yeh et al. (2008) reported that assessing the potential zone of groundwater recharge is extremely important for the protection of water quality and the management of groundwater systems. The authors carried out groundwater potential study in Taiwan with the help of remote sensing and the geographical information system (GIS) by integrating the five contributing factors: lithology, land cover/land use, lineaments, drainage, and slope. The weights of factors contributing to the groundwater recharge were derived using aerial photos, geology maps, a land use database, and field verification. The study was only incorporating five factors that influence the occurrence of groundwater in which the factors recommended should be more.

Singh et al. *(*2009) conducted study on water resources evaluation and management for Morar river basin in Gwalior district, Madhya Pradesh. Groundwater prospect of the basin had been delineated from the satellite data by the integration of geology, geomorphology, lineament and slope and classified as excellent to poor ground water potential zones using GIS. The results obtained from remotely sensed data were cross checked with the borehole well yield data and were found in good agreement. This depicted the positive prospective zones in the study area for exploration of groundwater in future. Net groundwater availability was estimated to be about 63.634 MCM. The calculated annual draft of groundwater from dug wells and tube wells for all users was 70.051 MCM which reveal a deficit in groundwater storage in the basin. The study was only incorporating four factors that influence the occurrence of groundwater in which the factors recommended should be more.

Machiwal et al. (2011) reported that remote sensing (RS) and geographic information system (GIS) were promising tools for efficient planning and management of vital groundwater resources, especially in data-scarce developing nations. A standard methodology was proposed to delineate groundwater potential zones using integrated RS, GIS and multi-criteria decision making (MCDM) techniques. Four groundwater potential zones were identified and demarcated in the study area. In the good zone, the mean annually exploitable groundwater reserve was estimated at 0.026 million cubic meters per km^2 (MCM/km^2), whereas it was 0.024 MCM/km^2 in the moderate zone, 0.018 MCM/km^2 in the poor zone, and 0.013 MCM/km^2 in the very poor zone. The groundwater potential map was finally verified using the well yield data of 39 pumping wells, and the result was found satisfactory.

In another development Kadam and Sankhua (2015) studied groundwater hydrology of Upper Karha watershed in India. In their study hydrogeomorphological mapping coupled with ground truth investigation was undertaken. Layers used in the study include hydrogeomorphology, landuse land cover, soil, slope and geology. Weighted overlay analysis in Arc-GIS environment was used to integrate the reclassified raster layers. Groundwater potential zones were identified to be 0.40% - excellent, 20.19% - good, 64.11% - moderate, 14.93% - poor and 0.36%- nil of the study area.

Kumar et al. (2014) conducted a study to identify the artificial groundwater recharge zones in Kallar watershed using remote sensing and Geographical Information System (GIS) for augmenting groundwater resources. The study area had been facing severe water scarcity due to intensive agriculture for the past few years. Morphometric parameters were analyzed to understand the watershed characteristics and its influence on the water resources. For instance, bifurcation ratio indicates high surface runoff and low recharge. Low drainage density showing permeable strata, dense vegetation and low relief. Analysis of shape parameters *i.e.* elongation ratio and circularity ratio suggested that Kallar watershed was elongated in shape. Moreover, slope, geology and geomorphological mapping was done to demarcate groundwater potential zones for future exploration in the study area. The integrated study helped in designing suitable sites for constructing water harvesting structures. Check dams, percolation tanks and nala bunds were proposed as 1st, 2nd or 3rd drainage orders at Micro Basins (MB-1) and MB-4 with pediment. Finally, the best feasible water harvesting structures had been proposed within the watershed area using RS and GIS.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location and climatic conditions of Study Area

The study was carried out in Embu County in Kenya. Embu County is located on the windward side of Mt. Kenya, with agro-ecological conditions ranging from the cold and wet upper zones to the hot and dry lower zones in the Tana River Basin (Jaetzold, 2007). Embu County falls in the shield lands of Eastern Kenya and within the upper Tana River watershed and covers approximately 2,826 km^2. The elevation ranges from about 520 m to 2200 m above the sea level, with an average annual rainfall of 550 mm to 1500 mm. The county comprises three sub-counties; Embu, Mbeere North, and Mbeere South. A rural settlement pattern characterizes Embu County except for central town area of Embu Municipality. The dominant land use system in Embu sub-County is intensive smallholder mixed farming while in Mbeere North and South livestock farming is a significant economic activity (Jaetzold, 2007). Embu Sub County occupies a total area of 729 km^2 with an annual average bimodal rainfall of 1,500 mm while Mbeere North and Mbeere South Sub Counties occupy a total area of 2,092 km^2 with an annual average bimodal rainfall of 550 mm (Ngetich et al., 2014). The map of the study area is shown in Figure 3.1.

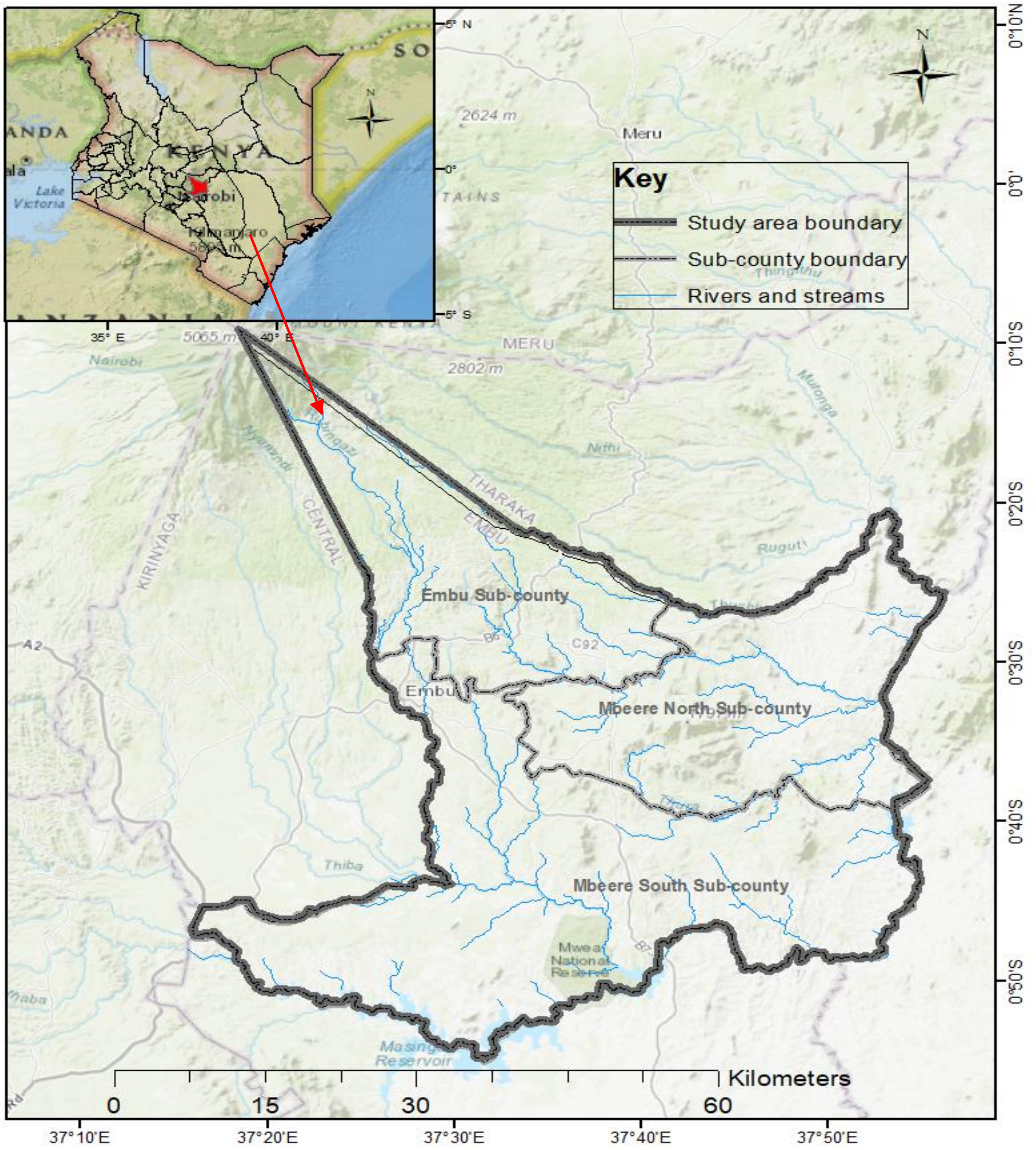

Figure Error! No text of specified style in document.**.2: The location of the study area and the distribution of streams**

3.1.2 Hydrogeology of Embu County

The geology of Embu County is majorly underlain by metamorphic rocks of the Neoproterozoic Mozambique Belt and volcanics (Schluter, 2006). The igneous rock around Mount Kenya was formed as a result of volcanic activity in the mountain, which is now extinct having erupted last 1.3-1.6 million years ago (Baker, 1967). The lower slope of the mountain has never been glaciated and comprises of unconsolidated soils or rocks from volcanic deposits, and these loose soil particles are prone to weathering and erosion (Baker, 2015). Embu sub-county, located in the Upper Tana River Basin is dominated by volcanic rock formations with exposed fractured rocks, which tend to be higher yielding (Knoop et al., 2012; Baker et al., 2015). Phonolites, trachyphonolites, basalts, ignimbrites, and trachytes of different phases of volcanism represent volcanics (Hughes et al., 2012).

Highlands (higher than 1,500 m above sea level) and Midlands (1200 m to 1500 m above sea level) and other topographical features like hills and valleys typical of Kenya's Eastern Highlands characterize the landscape of the sub-county. Mbeere North and Mbeere South Sub Counties slope from the northwest to southwest direction and is dominated by poor yielding metamorphic rocks. In locations where groundwater is utilized, localized issues like poor understanding of seasonal variation, salinity, fluoride, iron, and manganese dominate (Knoop et al., 2012). The area is floored by rocks of the Precambrian Basement System, which include granitoid gneisses, schists, granulites and crystalline limestone (Nyambok et al., 1979).

The drainage of the main rivers and their tributaries is determined by the slopes and shape of the tertiary volcanic, the directions of the slopes of the Mt. Kenya and the structure of the basement systems. Influenced by Mount Kenya, Embu County has largely radial drainage pattern predominating the upper and middle until the streams open out in the flatter sections of the basement system floor (Baker et al., 2015). Four major rivers, namely Rupingazi, Thuci, Kii and Ena, all following a southeast direction, drain through Embu sub-county while five major rivers (Tana, Rupingazi, Thiba, Thuci, and Ena) flow through Mbeere North and Mbeere South Sub Counties

3.2 Overall Research Design

A four-step approach was used. The first step was data acquisition, processing, and reclassification. The second step consisted of the assignment of the weights to the factors influencing groundwater potential. The third step involved the determination of the groundwater potential by integrating the thematic layers using a weighted overlay analysis in a GIS based DRASTIC model in order to generate the groundwater potential maps. The fourth and last step was the validation of the developed groundwater potential maps through a correlation approach using existing groundwater data. Figure 3.2 illustrates a methodological flowchart that was used.

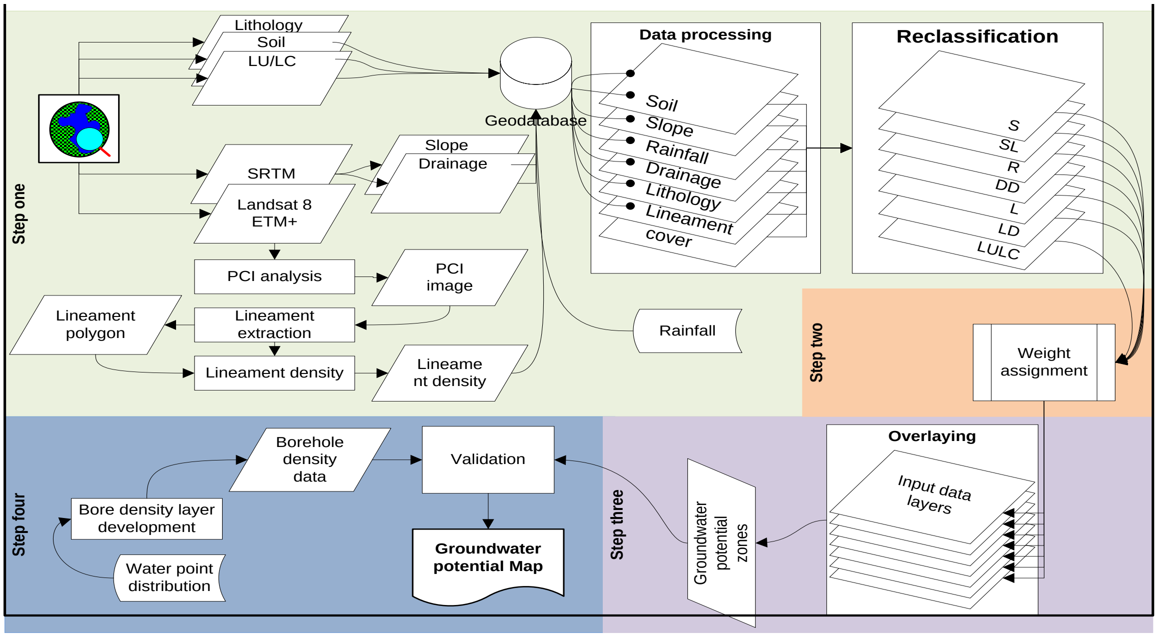

Figure Error! No text of specified style in document.**.2: Methodology flowchart for assessing groundwater potential zones**

3.2.1 Input datasets used in the study

Lithology, soil and land use /land cover datasets were acquired from different online sources. Data of the Landsat Enhanced Thematic Mapper (ETM+), 30 m-resolution, was used to generate the lineament density layer. The Shuttle Radar Topography Mission (SRTM), 90 m-resolution, was utilized in the drainage and slope layers' development. Gridded monthly average rainfall point data was acquired from Kenya Meteorological Department (KMD) and was used to develop the rainfall layer. The spatial datasets used in this study are presented in Table 3.1.

