University of Nairobi

School of Engineering

Application of Geospatial Technologies in Identification of Optimal Groundwater Yield Locations

Case Study: Woqooyi Galbeed Region, Somalia

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Declaration

I, **Michael Simiyu Makokha** hereby declare that this project is my original work. To the best of my knowledge, the work presented here has not been presented for a Master degree in any other Institution of Higher Learning.

………………………………………… …………………

Name of student Date

This project has been submitted for examination with our approval as university supervisor(s).

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Name of supervisor Date

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Name of supervisor Date

Dedication

I dedicate this project to my late mother, Christine Nakhumicha, for her emphasis on a child's education

Acknowledgement

I acknowledge the Almighty God for His faithfulness.

I acknowledge Somalia Water & Land Information Management unit (SWALIM) of FAO for data Provision.

I acknowledge my supervisor, Mr. Peter Wakoli with profound gratitude, for his support, assistance, guidance and advice offered at every stage throughout the preparation and conduction of my project research.

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Abstract

Groundwater is one of the most important resources on the globe and it is reducing rapidly. Consequently, there is a need for identification of potential groundwater zones. The use of conventional geophysical techniques in siting of boreholes, sometimes results in location of boreholes in unsuitable areas. This leads to low water volume yields, or depletion of groundwater storages especially during dry months due to excessive pumping compared to their ability to naturally recharge.

The study was proposed in quest to improve prediction of suitable groundwater zones, through the use of geospatial technologies to complement the existing geophysical surveys. The approach was timely, since many studies in hydrology had mostly left its application at a recommendation level. Therefore, the study sought to put such recommendation to a test, through the use of multi-criteria approach using weighted overlay analysis.

The research was carried out to identify potential groundwater zones in Woqooyi Galbeed region of Somalia using geospatial techniques. Thematic layers of geology, drainage density, lineaments density, soil, Long term mean rainfall and slope were used. These thematic datasets were weighted on a scale of 1-5, according to how they strongly relate to the existence of groundwater. Through a weighted overlay analysis, a map showing high, low and poor groundwater potential zones was produced as shown in Fig 17.

Validation of existing boreholes was done by overlaying them on the map of groundwater potential zones. Coincidentally, most of good performing boreholes fell within high potential groundwater zone, with a few in low and poor potential zones. It was also noted that although most of the good performing existing boreholes fell in high potential groundwater zone, they existed in concentrations and not evenly distributed within the zone. The observation lay bare the shortcomings of the geophysical survey methods.

These findings underscored the fact that, the use of geospatial techniques in borehole siting does not exclude the need for geophysical survey to determine groundwater quality and volumes but rather, geospatial techniques brings to focus suitable areas as a complement to geophysical surveys. From

the study; 29% of the study area constituted high potential groundwater zone, 51% low potential zone while poor potential zone accounted for 20%. The study recommended the need to undertake '*Groundwater Movement Pattern'* study, to explain isolated boreholes exhibiting high performance in poor Groundwater potential zones, and use of geospatial technologies and geophysical survey techniques in borehole siting with the former preceding the latter.

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CHAPTER 1: INTRODUCTION

1.1 Background

In the year 2015, many countries and governments signed up to implement the Sustainable Development Goals (SDGs): a global initiative that calls for concerted efforts towards ending poverty and improving the quality of life of the citizenry. Among the 17 goals that were adopted, '*campaigning for the realization of clean water and sanitation for all'*, was adopted as SDG number 6. This came from the realization that water scarcity and deprivation consigns large portions of the citizenry to poverty, vulnerability, scarcity and low prospects of human development (UNDP, 2006). Consequently, Under SDG number 6, whilst water has various applications, greater emphasis has been placed towards achieving safe and affordable drinking water under target 6.1 as well as to increase water use efficiency and ensure freshwater supplies under target 6.4 (United Nations, 2015). One Such country hit hard by high levels of poverty, scarcity and low prospects to human development is the republic of Somalia. Therefore, it is for this reason that such a study is timely to guide ongoing efforts by multinationals to help resolve such problems, main of which is clean water scarcity as shown on the global water scarcity map in figure 1.

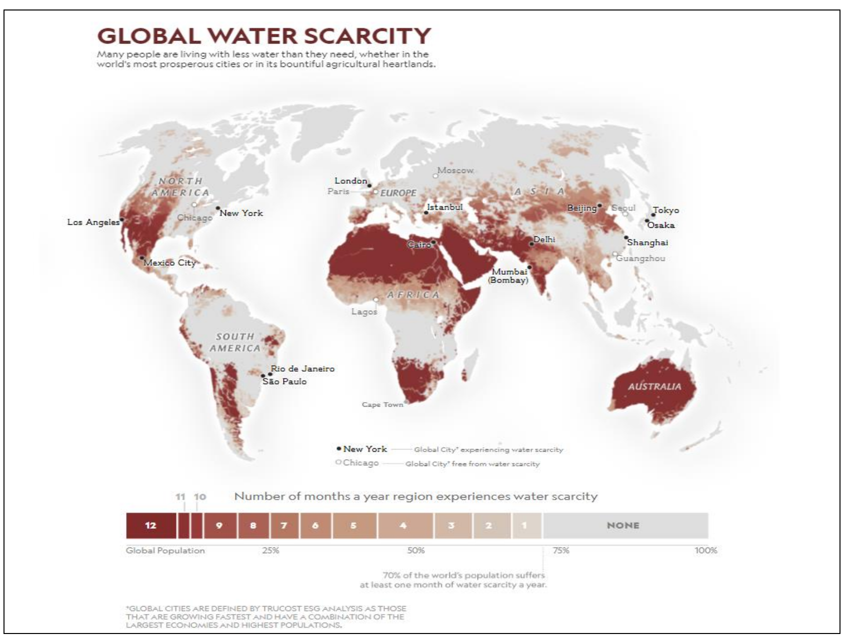

Figure 1: Global Water Scarcity
Source: Mekonnen et al, 2016

1.2 Problem Statement

Whilst a noble cause to afford sustainable water supply has been borehole drilling, various studies show that some of these boreholes end up in abandonment. This has been occasioned largely due to the poor location of boreholes in unsuitable geological areas. This results in depletion of groundwater storages and drying, especially during dry months, or yielding low water volumes, occasioned by excessive pumping from these groundwater storages compared to their ability to naturally recharge (Akudago et al, 2009).In retrospect, it leads to large economic losses partly in form of capital and time investments.

The currently applied geophysical techniques for sitting boreholes, such as geological triangulation, community discussions and village observations as well as ground conductivity among others, are largely dependent on geology. These techniques do not give consistent results under all conditions. The techniques can give results up to 90% accurate in one area whilst the same techniques could be useless in another location (MarcDonald et al, 2000).For this reason, it is necessary that newer and efficient methods be developed or used to compliment geophysical survey in evaluation of suitable sites to set up boreholes.

Multi-criteria method through applying geospatial technologies, was proposed by the study as one of the newer method to ensure that, there is a standard technique which can be applied across different geological conditions for siting optimal borehole locations. This new technique puts in consideration the weighting of surface factors that relate to the existence of groundwater, and carrying out weighted overlay analysis to determine the most suitable locations for optimal groundwater prediction.

1.3 Objectives

1.3.1 Main Objective

To apply geospatial technologies in identification of optimal and sustainable groundwater yield locations in Woqooyi Galbeed region of Somalia.

1.3.2 Specific Objectives

i) To identify criteria for locating optimal groundwater yield areas.

ii) To produce a thematic map of each criteria and discus its suitability to groundwater occurrence.

iii) To carry out multi-criteria analysis to produce groundwater potential zones map

iv) To evaluate the suitability of existing boreholes locations.

v) To evaluate suitability of geophysical survey technique as a method of boreholes siting.

1.4 Justification for the Study

There has been various efforts led by partners operating within the Water and Sanitation (WASH) space, to increase water supply through abstraction of groundwater by drilling boreholes. The emphasis of these efforts has mostly focused within underserviced rural arid and semi-arid areas. However, the challenge has always been; proper siting of suitable locations for borehole drilling, to ensure sustainability through natural groundwater recharge. Such interventions are continuously being undertaken in Somalia by FAO and UNICEF. Previous boreholes data in Somalia show that, indeed some boreholes are non-functional due to depletion of underground aquifers. This realization demonstrates negative economic value of such investment given that drilling a borehole involves huge capital, especially in unstable country like Somalia. Therefore, such a study will assist organizations and governments to optimize deep water exploration to provide access to clean and sustainable water sources for the citizenry.

1.5 Scope of work

The study involved GIS multi-criteria analysis of geological conditions, soils, drainage network, and slope. Presence of fractures (lineaments), land use land cover and long term mean rainfall were also included. However, the study did not involve field geological sampling but used existing geological data from secondary sources. The study area was a region in the northern Somalia called Woqooyi Galbeed. The study region was selected due to security issues and climatic conditions as well as existence of previously drilled boreholes to act as validation data.

1.6 Organization of the report

The report is comprised of five chapters; chapter one is the introductory chapter which contains a general background of the study, problem statement and objectives of the study. Chapter two comprised of reviews of other literatures previously done by other authors, covering or related to the subject of study, as well as explaining exhaustively basic concept of geospatial technologies, analysis and data management. Chapter three outlines the background of the study area, main materials and methodology used in the execution of the research. Chapter four provides the results obtained from the research work and the analysis of the same, whereas chapter five gives a summary of the study with conclusions that were drawn from the research work and recommendations deduced from the conclusions.

CHAPTER 2: LITERATURE REVIEW

2.1 Groundwater

There is a general consensus among researchers including Banks & Robins (2002) & Akudago *et al* (2009), who have defined groundwater as fresh water either from melting snow or rainfall that soaks into the soil and is stored within soil pores, fractures, fissures and other weak geological features or zones below the ground. Further, these researchers have pointed to the importance of ground as a source of portable water, because, water from the resource is relatively protected from bacteriological contamination and evaporation (*ibid*). This is important as the cost of abstraction and treatment before consumption is greatly reduced compared to surface water.

As a consequence, various locations have differential volumes of groundwater in the reservoirs that is controlled by a number of factors. These factors thus control the availability of underground storage aquifers and consequently result in the fluctuation of groundwater from region to region. In previous research these factors have been identified. They include; subsurface geology that constitute rock formation, the hydrological properties of the subsurface material, physical parameters of the aquifers such as transmissibility, storage coefficient and specific yield. In addition, other groundwater extraction activities in the area, topography of the area, terrain and groundwater gradient, natural discharge through spring discharge and the rainfall pattern including intensity and distribution.

There are three ways in which the groundwater fluctuates. These include; in the short term where water levels fluctuate with the use, seasonal variation which occurs depending on the rainfall intensity and distribution throughout the year, and secular variation that often extends over extended periods or years.

Banks & Robins (2002) have given three key parameters to be considered when planning to site a borehole. They have cited the need to consider logistical issues (access to the site of the borehole), vulnerability factors (sources of potential pollution to water in the borehole) and geological factors. When considering geological factors they propose that it would be prudent to site the borehole in an area of zones of intense fracturing and in areas with a moderate cover of superficial deposits.

2.2 Borehole Siting

2.2.1 Application of GIS and Remote Sensing in Groundwater exploration

Many factors have to be put in consideration when siting a borehole. In siting of boreholes, it is therefore important that these sites be situated in areas with large underground reservoirs. The existence of large groundwater storage is controlled by a number of factors which include but not limited to geological conditions, physiography, geology, hydrogeology, geomorphology, drainage, slope, depth of weathering, the presence of fractures and surface water bodies as has been observed by Argaz et al (2019). It is therefore important that careful consideration is made when planning to situate boreholes in an area. Remote Sensing, coupled with Geographic Information systems, have thus emerged as important tools for undertaking this task that often require an integration of multiple criterions for proper interpretation.

Several studies have been undertaken over the years, focusing on the use of remote sensing for groundwater exploration. Many of these researches have proceeded from the premise that boreholes provide an easy way to exploit groundwater and hence it is suitable to situate boreholes in areas that have vast amounts of groundwater. As a consequence, these researches have placed greater emphasis on the application of remote sensing in the identification, mapping and development of groundwater resources. However, little research has been done in the application of remote sensing to site suitable areas for borehole drilling.