Table Error! No text of specified style in document.**.1: Datasets and inputs used in the in the study**

Data	**Spatial resolution**	**Format**	**Source**
Lithology data	*NA	Vector	International Soil Reference and Information Centre (ISRIC, 2011) website (www.isric.org)
Soil data	NA	Vector	International Soil Reference and Information Centre (ISRIC, 2011) website (www.isric.org)
Land-use / Land-cover	0.5° x 0.5°	Vector	Global Land Cover Facility (GLCF), http://glcf.umd.edu/data/lc/
SRTM DEM	90 m	Raster	Shuttle Radar Topography Mission (SRTM) Digital Elevation Database (https://earthexplorer.usgs.gov).
Landsat 8 (ETM+)	30 m	Raster	https://earthexplorer.usgs.gov
Rainfall data (1981 to 2015)	0.5° x 0.5°	Vector	Kenya Meteorological Department (KMD)
Water point	N/A	Vector	Open Africa

data			(https://www.africaopendata.org)
Rivers/streams	N/A	Vector	International Livestock Research Institute (https://www.ilri.org)

*N/A means Not Applicable

3.3 Evaluation of the Factors Controlling Groundwater Occurrence

The factors influencing groundwater potential and their relative importance were retrieved from previous literature. The factors were combined and only representative factors were selected. The major factors selected were drainage density, slope, lithology, soil, lineament density, land use /land cover and rainfall which affects groundwater occurrence.

3.3.1 Drainage density layer

The drainage density map of the study area was generated from the SRTM digital elevation model (DEM) using the spatial analyst tool for ArcGIS® 10.4 (ESRI, Redlands California USA).The drainage density was calculated from the total stream's length of the study area per unit area using Equation 3.1 after Raghunath (2006).

$$Dd = \frac{\sum L}{A} \qquad (3.1)$$

Where:

Dd = Drainage density (km/km^2),

$\sum L$ = Total length of streams (km)

A = Surface area of the basin under consideration (km^2).

3.3.2 Slope data layer

Slope map was prepared from DEM using slope function in ArcGIS 10.4 Spatial Analyst toolbar. For each cell, slope calculates the maximum rate of change in value from that cell to its neighbours. Basically, the maximum change in elevation over the distance between the cell and its eight neighbours identifies the steepest downhill descent from the cell.

3.3.3 Lithology data layer

The lithological shapefiles showing lithological distribution was processed using ArcGIS® 10.4, from lithology database of ISRIC. The study area was divided into grids and assigned the percolation values of the lithological units guided by expert knowledge from literature (ISRM 1978, 1981; GSE 1995; Jha et al., 2007; Yeh et al., 2008). A map was then prepared to show zones of different lithological character concerning water potential.

3.3.4 Soil data layer

Soil map was prepared from soil database of ISRIC. Reclassification of soil types in relation to groundwater was done based on data on the type of soils obtained from digital soil and terrain database of East Africa (Batjes, 2010).

3.3.5 Lineaments data layer

Lineaments dataset was extracted from the acquired Landsat 8 ETM+ image following a step-wise lineament auto-extraction process. The first step involved the selection of Landsat 8 pan-sharpened reflected bands for lineament auto extraction and geospatial analysis, followed by Principal Component Analysis as described by Thannoun (2013). The second step entailed automatic lineaments extraction in PCI Geomatica® 2015 PCI Geomatica® 2015 software (PCI Geomatics, Ontario Canada) using line module parameters as described by Akinlalu et al. (2017). The output was a lineament polygon which was further processed in the third step. The third step involved splitting compound lines into simple lines, editing lineaments attributes, geospatial analysis of lineaments length and density in ArcGIS®. 10.4

3.3.6 Land cover/Land use data layer

A land use/land cover layer was obtained from the Global Land Cover Facility, Moderate Resolution Imaging Spectrometer (MODIS) land cover database (Channan et al. 2014). Eight key types of land use patterns were identified in the entire study area.

3.3.7 Rainfall data layer.

Rainfall data layer was prepared by spatially interpolating gridded monthly average rainfall data, acquired from Kenya meteorological department, to obtain the spatial rainfall layer. ArcGIS® 10.4 tools combined with DEM was used to generate average spatial rainfall that was utilized for data reconstruction purposes Average annual rainfall was calculated through the kriging interpolation method, using spatial analyst toolbox in ArcGIS® 10.4. The rainfall mapping followed steps similar to the approach used by Ngetich et al. (2014) and Kisaka et al. (2014).

Once all the required datasets were acquired, they were georeferenced using a projected coordinate system WGS 1984 UTM Zone 37S. All the layers were converted to raster format and values reclassified to a common scale of between 1 and 5. The reclassification was guided by literature information and expert knowledge which led to assigning of ranks to the domain of effects of each groundwater influencing factor (Table 3.2).

Table Error! No text of specified style in document..**2: Weight evaluations of the groundwater influencing factors.**

Factor	Domain of effect (Value)	Descriptive scale/Explanation	Rank	References
Drainage density (km^{-1})	0.014-0.080	Very high infiltration potential	5	Sener et al. (2005); Sreedevi et al. (2005); Jha et al. (2007); Sander (2007)
	0.080-0.277	High infiltration potential	4	
	0.277-0.763	Medium infiltration potential	3	
	0.763-1.736	Low infiltration potential	2	
	1.736-3.365	Very Low infiltration potential	1	
Slope (% rise)	0-12.218 (Nearly flat)	Very high infiltration potential	5	Sener et al. (2005); Sreedevi et al. (2005); Jha et al. (2007); Sander (2007); Yeh et al. (2008)
	12.218-21.992 (Very gently sloping)	High infiltration potential	4	
	21.992-36.304 (Gently sloping)	Medium infiltration potential	3	
	36.304-60.012 (Moderately sloping)	Low infiltration potential 10	2	
	>60.012(Strongly sloping)	Very low infiltration potential	1	
Lineament density (km^{-1})	0.005-0.173	Very low infiltration potential	1	Sener et al. (2005); Sreedevi et al. (2005); Jha et al.(2007);Sander
	0.173-0.352	Low infiltration potential	2	
	0.352-0.498	Medium infiltration potential	3	
	0.498- 0.662	High infiltration potential	4	

	0.662-0.915	Very high infiltration potential	5	(2007); Yeh et al. (2008)
Landuse / Landcover (m^2)	Barren Land	Very low infiltration potential	1	Sanford (2002); Shaban et al. (2006); Jha et al. (2007); Yeh et al. (2008)
	Bushlands and woodlands	Low infiltration potential	2	
	Forests	Medium infiltration potential	3	
	Sparse agriculture and Plantations	High infiltration potential	4	
Lithology (m^2)	Gneiss	Favourable sites for groundwater storage	5	ISRM (1978,1981); GSE (1995); Jha et al. (2007); Yeh et al. (2008)
	Migmatite	Favourable infiltration potential	4	
	Andesites, trachytes, phonolites,	Medium infiltration potential	3	
	Basalt	Medium infiltration potential	2	
	Pyroclastic unconsolidated rocks	Low infiltration potential	1	
Rainfall (mm)	511-630	Very low infiltration potential	1	Sener et al. (2005); Jha et al. (2007); Sander (2007); Yeh et al. (2008)
	630-705	Low infiltration potential	2	
	705-792	Moderate infiltration potential	3	
	792-872	High infiltration potential	4	
	872-1026	Very high infiltration potential	5	
Soil (m^2)	Acrisols	Very low infiltration potential	1	Jha et al. (2007); Yeh et al. (2008)
	Alisols	High infiltration potential	4	
	Andosols	Very high infiltration potential	5	
	Arenosols	High infiltration potential	4	
	Cambisols	High infiltration potential	4	
	Ferrasols	High infiltration potential	4	

Fluvisols	Very high infiltration potential	5
Gleysols	Low infiltration potential	2
Luvisols	Moderate infiltration potential	3
Nitisols	High infiltration potential	4
Regosols	Very high infiltration potential	5
Vertisols	Low infiltration potential	2

3.4 Determination of Groundwater Potential Zones

3.4.1 Weight assignment for GIS based DRASTIC modelling

Before weight assignment, the interrelationship between the seven groundwater influencing factors was established based on a procedure by Magesh et al. (2012). The factors that were considered to have a significant influence on the occurrence of groundwater were assigned a weight of 1.0 whereas, those with minor influence were assigned a weight of 0.5 (Magesh *et al*., 2012). The relative rates of each parameter were calculated by the cumulative sum of both major and minor effect followed by a score calculation of each influencing factor using Equation 3.2

$$Score = \left[\frac{(A+B)}{\sum A+B} \right] . \times 100.\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Where;

“*A”*= major effect of parameters

“*B”* = minor effect of parameters

The effect and interrelationship of the groundwater influencing factors, relative rates and score for each potential factor is shown in Table 3.3, modified from Magesh *et al*. (2012).

Table 3.3: Effect of groundwater influencing factor, relative rates and score for each potential factor

	Drainage	Lithology	Rainfall	Lineaments	LU / LC*	Slope	Soil	A	B	Relative	Weight (%)
Drainage	-	0	0	0.5	1	0	0	1	0.5	1.5	10
Lithology	1	-	0	1	1	0	1	4	0	4	27
Rainfall	1	0	-	0	0	0	0.5	1	0.5	1.5	10
Lineaments	1	0	0	-	1	0	0	2	0	2	13
Landuse/Landcover		0.5	1	0.5	-	0	0.5	1	1.5	2.5	17
Slope	1	0	1	0	0.5	-	0	2	0.5	2.5	17
Soil	0	0	0	0	1	0	-	1	0	1	7
Summation										15	100

* Land use/ Land cover

3.4.2 Integration based on the GIS based DRASTIC model approach

In order to produce the potential groundwater zone map integration of seven thematic layers: rainfall, soil, lithology, lineament density, slope, drainage density and land cover layers was conducted. The weighted overlay tool in the spatial analyst toolbox of ArcGIS 10.4 was used to overlay the scaled thematic layers. The derived weights from Table 3.3 were applied as the % influence (the influence of the factor compared to the other criteria as a percentage of 100) based on the GIS model Groundwater potential was then calculated as a Groundwater Potential Index (GPI) for each cell or pixel.(Equation3.3).

$$GPI = \sum_{i}^{n} D_x D_y + LD_x.LD_y. + L_x L_Y. + S_x.S_y + SL_x SL_y + LULC_x.LULC_y. + R_x R_y \ldots\ldots\ldots\ldots\ldots (3.3)$$

Where:

GPDI = The Groundwater Potential Index

x = Factor map

y = Factor subclass

DD = Drainage Density (km^{-1})

LULC = Land Use Land Cover (m^2)

L = Lithology (m^2)

S = Soil

SL = Slope (% rise)

R = rainfall (mm)

LD = Lineament Density (km^{-1})

The evaluation scale was set at five to allow the model to generate the potential zones up to a maximum of five classes. The output groundwater potential map had five relative classes that was used to define the range as: very low, low, moderate, high and very high.

3.5 Validation of the GIS based drastic model

The validation of the model result was accomplished by comparing the groundwater potential map produced with the borehole density map of the study area. The borehole distribution density map was developed using water well distribution dataset from Open Africa (Open Africa, 2017). Given the none uniformity of the borehole distribution data, an equivalent area was generated from the model output for comparative purposes. The density map was generated using ordinary kriging interpolation and applying a spherical semivariogram model in ArcGIS® 10.4. The borehole density map was then reclassified to the same scale as that of groundwater potential map/model output. The two maps were then compared using the minus tool in the spatial analyst tool of ArcGIS® 10.4 resulting in a suitability difference map. From the suitability difference map, the difference between the observed and the modeled outputs was retrieved from the attribute table and both the area (in ha) and the level of agreement (%) computed.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Influence of the parameters on the occurrence of groundwater

4.1.1 Drainage density

The mean drainage density of the study area was 0.90 km/km^2. The drainage density was higher in the northern part with an average of about 2.27 km/km^2. In the central part of the study area, the drainage density ranged from 0.08 to 0.76 km/km^2. The generated Drainage Density for Embu County is presented in Figure 4.1.

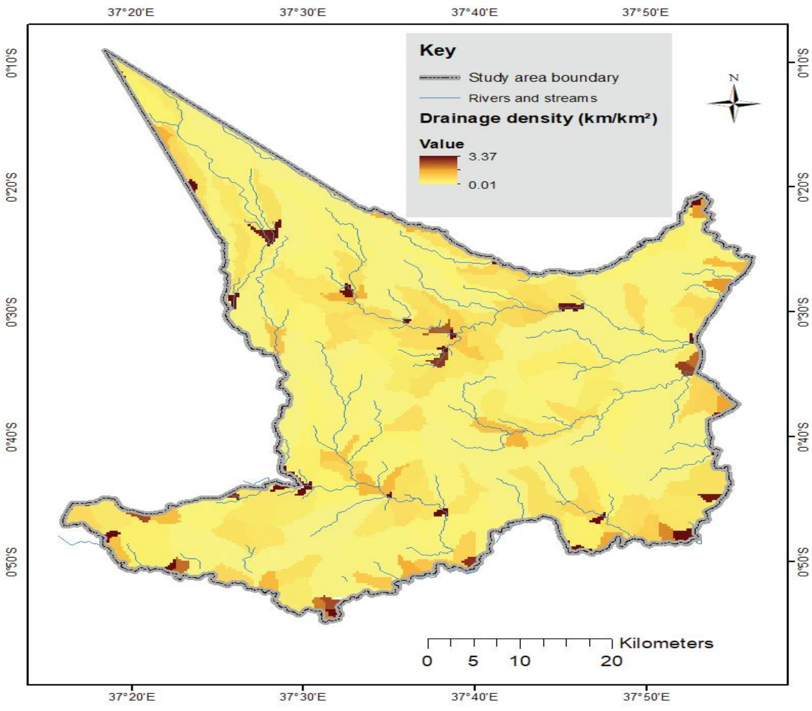

Figure 4.1: Drainage density of Embu County, Kenya

The areas of Embu County areas with high drainage density indicates that a large proportion of the precipitation is lost in the form of surface runoff. This means that the hydrologic response to rainfall event is relatively high. On the other hand, a low drainage density indicates that most rainfall infiltrates the ground and few channels are required to carry the runoff. The hydrologic response to a rainfall event is slow, meaning that the drainage basin is poorly drained. The results suggest moderate to high surface runoff generation potential in the study area. High drainage density is indicative of low groundwater potential due to a high likelihood of significant surface runoff generation. Besides correlation with infiltration and runoff generation, drainage density has been observed to correlate inversely with weathering (Ramírez-hern, Martín-loeches, Reyes-l, Martínez-santos, & Temi, 2018). A high drainage density is associated with erosion, and thus, results in thinner weathered formations.

According to Tewodros (2005) drainage density with respect to groundwater potential is determined by analyzing the drainage density calculated using the stream length within grid area. The higher the drainage density the lesser the infiltration capacity that is low void ratio of the terrain which in turn means that the lesser the groundwater potentiality. This is because much of water coming as rainfall goes as run off. In general drainage density is an important parameter that control groundwater occurrence and distribution.

4.1.2 Slope map

The slope of the study area varies from 6% to 89% .The area was classified in to five classes namely: (0-12.218%) nearly flat (12.218-21.992%) very gently sloping, (21.992-36.304%) gently sloping, (36.304-60.012%) moderately sloping, (>60.012%) strongly sloping. The north-western and the central part of the study area had a high slope gradient percentage while the south-western, south and the eastern part of the study area had relatively flat terrain. The generated slope map for Embu County is presented in Figure 4.2.

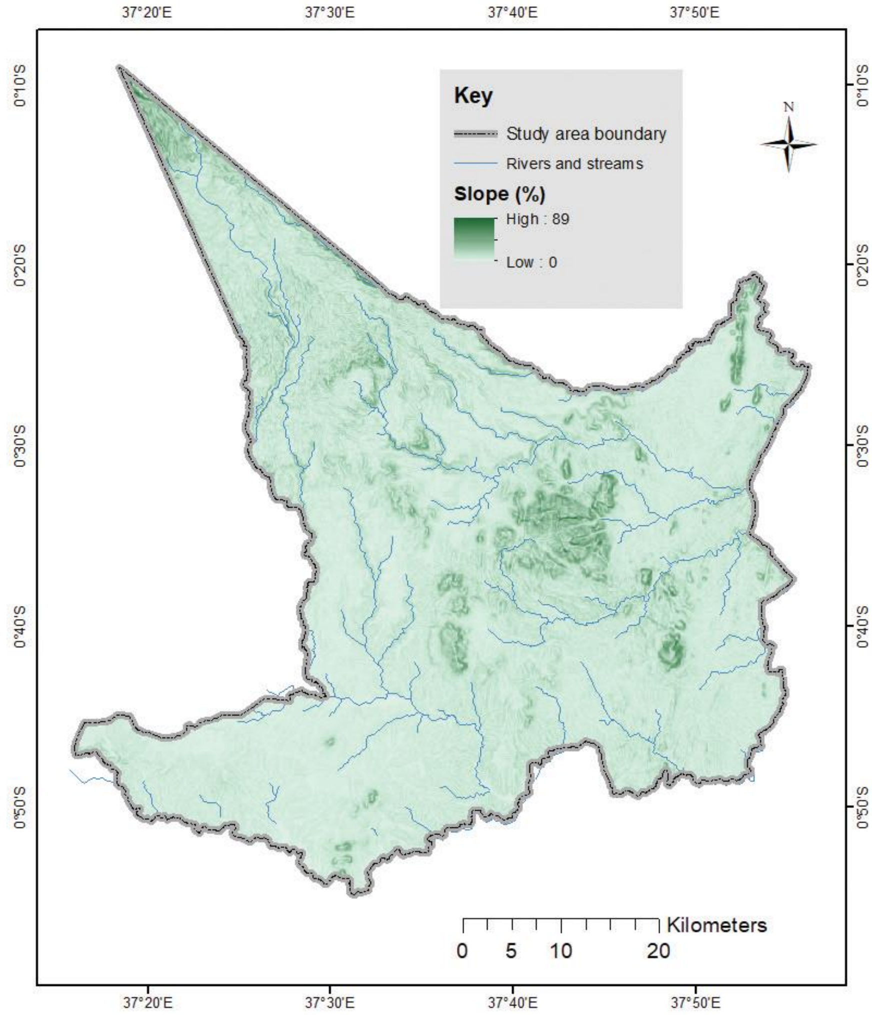

Figure Error! No text of specified style in document.**.3: The distribution of slope in Embu County, Kenya**

The slope is a factor that has a direct influence on the rainfall water infiltration. It controls the precipitation, whether it will be lost as runoff water or remains on the ground surface for long enough to infiltrate and recharge the groundwater (Abdalla, 2012). Steeper slopes generate less recharge because water runs off rapidly on the surface during rainfall, allowing insufficient time to infiltrate and recharge the groundwater aquifer. Given the inverse relationship between slope and groundwater recharge potential, low slope percentage rise was assigned a higher rank of the probability of groundwater availability while a higher slope percentage rise was categorised as a lower rank due to relatively high run-off. This is also supported by Nampak et al. (2014), who observed that a lower slope is indicative of high topographic wetness index and is positively correlated with groundwater occurrence which is indicative of a higher groundwater potential.

This was further supported by Yeh et al. (2016), who reported that high sloping region caused more runoff, less infiltration and have low groundwater prospects compared to the low slope region. Low slopping regions caused less runoff, high infiltration rate and have good ground water prospects. Fashae et al. (2013) also illustrated that slope highly influences groundwater infiltration and recharge. The study indicates that where steep slopes are present, groundwater potential is low because there is more surface runoff than infiltration. In areas characterized by flatlands, the groundwater potential was found to be high because it is easier for the water to infiltrate than to flow on the surface.

4.1.3 Lithology map

The study area consists of several lithological units. This includes metamorphic rocks (gneiss and migmatite) which cover the central and southern part of the study area. These types of rocks occur in a weathered basement complex environment. This combination results in a high potential but ubiquitous groundwater system. Pyroclastic unconsolidated rocks (agglomerates, lapilli tephra, coarse ash, and fine ash) are found on the north-western side of the study area. This is at the slopes of Mount Kenya. These rocks were produced from the consolidation of fine fragments into a coherent rock with poor groundwater movement. Hence, this area could be considered as a poor groundwater potential zone. Consequently, this area was assigned a low potential value of 1 on a scale of 1 to 5.

The remaining part of the study area consists mainly of intermediate igneous rocks (andesites, trachytes, phonolites, basalt). These types of rocks are the most dominant. These areas are generally considered as a moderate potential zone for groundwater (Earl, 2015). Lithology influences soil texture and drainage density thus provide an essential indication of the rate that rainfall infiltrates compared with the surface runoff (Abdalla, 2012). The lithological units is shown in Figure 4.3.

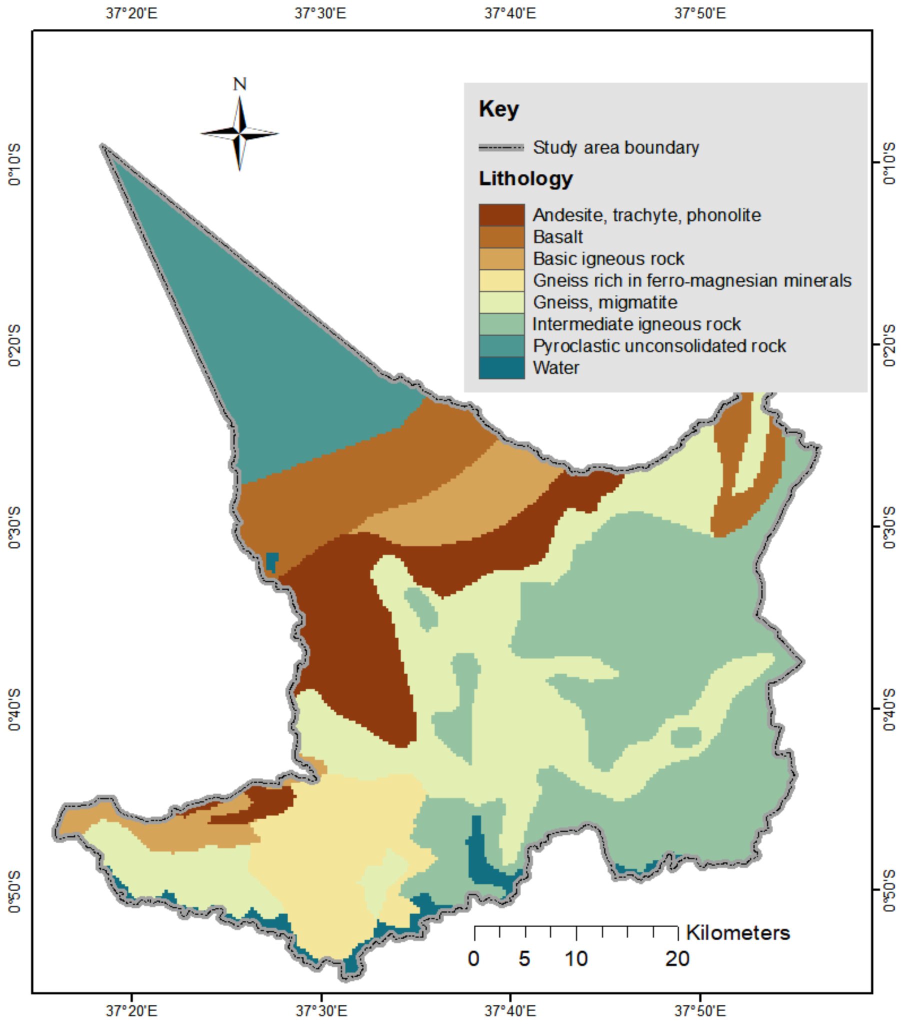

Figure Error! No text of specified style in document.**.4: Lithology of Embu County, Kenya**

4.1.4 Soil data layer

Thirteen soil units comprising Acrisols, Alisols, Andosols, Arenosols, Cambisols, Ferrasols, Fluvisols, Gleysols, Luvisols, Nitisols, Regosols, and Vertisols are distributed across the study area. Ranks were assigned subjectively to each soil unit after taking into account the type of soil and its water-holding capacity (Table 4.1).

Table 4.1.: Soil type and their rank as per suitability for groundwater potential

Soil type	Descriptive scale/Explanation	Rank	References
Acrisols	Very low infiltration	1	Jha et al. (2007); Yeh et al. (2008)
Alisols	High infiltration	4	
Andosols	Very high infiltration	5	
Arenosols	High infiltration	4	
Cambisols	High infiltration	4	
Ferrasols	High infiltration	4	
Fluvisols	Very high infiltration	5	
Gleysols	Low infiltration	2	
Luvisols	Moderate infiltration	3	
Nitisols	High infiltration	4	
Regosols	Very High infiltration	5	
Vertisols	Low infiltration	2	

The permeability of the topsoil is very crucial to infiltration potential vis-à-vis groundwater accumulation (Shaban et al., 2006; Jha et al., 2007; Yeh et al., 2008). Thus, soils, such as Acrisols which are relatively sandy have a low water-holding capacity and were assigned a lower score. This soil is located partly on the northern and western regions of the study area. Andosols, Fluvisols, and Regosols which have a relatively low bulk density, high clay content and hence high water-holding capacity were assigned higher scores. These areas are located in south-western and southern parts of the study area. The average soil units in the study area are presented in Figure 4.4.