The researches have demonstrated that before siting a borehole, it is important to understand the volume of the underlying groundwater reservoir and its long term trends to ensure sustainability, both in the abstraction and in meeting the demand of the population. The important factors to consider when studying the underlying groundwater include; groundwater depth and elevation, regional characteristics, subsurface characteristics, and hydrological conditions. To study these factors it is important that the researcher collects data from varying sources. However, the choice of the datasets is divergent on a case-by-case basis. Zhang *et al* (2019) have proposed that the primary data to be adopted include surficial geology, soil infiltration capacity, land use, elevation, infiltration and recharge rates, aquifer thickness, aquifer hydraulic conductivity, aquifer storability, and historical changes in water table elevation.

2.2.2 Groundwater Depth Measurement

In a bid to determine the depth of groundwater resources in arid and semi-arid conditions during the various seasons in a year, Ahmadi & sedghamiz (2008) employed a geostatistical and modeling methodology of kriging and cokriging. Under the methodology, the pair proceeded with the theoretical approach of spatial dependence between neighboring observations as expressed in the semi-variogram. On the other hand, kriging technique employs interpolation estimator, to find the best unbiased linear estimate. Therefore using various variables that were measured across an aquifer throughout the year from 500 wells, the team came up with five parameters including maximum, minimum and mean groundwater depth that was measured across each well. These parameters were used as variables in the variogram and also to produce linear depth measurements. The results were cross validated and revealed that water depths were correlated. Similar studies that have been undertaken by Kompanizare (2009), have also yielded the same results.

2.2.3 Application of GIS in borehole siting

Minor *et al* (1994), while combining hydrogeological phenomena, and the relationships drawn from remote sensing data, they were able to combine a number of analytical methods, data types and data features to identify potential well areas in Ghana. Using GIS, the team was able to map out fracture traces and lineaments from soil and geologic data sheets of the country. Fracture traces and lineaments were believed to be important factors in controlling the occurrence, movement and storage of groundwater, especially in crystalline and sedimentary rocks. The belief was based on previous finding by Bernaman (1988) which concluded that; fracture zones act as storages and pathways for water movement. By mapping these fractures and correlating them with productive groundwater zones, they hoped to increase accuracy of site selection for situating new wells.

Mapping out of fractures was done through integrating remote sensing and Geographic Information Systems to combine physiographic, geological, hydrogeological, and geochemical data in a spatially referenced model. Various data types were used that included: aerial photography, satellite imagery, topographic setting, rainfall data, land use land cover, geophysical logs and surveys, borehole locations and its related hydrological information, including yields from the wells, water level, and aquifer test data.

In the Minor *et al* (1994) methodology, understanding spatial distribution of existing wells was an important step because, the team was first able to map out wells and classify them into ‘productive’ and dry. Productive wells were used to denote those with active yield, while dry wells referred to sites where the groundwater had already been depleted. Further the team used elevation data of existing well sites was collected using Global Positioning Systems (GPS) receivers and used to prepare potentiometric maps. All these datasets were integrated in GIS using a multi-criteria decision tree method and several models were developed. The vegetation in an area, especially those with tap root systems, were used as an indication of a possible lineament. The research methodology helped to shine a light on the potential applications of remote sensing in the identification of suitable sites for the situating boreholes.

A similar methodology as employed by Minor et al (1994) was used by Gustaffson (1993). Under his research, he identified the usefulness of the Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM), for creation of drainage networks. These networks were then used for correlation with the areas where lineaments had been identified.

The ability to identify various features on the ground using remote sensing; that may be used as either direct or indirect indicators of the availability of groundwater, has increased the use of satellite imagery in groundwater exploration studies (Bahuguna et al., 2003). As a consequence, many groundwater prospecting methodologies, employ a method of mapping lineaments and landforms. This is often followed by a combination of statistical decision tree analysis and modeling methods, such as the Analytical Hierarchy Process (AHP) that was developed by saaty (1980) and the Multi-Criteria Decision Analysis method. AHP considers a set of criteria according to the decision maker's pairwise comparisons of the criteria.

2.3 Aquifers and Groundwater

Groundwater is held within rock voids and unconsolidated sediments. Rocks and sediments close to the surface, are under less pressure, thus containing more air spaces compared to those at a considerable depth. Therefore, most of ground water accessible by users are within the first 100m of the surface. Also, it is expensive to drill deep wells. It is important to note that, deeper groundwater tend to be of lower quality, putting a limit to how deep drilling can be done. The deep waters are mostly desired by users with high water consumption such as industrials and agriculture.

Porosity is the percentage of open space within a rock or unconsolidated sediments compared to the total rock or sediment volume. It is the measure of water volume that can be stored in geological materials. The ability of geological materials to store water in air spaces within them, varies from one material to another. Since the best material to constitute a good aquifer is determined by the amount of water they are able to store, then it goes without saying that more porous geological materials form the best groundwater storage. Porosity can be divided into primary and secondary. Spaces between particles in a sediment or a sedimentary rock, constitutes primary porosity, while Secondary porosity develops after rock formation process. Secondary porosity can include fracture porosity, which is the space within fractures in any rock type. Some volcanic rocks have a special type of porosity that relates to vesicles, while some limestone has extra porosity related to cavities within fossils.

Figure 2 below, shows typical porosity ranges of a number of different geological materials. Unconsolidated sediments tend exhibit higher porosity compared to consolidated ones, because most have not been strongly compressed and have no cement. Geological materials with fine grains, such as clay and silt, tend to have greater porosity, unlike coarser materials such as gravel. Well-sorted sediments tend to have higher porosity compared to poorly sorted sediments.

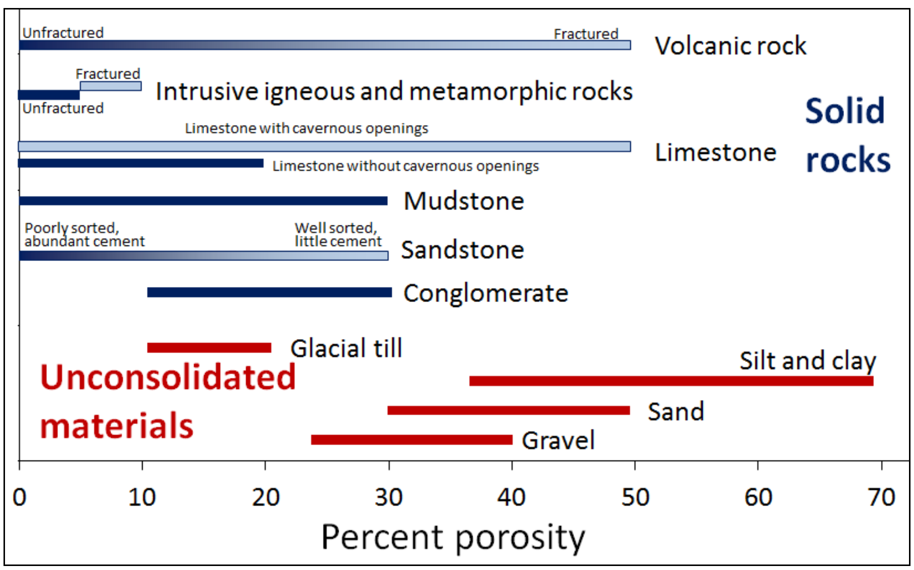

Figure 2: The figure shows porosity ranges of a number of different geological materials

Whilst Porosity is how much pore space volume is available in a geological material to hold groundwater, how those pores are interconnected and shaped is referred to as permeability. This determines how easy water infiltrates through the pores in rocks or unconsolidated sediments, and the ease with which water can be retrieved. A permeable material has a significant number of larger, well-connected pores spaces, whereas an impermeable material has lesser, smaller poorly connected pores. Large pores allow water to freely flow with less frictional resistance compared to smaller pores which exerts friction as water flows through them. Permeability is the most significant variable in groundwater. Permeability of a geological material is measured by its hydraulic conductivity with symbol K commonly expressed in m/s although there are many other units.

Figure 3 below shows that there is a widespread range of permeability in geological materials from 10-12 m/s (0.000000000001 m/s) to around 1 m/s. A comparison between sand (unconsolidated) and sandstone (consolidated) shows that sand is more permeable than its corresponding rock; sandstone, underscoring the fact that unconsolidated materials are more permeable than consolidated ones. Coarser materials are much more permeable compared to finer ones. The least permeable rocks are unfractured intrusive igneous and metamorphic rocks, followed by unfractured mudstone, sandstone, and limestone. The permeability of sandstone can vary widely depending on the degree of sorting and the amount of cement that is present. Fractured igneous and metamorphic rocks, and especially fractured volcanic rocks, can be highly permeable, as can limestone that has been dissolved along fractures and bedding planes to create solutional openings.

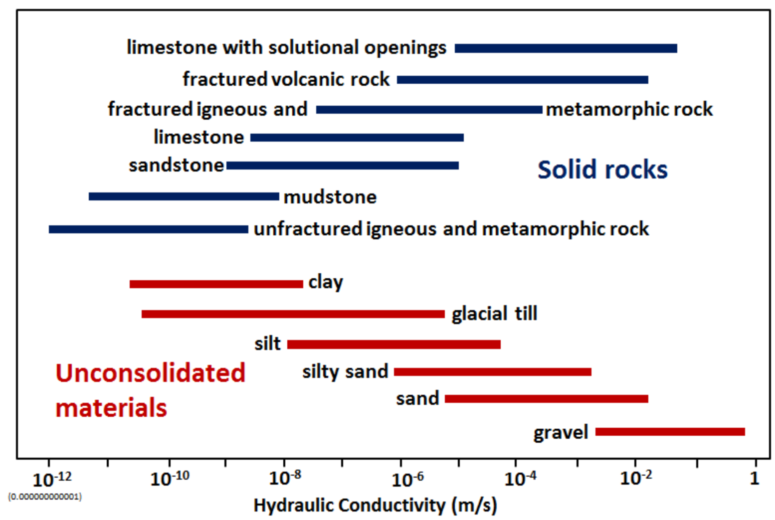

Figure 3: The figure shows hydraulic conductivity of different geological materials

Materials such as sand and clay are porous but sand is more permeable than clay because of the larger pores in sand compared to clay.

An **aquifer** is therefore defined as a body of rock or unconsolidated sediment that has sufficient permeability to allow water to flow through it. Unconsolidated materials such as gravel, sand, and even silt make relatively good aquifers, as do rocks like sandstone. Well fractured rocks can be good aquifers. Some materials such as clay, till, or poorly fractured igneous or metamorphic rocks do not allow transmission of a significant amount of water, these materials are called aquitards. Aquitards is a relative term, not absolute, and are usually defined based on someone's desire to pump groundwater; what is an aquifer to someone who does not need a lot of water, may be an aquitard to someone else who does. An unconfined aquifer is that, that is exposed at the ground surface. An aquifer where there is a lower permeability material between the aquifer and the ground surface is known as a confined aquifer, and the aquitard separating ground surface and the aquifer is known as the confining layer.

Figure 4 below shows a cross-section of a series of rocks and unconsolidated materials, some of which might serve as aquifers and others as aquitards or confining layers. The granite is much less permeable than the other materials, and so is an aquitard in this context. The yellow layer is very permeable and would make an ideal aquifer. The overlying grey layer is a confining layer.

The upper buff-coloured layer (K = 10-2 m/s) does not have a confining layer and is an unconfined aquifer. The yellow layer (K = 10-1 m/s) is "confined" by the confining layer (K = 10-4 m/s), and is a confined aquifer. The confined aquifer gets most of its water from the upper part of the hill where it is exposed at the surface, and relatively little by seepage through the fine silt layer.

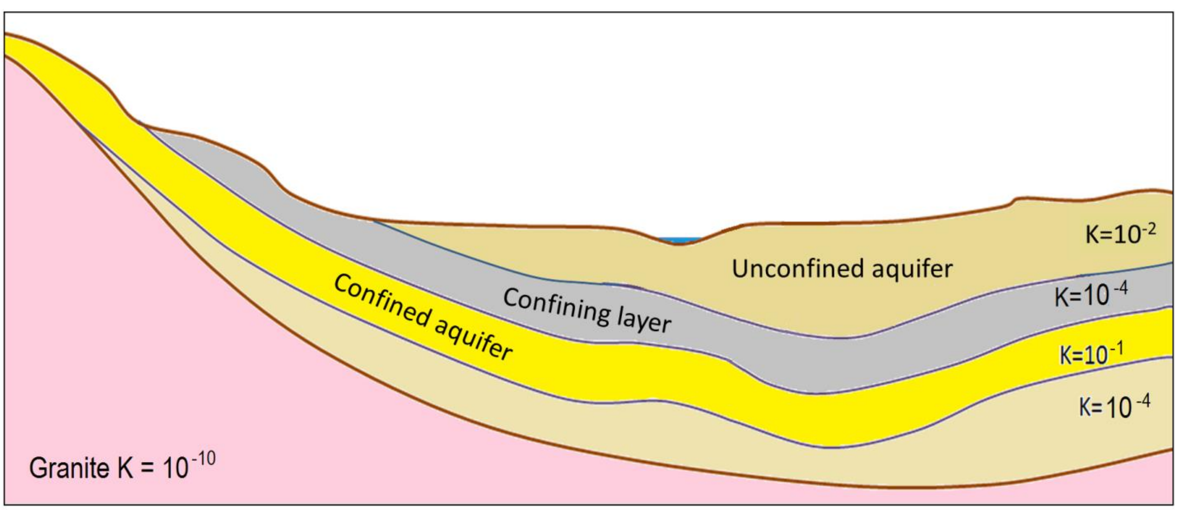

Figure 4: A cross-section showing materials that might serve as aquifers and confining layers.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study area

The figure 5 below shows a map of the project study area.

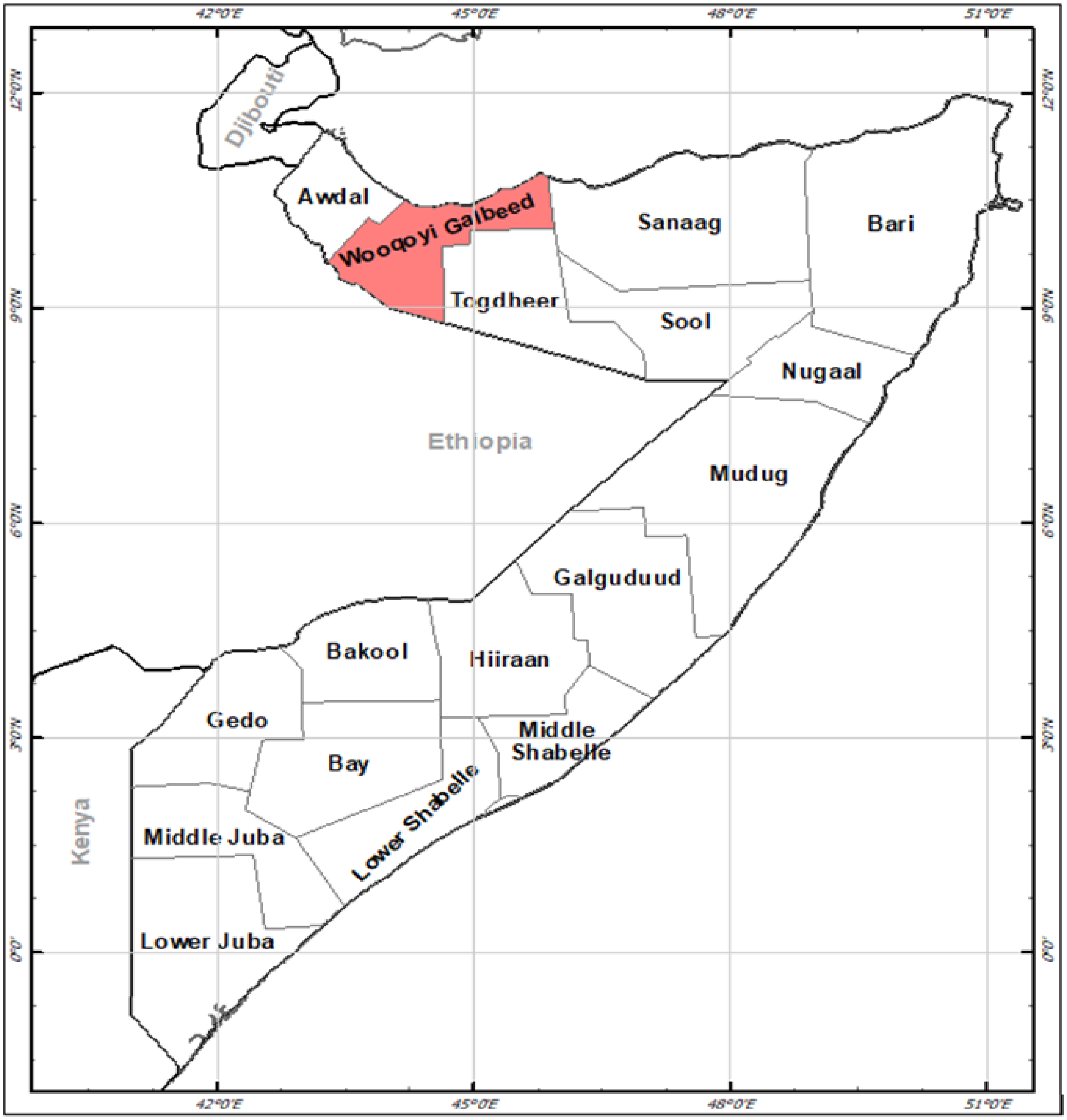

Figure 5: Study Area

Source: Author

Woqooyi Galbeed is located in northern Somalia (Somaliland) between Awdal region to the west, and Togdheer region to the east. It also borders Ethiopia to the south and the Gulf of Aden to the north. The region has an estimated population of 1,242,003 with a 2:1 urban/rural ratio (UNFPA 2014). Somaliland's capital city Hargeisa and the northern port town of Berbera are found in the region. The region consists of three districts: Berbera, Hargeisa, and Gabiley.

There are four livelihood zones in the region, namely: Guban pastoral zone (tending sheep, goats, camels), which runs along the northern coast; the west Golis pastoral zone (rearing sheep, goats, camels) running from east to west below Guban, the largest zone in the region; north-west agro-pastoral zone (cultivating sorghum, raising cattle) extending from east to west below west Golis; and the Hawd pastoral zone (tending sheep, goats, camels) along the southern border with Ethiopia (OCHA 2012).

Most parts of the region receive near normal to normal Gu (wet season) rains that replenish water levels and regenerate pastures. Hargeisa, which is the main city in Woqooyi Galbeed, is home to the highest concentration of IDPs in Somaliland, which according to UNHCR estimates, numbers at 45,000 people. The majority of the IDPs in the region have resided in settlements for years. Many fled the early 1990's civil war in Somalia and returned to Somaliland from Ethiopia. There are more arrivals in recent years due to drought.

Like in other north-western agro-pastoral zones, people in Woqooyi Galbeed have trouble in accessing safe water, sanitation and health facilities. According to Food Security Analysis Unit (FSNAU) of FAO Somalia, surveys from 2009 to 2011, 20-40 per cent of the population access improved sanitation, and less than 40 per cent have access to a protected water source. In Hargeisa district, less than 20 per cent of the population accesses a protected water source, and in the majority of IDP settlements, water trucking remains the most prevalent source of household water

3.2 Methodology Overview

Figure 6 below shows the methodology flow chat.

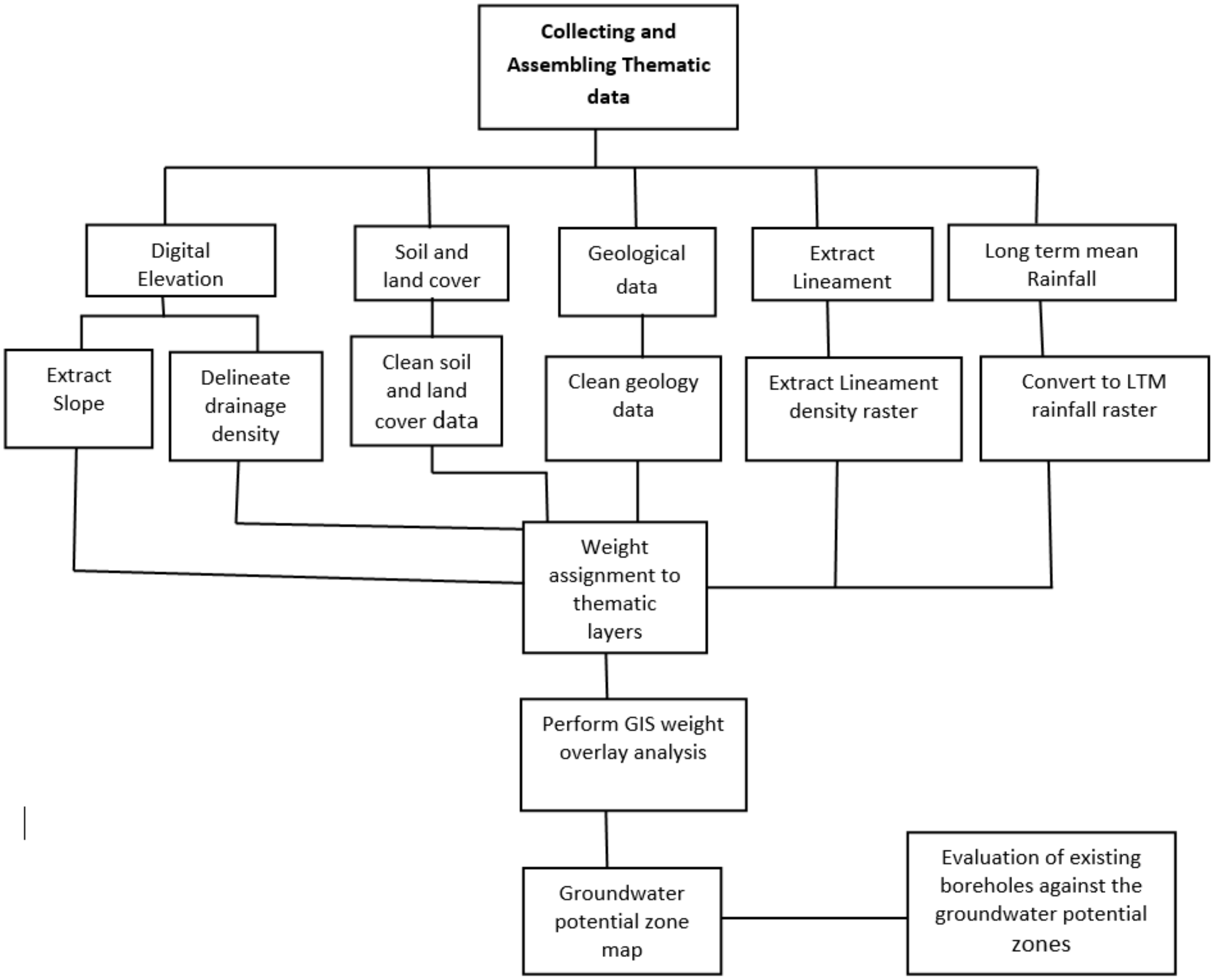

Figure 6: Methodology flow chat

The following steps were carried out to identify the most suitable groundwater sites using multi-criteria method which involved : (a) assembling groundwater occurrence data and building of geo-database , (b) establishing the relationship between the groundwater occurrence and surface factors (c) the results was used to evaluate suitability of the existing boreholes in the region.

Thematic layers such as drainage, slope, geology, soil, rainfall, lineaments and land cover, were prepared from various sources and classified into types denoted as classes. A rank of 1 to 5 was assigned to each thematic layer based on their importance in the relationship with groundwater resources. After which these allotted ranks were given proper weighting values from 0 to 100% by using Analytic Hierarchy Process (AHP), rendering their influence relative to other classes in the same thematic layer. To establish the potential zones for groundwater, all the thematic layers were overlaid based on their weighted influence.

The figure 7 below shows the priority percentages by AHP decision method.

Resulting Priorities

Priorities

These are the resulting weights for the criteria based on your pairwise comparisons:

Cat		Priority	Rank	(+)	(-)
1	Geology	14.2%	2	6.2%	6.2%
2	Land Use Land Cover	8.0%	7	2.0%	2.0%
3	Linearment Density	10.5%	4	3.7%	3.7%
4	Slope	11.1%	3	4.4%	4.4%
5	Rainfall	38.4%	1	16.8%	16.8%
6	Drainage Desnsity	8.6%	6	2.6%	2.6%
7	Soils	9.2%	5	4.3%	4.3%

Number of comparisons = 21
Consistency Ratio CR = 5.5%

Decision Matrix

The resulting weights are based on the principal eigenvector of the decision matrix:

	1	2	3	4	5	6	7
1	1	3.00	1.00	2.00	0.20	1.00	2.00
2	0.33	1	1.00	1.00	0.20	1.00	1.00
3	1.00	1.00	1	1.00	0.20	1.00	2.00
4	0.50	1.00	1.00	1	0.50	2.00	1.00
5	5.00	5.00	5.00	2.00	1	5.00	2.00
6	1.00	1.00	1.00	0.50	0.20	1	1.00
7	0.50	1.00	0.50	1.00	0.50	1.00	1

Principal eigen value = 7.440
Eigenvector solution: 5 iterations, delta = 7.4E-9

Figure 7: AHP Ranking Decision Matrix

The participating thematic layers were put in the order of priorities from highest to lowest as follows: rainfall, geology, slope, lineament density, soils, drainage density and finally land use land cover.