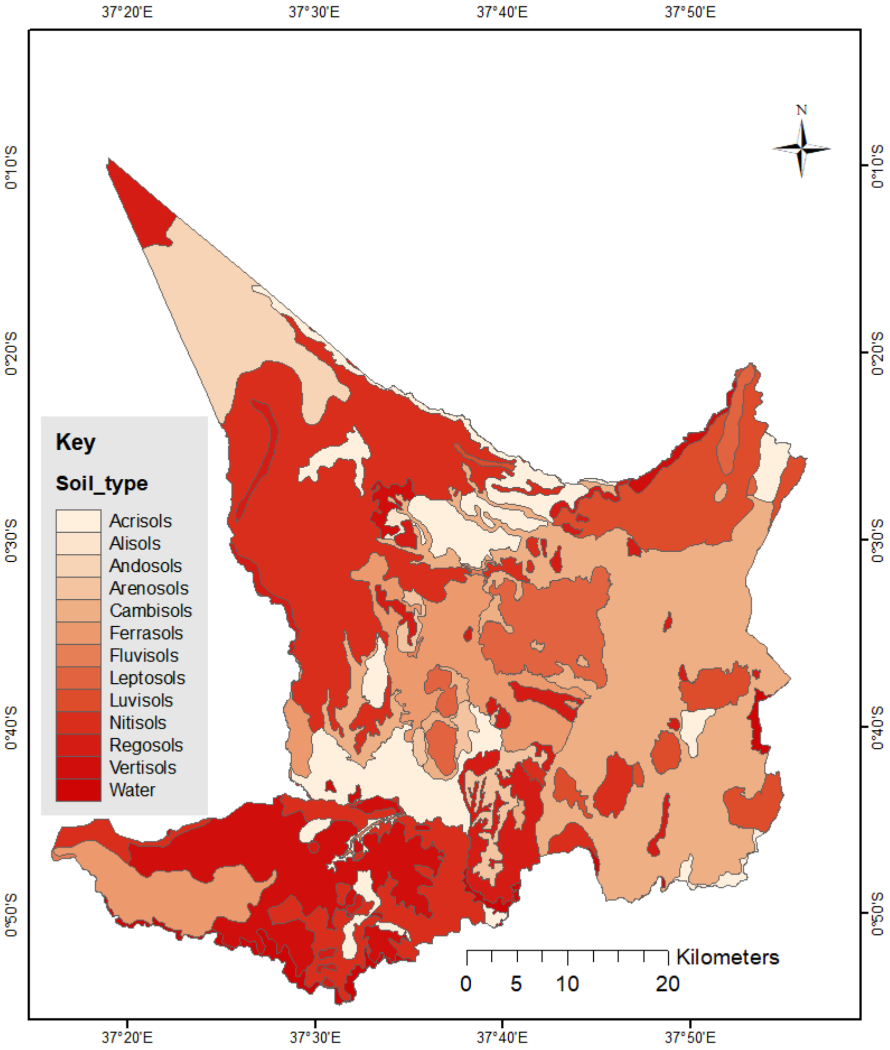

Figure Error! No text of specified style in document.**.5: The distribution of soil types in Embu County, Kenya**

According to Tewodros (2005) most Cambisols are medium-textured and have a good structural stability, a high porosity, and good water holding capacity and good internal drainage. Most Cambisols also contain at least some weatherable minerals in the silt and sand fractions. Based on these characteristics, Cambisols have good infiltration capacity to recharge groundwater. On the other hand, leptosols are found in all climatic zones, particularly in eroded areas and are have low water holding capacity.

4.1.5 Lineaments data layer

The study area was found to have diversified lineament distribution. The lineament density was classified into five categories (0.005-0.173, 0.173-0.352, 0.352-0.498, 0.498- 0.662 and 0.662-0.915) km/km^2 as presented in Table 4.2. The eastern, south and south-western parts of the study areas had high lineaments resulting in high lineament densities of over 0.5 km/km^2. The northern and north-western parts of the study area had a low number of lineaments, hence low lineament density. Areas with highest lineament density of between 0.662 to 0.915 km/km^2 were assigned a higher rank while areas with lowest lineament density of between 0.005-0.173 km/km^2 were assigned a lower rank. A summary of the results and the corresponding assigned ranks from the study area is presented in Table 4.2.

Table Error! No text of specified style in document.**.2: Lineament density and its rank as per suitability for groundwater potential**

Rank	**Lineament density (Km/Km^2)**	**Descriptive scale/Explanation**
1	0.005-0.173	Very low infiltration
2	0.173-0.352	Low infiltration
3	0.352-0.498	Moderate infiltration
4	0.498- 0.662	High infiltration
5	0.662-0.915	Very high infiltration

It can be inferred that the higher the lineament density, the higher the probability of the groundwater potential. The higher the lineament density, the higher the chances of the groundwater occurrence (Nampak et al., 2014; Selvam et al., 2015), and vice versa. The lineaments were identified to be of different lengths which shows the short-long range of the linear features. This results in low to medium level of percolation except for those areas where the density of the lineaments is high. The lineament map and lineament density map from the study area is given in Figure 4.5 and Figure 4.6.

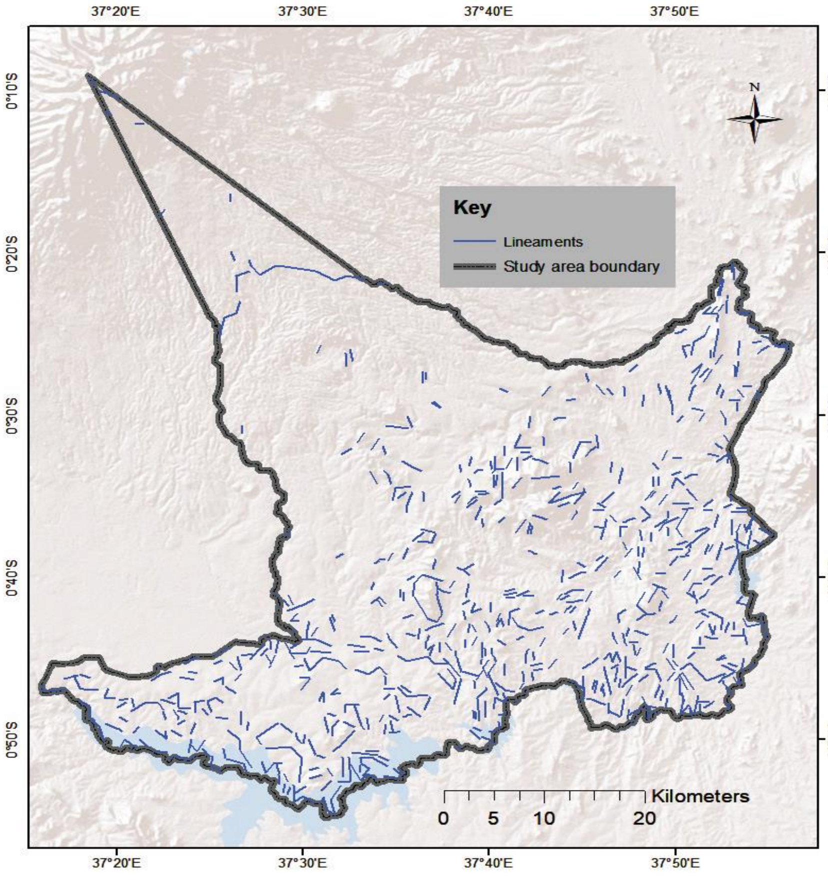

Figure Error! No text of specified style in document.**.6: Lineaments in Embu County, Kenya**

From Figure 4.5 it can be seen that lineament characteristics were mainly found along the SE–SW and the NE–SE directions, and were along the E–W directions near Mount Kenya. Similar findings were also reported by Surajit (2014) in which the author was analyzing groundwater potential zones using electrical resistivity, RS & GIS techniques in a typical mine area of Odisha area in India. The author reported that the lineament were mainly found along the SW–SE and the NE–SE directions, and a very few are along the E–W and the N–S directions which complement with findings from this study.

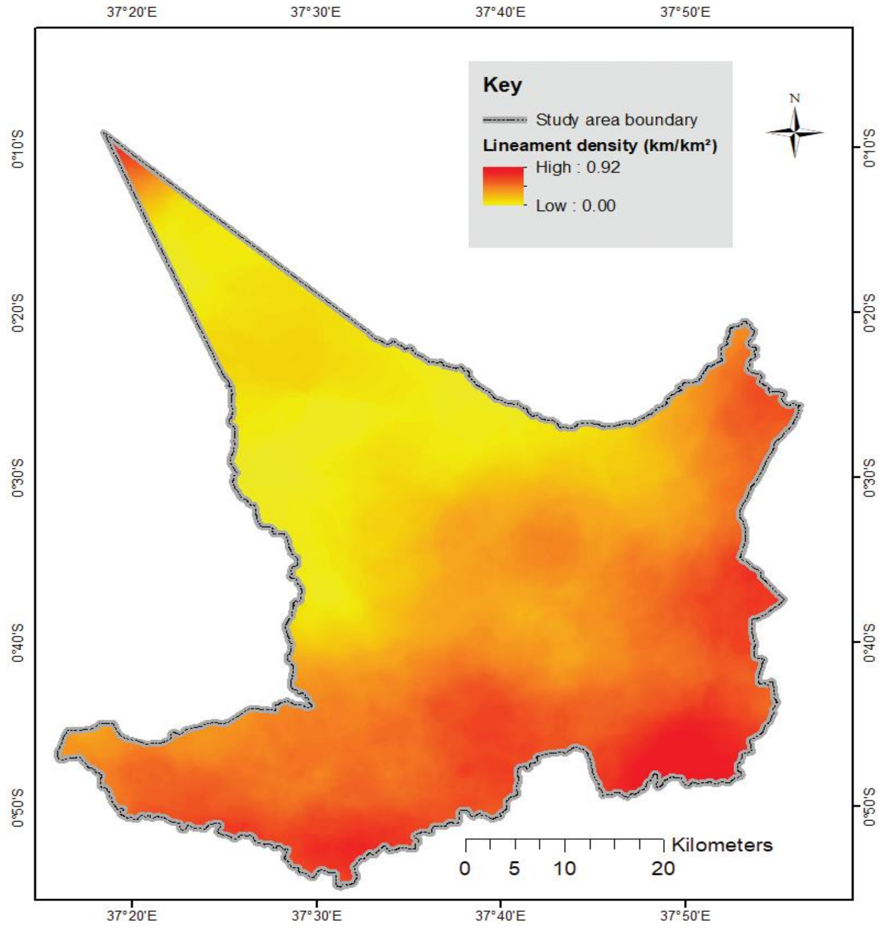

Figure Error! No text of specified style in document.**.7: Lineament density of Embu County, Kenya**

Results from Figure 4.6 closely agree with findings by Krishnamurthy et al. (2000) who pointed out that a buffer zone of 300 m around fracture system of faults and lineaments are treated as appropriate groundwater recharge and availability zones. The results as presented in the Figure 4.6 also corresponds to that of Anudu et al. (2011) in which the authors state that areas having high lineament density represented areas with relatively high groundwater potential.

4.1.6 Land cover / Land use layer

The study area consisted of eight types of land uses and land cover. These were crop agriculture (both dense and sparse), barren land, forest, plantation, and woodland (Table4.3).

Table Error! No text of specified style in document.**.3: Land use/Landcover types and rank**

Type of Landuse/ Land cover	Rank
Barren Land	1
Bushlands	2
Forests	3
Sparse agriculture	4
Dense agriculture	4
woodland	2
Plantations	4

Land-uses influences the fate of rainwater. Depending on the land-uses, the rainfall water can evaporate, infiltrate into the soil or is lost/drained to the sea as runoff (Nanda et al., 2017). Cultivated lands for agriculture were assigned a high rank because it is mostly associated with good underlying groundwater potential sites, fine/medium texture. One of the dominant land use/land cover categories in the area is bush lands which were assigned a lower rank. The land use/land cover areas such as barren lands, have poor water holding capacity and therefore were assigned low rank. The land uses and land cover types is shown in given in Figure 4.7.

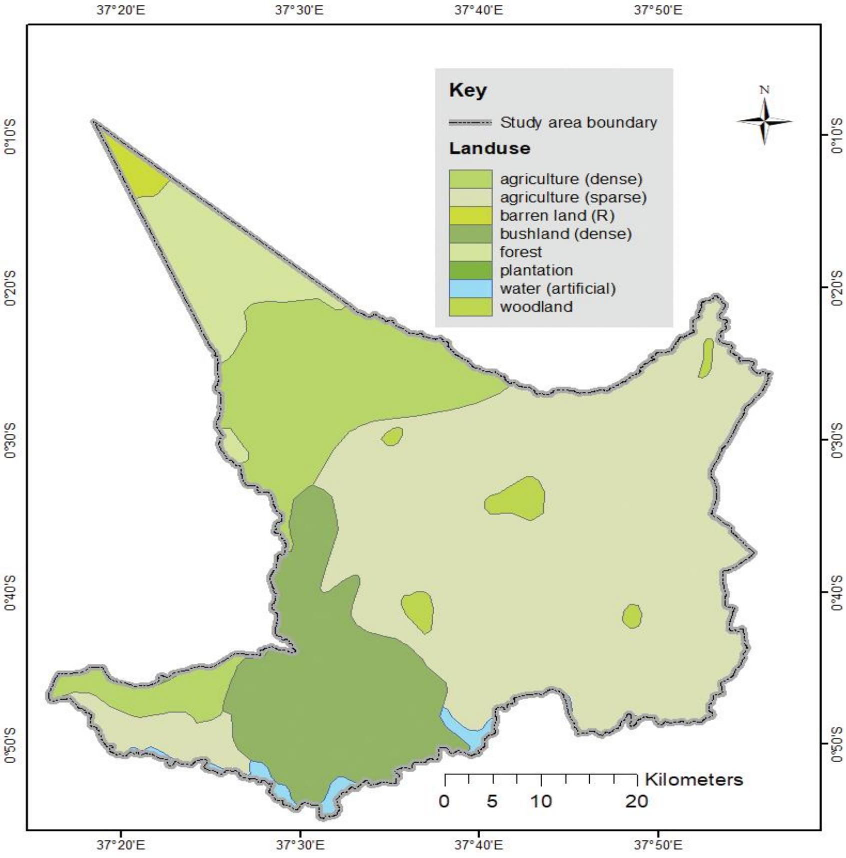

Figure Error! No text of specified style in document.**.8: Land use/land cover of Embu County, Kenya**

Results from Figure 4.7 corresponds with that of Chowdary et al. (2009) which stated that 60% of the area covered by forest, farmland land and water bodies are favorable for groundwater potential. This results also coincided with the findings of Gouri et al. (2012) in which the presence of high dense vegetation in the study areas indicates possibility conduit for subsurface movement and for the storage of groundwater. The findings of the study are similar to that Magesh et al., 2011 in which it shows that the woodlands associated with volcanic activities and hills are of low groundwater potential.

4.1.7 Rainfall map

Rainfall in Embu County shows significant spatial variation. The results of the study shows that the annual average rainfall ranged from 510 mm to 1025 mm for a period of 34 years. A map showing the range was prepared by spatially interpolating gridded monthly average rainfall data, acquired from Kenya Meteorological Department. Rainfall is a significant source of recharge. It plays a vital role in the hydrologic cycle, which controls groundwater potential. The rainfall amount determines the amount of water that would be percolating into the groundwater system as the major source of recharge (Nampak et al. 2014). Hence, areas with a high amount of rainfall were assigned higher rank value compared to areas with low annual rainfall during the analysis. The annual rainfall of the study area was grouped into five classes namely very low (511-630 mm), low (630-705 mm), medium (705-792 mm), high (792-872 mm) and very high (872-1026 mm). The rainfall map for the study area showing annual spatial distribution range was developed and is presented in Figure 4.8.

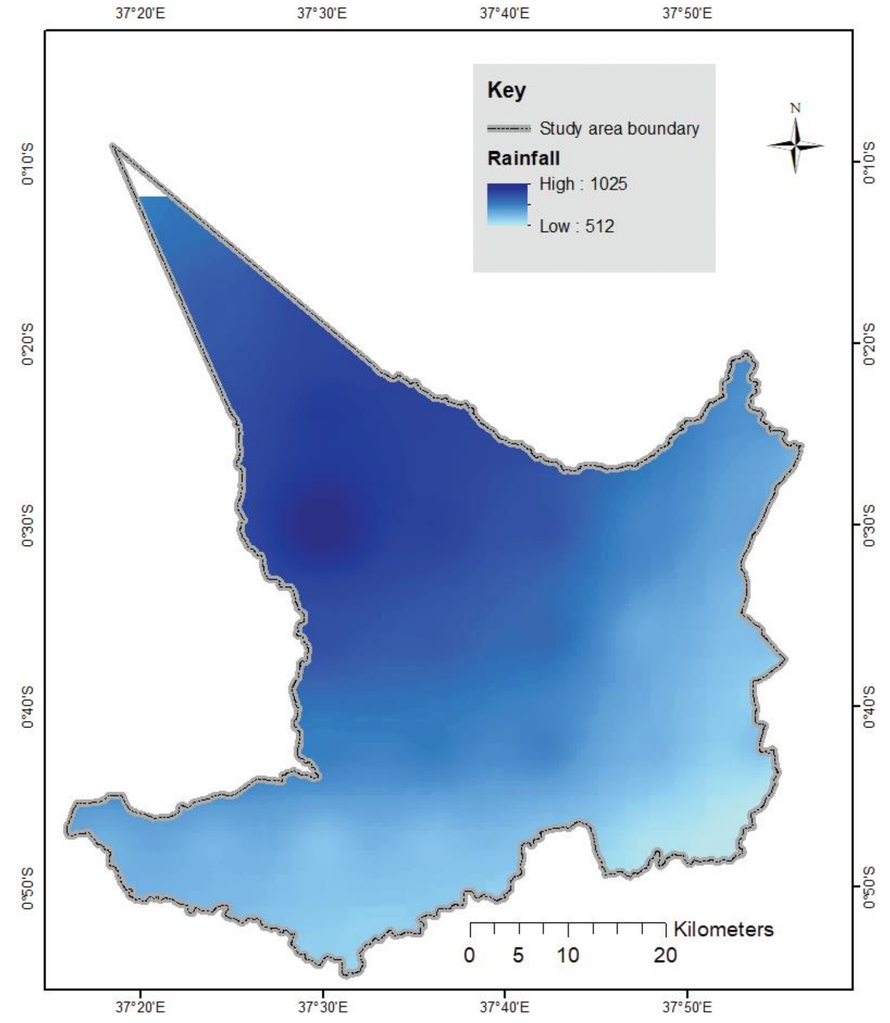

Figure Error! No text of specified style in document.**.9: Rainfall of Embu County Kenya**

These results agree with the findings of Adiat (2012) in which the author observed that the study area (9.42 km^2) had appreciable amount of annual rainfall. The southern part of their study area received the largest amount of rainfall while the north-western part received the lowest amount of rainfall. The larger part of the area however received annual rainfall of between 2092 and 2218mm. The resultant rainfall map was grouped into five classes which are 1749–2092; 2092–2218; 2218–2276; 2276–2324 and 2324–2,532 mm/year.

4.2 Groundwater potential zones

4.2.1 Weight assignment and reclassification for modelling

Suitable weights were assigned to the seven parameters and their individual features. The weights assigned to different classes of all the thematic layers were previous presented under Table 3.3. In Table 4.4 are the factors, the corresponding domain value and the rank/class. The same information was used to reclassify the parameters and presented as reclassified and ranked maps shown in Figures 4.9 (a-g).

Table Error! No text of specified style in document.**.4: Influencing f actor, domain of effect and rank**

Factor	Domain of effect (Value)	Rank/class
Drainage density	0.014-0.080	5
(km^{-1})	0.080-0.277	4
	0.277-0.763	3
	0.763-1.736	4
	1.736-3.365	1

Slope (% rise)	0-12.218	5
	12.218-21.992	4
	21.992-36.304	3
	36.304-60.012	2
	>60.012	1
Lineament density (km-^{1})	0.005-0.173	1
	0.173-0.352	2
	0.352-0.498	3
	0.498-0.662	4
	0.662-0.915	5
Factor	**Domain of effect (Value)**	**Rank/class**
Lithology (m^2)	Gneiss	5
	Migmatite	4
	Andesites, trachytes,	3
	phonolites,	2
	Basalt	1
	Pyroclastic unconsolidated rocks	

Landuse / Landcover (m^2)		Barren Land	1
		Bushlands and woodlands	2
		Forests	3
		Sparse agriculture and Plantations	4
Soil (m^2)		Acrisols	1
		Alisols	4
		Andosols	5
		Arenosols	4
		Cambisols	4
		Ferrasols	4
		Fluvisols	5
		Gleysols	2
		Luvisols	3

	Nitisols	4
	Regosols	5
	Vertisols	2

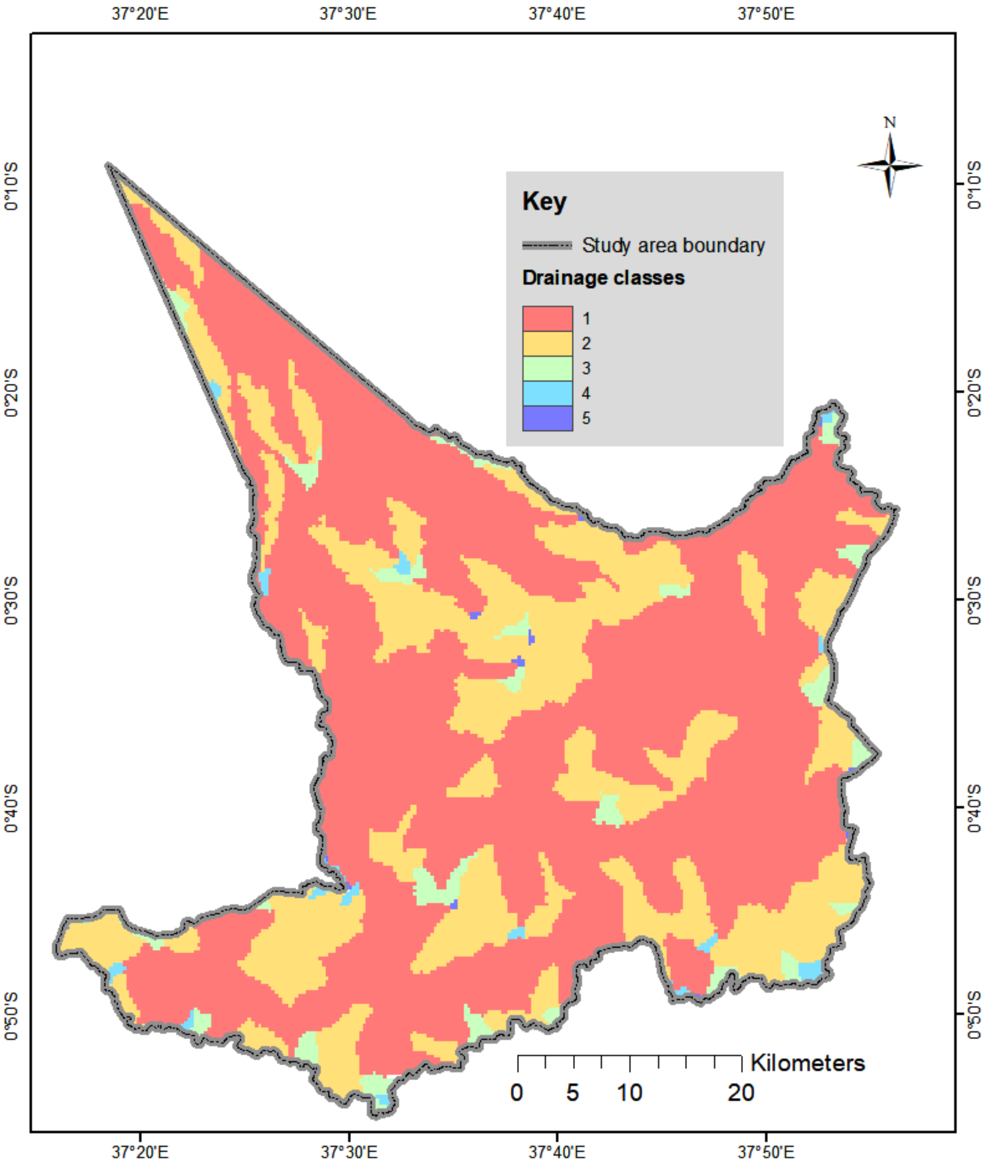

Figure Error! No text of specified style in document.**.10 (a): Reclassified and ranked Drainage density of Embu County**