3.3 Data Collection

The following thematic data was obtained from FAO Somalia, SWALIM unit; geology, land use land cover, fault lines, soils and long term mean rainfall (1983-2019).Slope and drainage network datasets were derived from a 30m STRM DEM through hydrological modelling in ArcGIS environment.

3.3.1 Drainage Network Derivation

Figure 8 below shows drainage network and basins delineation model.

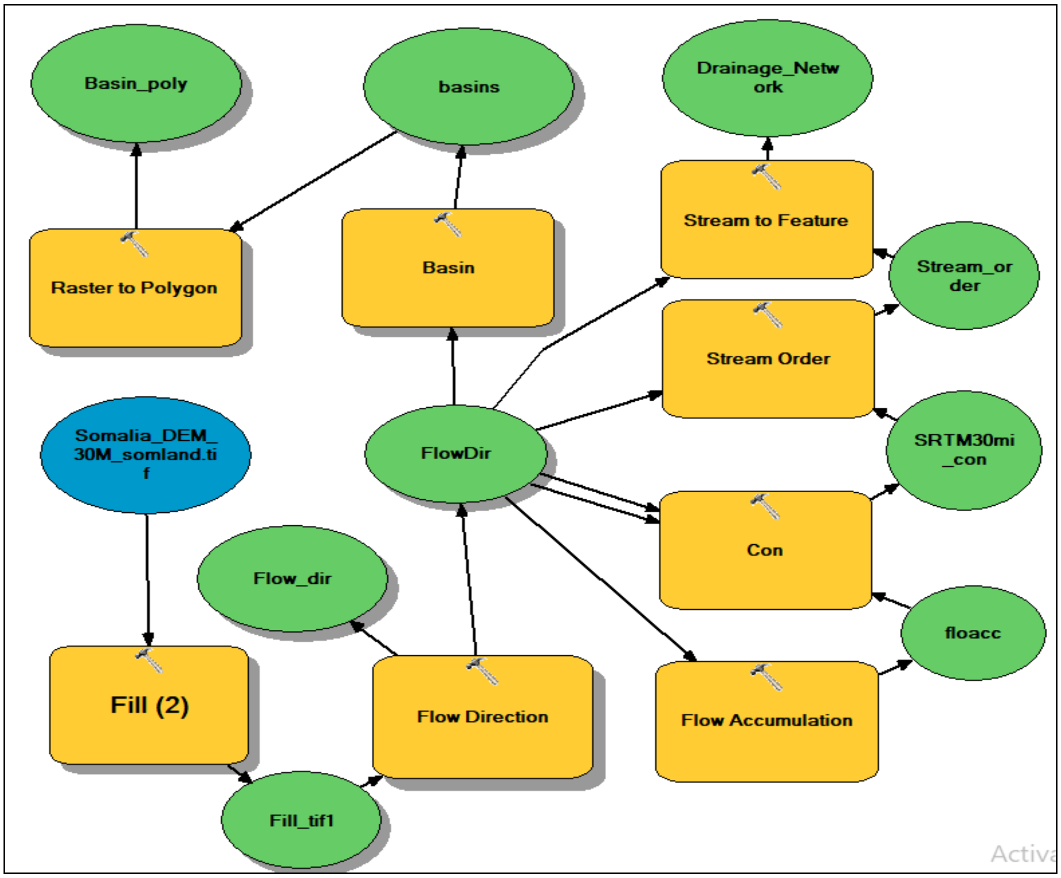

Figure 8: Drainage network derivation model

The process of delineation was achieved by the use of 30m SRTM DEM. The sinks in the DEM were filled by *Fill* tool, then *Flow Direction* computed, which was followed by *Flow accumulation*, *conditioning* of *stream flow direction*, *stream order* and the resulting raster was converted to *stream features.*

3.4 Data Preparation and Editing

The datasets in their original form covered the entire Somalia, therefore, it was clipped to fit within the area of interest. For consistency during data processing, all the datasets were transformed into similar projection system and care was taken to ensure they were georeferenced.

3.5 Data Processing

3.5.1 Vector to Raster Conversion

The vector data was converted into raster data using the *polygon to raster* conversion tool in ArcGIS. This was done to facilitate reclassification of data.

3.5.2 Drainage & lineament density computation

The aspect that relates to groundwater existence for both drainage network and lineaments is their densities. Therefore, the density computations was done using *Focal statistics tool* in ArcGis software.

3.5.3 Data re-classification

Weighted overlay analysis requires reclassified data as input to allow allocation of scale ranks depending on the relationship of each factor to the occurrence of groundwater. This made it necessary for re-classification of all integer raster datasets into five classes. Re-classification of geology, land use land cover and soils into five classes was not possible because of the nominal nature of the data. However, this was achieved during the allocation of scale ranks in the weighted overlay table.

3.5.4 Weighting and scale ranking

There were seven datasets layers that participated in the analysis. These dataset related to occurrence of groundwater in different magnitudes. AHP ranking method was applied to determine the weights of each factor relative to each other, in determining the occurrence of groundwater, as shown in Figure 3 above. The following were the weights assigned to each factor; geology-14%, Land Use land cover-8%, Lineaments density-11%, Slope-11%, Rainfall-38%, Drainage density-9% and Soils-9%. The relationship of each factor to the occurrence of groundwater discussed below;

i) Geology

The geology of an area determines the type of aquifer. Aquifers can be classified into consolidated and unconsolidated. Unconsolidated materials like alluviums (sand, gravel and silt) and glacial sediments make good aquifers due to their good porosity and permeability compared to consolidated materials such as sedimentary bed rocks and igneous metamorphic rocks.

In the study area, there were 17 sub categories of geological materials that fell within three categories of; *Ignous metermorphic rocks*, *Sedimentary rocks* and *Alluviums***.**According to (Steven Earle, 2015), alluviums are higly porous and permeable , followed by sedimentary rocks and lastly, ignous & metarmorphic rocks.The 17 geology sub classes were ranked by a scale of 1 to 5 by 1 with 5 being the best.The ranking was based on the geological material composition within each sub category, suitable for a good aquifer to hold groundwater and allow natural recharge.

ii) Land Use Land Cover

Land Use land cover data used, had 7 categories of land use types namely; irrigated crop (IC), rain fed crop (RC), natural woody vegetation closed to open (NVCO), natural woody vegetation sparse or herbaceous (NVSH), Bare areas (BA), built up areas (BU) and finally water bodies (WB).Land use types relate with the occurrence of groundwater by their ability to hold water on a permeable ground long enough, to allow seepage into the ground to recharge aquifers. Based on the assertion, WB (5) ranked highest, followed by NVCO (4), NVSH (4), IC (3), RC (2), BU (1) and finally BA (1).This meant that areas with water bodies were high potential zones for groundwater, while bare areas are least potential.

iii) Lineament Density

Lineament in this case referred to geological fault lines within the study area. This goes without saying that, areas with concentrated fault lines, makes it suitable for passage of surface water into the ground pores to recharge the aquifers. These areas are therefore considered potential zones for groundwater occurrence and sustainability. The ranking scale was 1 for less dense to 5 for more dense areas.

iv) Slope

Slope is inversely proportional to potential zones for groundwater occurrence. The higher the slope, the less suitable the area for groundwater occurrence. Undulating slope allows time for surface water to seep through the porous and permeable ground to recharge underground aquifers. In addition, aquifers located at the lower slope experiences recharge from higher locations due gravitational energy. Water may move directly as surface runoffs down slope or seep through the ground and move through ground pores. Consequently, ranking was done by assigning higher rank (5) to lower areas and lower rank (1) to higher areas implying that lower areas are suitable for groundwater occurrence and sustainability.

v) Rainfall

Rain water is a major natural source of groundwater recharge. Therefore, the amount of rainfall experienced in an area is directly proportional to groundwater levels, assuming that the geological materials in the area are porous and permeable with undulating slope. In the study area, the long term rainfall mean from 1983 to 2019 showed that, the highest mean rainfall was 179mm and the lowest was 12mm, with the areas bordering Ethiopia experiencing more rainfall compared to other parts of the region. Therefore, the highest rank (5) was given to higher rainfall means, implying that these areas are high potential zones for groundwater occurrence than those experiencing low rainfall.

vi) Soils

The soil categories within the region of study were; *Arenosols, Vertisols, Leptosols, Regosols, Cambisols, Solonchaks and Calcisols*.To understand how soil type influence occurrence of groundwater, hydraulic properties of each soil category were studied. More porous and permeable soils categories allow easy seepage of surface water into the ground pores to recharge underground aquifers. The following were the hydraulic properties of soils within Woqooyi Galbeed region; *Arenosols* are loamy sand or sandy texture to a depth of 100cm with a low water holding capacity. Therefore, it allows water to drain to recharge groundwater. *Vertisols* are characterised by low porosity that are broken and discontinuous with mainly only micro pores and low water transmission capacity. *Leptosols* Soils that are either shallow (< 25 cm deep) over hard rock, or that are extremely gravelly (> 80% gravel, stones or boulders by volume). Leptosols have low water-holding capacity due to their shallow depth or extreme coarse texture.

Regosols are weakly developed soils in unconsolidated materials that are not very shallow such as Leptosols, or sandy (Arenosols), or wet (Gleysols), or that consist of alluvial material (Fluvisols).Regosols have high water permeability which makes them susceptible to erosion. *Cambisols* have good structural stability, high porosity, good water-holding capacity, good internal drainage and not prone to erosion. *Calcisols* have accumulation of secondary calcium carbonate ($CaCO_3$), forming calcic or petro-calcic horizons. These soils have good water holding capacity but are prone to slaking and crusting. *Solonchaks* have accumulation of salts more soluble than gypsum (salic horizon).

The ranks of the soils with the above hydraulic conductivity found within the study area, were ranked from the least suitable (1) to most suitable (5) soils that favours occurrence of ground water; *Vertisols (1), Solonchaks (2) Arenosols (3), Calcisols (3) Cambisols (3) Regosols (4) and finally Leptosols (5)*

vii) Drainage Density

Densely drained area has high potential for groundwater occurrence due to the easy ability of groundwater to recharge. Therefore, the highest ranks in terms of suitability of groundwater potential occurrence was given to high density values.

3.6 Model Building

The seven factors were weighed as explained above. The next process was to perform a weighted overlay analysis and assigning scale ranking for each factor depending on how they related to the potential occurrence of groundwater in a location. The weighted overlay model in figure 9 below was developed.

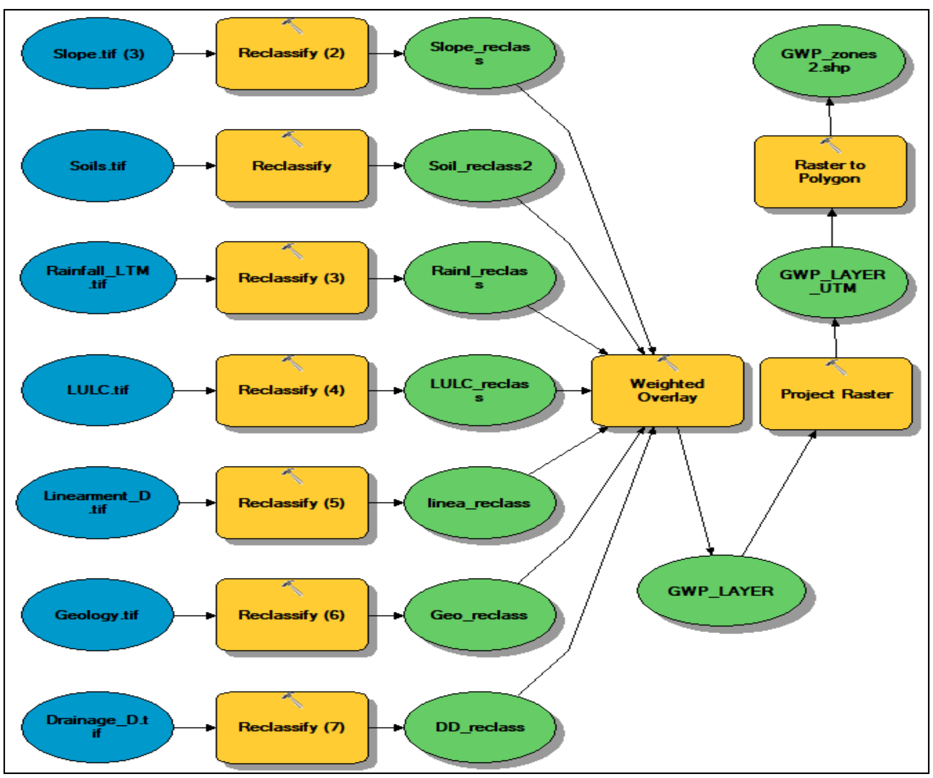

Figure 9: Groundwater potential model

Figure 10 below shows a weighted overlay table from ArcGIS software.