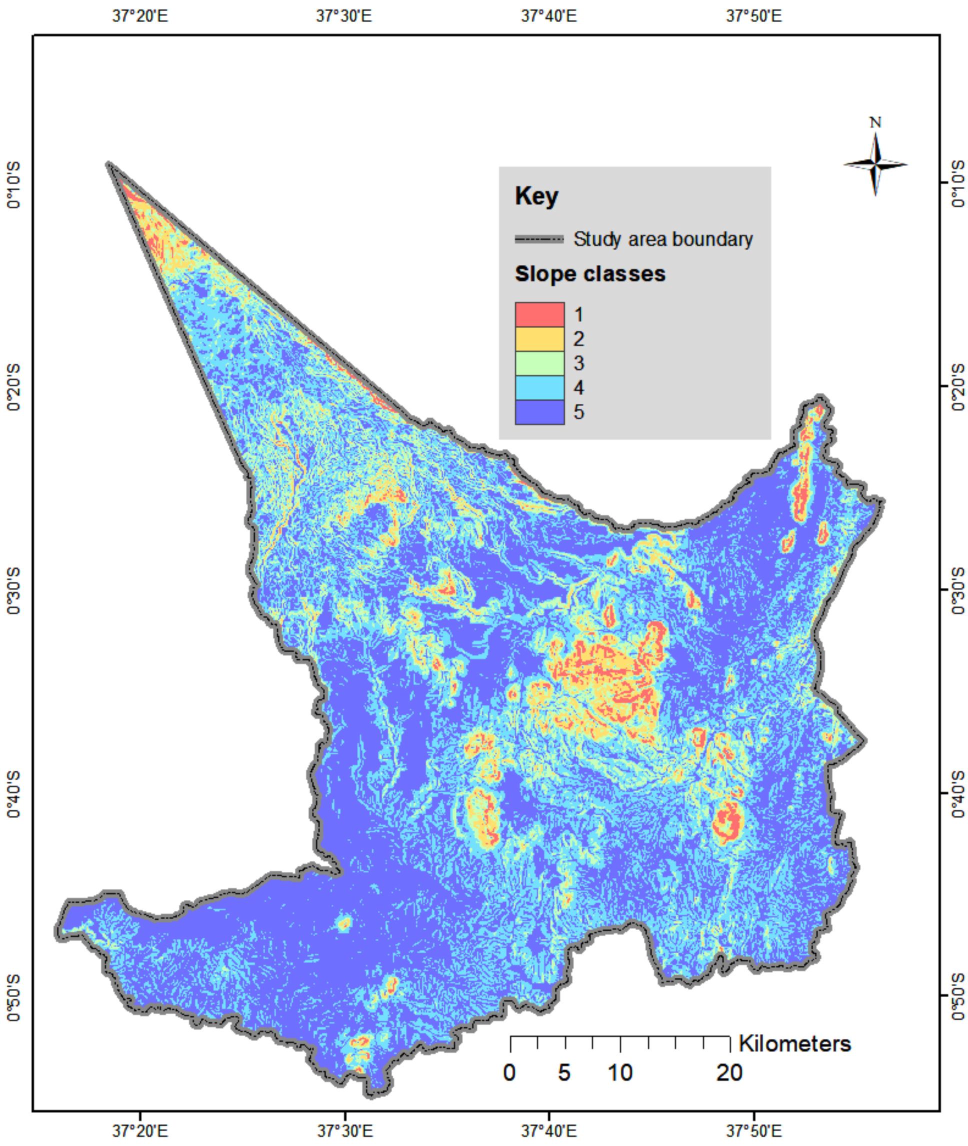

Figure Error! No text of specified style in document.**.11 (b): Reclassified and ranked slope of Embu County**

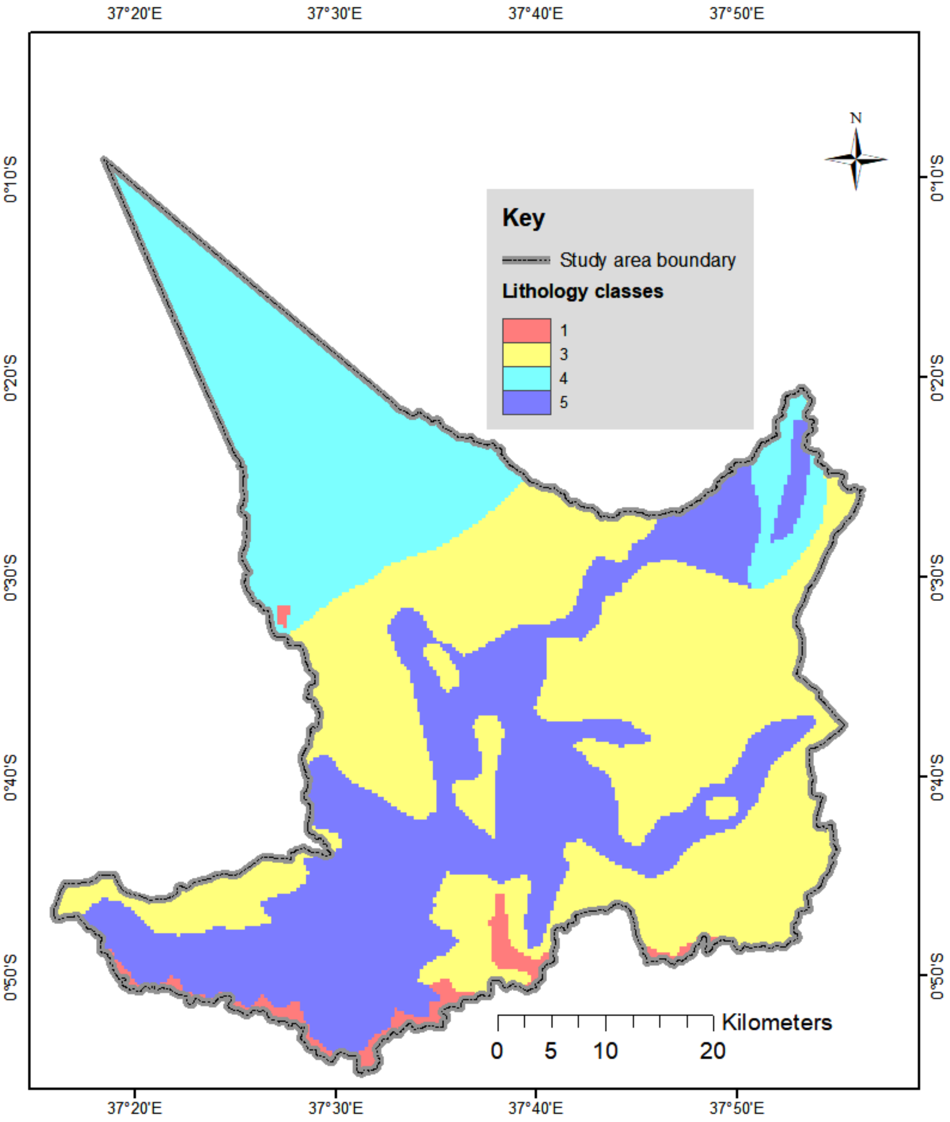

Figure Error! No text of specified style in document.**.12 (c): Reclassified and ranked Lithology of Embu County**

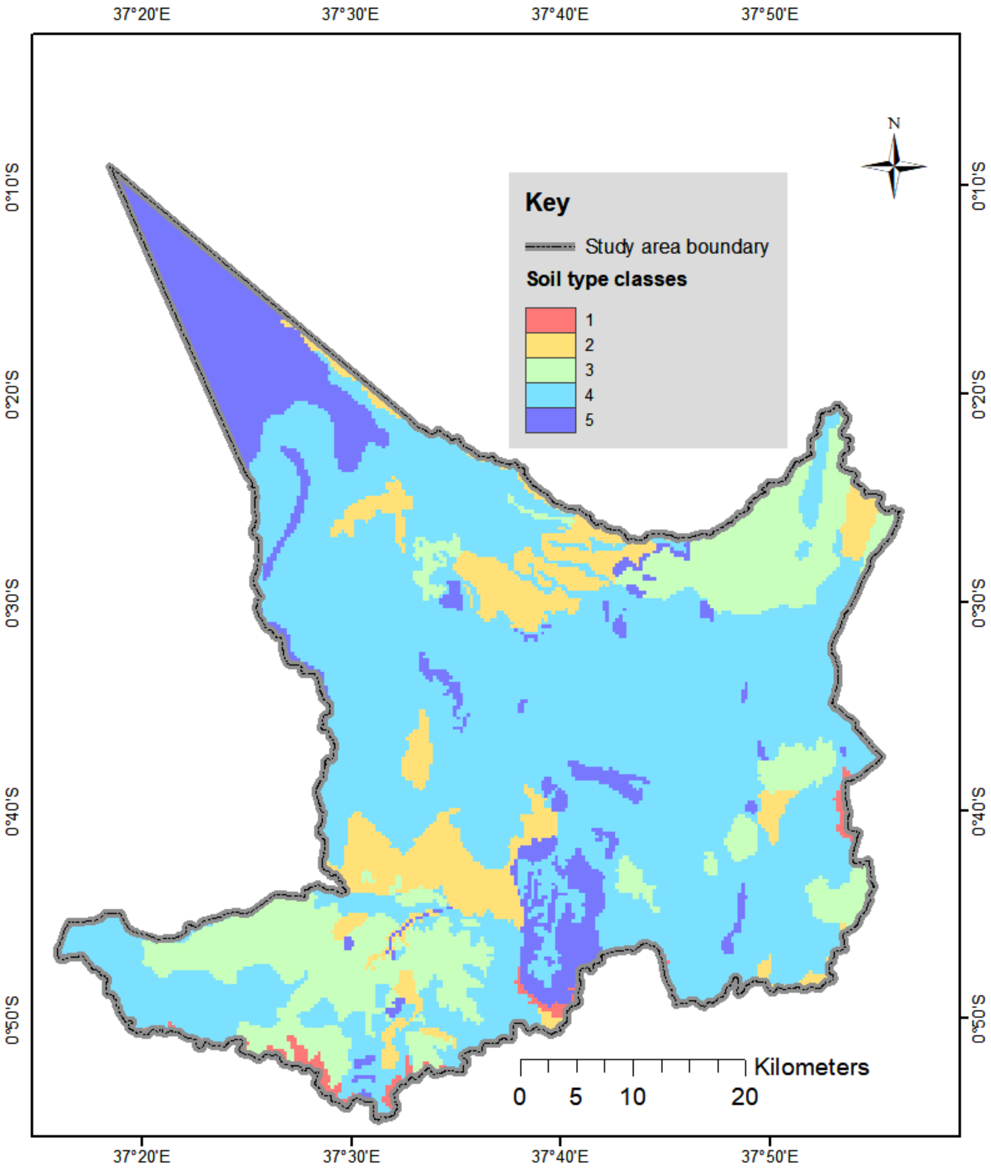

Figure Error! No text of specified style in document.**.13 (d): Reclassified and ranked soil types of Embu County**

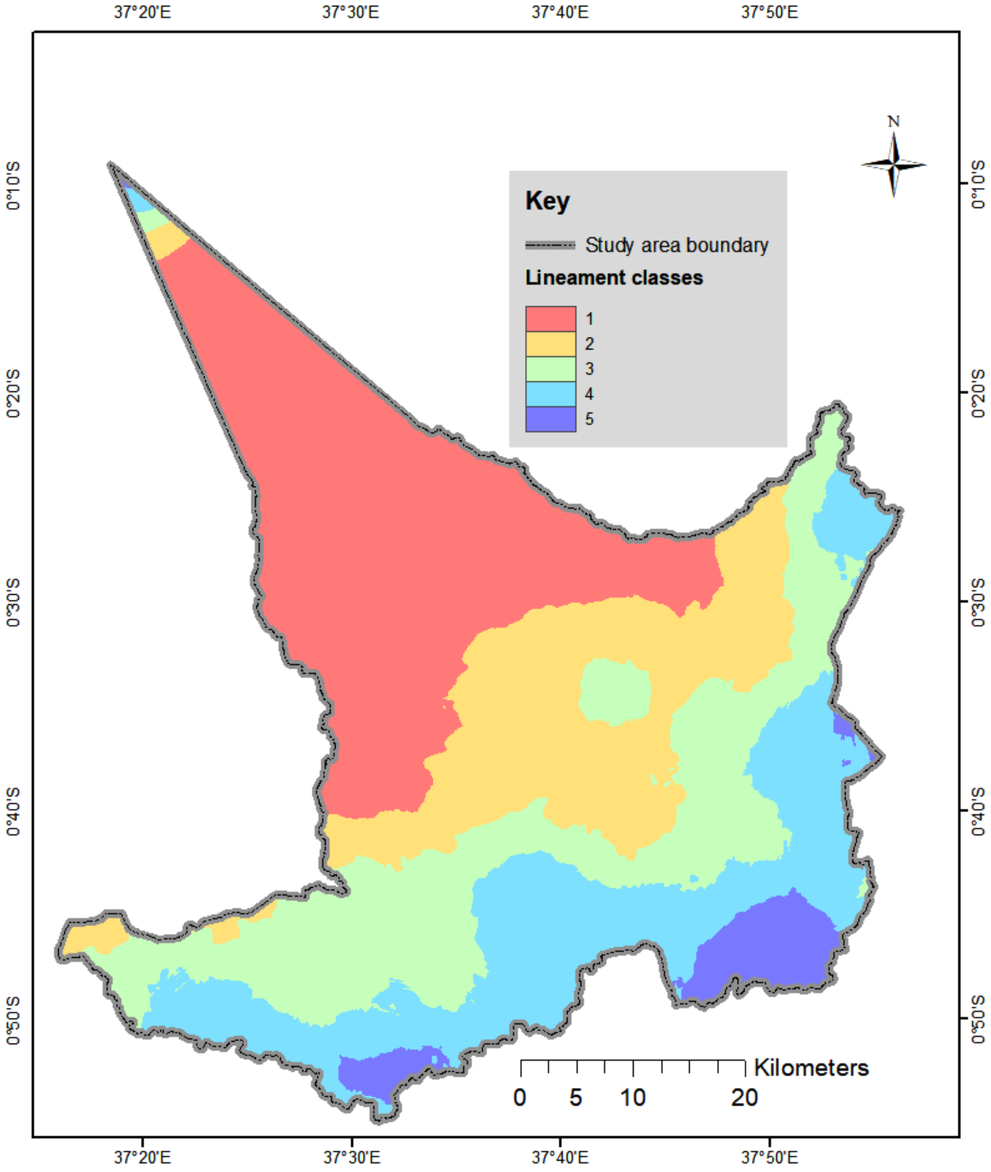

Figure Error! No text of specified style in document.**.14 (e): Reclassified and ranked lineament density of Embu County**