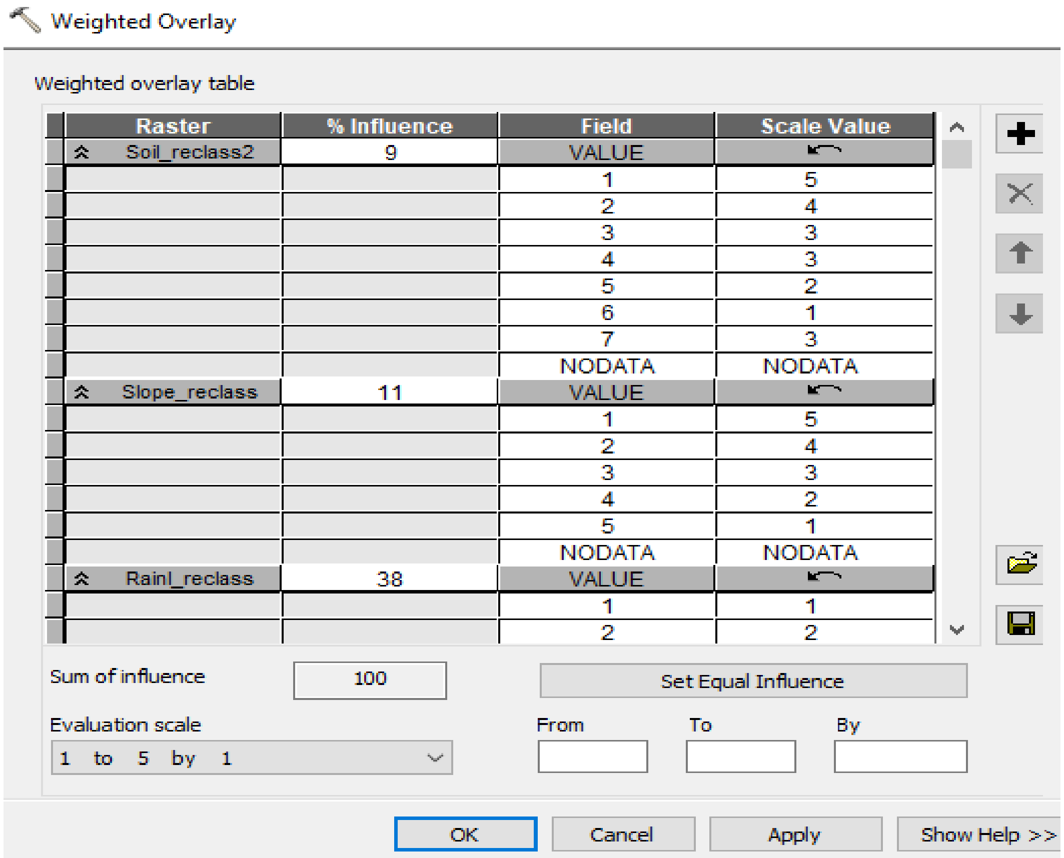

Figure 10: Weighted overlay analysis table window

The weighted overlay table in figure 10 above shows how each thematic layer was assigned a percentage influence and ranking of each factor in respective thematic layer.

3.7 Groundwater Potential Zones Validation

The study area had existing boreholes. They were overlaid on the groundwater potential zones map and their characteristics evaluated against the potential zone type they fell in. This acted as a validation of the weighted overlay analysis model used. The process also acted as a counter validation of the existing boreholes' viability within respective zones they fell in. By doing so, by extension would be validating the geophysical survey method that was used during siting of the existing boreholes. Further validation of existing boreholes was done by observing them against accessibility and settlements in the study area vis a vis potential groundwater zones.

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter focuses on presentation of the results produced from the analyses that were carried out during the implementation of this project. The overall objective of the study was to identify the most likely sites for optimal and sustainable groundwater yield in Somalia, using geospatial technologies. Consistent with the set objectives, the following results were obtained;

a) Geological suitability map for groundwater potential
b) Lineament suitability map for groundwater potential
c) Land Use Land Cover suitability map for groundwater potential
d) Rainfall suitability map for groundwater potential
e) Slope suitability map for groundwater potential
f) Soil suitability map for groundwater potential
g) Drainage suitability map for groundwater potential
h) Groundwater potential zone map
i) Analysis validation maps using existing boreholes ,settlements and roads

4.1 Geological suitability map for groundwater potential

Figure 12 below shows geological map for ground water potential of the study area.

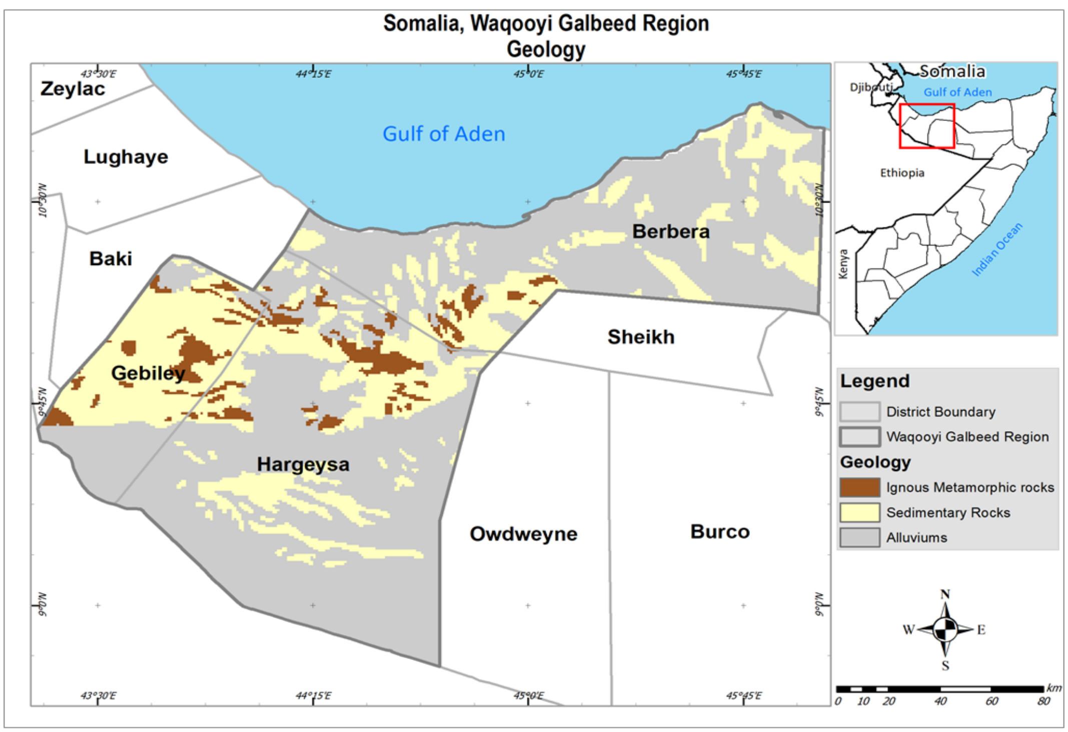

Figure 11: Geological map for groundwater potential

From the criteria ranking in chapter 4, alluviums constituted high potential zones, followed by sedimentary rocks; moderate potential and finally igneous & metamorphic rocks; poor potential zone for groundwater occurrence. Based on geology alone, suitable regions (grey) for groundwater occurrence potential fell mostly on the southern and north-eastern part of the study area with some small patches at the central region. Large portion of the central regions was considered less suitable (yellow & brown).

4.2 Lineament suitability map for groundwater potential

The map in figure 12 below shows density of geological fault lines within the study area.

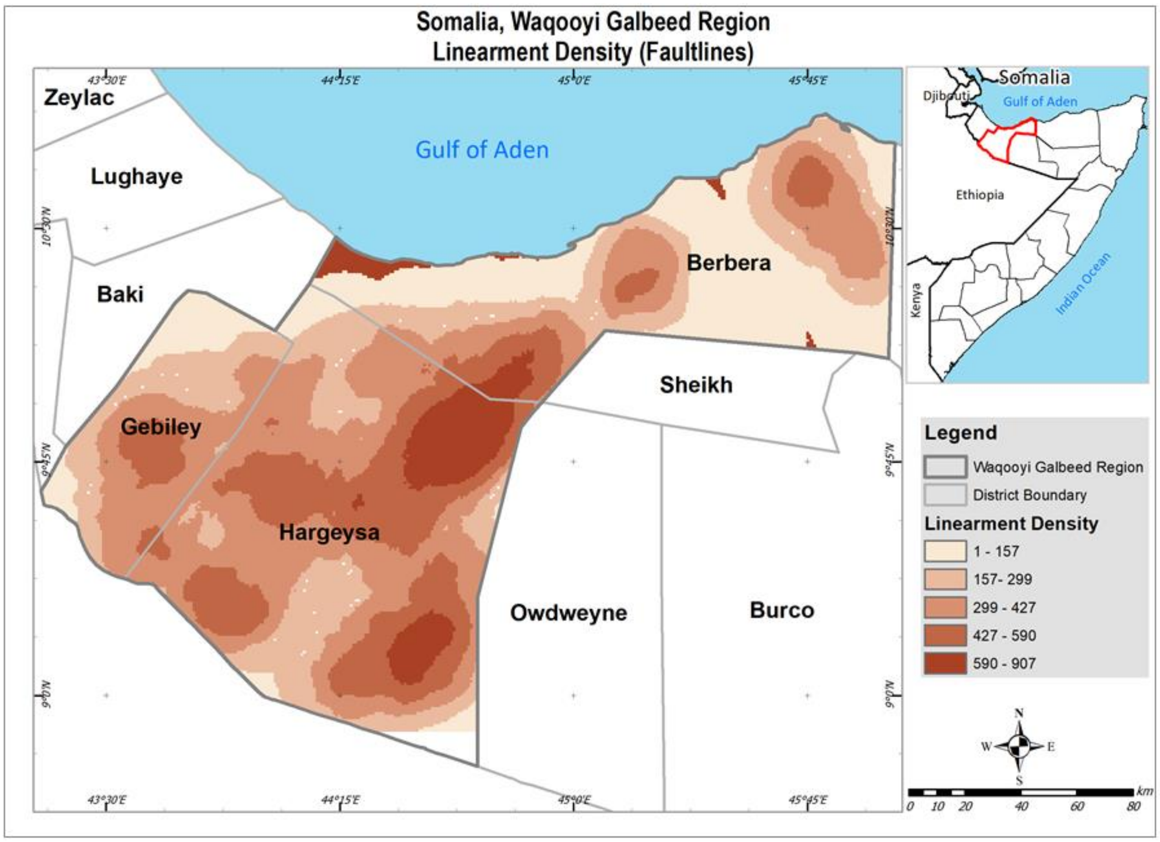

Figure 12: Lineament density map for groundwater potential

As discussed in chapter 4, high density lineaments makes it easier for water to percolate into the ground to recharge aquifers. Therefore, from the map below, dark brown areas denoted high lineament density compared to lighter brown regions. Considering lineament density alone, suitability decreases with the decrease of density. Therefore dark brown zones were more suitable mostly around the central, southern and part of the north-eastern part of the study area.

4.3 Land Use Land Cover suitability map for groundwater potential

The map in Figure 13 below shows land use land cover classes in the study area.