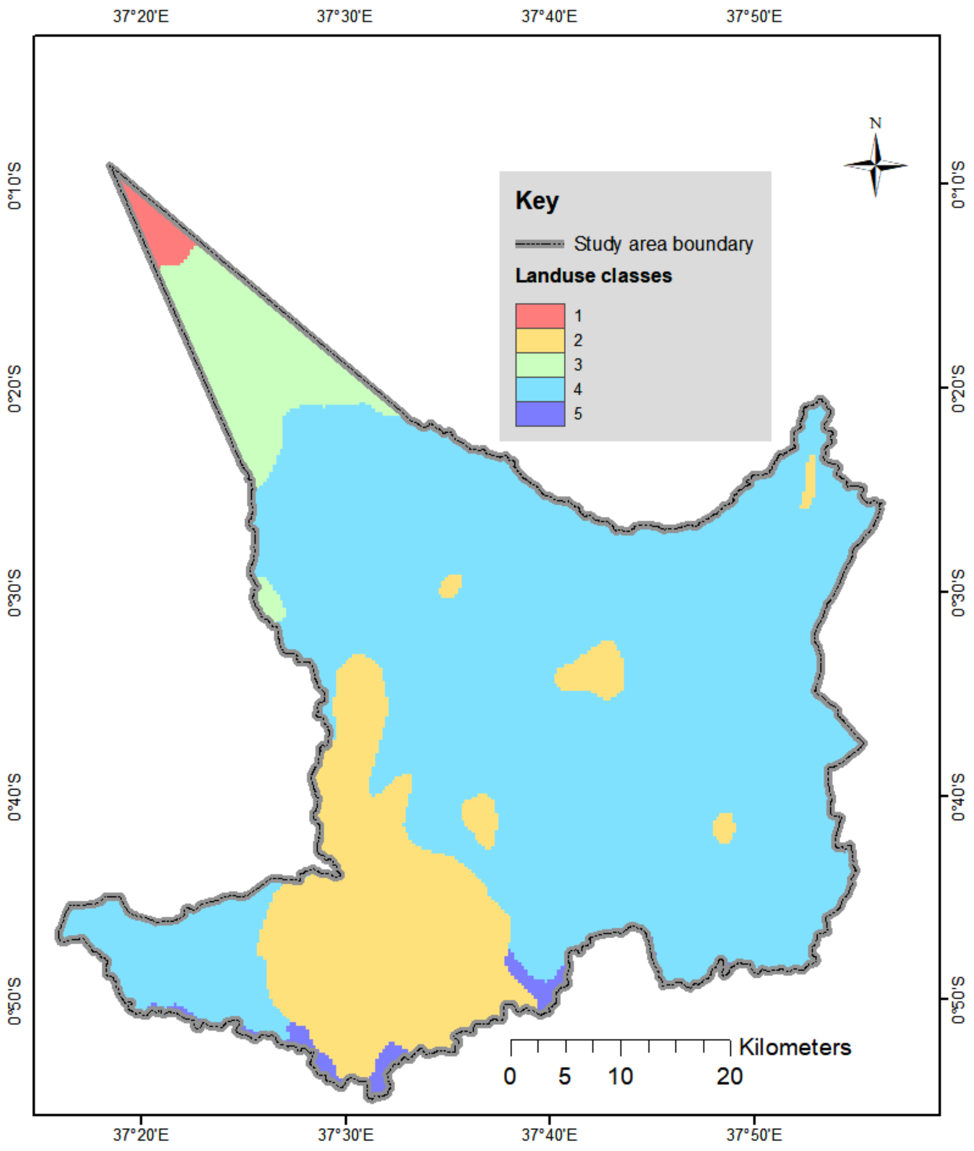

Figure Error! No text of specified style in document.**.15 (f): Reclassified and ranked land use of Embu County**

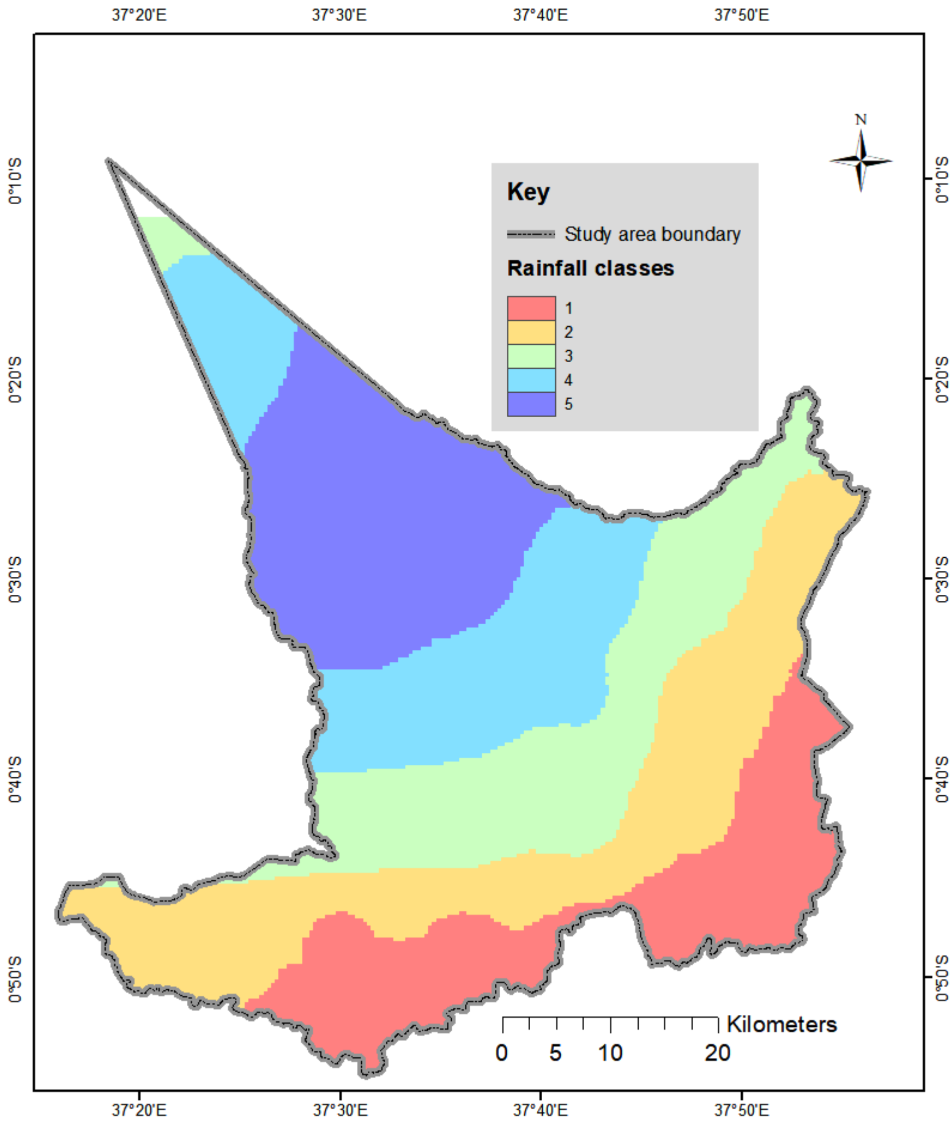

Figure Error! No text of specified style in document.**.16 (g): Reclassified and ranked rainfall of Embu County**

The results of Figures 4.9(a-g) showed the reclassification of the seven parameters using the weightage summarized under Table 4.4. During reclassification, the value 5 was given for very highly controlling units, 4 for highly controlling units, 3 for moderate controlling units, 2 for low controlling reclassified units and 1 for very low controlling units. The reclassification is similar to that of Singh et al. (2009) which used a similar procedure to study water resources evaluation and management for Morar river basin. The authors delineated groundwater prospects of the basin by integration of these parameter: geology, geomorphology, lineament and slope. The authors then reclassified the parameters into 4 classes as excellent, good, moderate and poor ground water potential zones using GIS.

4.2.2 Groundwater potential zones map /model output

The groundwater potential map produced consists of five classes, from the lowest to the highest potential degree: very low potential (1) [presented in red], low potential- (2) [presented in yellow], moderate potential (3) [presented in green], high potential (4) [presented in sky blue] and very high potential zones (5) [presented in dark blue]. The groundwater potential map for the entire study area was produced and is presented in Figure 4.10.

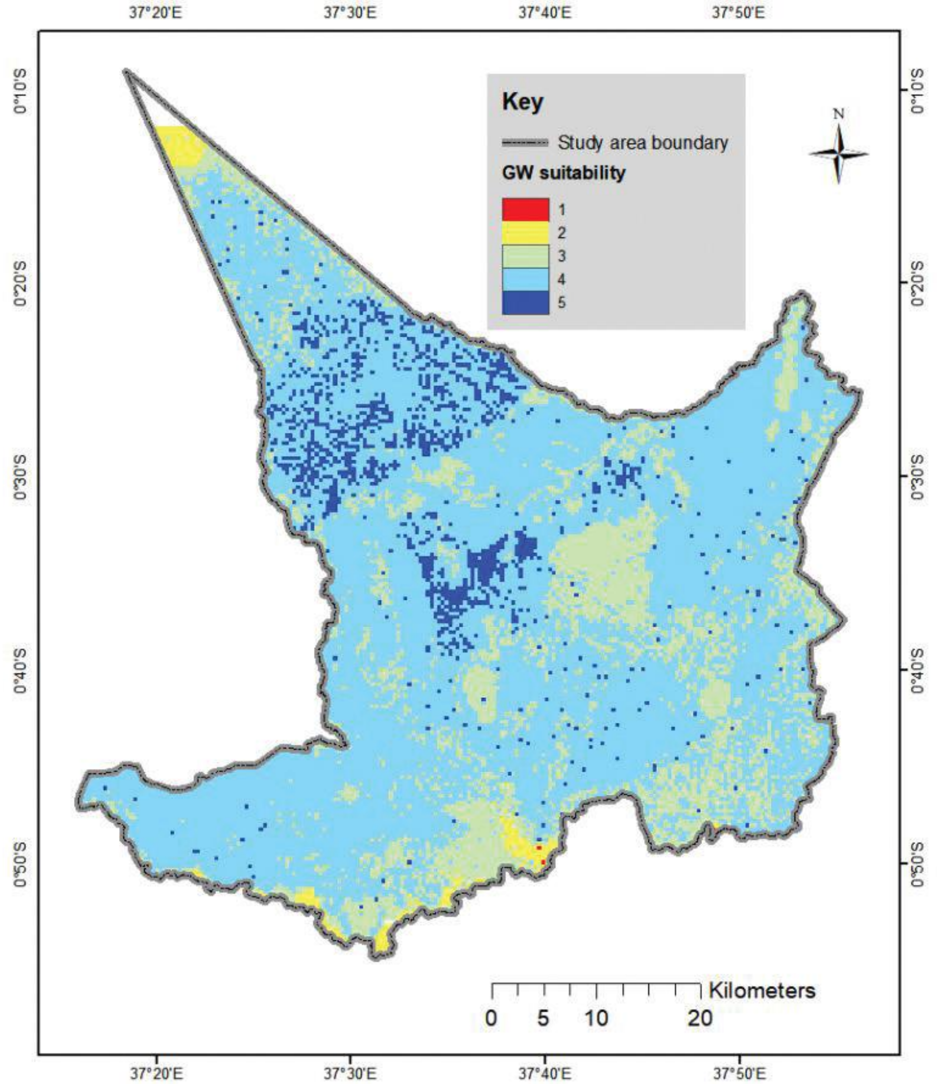

Figure Error! No text of specified style in document.**.17: The Groundwater potential zones in Embu County, Kenya**

The very high potential zones cover about 5% of the study area (see summary under Table 4.5) and correspond mostly with dense agricultural land-use system and forests. The predominant soil types were Nitisols and Acrisols soils which have a high water holding capacities. From Table 4.5 it can be seen that the high groundwater potential zone occupies 73% of the study area. This indicates that occurrence of groundwater in the study area is very high.

Table Error! No text of specified style in document.**.5: The area coverage of the groundwater potential zones in Embu County**

Class	Groundwater potential zone	Area coverage (km^2)	%
1	Very low	0.29	0.01%
2	Low	45.50	1.64%
3	Moderate	565.35	20.34%
4	High	2019.0	72.63%
5	Very high	149.53	5.38%

These zones coincided with the low drainage density and high lineament density areas. The predominant soil type was the Vertisols, Arenosols, Cambisols, and Regosols. The low potential zones are mainly present in the mountain peaks which have cliffs, where low fractured rocks formation exists. These areas have high drainage density and low lineament density and covered about 2% of the study area. The drainage density is an inverse function of permeability, meaning, the less permeable a rock is, the less the infiltration of rainfall, which conversely tends to be concentrated in surface runoff (Thomas and Duraisamy, 2017).Most of the high potential zones in the study area had low drainage density values reflecting the relatively permeable sub-surface strata and medium relief, hence more infiltration than runoff and groundwater recharge occurs. (Mosaad , 2017)

High lineament occurrence significantly controls the permeability of the rocks in the basin apart from other parameters, in which most of the springs, and drainage lines following these fracture zones that would favour groundwater flow. The final groundwater potential zones map is given in Figure 4.10. Areas with high concentration of lineaments and high lineament density coincided with High to very high groundwater potential areas. This can be attributed to lineament related joints and fractures in the underlying rocks which can structurally control the drainage pattern of an area influencing both the groundwater and surface water flow directions (Anudu et al., 2011). Lineaments reflect rock structures through which water can percolate and travel up to several kilometres and depending upon the terrain, the lineament is a zone of influence (Lee et al., 2015). Groundwater potential increases with increasing lineament density (Edet et al., 1994; Anudu et al., 2011; Mogaji et al., 2011). This is true as indicated in this study where high lineament density coincided with high to very high groundwater potential areas in Embu County.