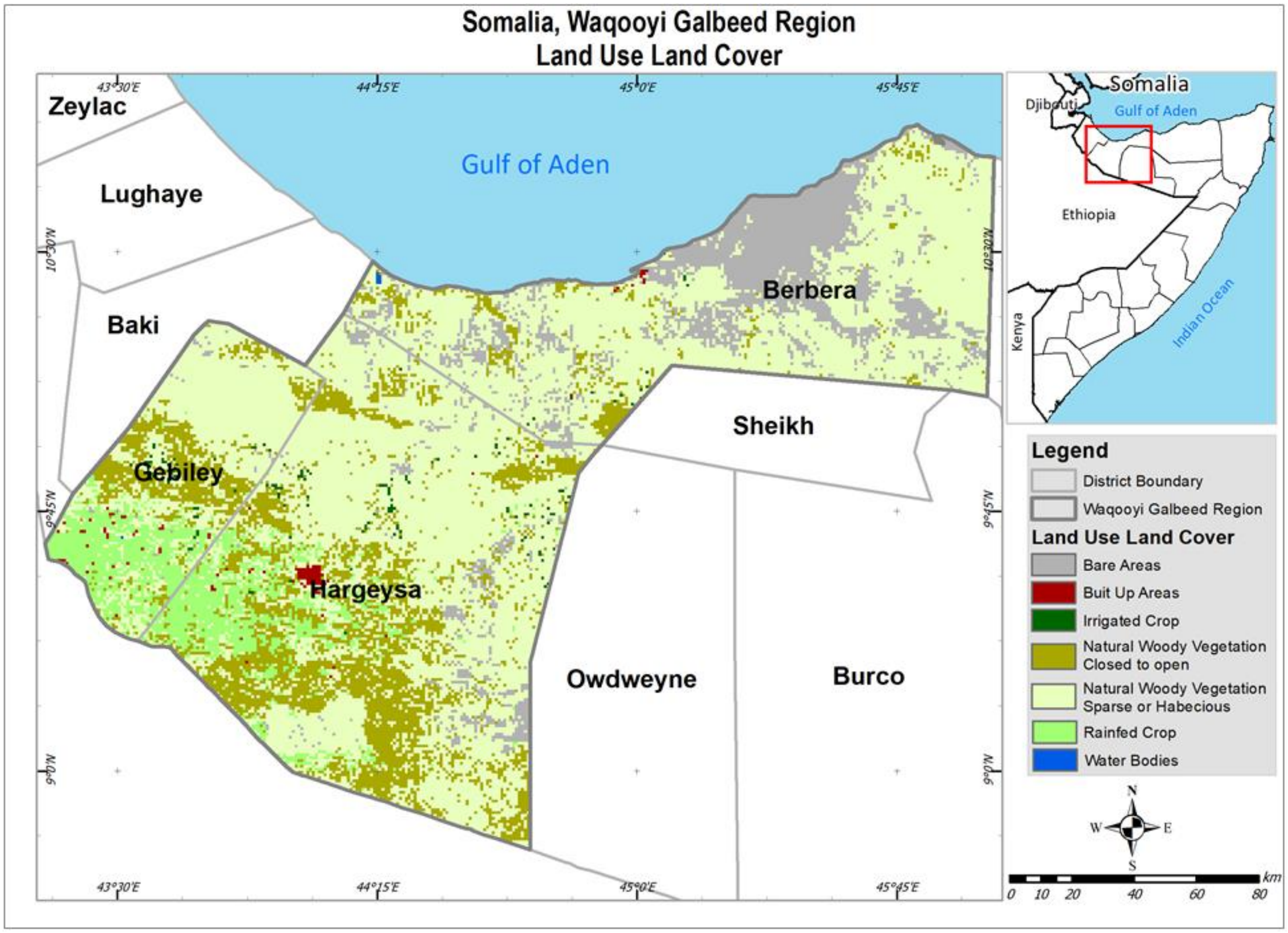

Figure 13: Land use land cover map for groundwater potential

The land use with more surface cover was considered suitable for groundwater potential occurrence than bare ground. Therefore, the most suitable land use land cover type were water bodies, followed by natural vegetation, irrigated agriculture, rain fed agriculture, built up areas and finally bare areas. From the map, potential areas for groundwater occurrence were around south-western and southern part of Hergeysa and Gibiley districts respectively. The northern part of the study area was generally considered low potential due to the existence of bare areas especially the north- eastern part of Berbera district.

4.4 Rainfall suitability map for groundwater potential

Figure 14 below shows long term mean rainfall from 1983 to 2019 of the study area.

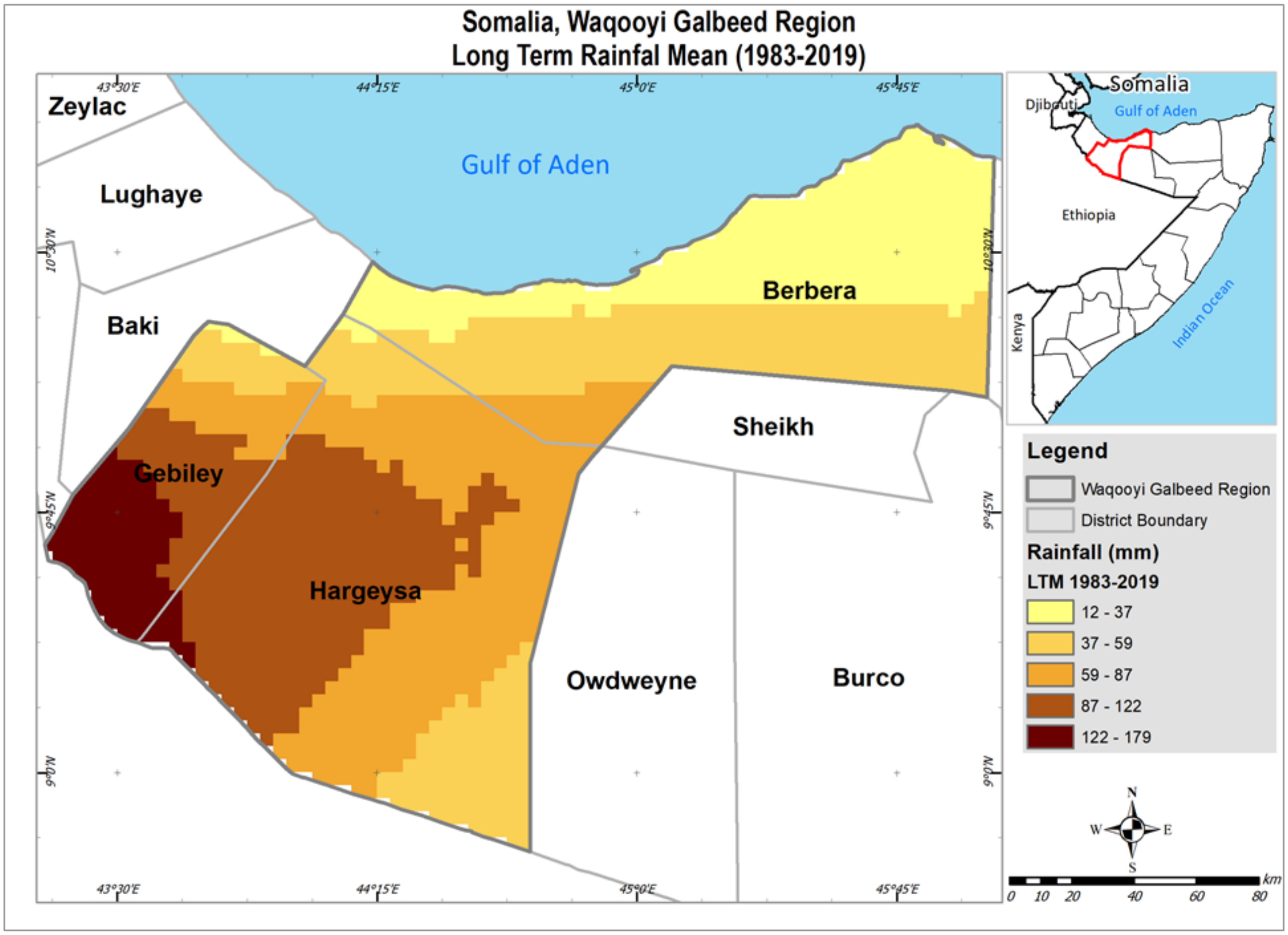

Figure 14: Long term mean rainfall map for ground water potential

The map shows that areas along Ethiopian boarder and part of Hargeysa district receive relatively high mean rainfall of between 87mm-179mm.These areas were considered potential for groundwater occurrence as discussed in chapter 4. Based on rainfall as a factor, the northern and south-eastern part of the study area was considered less suitable because they receive reduced mean rainfall between 12mm -37mm.

4.5 Slope suitability map for groundwater potential

Figure 15 below shows a slope map of the study area derived from 30m SRTM DEM.

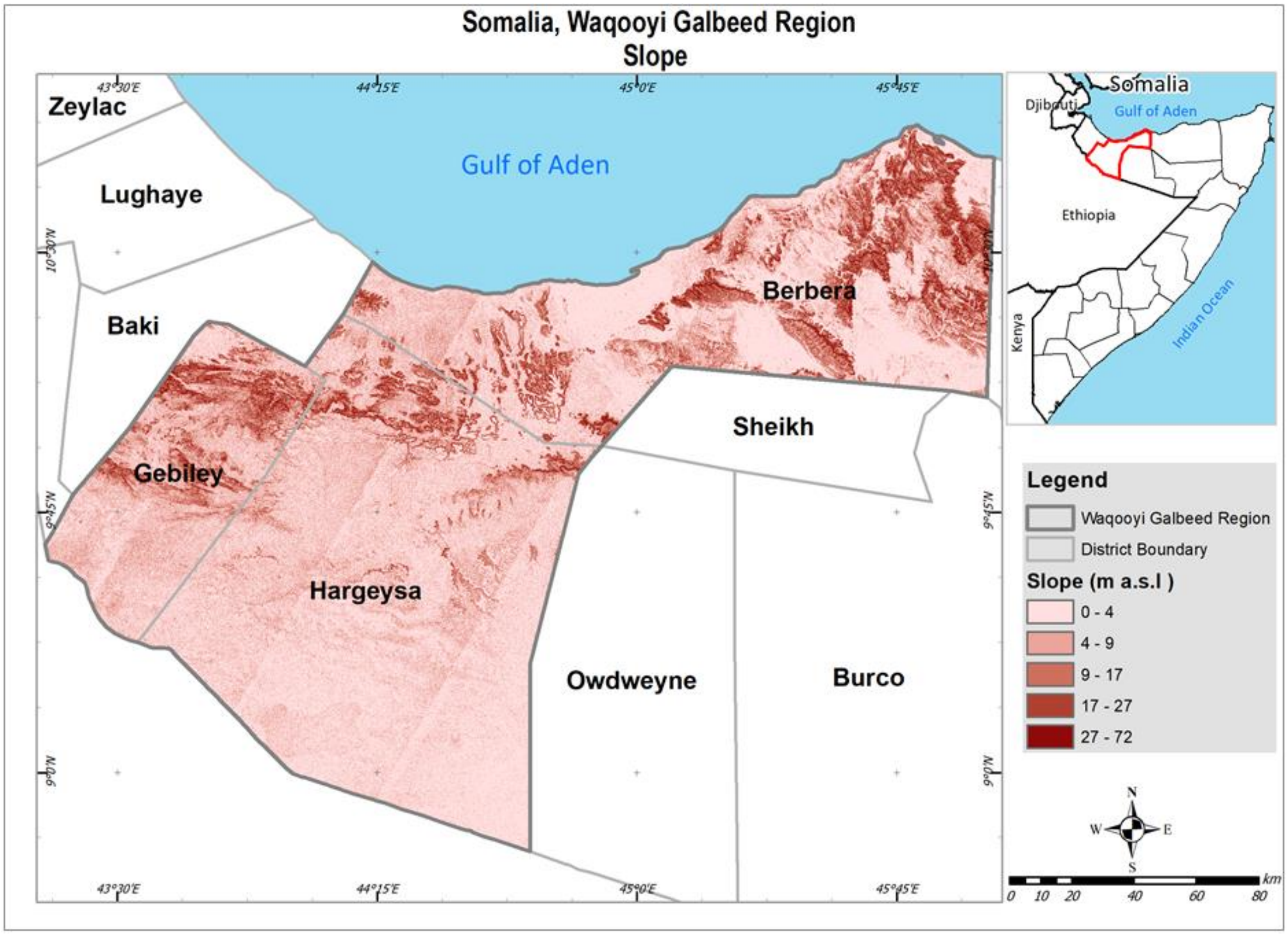

Figure 15: Slope map for groundwater potential

Slope relate to the occurrence of groundwater inversely as discussed in literature review in chapter 4. The higher the slope, the lower the potential for groundwater occurrence. The slope map above shows the low lying areas which were considered suitable areas for groundwater occurrence while the high areas were considered poor potential zones. From the map, low lying areas fell on the southern part of the study area while the northern areas were relatively higher. This led to a conclusion that, based on the relationship between slope and potential groundwater occurrence, the southern area (light brown) of the area was considered more suitable while the northern region (dark brown) less suitable.

4.6 Soil suitability map for groundwater potential

The map in figure 16 below shows different soil groups in Woqooyi Galbeed region.

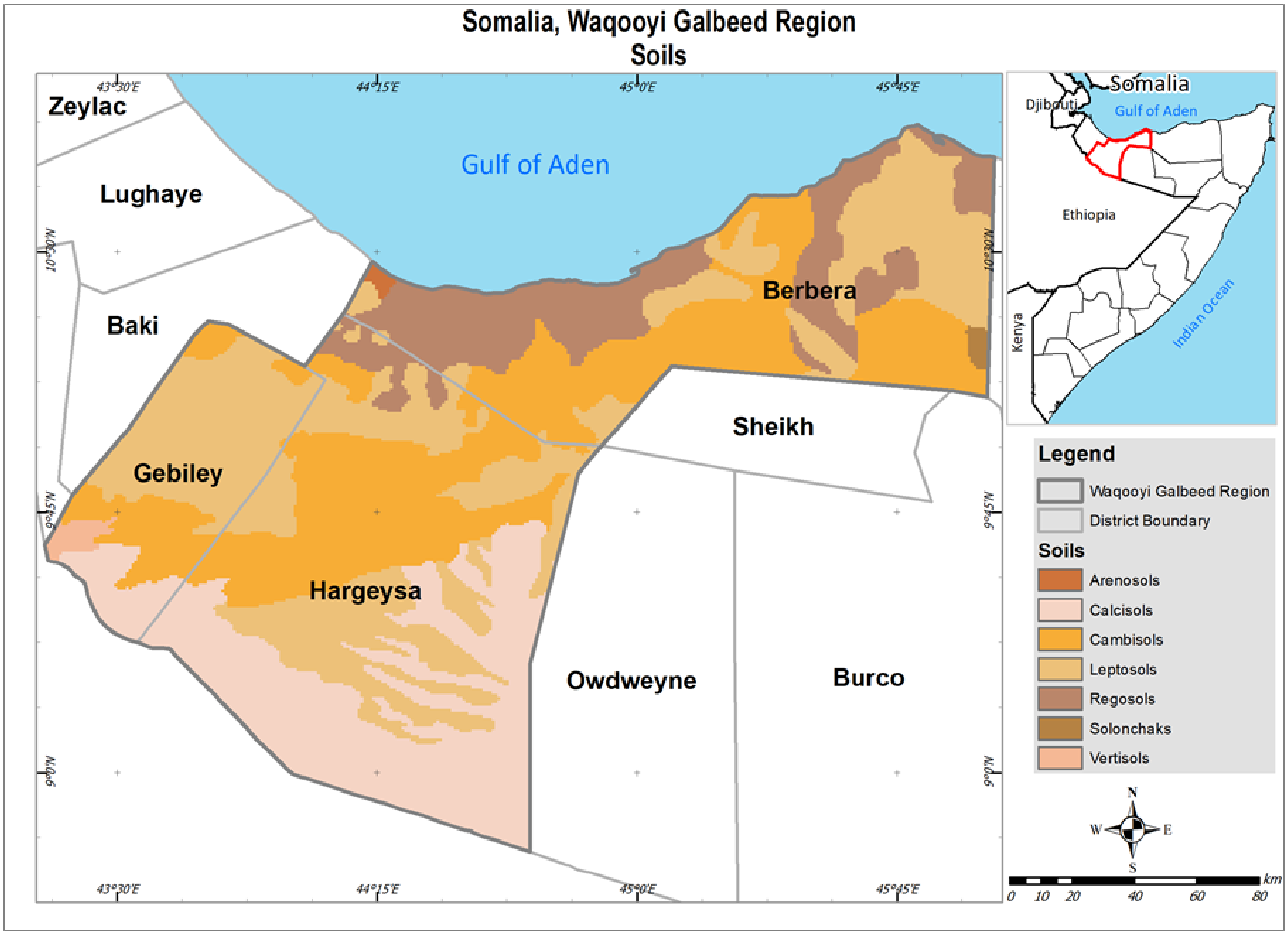

Figure 16: Soils map for groundwater potential

The map above show seven soil groups that were identified within the study area. Soil hydraulic conductivity determines its ability to allow water to recharge underground aquifers. The hydraulic properties of these soils were extensively discussed in chapter 4.The groundwater occurrence potential rankings (1-5) of the soils present in the study area was conducted. The ranking was based on the hydraulic properties; porosity and permeability resulting in the following order; Laptosols (5), Regosols (4), Arenosols (3) ,Cambisols (3) ,Calcisols (3) Solonchaks (2) and Vertisols (1) .It is important to mention that Solonchaks are too salty and therefore could compromise the water quality. Based on soil rankings, it was evident that most of the study area is relatively suitable for groundwater occurrence except small portions of Vertisols soils on the far south-western part and Solonchaks soils on the far north-eastern part.

4.7 Drainage density suitability map for groundwater potential

The map in Figure 17 below shows drainage density of the study area. The density was derived from drainage network that was delineated from 30m SRTM DEM.

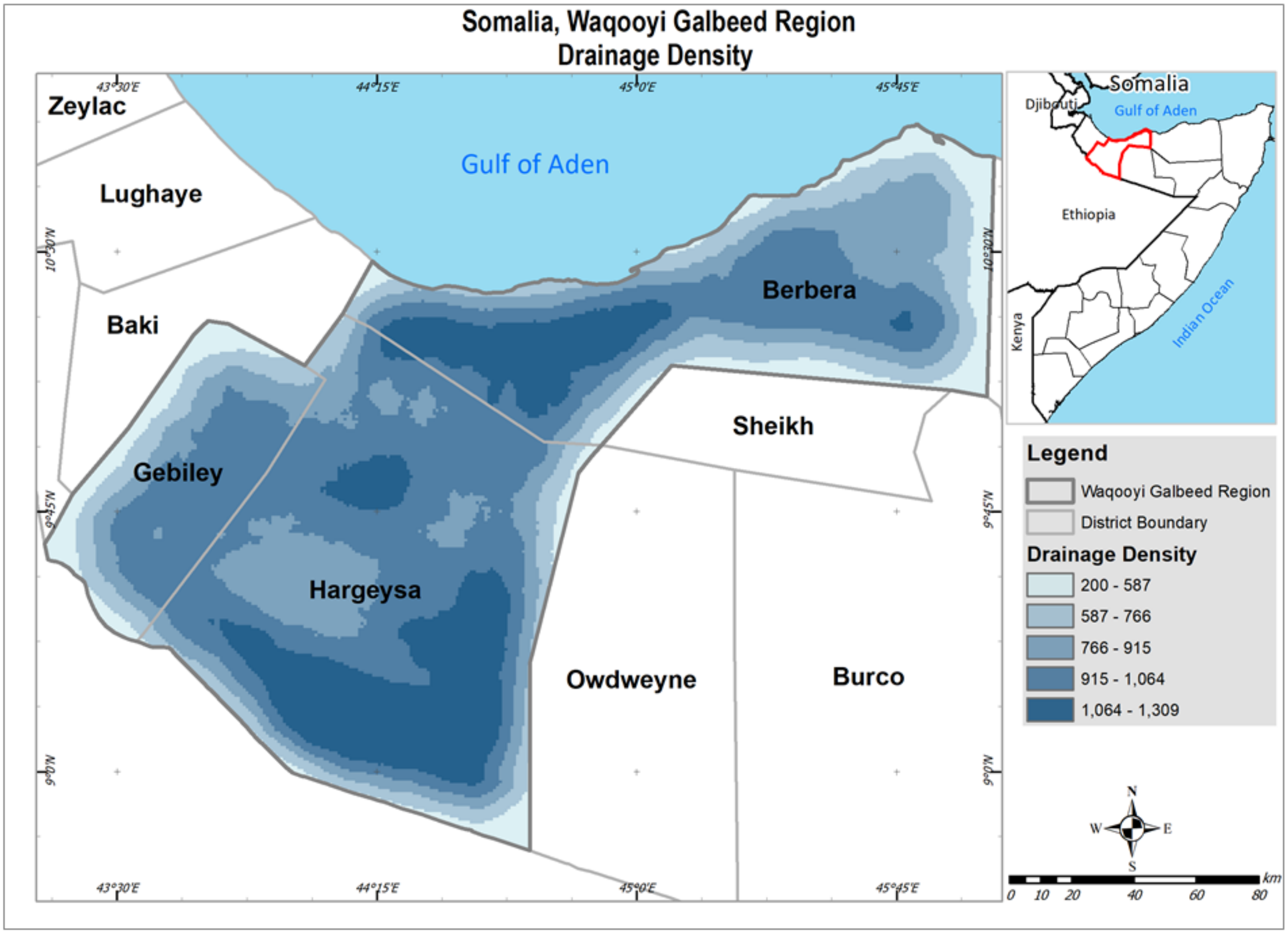

Figure 17: Drainage density map for groundwater potential

The areas with high drainage density (dark blue) as shown on the map, were considered high potential zones for groundwater occurrence while areas with low drainage network density (light blue) were considered poor potential zones. Considering drainage density in determining the suitability of groundwater occurrence, the map above indicates that south-eastern part of the study area, northern portion and small part of the central region were highly potential areas.

4.8 Groundwater potential zone map

Figure 18 below shows a groundwater potential map of the study area.

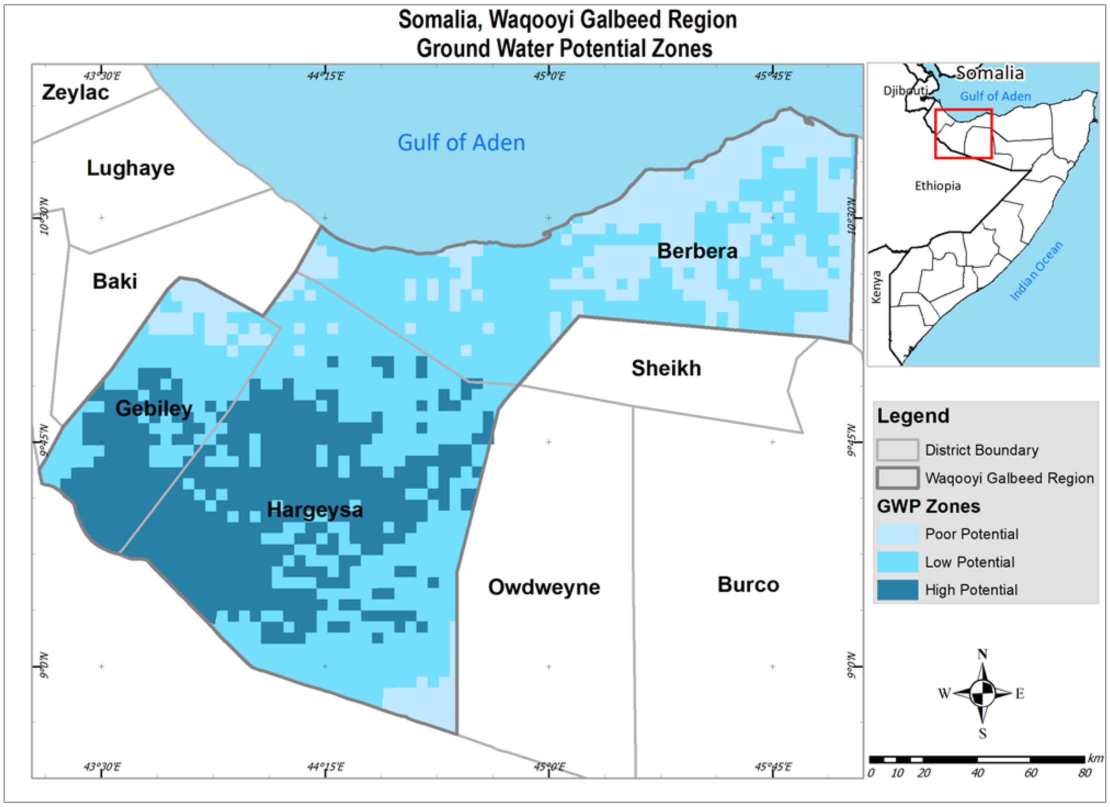

Figure 18: Groundwater potential zones map

The map was produced through a weighted overlay analysis process by considering the seven thematic layers. The map show three zones of poor, low and high potential groundwater occurrence zones. South-western region of the study area emerged as high potential zone. South-eastern and northern part of Hargeisa district stood out as low potential zones and northern Gebiley district and portions of eastern part of Berbera district were poor potential zones. From the table below, a large portion of the study area is a low potential zone for groundwater occurrence.