4.3 Validation of the GIS model

The validation process was based on the borehole spatial distribution data (Figure 4.11), used to derive borehole density map (Figure 4.12) and the observed groundwater potential output map (Figure 4.10). The reclassification of the density map was based on the assumption that the higher the distribution density, the higher the ground water potential. The selection of this approach was informed by the lack of detailed borehole data of the study area, except the borehole location data (Adiat et al., 2012). For comparative purposes, an equivalent area of the modelled groundwater suitability map was clipped (Figure 4.14).

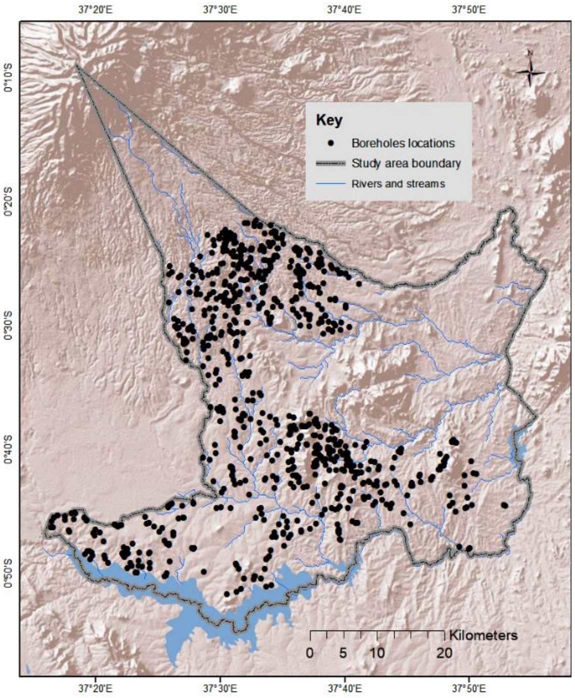

Figure Error! No text of specified style in document.**.18: The distribution of boreholes in Embu County**

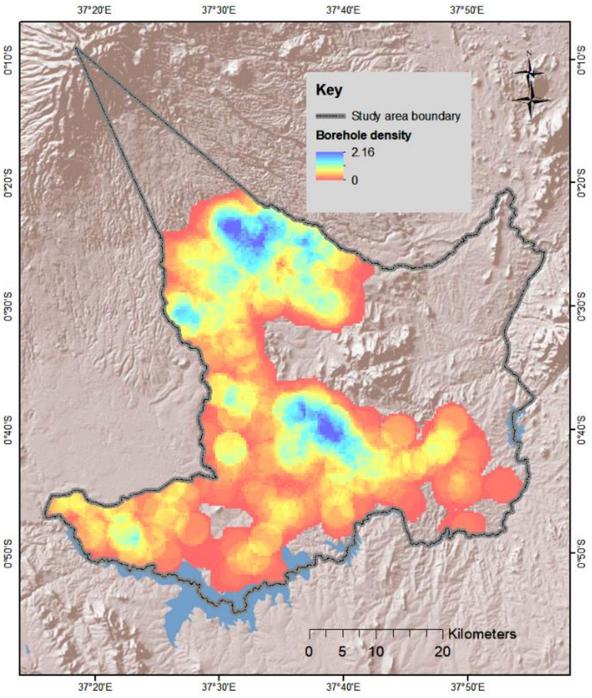

Figure Error! No text of specified style in document.**.19: Borehole distribution density / Observed data**

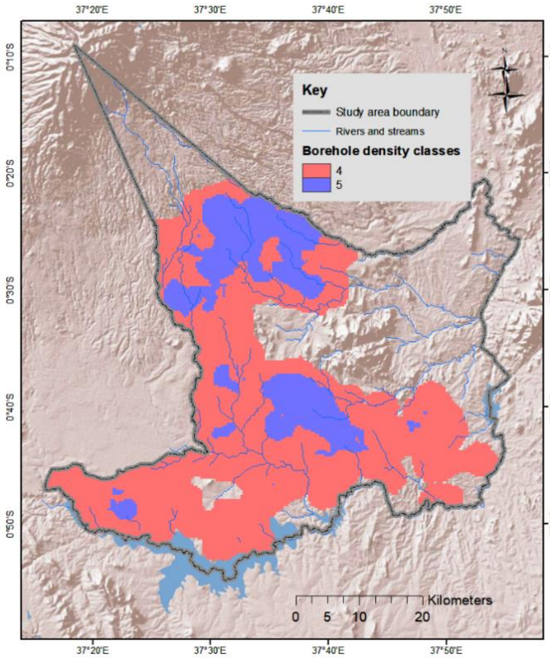

Figure Error! No text of specified style in document.**.20: Reclassified borehole distribution density**

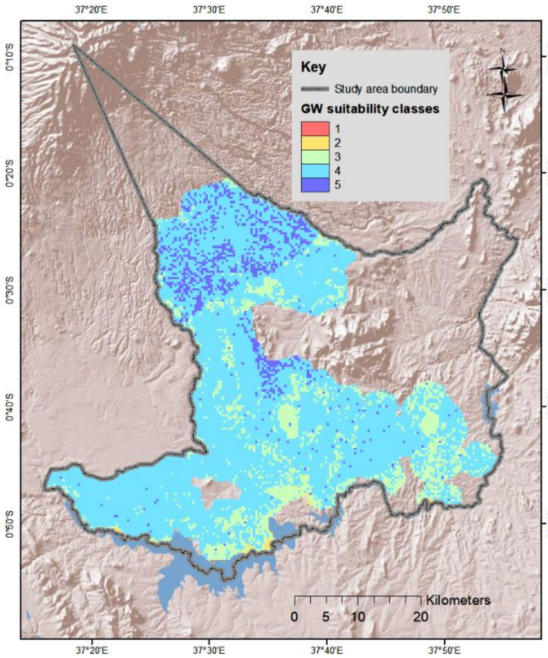

Figure Error! No text of specified style in document.**.21: Groundwater potential /model output**

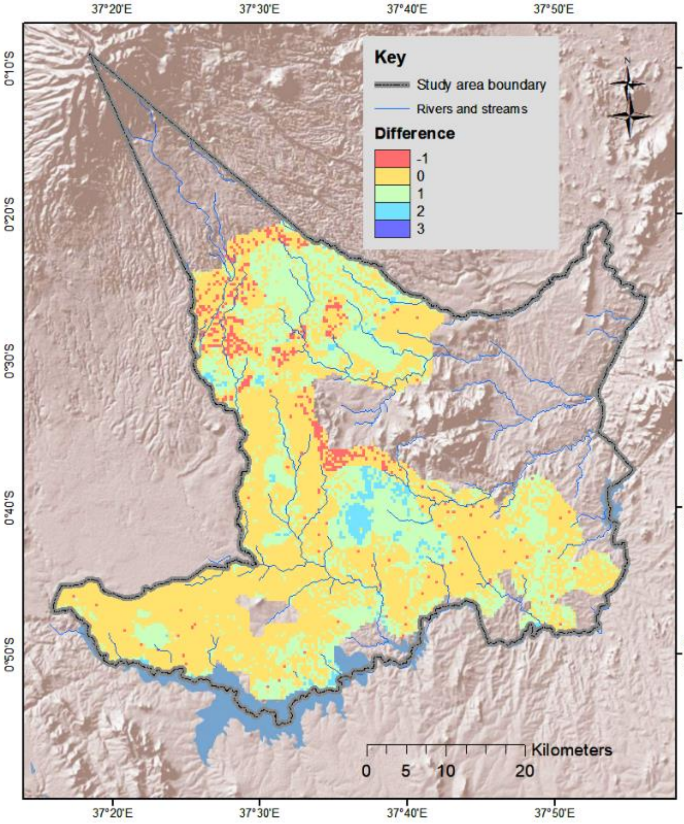

Figure Error! No text of specified style in document.**.22: Comparison of the groundwater potential map produced with the borehole distribution in the study area**

From the study, it was observed that the zonation of groundwater potential using integrated GIS and Remote Sensing techniques strongly related to the available borehole inventory data (Figure 4.11). The number of wells/boreholes was few in the poor potential zone suggesting a good confirmation of the results. From the comparative evaluation, it was observed that there was 62% total agreement with 0 difference between the observed and the modelled groundwater potential maps (Table 4.6). The model underestimated about 4% and overestimated by about 31%, but both were within the moderately suitable range.

Table Error! No text of specified style in document.**.6: The difference between the observed data and the modelled output**

*Difference	Area HA	% Agreement
-1	3,294	4%
0	54,249	62%
1	27,431	31%
2	2,289	3%
3	6	0%
Total	**87,268**	**100%**

* is the difference between the borehole density and the derived groundwater potential maps

The result obtained from this study is not different from the observation of Adiat et al. (2012) that concluded that areas characterized by high yields indicates good groundwater Potential. The finding is also in agreement to that of Fashae et al. (2013) where moderate potential has 79.5%, high 17.24% and 3.23% is low potential.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

In this study, an integrated approach using GIS, DRASTIC model and remote sensing was adopted to find the potential sites for groundwater exploration in Embu County, Kenya. The importance and relationship between annual rainfall, lithology, lineament density, soil, slope, land cover and drainage density was identified and their influence on the natural occurrence of groundwater in Embu County was established. GIS based DRASTIC model was implemented using the seven different effective weighted parameters. The potential zones were identified through integration of various thematic maps by applying DRASTIC model in a GIS environment. Based on the study carried out, the various conclusions were drawn:

The importance of the seven parameters varied widely in relation to their influence on the natural occurrence of groundwater in Embu County. The results of drainage give moderate to high surface runoff generation potential in the study area. Its relationship with groundwater is that the higher the drainage density the lesser the infiltration capacity resulting to having lesser the groundwater potentiality. The slope of the study area was found to vary between 6 and 89% rise. The slope was found that it had a direct influence on the rainfall water infiltration. It controlled the precipitation, whether it will be lost as runoff water or remains on the ground surface for long enough to infiltrate and recharge the groundwater. The study area was found to have diversified lineament distribution. Its relationship with Groundwater is that the higher the lineament density, the higher the probability of the groundwater potential. In general, Lithology had the most weighted factor of 27% followed by slope and land cover and land use both having 17%. Drainage density and Rainfall had both a weighted factor of 10% each. The lowest being soil with a weightage of 7%.

The groundwater potential map was obtained by applying the DRASTIC GIS based model on these parameters. Approximately, 78% of the total area was within the ‘high’ to ‘very high’ groundwater potential zones indicating that significant parts of the study area have good groundwater potential. About 20% of the study area was of moderate potential, while the low and very low potential zones comprised about 2% of the study area.

From the study, it was observed that the zonation of groundwater potential using integrated GIS and Remote Sensing techniques strongly related to the available borehole inventory data. The number of wells/boreholes was few in the poor potential zone suggesting a good confirmation of the result. From the comparative evaluation, it was observed that there was 62% total agreement with 0 difference between the observed and the modelled groundwater potential maps. The model underestimated about 4% and overestimated about 31%, but both were within the moderately suitable range. The outcomes of the research can be helpful in future as first-hand information planners and local authorities for assessment, planning, management, administration, sustainable utilisation of water resources in Embu County.

5.2 Recommendations

In line with the findings that the ground water potential is dependent on lithology, land use/land cover, slope, drainage density, lineament density rainfall and slope the following recommendations were made.

i. Since approximately, 78% of the total area was within the ‘high’ to ‘very high’ groundwater potential zones indicating that significant parts of the study area have good groundwater potential. It is important that the decision makers consider these areas when caring out ground water exploration. The groundwater potential map produced along with the other thematic maps serve as resource information database which can be updated from time to time by adding new information.

ii. Remote sensing data and GIS are powerful tools to improve our understanding of groundwater systems. They provide continuous detailed terrain information and allow the mapping of features significant to groundwater development therefore it is important to incorporate them in the data collection stage of groundwater exploration works. Groundwater modelling studies is recommended to determine the sustainable exploitations of this groundwater potential since the field data indicates that water supply in the study area is highly dependent on groundwater sources.

iii. Catchment Protection is highly recommended in order to conserve groundwater or recharge zones. Also, land use control is recommended in the County to protect groundwater resource. Therefore public awareness and education should be administered to avoid groundwater resource depletion in the county

iv. Further groundwater studies, research and methodologies on the distribution of groundwater like horizontal electrical profiling in 2D and 3D should be employed in future works for analysis of groundwater potential in the study area.

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