Table 1: Estimate of groundwater potential zones in the study area

Ground Water Potential zone Size			
No	Zone	Area (Sq Km)	Percentage of AOI
1	Poor Potential	5,594	20%
2	Low Potential	14,548	51%
3	High Potential	8,137	29%
Total		**28,279**	

4.9 Analysis Result Validation

4.9.1 Groundwater Potential zones with existing boreholes

The map in figure 19 below, shows an overlay of existing boreholes and groundwater potential zones.

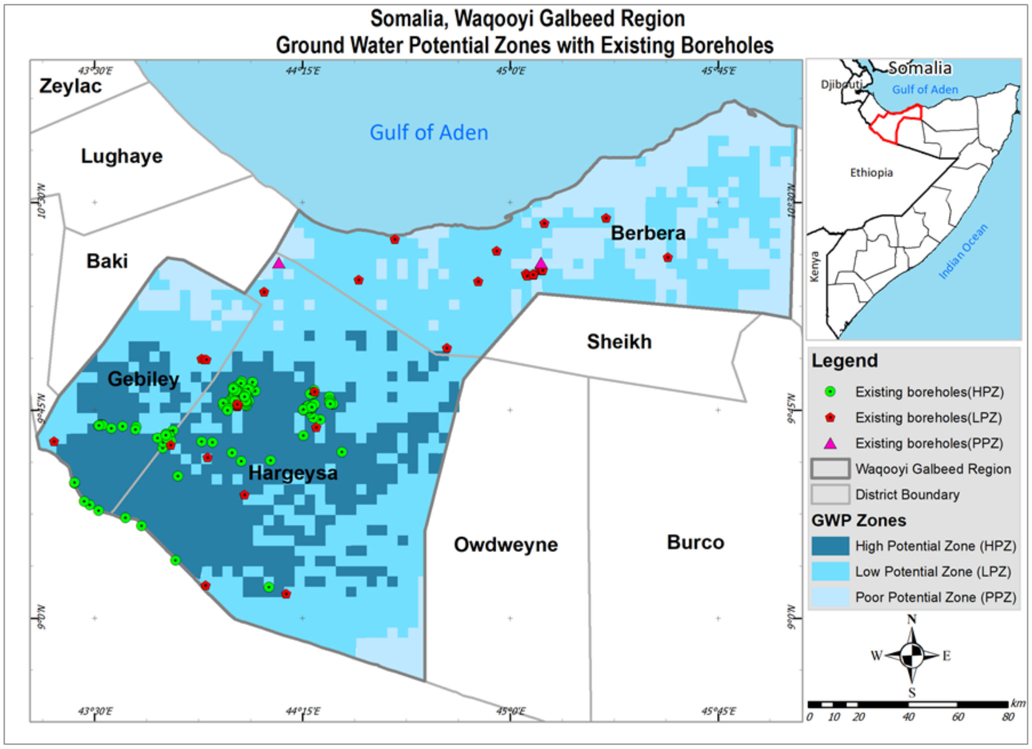

Figure 19: A map of groundwater potential zone and the existing boreholes

The existing boreholes dataset, updated in 2020 by FAO SWALIM, showed that 186 boreholes were within the area of study. Although, according to available data, there were other surface water sources within the area, boreholes were isolated because they are the best method for exploration of groundwater. From the analysis, there were 146 boreholes within high groundwater potential zone (HPZ), 38 boreholes in low groundwater potential zone (LPZ) and finally, 2 boreholes in poor potential zone (PPZ). This translated to 78.5 %, 20.4% and 1.1% respectively.

The findings gave an indication of what was possibly happening on the ground in terms of borehole siting through the use of geophysical survey. The revelation implied a high confidence validation of the groundwater potential weighted overlay analysis and counter-validation of geophysical survey methods used to site the existing boreholes.

The characteristics of the existing boreholes within Woqooyi Galbeed region were further studied for in depth understanding. It was done by analysing borehole depth, borehole yield, and borehole recovery time as well as borehole static level. In the table 2 below, it is evident that boreholes located within high groundwater potential zone have a higher water yield range compared to the low and poor potential zones. Despite of more boreholes being concentrated within high potential zones, a look at the information on the borehole depth within the poor potential zone, indicated that water table was high at the locations of the two boreholes. This inconsistency could not be explained but perhaps, there could be either a fault line emanating from outside the location or the fact that there has been no study yet in Somalia on the movement pattern of ground water.

Table 2: Borehole characteristics per groundwater potential zone

Ground Water Potential zone Size & Existing Borehole chracteristics									
No	Zone	Area (Sq Km)	Percentage of AOI	Number of Boreholes	BH Depth Range(m)	BH Yield Range (m3/hr)	BH Recovery Range(Hrs)	BH Static Level(m)	PH Range
1	Poor Potential	5,594	20%	2	70 to 80	8 to 35	1	50 to 40	7.6 to 7.9
2	Low Potential	14,548	51%	38	30 to 400	2 to 45	1 to 6	5 to 360	7.0 to 8.3
3	High Potential	8,137	29%	146	30 to 377	1 to 60	1 to 6	2 to 245	6.5 to 8.55

The PH ranges of water in all of the existing boreholes indicated being within a normal drinking water range of 6.5 to 8.5 according to U.S. Environmental Protection Agency (EPA).This could be attributed to none of them falling within *Solonchaks* soil group.

4.9.2 Groundwater Potential zones with Road network and settlements

The map in figure 20 below shows settlements distribution and road network within the study area. The map shows that the existing boreholes were concentrated in spots and not evenly distributed within the high potential zone. From field information, Somali community is pastoralists in nature, therefore, water sources including boreholes, are strategically placed along routes used by animals. They to provide water during animal movements, either to markets or in search for pastures. Another contribution, is the economic and logistical reasons during boreholes surveys and drilling. The settlements within the high potential groundwater zone with low accessibility are forced to establish surface water sources such as dams, wells, and berkads-sub surface reservoir for collecting rain water, or rely on natural sources for their water needs such as springs. The quality of water from these sources cannot be compared to ground water.

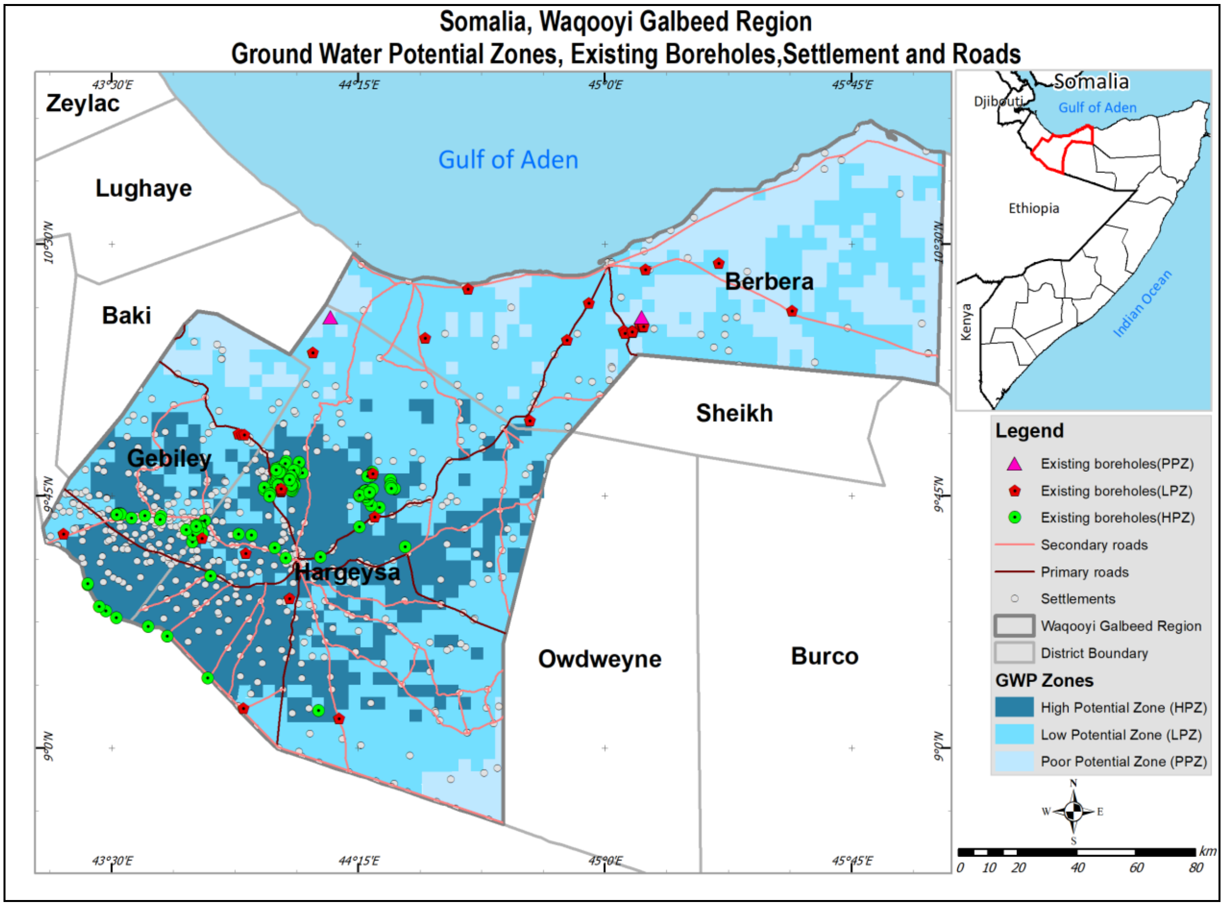

Figure 20: A map of settlements, road network, existing boreholes and ground water potential zones

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Through the use of geospatial technologies by carrying out weighted overlay analysis of seven thematic layers, groundwater potential zones map produced, revealed existence of three groundwater potential zones. These were; high groundwater potential zone which accounted for 29% of the study area, low potential zone (51%) and poor potential zone (20%).

The validation results indicated that 78% of existing boreholes fell within the region predicted as high potential groundwater zone. Therefore, it was deduced that the model agreed to a larger extent with the geophysical survey methods used in siting existing boreholes. However, it was evident from the map shown in figure 20 above, that existing boreholes were congested in particular areas and unevenly distributed within the groundwater potential zones as predicted by the model.

The uneven distribution was attributed to the fact that the geophysical methods used, had limited extent of predicting suitable borehole siting locations. Boreholes within high groundwater potential zone, exhibited low depths compared to those in low potential zones. The findings emphasised that high water table existed in high groundwater potential zone.

The methodology and results of the study revealed the possible power of geospatial technologies in narrowing down to potential locations where detailed geophysical survey can be carried out to determine other factors such as water quality and groundwater volumes.

Finally, it is important to note that the result of the model could have been even better if important datasets such as boreholes logs within the study area was available and incorporated.

5.2. Recommendations

The following were the recommendations drawn from the study;

The two methods should be used side by side with geospatial techniques preceding geophysical survey methods, to achieve best results, minimise costs and optimize cumulative time of groundwater exploration by borehole drilling.

A study on *'Groundwater Movement Pattern'* should be carried out to better understand some unusual behaviour of boreholes exhibiting good characteristics while they exist is poor potential zone.

Agencies working in water and sanitation (WASH) sector, should utilize the model to evenly optimize ground water exploration in Somaliland.

Somaliland government should create a legislation to compel all boreholes logs in the country, done by different actors in water and sanitation sector, to be submitted to relevant government agency for archiving and maintenance. This will enhance hydrological studies within the country and as consequence optimize the exploration of deep waters.

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